Doctoral Dissertation

Energy-saving Modifications Through Passive Cooling for Urban Houses in Hot-humid Climate of Malaysia

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Abstract

The aim of this doctoral thesis was to develop the comprehensive energy-saving modification techniques through passive cooling for existing urban houses in the hot-humid climate of Malaysia. In the current urban areas of Malaysia, majority (41% as of 2016) of the existing housing units are terraced houses, which are mostly constructed using bricks for their outer walls. The use of large thermal mass building materials along with the lack natural ventilation often result in hot indoor conditions particularly during the night-time. Based on the literature review, there are two types of natural ventilation strategy that have potential to provide an acceptable indoor comfort condition without the required the energy for cooling. Those natural ventilation types are structural cooling (night-ventilation) and comfort ventilation (full-day ventilation). However, there is a trade-off in term of selection the optimum ventilation techniques in hot-humid climate. By the application of night-ventilation, the windows are closed during the daytime to prevent the heat fain from outdoor. However, this practice would increase the indoor relative humidity during daytime. On the other hand, the window will be opened during daytime in the comfort ventilation strategy and allow warm air to flow into the indoor condition. As a result, indoor air temperature increases closely as the outdoor. This study will investigate the optimum passive cooling strategies for modern urban houses in hot-humid climate especially in Malaysia by the application of natural ventilation and other passive cooling modification strategies.

The review in Chapter 2 focused on thermal comfort by natural ventilation and the passive cooling strategies for building. The review determined that due to climatic differences and lack of basic field data in hot-humid climate, both basic and comprehensive studies would be required to assist application and development of passive cooling techniques for the region.

Chapter 3 covered field measurement in the traditional Chinese shophouses (CSHs). The objective was to identify the thermal functions of internal courtyards in traditional CSHs located in the hot-humid climate of Malaysia. The aim is to provide useful passive cooling strategies for modern urban houses. In term of courtyard form, it was found that the daily maximum air temperature in internal courtyards can be explained using the sky view factor (SVF) and the height of the courtyard. In contrast, the daily minimum air temperature is determined by the difference in the heights of the building and walls that form the courtyard. Meanwhile the key parameter that affecting the absolute humidity in the courtyard is the ratio of the courtyard area to the entire building area. As for relative humidity, the parameter that

affecting the maximum value is the difference in the heights of a courtyard, while the height of the courtyard and the opening area of the courtyard influenced the its minimum value. The courtyard forms that characterized their thermal environments were classified into five types. In the detailed case study, it was found that the different types of courtyards performed different functions with respect to improving the indoor thermal comfort in the adjacent living halls. The living hall in CSH1 located adjacent to the deep and closed courtyard (Type 5) where the indoor air flow is almost absent. In daytime, the air temperature in both spaces (living hall and courtyard) maintained relatively low values in daytime by about 4.0ºC lower than the corresponding outdoor temperature. Meanwhile, the living hall in CSH3 located between two courtyards (Type 5 and 2) without partition wall. Cross ventilation generated by two courtyards increase the indoor wind speed to approximately 0.2 to 0.4 m/s. Though this inflow increased indoor wind speeds, it simultaneously increased indoor air temperatures. The daytime air temperature in the living hall was only 1.5ºC lower, on average, than the outdoor temperature. Based on the thermal comfort evaluation by operative temperature (OT) indices, the living hall of CSH 1 was considered superior to that of CSH 3 because of its lowered air temperatures. Nevertheless, when the evaporative cooling effect was taken into account by using SET*, the condition of CSH 3 was similar to that of CSH 1 because of its higher indoor wind speeds. Due to higher indoor wind speed and lower humidity level, it was concluded that the humidity in the living hall in CSH 3 was more tolerable than that in CSH 1.

Chapter 4 introduced the full-scale experimental house that has been constructed in 2015. The experimental houses were designed to represent the typical two-storey terraced house in Malaysia. As for the experimental purposes, the house has been constructed to be oriented to the north-south direction where better indoor thermal condition can be obtained based on the previous simulation. In addition, the forced ventilation fan (i.e. whole house ventilation, attic fan and master bedroom fan) and the slit windows were also installed into the building. Moreover, the party wall insulation has been installed to eliminate the thermal effects form the surrounding. Brief experiment has been conducted to investigate the effects of the end wall insulation under night-time and day-time ventilation. The results showed that the average air temperature and the surface temperature in the master bedroom of both house were almost similar under night-time and daytime ventilation condition. This indicates that the external wall insulation successfully eliminates the thermal effects from the surrounding. Therefore, fair comparison between the results in both houses can be obtained.

Chapter 5 discussed the results of a numerical simulation study. The full-scale experiment terraced houses was modelled using the TRNSYS and COMIS programs. The simulation has been conducted to investigate the effects of the modification techniques under structural cooling (night-ventilation) and comfort ventilation (full-day ventilation) strategy. Meanwhile, the modifications techniques considered in the study cases covered the application of strategies on the roof, wall, windows and the forced ventilation. The improvement of thermal condition in the master bedroom and the living hall is the main interest of this study. In the results of single modification under the structural cooling strategies, the high-reflective roof coating is found to reduce the maximum temperature the most by approximately 1.1°C. Meanwhile, the outside insulation for external wall was found to be more effective than the internal insulation in reducing the maximum temperature in the master bedroom. Among the modifications for windows considered in this analysis, the external shading gives the largest cooling effect for the maximum temperature, which is 0.9°C. Forced ventilation techniques by whole house ventilation is the most effective in reducing nocturnal operative temperature. The whole house ventilation reduces the minimum temperature by approximately 0.8°C, while it reduces maximum temperature of the next day due to the structural cooling effect by approximately 0.4°C. Meanwhile, in the case of full-day ventilation, the cooling effects of respective modifications on the maximum temperatures are reduced to approximately 0.1-0.6°C compared to the former ventilation strategy. The simulation of combined techniques was conducted to find the optimum combinations of modification techniques to reduce with the aim to reduce nocturnal operative temperature as much as possible in the master bedroom, whereas to minimize the exceeding period of operative temperature in the living room. In the case of structural cooling strategy, the optimum combination to reduce the nocturnal operative temperature in the master bedroom is by the application of whole house ventilation, external shading of window, external outside insulation and low-E glass where the total reduction is about 1.2°C. As for the living room, the external shading is better able to reduce the maximum operative temperature with the specific reduction of about 0.6°C. The external wall outside insulation was chosen as the next option, followed by the roof insulation. In the case of comfort ventilation, the resulting combination techniques is similar to that of structural cooling. As for the living room, the external shading is found to be the most effective, followed by the external wall outside insulation, the whole house ventilation and roof insulation. The optimum combinations of energy-saving modifications for the experimental houses were determined by combining the optimum combinations for the master bedroom and the living room. As a result, the proposed modifications include roof insulation, external wall outside insulation, external shading, and whole house ventilation.

Chapter 6 presented the results of full-scale experiment in the experimental house with the proposed modification techniques derived from the simulation studies. The purpose is to confirm the resulting effects of the proposed energy-saving modification techniques. It was found that, the application of proposed modifications, i.e. roof insulation, external wall insulation, external shading and whole house ventilation successfully reduced indoor air temperatures by about 0.8°C during the day and night under the structural cooling strategy. In the case of comfort ventilation strategy, the temperature reduction during the night-time is about 0.7°C while only small reduction observed in the daytime. Nevertheless, the whole house ventilation was not able to reduce the nocturnal indoor air temperatures as low as outdoor in both cooling strategies. Ventilation through the slit window provided slightly larger reduction of indoor air temperature in the master bedrooms at night. It was also seen that the surface temperatures of inner walls, especially the ceiling, was cooler by up to 1.7°C when the slit windows were opened instead of the main windows at night. The resultant indoor thermal comfort of two different cooling strategies, i.e., structural cooling and comfort ventilation was evaluated by using operative temperature (OT) and SET*. Based on the results of OT in the master bedroom and living hall in structural cooling showed lower values than those of comfort ventilation. However, the SET* of these spaces in both cooling strategies was almost the same during the daytime (approximately 30.0°C and 30.3°C SET*).

Chapter 7 presented the detailed discussion on the results of the field measurement. the discussion focuses on the thermal comfort evaluation of the indoor spaces (i.e. master bedroom and the living hall), the effects of the passive techniques and the effects of window opening pattern., it was found that the cooling strategy of comfort ventilation is probably preferable than that by the structural cooling for the hot-humid climate of Malaysia. This is because the effect of lower humidity level and relatively high indoor wind speed can offset the effect of air temperature reduction obtained by structural cooling during daytime. The application of roof insulation, external (outside surface) insulation and external window shading successfully reduced the daytime air temperature in the master bedroom and the living hall. Meanwhile, the application of whole house ventilation is effective in providing lower nocturnal indoor air temperature in the respective indoor spaces (i.e. master bedroom and the living hall) compared to the master bedroom and attic ventilation. In term of window opening position, the application slit windows with the whole house ventilation under the night-time ventilation is found can reduce not only nocturnal air temperature of the master bedroom but also the surface temperature of the floor and ceiling. In the last section, the recommendation of energy-saving modifications for urban houses is discussed. As for natural ventilation strategy, the comfort ventilation strategy with other passive cooling modifications (i.e., roof insulation, external shading and whole house ventilation) is recommended for urban houses in the hot-humid climate.

Chapter 8 summarized the main findings of this study and recommended key areas for further studies based on the limitations of this thesis.

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This thesis was completed with the greatest continuous support from many people and organizations. Firstly, I would like to express my sincere appreciation to my academic advisor, Associate Prof. Tetsu Kubota, for giving me this opportunity to complete the thesis at the BUESA laboratory in the Graduate School for International Development and Cooperation of Hiroshima University. Throughout the development of the thesis, Associate Prof. Kubota has provided invaluable advice, knowledge, meaningful discussion and exemplary effort not only in the laboratory but also in field work. Also, I wish to thank my academic co-advisors, Prof. Zhang Junyi, Prof. Haruyuki Yamamoto, Prof. Daisaku Nishina and Associate Prof. Dr. Lee Han Soo, for examining my thesis and giving useful comments.

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List of Acronyms

ACH	Air changes per hour
ACS	Adaptive comfort standard
AIJ	Architectural Institute of Japan
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BSI	British Standards Institute
CO_2	Carbon dioxide
COMIS	Conjunction of Multizone Infiltration Specialists
CSH	Chinese shophouse
Din	Dining hall
F. A	Family area
H1	House 1
H2	House 2
IEA	International Energy Agency
ISO	International Organization for Standardization
Kitc	Kitchen
Liv_N	Living hall North
MB	Master bedroom

MBE	Mean bias error
MRT	Mean radiant temperature
N	North
NAPIC	National Property Information Centre
NUS	National University of Singapore
OT	Operative temperature
RH	Relative humidity
RMSE	Root mean square error
S	South
SET*	Standard effective temperature
SF	Shading factor
Stair	Staircase
SVF	Sky view factor
TMY	Typical meteorological year
TRNSYS	Transient Systems Simulation Program
UTM	*Universiti Teknologi Malaysia*
WMO	World Meteorological Organization

Nomenclature

C_{bg}	Background CO_2 concentration (ppm)
C_0	Initial CO_2 concentration (ppm)
C_f	Final CO_2 concentration (ppm)
D	Depth (m)
H_1	Height of front courtyard (m)
H diff.	Difference of courtyard height (m)
N	Air change rate
p	Significance value
$\dot{Q}$	Volume flow (m^3/s)
R^2	Coefficient of determination (-)
RH	Relative humidity (%)
T_a	Air temperature (°C)
T_g	Globe temperature (°C)
T_{upper}	Indoor comfort temperature (°C)
T_{neutop}	Indoor neutral operative temperature (°C)
T_{op}	Operative temperature (°C)
T_{outdm}	Daily mean outdoor air temperature (°C)

W	Width (m)
v	Indoor air speed (m/s)

List of Publications

Refereed Journal Papers

Kubota, T., **Zakaria, M.A.**, Abe, S., Toe, D.H.C. (2017). Thermal functions of internal courtyards in traditional Chinese Shophouses in the hot-humid climate of Malaysia. *Building and environment*, 112, 115-131.

Zakaria, M.A., Kubota, T. (2014). Environmental design consideration for courtyards in residential buildings in hot-humid climates: A review, *International Journal of Built Environment and Sustainability*, 1(1), 45-51.

Refereed Conference Papers

Zakaria, M.A., Kubota, T., Toe, D.H.C., Ahmad, M.H. Full-scale experiment on energy-saving modifications for urban houses in hot-humid climate of Malaysia. *In: Proceedings of Passive and Low Energy Architecture (PLEA 2017)*, July 3-5, Edinburg, Scotland.

Zakaria, M.A., Kubota, T., Toe, D.H.C. (2015). The effects of courtyards on indoor thermal conditions of Chinese shophouse in Malacca, *Procedia Engineering*, 121, 468-476.

Zakaria, M.A., Kubota, T., Abe, S. (2015). Indoor thermal environments in traditional Chinese shophouses with courtyards. *In: International Joint conference SENVAR-iNTA-AVAN (SiA 2015)*, Nov 24-26, Universiti Teknologi Malaysia (UTM), Skudai, Malaysia.

Non-Refereed Conference Papers

Kubota, T., **Zakaria, M.A.**, Ohashi, M. (2017). Full-Scale Experiments on Energy-Saving Modification for Existing Urban Houses in Malaysia Part 1. Numerical simulation on optimum combinations of passive cooling techniques. In: *Summary of Technical Papers of Annual Meeting, AIJ, 2017*, Aug 31- Sep 3, Hiroshima, Japan.

Zakaria, M.A., Kubota, T. (2017). Full-Scale Experiments on Energy-Saving Modification for Existing Urban Houses in Malaysia Part 2. Results of full-scale experiments. *In: Summary of Technical Papers of Annual Meeting, AIJ, 2017*, Aug 31- Sep 3, Hiroshima, Japan.

Zakaria, M.A., Kubota, T., Abe, S. (2016). Effect of courtyard form on its indoor thermal environments in traditional Chinese shophouses in hot-humid climate of Malaysia. ISAIA 2016, September, Tohoku, Japan.

Ohashi, M., **Zakaria, M.A**., Kubota, T. (2016). Cooling effects of forced ventilation techniques for urban terraced houses in hot-humid climate of Malaysia. *In: Summary of Technical Papers of Annual Meeting, AIJ, 2016*, 24-26 Aug, Kyusyu, Japan.

Abe. S., **Zakaria, M.A.**, Kubota, T. (2016). Field investigation of thermal comfort in traditional Chinese shophouses with courtyards in hot-humid climate of Malaysia Part 2. Thermal comfort evaluation. *In: Summary of Technical Papers of Annual Meeting, AIJ, 2016*, 24-26 Aug, Kyusyu, Japan

Kusunoki, T., Morishita, M., **Zakaria, M.A**., Kubota, T. (2015). Effects of whole house ventilator on indoor thermal comfort for urban houses in hot-humid climate of Malaysia. In: *Summary of Technical Papers of Annual Meeting, AIJ, 2015*, September 4-6, Tokai, Japan.

Abe, S., **Zakaria, M.A.**, Kubota, T. (2015). Effects of courtyards form on indoor thermal formation in traditional Chinese shophouses in Malacca. In: *Summary of Technical Papers of Annual Meeting, AIJ, 2015*, September 4-6, Tokai, Japan.

Zakaria, M.A., Kubota, T. (2014). Environmental design considerations for courtyards in hot humid climate: A review. *In: Grand Renewable Energy 2014 International Conference and Exhibition (GRE2014)*, July 27-August 1, Tokyo, Japan.

1. Introduction

1.1 Backgrounds

1.1.1 Energy consumption and carbon dioxide (CO2) emissions in residential sector in developing countries

The rapid growth in economic development and population has led to the increase in world energy demand and this trend is expected to continue in the future. The countries in Asia and the Pacific are predicted to have a rapid growth of energy consumption than the world average between 2010 to 2035 with their primary energy demand is projected to increase about 2.1% per year (APEC,2013). In fact, among the countries in Asia and the Pacific, the primary energy demand in developing region is projected to increase faster than the developed region at about 2.3% per year during the same period.

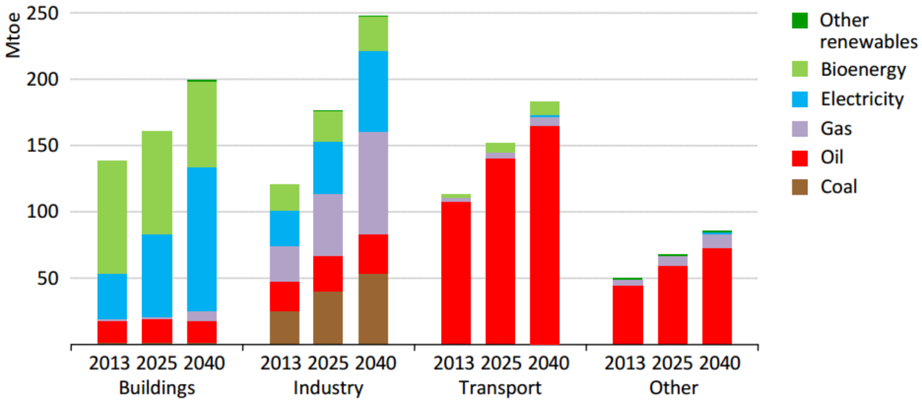
As a developing region, the growth of energy consumption in Southeast Asia is predicted to be the third-largest in the future behind the East Asia and South Asia region. Based on the latest report in Southeast Asia Energy Outlook 2015 (IEA, 2015), the total primary energy demand of Southeast Asia will grow by about 80% from 2013 to 2040, increasing from 594 million tonnes of oil equivalent (Mtoe) to 1070 Mtoe (Table 1.1). As a result, the total increase of the primary energy demand in Southeast Asia is accounted about 4% of global energy demand.

In most of developed countries, building sector is one of the largest energy end-use sectors which their energy consumption is higher than the industry and transportation sector. Globally, buildings sector is accounted for about 40% of the total primary energy requirement and contribute to more than 30% of the carbon-dioxide (CO_2) emissions (Costa *et al.*, 2013). Meanwhile, in the developing region of Southeast Asia, the energy demands in the buildings represent the second-largest after the industry sector. Figure 1.1 shows the final energy consumption by fuel and sector in Southeast Asia from 2013 to 2040 (IEA, 2015). As shown, the energy demand in buildings, which includes residential and services, grows at an annual average of 1.4% between 2013 and 2040 and the increment is larger than the transportation and other sectors.

Table 1.1. Primary energy demand in Southeast Asia (Mtoe).
Source from IEA, 2015.

					Shares		CAAGR*
	1990	2013	2020	2040	2013	2040	2013-2040
Fossil fuels	131	437	547	838	74%	78%	2.4%
Coal	13	91	151	309	15%	29%	4.6%
Gas	30	133	149	220	22%	21%	1.9%
Oil	89	213	247	309	36%	29%	1.4%
Nuclear	-	-	-	8	-	1%	n/a
Renewables	102	156	169	223	26%	21%	1.3%
Hydro	2	9	10	22	2%	2%	3.1%
Bioenergy	93	122	127	134	21%	13%	0.4%
Other **	7	25	32	67	4%	6%	3.8%
Total	233	594	716	1 070	100%	100%	2.2%

*compound average annual growth rate. ** Include solar PV, wind, and geothermal.

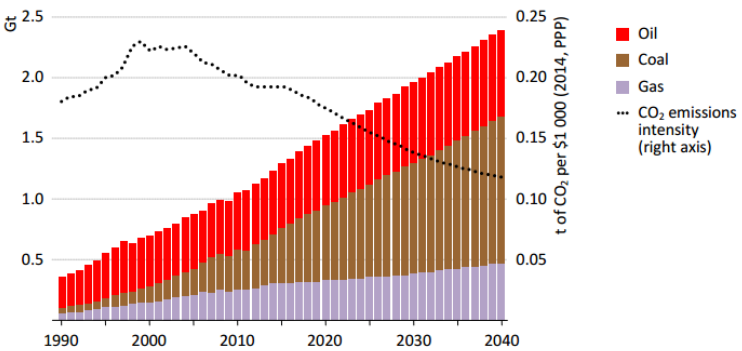


Notes: Building sector includes residential and services. Other includes agriculture and non-energy use. Other renewables include solar PV, wind and geothermal.

Figure 1.1. Final energy consumption by fuel and sector in Southeast Asia.
Source from IEA, 2015.

The biggest share of electricity consumption in the buildings is mainly contributed by the building's appliances which accounted for over half of residential electricity demand by 2040, followed by cooling (IEA, 2015). The increase in energy demand in the residential buildings is driven by several key factors such as the rise of living standards, urbanization and the improvement of electricity access in the rural areas. Meanwhile the energy used in commercial and institutional buildings are expected to be increased more than doubles due to the rising demand for electricity for lighting, appliances and cooling.

Since the main source of energy of this region is by the fossil fuels, the increase in the energy demand will reflect the level of CO_2 emission. Currently, the oil is the largest contributor for the CO_2 emissions in the region, but it is expected to be overtaken by coal before 2020. The coal is accounted to contribute about half of the CO_2 emission in the region followed by oil and natural gas at 30% and 20% respectively (Figure 1.2). Compared to the global averages of CO_2 emission, Southeast Asia has a high-carbon intensity per dollar of gross domestic product (GDP). Nevertheless, the intensity of CO_2 emission is expected to decrease in the future due to the development of environmental policy promoting to shift from the usage of higher carbon content fuels such as coal and oil to less carbon-intensive energy such as nuclear, natural gas, and renewable energy (APEC, 2013). Therefore, the carbon intensity in Southeast Asia improves significantly by 2040, falling by nearly 40% compared with 2013.



Notes: T=tonnes, PPP= purchasing power parity; Gt=gigatons

Figure 1.2. CO_2 emission from fossil fuels and CO_2 emission intensity in Southeast Asia, 1990-2040.

Source from IEA 2015.

1.1.2 Energy consumption and carbon dioxide (CO2) emissions in Malaysia

Malaysia has the third-largest economy in Southeast Asia and it is also representing the third-largest energy consumption per capita in the region (Figure 1.3). As shown, the final energy consumption per capita of Malaysia has increased from 0.01 Mtoe/million to 1.54 Mtoe/million between 1971 to 2012. This trend is expected to increase in the future where the primary energy demand is estimated to be increased by almost doubled from 89 Mtoe in 2013 to 160 Mtoe in 2040 (IEA,2015). The energy demands will grow at an average annual rate of 2.2% per year. Fossil fuels remain dominant in Malaysia's energy mix where the share exceeding 90% by 2040. The demand for renewables energy will increase nearly double by 2040 with their share of electricity generation rising to 16%. In 2014, the energy consumption in buildings, i.e. residential and commercial, is accounted for the third-largest with the share of 14% after the transportation (46.6%) and industrial (25.2%) sector.

In the building sector, the energy consumption of the residential buildings has been increased by more than threefold between 1998 to 2014 (Malaysia Energy Information Hub, retrieved from http://meih.st.gov.my/statistics). As shown in Figure 1.4, the energy demand was increased with the increase in population in Malaysia. Along with the economic growth, the increase of energy consumption can be related to the increase in the living standards. In general, the increase in population, enhancement of building services and comfort levels, together with the rise in time spent inside buildings will contribute to the increase of energy in buildings compared to the other sectors (Perez-Lombard *et al*., 2008).

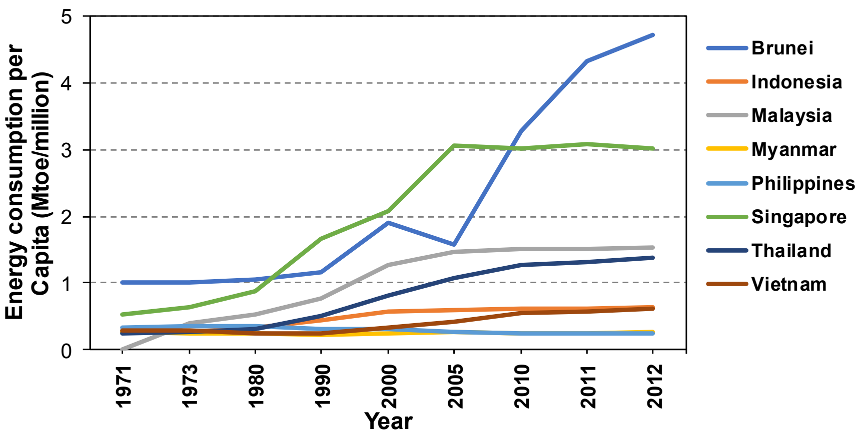


Figure 1.3. Energy consumption per capita in ASEAN countries.
Source from Malaysia Energy Statistics Handbook 2015.

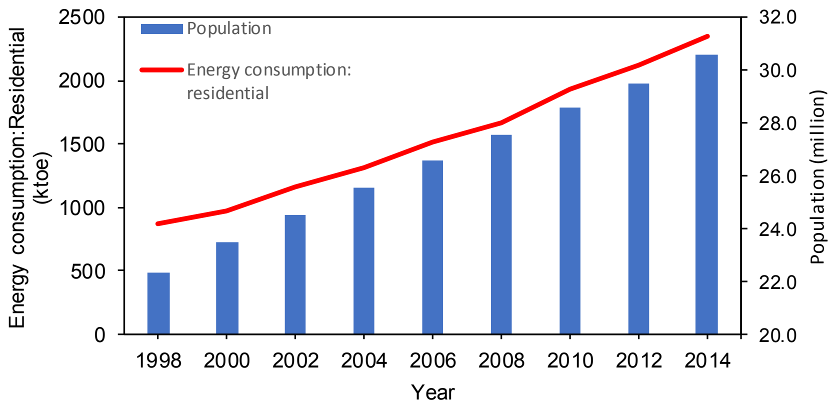


Figure 1.4. Population and energy consumption in residential sector
Source: Department of Statistics Malaysia, Malaysia Energy Information Hub, retrieved from http://meih.st.gov.my/statistics

Final energy consumption in the residential buildings in Malaysia can be divided into five main categories, i.e. home cooking, space cooling, lighting, laundry/cleaning and others. Jeong *et al.* (2010) found that space cooling accounted for 29% of total energy consumption which is the second-largest after cooking. In Malaysia, it has been reported that the increase in the energy consumption in buildings could be attributed by the electricity consumption from the air conditioning since the ownership expand among households for more than three folds from 1990 to 2000 (Mahlia *et al.*, 2004). In general, the heating, ventilation and air-conditioning (HVAC) installations are required in response to the growing demand for better thermal comfort within the built environment (Yang *et. al.*, 2014). Considering the significant increase in cooling load in the buildings, the development of strategies to improve the building thermal performance and of innovative technologies are required for reduce the energy consumption.

Malaysia is currently accounts for over one-sixth of Southeast Asia's total energy-related CO_2 emissions and the share is expected to remain stable until 2040. The major contributor is from the power generation sector where the total CO_2 emissions grows by 14% from 2013 to 2040 and represent about half of the total CO_2 emission. Meanwhile, the buildings sector is the least contributor for the CO_2 emission. However, because of the increasing trend of the energy consumption in building (i.e. residential and commercial), the preventive measures are required in order to contribute a lower CO_2 emission in Malaysia.

1.1.3 Urban houses in Malaysia

In Malaysia, modernization and mass construction of residential buildings have occurred alongside the rapid economic growth. As a result, the number of residential buildings has increased about 27% from 2006 to 2016 (NAPIC, 2016). The urban houses in Malaysia can be divided into eight categories, i.e. terraced, semi-detached, detached, townhouse, cluster, low-cost house, flat and condominium/apartment. In the recent years, the terraced-house is accounted as the largest housing stock in Malaysia which is about 41% compared to the other types of residential building (NAPIC 2016).

Terraced houses are constructed of high thermal mass materials such as brick and concrete for their outer walls (Department of Statistics Malaysia, 2012). They are constructed as a single storey or double to three storey. However, the double storey is much known as a typical design of a terraced house in Malaysia since their numbers are larger than that of single storey. The terraced houses are built in a row and shared party walls with the adjacent houses. Therefore, the available openings (windows) are located at only on their two facades, i.e. front and back. This condition would reduce the rate of natural ventilation flow and the exposure of natural lighting to the indoor condition if the design of those openings is not being considered properly.

In terms of indoor thermal condition, high thermal mass buildings such as brick houses are known to store a large amount of heat during the daytime and release it at night. The use of large thermal mass building materials along with the lack natural ventilation often result in hot indoor conditions particularly during the night-time. Moreover, it has been reported that most of occupants in the typical Malaysian urban houses tend to open windows during the daytime rather than night time (Kubota *et al.*, 2009). This practice will create warmer indoor condition at night-time and as a consequent, the occupants tend to use air-conditioner at the night-time. This is probably one of the reason of the increase in air conditioner ownership among the households in Malaysia (section 1.1.2).

In general, the amount and type of energy used in dwellings are mainly related to weather, architectural design, energy systems and economic level of the occupants (Perez-Lombard *et al.*, 2008). Since the terraced houses represent the majority of housing unit in this country, the reduction of energy consumption in this type of building will largely contribute to the reduction of total energy by the residential buildings in Malaysia. Energy-saving measures in the form of passive cooling techniques is believed as one of the alternatives that can reduce the cooling load of the buildings, thus reduce the energy consumption in the houses.

1.2 Problem statement and research scope

As discussed in the previous sections, the energy consumption for space cooling especially for residential buildings has been particularly rising in growing cities of Southeast Asia, where hot-humid conditions continue throughout the year. Driven by the global warming and urban heat islands, the thermal comfort in the modern urban houses in Malaysia has been deteriorated due to the use of high thermal mass structure and inappropriate practice of ventilation techniques. Thus, the occupants tend to rely on the air-conditioner as a simple alternative to improve the thermal comfort in their houses especially at night. This practice will contribute to the increase in energy consumption of buildings and CO_2 emissions in the country.

As Malaysia is moving toward the modernization process, there has been little scientific reference about passive cooling techniques that are suitable to be applied in the modern houses. In addition, there are no specific requirement suggested in the building regulation of Malaysia (Legal Reseach Board, 2012) for the thermal performance and thermal comfort in houses. The scientific studies that attempt to improve thermal performance of urban terraced houses remain few and this could be a reason for the lack of proper building regulations and practice that can help in energy saving. Meanwhile, it is said that vernacular buildings have been subtly crafted over generations in response to experience of conditions and use (Oliver, 2006). In the case of Malaysia, the traditional Chinese Shophouses can be a good example as they are also constructed with a high thermal mass structure and located in the dense urban areas. However, the number of the scientific references are also limited especially on thermal function of the internal courtyards on its indoor environments in the hot-humid climate.

In terms of ventilation strategy, natural ventilation is a basic passive cooling method that can improve the indoor thermal condition and traditionally used in hot and humid climate However, since the modern buildings are constructed with heavy-weight brick-walled structure, the suitable ventilation techniques to be used in the modern buildings seem to be uncertain. Based on our review, there are two types of natural ventilation strategies that are suggested for the buildings in the hot-humid climate. They are comfort ventilation (full-day ventilation) and structural cooling (night ventilation). In general, comfort ventilation (windows are opened during daytime) can increase the indoor wind speed but also increase the indoor air temperature in the daytime. In contrast, when the structural cooling is adopted in a hot-humid climate (windows are closed during daytime), relative humidity tends to be high during the daytime, though the air temperature is reduced. This indicates that, there is a major trade-off in achieving indoor thermal comfort which is either by maintaining lower indoor air temperatures through reducing air-changes with the outdoors, i.e., night ventilation or increasing indoor wind speeds for sweat evaporation by improving natural ventilation while allowing an increase in temperature during daytime.

Figure 1.5 Typical modern terraced houses in Malaysia.

1.3 Research objectives

The main goal of this thesis is to develop comprehensive energy-saving modification techniques through passive cooling for existing urban houses in the hot-humid climate of Malaysia. In order to reach this goal, the objectives of the thesis are determined as follows:

1. To identify the traditional passive cooling techniques in Chinese Shophouses (CSHs) with the aim of providing useful cooling strategies for modern houses. We particularly focus on the thermal functions of internal courtyards in CSHs. It is most logical to firstly make scientific reference to past local buildings since they have been constructed over generation to incorporate passive systems in response to the climate of this region. Moreover, modern terraced houses in Malaysia are constructed of high thermal mass material and built in a row in the dense urban areas which is quite similar to the CSHs.

2. To develop and propose the energy-saving modification techniques that can improve the indoor thermal comfort of the modern terraced houses. In this work, we investigate the effects of passive cooling modifications in different two cooling strategies, i.e., structural cooling (night-ventilation) and comfort ventilation (full-day ventilation). Both ventilation modes are considered as an effective cooling strategy to be adopted in a high thermal mass building in a hot-humid climate. Nevertheless, this aspect has not been addressed sufficiently in scientific research. The numerical model is developed based on the experimental houses located in Universiti Teknologi Malaysia (UTM), Johor, Malaysia, for the simulation experiments.

3. To confirm the resulting effects of the proposed energy-saving saving modifications through full-scale measurements in the experimental houses in UTM. The effects of the proposed energy-saving modifications will be evaluated including their thermal comfort level. In this study, full-scale measurement is required to compensate the limitation of simulation study on the evaluation of the optimum passive cooling technique.

1.4 Structure of thesis

Firstly, this thesis presents the literature review of the study in chapter 2. The literature review focuses on the thermal comfort criteria and the passive cooling techniques in the hot-humid climate. The strategies of the ventilation techniques are also included in this chapter.

Chapter 3 covered the investigation of passive cooling techniques in traditional Chinese shophouses through the field measurement. The investigation focuses on two main objectives which is 1) the effects of courtyard form on their thermal environment and 2) thermal comfort in the Chinese shophouse with courtyards. The final outcome of this chapter is to provide recommendations of passive cooling techniques for modern houses based on the results of analysis in the Chinese shophouses.

Chapter 4 presents the design and the construction of the experimental houses in Universiti Teknologi Malaysia (UTM), Johor, Malaysia. The houses have been constructed based on the typical design of modern terraced houses in Malaysia. The experimental house is the main reference for the study conducted in Chapter 5 (simulation) of this thesis. In this chapter, the brief results of the experimental setup are also included.

Chapter 5 discussed the results of numerical simulation study. The experimental houses were modelled using TRNSYS and COMIS programs. Several passive cooling techniques that might improve the indoor thermal condition of the houses were simulated based on the weather data of Typical Metrological Year (TMY) of Kuala Lumpur for the structural cooling (night-ventilation) and comfort ventilation (full-day ventilation) conditions. The passive cooling techniques were analysed in term of single and combined techniques. The outcome of this chapter is to proposed energy-saving modification for the urban terraced houses in Malaysia.

In Chapter 6, the full-scale field measurement was conducted in the experimental houses in UTM to confirm the effects of the proposed energy-saving modifications obtained from the numerical simulation under the structural cooling and comfort ventilation strategies. In addition, the influence of window position for natural ventilation condition is also included in the analysis.

Chapter 7 presents the detailed discussion of the result of the full-scale measurement in the experimental house in term of thermal comfort evaluation, effects of passive techniques and the window opening patterns. The results from the building simulation and the field measurement in the CSHs are also included in the discussion. Finally, the guideline of energy-saving modifications for urban houses are proposed based on the results of the analysis.

For the final conclusion, Chapter 8 summarized the main finding of this study and recommended key areas for further studies based on the limitation of this thesis.

2.

Literature review

This chapter provides a literature review of relevant studies of thermal comfort and passive cooling in building in the hot humid climates.

2.1 Thermal comfort in the tropics

2.1.1 Adaptive thermal comfort

One of the most important aspects that need to be considered for the satisfaction of building occupants and energy consumption in buildings is the thermal comfort (Milne, 1995; Nicol et al., 2012). Therefore, the best way to design the building is by referring to a suitable building standard. Therefore, the standards for building especially for the internal thermal environments should be able to be a guideline in providing better indoor thermal environment and energy efficient.

The current standard can be found either based on heat balance or adaptive modeling. The most important example of the thermal comfort evaluation is by the predictive mean votes (PMV) which is developed by Fanger (1972). Currently it is employed in ISO 7730 (BSI, 2006) and ASHRAE Standard 55 (ASHRAE, 2010). Similar to the heat balance model, the adaptive model is also used in ASHRAE Standard 55 (ASHRAE, 2010) as a code for a naturally ventilated space and in EN15251 (BSI, 2008) for buildings without mechanical cooling systems during the cooling seasons. The natural ventilated spaces are defined by ASHRAE (2010) as a space where the thermal condition is usually controlled by the occupants through the opening and closing of the windows. Mechanical ventilation is allowed in the space as long as the air is unconditioned (ASHRAE, 2010). Furthermore, there may be other low energy methods to control and improve the condition of internal environment by such as fans, shutters and night ventilation (BSI, 2008).

Basically, the heat balance model analyzes the thermal physiology by assuming a steady state condition and high accuracy for all analyzed variables such as activity level, clothing heat resistance, air temperature, mean radiant temperature, relative air velocity and water vapor pressure in the ambient air (Fanger, 1972). On the other hand, the adaptation model investigates the dynamic relationship between the occupants and their surrounding environment generally based on the principle that people tend to react to changes that produce discomfort by finding ways to restore their level of comfort (Humphreys and Nicol, 1998).The heat balance model by Fanger (1972) tends to overestimate the cold sensation of users, mainly for building with natural ventilation modes, and did not properly predict the percentage of thermal dissatisfaction of the occupants (Nguyen et al., 2012; Humpreys and Nicol, 2002). The analytical model seems to be more suitable to be used for the building with air-conditioning system (Forgiarini Rupp and Ghisi, 2017). Meanwhile, the adaptive model is more suitable for building with naturally ventilated condition (Cao *et al*., 2011; Daghigh and Sopian, 2009).

The adaptive model has been standardized for the first time in ASHRAE Standard 55-2004 (ASHRAE, 2004; de Dear and Brager, 2002). The thermal comfort index for the adaptive model is the operative temperature. Operative temperature is the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual nonuniform environment. To date, the adaptive model has no limits on air speed, humidity and clothing. This indicates that the model promotes the adoption of such adaptive controls to achieve thermal comfort (ASHRAE, 2010; BSI, 2008). In this thesis, the evaluation of thermal comfort of indoor environment will be based on the adaptive thermal comfort standard.

2.1.2 Effects of wind on thermal comfort

Human perception of air movement depends on air velocity, air velocity fluctuations, air temperature, and personal factors such as overall thermal sensation, clothing insulation and physical activity level (metabolic rate) (Toftum, 2004). Air velocity affects both convective and evaporative heat losses from the human body, and thus influences thermal comfort conditions (Mcyintre, 1978).

Thermal environments that are slightly warmer than the preferred or neutral can still be acceptable to building occupants, as suggested in the adaptive comfort model (De Dear and Brager, 2002). Therefore, the introduction of airflow with higher velocities into such environments might be universally regarded as desirable. Higher velocities effect will remove the sensible and latent heat from the body, so body temperatures will be restored to their comfort set-points. This hypothesis is obtained from the physiological principle of alliesthesia (Cabanac, 1971).

Alliesthesia explained the phenomenon whereby a provided stimulus can induce either a pleasant or unpleasant sensation, depending on the subject’s internal state (Cabanac, 1971).

The cold receptors which are closer to the skin surface than warm receptors explain why the draft represents an unpleasant stimulus (negative alliesthesia) in cold environments. Meanwhile, the same level of air movement is perceived as pleasant (positive alliesthesia) in the warm environments. It also illustrates the concept of draft in a warm environment that is not logical, which accounts for the widely-reported inadequacy of the Fanger *et al*. (1988), Draft Risk (DR) at explaining air movement preferences of occupants into warm environments (De Dear, 2009).

Indoor air speed of 0.15-0.8 m/s has been deemed in ASHRAE Standard 55 (ASHRAE, 2004) to be the threshold of draft perception inside air-conditioned buildings where occupants have no direct control over their environment. Meanwhile, as for buildings where occupants have direct control over their environment the indoor air speed upper limit is at 1.2 m/s.

2.1.3 Effects of humidity on thermal comfort

One of the main features of a hot-humid climate is its high air temperature and humidity level. High humidity level in the building reduces both the evaporative and respiratory heat loss of the human body and aggravates thermal discomfort by high temperature (Jin et al, 2017). While the effects of relative humidity (RH) on all aspects of human comfort have yet to be established (Tsutsumi *et.al*, 2007; Rijal *et.al,* 2015; Damiati *et al.,* 2016; He *et al*., 2016), it is generally recognized that extreme levels of humidity are the most detrimental to human comfort, productivity, and health (ASHRAE, 2016).

Numerous discussion and arguments about the humidity limit have occurred throughout history. For instance, Bauman (1996) conducted a climatic chamber experiment at the University of California, Berkeley and suggested that the humidity upper limit of 60% assigned in the ASHRAE55-1992 standard was too strict and should be close to 70%. Meanwhile, the result of a human thermal response experiment conducted by Tanabe and Kimura (1994) in a climatic chamber at Waseda University in Japan showed that relative humidity should be regulated lower than 80%. Table 2.1 shows the range of the acceptable level of relative humidity based on the previous study. As shown, in most of the cases, the maximum acceptable upper limit of relative humidity was lower than 70%. In the recent version of ASRAE Standard 55 (2013), the upper limit of humidity level was revised to be 12 g/kg.

Table 2.1: Acceptable range of relative humidity for thermal comfort

Reference	Country	RH acceptable range
ASHRAE Standard 55-2013	General guideline (thermal comfort)	Lower limit: 55% at 25°C Upper limit: 65% at 28.3°C
ASHRAE 62.1 2013	General guideline (acceptable indoor air quality)	<65%
Tsutsumi et *al*., 2007	Climatic chamber	>70% (respondent tends to feel tired)
He et *al*., 2016	China (summer)	Upper limit: 48.7-69.6%
Kumar et *al*., 2016	India (hot humid)	20-80% (at wind speed of 0.2-1.0 m/s)
Toftum et *al*., 1998	Climatic chamber	<57% at 23°C <36% at 26°C
Djamila et *al*., 2014	Malaysia	73% at 30°C

Meanwhile, the high level of humidity may not only affect the thermal comfort of the occupants, but it also would bring negative effect to the building material and structure. Johansson *et al*. (2017) argued that some building materials tolerate being in air with high relative humidity without mould growth occurring, while on others mould can grow at a relative humidity as low as 75%.

2.1.4 Adaptive behavior

Lowering the temperatures and increasing air velocity are the two most effective methods to quickly relieve thermal discomfort. This can be achieved simply by the adaptive behavior by the building occupants. It has been reported that people having higher degree of control of indoor thermal environment were thermally comfortable at warmer temperature than the people with lower of control (Brager *et al*., 2004). There are various adaptive behaviors that can be used by the building occupants based on their preference and the availability of control in the building. Examples of adaptive behavior are opening the window, using electric fan, adjusting clothing level, drinking, taking shower, turn on the air-conditioner and others (Hwang *et al.*, 2009; Feriadi and Wong, 2004).

From the above-mentioned adaptive strategy, the adaptive behavior that are most preferable are opening window, electric fan and switch-on the air-conditioner (Brager *et al.*, 2004; Zhang *et al*., 2010; Hwang *et al*., 2009; Feriadi and Wong, 2004). This is probably because this strategy can modify the indoor thermal condition and providing comfortable environment faster than the other method.

2.2 Effect of humidity on health

Humidity in the building will not only affecting the thermal comfort for occupant but it also affecting the human health if the level is not properly control. Based on ASHRAE standard 62.1, the RH levels was limited to 65% or less for mechanical ventilation system with dehumidification capability. Meanwhile, no lower level indicated in the guideline. However, the guideline does mention that very low relative humidity (RH) level can caused skin drying, irritation of mucus membranes and dryness of eyes. In low relative humidity condition, the evaporation from membranes of nose and throat tend to increase higher than the suggested humidity level.

Detailed investigation of suitable humidity level has been conducted by Sterling *et al.*, (1985) and the suitable RH for human occupancy is between 30-60%. Other than this range, both the growth of bacteria, biological organism and the speed at which chemical interaction is occurred. Based on their finding, the viruses and bacteria can be occurred at RH level below 30%. Moreover, there is a possibility of health problem such as respiratory infection, allergic rhinitis and asthma. Meanwhile the same negative effects can occur at RH level above 60%. Above this level, there is also a possibility of the growth of fungi and mites in building.

One of the method to prevent the above-mentioned problem is by regulation the indoor RH to be not exposed to high humidity condition for a long time. A study by Arlian *et al.,* (1999) suggested that maintaining RH below 50% even when RH rise above 50% for 2 to 8 hours effectively restrict the population growth dust mites and thus the production of allergen. To completely prevent the growth of these mites, RH must be maintained below 35% for at least 22 hours per day when the daily RH is 75% or 85% for the remainder of the day.

2.3 Passive cooling techniques

2.3.1 Natural ventilation: Structural cooling strategy and comfort ventilation strategy

Passive cooling by natural ventilation is the suitable option for providing indoor thermal comfort in the building without required the cost of electricity. As for hot-humid climate, there are two possible options of natural ventilation strategies that were mostly suggested, i.e., continuous ventilation and structural cooling.

Continuous ventilation (or comfort ventilation) is a common method for achieving indoor thermal comfort in a hot-humid climate (Givoni, 1994; Koch-Nielsen, 2002). The design of the buildings should promote the maximum air movement with less internal obstruction. This approach has been practiced in the traditional wooden house which has a raised floor level with multiple window openings on the building's façade to achieve the necessary cross ventilation condition. Meanwhile, as previously discussed, night ventilation (or structural cooling) is known as an effective cooling strategy particularly when the diurnal temperature range is large such as in a hot-dry climate. However, when the night ventilation is adopted in a hot-humid climate (windows are closed during daytime), relative humidity tends to be high during the daytime, though the air temperature is reduced.

In these circumstances, there is a major trade-off in achieving indoor thermal comfort which is whether by maintaining lower indoor air temperatures through reducing air-changes with the outdoors, i.e., night ventilation or by increasing the indoor wind speeds for sweat evaporation by improving natural ventilation in day time while allowing an increase in temperature. In this context, considering the effects of high humidity on indoor thermal comfort and air quality (e.g. mold growth and mite), the continuous ventilation (i.e. full-day ventilation) can be a good option for the hot-humid climates.

If windows are closed during daytime (i.e. structural cooling), indoor air temperature can be several degrees lower than the outdoors in a high thermal mass building although increase in indoor wind speed cannot be expected. On the other hand, if windows are opened during daytime (i.e. comfort ventilation), indoor air temperature would be increased but indoor wind speed can be increased due to the cross ventilation as long as outdoor wind is sufficient. This means that at least there are two different approaches in improving indoor thermal comfort in the tropics. In this study, we will investigate the effect of each ventilation strategy in detail to find the most suitable approach to be applied in the modern urban houses in this hot-humid climate region.

2.4 Vernacular building

2.4.1 General

References to vernacular buildings are very important in the passive cooling study (Kimura, 1994). This is because vernacular buildings have been carefully crafted based on local weather and maintained for generations in response to the state of use including and human comfort requirements. In-depth studies with reference to the passive cooling techniques based on vernacular buildings are still minimal, especially quantitative studies, including in Malaysia (Hassan and Ramli, 2010). However, a detailed study of specific passive cooling systems was conducted by Ryu *et al.* (2009).

One of the benefits in quantitative research is that learning can be done not by only copying but through analysis for the current use (Rapoport, 2006). For example, two studies show some misconceptions or adaptations about the true function of traditional cooling techniques believed to work in non-scientific texts. Meir and Roaf (2006) show that the use of high-thermal mass structure in vernacular houses in desert areas in the Middle East may be excessive. This is because extreme heat inertia cannot utilize the advantage of solar gains in winter and night cooling by ventilation in summer season. This is because of its limited fenestration due to limited construction technology. As a result, the indoor thermal conditions are uncomfortable whether in the summer or in winter especially in lowland and humid coastal areas.

2.4.2 Courtyard building

Previous studies have been conducted regarding courtyard houses and their thermal effects, but most were conducted in hot-dry climates rather than in hot-humid climates. In these hot regions, some of the most important environmental functions of the internal courtyards in residential buildings are shading and ventilation. Several studies have indicated that courtyard geometry influences the amount of solar radiation received and the temperature in a courtyard through the design of the generic building forms such that smaller, deeper courtyards provide better shading than larger, wider courtyards (Meir *et al.,* 1995; Muhaisen, 2006; Berkovic *et al.*, 2012). Sadafi *et al.* (2011) studied the thermal performance of terraced housing in the hot-humid region of Malaysia by examining internal courtyards. The results indicated that by adding a shading roof to the courtyard, the solar heat gain for the indoors decreased, and accordingly, the roof improved the thermal conditions of the adjacent spaces. Meanwhile, Koch-Nielsen (2002) determined that solar radiation is more diffuse than direct in warm, humid regions where the sky is often overcast, implying the greater importance of shading devices for diffuse sky radiation compared to that of direct solar radiation in hot-humid regions.

Air flows in and around a courtyard can be induced by wind-driven ventilation and/or stack effect ventilation. In hot-dry regions, outdoor air during the daytime is usually dry with the occurrence of some wind gusts. Therefore, buildings in these regions are often designed with fewer openings on the external walls (Edwards *et al.* 2006). Furthermore, vegetation and water bodies are commonly used as design elements in the courtyards to facilitate evaporative cooling. As the diurnal temperature range is usually large in these regions, night ventilation is often recommended (Koch-Nielsen, 2002; Givoni, 1994). In contrast, to achieve thermal comfort in hot-humid regions, all-day (full-day) ventilation is generally required to remove the heat and humidity from buildings and improve the sweat evaporation of occupants. Moreover, several researchers have argued that wind orientation is usually more important than solar orientation in hot-humid regions (Koch-Nielsen, 2002; Givoni, 1998). Rajapaksha et *al.* (2003) investigated the potential use of a courtyard for passive cooling in a single-storey, high thermal mass building located in Colombo, Sri Lanka. The results indicated that the indoor thermal conditions were improved when the courtyard acted as an air funnel by discharging indoor air to the sky, i.e., upward airflow, compared to when the courtyard acted as a suction zone, i.e., receiving air from the outside. Moreover, Sharples and Bensalem (2001) suggested that covering a courtyard with a porous roof to form an atrium enabled the large pressure fields on the roof to provide stronger ventilation pressure differentials (suction). Meanwhile, Dili *et al.* (2010), focusing especially on the environmental functions of an internal courtyard, presented the results of field measurements in a typical vernacular residential building located in Kerala, India. They observed that a low-pressure zone created in the courtyard caused a stack ventilation effect that induced air movement from the outside to the courtyard through the surrounding spaces.

As previously indicated, though there are some studies on courtyard houses in hot-humid climates, most of the extant literature focused on detached houses, which differ from the row CSHs that have narrow, deep courtyards. Unlike detached houses, an elongated row house typically has only a few openings on the external walls, thus making cross-ventilation often unsatisfactory.

2.5 Recent studies on passive techniques

The purpose of passive cooling is to provide a necessary level of protection from the solar radiation during daytime and good indoor condition at night by the application of natural ventilation. The aim is to reduce indoor thermal condition of building to an acceptable level for the occupants, thus less dependencies of mechanical cooling devices can be achieved in order to reduce the energy consumption for cooling load.

Generally, reduction of cooling loads can be carried out by using the shading device for windows, consideration of window opening size, thermal insulation for building, green roof, solar reflectance roof, thermal mass, natural ventilation and others. Based on the previous study in hot-humid climate, recent researcher are more focuses on the protection of direct solar for the roof, building's wall and window.

2.5.1 Roof techniques

The reduction of the heat transfer from roof to the occupied space is essential because the solar heat gain is so high that it causes high indoor air temperature and brings thermal discomfort to the occupants (reduce surface temperature on the roof tile and attic. Among the problems of modern houses situated in tropical countries, the most important concern is the heat accumulation under the roof structure which resulting the upstairs rooms hot in the afternoon. (Buranasomphob, 1987). Moreover, it was reported that sixty percent of the thermal transfer occurs in the roof (Soubdan *et al.*, 2005).

Chungloo and Limmeechokchai (2009) investigate the solar reduction techniques by the application of cool roof with solar chimney. In their study, the solar chimney in roof is simply constructed by providing a small air gap under the roof. Therefore, the hot air in the room can be removed by the flowing of air through the air gap due to the thermal buoyancy effect. Based on this technique, they manage to reduce the ceiling temperature of the building by about 2-4°C. Meanwhile, the indoor air temperature has been reduced by about 0.5-0.7°C. The air temperature reduction was obtained by the ventilated attic space during daytime and assisted by cool roof system by using water bodies. Thus, the warm air was remove to the outdoor and the water cools the ceiling of the roof. However, the performance of this strategy is affected by the area of solar chimney per volume of room, material of the ceiling and the stack effect. Nearly similar approach was investigated by Chungloo and Bundit (2007). They investigate the combination of solar chimney and the wetted roof. The indoor air temperature reduction by the solar chimney alone is about 1.0-1.3°C. Meanwhile the application of wetted roof could recue the indoor air temperature about 1.0-3.2°C. The combination effect of both techniques resulted to the reduction of indoor air temperature about 1.4-3.0°C.

Khedari et *al.* (1997) investigated the effect of roof solar collector in order to reduce the air temperature in the attic. They found that the high temperature of solar collector will resulted to the increase of air speed in the attic. Thus, the attic temperature can be reduced.

Other attempt of reducing the air temperature in the attic spaces is by the application of insulation material in roofing (Soubdan et *al*., 2005). In this study, they compared the effect of roof insulation material, i.e., radiant barrier, fiber glass and polystyrene. Based on their result, the application of polystyrene shows better performance than the other materials. More complex strategy for roof was introduced by Hanif et *al.* (2014). They employed radiative cooling system to reduce the surface of roof and wall of the building. They claimed that by that technique, the energy consumption for cooling was reduced to about 44-48 W/m^2. Radiator on roof (high conductivity plate) in which the water was circulated, allowed the heat to be transferred from the heat carrier (water) to the roof top (ceiling and wall).

2.5.2 Wall insulation

Heat gain through walls is believed will contribute substantial cooling load to the air-conditioner. With strong solar radiation and high ambient temperature of a typical tropical climate, the heat gain through opaque wall is expected to contribute significantly to such load. The heat is transferred through an opaque wall by conduction. The rate of heat transfer is influenced mainly by thermal resistance, thermal mass and other thermal properties of a wall. The use of the solar insulating materials is the most efficient and cost effective passive methods for reducing the cooling requirements for the buildings. Thermal insulation are materials or combinations of materials that are used to provide resistance to the heat flow. They should have low conductivity for building application in order to reduce the cooling demand in hot climate.

The study of the application of wall insulation in tropics is still relatively few. Recent attempt conducted by Chirarattananon et *al.* (2012) by investigating the effect of wall insulation for air-conditioned residential house in Thailand by a computer simulation. They highlighted that in the case of residential house with air-conditioned system, internal insulation performed better than the outer wall insulation. This is because the internal wall insulation enables the indoor surfaces to follow set point air temperature more closely. Meanwhile, the external wall insulation prevents the heat from transferred out to exterior surface and increase indoor temperature during night-time. Other research related to wall insulation conducted by Rehman (2017). The author investigates the effect of application of solid concrete with dry insulation material in order to reduce the energy consumption in summer climate of UAE. The application of technique reduced the energy saving by about 7.6 to 25.3% in average. This is mainly because the heat flux of that wall was reduced to about 22-75%.

2.5.3 External shading

Ellis *et al.*, (2002) have identified that HVAC system is responsible for more than 30% of building total energy consumption and according to Hsieh *et al.*, (2007), solar irradiation through fenestration, heat from artificial lighting, latent heat from moisture, ventilation and infiltration are the major influencing variable of the cooling load of a HVAC system in building. Grynning *et al.*, (2013) revealed that windows are responsible for maximum amount of heat gain/loss inside the building which is almost 45%, whereas roof, wall and floor are responsible for 8%, 8% and 9% respectively. Kim et *al.* (2012) have conducted a series of simulations by an energy analysis program IES VE and revealed that the external shading device promises the most efficient performance compared to the internal shading devices. It is evident from literature review that external shading of building envelops, especially for window is one of the appropriate strategy to control unwanted heat from being transferred into the building. This is because the windows are responsible for maximum amount of heat gain into a building.

Dutta et *al.* (2017) investigate the effect of movable exterior window shading for a hospital in India by numerical simulation. The application of the techniques is expected can improve the energy saving for the building by about 9.8% and the payback of the installation cost can be obtained as early as 6 months. Meanwhile, Al-Tamimi and Fadzil (2011) investigate various shapes of vertical and horizontal shading techniques to reduce the air temperature near the window. They found that the egg crate type of shading techniques reduced the indoor condition by up to 5.1°C and 1.4°C in non-ventilated and ventilated indoor condition. In average, the reduction of indoor air temperature by this technique is about 1.4°C and 0.4°C, respectively. Bessoudo et *al.* (2012) compare the performance of roller shade and venetian blind for office building in winter climate, they highlighted that the roller shade could reduce the maximum indoor air temperature by about 1.0°C compared to no shading condition. Meanwhile, further reduction observed when the venetian blind was applied where the reduction of maximum indoor air temperature is about 2°C compared to no shading condition.

Based on the review, it is clearly showed that the application of passive cooling techniques with the special attention to the roof, wall and window have a potential to provide necessary heat gain protection for building. However, the study about the effect those techniques with the application of natural ventilation is relatively few. Therefore, in this study, passive solar reduction techniques will be investigated together with the natural ventilation strategy to obtain the optimum passive cooling strategy for modern urban houses in hot-humid climate.

2.6 Summary

This chapter reviews the thermal comfort for occupants in building and passive cooling techniques in the hot-humid climate. To date, the adaptive model places no limit on air speed, humidity and clothing, which reflects its intention to encourage use of such adaptive controls to achieve thermal comfort. Meanwhile the effects of air speed and humidity significantly will affect the thermal comfort of occupant is the building. Thermal environments that are slightly warmer than preferred or neutral can still be acceptable to building occupants, if the indoor wind speed is increased. Meanwhile, the increase of humidity level in building can reduce the comfort level of the occupant in the building and causes the other problem such as mold growth in the building.

It was found that the development of passive cooling in the tropic is still limited especially for the residential building. The most common way is by utilizing the night ventilation. While night-ventilation is preferable for reducing the indoor thermal environment especially in the high-thermal mass building, in the same time, the indoor humidity level will also increase especially in the hot-humid climate. Continuous ventilation (or comfort ventilation) seems as the other alternative since the indoor wind speed can be increased due to the cross ventilation along with the reduction of relative humidity especially in daytime.

Meanwhile, passive cooling by courtyard is one of the alternative that can provided natural ventilation and lighting. However, most of the extant literature focused on detached houses or simplified building, which differ from the modern urban houses which constructed in a row and located in the dense urban area.

Furthermore, most of the recent researcher investigates the strategies for reducing the effect of solar radiation on the roof, wall, and windows of the building. However, their investigations were limited to the effect of only single techniques (one technique at a time). There are still few investigations that considered the optimum combination of passive cooling techniques for hot humid climate. Therefore, this study will comprehensively investigate the effects of the passive cooling strategies as combined strategies, thus providing the optimum passive cooling strategy that an be apply in the modern house in the hot-humid climate.

3.

Passive cooling techniques in Traditional Chinese Shophouse

3.1 Introduction

3.1.1 The Traditional Chinese Shophouses

In Malaysia, the traditional Chinese shophouse is one of the fine examples of vernacular building (Chen, 1998). The Chinese shophouse (CSHs) has been introduced in Malaysia since 19^{th} century until World War II due to the influx of Chinese immigrants from densely populated southern coastal provinces of China (Chen, 1998). By the early 20^{th} century, this urban design has spread to every major town in Malaysia. Generally, the traditional Chinese shophouse is a narrow, deep-plan brick building situated in rows in relatively dense urban areas. Chinese shophouses in Malaysia have traditionally been two storeys high, with the lower floor used for trading and the upper floor for residential purposes (Chen 1998). One of the important features of CSHs is that each building has one or more internal courtyards are incorporated in a CSH in the middle and/or the corner of the building.

Courtyard building can be defined as a building that has an internal space opened to the sky (Koch-Nielsen, 2002). Courtyard houses can be found not only in China and Southeast Asia but also in many other parts of the world (Edwards *et al*., 2006). One of the major roles of courtyard spaces is to protect the occupants from the harsh outdoor conditions and provide environmental functions such as natural lighting and ventilation (Hyde, 2000). The form of courtyard was strongly influenced by the climatic conditions of the region. For instance, in China, courtyard houses were originally found in residences throughout the country, but their compositions and scales varied depending on their locations (Knapp, 1999). In general, the proportion of courtyard space to the structural space diminishes significantly from Northeast to Southeast China to restrict the infiltration of direct solar radiation and facilitate ventilation (Knapp, 1999). Most of the courtyards in the Malaysian CSHs are the narrow and deep courtyards that originated from the southern part of China.

Similar to the CSHs, most of the modern houses in Southeast Asia are constructed of brick and situated in rows in the dense urban areas. In Malaysia, for example, these brick houses accounted for 93% of the existing urban housing stocks as of 2010 (Department of Statistics Malaysia, 2010). Because of the similarities not only in terms of the climate but also the building materials, it is worth discussing potential passive cooling techniques employed in the traditional CSHs to determine energy-saving strategies for high thermal mass, modern urban houses in Malaysia and other Southeast Asian countries.

3.1.2 Objectives

The primary objective of study in this chapter is to identify the thermal functions of internal courtyards in traditional CSHs located in the hot-humid climate of Malaysia with the aim of providing useful passive cooling strategies for modern urban houses. In order to meet the objective, the field measurements were conducted in the selected CSHs in the historical city of Malacca in 2011 and 2014. The field measurements are not only focuses on the indoor thermal environment of the CSH but also on the dimensions and thermal properties of the CSHs and the courtyards. The analyses were divided into two steps.

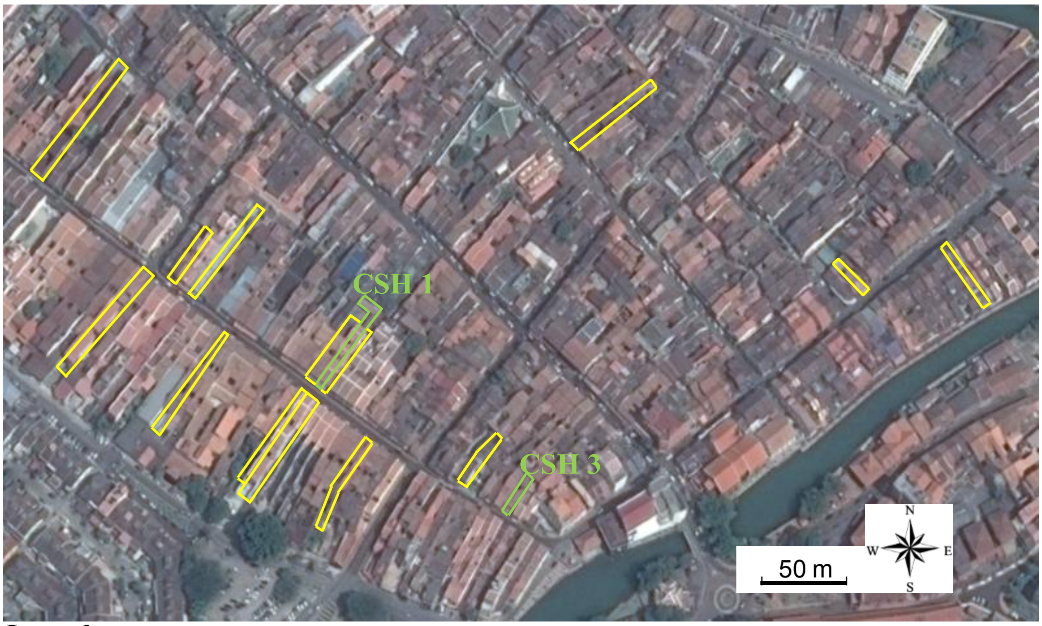
Firstly, the study analyses the effects of courtyard form on their indoor thermal environment based on the results of field measurement conducted in 16 CSHs. Second, the detailed thermal environments of the selected two traditional CSHs with the different courtyard types were investigated to discuss the thermal functions of courtyards. The design recommendations for the internal courtyards and the passive cooling techniques in the CSHs are then made based on the results of the analyses.

3.1.3 Case study shophouses

The field measurements were conducted in 16 shophouses located at the Malaccan Heritage site (2.2°N, 102.2°E), Malaysia, in 2011 and 2014. Figure 3.1 shows the location of the CSHs in Malacca. The 16 CSHs had a total of 29 courtyards. As shown, most of the studied CSHs are elongated in the northeast-southwest direction and were constructed between the late 1700s and the middle of 1900s. Figure 3.2 shows the external and the internal view of the CSHs. Most of the courtyards in the study CSHs are used either as an internal garden, working spaces or the source of environmental functions, i.e. natural lighting and ventilation. The living hall is located at the adjacent of the courtyard on the ground floor.

The typical building structures were constructed of load bearing lime-plastered brick walls, concrete and timber frame. The typical roofing material was Chinese U-shaped clay tiles laid in two layers using the traditional method. No thermal insulation was used in the

CSHs. A detailed description of the two case study houses (CSHs 1 and 3) is provided in the section 3.3.



Legend

CSHs for comparative analysis

Detailed measurement case

Source: Google Earth

Figure 3.1. Location of the study shophouses

(a)

(b)

Figure 3.2. (a) Exterior view of the CSHs (b) Interior view CSHs

The dimensions of the courtyards include the sky view factors (SVFs) and the adjacent living hall were measured to obtain the information of the courtyard forms (Figure 3.3 and Table 3.1). The SVF means the exposure rate of courtyard to the sky (percentage). The SVF was estimated based on the fish-eye lens photo taken at 1.5m above the floor in the center of courtyard using the equisolid-angle projection lens. Then the photos were analyzed using the CanopOn2 program to calculate the SVF (http://takenaka-akio.org/etc/canopon2/). Figure 3.4 shows the examples of measured SVFs in the CSHs. In addition to the above variables, the dimension of plants and water bodies in the courtyard were also being measured during the measurement.

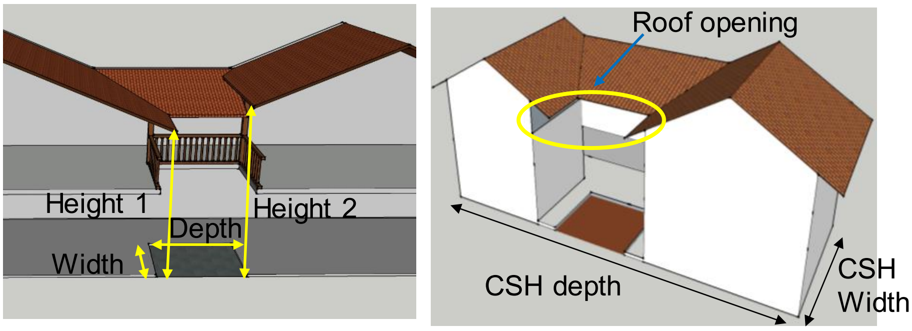


Figure 3.3 Dimension of courtyard and CSHs

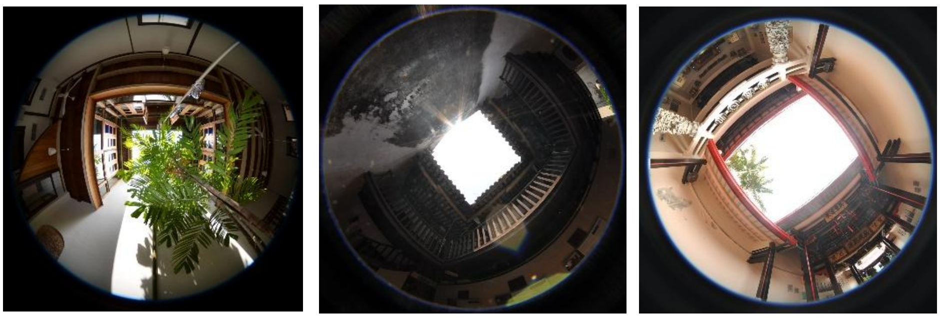

SVF: 0.2% SVF: 6.3% SVF: 12.2%

Figure 3.4. Examples of SVFs in the courtyard

The summary of the building dimensions and the thermal properties is presented in Table 3.1. As shown, the frontages of the CSHs range from 3.6 to 8.3 m, and their depths vary from 22.1 to 84.5 m. Meanwhile, the areas of the courtyards range from 3.0 to 25.0 m^2, and their heights vary from 2.6 to 8.9 m, depending primarily on the building storey. Accordingly, the SVFs vary widely, ranging from 0.2 to 14.7%. The height of a courtyard was measured using two values when the courtyard was situated between buildings/walls of different heights (see Figure 3.3). This often happened when the courtyard was located at the end of a building. The difference in the height of a courtyard, ‘H. diff.’, denotes this situation. Thermal properties of courtyards were also estimated herein by using the typical values obtained from books and specification sheets. As for the U-values of the floor, the estimation was made based on the equation in ISO 13370. The internal (R_{si}) and external (R_{se}) surface resistance of the floor were assigned as 0.17 m^2K/W and 0.04 m^2K/W, respectively. Meanwhile, the thermal conductivity of the ground (λ) was assumed to be 2.0 W/mK. As a result, the U-values of floor range from 0.96 to 1.72 W/(m^2K), and their reflectance varies from 0.3 to 0.8. Most courtyards had several potted plants, and their coverage areas per courtyard recorded up to 9.7 m^2. Other variables, such as the sky plant coverage, the area of water bodies, the building orientation, and the location of the courtyard, were also quantified. This resulted in 26 variables for the comparative analysis conducted herein.

To be noted that all of the measured CSHs (16 units) were considered in the comparative analysis (section 3.2) while only two of them were included in the detailed case studies (section 3.3).

Table 3.1. Measured dimensions and thermal properties of courtyards and study CSHs (selected parameters)

	CSH code	CY code	CY dimensions									CY thermal property		Plants/water bodies		Building dimensions	
			W (m)	D (m)	H_1 (m)	H diff. (m)	Area (m^2)	Volume (m^3)	Overhang area (m^2)	Roof area (m^2)	SVF (%)	Floor U-value (W/(m^2·K))	Floor reflectance (-)	Green coverage (m^2)	Water bodies (%)	W (m)	D (m)
1	CSH 1	CY 1	3.6	3.9	7.5	0.0	13.9	104.4	7.0	71.2	0.2	1.23	0.4	1.7	0	4.7	56.9
2	CSH 1	CY 2	3.9	4.6	7.2	0.0	17.6	126.9	6.1	57.4	3.5	1.21	0.6	2.1	2	4.7	56.9
3	CSH 2	CY 1	2.6	3.8	7.2	0.0	9.8	70.2	4.9	57.1	1.7	1.40	0.6	0.0	3	4.7	37.2
4	CSH 2	CY 2	4.7	4.9	3.6	3.6	23.1	83.3	0.0	34.8	9.9	1.01	0.4	0.0	0	4.7	37.2
5	CSH 3	CY 1	2.3	4.2	5.0	0.0	9.5	47.7	5.8	49.7	6.3	1.48	0.3	1.2	4	4.7	22.1
6	CSH 3	CY 2	2.9	2.1	5.6	3.4	6.0	33.5	1.0	6.5	3.1	1.61	0.3	2.4	0	4.7	22.1
7	CSH 4	CY 1	5.0	4.0	5.9	0.3	20.2	119.8	5.5	69.9	3.0	1.01	0.4	4.6	39	8.0	41.5
8	CSH 4	CY 2	2.9	6.6	3.9	2.1	19.2	74.6	7.6	88.1	6.4	1.06	0.4	7.2	0	8.0	41.5
9	CSH 5	CY 1	2.7	4.0	6.4	0.0	10.8	69.2	6.9	51.6	1.0	1.15	0.4	6.7	9	4.9	71.1
10	CSH 5	CY 2	2.2	3.6	6.3	0.1	8.0	49.7	5.4	41.1	0.4	1.21	0.4	2.7	0	4.9	71.1
11	CSH 6	CY 1	3.8	5.2	6.3	0.1	19.6	122.4	12.6	97.0	4.9	1.14	0.3	1.3	8	7.9	70.9
12	CSH 6	CY 2	5.4	4.6	5.7	0.4	25.0	141.7	18.8	84.1	4.7	0.96	0.4	4.5	2	7.9	70.9
13	CSH 7	CY 1	2.1	3.8	6.7	0.1	8.1	54.1	4.0	75.8	2.2	1.50	0.8	2.4	55	4.8	36.2
14	CSH 8	CY 1	3.8	5.3	6.6	0.0	19.9	131.2	7.6	80.3	5.7	1.12	0.4	1.9	2	6.1	60.7
15	CSH 8	CY 2	3.1	3.9	4.0	2.7	12.1	48.6	4.9	58.8	3.4	1.15	0.4	0.3	6	6.1	60.7
16	CSH 8	CY 3	3.3	2.9	3.7	2.7	9.5	34.7	4.1	33.5	7.4	1.20	0.4	0.7	0	6.1	60.7
17	CSH 8	CY 4	1.2	2.4	2.9	3.7	3.0	8.6	2.3	33.5	7.2	1.72	0.8	1.7	0	6.1	60.7
18	CSH 9	CY 1	2.9	3.8	4.3	1.4	11.1	47.7	10.1	95.3	14.7	1.16	0.4	0.4	0	8.3	78.4
19	CSH 9	CY 2	3.8	3.9	5.1	0.3	14.6	74.7	14.3	114.1	12.2	1.10	0.4	0.5	0	8.3	78.4
20	CSH 10	CY 1	2.4	4.4	2.6	4.3	10.6	27.8	3.8	32.7	7.3	1.17	0.4	0.0	5	4.7	71.0
21	CSH 11	CY 1	3.4	2.8	2.6	0.3	9.7	25.2	4.2	48.8	9.2	1.37	0.3	2.1	0	3.7	23.8
22	CSH 12	CY 1	1.9	3.6	8.9	0.0	6.9	61.2	4.2	78.1	0.8	1.31	0.4	0.6	11	5.5	43.0
23	CSH 12	CY 2	3.3	3.3	7.7	1.2	10.9	84.0	4.1	56.3	1.7	1.19	0.4	3.8	0	5.5	43.0
24	CSH 13	CY 1	5.0	3.8	5.8	2.8	19.1	110.2	7.8	95.3	5.7	1.15	0.3	3.8	0	6.6	84.5
25	CSH 14	CY 1	3.4	5.5	3.8	3.1	18.4	70.9	6.8	43.6	6.1	1.08	0.4	3.4	0	6.1	69.2
26	CSH 14	CY 2	2.2	9.6	3.5	0.1	21.3	75.1	8.5	44.0	7.9	1.15	0.4	3.5	5	6.1	69.2
27	CSH 15	CY 1	2.4	3.7	6.8	0.0	8.8	59.9	6.3	28.1	1.2	1.44	0.4	1.4	0	3.6	27.4
28	CSH 16	CY 1	2.0	2.9	6.1	0.1	5.8	35.1	4.3	62.1	1.6	1.27	0.4	1.1	3	5.4	54.6
29	CSH 16	CY 2	2.1	6.9	3.1	3.0	14.0	43.5	6.3	40.9	7.5	1.16	0.4	9.7	0	5.4	54.6

Note. CSH: Chinese shophouse; CY: courtyard; W: width; D: depth; H: height; SVF: sky view factor.

3.2 Effects of courtyard forms on their thermal environments

3.2.1 Methods

As shown in Figure 3.5, the air temperature and relative humidity were measured at 1.5m above the ground floor in the center of courtyards and the adjacent living halls of the CSHs (T&D TR-72U). In addition, air temperature was also measured at the first-floor level in the courtyards (T&D TR-52i). Each sensor was shaded with a paper cups wrapped with the aluminum foil to prevent the effect of direct thermal radiation. Measurement were taken for approximately 4 to 6 days continuously in each building from 23rd September to 23rd October 2014. The outdoor weather data were recorded from the veranda (T&D TR-73U) of selected shophouses as well as at the weather station (Davis, Vantage Pro 2), which was located in a small open space approximately 500m from the measurement sites and at 4.5m height above ground. The main measured variables for the outdoor were air temperature, relative humidity and air pressure. The additional measured variables, i.e. rain falls, solar radiation, wind speed and wind direction were recorded from the weather station. Air-conditioning was not used in any of the measured spaces during the measurement period. The accuracy levels of the used instruments are summarized in Table 3.2.

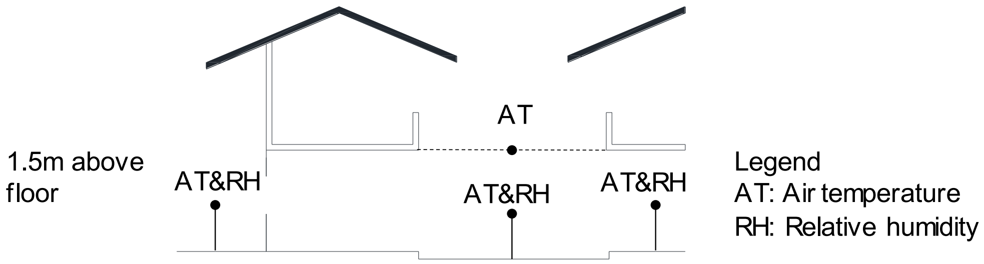


Figure 3.5. Measuring points in study CSHs for the comparative analysis

Table 3.2. Description and accuracy of measurement instruments

Measured variable	Instrument model	Accuracy
Air temperature, RH and air pressure	T&D TR-73U	±0.3°C, ±5%RH, ±1.5hPa
Air temperature and RH	T&D TR-72U	±0.3°C, ±5%RH
Air temperature	T&D TR-52	±0.3°C
Outdoor weather station (air temperature, RH, wind speed, wind direction, solar radiation and rain fall)	Davis, Vantage Pro 2	±0.5°C, ±3%RH (±4%RH when RH>90%), ±1 m/s or ±5% of rdg (wind speed), ±3° (wind direction), ±5% of full scale (solar radiation), ±4% of full scale (rain fall)

3.2.2 Determinant for profiles of thermal environment in courtyards

Figure 3.6 shows the outdoor weather condition throughout the measurement period. As shown the maximum outdoor air temperatures were approximately 32 to 34°C, while the nocturnal outdoor air temperatures were approximately 26 to 28°C on the front verandas on fair weather days. Meanwhile, the outdoor relative humidity remained relatively high throughout the day, ranging between 50% (day) and 80% (night). In this study, the fair-

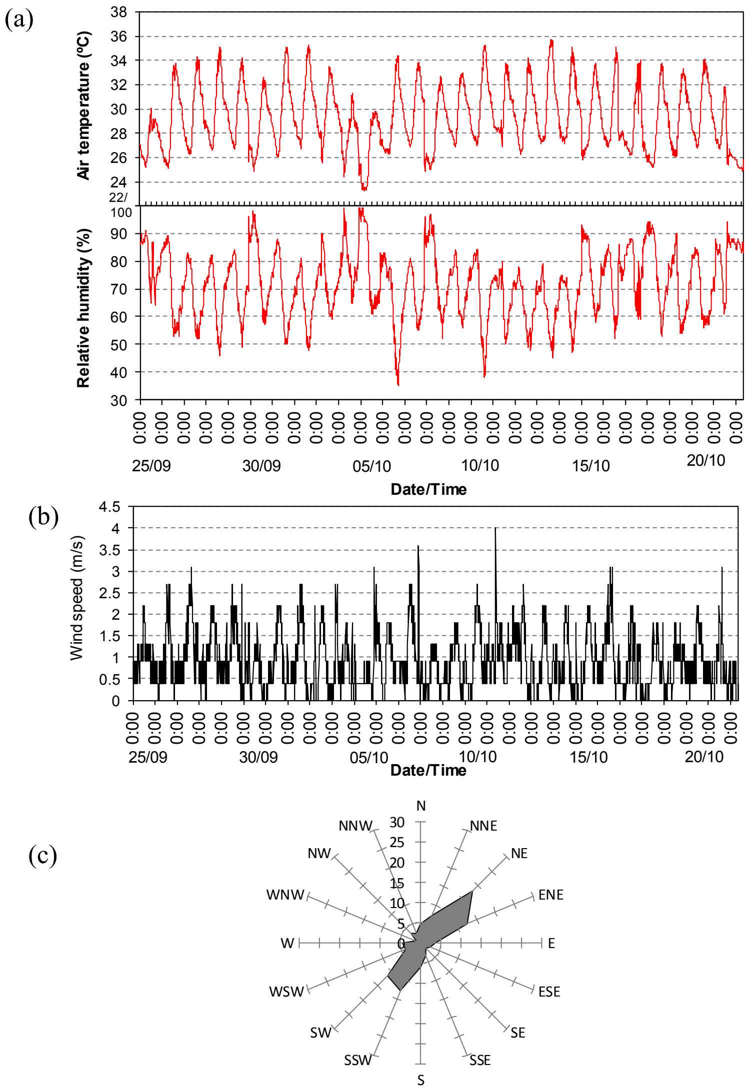


Figure 3.6. Outdoor weather condition during the measurement period (a) Air temperature and relative humidity (b) Windspeed (c) wind direction

weather days is defined by considering the corresponding maximum air temperature of at least 32°C and solar radiation of more than 800 W/m^2. As for the outdoor wind speed, the south-westerly sea breezes (approximately 1 to 3 m/s) during the day and north-easterly land breezes (up to 1 m/s) during the night were observed at the weather station.

Figure 3.7 shows the statistical summary of air temperature in measured courtyards (ground floor and first floor levels) and the adjacent spaces (ground floor). The data excludes those measured during the rainy days. As shown in Figure 3.7a, overall, the average air temperatures in more than half of the courtyards are lower than the outdoor average temperatures on the ground floor, by up to 2.0ºC. As expected, the average air temperatures at the first-floor level are approximately 0.5ºC higher than those of the ground floor level, and less courtyards maintain the lower average air temperature than the outdoors (Figure 3.7b). Diurnal variations of air temperature range largely from 25.3 to 33.8ºC at the ground floor level, while it is 24.8 to 33.7ºC at the first-floor level. In contrast, the diurnal variations in the adjacent rooms are smaller than those in the courtyards as well as the outdoors in most cases (Figure 3.7c). Despite the small diurnal temperature ranges, the adjacent rooms recorded higher average air temperature than the outdoors in most of the courtyards, by up to 1.8°C. It should be noted that the average air temperatures in the courtyards on the ground floor are lower than those in the adjacent rooms in many cases.

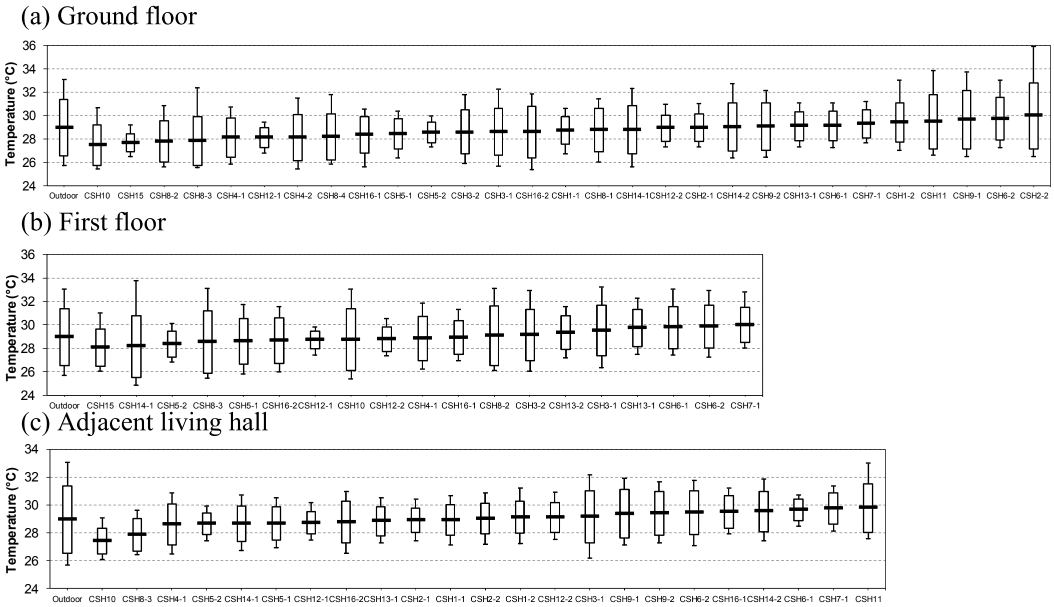


Figure 3.7. Statistical summary (5th and 95th percentiles, mean and ± one S.D.) of air temperature at the courtyards and the adjacent living hall (a) Courtyard ground floor (b) courtyard first floor (c) adjacent living hall

Simple and multiple regression analyses were conducted to determine the variables that explain profiles of air temperature and humidity in the courtyards. The regression analyses were conducted by using the statistical analysis program (SPSS) with stepwise method. The dependent variables were the 'differences' of (a) air temperature, (b) relative humidity (RH) and (c) absolute humidity (AH) between those measured in the courtyards (at 1.5 m above floor) and the corresponding outdoor values measured on the front verandas in terms of (1) the 95th percentile (maximum), (2) the mean, and (3) the 5th percentile (minimum). The term of 'difference' indicates the difference of indoor thermal variables compared to the corresponding outdoor, i.e. air temperature, relative humidity and absolute humidity. Negative value means the indoor thermal parameter is smaller than those of outdoor. Meanwhile, the independent variables consist of the dimension of courtyard and the CSHs, ratio of courtyard size, thermal properties of materials in the courtyard, plants, water bodies and the condition of the courtyards. Table 3.3 presents the description of the independent variables used in the analysis. To be noted that the independent variables were selected based on the result of bivariate correlation where the unnecessary variables that has a high multicollinearity with the other variables were removed.

Table 3.3. Description of the independent variables

	Independent Variables	Description
1	Sky view factor	Sky view factor (%)
2	CY_H1 (lower)	Height of courtyard 1
3	CY_H2 (higher)	Height of courtyard 2
4	CY_Area/H1	Ratio of courtyard area to the courtyard height 1
5	AS_Height	Height of the adjacent space
6	OP_Area	Area of courtyard opening
7	OP_Area/CY_Area	Ratio of courtyard opening to courtyard area
8	House_Area	Area of CSH
9	CY_Area/House_Area	Ratio of courtyard area to the CSH area
10	CY_Height diff. (H2-H1)	Difference of courtyard height
11	CY_W/D	Ratio of courtyard width to its depth
12	OP_W/D	Ratio of courtyard's width to courtyard depth
13	CY_Volume	Volume of courtyard
14	Overhang_Area/CY_Area	Ratio of overhang area to the courtyard area
15	Roof_Area	Area of roof
16	AS_H/CY_Area	Ratio of the height of the adjacent space to the courtyard area
17	Sky_Plant coverage	Coverage of plant in the courtyard (%)
18	Floor_Green Area	Green area in courtyard (%)
19	Floor_Water ratio	Water bodies in the courtyard (%)
20	Floor_U value (W/m^2K)	Thermal properties: U value of floor
21	Floor_Reflectance (ρ)	Thermal properties: Reflectance of floor surface
22	Floor_Soil Area	Area of soil in the courtyard
23	Roof_U value (W/m^2K)	Thermal properties: U value of roof
24	Roof_Emissivity (ε)	Thermal properties: Emissivity of roof surface
25	Number of open walls	Number of wall that surrounded the courtyard
26	CY_Corner (dummy)	Location of courtyard (end of building)

Table 3.4 summarizes the results of single regression analysis between the independent variables and the air temperature difference in term of the 95th percentile, the mean, and the 5th percentile. As shown, the sky view factor (SVF), height of courtyards (CY_H1& CY_H2), ratio of courtyard area to the courtyard height (CY_Area/H1) and the height of the adjacent spaces (AS_Height) are statistically significant in affecting the maximum air temperature difference. The SVF, CY_Area/H1 and AS_Height has positive correlation with the maximum air temperature difference. This indicates that by increasing this value, the air temperature in the courtyard will increase closely to the maximum outdoor values. Meanwhile, the height of courtyards (CY_H1& CY_H2) are negatively correlated with maximum air temperature difference. Increasing the height of courtyard would decrease the maximum air temperature in the courtyards. Most of these variables have significant correlation with the mean air temperature except for the CY_H1. In addition, the area of the house (House_Area) and the opening of courtyard (OP_Area) showed significant contribution to the mean values. As for the minimum air temperature difference, the difference of courtyard height (CY_Height diff. (H2-H1)), location of courtyard (CY_Corner (dummy)) and CY_Area/H1 are negatively correlated to the minimum values. This indicates that when the value of these variable increases, the minimum air temperature in the courtyard will be reduced. In contrast, increasing the height of courtyard 1 (CY_H1) and the ratio of the overhang to the courtyard area (Overhang_Area/CY_Area) will increase the minimum air temperature of the courtyard.

Table 3.4. Results of single regression analysis. Correlation between the independent variables and air temperature difference (courtyard-outdoor) (a) 95th percentile (b) mean (c) 5th percentile

(a) Air temp-diff (95th percentile)

Independent Variables	R	Sig.
Sky view factor	0.789	0.000 **
CY_H1 (lower)	-0.724	0.000 **
CY_H2 (higher)	-0.626	0.000 **
CY_Area/H1	0.534	0.003 **
AS_Height	0.397	0.033 *
OP_Area	0.337	0.074
OP_Area/CY_Area	0.332	0.078
Sky_Plant coverage	-0.297	0.117
CY_Corner (dummy)	0.291	0.126
CY_Height diff. (H2-H1)	0.265	0.165
House_Area	0.247	0.197
Floor_Water ratio	-0.176	0.361
CY_Volume	-0.174	0.366
CY_Area/House_Area	0.146	0.451
Number of open walls	-0.132	0.494
Roof_Emissivity (ε)	0.129	0.505
Floor_Reflectance (ρ)	-0.123	0.525
OP_W/D	0.112	0.563
Floor_U value (W/m2K)	-0.103	0.594
CY_W/D	0.097	0.617
Roof_U value (W/m2K)	0.095	0.625
AS_H/CY_Area	0.087	0.653
Overhang_Area/CY_Area	-0.045	0.818
Roof_Area	-0.022	0.909
Floor_Green Area	-0.008	0.965
Floor_Soil Area	-0.002	0.991

(b) Air temp-diff (Mean)

Independent Variables	R	Sig.
Sky view factor	0.526	0.003 **
CY_H2 (higher)	-0.504	0.005 **
AS_Height	0.480	0.008 **
House_Area	0.395	0.034 *
OP_Area	0.377	0.044 *
OP_Area/CY_Area	0.357	0.057
Roof_Area	0.279	0.143
CY_Area/H1	0.270	0.156
Sky_Plant coverage	-0.252	0.187
CY_H1 (lower)	-0.233	0.223
Overhang_Area/CY_Area	0.221	0.248
Number of open walls	0.200	0.298
CY_Height diff. (H2-H1)	-0.190	0.323
Floor_Soil Area	-0.147	0.445
CY_Volume	0.114	0.557
Floor_Reflectance (ρ)	0.084	0.665
Floor_U value (W/m2K)	-0.077	0.691
AS_H/CY_Area	0.076	0.695
CY_Corner (dummy)	-0.068	0.727
Roof_Emissivity (ε)	-0.047	0.810
Roof_U value (W/m2K)	0.039	0.842
CY_Area/House_Area	-0.038	0.846
CY_W/D	0.035	0.855
Floor_Green Area	-0.022	0.909
OP_W/D	-0.016	0.936
Floor_Water ratio	0.016	0.936

(c) Air temp-diff (5th percentile)

Independent Variables	R	Sig.
CY_Height diff. (H2-H1)	-0.585	0.001 **
CY_H1 (lower)	0.548	0.002 **
Overhang_Area/CY_Area	0.402	0.031 *
CY_Corner (dummy)	-0.396	0.033 *
CY_Area/H1	-0.384	0.040 *
Floor_Soil Area	-0.332	0.079
Sky view factor	-0.311	0.101
Number of open walls	0.260	0.174
Roof_Emissivity (ε)	-0.246	0.198
Floor_Water ratio	0.221	0.249
Floor_U value (W/m2K)	0.208	0.279
CY_Volume	0.200	0.299
Roof_Area	0.174	0.366
Floor_Reflectance (ρ)	0.161	0.405
OP_W/D	-0.144	0.455
CY_Area/House_Area	-0.125	0.518
Floor_Green Area	-0.101	0.604
CY_W/D	-0.100	0.607
OP_Area	-0.089	0.647
Sky_Plant coverage	-0.073	0.706
House_Area	0.071	0.716
OP_Area/CY_Area	-0.060	0.758
CY_H2 (higher)	0.050	0.796
AS_Height	0.028	0.885
Roof_U value (W/m2K)	-0.007	0.971
AS_H/CY_Area	0.000	1.000

The existence of plants and the existence of water bodies resulted in the decrease in air temperature of the courtyards during both day and night, although none were statistically significant. Figure 3.8 shows the correlation between the air temperature difference and the related variables. The sky plant coverage has a weak but negative correlation with the daily maximum air temperature difference in the courtyards (R^2=0.09, p=0.12). This indicates that by increasing of the coverage of the plant in the courtyard could reduce the maximum air temperature in the courtyards. Meanwhile, the water ratio in the courtyard have a weak but negative correlation with the daily maximum air temperature difference in the courtyards (R^2=0.03, p=0.36), while they have a weak, positive relationship with the daily minimum air temperature (R^2=0.05, p=0.25).

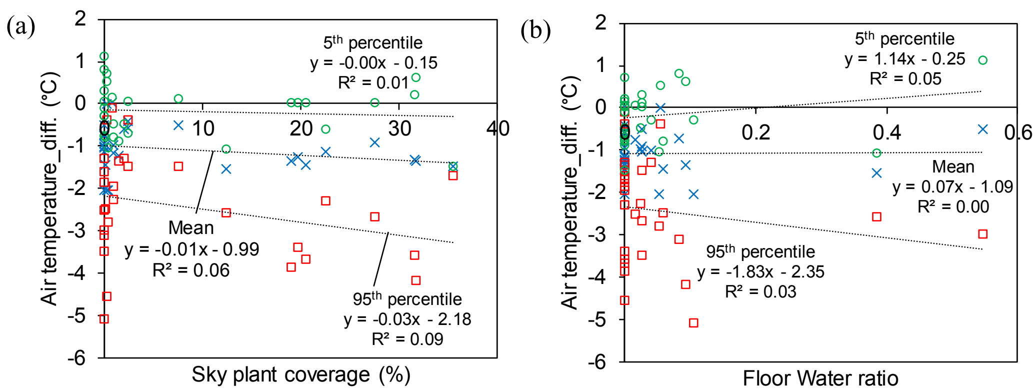


Figure 3.8. Correlation between air temperature difference (courtyard-outdoor) with (a) Sky plant coverage and (b) Floor water ratio

The orientation of courtyards/CSHs may affect the profile of air temperature in the courtyards as presented in the previous studies (Meir *et al.*,1995; Berkovic *et al.*, 2012), but this was not analysed in this study due to the small sample size. In this study only two different building orientations were available as previously described herein (see Figure 3.1). Nevertheless, the influence of the building/courtyard orientation on its air temperature might be limited because the solar exposure is basically small in a narrow, deep internal courtyard, which is the main interest of this study. A numerical simulation study is necessary in the future to clarify these effects in narrow, deep courtyards in the tropics.

Among the variables with respect to thermal properties, the U-values of courtyard floor have a weak but negative correlation with the daily maximum air temperature in the courtyards (R^2=0.01, p=0.59), while they have a weak, positive relationship with the daily minimum air temperature (R^2=0.04, p=0.28). In contrast, the emissivity of roofs is negatively correlated with the daily minimum air temperature in particular (R^2=0.06, p=0.20). This is primarily because the high emissivity, such as that of zinc roof, increased the effect of nocturnal radiant cooling from the roofs. Figure 3.9 shows the correlation between the air temperature difference and the related variables.

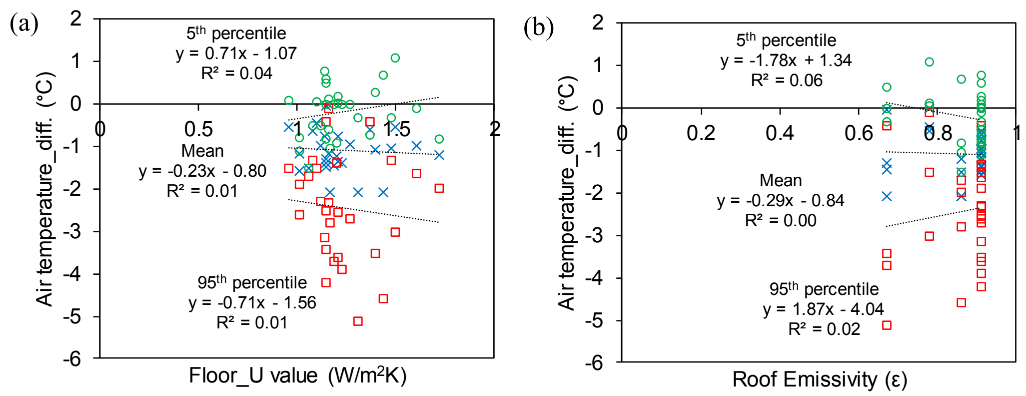


Figure 3.9. Correlation between air temperature difference (courtyard-outdoor) with (a) U value of floor (b) Emissivity of roof

Table 3.5 summarizes the results of single regression analysis between the independent variables and the air absolute humidity difference in term of the 95th percentile, the mean, and the 5th percentile. As shown, only the ratio of courtyard area to the house area (CY_Area/House_Area) has a significant correlation with the maximum and mean values of the absolute humidity difference. Meanwhile, three variables have significant correlation with the minimum absolute humidity difference, i.e. CY_Height diff. (H2-H1), CY_Area/House_Area and CY_H1. As expected, green coverage, the existence of plants and the existence of water bodies are positively correlated with maximum absolute humidity, although none were statistically significant.

Table 3.5. Results of single regression analysis. Correlation between the independent variables and absolute humidity difference (courtyard-outdoor) (a) 95th percentile (b) mean (c) 5th percentile

(a) Abs. Humidity-diff (95th percentile)

Independent Variables	R	Sig.
CY_Area/House_Area	-0.374	0.046 *
CY_Height diff. (H2-H1)	0.342	0.069
CY_H1 (lower)	-0.311	0.100
CY_W/D	-0.310	0.102
CY_Volume	-0.300	0.114
CY_Corner (dummy)	0.254	0.183
Floor_Reflectance (ρ)	0.219	0.253
Sky view factor	0.205	0.287
Floor_Water ratio	0.186	0.334
OP_Area	-0.159	0.409
House_Area	0.143	0.458
AS_H/CY_Area	0.132	0.495
Floor_Soil Area	-0.100	0.607
AS_Height	0.097	0.615
Floor_Green Area	0.092	0.635
Number of open walls	0.084	0.666
Sky_Plant coverage	0.076	0.695
Roof_Area	-0.059	0.761
CY_Area/H1	0.046	0.813
Floor_U value (W/m2K)	-0.038	0.844
Roof_Emissivity (ε)	-0.036	0.853
Overhang_Area/CY_Area	-0.035	0.857
OP_W/D	-0.028	0.884
Roof_U value (W/m2K)	0.018	0.926
CY_H2 (higher)	-0.018	0.927
OP_Area/CY_Area	0.010	0.959

(b) Abs. Humidity-diff (mean)

Independent Variables	R	Sig.
CY_Area/House_Area	-0.394	0.035 *
CY_Height diff. (H2-H1)	0.362	0.054
Floor_Water ratio	0.292	0.124
CY_Volume	-0.257	0.179
CY_H1 (lower)	-0.255	0.182
CY_Corner (dummy)	0.215	0.263
Floor_Reflectance (ρ)	0.196	0.307
Number of open walls	0.189	0.326
Sky view factor	0.170	0.377
OP_Area	-0.164	0.396
Roof_Emissivity (ε)	-0.154	0.425
Floor_Green Area	0.138	0.476
House_Area	0.135	0.486
CY_W/D	-0.135	0.486
OP_W/D	0.134	0.487
Overhang_Area/CY_Area	-0.108	0.577
AS_H/CY_Area	0.094	0.627
Sky_Plant coverage	0.087	0.653
CY_H2 (higher)	0.076	0.693
OP_Area/CY_Area	0.050	0.795
Roof_U value (W/m2K)	-0.038	0.844
Roof_Area	0.033	0.864
Floor_Soil Area	0.015	0.937
Floor_U value (W/m2K)	-0.008	0.968
CY_Area/H1	0.007	0.971
AS_Height	-0.002	0.991

(c) Abs. Humidity-diff (5th percentile)

Independent Variables	R	Sig.
CY_Height diff. (H2-H1)	0.505	0.005 **
CY_Area/House_Area	-0.429	0.020 *
CY_H1 (lower)	-0.418	0.024 *
CY_Corner (dummy)	0.331	0.080
CY_Volume	-0.289	0.128
OP_W/D	0.216	0.260
Floor_Reflectance (ρ)	0.214	0.265
Sky view factor	0.205	0.287
Floor_Water ratio	0.188	0.329
OP_Area	-0.181	0.347
House_Area	0.176	0.360
Overhang_Area/CY_Area	-0.157	0.416
AS_H/CY_Area	0.142	0.463
Floor_Soil Area	0.119	0.539
CY_W/D	-0.113	0.560
CY_Area/H1	0.089	0.648
Number of open walls	0.064	0.743
Roof_Area	-0.060	0.759
AS_Height	-0.054	0.780
OP_Area/CY_Area	0.041	0.834
Roof_Emissivity (ε)	-0.040	0.838
CY_H2 (higher)	0.025	0.896
Floor_Green Area	0.023	0.906
Floor_U value (W/m2K)	-0.020	0.918
Roof_U value (W/m2K)	-0.016	0.935
Sky_Plant coverage	-0.006	0.977

Table 3.6 summarizes the results of single regression analysis between the independent variables and the relative humidity difference in term of 95th percentile, the mean, and the 5th percentile. As shown, the difference of courtyard height (CY_Height diff. (H2-H1)) is positively correlated with the maximum and mean relative humidity difference and was statistically significant. Meanwhile, the height of courtyard 1 (CY_H1) is negatively correlated with the maximum difference. As for the minimum relative humidity difference, the height of courtyard 2 (CY_H2) shows positive correlation and statistically significant. In contrast, the SVF, opening area (OP_Area), ratio of courtyard to the house area (CY_Area/House_Area) and the ratio of courtyard area to its height (CY_Area/H1) are negatively correlated with the minimum relative humidity and were statistically significant. Additionally, it was also found that the existence of plants and the existence of water bodies are positively correlated with RH levels during both day and night, though they were determined to be the factors affecting the air temperature reductions.

Table 3.6. Results of single regression analysis. Correlation between the independent variables and relative humidity difference (courtyard-outdoor) (a) 95th percentile (b) mean (c) 5th percentile

(a) Relative humidity-diff (95th percentile)

Independent Variables	R	Sig.
CY_Height diff. (H2-H1)	0.434	0.019 *
CY_H1 (lower)	-0.401	0.031 *
Overhang_Area/CY_Area	-0.360	0.055
Roof_Emissivity (ε)	0.326	0.084
CY_Volume	-0.246	0.198
Roof_Area	-0.205	0.287
CY_Corner (dummy)	0.200	0.298
Sky_Plant coverage	0.198	0.303
OP_W/D	0.180	0.349
CY_Area/H1	0.175	0.364
Number of open walls	-0.149	0.439
Floor_Reflectance (ρ)	-0.148	0.445
Floor_U value (W/m2K)	-0.141	0.467
Sky view factor	0.138	0.475
Floor_Water ratio	-0.133	0.492
House_Area	-0.101	0.601
CY_W/D	0.078	0.687
AS_Height	-0.076	0.694
OP_Area/CY_Area	0.076	0.696
Roof_U value (W/m2K)	0.068	0.724
Floor_Green Area	0.063	0.747
CY_H2 (higher)	-0.031	0.873
Floor_Soil Area	0.008	0.965
OP_Area	-0.005	0.980
CY_Area/House_Area	0.002	0.994
AS_H/CY_Area	0.001	0.996

(b) Relative humidity-diff (mean)

Independent Variables	R	Sig.
CY_Height diff. (H2-H1)	0.446	0.015 *
CY_H2 (higher)	0.362	0.054
OP_Area	-0.346	0.066
AS_Height	-0.298	0.116
CY_Volume	-0.289	0.128
Overhang_Area/CY_Area	-0.267	0.162
CY_Area/House_Area	-0.264	0.166
CY_Corner (dummy)	0.257	0.178
Sky_Plant coverage	0.242	0.207
Floor_Water ratio	0.197	0.306
OP_Area/CY_Area	-0.174	0.367
Roof_Area	-0.171	0.374
Sky view factor	-0.166	0.390
House_Area	-0.155	0.423
Floor_Green Area	0.139	0.473
CY_W/D	-0.133	0.492
CY_Area/H1	-0.118	0.541
OP_W/D	0.111	0.566
Floor_Soil Area	0.110	0.571
CY_H1 (lower)	-0.102	0.597
Floor_Reflectance (ρ)	0.083	0.667
Roof_Emissivity (ε)	-0.063	0.744
Roof_U value (W/m2K)	-0.041	0.832
Floor_U value (W/m2K)	0.019	0.921
AS_H/CY_Area	0.012	0.950
Number of open walls	-0.006	0.975

(c) Relative humidity-diff (5th percentile)

Independent Variables	R	Sig.
CY_H2 (higher)	0.542	0.002 **
Sky view factor	-0.478	0.009 **
OP_Area	-0.410	0.027 *
CY_Area/House_Area	-0.401	0.031 *
CY_Area/H1	-0.373	0.046 *
AS_Height	-0.344	0.068
CY_H1 (lower)	0.276	0.147
OP_Area/CY_Area	-0.274	0.150
Floor_Reflectance (ρ)	0.266	0.163
Floor_Water ratio	0.262	0.170
Sky_Plant coverage	0.237	0.216
CY_Height diff. (H2-H1)	0.176	0.360
Number of open walls	0.163	0.399
OP_W/D	0.134	0.490
CY_W/D	-0.127	0.511
House_Area	-0.083	0.669
Overhang_Area/CY_Area	-0.078	0.688
CY_Volume	-0.075	0.701
Roof_Emissivity (ε)	-0.068	0.724
Floor_U value (W/m2K)	0.068	0.724
Floor_Soil Area	0.052	0.789
AS_H/CY_Area	0.030	0.878
Roof_Area	-0.028	0.886
Floor_Green Area	0.022	0.911
Roof_U value (W/m2K)	-0.008	0.966
CY_Corner (dummy)	-0.004	0.985

Table 3.7 summarizes the results of the multiple regression analyses. Meanwhile, the scatter charts shown in Figure 3.10 reveal the correlations between air temperature or humidity differences and the selected key variables. As presented, the sky view factor (SVF) is highly correlated with daily maximum air temperatures and mean values. Furthermore, as indicated in Table 3.7 a-1, the SVF (β=0.63), height (H_2) of the courtyard (CY) (-0.38) and ratio of the overhang area (OH) to the courtyard area (-0.22) explain the daily maximum air temperature difference with a high determination level (adjusted R^2=0.71, p<0.01). These

data suggest that as a courtyard becomes narrower, deeper (in height) and shadier, the daily maximum air temperatures of the courtyards are reduced. As presented in Figure 3.10 a-1, the difference in the daily maximum air temperature is a negative value, indicating that the temperature inside the courtyard is lower (cooler) than the outdoor temperature when the SVF is below (approximately) 14% and the observed difference was up to 5°C. The air temperature difference is projected to be a positive value, in other words, it is warmer inside the courtyard than it is outdoors when the SVF exceeds (approximately) 14%. In contrast, the SVF has a weak but negative correlation with the daily minimum air temperature difference (Figure 3.10 a-1).

Table 3.7. Results of multiple regression analyses. (a) Air temperature differences; (b) relative humidity differences; (c) absolute humidity differences.

(a)

(1) 95th percentile

Variable	*β*	*r*
SVF	0.63**	0.79**
CY_Height 2 (H_2)	-0.38**	-0.63**
OH/CY_Area	-0.22*	-0.05
R^2	0.74**	
Adj. R^2	0.71**	
n	29	

(2) Mean

Variable	*β*	*r*
SVF	0.60**	0.53**
CY_H. difference	-0.54**	-0.19
OP/CY_Area	0.32*	0.36
R^2	0.53**	
Adj. R^2	0.48**	
n	29	

(3) 5th percentile

Variable	*β*	*r*
CY_H. difference	-0.59**	-
R^2	0.34**	
Adj. R^2	0.32**	
n	29	

(b)

(1) 95th percentile

Variable	*β*	*r*
CY_H. difference	0.43*	-
R^2	0.19*	
Adj. R^2	0.16*	
n	29	

(2) Mean

Variable	*β*	*r*
CY_H. difference	0.55**	0.45*
OP_Area	-0.47**	-0.35
R^2	0.41**	
Adj. R^2	0.36**	
n	29	

(3) 5th percentile

Variable	*β*	*r*
CY_Height 2 (H_2)	0.55**	0.54**
OP_Area	-0.42**	-0.41*
R^2	0.47**	
Adj. R^2	0.43**	
n	29	

(c)

(1) 95th percentile

Variable	*β*	*r*
CY/CSH_Area	-0.41*	-0.37*
CY_Height 1 (H_1)	-0.35*	-0.31
R^2	0.26*	
Adj. R^2	0.20*	
n	29	

(2) Mean

Variable	*β*	*r*
CY/CSH_Area	-0.64**	-0.39*
OH/CY_Area	-0.45*	-0.11
R^2	0.30*	
Adj. R^2	0.25*	
n	29	

(3) 5th percentile

Variable	*β*	*r*
CY_H. difference	0.56**	0.51**
CY/CSH_Area	-0.39*	-0.43*
Water bodies	0.33*	0.19
R^2	0.51**	
Adj. R^2	0.45**	
n	29	

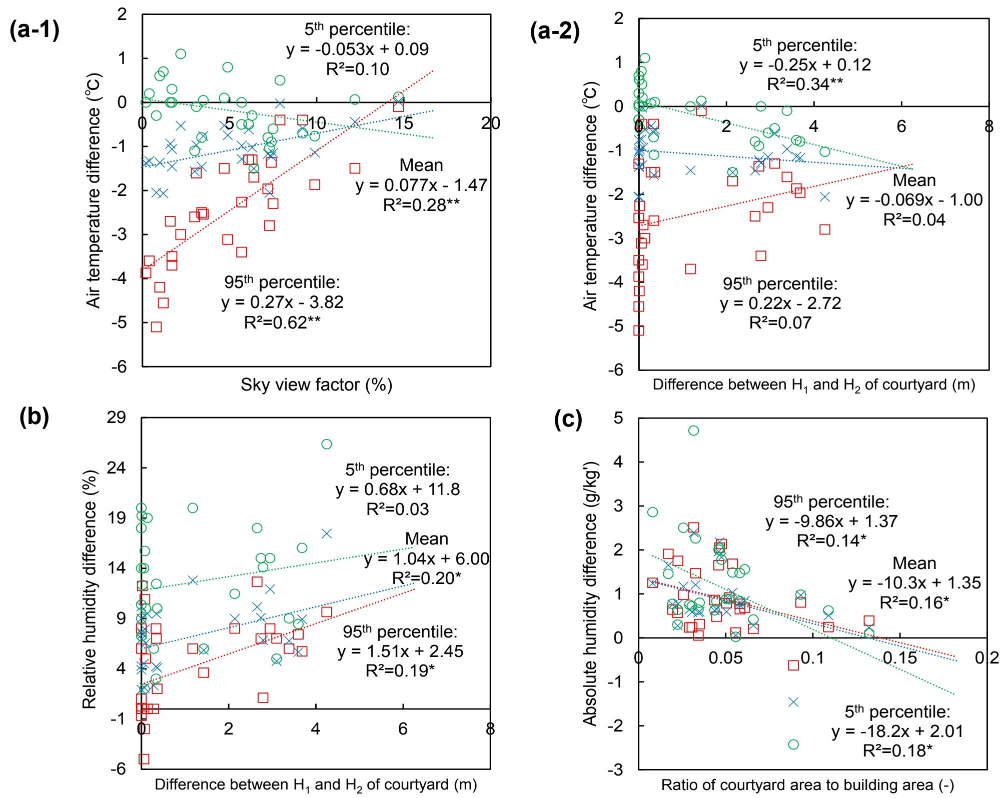


Figure. 3.10. Results of regression analyses. (a-1) SVF and air temperature difference; (a-2) difference of courtyard heights and air temperature difference; (b) difference of courtyard heights and relative humidity difference; (c) ratio of courtyard area to building area and absolute humidity difference.

Furthermore, the difference in the heights of a courtyard (CY_H. difference) is considered a significant variable that explains the daily minimum air temperature of courtyards (Table 3.7 a-3, Figure 3.10 a-2). As presented in Figure 3.10 a-2, as the difference in the heights of a courtyard increases, the daily minimum air temperature in the courtyard decreases (R^2=0.34, p<0.01). This means that when a courtyard is situated between buildings/walls of different heights (i.e., staggered form), the daily minimum air temperature of the courtyard tends to decrease. This is likely because, in the case of the staggered form, the floor and higher wall of the courtyard are well exposed to the night sky, and thus, the surfaces are cooled through nocturnal radiant cooling. Moreover, the small volume of the courtyards may retain the cooled air from the roofs that lean towards the courtyards, as indicated in (Toe and Kubota, 2015; Koch-Nielsen, 2002). Furthermore, the staggered form may increase the air flow entering the courtyards at night compared with the air flow entering flat, deep courtyards.

As shown in Table 3.7c, the ratio of the courtyard area to the whole building area (CY/CSH_Area) was determined to be a key variable that explains the AH levels in the courtyards. As presented in Figure 3.10c, the increase in the ratio almost flatly decreases the maximum, minimum and mean values, which implies that the size of the courtyard compared to that of the entire building is one of the key factors affecting the degree of AH.
Consequently, the RH in the courtyards is explained by certain key variables affecting air temperatures and/or AH (Table 3.7b, Figure 3.10b). In particular, the difference in heights of the courtyard (CY_H. difference) affects the maximum values (night-time), while the height of the courtyards (CY_Height 2) and the opening area of the courtyards influence the minimum values (daytime). Thus, the mean values of RH can be explained by these variables (Table 3.7 b-2).

3.2.3 Typology of courtyard forms

A principle component analysis (PCA) and a cluster analysis were carried out by using the 29 samples of courtyard to classify the courtyards in term of their forms and characteristics that affect the profiles of their thermal environments. Before the PCA analysis was conducted, all variables were standardized as Z-scores. After an initial analysis, four components that explained 62% of variance were determine. The results of the PCA analysis is as shown in Table 3.8. The variables that clustered on the same components suggested that Component 1 denotes "Space volume", Component 2 represents "Openness", Component 3 signifies "Courtyard height" and Component 4 represents "Plants".

Table 3.8. Component matrix of PCA analysis

Variable	Component			
	1	2	3	4
Roof_Area	0.874	-0.178	0.006	-0.024
OH_Area	0.853	-0.026	-0.027	0.058
CSH_Width	0.819	0.164	0.205	0.112
CSH_Depth	0.674	0.108	0.275	0.129
Floor_U-value	-0.673	-0.441	0.389	0.006
No. of open walls	0.657	-0.520	0.131	-0.059
CY_Volume	0.615	0.014	-0.621	-0.171
AS_Height	0.581	0.067	0.550	-0.204
OH/CY_Area	0.455	-0.509	0.529	0.180
OP_Area	0.411	0.645	-0.044	-0.288
CY_Corner (dummy)	-0.405	0.655	0.212	0.373
CY_Area/H_1	0.252	0.907	-0.188	0.076
CY_Height 1 (lower)	0.151	-0.754	-0.446	-0.158
SVF	0.298	0.635	0.571	-0.176
CY_Height diff. (H_2-H_1)	-0.332	0.602	0.326	-0.002
AS_H/CY_Area	-0.197	-0.347	0.852	0.117
OP/CY_Area	-0.016	0.207	0.619	-0.195
CY/CSH_Area	-0.373	0.389	-0.466	-0.313
CY_W/D	0.089	0.019	-0.186	-0.686
Floor green coverage	0.137	0.223	-0.378	0.676
OP_W/D	-0.121	-0.117	0.135	-0.591
Sky plant coverage	0.157	-0.057	-0.266	0.528
Floor soil coverage	0.139	0.140	-0.133	0.373
Floor_Reflectance	-0.214	-0.324	0.313	0.315
Water bodies	0.003	-0.320	-0.244	0.228
CY_Height 2 (higher)	-0.174	-0.293	-0.211	-0.202
% of variance	20.7	17.3	14.5	9.5

Note: Component 1, Space volume; Component 2, Openness; Component 3, Courtyard height; Component 4, Plants. n = 29.

A further regression analysis was conducted and it was found that Component 1 (space volume), Component 2 (openness) and component 3 (courtyard height) exhibit significant relationship with air temperature and relative humidity in the courtyards in particular, whereas none of the components had significant relationship with absolute humidity (Table 3.9).

Table 3.9. Single regression analysis: Correlation between components and thermal parameters. (a-1) Air temperature in courtyards (a-2) air temperature difference (courtyard-outdoor) (b-1) absolute humidity in courtyards (b-2) absolute humidity difference (courtyard-outdoor) (c-1) relative humidity in courtyards (c-2) relative humidity difference (courtyard-outdoor)

(a-1) Air temperature

Component	R		
	95th percentiles	Mean	5th percentiles
1	0.16	0.39*	0.22
2	0.56**	0.03	-0.50**
3	0.35	0.29	0.05
4	-0.24	-0.27	-0.28

(a-2) Air temperature difference

Component	R		
	95th percentiles	Mean	5th percentiles
1	0.13	0.39*	0.16
2	0.60**	0.19	-0.52**
3	0.41*	0.32	-0.08
4	-0.13	-0.12	-0.04

(b-1) Absolute humidity

Component	R		
	95th percentiles	Mean	5th percentiles
1	-0.23	-0.24	-0.34
2	0.10	0.05	-0.01
3	0.07	-0.14	-0.32
4	0.23	0.24	0.19

(b-2) Absolute humidity difference

Component	R		
	95th percentiles	Mean	5th percentiles
1	-0.04	-0.02	-0.08
2	0.09	0.05	0.16
3	0.28	0.22	0.29
4	0.30	0.23	0.22

(c-1) Relative humidity

Component	R		
	95th percentiles	Mean	5th percentiles
1	-0.27	-0.44*	-0.36
2	0.32	0.07	-0.32
3	-0.21	-0.28	-0.48**
4	0.21	0.39*	0.27

(c-2) Relative humidity difference

Component	R		
	95th percentiles	Mean	5th percentiles
1	-0.19	-0.28	-0.17
2	0.31	-0.03	-0.37*
3	0.06	-0.03	-0.12
4	0.00	0.27	0.23

Based on the factor scores of these three components, i.e. space volume, opened and courtyard height, the hierarchical cluster analysis was conducted by applying the Ward's minimum variance method. The distances of the samples were measured using the squared Euclidean differences. By considering the typology of the courtyards, five clusters (hereafter, courtyard types) were determined for the 29 courtyards (Figure 3.11). As presented in Figure 3.12, these five types of courtyards are well characterized by the three components. For instance, Type 5 courtyards are deep, closed courtyards (Figure 3.12c), whereas Type 2 courtyards tend to be shallow and small (Figure 3.12b).

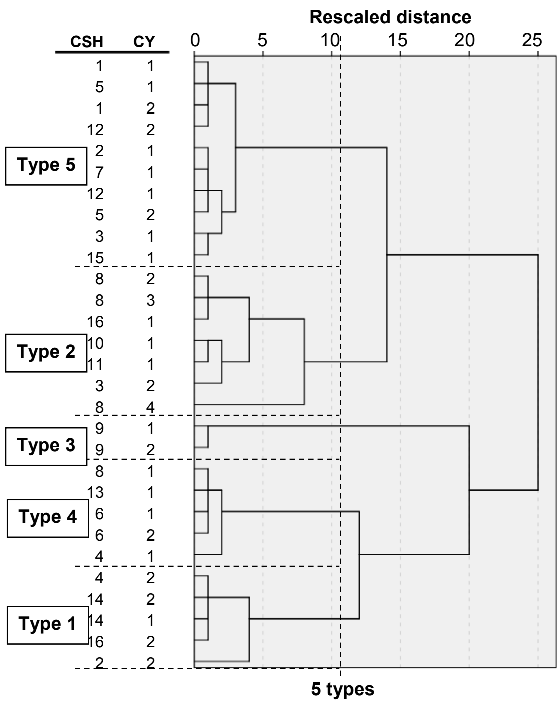


Figure 3.11. Dendrogram using ward linkage.

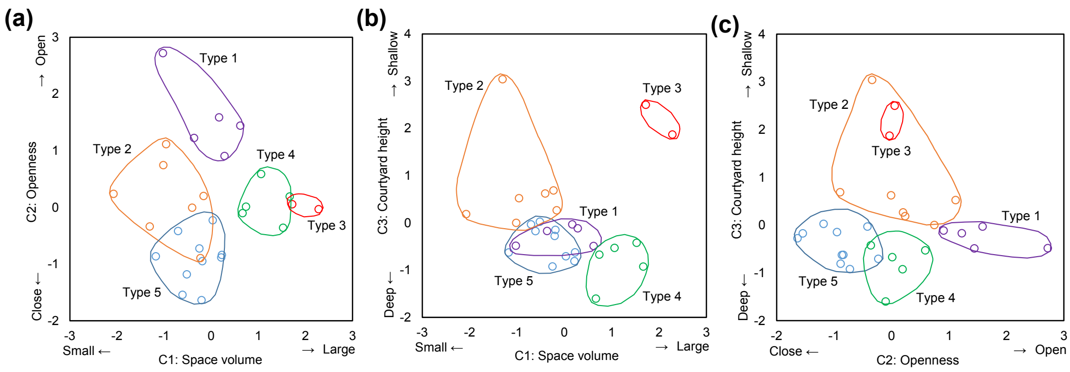
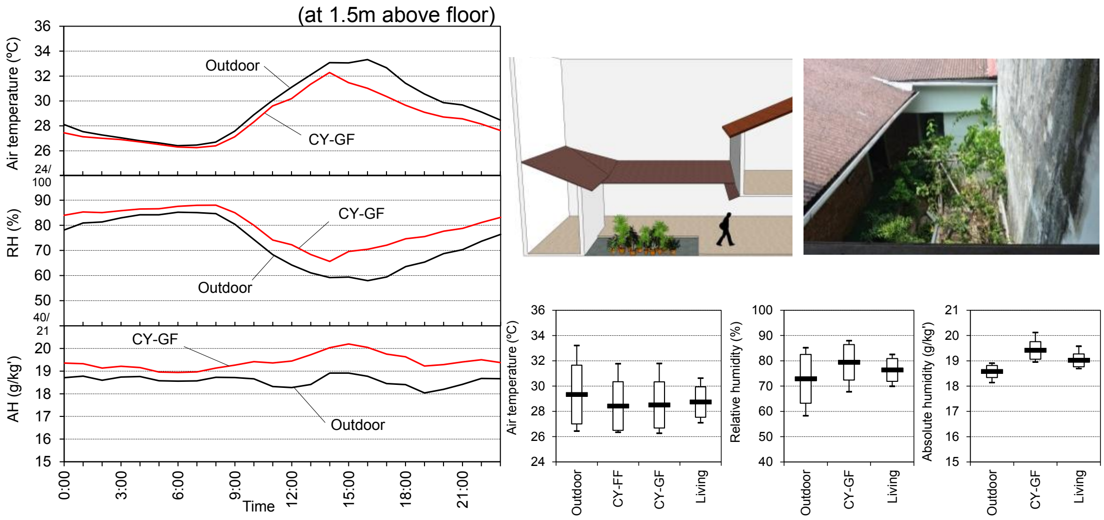


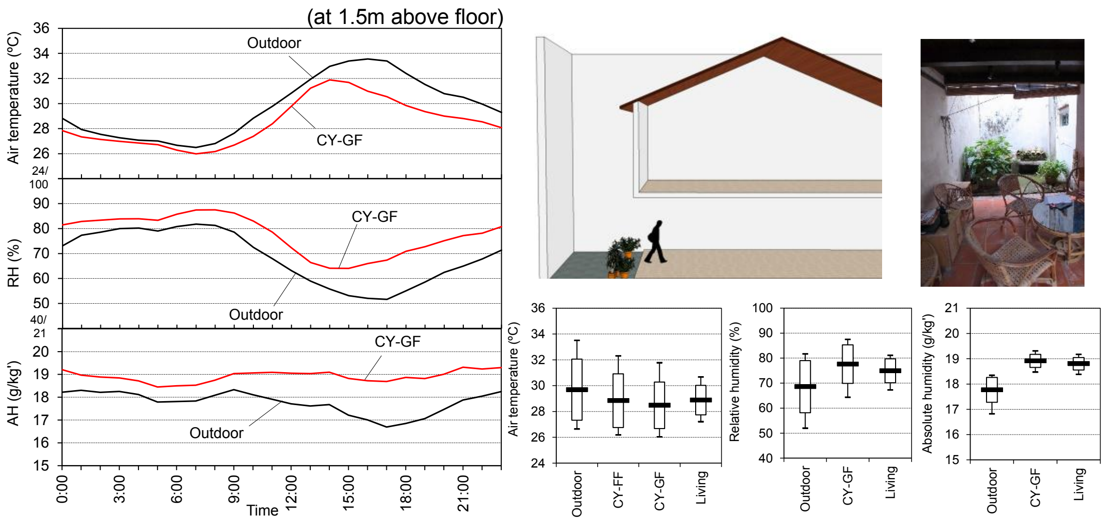
Figure 3.12. Results of cluster analyses. (a) Space volume and openness; (b) space volume and courtyard height; (c) openness and courtyard height.

3.2.4 Profiles of thermal environments for respective courtyard types

Figure 3.13 presents the daily averaged profiles of air temperature (left) and statistical summaries of air temperatures and humidity (right) measured on fair weather days for the various courtyard types. The illustrations and pictures represent their typical situations.



(a) Type 1: Open and staggered



(b) Type 2: Small and staggered

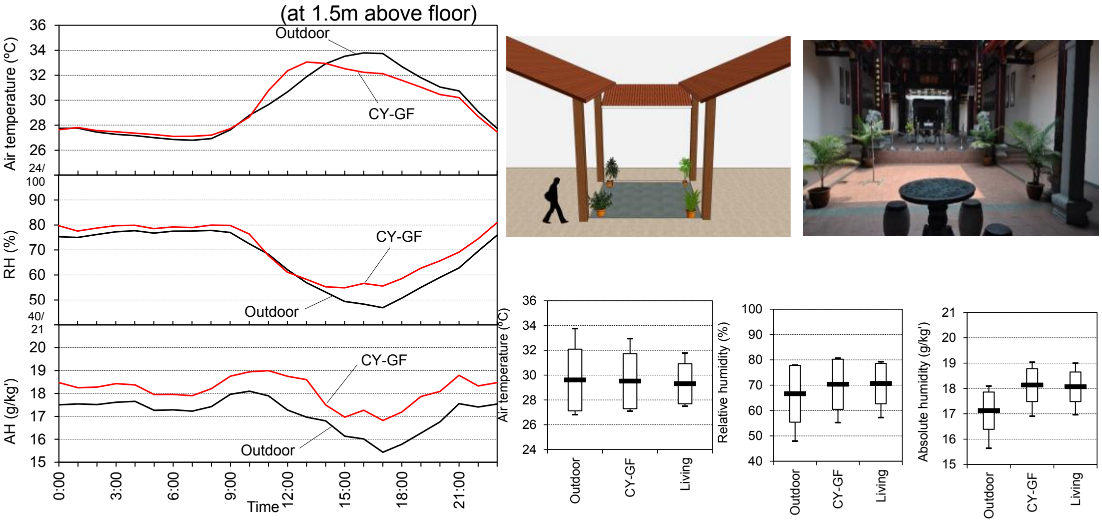
Figure 3.13. Profiles of air temperatures and humidity levels in courtyards and adjacent living halls. Note: Statistical summaries (right) reveal 5th and 95th percentiles, mean and ± one S.D.

As shown in Figure 3.13a, Type 1 courtyards can be described as open and staggered and they were usually rectangular in shape with width (W) < depth (D). They were also relatively compact (small in volume) and open to the sky because they were surrounded by low-rise buildings. The SVF of Type 1 courtyards ranged from 6.1 to 9.9%, with an average of 7.6%. In this case, the nocturnal air temperatures inside the courtyards tended to be almost the same levels or even lower than the corresponding outdoor temperatures because the differences in the heights of the courtyards were relatively large (2 to 3 m, on average) in the Type 1 and 2 courtyards. It is further noted that the nocturnal air temperatures in the courtyards can be lower than the outdoor temperatures even at the first-floor level which is located at 3 to 4 m above ground. Similarly, the daytime air temperatures in the courtyards were lower than the outdoor temperatures by up to 2.5°C.

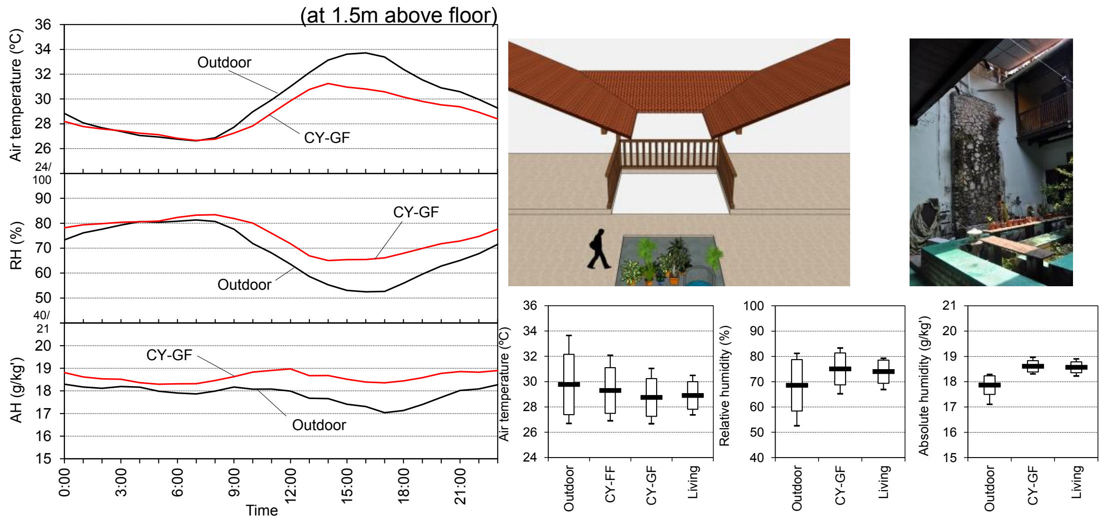
Type 2 courtyards were small and staggered and were square in shape, but they were generally located at the end of the buildings as shown in Figure 3.13b. The SVFs were averaged at 5.6%, and the air temperature profiles were almost similar to those of the Type 1 courtyards. However, the temperature reductions during both day and night were slightly larger than those of the Type 1 courtyards. In addition, it can be seen that the nocturnal relative humidity difference between courtyard and outdoor is also slightly larger compared to the those of Type 1. Meanwhile, the Type 3 courtyards, which were large and shallow, recorded higher daytime air temperatures than the other types because they (Type 3 courtyards) received more solar radiation (Figure 3.13c) In this case, the courtyards were square-shaped and located in the center of the buildings with no surrounding walls. The SVFs were 12.2 and 14.7%, respectively. Due to the warm condition during the daytime, the relative humidity of the courtyard was reduced to approximately 55%. In contrast, during the night-time, the relative humidity of courtyard increased with the increases of outdoors by up to 80%.

As shown in Figure 3.13d, Type 4 courtyards were deep and large and their approximate dimensions were 4-5 m (W) x 4-5 m (D) x 6-7 m (H) and SVF=3.0-5.7%. In this case, the daytime air temperatures tended to be lower than the corresponding outdoor temperatures by up to 3°C, while the nocturnal air temperatures in the courtyards could be as low as the outdoor temperatures. As for the relative humidity in the courtyard, it was about 15% higher than the corresponding outdoor in the daytime. Meanwhile, at the night-time, the relative humidity in the courtyard is almost similar to the corresponding outdoor at about 80%.

Compared to the other types of courtyard, a significant temperature drop is observed during peak hours in the Type 5 courtyards as shown in Figure 3.13e. These deep, closed courtyards recorded lower daytime air temperatures compared to outdoor temperatures by up to 4°C, on average. The SVFs of the Type 5 courtyards were determined to be between 0.2 and 6.3%, with an average of 1.9%. It is further noted that the daytime peak temperatures in the courtyards were even lower than those recorded in the adjacent living halls. Accordingly, the findings indicate that the shading effect of deep, closed atrium-type courtyards and the cooling effects of plants contributed to lower air temperatures. Conversely, however, the nocturnal air temperatures in the courtyards were slightly higher than the outdoor temperatures by up to 0.5°C, on average. In this case, it can be seen that the daytime relative humidity is higher than most of the cases where the values are more than 70%.



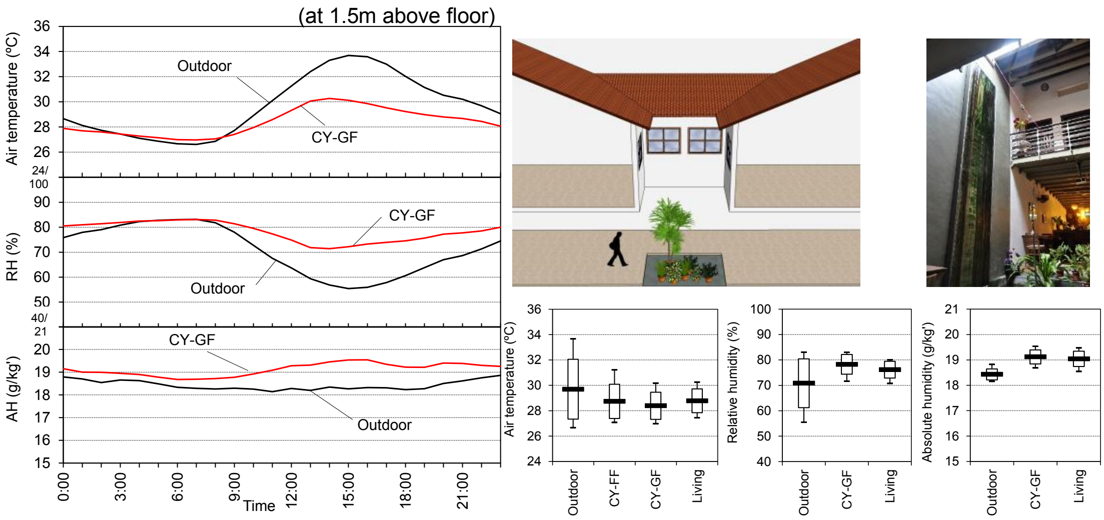
(c) Type 3: Shallow and large



(d) Type 4: Deep and large

Figure 3.13. Profiles of air temperatures and humidity levels in courtyards and adjacent living halls (continued).

Note: Statistical summaries (right) reveal 5th and 95th percentiles, mean and ± one S.D.



(e) Type 5: Deep and close

Fig. 3.13. Profiles of air temperatures and humidity levels in courtyards and adjacent living halls (continued).
Note: Statistical summaries (right) reveal 5th and 95th percentiles, mean and ± one S.D.

Meanwhile, the profiles of absolute humidity do not show any clear differences among the five courtyard types (Figure 3.13). For the most part, the absolute humidity of courtyards was found to be always higher than the corresponding outdoor levels regardless of courtyard type. In addition, the AH differences were constantly larger in the case of Type 2 courtyards, ranging, on average, from 0.6 to 2.0 g/kg', compared with the other courtyard types. This is primarily because of the relatively small size of the Type 2 courtyards (e.g., the ratio of the courtyard area to the whole building is, on average, 4%).

In summary, the degree of exposure of the courtyard to the outdoor space (sky) is a key factor that influence the profiles of indoor air temperature in the courtyards. If the courtyard is well exposed to the outdoor such Type 1 and Type 2, a high reduction of air temperature in the courtyard during the daytime is cannot be expected. In contrast, the nocturnal air temperature in the courtyard could be lower than the corresponding during the night-time. Meanwhile, if there are too much exposure to the outdoor such as the courtyard of Type 3, the daytime air temperature in the courtyard will increase closely follows the outdoors and resulted to the warm indoor conditions. In contrast, a significant temperature reduction can be achieved during the daytime if the courtyard is less exposed to the outdoors as shown in the courtyard of Type 4 and 5. However, in the night-time, the nocturnal air temperature in the courtyard tends to be higher than the corresponding outdoor. This is primarily because a large exposure of the courtyard enables more solar radiation to the courtyard area during the daytime, while increase the nocturnal radiant cooling rate during the night-time.

3.3 Thermal comfort in Chinese shophouse with courtyards

In this section, two units of CSHs has been selected for a detailed field measurement to investigate the indoor thermal condition of the shophouse with courtyards. Both CSHs are already included in the previous section, namely, CSH 1 and CSH 3 (see Table 3.1). The measurements were conducted in October 2011 (CSH 1) and in September 2014 (CSH 3). Figure 3.14 and 3.15 shows the picture and the plan of CSH 1 and CSH 3. The CSH 1 was originally constructed around the time of the Dutch colonial era in the 19th century, and it was restored in 2004 by the National University of Singapore (NUS) as an academic centre. It was occupied by two staff members on alternate weekdays from 10 a.m. to 5 p.m. during the measurement period. The external windows were open only on the first floor when occupied. In contrast, the CSH 3 was originally built between the 17th and 19th centuries and was strongly influenced by Dutch architecture. It was recently restored by the Heritage of Malaysia Trust. The building is currently used as an exhibition facility for tourists, operating between 11 a.m. and 4 p.m. on weekdays. The building was occupied by only one staff and two or three researchers during the time the measurements were taken. The external doors and windows were open during the period of operation. Ceiling fans were installed in most rooms in both CSHs, but they were not used during the time the measurements were taken. There was no air conditioner installed in either of the CSHs.

(a)

(b)

Figure 3.14. CSH 1. (a) Front exterior view and courtyard; (b) floor plans.

(a)

(b)

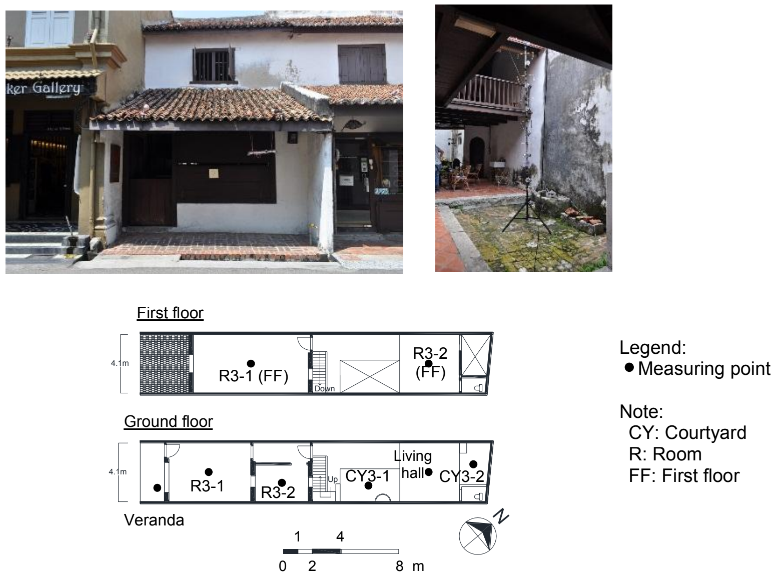


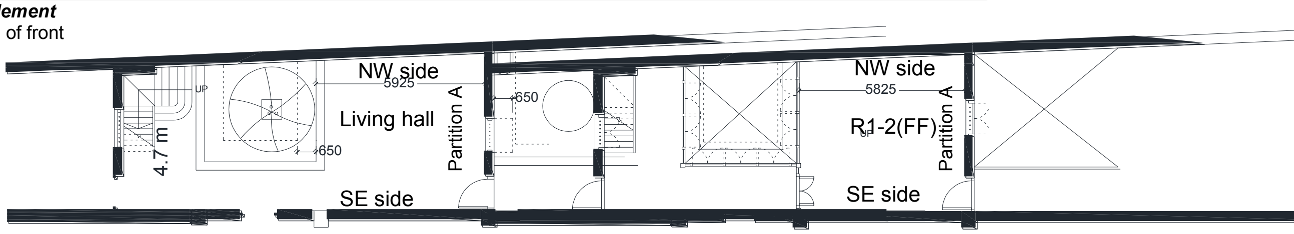
Figure 3.15. CSH 3. (a) Front exterior view and courtyard; (b) floor plans.

The detailed descriptions of CSHs 1 and 3 are presented in Tables 3.10 and 3.11. As shown in the tables, the building structures of both CSHs were of load bearing lime-plastered brick walls with thicknesses of 250-350 mm (CSH 1) and 150-300 mm (CSH 3), concrete, and timber frame. The U-values of walls in CSH 1 range from 1.6 to 1.9 W/(m^2K), while those in CSH 3 vary from 1.7 to 2.5 W/(m^2K). The thermal masses of their living halls are high at about 1270-1300 kg/m^2 in CSH 1 and about 470-490 kg/m^2 in CSH 3.

As presented in Figure. 3.14 and 3.15, each of the CSHs has two internal courtyards. As indicated in Figure 3.14, the front courtyard of CSH 1 (hereafter, CY 1-1) and the second courtyard (CY 1-2) were classified as a Type 5 courtyard (deep and closed). Meanwhile, in CSH 3, the front courtyard (CY3-1) was classified as a Type 5 and and CY 3-2 as a Type 2 (small and staggered) (see Figure 3.13). An important difference between CSHs 1 and 3 is that the two courtyards in CSH 1 were separated by a partition, though there were permanent ventilation openings in the partition. In contrast, the courtyards in CSH 3 did not have any partitions between them. Therefore, in CSH 3, sufficient cross-ventilation was allowed between the two courtyards.

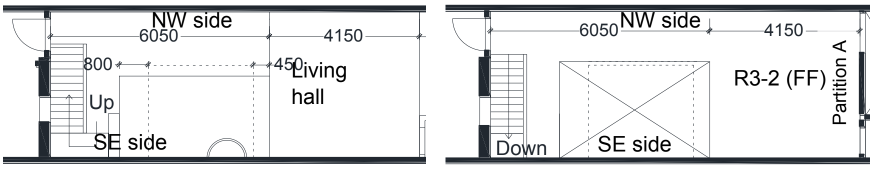
Table 3.10. Detailed descriptions of the Chinese shophouse 1 (CSH 1)

Aspect	Description	
	Living hall (ground floor)	**First floor room**
Building material		
Structure	Load bearing brick wall structures	Concrete column and timber frame structures
Roofing	Chinese U-shaped clay tiles with wooden board (without insulation) (U-value: 3.27 W/(m^2·K))	
Ceiling	Wooden board of the floor above (U-value: 5.23 W/(m^2·K))	Wooden board (sloped ceiling, U-value same as roof)
Flooring	Cement rendering (U-value: 0.93 W/(m^2·K))	Wooden floor board (U-value: 5.23 W/(m^2·K))
External wall	Brick with lime plaster (for the building) (U-value: 1.92 W/(m^2·K))	
Party wall	Brick with lime plaster (U-value: 1.55 W/(m^2·K))	
Internal partition	Brick with lime plaster (U-value: 1.66 W/(m^2·K))	
Fixed upper ventilation opening	Precast concrete ventilation holes (in other rooms)	Precast concrete ventilation holes; wooden louvers
Window	Open grille window	Wooden and frosted glass panel window
Door	Open grille door	Wooden panel swing door
Shading element		
Roof eaves of front courtyard		



	Roof eaves dimension: 650 mm	
Awning	Awning above window: 650 mm	Nil
Plant	Palm tree Approximate height: 7.5 m (roof eaves level) Approximate crown width: 3 m	Nil
Surrounding building	Traditional Chinese shophouses in row layout Adjacent building heights (NW and SE sides): Same as the case study building (i.e. 10.5 m at roof ridge level)	
Opening element		
Internal partition (Type; size; position; % wall area; usage conditions)	Partition A Half-height open grille window; 1050 mm (W) x 1170 mm (H); 890 mm above floor; 5%; fixed open, no curtain. Open grille swing door; 1020 mm (W) x 2100 mm (H); -; 10%; always open, no curtain.	Partition A Wooden panel swing window; 1080 mm (W) x 1200 mm (H); 830 mm above floor; 7%; always open, no curtain. Wooden panel swing door; 1020 mm (W) x 2180 mm (H); -; 11%; always open, no curtain. Partition B Half-height wooden and frosted glass panel swing window; 1130 mm (W) x 1380 mm (H) x 2 units; 1010 mm above floor; 17%; open during daytime, no curtain. Wooden swing door; 1020 mm (W) x 2180 mm (H); -; 12%; open during daytime, no curtain. Wooden louvres (fixed upper ventilation opening); 1020 mm (W) x 760 mm (H); above door; 4%; fixed open, no curtain.
Roof opening of front courtyard	2700 to 2800 mm (W) x 2600 mm (D)	
Other attribute		
Roof surface	Brown clay tiles (solar reflectance: 0.2-0.3)	
External wall surface	White paint (solar reflectance: 0.8-0.9)	
Party wall surface at front courtyard	White paint (solar reflectance: 0.8-0.9)	
Floor surface	Greyish (solar reflectance: 0.4-0.6)	Light brown (solar reflectance: 0.3-0.4)
Thermal mass	1308 kg/m^2 floor areas	1273 kg/m^2 floor areas
Room height	4.0 m	3.5-4.5 m (sloped ceiling)

Table 3.11: Detailed descriptions of the Chinese shophouse 3 (CSH 3)

Aspect	Description	
	Living hall (ground floor)	First floor room
Building material		
Structure	Load bearing brick wall structures	Concrete column and timber frame structures
Roofing	Chinese U-shaped clay tiles (without insulation) (for the building) (U-value: 5.41 W/(m^2·K))	
Ceiling	Wooden board of the floor above (U-value: 5.23 W/(m^2·K))	No ceiling
Flooring	Terracotta tiles (U-value: 1.22 W/(m^2·K))	Wooden floor board (U-value: 5.23 W/(m^2·K))
External wall	Brick with lime plaster (for the building) (U-value: 1.72 W/(m^2·K))	
Party wall	Brick with lime plaster (U-value: 2.53 W/(m^2·K))	
Internal partition	Brick with lime plaster (U-value: 1.72 W/(m^2·K))	
Fixed upper ventilation opening	Precast concrete ventilation holes (in other rooms)	Wooden louvres
Window	Wooden panel swing window	Open wooden grille window
Door	Wooden panel swing door	
Shading element		
Roof eaves of front courtyard	 Roof eaves dimension: 450-800 mm	
Awning	Nil	
Plant	Nil	
Surrounding building	Traditional Chinese shophouses in row layout Adjacent building heights: • NW side: About 0.5 m higher than the case study building (i.e. 8 m at roof ridge level) • SE side: Same as the case study building (i.e. 7.5 m at roof ridge level)	
Opening element		
Internal partition (Type; size; position; % wall area; usage conditions)	No partition (exposed to CY1 and CY2)	Partition A Wooden panel swing window; 1110 mm (W) x 1000 mm (H); 1130 mm above floor; 9%; always open, no curtain. Wooden panel swing door; 730mm (W) x 2000 mm (H); -; 12%; open during daytime, no curtain. Wooden louvres 1 (fixed); 1110 mm (W) x 980 mm (H); 150 mm above floor, no curtain. Wooden louvres 2 (fixed); 1400 mm (W) x 370 mm (H); 2130 mm above floor, no curtain.
Roof opening of front courtyard	2600 mm (W) x 2900 mm (D)	
Other attribute		
Water body (well)	3.9% of the floor area of courtyard	
Roof surface	Brown clay tiles (solar reflectance: 0.2-0.3)	
External wall surface	Weathered white lime plaster (solar reflectance: 0.5-0.7)	
Party wall surface at front courtyard	Weathered white lime plaster (solar reflectance: 0.5-0.7)	
Floor surface	Red (solar reflectance: 0.3-0.4)	Dark brown (solar reflectance: 0.1-0.2)
Thermal mass	472 kg/m^2 floor areas	489 kg/m^2 floor areas
Room height	2.7 m	2.1 - 3.5 m (sloped roof)

3.3.1 Methods

The detailed methods of measurement in CSH 1 are presented in (Toe and Kubota, 2015; Kubota *et al*., 2014). In the recent measurements (CSH 3), the air temperature and relative humidity at 1.5m above floor were measured at the centers of all the rooms (T&D TR-72). Moreover, the detailed thermal parameters including globe temperature and wind speed were additionally measured in the living hall (ground floor) for thermal comfort evaluation (Vaisala HMP155 and Kanomax 0965-03). In addition, the vertical distribution of air temperature in the two courtyards (in every 0.5m from the floor to the top) and the surface temperatures of roofs near the courtyards were measured, respectively (4.9-5.7m above ground floor level). Wind speed sensors were installed at the center of front and rear windows on each floor and at the top of both courtyards (4.8m (CY1) and 5.3m (CY2) above floor), respectively. Wind directions were also observed (using a simple ribbon) at all the windows by taking the sequential photographs (Recolo IR7). In addition, a smoke test (PSLaser Z-400) was conducted to investigate air flow patterns in and around the courtyards during daytime and night-time of the day (24th September). Meanwhile, outdoor air temperature, relative humidity and atmospheric pressure were recorded at the veranda of the CSH, whereas a weather station (Davis Vantage Pro2) was placed on a small open space located about 500m away from the measurement site (at 4m above the ground). The degrees of accuracy of the instruments used are provided in Table 3.12.

Table 3.12. Description of measurement instruments

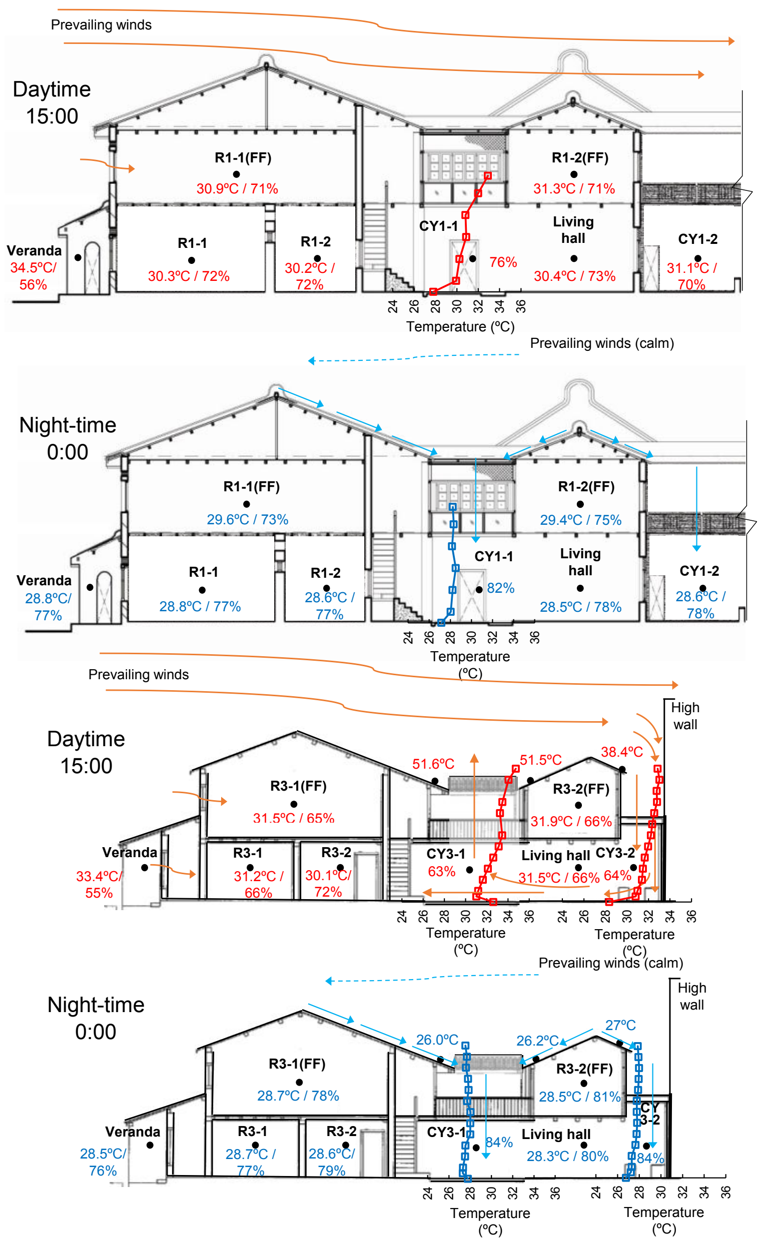
Measured variable	Instrument model	Accuracy
Air temperature, RH and Air pressure	T&D TR-73U	±0.3°C, ±5%RH, ±1.5hPa
Air temperature and RH at 1.5m above floor (Living halls)	Vaisala HMP155A	±0.17°C, ±1% (0-90%RH); ±1.7% (90-100%RH)
Air temperature and RH at 1.5m above floor (other rooms)	T&D TR-72U	±0.3°C, ±5%RH
Air temperature (vertical distribution)	Type T thermocouple and Graphtec GL820	±0.1%+0.5°C plus ±0.5°C for cold junction compensation
Air speed	Kanomax 6244 with sensors (0965-03)	0.1-4.99m/s: ±0.15m/s, 5.00-9.99m/s: ±0.3m/s, 10.0-25.0m/s: ±0.6m/s
Outdoor weather station (Air temperature, RH, Wind speed, Wind direction, Solar radiation and Rain fall)	Davis, Vantage Pro 2	±0.5°C, ±3%RH (±4%RH when RH>90%), ±1 m/s or ±5% of rdg (wind speed), ±3° (wind direction), ±5% of full scale (solar radiation), ±4% of full scale (rain fall)

3.3.2 Variations in thermal environments of whole houses

Figure 3.16 illustrates the average air temperatures in indoor spaces in both CSHs during the day (15:00) and the night (0:00). Vertical distributions of air temperatures in courtyards were also analysed. Figure 3.17 presents the statistical summary of air temperatures and degrees of humidity in these spaces. As indicated in Figure 3.17, outdoor air temperatures ranged from 26.5 to 35.0ºC with an average of 30.0ºC in CSH 1 during the fair-weather days, while those of CSH 3 ranged from 25.5 to 33.5ºC with an average of 29.5ºC. Meanwhile, the outdoor relative humidity during the same days ranged from 54 to 85% in CSH 1, whereas that in CSH 3 ranged from 53 to 89%. In both cases, the prevailing wind directions were from SSW to SW during the daytime (winds blew towards the front façade at (almost) a right angle) and from NE to ENE during the night with average wind speeds of 0.7 to 1.0 m/s.

In CSH 1, CY 1-1 (Type 5) recorded a steep temperature gradient (thermal stratification) during the day, particularly at the ground floor ceiling level and above (Figure 3.16a). As evidenced from Figure 3.17a, the average daily maximum air temperature in CY 1-1 was close to the air temperatures in the surrounding indoor spaces, which were approximately 4.0°C lower than the corresponding outdoor temperature. In contrast, the average daily maximum temperature in CY 1-2 (Type 5) was approximately 2.0°C higher than that in the living hall. As the living hall was situated next to the CY 1-1 with no partition, its air temperature was nearly the same as that of the courtyard. As a result, the daytime air temperature in the living hall was approximately 4.0°C lower than the corresponding outdoor temperature. In contrast, the daily minimum air temperatures were lowest in these two courtyards and were almost the same as the corresponding outdoor temperature (Figure. 3.16a, 3.17a). Moreover, the temperature gradient was almost absent in the courtyard at night, which clearly indicates that the cool outdoor air sufficiently entered the building through the courtyard as all external windows and doors were closed. Thus, it is concluded that the courtyards serve as cooling sources to the surrounding spaces during the night.

In CSH 3, the lowest daytime air temperatures were observed not in the courtyards but rather in the room located on the ground floor (R3-2) (Figure. 3.16b, 3.17b). This was due primarily to the structural cooling effect of the high thermal mass building. Meanwhile, the daily maximum air temperatures in the three spaces, i.e. CY 3-1 (Type 5), living hall and CY 3-2 (Type 2), recorded almost the same values (approximately 32°C), which were only 1.5°C lower than the corresponding outdoor temperature. As presented in Figure 3b, a steep temperature gradient is evident, especially in the CY 3-1 during daytime hours, but the clear gradient is found only at the lower levels, i.e., below the ground floor ceiling level. This means that the stratum of relatively cooled air in the CY 3-1 is thinner than that of the CY 1-1. This is primarily because the two courtyards (CY 3-1 and CY 3-2) were connected without any partition, and thus cross-ventilation (i.e. inflow of outdoor air) was improved by the two courtyards in CSH 3. CY 3-2 was situated at the end of the building, and the height of the adjacent building was 3.4 m higher than the original CSH, i.e. staggered form (see Figure 3.16b). Furthermore, it was observed that the prevailing winds hit the high wall of the adjacent building and created downward winds that then flowed into CY 3-2 as illustrated in Figure 3b. As the air flow went downward, it travelled through the living hall toward CY 3-1, thus generating upward winds in the courtyard. The inflow of outdoor warm air increased the indoor air temperature and equalized air temperatures between the two courtyards as well as the air temperatures in the living hall. The nocturnal air temperature profiles for CSH 3 were similar to those for CSH 1.



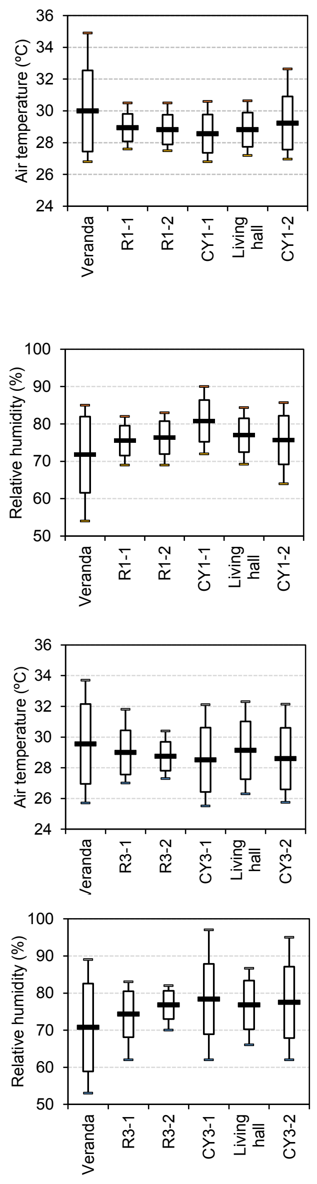


Figure 3.16. Distribution of air temperatures in (a) CSH 1 and (b) CSH 3.
Note: Sectional drawings with permission of TTCLC, National University of Singapore and The Heritage of Malaysia Trust.

Figure 3.17. Statistical summary (5th and 95th percentiles, mean and ±one S.D.) of measurements (at 1.5m above floor) in (a) CSH 1 and (b) CSH 3.

3.3.3 Cooling effect of courtyards on adjacent spaces

The cooling effect of courtyards on adjacent spaces was further analysed through the comparison of thermal conditions in the living halls located next to the courtyards and the rooms without courtyards in CSHs 1 and 3, respectively. Figure 3.18 displays the temporal variations in air temperatures and humidity with the corresponding outdoor conditions in these spaces. The results of the first-floor rooms located above the spaces of subject are also presented in the figures.

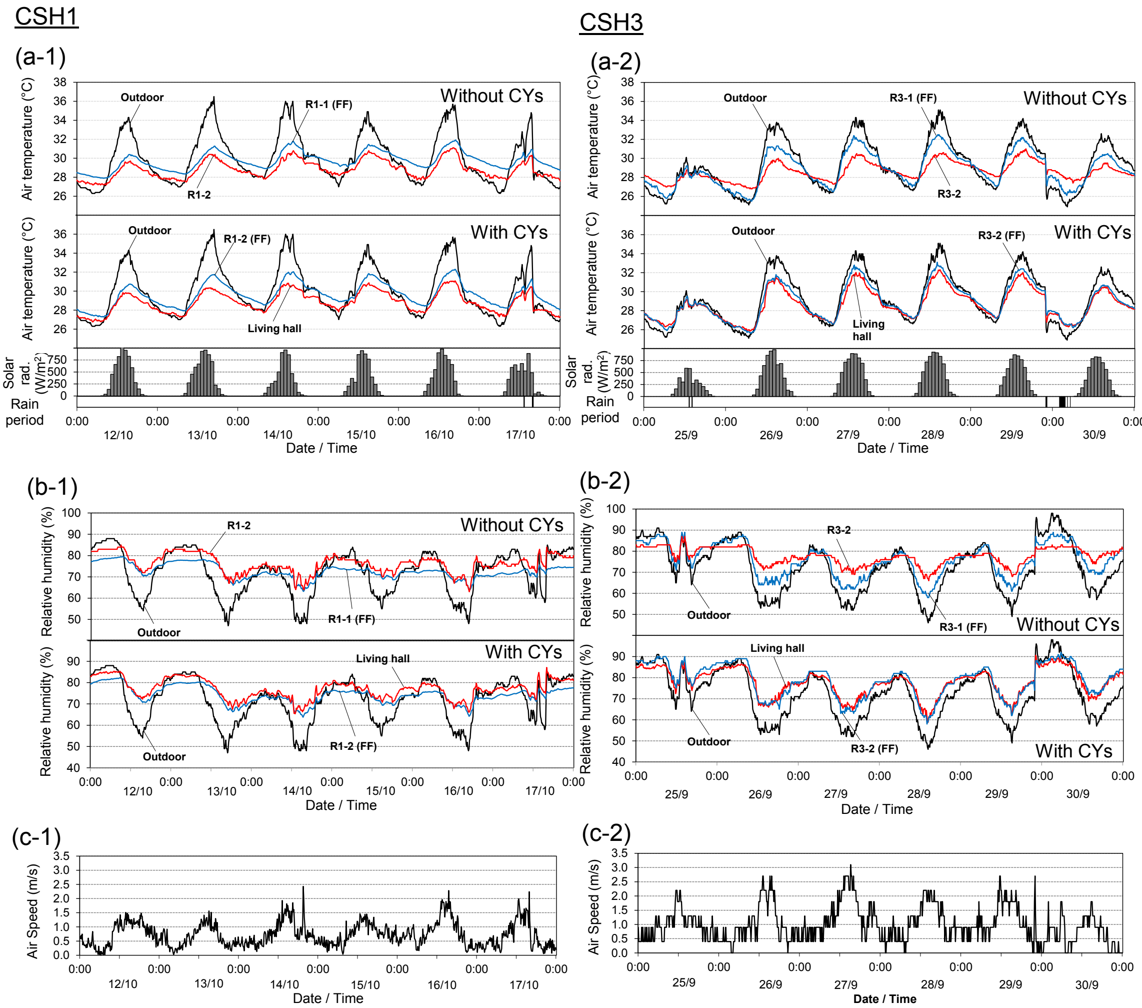


Figure 3.18. (a) Air temperature in adjacent spaces with the corresponding outdoor conditions (air temperature, solar radiation and rain period); (b) relative humidity in adjacent spaces and outdoors; and (c) outdoor wind speed.

As previously discussed herein, in CSH 1, the living hall is situated next to the CY 1-1 (see Figures 3.14b and 3.16a), which is a deep atrium-type courtyard with a shade tree (sky view factor (SVF): 0.2%). Consequently, the air temperatures in the living hall of CSH 1 maintained lower degrees throughout the day. The air temperatures in the first-floor room located above the living hall were approximately 0.5 to 1.5ºC higher than those of the living hall almost constantly throughout the day. This means that on the first floor, the cooling effect from the courtyard was not evident during the night not only in the enclosed room (R1-1 (FF)) but also in the room located next to the CY 1-1 (R1-2 (FF)). This is because the ventilation was not sufficient in the R1-2 (FF) due to the closed partitions (see Table 3.10). The air temperature and humidity variations in the room without courtyard (R1-2) depict similar profiles of those in the living hall (Figures. 3.18a-1, 3.18b-1). This is because R1-2 was open to the corridor and to the courtyard (CY 1-1) as illustrated in Figures. 1b and 3a.

Meanwhile, in CSH 3, the living hall was located between the two courtyards, CY 3-1 and CY 3-2 (see Figures. 3.15b and 3.16b). The SVF of CY 3-1 (Type 5) was measured at 6.3%, while that of CY 3-2 (Type 2) was 3.1%. As previously discussed herein, the daytime air temperatures in the living hall were only 1.5ºC lower than the outdoor temperatures due primarily to the inflow of warm outdoor air. On the other hand, the ground floor room, R3-2, was enclosed, and thus the profiles of air temperature and humidity differ from those in other ventilated spaces (Figures 3.18a-2, 3.18b-2). While the daytime air temperatures in R3-2 were approximately 1.5ºC lower than those in the ventilated living hall during the fair-weather days on average, the air temperatures during the night in R3-2 were approximately 1ºC higher than those in the living hall. As air temperatures maintain lower degrees in R3-2, the relative humidity was always high at about 70% and above. Furthermore, it should be noted that on the first floor, air temperatures during the night in both R3-1 (FF) and R3-2 (FF) were similarly decreased to almost the same levels as those on the ground floor (i.e., CY 3-1 and living hall). This is primarily because both of the rooms were well ventilated by the cooled courtyards. It is concluded that while courtyard design should be of primary importance, it is also important to ensure sufficient ventilation in indoor spaces from courtyards particularly during the night.

3.3.4 Thermal comfort in the living hall

Figure 3.19 presents the temporal variations of measured major thermal parameters in the living halls of CSHs 1 and 3. As a result of the difference in the locations of the living halls, the daytime air temperatures in the living hall of CSH 3 were approximately 1.5ºC higher than those of CSH 1, although the outdoor air temperatures of CSH 1 were approximately 1ºC higher than those of CSH 3. Moreover, outdoor wind speeds were relatively the same during the two measurements, ranging from 0.1 to 3.0 m/s (see Figure 3.18c). However, indoor wind speeds in the living halls varied, particularly during the day with the indoor wind speed in CSH 3 being nearly twice as high as that in CSH 1 (Figure 3.19b). This indicates that the courtyards of the two CSHs performed different thermal functions. In CSH 1, the narrow, deep internal courtyard (CY 1-1) created "cool but still" indoor thermal conditions, whereas in CSH 3, the connected two courtyards (CY 3-1 and CY 3-2) led to "warm but breezy" conditions.

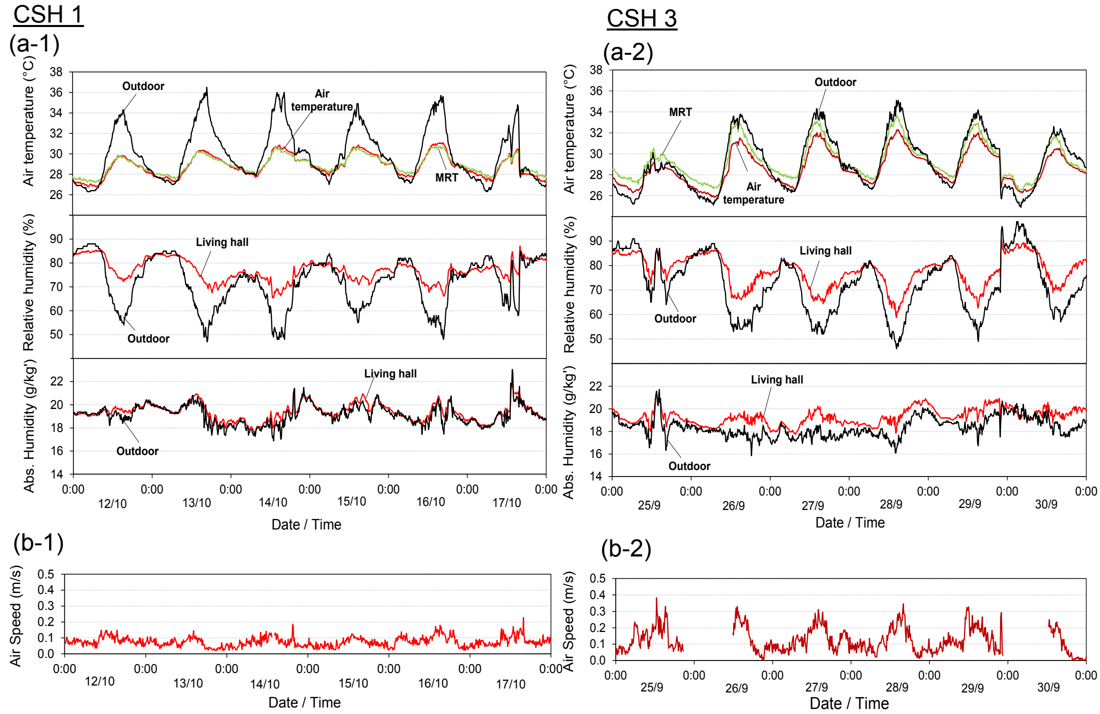


Figure 3.19. (a) Air temperature, MRT, relative and absolute humidity in the living halls of case study CSHs with the corresponding outdoor conditions. (b) Wind speed in the living halls.

In this study, operative temperature (OT) and SET* were used as indices to evaluate thermal comfort in the living halls (Figure 3.20). The operative temperature is defined as the uniform temperature of an imaginary black enclosure in which occupant would exchange the same amount of heat by radiation plus convection as in the actual nonuniform environment (ASHRAE, 2010). The operative temperature was estimated according to an equation given in ISO 7726 (BSI,2002), which is as follows:

$$T_{op} = \frac{T_a\sqrt{10v}+MRT}{1+\sqrt{10v}} \qquad (1)$$

where, T_{op} is operative temperature (ºC), v is indoor air speed (m/s) and MRT is the mean radiant temperature (ºC). The MRT is calculate based on the globe temperatures obtained from the field measurement. The MRT is estimated by considering the expression of forced convection (BSI,2002) and the equation given by the same standard is as follows:

$$MRT = \left[\left(T_{\mathrm{g}} + 273\right)^4 + \frac{1.1\times10^8\times v^{0.6}}{\varepsilon_{\mathrm{g}}\times D^{0.4}}\left(T_{\mathrm{g}} - T_{\mathrm{a}}\right)\right]^{1/4} - 273 \quad (2)$$

where *MRT* is mean radiant temperature (ºC), T_{g} is globe temperature (ºC), v is air speed (m/s), εg is emissivity of the black globe (-) and D is diameter of the globe (m). In this measurement, the diameter of the globe is 75 mm. The emissivity of the black globe is taken as 0.98 in all the calculations in this thesis. As shown in the upper part of the figures, the thermal comfort was evaluated on the basis of an adaptive comfort equation (ACE) developed by the authors for naturally ventilated buildings in hot-humid climates (Toe and Kubota, 2013). The 80% adaptive comfort upper limit of the OT was used for the evaluation. The equation used for determining the 80% adaptive upper limit are as follows:

$$T_{\mathrm{upper}} = T_{\mathrm{neutop}} - 0.7 \quad (3)$$

where T_{upper} is the upper operative temperature limit of 80% (ºC) and T_{neutop} is the neutral operative temperature (ºC) which is calculated based on the following equation:

$$T_{\mathrm{neutop}} = 0.57T_{\mathrm{outdm}} + 13.8 \quad (4)$$

where T_{outdm} is daily mean outdoor air temperature (ºC).

Meanwhile, the SET is considered as one of the most comprehensive thermal comfort indices, which integrates the effects of air temperature, humidity, radiation, air velocity, clothing insulation and metabolic rate on human thermal comfort. SET* is estimated by a program based on the human-body heat balance model proposed by Gagge et *al.* (1986). A metabolic rate of 1.0 met and a clothing value of 0.4 clo were applied in the calculation of SET*.

As presented in Figure 3.20, with respect to the OT, the living hall of CSH 1 recorded lower values (27.0 to 31.0ºC) than the living hall of CSH 3 (26.5 to 32.5ºC) during daytime hours. The calculated OT of CSH 1 generally fell within the limits; however, the OT of CSH 3 exceeded the limit over 40% of the time during the measurement period. When SET* was used for the evaluation, however, both of the living halls recorded highly similar maximum SET* values during the day (approximately 32.0ºC SET*). This clearly indicates that the indoor thermal comfort in the living hall of CSH 3 was improved by the increased wind speed caused by the connected two courtyards.

Conversely, the RH exceeded 70% throughout most of the measurement period in the living hall of CSH 1, whereas it dropped to as low as 60% during the daytime in CSH 3 (Figures. 3.19a-1, 3.19a-2). While the effects of RH on all aspects of human comfort have yet to be established (Tsutsumi *et al*., 2007; Rijal *et a*l., 2015; Damiati *et al*., 2016; He *et al*., 2016; Kumar *et al*., 2016), it is generally recognized that extreme levels of humidity are the most detrimental to human comfort, productivity, and health (ASHRAE, 2016). Sterling *et al*. (1985) reviewed a number of studies regarding the effects of humidity on human health and comfort from various viewpoints, including biological contaminants, airborne pathogens and chemical interactions. As a result, the study proposed that an RH range between 40 and

60% provides the best conditions for human occupancy. Meanwhile, Johansson *et al*. (2012) argued that some building materials tolerate being in air with high relative humidity without mould growth occurring, while on others mould can grow at a relative humidity as low as 75%. Therefore, it can be concluded that the humidity in the living hall in CSH 3 is more tolerable than that in CSH 1.

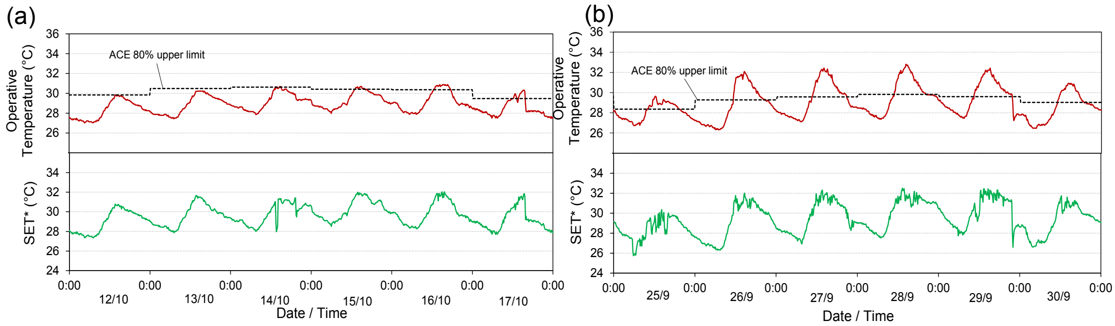


Figure 3.20. Operative temperature (OT) with corresponding ACE 80% upper limits and SET* in the living halls. (a) CSH 1; (b) CSH 3.

3.4 Recommendations

Basically, as a large amount of cross-ventilation cannot be expected in an elongated row house like the traditional CSHs, a high thermal mass structure can be a good option even in a hot-humid climate for achieving indoor thermal comfort by lowering daytime air temperatures. As previously presented herein, internal courtyards are effective in securing air flow as well as daylighting particularly in a deep-plan house. It was found that a deep (in height), closed internal courtyard, such as the Type 5 courtyard, is better able to maintain lower indoor air temperatures in a hot-humid climate, particularly during the day, even though the reduction in air temperature will increase the indoor RH throughout the day. As a living space, it is important to utilize air flow to improve sweat evaporation of occupants while also avoiding excessive humidity, even though cross-ventilation would increase indoor air temperature to a certain extent. Therefore, to achieve indoor thermal comfort in and around the courtyards, closed, cross-ventilated courtyards with a low SVF are recommended in hot-humid climates. One way to implement the closed but cross-ventilated courtyard in a deep-plan house is to design multiple closed courtyards that are connected with each other, as presented in CSH 3. A viable alternative, however, is to connect the courtyard with the street via a hallway, as suggested in (Rojas *et al.,* 2012; Ok *et al*., 2011).

As evidenced in the previous sections, internal courtyards would serve as cooling sources to the surrounding spaces especially during the night. The cooling effect was increased when a courtyard was situated between buildings/walls of different heights (i.e., staggered form), which was often located at the end of the building. Furthermore, it was found by the previous study (Toe and Kubota, 2015) that V-shaped roofs of a courtyard would contribute to increase the inflow of cooled air from the roofs during the night as illustrated in Figure 3.16. Hence, it is recommended that a staggered form courtyard with V-shaped roofs should be designed at the corner of a deep-plan house as a nocturnal cooling source, while designing above-mentioned closed but cross-ventilated courtyards within the same building.

Meanwhile, plants, particularly shade trees, would be effective at lowering air temperatures in and around the courtyards, though they would increase humidity levels simultaneously. Previous studies, most of which were conducted in hot-dry climates, showed that the orientation of buildings/courtyards is one of the keys to reduce the solar radiation received (Meir *et al.*, 1995; Berkovic *et al.*, 2012). Nevertheless, the solar orientation should not be of primary importance because the solar exposure is basically limited in a narrow, deep internal courtyard, which is the main interest of this study. Rather, the wind orientation is more important for the narrow, deep courtyards to improve the cross-ventilation for the building. In summary, an elongated courtyard house should be oriented toward the prevailing wind directions as presented in most of the study CSHs in Malacca.

3.5 Summary

The field measurements were conducted in the selected CSHs in the historical city of Malacca in 2011 and 2014 to identify the thermal function of an internal courtyards. Firstly, the study analyses the effects of courtyard form on their indoor thermal environment based on the results of field measurement conducted in 16 CSHs. Second, the detailed thermal environments of the selected two traditional CSHs with the different courtyard types were investigated to discuss the thermal functions of courtyards.

The finding of the first analysis are as follows:

- It was determined that the daily maximum air temperature in internal courtyards can be explained using the sky view factor (SVF) and the height of the courtyard. In contrast, the daily minimum air temperature is determined by the difference in the heights of the building and walls that form the courtyard. Hence, the daily mean air temperature in courtyard areas is the result of the SVF and the heights of the surrounding walls and buildings.
- The ratio of the courtyard area to the entire building area was one of the key variables affecting AH levels in the courtyards. Meanwhile, the difference in the heights of a courtyard affected the daily maximum RH, while the height of the courtyard and the opening area of the courtyard influenced the minimum value.

- The courtyard forms that characterized their thermal environments were classified into five types. Of these, space volume, openness and courtyard height were the significant components affecting the air temperature and RH profiles. For instance, small and staggered courtyards tended to provide lower nocturnal air temperatures (even lower than the corresponding outdoor temperatures). In contrast, deep and closed (with a low SVF (<2%)) courtyards exhibited a substantial reduction in peak air temperatures.

The main findings from the detailed case studies are presented below:

- The different types of courtyards performed different functions with respect to improving the indoor thermal comfort in the adjacent living halls. The living hall of CSH 1 was located next to the deep, closed courtyard of Type 5 (SVF: 0.2%). Although the indoor air flow was almost absent even during the day (<0.2 m/s), the air temperatures in the courtyard and the adjacent living hall maintained relatively low values that were approximately 4.0ºC lower than the corresponding outdoor temperature.
- The other living hall (CSH 3) was situated between the two courtyards of Types 5 and 2. The indoor wind speeds of approximately 0.2 to 0.4 m/s were generated due to the circulating air flow between the two courtyards during the day. Though this inflow increased indoor wind speeds, it simultaneously increased indoor air temperatures. The daytime air temperature in the living hall was only 1.5ºC lower, on average, than the outdoor temperature.
- Based on the thermal comfort evaluation by operative temperature (OT) indices, the living hall of CSH 1 was considered superior to that of CSH 3 because of its lowered air temperatures. Nevertheless, when the evaporative cooling effect was taken into account by using SET*, the condition of CSH 3 was similar to that of CSH 1 because of its higher indoor wind speeds. Meanwhile, the RH in the living hall of CSH 3 was lower by up to 10% compared to that in CSH 1. Therefore, it was concluded that the humidity in the living hall in CSH 3 was more tolerable than that in CSH 1.
- For elongated row houses of high thermal mass structure in hot-humid climates, it is suggested that closed (with a low SVF), cross-ventilated courtyards be embedded to achieve indoor thermal comfort and avoid excessive humidity. Hence, the wind orientation should be more important than the solar orientation for the elongated row houses in the tropics. Meanwhile, it is also recommended that a staggered form courtyard with V-shaped roofs should be designed at the corner of the house as a nocturnal cooling source.

4.

Full-scale experimental houses

4.1 Introduction

The full-scale experimental houses (two adjacent houses) were constructed in Universiti Teknologi Malaysia (UTM), in the city of Johor Bahru (Figure 4.1a). The construction was officially completed in December 2015. The purpose of the construction is to confirm the effects of proposed energy-saving modification techniques by the full-scale field measurement. The houses were located approximately 1 kilometers away from the main campus areas of UTM as shown in Figure 4.1b.

As shown in Figure 4.1c, the houses were constructed in an open space with the total boundary area of 1156 m^2. The surrounding areas of the experimental houses has minimal wind flow obstruction due to the surrounding trees are located about 15-20 m away from the boundary areas at east and west side. Figure 4.2 shows the construction process of the experimental houses from the site clearing phase until the completion. The construction period was about 8 months before the completion.

Figure 4.1. (a) Location of Universiti Teknologi Malaysia, Johor Bahru (b) Location of the experimental houses in UTM (c) Layout of site boundary of the experimental houses.

Figure 4.2. The construction process of the experimental house from site clearing until the completion phases.

4.2 Design of the experimental houses

The experimental houses were designed to represent the typical floor plans of two-storey terraced house in Malaysia except for the first floor where the main test rooms (i.e., master bedrooms) are located. Figure 4.3 shows the detail design of the houses. Each house has two master bedrooms on the first floor with each room facing North and South, respectively (Figure 4.3b). In the ground floor, there are three available spaces which is divided into living hall, dining hall and kitchen (Figure 4.3a). The living hall is located at the front side of house (facing North), while the kitchen is at the back side of the house (facing South). The dining hall is located between the living and the kitchen. The total floor area of each house is 127 m^2. Meanwhile the height of each floor is 3.05 m from floor to ceiling level.

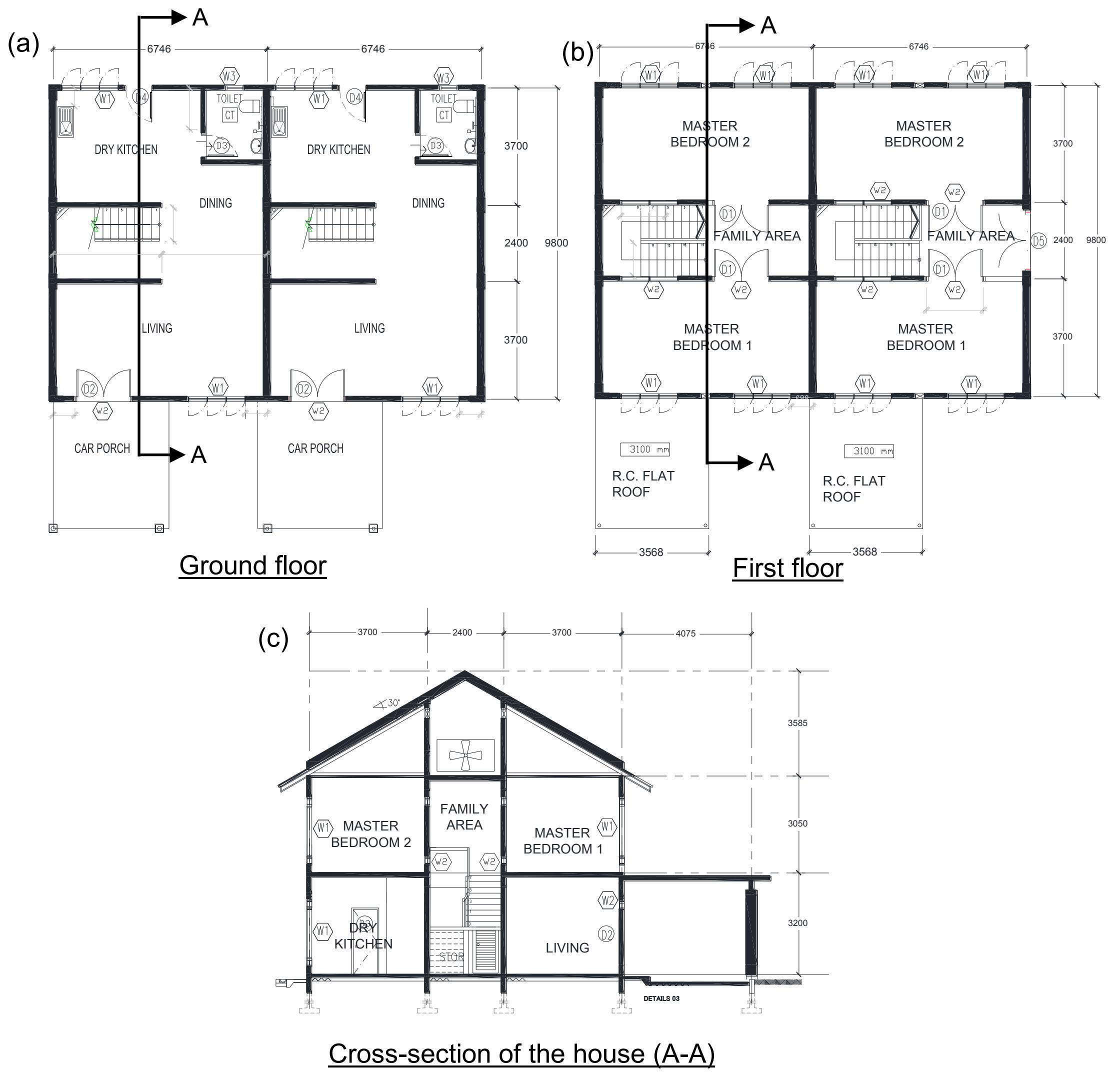


Figure 4.3. Design of the experimental houses (a) Ground floor plan; (b) First floor plan; and (c) cross-section of the house (A-A)

The experimental houses were made of brick wall and concrete structure. The thickness of the cement plastered brick wall is 225 mm for the party walls and 150 mm thick for the other walls. All walls were painted with the white color paint. The floors on both ground and the first floors were reinforced concrete slabs of 150 mm thick and finished with cement render. Meanwhile, the concrete roof tiles were laid with a thin layer of double-sided aluminum foil underneath as radiant barrier. In addition, thin plasterboards were installed under the aluminum foil. The purposes of the plasterboard are to provide a proper surfaces (flat) for the installation of roof insulation and as a prevention from the leaking of rain water. The ceiling on the first floor was fibre-cement boards of 6 mm thick and 3.2 mm thick in the master bedrooms and the family area, respectively.

All main windows were casement type of 6 mm single layer glass with aluminum frame. In addition to the original plans, small slit windows were added onto the upper and lower parts of the main windows and partition walls as shown in Figure 4.4a and b. Meanwhile, only the top part of the door was installed with the small slit windows (Figure 4.4c). The additional slit windows were installed to investigate the effects of air flow near to the building structure in the later part of the experiment. Moreover, exhaust fans were installed in the attic spaces, master bedrooms and staircase halls which is also for the experimental purpose (Figure 4.5).

Figure 4.4. Position of slit windows (a) Upper and lower part of the main windows; (b) Upper and lower parts of partition walls; and (c) Upper part of door

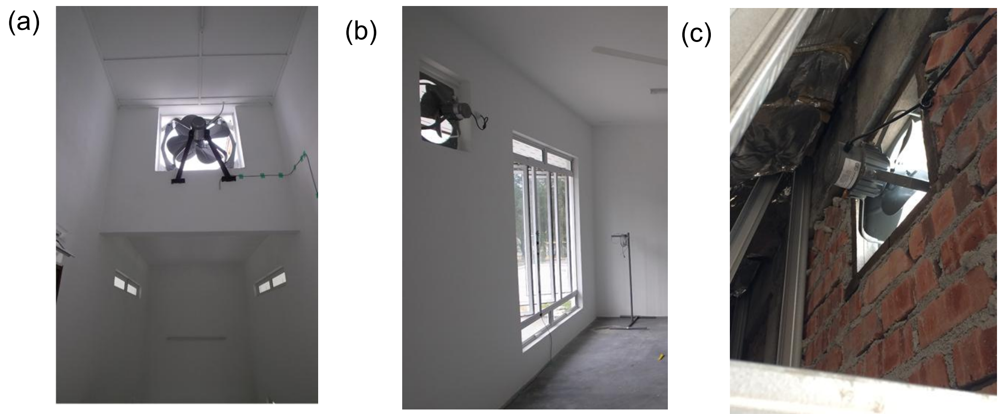


Figure 4.5. Exhaust fan in (a) the staircase halls; (b) master bedrooms; and (c) attic spaces

The houses are not insulated except that insulation is insulated on both end walls to eliminate the thermal influences from the surrounding (Figure 4.6). The total thickness of the insulation layer is 120 mm. As shown in Figure 4.6b, the insulation layers consist of 100 mm thick of MG board (rock wool) and 20 mm of air cavity. The MG board were installed on the end wall surfaces by using special anchor namely ‘brong’ anchor and washer. The insulation layers were covered by light-weight zincalume sheets. The zincalumes were supported by c-purlin steel that were installed on the wall with the interval of 1200 mm height. Figure 4.7 shows the actual installation process of the end wall insulation.

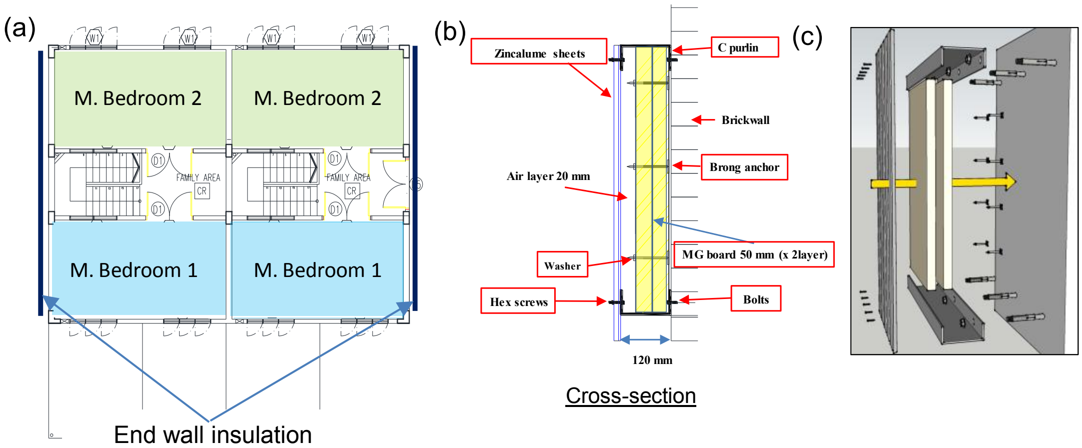


Figure 4.6. End wall insulation (a) Location of the insulation; (b) Detailed insulation layers; and (c) Illustration of the installation of insulation

Figure 4.7. The installation process of the end wall insulation.

4.3 Experimental setup

Field measurement were conducted in September to November 2015 to investigate the effects of end wall insulation on its indoor air and surface temperature. The experimental cases were conducted as outlined in Table 4.1. Case 1-2 compared night ventilation without and with the end wall insulation. Meanwhile, case 3-4 compared the day ventilation without and with the end wall insulation. Night ventilation was obtained by opening the window from 8 p.m.to 8 a.m. and closing them from 8 a.m. to 8 p.m. In contrast, day ventilation was obtained by opening the window from 8 a.m.to 8 p.m. and closing them from 8 p.m. to 8 a.m.

Table 4.1: Ventilation and end wall conditions of filed measurement in the experimental houses

Case	Condition of both House 1 and House 2
1	Night ventilation without end wall insulation
2	Night ventilation with end wall insulation
3	Day ventilation without end wall insulation
4	Day ventilation with end wall insulation

4.3.1 Methods

The main variables for the thermal comfort assessment were measured in the master bedrooms (first floor) and living halls (ground floor) of the two houses at 1.1m height above the floor. The measured variables were air temperature, relative humidity, wind speed and globe temperature. In addition, air temperature and relative humidity were also measured in the attics and at the other spaces located in the ground floor i.e. dining halls, kitchens and staircases of both houses. Furthermore, vertical air temperatures were taken in the master bedrooms at 0.1 m, 0.6 m, 1.1 m, 1.7 m, 2.3 m and 2.9 m and in the family areas at 0.1 m, 0.6 m, 1.1 m, 1.7 m, 2.3 m, 2.9 m, 3.5 m, 4 m, 4.4 m and 4.7 m. Surface temperatures were also recorded in the master bedrooms, family area, attic spaces and between the insulation layers. Figure 4.8 shows the position of the measurement equipment in the experimental houses. Meanwhile, the outdoor weather data were recorded by a weather station (HOBO Pro V2 U23-001), which located in an open space approximately 40m from the backside of the houses. The recorded data were air temperature, relative humidity, wind speed and direction, global horizontal solar radiation and rainfall throughout the experiment. All indoor and outdoor measurements were logged automatically at 1-minute intervals. The measurement instruments used and the accuracy level are presented in Table 4.2.

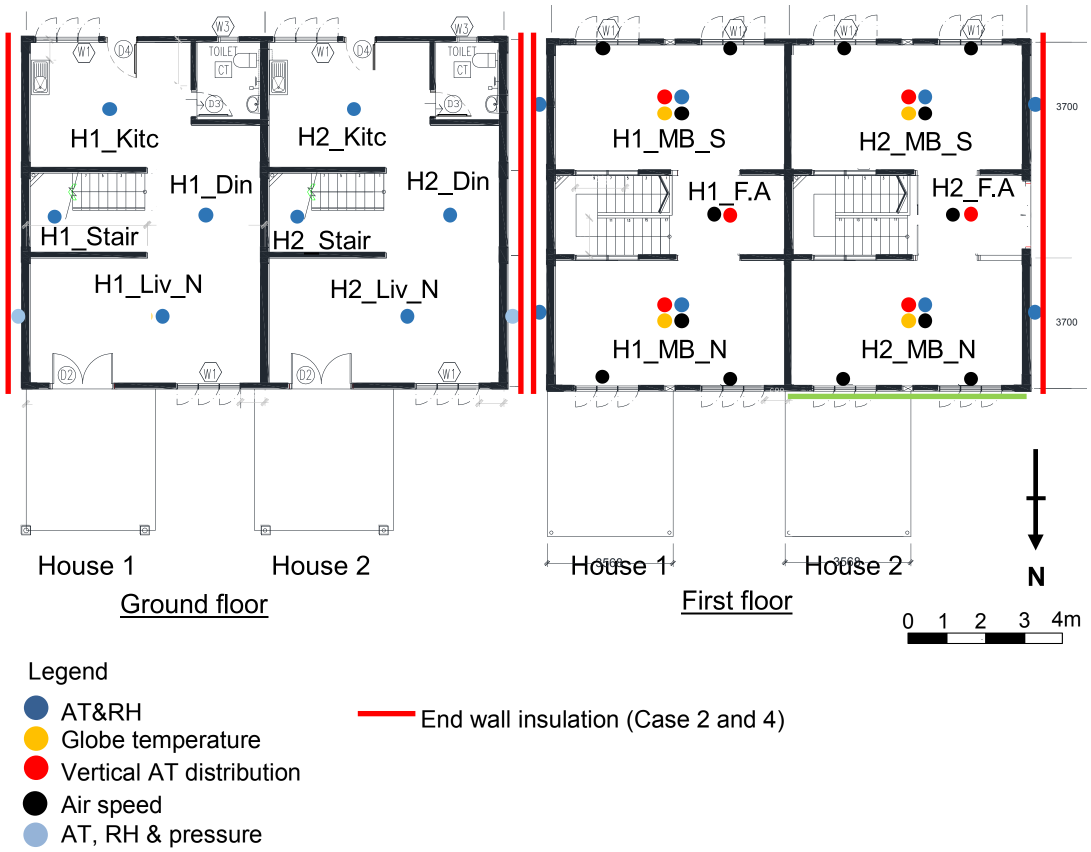


Figure 4.8: The floor plans of the experimental houses and the location of the measurement equipment.

Note: H1= House 1; H2=House 2; MB= Master bedrooms; N= North; S=South; F. A= Family area; Liv_N= Living hall North; Din=Dining; Kitc=Kitchen; Stair=Staircase

Table 4.2: Description of measurement equipment.

Measured variable	Instrument model	Accuracy
Air temperature and RH	T&D TR-72WF	±0.3°C, ±2.5%RH (10 to 85%RH), ±3.5%RH (0 to 10, 85 to 99%)
	Vaisala HMP155-A	±0.1°C, ±1% at 0 to 90%RH
	T&D TR-72U	±0.3°C, ±5%RH
Globe temperature	Type T thermocouple and Globe ball 75 mm	±0.1%+0.5°C plus ±0.5°C for cold junction compensation
Air velocity	Kanomax sensors (0965-03)	0.1-4.99m/s: ±0.15m/s, 5.00-9.99m/s: ±0.3m/s, 10.0-25.0m/s: ±0.6m/s
	Hobo T-DCI-F900-L-P	± 0.05m/s
Vertical air temperature distribution	Type T thermocouple and Graphtec GL820	±0.1%+0.5°C plus ±0.5°C for cold junction compensation
Surface temperature	Type T thermocouple and Graphtec GL820	±0.1%+0.5°C plus ±0.5°C for cold junction compensation
Heat flux	Eto Denki S11A and Graphtec GL820	N. A
Weather station (outdoor) (Air temperature, RH, Wind speed, Wind direction, Solar radiation, Rain fall and Air pressure)	HOBO Pro V2 U23-001	±0.21°C (0 to 50°C); ±2.5% (10-90% RH) ±3.5 (to a maximum); ±0.5m/s; ±5°; ±10 W/m2 or ±5° (Whichever is greater); ±1.0% at up to 20 mm/hr; ±3.0 mbar (= 1hPa)

4.3.2 Air temperatures in the master bedrooms

Figure 4.9 shows the statistical summary of air temperature in the master bedrooms for all cases. In case 1 (Figure 4.9a), the average air temperatures in the north facing master bedrooms is about 27.3°C for both houses. Meanwhile, the average air temperature in the south facing master bedrooms were slightly higher by about 0.5°C compared to the north facing rooms in both houses. Average air temperatures of all master bedrooms were higher by up to 1°C compared to the outdoor.

As shown in Figure 4.9b, the north facing rooms still recorded lower air temperatures compared to the south facing rooms with an average of about 0.5°C in both houses. The lowest minimum air temperatures were recorded in north facing rooms which is around 25°C, while the highest maximum air temperature was recorded in both south facing rooms which is about 29 °C.

In case 3, higher indoor air temperatures were recorded in all master bedrooms with an average difference of up to 2.5°C compared to outdoors. In contrast, the average air temperatures are almost similar in all rooms which is about 29.5°C, except for the south facing room in House 2 which is slightly higher by about 0.5°C. In case 4, almost similar average air temperatures recorded in all master bedrooms which is about 28.5°C. In this case, the average difference of indoor and outdoor air temperature is about 2°C.

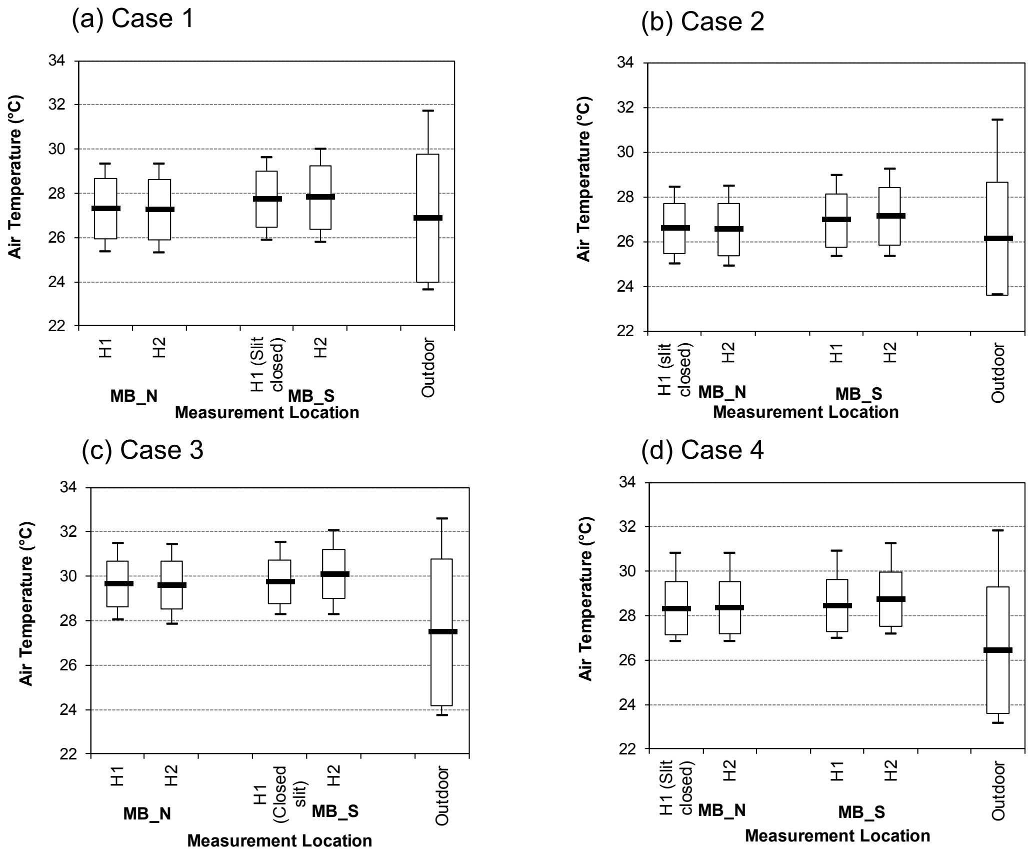


Figure 4.9 Statistical summary (5th and 95th percentiles, mean and ± one standard deviation) of air temperature measured at 1.1m above floor level in the master bedrooms (a) Case 1: Night ventilation without end wall insulation; (b) Case 2: Night ventilation with end wall insulation; (c) Case 3: Day ventilation without end wall insulation; and (d) Case 4: Day ventilation with end wall insulation.
Note: H1= House 1, H2= House 2, MB_N= Master bedrooms that are located facing North, MB_S=Master bedrooms that are located facing South.

4.3.3 Surface temperatures in the master bedrooms

Figure 4.10 shows the statistical summary of surface temperatures of both end walls and party walls for case 1. As shown in Figure 4.10 a and b, maximum temperatures (95th percentiles) were recorded on the end wall's outer surfaces which is about 35-35.5°C of both walls. Meanwhile, the maximum temperatures on the end walls inner surfaces were lowered by up to 5.5°C compared to its outer surfaces. In average, surface temperatures on indoor end wall surfaces were lowered by 0.6°C compared to the outer surface. The party wall's average surface temperatures were almost the same between both houses which is about 27.5°C and they are lower by up to 1°C compared to the temperatures on the inner surface of end walls.

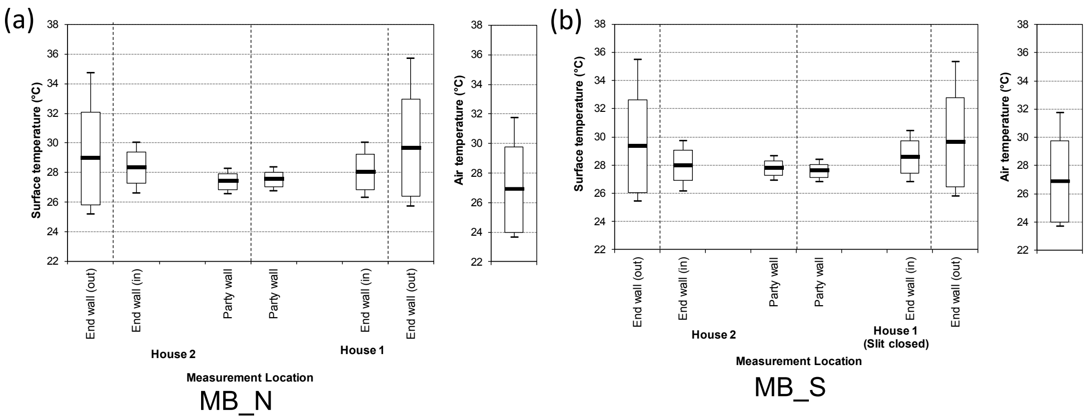


Figure 4.10 Statistical summary (5th and 95th percentiles, mean and ± one standard deviation) of temperatures on the end wall and party wall surfaces in the master bedrooms in Case 1: Night ventilation without end wall insulation (a) North facing master bedrooms (MB_N) and (b) South facing master bedrooms (MB_S).

Figure 4.11 shows the statistical summary of surface temperatures of both end walls and party walls for case 2. As shown in Figure 4.11ab, the average surface temperatures of all walls were almost similar which is about 26.5-27°C. Thanks to the insulation, the outer surface of end walls were not exposed to the direct solar radiation. The maximum temperatures of the outer surface of end wall were lowered by up to 4°C compared to outdoor.

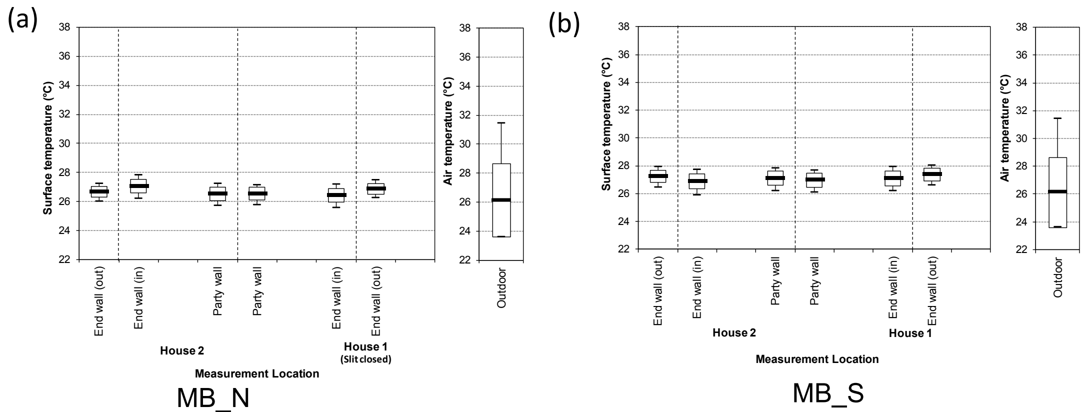


Figure 4.11 Statistical summary (5th and 95th percentiles, mean and ± one standard deviation) of temperatures on the end wall and party wall surfaces in the master bedrooms in Case 2: Night ventilation with end wall insulation (a) North facing master bedrooms (MB_N) and (b) South facing master bedrooms (MB_S).

Figure 4.12 shows the statistical summary of surface temperatures of both end walls and party walls for case 3. As the result in case 1, the maximum temperatures (95th percentiles) were recorded on the end wall's outer surfaces when it was not covered with the insulation. The maximum temperatures range is about 35-36.5°C for both walls. In average, surface temperatures on the outer end wall surfaces were higher about 0.6°C compared to its inner surfaces for both end walls. The party wall's average surface temperatures were almost the same between both houses which is about 29.5°C and they are lowered by up to 0.5°C compared to the temperatures on the inner surface of end walls.

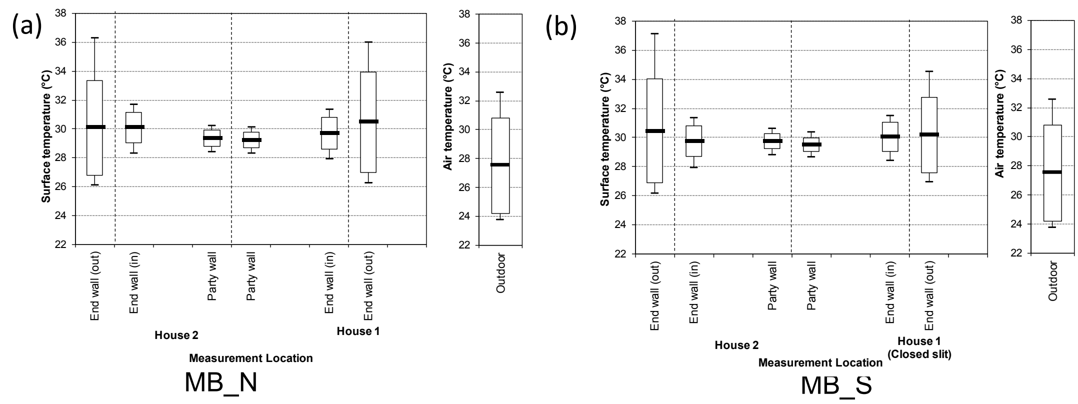


Figure 4.12 Statistical summary (5th and 95th percentiles, mean and ± one standard deviation) of temperatures on the end wall and party wall surfaces in the master bedrooms in Case 3: Day ventilation without end wall insulation (a) North facing master bedrooms (MB_N) and (b) South facing master bedrooms (MB_S).

Figure 4.13 shows the statistical summary of surface temperatures of both end walls and party walls for case 4. As shown in Figure 4.13ab, the average surface temperatures of all walls were almost similar which is about 28.5°C. The average surface temperatures of all wall were higher than the outdoor by about 2°C.

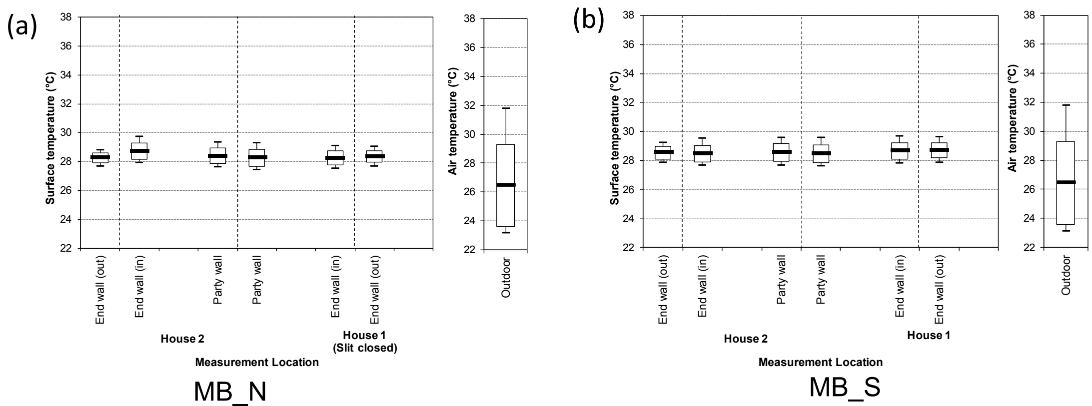


Figure 4.13 Statistical summary (5th and 95th percentiles, mean and ± one standard deviation) of temperatures on the end wall and party wall surfaces in the master bedrooms in Case 4: Day ventilation with end wall insulation (a) North facing master bedrooms (MB_N) and (b) South facing master bedrooms (MB_S).

4.3.4 Heat fluxes on the end wall surfaces

Figure 4.14 shows the temporal variation of heat fluxes on the end wall surfaces in all the master bedrooms for Case 1. Heat fluxes on the end wall surfaces of both north facing rooms ranged from -8 to 8 W/m^2 during the measurement period (Figure 4.14a). Meanwhile, the heat fluxes on the end wall surfaces of south facing rooms ranged from -9 to 9 W/m^2(Figure 4.14b). The difference of heat fluxes between both end walls in the north and south facing master bedrooms were less than 3 W/m^2 during the measurement period.

(a)

(b)

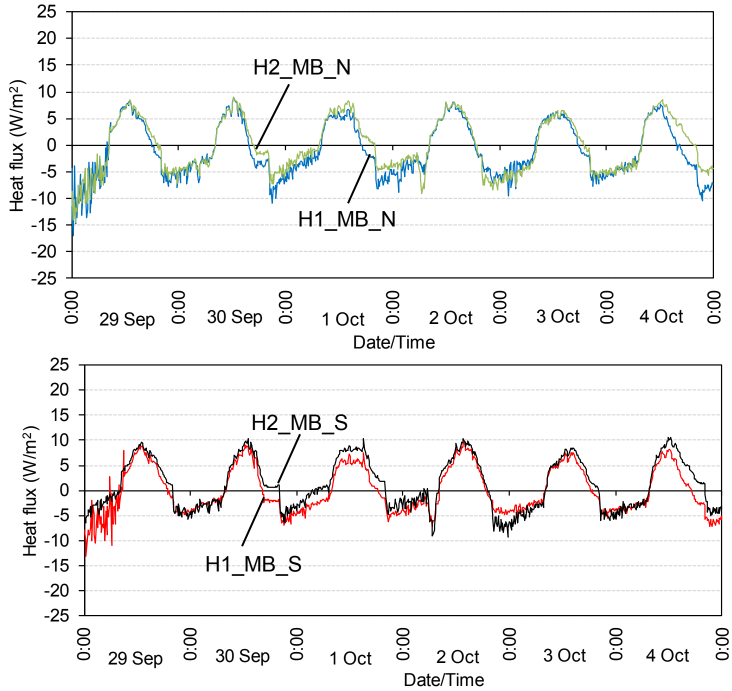


Figure 4.14 Temporal variation of heat fluxes on the end wall in all master bedrooms for Case 1: Night ventilation without end wall insulation (a) North facing room and (b) South facing rooms

Figure 4.15 shows the temporal variation of heat fluxes on the end wall surfaces in all the master bedrooms for Case 2. Heat fluxes on the end wall surfaces of both north facing rooms ranged from -5 to 15 W/m^2 during the measurement period (Figure 4.15a). Meanwhile, the heat fluxes on the end wall surfaces of south facing rooms ranged from -5 to 14 W/m^2(Figure 4.15b). In this case, smaller heat fluxes recorded during the night-time which is about -3W/m^2 compared to the daytime.

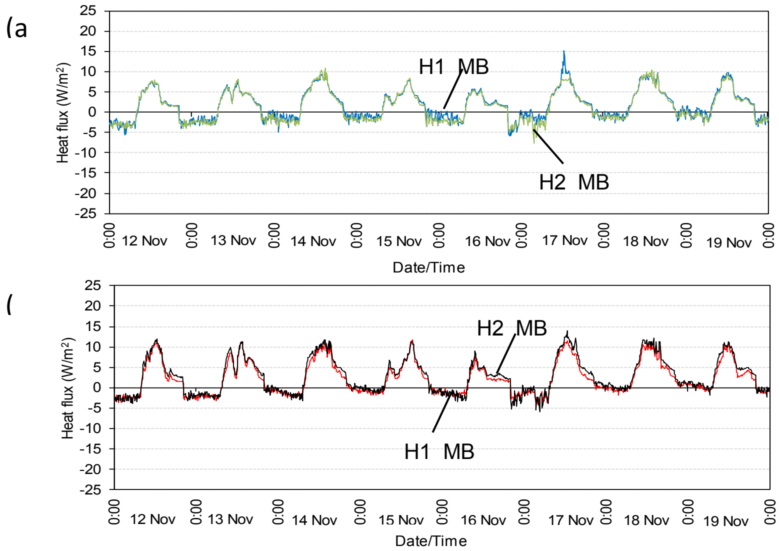


Figure 4.15 Temporal variation of heat fluxes on the end wall in all for Case 2: Night ventilation with end wall insulation (a) North facing room and (b) South

In case 3, heat fluxes on the end walls of House 2 recorded slightly higher than that of House 1 in both north and south facing rooms. In the north facing rooms, the heat fluxes in house 2 (H2_MB_N) were 10W/m^2 higher than that of house 1 (H1_MB_N) on average during the daytime (Figure 4.16a). Meanwhile, in the south facing rooms, the heat fluxes in house 2 (H2_MB_S) were 6W/m^2 higher than that of house 1 (H1_MB_S) on average during the daytime (Figure 4.16b). At night-time, the heat fluxes were lower in all rooms with the range of less than 10W/m^2 compared during the daytime.

Figure 4.17 shows the temporal variation of heat fluxes on the end wall surfaces in all the master bedrooms for Case 4. Heat fluxes on the end wall surfaces of both north facing rooms ranged from -20 to 20 W/m^2 during the measurement period (Figure 4.17a). Meanwhile, the heat fluxes on the end wall surfaces of south facing rooms ranged from -18 to 10 W/m^2(Figure 4.17b). The difference of heat fluxes between both end walls in the north and south facing master bedrooms were less than 3 W/m^2 during the measurement period.

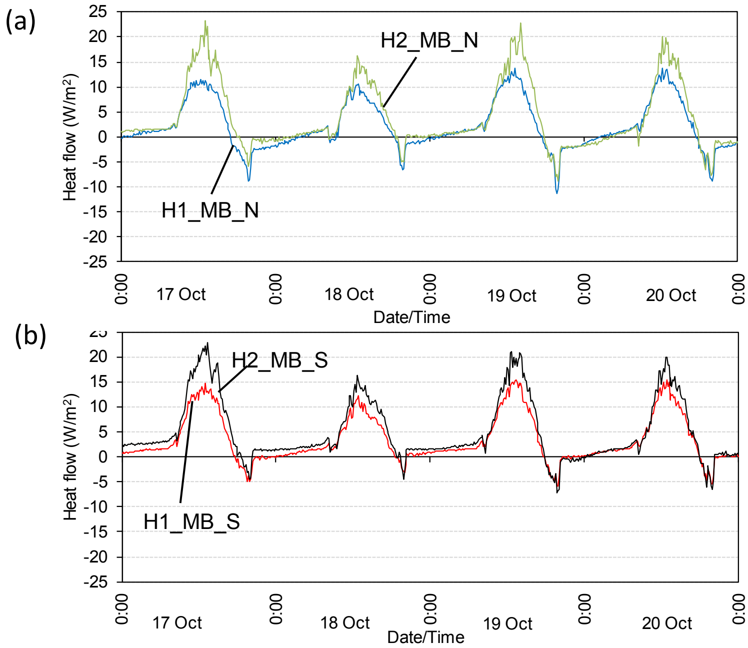


Figure 4.16 Temporal variation of heat fluxes on the end wall in all master bedrooms for Case 3: Day ventilation without end wall insulation (a) North facing room and (b) South facing rooms

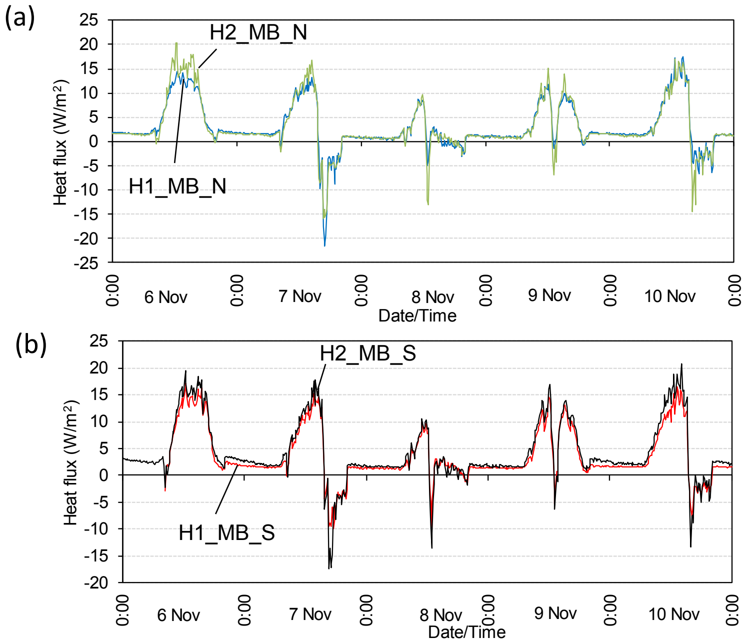


Figure 4.17 Temporal variation of heat fluxes on the end wall in all master bedrooms for Case 4: Day ventilation with end wall insulation (a) North facing room and (b) South facing rooms

4.3.5 The effects of end wall insulation.

Based on the results of indoor air temperature (Figure 4.9), indoor air temperatures in both north and south facing rooms showed almost similar values when compared side by side during without or with the insulation. It seems that that the end wall insulation probably has only small effects on the indoor air temperatures.

In contrast, the surface temperature of the outer surface of end wall were successfully reduced nearly to the level of inner surfaces when the end wall insulation was applied (Figures 4.11 and 4.13). Furthermore, all walls (end wall and party wall) has almost similar surface temperature after the application of end wall insulation.

The results of heat fluxes showed that similar heat flow pattern obtained on both end walls. In addition, the heat fluxes are almost none during the night-time (less than $3W/m^2$). In summary, the application of the end wall insulation successfully prevents the thermal influences from the surroundings.

4.4 Summary

The full-scale experimental houses (two adjacent houses) were constructed in Universiti Teknologi Malaysia (UTM), in the city of Johor Bahru. The experimental houses were designed to represent the typical floor plans of two-storey terraced house in Malaysia. For the experimental purposes, the houses have been constructed to be oriented to the north-south direction to obtain relatively good indoor thermal condition based on the previous simulation study. In addition, the forced ventilation fan (i.e. whole house ventilation, attic fan and master bedroom fan) and the slit windows were also installed to the building. Moreover, the party wall insulation has been installed to eliminate the thermal effects form the surrounding.

Brief experiment has been conducted to investigate the effects of the end wall insulation under night-time and day-time ventilation. The results showed that the average air temperature and the surface temperature in the master bedroom of both houses were almost similar under night-time and daytime ventilation condition. This indicates that the end wall insulation successfully eliminates the thermal effects from the surrounding. In addition, due to nearly same indoor condition in both houses, it is possible to make a fair comparison of the experimental result between both houses.

5.

Numerical simulation of energy-saving modifications for urban houses

5.1 Objectives

In recent years, there are various applications of passive cooling techniques for the buildings has been developed in order to achieve an acceptable level of comfort and energy efficient. In hot humid-climate, the techniques or modifications can be divided into two categories, i.e. reducing the effects of solar radiation and providing adequate level of ventilation. However, to investigate the effects of each techniques in an actual condition required a lot of resources and time consuming. Therefore, one of an effective mean is by conducting such experiments by using a numerical simulation. A numerical simulation is a calculation that is run on a computer according to a program that implements a mathematical model for a physical system. Numerical simulations have the ability to predict the behavior of systems with a complex mathematical model to provide analytical solutions especially for the nonlinear system. In this study, the numerical simulation programs were employed to examine the optimum combinations of modification techniques for the urban houses in the hot-humid climate of Malaysia. Two types of numerical simulation program were used which is TRNSYS and COMIS.

5.2 Simulation Program Used

5.2.1 Overview of the Simulation Program

In the recent years, there are various simulation programs for building that has been developed and used throughout the building energy community. About 417 building software tools were listed to evaluate energy efficiency, renewable energy, and sustainability in buildings (US Department of Energy, 2015). However, each of program has been developed to performed for only some specific of task and the biggest concern is the reliability of their results. Therefore, it is important to choose the appropriate simulation tools to achieve our objective. It was found that the capabilities of TRNSYS developed by Solar Energy Laboratory (SEL) at University of Wisconsin completely satisfied most criteria and requirements of this research for conducting the simulation of building thermal system. This is due to its comprehensive and flexible dynamic solution. In addition to the TRNSYS software, we utilized the COMIS program for the multizone air flow network simulation due to its compatibility to be used with TRNSYS. Further details of TRNSYS and COMIS are given in the next section.

5.2.2 TRNSYS-COMIS Coupled Simulation Program

TRNSYS is a transient system simulation program of thermal system with a modular structure. The software was developed by Solar Energy Laboratory at University of Wisconsin-Madison, and it has been available since 1975. This simulation program consists of two main parts, i.e., 1) the engine (called the kernel) and 2) an extensive library of components. The engine works in a several steps. Firstly, it reads and processes the input file. Then, the engine will iteratively solve the system until it reaches a convergence state. Lastly, it will plot system variables as a result. Meanwhile, the extensive library provides various options of components as a selection to be use in the simulation. About 150 models of components were included in the library, which range from pumps to multizone buildings, wind turbines to electrolyzers, weather data processors to economic routines, and basic HVAC equipment to cutting edge emerging technologies. In TRNSYS, each project comprised of selected components called Type. These components (Type) were connected graphically in the Simulation Studio and compiled internally as a TRNSYS input file known as the deck file for the simulation engine. The Simulation Studio is a complete simulation package that integrates the simulation engine, components, components' connections, and output in the form of user interface tools. In this study, TRNSYS Version 17.01.0025 was used for the simulation work.

Meanwhile, COMIS is a multi-zone airflow simulation tool that can simulate infiltration and ventilation through crack flow and flow through large openings in multi-zone buldings (Dorer *et al*., 2005; Feustel, 1999). It can be used independently or coupled to the multizone building model of Type 56. It was first developed through an international workshop hosted by Lawrence Berkeley National Laboratory (LBNL) in 1988-1989. The COMIS version 4.2.0.28 was used in our model. The COMIS model works in a modular structure that is similar to TRNSYS in the Simulation Studio.

In our study, TRNSYS Type 56 'Multi-zone Building' were used to model the thermal zones of the terraced house. Therefore, the coupling between TRNSYS and COMIS is possible by using the component of Type 157 in TRNSYS. In the simulation, Type 157 was called in each iteration step until the mass and energy balance per zone reached convergence state. Data that were transferred from Type 157 to Type 56 were the air flow rates per zone. Meanwhile, data that were transferred from Type 56 to Type 157 were the air temperatures of the zone. The weather data, simulation time and schedules were defined in TRNSYS and used simultaneously by both TRNSYS and COMIS. To be noted that the detail properties of the building model were defined in TRNSYS 3D plug in in Google Sketchup TM. These data, then, were read in TRNBUILD of TRNSYS software. Figure 5.1 describes the coupling relationship between the two programs in the simulation model.

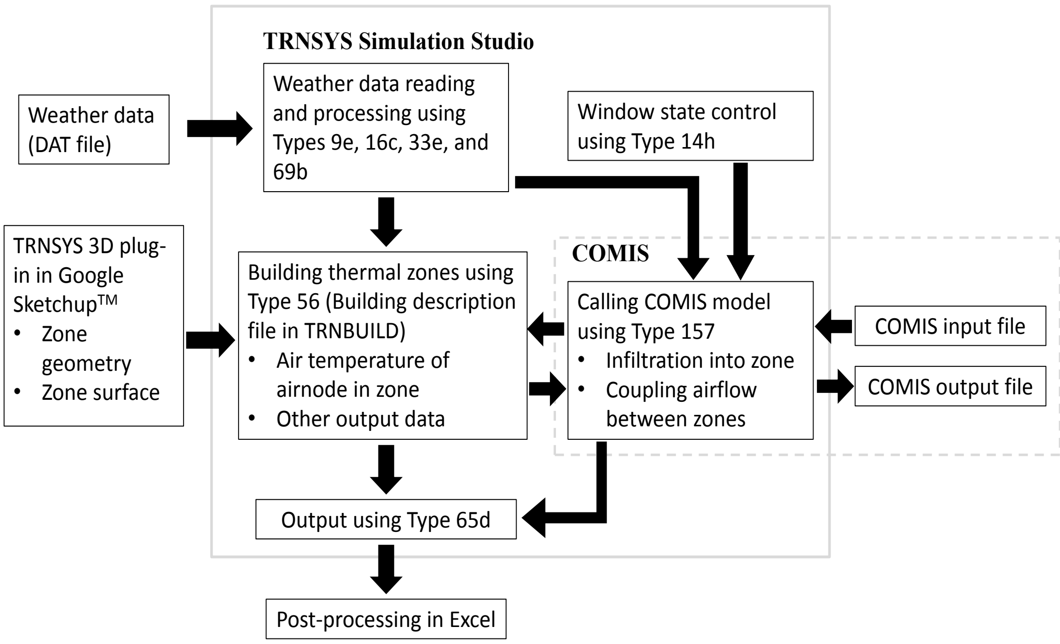


Figure 5.1. Components and data transfer in the TRNSYS and COMIS simulation model of this study. (Based on Toe (2013))

5.2.3 The Numerical Solver and Components used

The components that were used for the simulation in this study are as shown in Figure 5.1. The source code of the TRNSYS and COMIS simulation engines was documented in detail in their respective user manuals (Dorer *et al*., 2005, Klein *et al.,* 2012) including the references list. In this section, we highlight some of the key points.

The TRNSYS Solver

The TRNSYS simulation engine that simultaneously solves a set of algebraic and differential equations in the system model at each simulation step based on the parameter and input values at the beginning of the time step (Toe, 2013). Results are returned as average values for every time step. The Modified-Euler method was selected for solving differential equations used in the components (Klein *et al.*, 2012). Furthermore, the successive solution method which is recommended for buildings and systems with a thermal capacity, as in our case, was applied. All the simulation attained convergence within a tolerance of 0.0, i.e. changing less than 1% of the iteration value.

The Comis Solver

In COMIS, the building was modelled as a network of pressure nodes linked by air-mass flow paths. In specific, these paths included flow resistances caused by open or closed doors and windows as well as air leakage through walls and other building surfaces. The air volume which is the room or zone, represented by each internal pressure node and is assumed to be well mixed and has a fixed uniform pressure and temperature at each time step. The wind pressure field around the building is attributed to external pressure nodes. A system of non-linear equations was linearized initially based on the principle of air mass conservation, and then solved in iterations using a modified Newton-Raphson method known as Solver 6 ‘trust region line search’ (Feustel and Raynor-Hoosen, 1990). As the results, the flow rates are functions of pressure differences between nodes that consider the wind distribution and thermal buoyancy.

The Thermal Model of Type 56 Multi-zone Building

In this component, the building model are divided into different thermal zones and air nodes through the TRNBUILD user interface. All thermal zones in the simulation are assigned with one air nodes except for the staircase area, where the two air nodes are used, i.e. upper node and lower node. In general, the heat balance model for the whole model are based on: 1) convective heat fluxes to the air nodes; 2) short-wave and long-wave radiation, conduction and convection heat fluxes to the walls and windows; and 3) thermal history of high thermal mass walls (Klein *et al.,* 2012).

Standard models for beam and diffuse radiation distributions to inside surfaces and long wave radiation exchange within each zone were used except for the staircase zone. The standard models distribute the radiation based on absorbance weighted area ratios of all inside surfaces in a zone and model the radiation exchange using an artificial temperature node. Meanwhile, in the staircase zone, the detailed model for internal long-wave radiation exchange was used since it has two air nodes. The detailed model uses a three-dimensional matrix method that considers view factor among inside surfaces and the air nodes (Toe, 2013). As for the windows, it has been modelled using the template from the WINDOW 4.1 program developed at LBNL (Mitchell *et al.,* 2011). The window model will calculate the transmission, reflection and absorption of solar radiation for the window glazing and frame. In addition, the external and internal shading devices and edge correction for glazing spacers are considered. The external shading was modelled using TRNSHD that was developed by Hiller *et al.* (2000). The program automatically determines all external walls and obstructions as potential shadow casting surfaces. Thus, roof overhangs, self-associate façade obstructions and adjacent building are included. The TRNSHD program estimates both direct and diffuse radiation fractions according to the solar position and solar geometry in patches. The diffuse fraction is being assumes as an isotropic sky. The effects of shading on opaque walls in not being considered here. On the other hand, shading from diffuse radiation was accounted for all external surfaces by multiplying the diffuse sunlit fractions of TRNSHD with the sky view factors of respective surfaces in unobstructed condition to obtain the 'obstructed' sky view factors.

The effective capacitance humidity model was included in simulation as for the consideration of the latent load. The above-mentioned model defines absorption effects of adsorptive/desorptive materials with an enlarged moisture capacity of the air (Klein *et al*., 2012).

The Air Flow Components

One of the air flow components in the COMIS is the infiltration and ventilation through crack flow. In this simulation program, the crack flow is calculated by the following power law equation:

$$\dot{Q} = C_{\dot{Q}} (\Delta P)^{n} \quad (1)$$

where $\dot{Q}$ is volume flow (m^3/s), $C_{\dot{Q}}$ is volume flow coefficient (m^3/sPa^n), ΔP is pressure difference across the link (Pa) and n is flow exponent (-) (Feustel and Raynor-Hoosen, 1990; Orme *et al*., 1998). The coefficient of the flow is based on the form and size of the crack while the flow exponent describes the type of the flow such as laminar, transitional or turbulent. Due to the limitation of the measurement data, the temperature correction in the crack was not applied in this study. Instead, the standard reference data were used for the flow coefficients. Based on this condition, it was reasonable to assume that the air and the wall would have the same temperatures due to the tiny crack form in solid wall constructions such as that of the terraced house. The crack flow calculates one-directional flow, i.e. no thermal difference over the height is assumed.

Windows and doors were modelled as large vertical openings. In COMIS, each large opening is divided into several vertical layers at equal distance and the mass flow is solved for each layer. The model accounts for steady-state gravitational flow based on Bernoulli's equation that assuming the density stratification on both sides of the opening is linear. Meanwhile, the turbulence effects are represented by an equivalent pressure difference profile (Feustel and Raynor-Hoosen, 1990). When the window is closed, pressure difference calculations are applied to the entire window frame, which includes a bottom crack, a top crack and vertical side cracks. The air flow for the vertical cracks is calculated by the summation of the flows over the vertical height (Feustel, 1999). When the window is opened, bi-directional flow is calculated by considering a discharge coefficient that represents a contraction effect on the flow due to the existence of the opening and an effective area of the opening.

5.3 Model specification and simulation condition

5.3.1 The specification of the base model.

The base model of the simulation was developed based on the design of the actual experimental houses. The reason is the actual measurement will be conducted in the experimental houses to confirm the effects of the proposed modification techniques by the simulation in the later part of study. The description of the real houses and the floor plans are given in Chapter 4. Table 5.1 shows the specifications of the building material used in the simulation model. Thermal properties of building material were obtained from the actual construction record, Malaysian manufacturers or reference data to correspond with the actual construction. Meanwhile, the description of the constructed layers and their reference U-values in the numerical model is given in Table 5.2.

Table 5.1. Thermal properties of the building materials in the base model.

Material	Density (kg/m^3)	Specific heat capacity (kJ/kgK)	Thermal conductivity (kJ/hmK)	Thermal resistance (hm^2K/kJ)
Clay brick	1827	0.852	3.035	n/a
Cement plaster	1495	0.890	1.906	n/a
Concrete slab	2367	0.901	6.463	n/a
Cement screed	1650	0.840	2.368	n/a
Ceramic tile	2022	1.250	3.987	n/a
Soil	2100	0.960	4.680	n/a
Timber	851	2.006	0.774	n/a
Concrete roof tile	2100	1.500	5.400	n/a
Aluminium foil	n/a	n/a	n/a	0.0210
Ceiling board (master bedroom)	n/a	n/a	n/a	0.0139
Ceiling board (other zones)	n/a	n/a	n/a	0.0030

Table 5.2. Constructional layers and reference U-values of the base model.

Building element	Constructional layers	Reference U-value[a] (W/m²K)
External and internal walls	25mm thick cement plaster + 100mm thick clay brick + 25mm thick cement plaster	2.61
Party wall	13mm thick cement plaster + 200mm thick clay brick + 13mm thick cement plaster	2.19
First floor	15mm thick cement screed + 100mm thick concrete slab + 20mm thick cement plaster	3.49
Ceiling (master bedroom)	6mm thick ceiling board	4.55
Ceiling (other zones)	3.2mm thick ceiling board	5.54
Pitched roof	20mm thick concrete roof tile + aluminium foil	3.86
Flat roof	22mm thick cement screed + 100mm thick concrete slab + 20mm thick cement plaster	3.37
Window	6mm thick single layer float glass	5.61

Two units of experimental houses were modelled in three dimensions using the TRNSYS3D plug-in in Google SketchUp software so that the three-dimensional data were read in TRNBUILD. The model of each house was composed of 12 thermal zones to represent each partitioned room or functional spaces, i.e. living, dining, dry kitchen, washroom, stairs, family area, master bedroom 1(north-facing room) and 2 (south-facing room), attic1, attic2, attic3. As mentioned in the previous section, the staircase area was divided into two air nodes which to represent the lower zone and the upper zone connection. Attic 1 and attic 2 is located above the master bedroom 1 and master bedroom 2, respectively. Meanwhile, attic 3 is located above the upper zone of the staircase. The outer party walls on both sides of the houses were modeled as boundary walls with the assumption of an identical zone temperatures. Meanwhile the boundary condition for the ground floor was the constant soil temperature assumed to be the average air temperature at the site over the simulation period.

Figure 5.2 presents the initial values of boundary condition for each zone in the simulation model including the outdoor condition. The values (average) were obtained from the actual field measurement at night-time (00:00). The values at the night-time was selected because the initial data set of weather conditions (input) will begin from the night-time. As shown, for the zones in the ground floor including the staircase area, the initial values for the air temperature is 28.0 °C and the relative humidity of 77%. Meanwhile, for the zones in the first floor including the attic spaces, the values for the air temperature and the relative humidity are 28.5°C and 75%, respectively. As for the outdoor condition, the values for the air temperature and the relative humidity is 26.4°C and 81%, respectively.

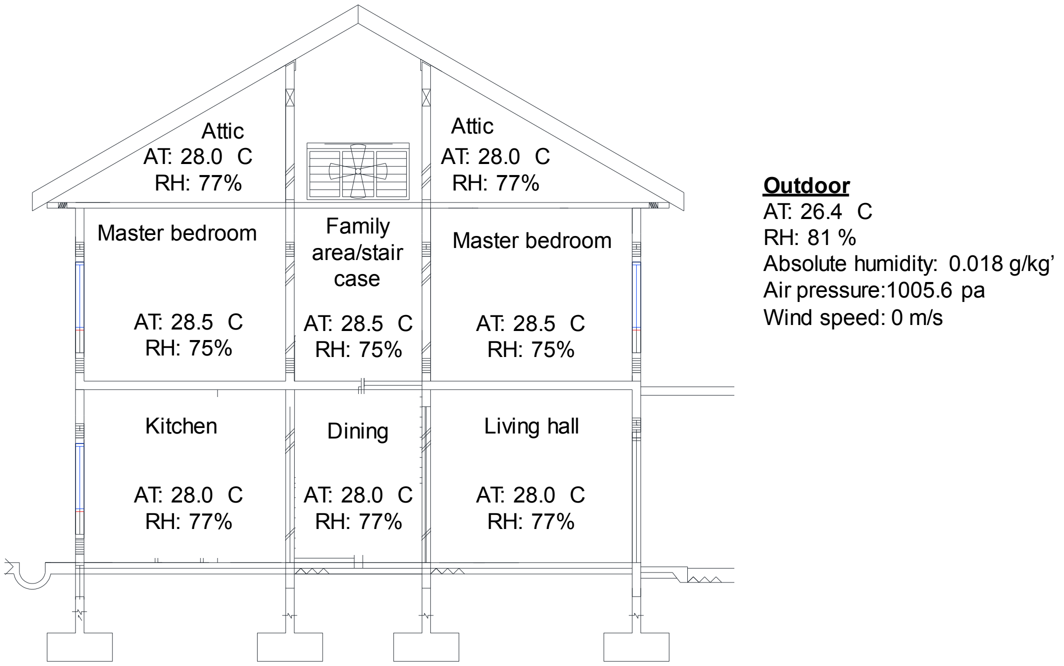


Figure 5.2. Initial **values** of the boundary conditions for indoor spaces and outdoor in the simulation model.

The geographical location of the base model was assigned with the actual location of the experimental houses, i.e. 1°29'N 103°44'E at an elevation of 38m above sea level. As the actual building, the simulation model was oriented towards north, where the front master bedroom (first floor) and the living hall (ground floor) faces north.

Since the input value for wind and air flows is not available from the field measurement and because of limitation to find the suitable empirical data for all specific cases, we employed the CPCALC^{+} program to estimate the wind pressure coefficient. The program was developed by Grosso (1992, 1995). The calculation considers terrain roughness (exponential wind profile), surrounding buildings (building height and density), aspect ratios and wind direction. Meanwhile, discharge coefficients were calculated internally in COMIS or estimated using function given in the manual (Dorer *et al*., 2005). Table 5.3, summarizes the derived data of wind pressure coefficient that we applied to the simulation model.

Table 5.3. Summary of wind pressure coefficient on the building facades for the simulation model**.**

House 1

Building façade	Wind direction relative to building							
	0°	45°	90°	135°	180°	225°	270°	315°
Ground floor								
Front North	-0.097	-0.067	-0.059	-0.059	-0.167	0.022	0.043	0.006
Back_South	-0.097	0.006	0.043	0.022	-0.167	-0.059	-0.059	-0.066
End wall 1_East	-0.047	-0.054	-0.071	0.001	0.036	0.023	-0.131	-0.044
End wall 2_East	-0.047	-0.051	-0.112	0.017	0.054	0.017	-0.112	-0.051
End wall 3_East	-0.047	-0.044	-0.131	0.023	0.036	0.001	-0.071	-0.054
First floor								
Front North	-0.151	-0.103	-0.093	-0.092	-0.264	0.060	0.116	0.015
Back_South	-0.150	0.016	0.117	0.060	-0.262	-0.091	-0.092	-0.103
End wall 1_East	-0.073	-0.084	-0.109	0.003	0.102	0.065	-0.204	-0.069
End wall 2_East	-0.073	-0.078	-0.172	0.047	0.148	0.047	-0.172	-0.078
End wall 3_East	-0.073	-0.069	-0.204	0.065	0.102	0.003	-0.109	-0.084
Roof								
Roof front North	-0.021	-0.028	-0.016	-0.023	-0.032	-0.007	-0.014	-0.012
Roof side North	-0.006	-0.010	-0.007	-0.009	-0.008	-0.006	-0.005	-0.005
Roof back South	-0.020	-0.011	-0.013	-0.005	-0.030	-0.022	-0.016	-0.027
Roof side South	-0.006	-0.005	-0.005	-0.005	-0.008	-0.008	-0.007	-0.009

House 2

Building façade	Wind direction relative to building							
	0°	45°	90°	135°	180°	225°	270°	315°
Ground floor								
Front North	-0.075	-0.052	-0.046	-0.046	-0.132	0.030	0.058	0.008
Back_South	-0.167	0.022	0.043	0.006	-0.097	-0.067	-0.059	-0.059
End wall 1_West	0.036	0.001	-0.071	-0.054	-0.047	-0.044	-0.131	0.023
End wall 2_West	0.054	0.017	-0.112	-0.051	-0.047	-0.051	-0.112	0.017
End wall 3_West	0.036	0.023	-0.131	-0.044	-0.047	-0.054	-0.071	0.001
First floor								
Front North	-0.262	-0.091	-0.092	-0.103	-0.150	0.016	0.117	0.060
Back_South	-0.264	0.060	0.116	0.015	-0.151	-0.103	-0.093	-0.092
End wall 1_West	0.102	0.003	-0.109	-0.084	-0.073	-0.069	-0.204	0.065
End wall 2_West	0.186	0.059	-0.165	-0.072	-0.070	-0.072	-0.165	0.059
End wall 3_West	0.099	0.063	-0.205	-0.069	-0.073	-0.085	-0.110	0.003
Roof								
Roof front North	-0.032	-0.023	-0.016	-0.028	-0.021	-0.012	-0.014	-0.007
Roof side North	-0.015	-0.006	-0.007	-0.010	-0.009	-0.006	-0.005	-0.006
Roof back South	-0.028	-0.005	-0.013	-0.010	-0.019	-0.025	-0.015	-0.021
Roof side South	-0.016	-0.006	-0.005	-0.006	-0.009	-0.010	-0.008	-0.006

5.4 Weather condition for simulation

In this study, two sets of weather data were used to fulfill the requirement of model validation and during the parametric simulation case. As for model validation purpose, the numerical model was performed using the field measurement data, which was conducted in June 2016. Based on this data, the indoor thermal condition of the simulated model and the actual result from the field measurement were compared.

Meanwhile, the second set of weather data was based on the Typical Meteorological Year (TMY) of Kuala Lumpur (3°07'N 101°33'E, 22m above sea level). This type of weather data was chosen to replicate the critical ambient condition of urban areas where the heat-island phenomenon is occurred. The simulation for the test cases were run using the above weather file for two months of April and May. Subsequently, simulation results for a 10-day period of continuous typical fair-weather days were analyzed in this study. Figure 5.3 shows the temporal variations of weather data for the simulation analysis period.

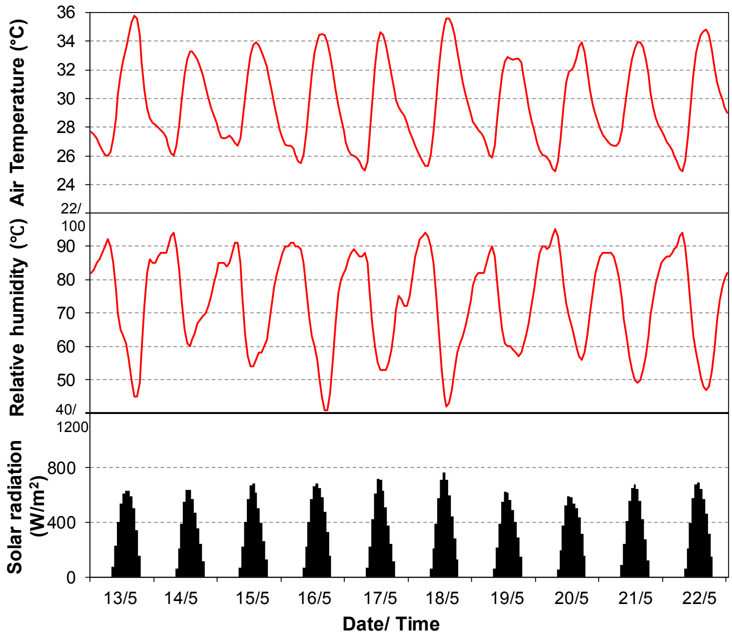


Figure 5.3. Temporal variations of weather data for the simulation analysis period.

The main parameters of weather data that were included in the simulation is the air temperatures, relative humidity, wind speed and direction, barometric pressure and solar radiation. As for the simulation for the validation, the simulation time step was set to coincide with weather data of the field measurement at 10-minute intervals. Meanwhile, for the simulation of the test cases, the simulation time step was set to coincide with weather data of TMY at 1-hour intervals.

In the simulation, we applied two sets of weather file data. The first set of data is obtained from the field measurement works that has been conducted in the experimental house (UTM) from June to September 2016. This data sets are being use for the validation of the simulation program. Meanwhile, the second set of data were taken from the Typical Metrological Year (TMY) of Kuala Lumpur (3°07'N 101°33'E, 22m above sea level). After the model has been validated, the simulation was run by using the TMY weather file for two whole months of April and May. Subsequently, simulation results for a 10-day period of continuous typical fair-weather days were analyzed in this study.

5.5 Model validation

Empirical validation was performed using the afore-mentioned field measurement data. This study focuses particularly on the results in the master bedroom. This is because it has been reported that the existing households in Malaysia used air conditioning mainly in the master bedrooms (Kubota *et al.,* 2009). It is implied that the cooling energy can be reduced if the thermal comfort of the room is improved through passive cooling. Since the main interest of this study is to investigate the performance of the passive modification techniques under night and full-day ventilation conditions, therefore, the simulation for the model validation has been conducted under both conditions.

As for the evaluation for the simulation results, two statistical error tests were adopted to check the deviations of the simulation results from the actual data. Those statistical tests are the mean bias error (MBS) and the root mean square error (RMSE). They are calculated as follows:

$$\text{MBE} = \sum_{i=1}^{N}(L_{is} - L_{i\text{m}})\,/N \quad (2)$$

$$\text{RMSE} = \sqrt{\sum_{i=1}^{N}(L_{is} - L_{i\text{m}})^2/N} \quad (3)$$

where L_{is} is the where L_{is} is the *i*th simulated value, $L_{i\text{m}}$ is the *i*th measured value and *N* is the total number of data pairs (Jiang, 2009). A smaller error generally means better predictions by the evaluated model. In addition, coefficients of determination (R^2) were also use for further test the linear relationships between the simulated and measured values.

Figure 5.4 shows the temporal variations of the simulation results compared to the measurement data at 1.5 m height above the floor in the master bedroom in the night ventilation condition. In general, good agreement was found between the simulation and the measurement especially for air temperature and relative humidity. As shown, the simulation was just slightly underestimate the air temperature during the daytime with the average difference was less than 0.3°C. In contrast, almost similar air temperatures value observed during the night-time. Same situation found in the results of relative humidity where the simulation successfully generating almost similar relative humidity value compared to the measurement during the daytime but slightly overestimate during the daytime. Meanwhile, in the case of absolute humidity, the result from the simulation were slightly higher than the measurement by up to 1g/kg' during the whole simulation period. The calculated MBE for air temperature relative humidity and absolute humidity are -0.22, 2.73 and 0.94 respectively. RMSE value for the same variables are 0.37, 4.95 and 1.35 respectively. As for the coefficients of determination (R^2), air temperature and relative humidity show a high correlation to the measurement with the value of over 0.90. In contrast, lower correlation was found for the absolute humidity with the value of 0.48.

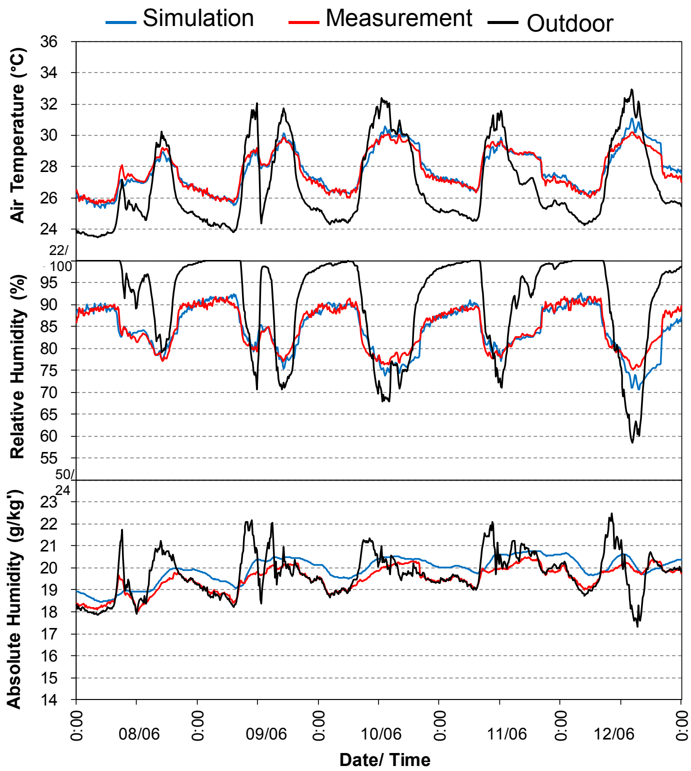


Figure 5.4. Temporal variations of the simulated and measurement data in the master bedroom in night ventilation condition (1.5 m above floor).

Table 5.4. Statistical error of MBE, RMSE and R^2. (Case: Night-ventilation)

	MBE	RMSE	R^2
Air temperature	-0.22	0.37	0.97
Relative humidity	2.73	4.95	0.91
Absolute humidity	0.94	1.35	0.48

Figure 5.5 shows the temporal variations of the simulation results compared to the measurement data at 1.5 m height above the floor in the master bedroom in the full day ventilation condition. As shown, the simulated values for the air temperatures were almost similar to that of measurement with high level of coefficients of determination (0.92). Meanwhile, as for relative humidity, the simulated value showed high agreement with the measurement value during night-time but slightly overestimate during the daytime by up to 10%. Nevertheless, the correlation between both results still can be considered high with the R^2 value of 0.85. In this case, the simulated value of absolute humidity was improved and just slightly higher than the measurement value by up to 0.5 g/kg' for the whole simulated period. The resultant R^2 value was 0.80. As shown in Table 5.5, the calculated MBE for air temperature relative humidity and absolute humidity are -0.21, 0.68 and 0.44 respectively. Meanwhile, RMSE value for the same variables are 0.43, 1.97 and 0.52 respectively.

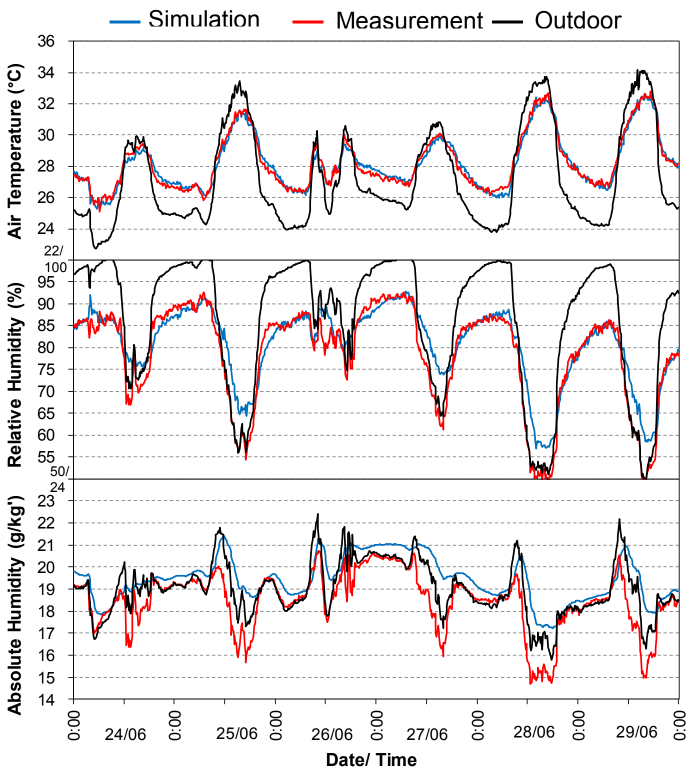


Figure 5.5. Temporal variations of the simulated and measurement data in the master bedroom in full-day ventilation condition (1.5 m above floor).

Table 5.5. Statistical error of MBE, RMSE and R^2. (Case: Full-day ventilation)

	MBE	RMSE	R^2
Air temperature	-0.21	0.43	0.92
Relative humidity	0.68	1.97	0.85
Absolute humidity	0.44	0.52	0.80

Overall, the validation results were satisfactory compared to the measurement especially for the air temperatures. In another simulation study related to a terraced house in Malaysia, the average air temperature difference between simulation and field measurement of 0.4°C was considered acceptable (Sadafi *et al*., 2011). Furthermore, a study of night ventilated building model showed the acceptable resulting error of MBE and RMSE were 0.46°C and 0.88°C respectively (Finn *et al.,* 2007). A simulation model which had a mean difference between simulated and measured temperatures of 0.3 °C with an R^2 of 0.90 has been used in a study of the evaluation of night ventilation (Geros *et al.,* 1999). Meanwhile, for the relative humidity, the error range of MBE and RMSE were lower than 5% with the R^2 value range of 0.86-0.91 in both natural ventilation cases. Considered the accuracy of the relative humidity sensors used for the field measurement which ranges 2.5-5%, the errors can be considered acceptable. Therefore, it is concluded that the based model in this study is satisfactory accurate in describing the thermal behavior of the terraced house despite the acknowledged model limitation on the absolute humidity.

5.6 Simulation experimental cases

Theoretically, passive cooling for building can be defined by two methods, i.e., 1) reduce the solar radiation heat gain through the building envelop and 2) removing of internal heat to the outside by natural means (Lee *et al.,* 2017). As for the first method, solar radiation heat gain can be reduced by the application of artificial structures for shielding, shading effects from trees and plants, an increase of the reflectance material and the installation of high insulation materials into the building walls and roof. Meanwhile, as a method of removing heat, natural ventilation is a common way especially by cross-ventilation and they are traditionally used in hot and warm climate region (Givoni, 1992).

In this study, as our main objective, both the above-mentioned methods were considered in order to investigate the optimum passive cooling strategies for modern urban houses in Malaysia. As for the simulation, we focus on five aspects of passive cooling techniques, i.e, natural ventilation, strategy for roof, strategy for the walls, strategy for windows and lastly the forced ventilation. Table 5.6 shows the simulation test cases.

Table 5.6. The simulation test cases and their test condition

Test Condition	
Natural ventilation	**Techniques**
Night ventilation	**Techniques for roof** • Roof insulation (R=3) • Ceiling insulation (R=3) • High reflectance roof coating (reflectance = 0.8) **Techniques for wall** • External wall insulation (outside surface) (R=3) • External wall insulation (inside surface) (R=1.5) **Techniques for window** • External shading (SF=0.75) • Internal shading (SF=0.75) • Low-E glass (U-value= 2.53m^{2}K/W, g-value=0.44) **Forced ventilation techniques** • Whole house ventilation (30 ACH) • Master bedroom ventilation fan (40 ACH) • Attic ventilation fan (40 ACH)
Full-day ventilation	**Techniques for roof** • Roof insulation (R=3) • Ceiling insulation (R=3) • High reflectance roof coating (reflectance = 0.8) **Techniques for wall** • External wall insulation (outside surface) (R=3) • External wall insulation (inside surface) (R=3) **Techniques for window** • External shading (SF=0.75) • Internal shading (SF=0.75) • Low-E glass (U-value= 2.53m^{2}K/W, g-value=0.44) **Forced ventilation techniques** • Whole house ventilation (30 ACH) • Master bedroom ventilation fan (40 ACH) • Attic ventilation fan (40 ACH)

As our main interest in this study is to investigate the modification techniques under structural cooling (night ventilation) and full day ventilation, therefore the simulation case of the respective modification techniques was simulated under both ventilation conditions. In the night ventilation case, the windows were closed during daytime from 8:00 to 20:00 and opened during night-time from 20:00 to 8:00. In contrast, the windows were kept opened for the whole day in the full-ventilation case.

The techniques that were considered for the simulation test case were selected by considering their practicality to be applied in the existing terraced houses through relatively simple building modification and/or behavioral adjustment. As shown in the table, three passive cooling techniques were considered for the heat reduction on the roof. They are roof insulation, ceiling insulation and the high reflectivity roof coating.

Meanwhile, two locations of thermal insulation were considered to reduce the heat gain on building wall, i.e., external wall outside surface and external wall inside surface. In this context, external wall means the outer wall of building which exposed to the direct solar radiation. To be note that, thermal insulation on buildings is not a common practice in Malaysia at present.

Since the short-wave solar radiation can easily penetrate the building through the window, thus, we considered several options for the windows strategies in the simulation, i.e., external shading, internal shading and low-e glass.

Furthermore, forced ventilation techniques were also included as the passive cooling strategies, i.e., whole house ventilation fan, master bedroom's exhaust fan and attic fan, to examine whether they could improve the effects of nocturnal structural cooling. Generally, passive cooling requires no mechanical energy input, but mechanical means with small amount of energy can also be considered as one, e.g., forced ventilation (Levine *et al.,* 2007).

In the simulation, the thermal resistant or R-values for all insulations has been defined as 3m^2.K/W except for that of external wall-internal surfaces which was 1.5 m^2.K/W. Meanwhile, the specification of high reflectivity coating of roof was 0.8 for its solar reflectance and long wave emissivity. As for the window shading, the specification was defined as a shading factor. The shading factor means the ratio of the opaque area of the shading device to the whole window area with the smallest value (0) means no shading effects to the windows. In this simulation, the shading factor of 0.75 was selected. Furthermore, the thermal property of the Low-E glass was chosen from the TRNSYS library with the thermal transmittance value (U-value) of 2.54W/m^{2}K and solar energy transmittance of glass (g-value) of 0.44. All the above-mentioned specification has been considered and selected based on the simulation results in Toe, 2013. Meanwhile, the speed of the forced ventilation has been selected based on the maximum speed of the actual fan that has been installed in the experimental house. The speed of the small fans, i.e., master bedroom's fan and attic fan, is 40 air change rates per hour (ACH) and the speed of the large whole house ventilation fan is 30 ACH.

The base model of the simulation was specified to have thermal insulation on the end walls of both houses with R-value 3 m^2.K/W. As mentioned earlier, the purpose of the end wall insulation is to eliminate thermal influences from outdoors. Meanwhile, the orientation of the houses is facing North. Therefore, only the results of with this type of orientation will be presents in the results.

5.7 Results: Natural ventilation

This section analyzed the thermal effects of natural ventilation in the master bedroom and the living hall under the base natural ventilation condition, i.e. structural cooling (night ventilation) and comfort ventilation. Master bedroom and the living hall were selected for the analysis because the occupants mostly spends their time in the master bedroom at night and at the living hall during the daytime. Furthermore, due to the seasonal condition in the weather data used in the simulation, the north-facing spaces (indoor) of the building model experienced hotter condition compared to that of south-facing spaces. This is because the sun-angle was slightly towards the northern side in the month of April to May. Therefore, from this section on, we will present the analysis and results of north-facing master bedroom and living hall of the building model where the hotter side is considered as a critical condition. Operative temperature (OT) was used as indices to evaluate the thermal comfort in the master bedroom and the living hall.

Figure 5.6 shows the temporal variations of air temperature and relative humidity (RH) of the master bedroom and living hall under the structural cooling (night-ventilation) condition. As shown, outdoor air temperature during the simulation period ranges from 25.5°C to 26°C, while the corresponding RH ranges from 40-95%. In general, the air temperatures in the master bedroom and the living hall were lower than the outdoor during the daytime. The air temperature is lower than the outdoor by up to 2°C and 4°C in the master bedroom and living hall, respectively. This is due to the thermal mass effects of the night structural cooling and closed window condition at daytime. It was found that the air temperature in the master bedroom was slightly than that of the living hall. This is simply because the master bedroom received the radiation heat from the warm attic spaces. Meanwhile, the nocturnal air temperature of both spaces was almost the same and they are about 1-2°C higher than the outdoors. The RH both spaces are ranges from 60 to 85% during the whole simulation period. RH in the master bedroom was slightly lower than the living hall during the daytime by up to 7% due to warmer indoor condition.

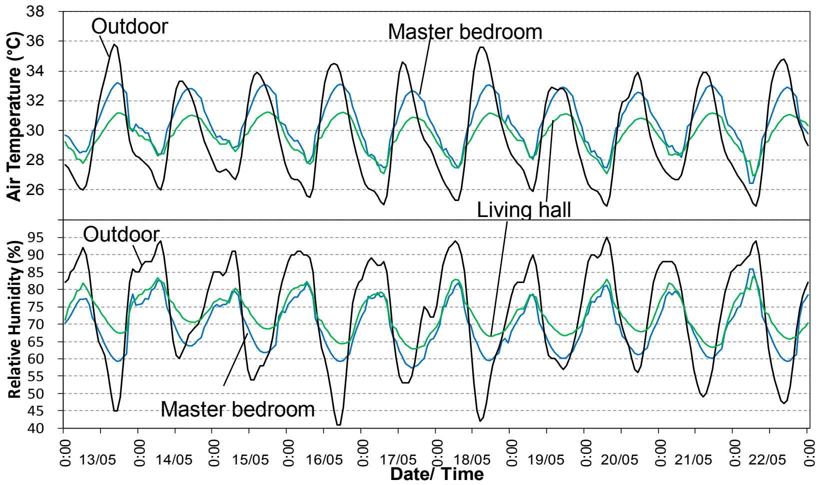


Figure 5.6. Temporal variations of simulated air temperature and relative humidity (RH) of the master bedroom and living hall under the structural cooling (night ventilation) condition.

Figure 5.7 shows the temporal variations of air temperature and RH of the master bedroom and living hall when the comfort ventilation condition (full-day ventilation) was applied. In contrast to the structural cooling condition, both indoor spaces are ventilated through the day and the resultant air temperatures increased closely to the corresponding outdoor. The air temperatures in the master bedroom are almost similar to the corresponding outdoor during the daytime. Meanwhile the air temperatures of living hall are slightly lower than the corresponding outdoor by approximately 1-2°C. Nevertheless, the daytime RH were reduced to as low as 45% and 50% in the master bedroom and the living hall, respectively. The nocturnal air temperature in both rooms are almost similar to the previous strategy which is about 1-2°C higher than the outdoors. Meanwhile the nocturnal RH in both rooms are ranges from 78%-85% during the whole simulation period.

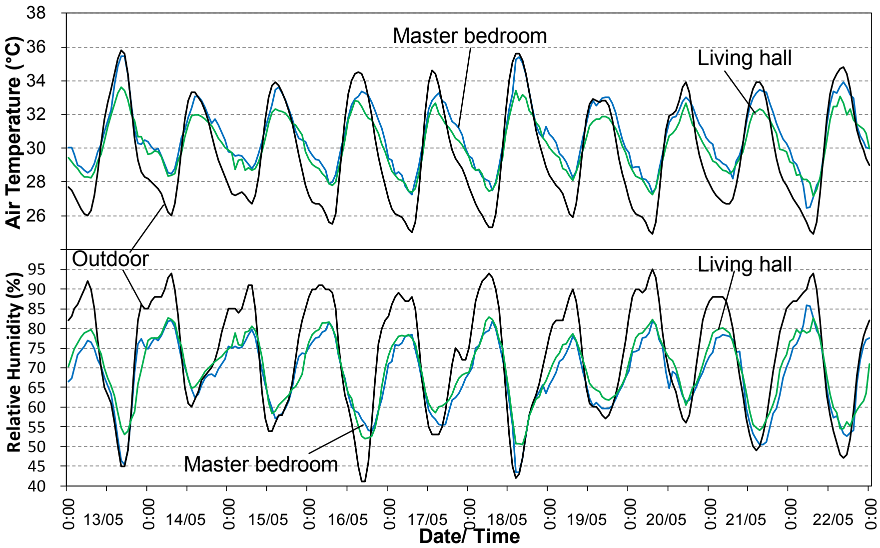


Figure 5.7 Temporal variations of simulated air temperature and relative humidity (RH) of the master bedroom and living hall under the comfort ventilation (full-day ventilation) condition.

Figure 5.8 present the resulting daily averaged air temperature and relative humidity in the master bedroom under both cooling strategies. As shown, night ventilation provides the lowest daily mean and maximum air temperature in the master bedroom and the living hall, while full day ventilation obtains slightly lower minimum air temperature at night. However, it can be seen that indoor relative humidity exceeds 60% through the day when the night ventilation is adopted. As far as indoor humidity condition is concerned, full-day ventilation is prior to the night ventilation.

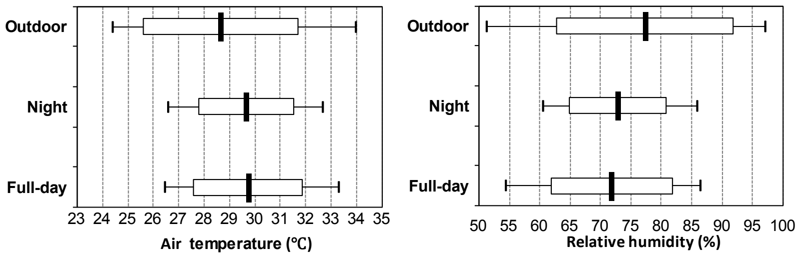


Figure 5.8. Daily averaged of simulated air temperature and relative humidity in the master bedroom under both cooling strategies.

Figure 5.9 presents the results of calculated OT in the master bedroom and the living hall under both ventilation strategy. As shown, the range of OT in both indoor spaces in structural cooling are slightly lower than that of comfort cooling. Nevertheless, the OT in both cases exceeded the 80% upper limit for most of the daytime. This indicates that the natural ventilation strategies alone is not sufficient to improve the thermal comfort condition of the indoor spaces especially during the daytime. Therefore, the passive cooling should be considered wherever possible to improve the thermal comfort condition of the modern houses.

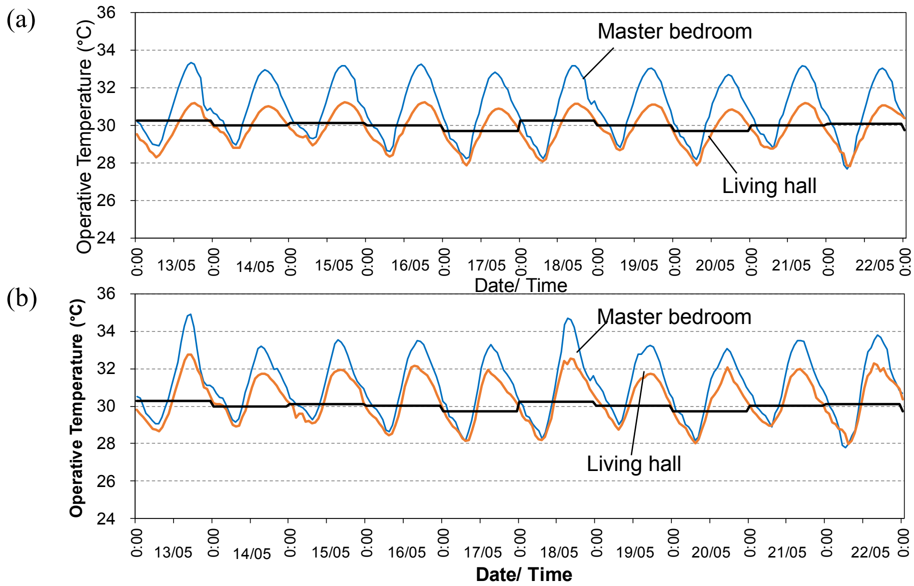


Figure 5.9. Temporal variations of simulated operative temperatures (OT) and the corresponding temperature limits of thermal comfort in the master bedroom and living hall (a) night-ventilation (b) full-day ventilation

5.8: Structural cooling strategy (night ventilation)

This section analyzed the thermal effects of respective modification techniques under the night ventilation condition. Firstly, we investigate the effects of each techniques by analyzing the resulting operative temperatures in the master bedroom and the living hall compared to the base night ventilation condition (base case). Secondly, we investigate the effects of combination of each technique that can provide optimum OT reduction in the master bedroom and living hall in night-time and day-time, respectively.

5.8.1 Single techniques

5.8.1.1 Effects of roof insulation

Figure 5.10 shows the statistical summary of air temperature in the master bedroom and the living hall when the roof insulation is installed. As shown, the maximum (95^{th} percentile) and mean air temperature of the master bedroom and the living hall with roof insulation are lower than those of night ventilation without techniques (base case). The reduction of maximum and mean air temperature in the master bedroom is about 1°C and 0.5°C, respectively. Meanwhile, the reduction of maximum and mean air temperatures in the living hall are minimal which is about 0.2 and 0.1°C, respectively. This indicates that the roof insulation successfully reduces the solar heat gain in the attic, thus, smaller radiant heat is transferred to the master bedroom through the ceiling board. As the living hall is not directly connected to the attic spaces, therefore, the air temperature of that spaces is not much affected by the cooling effects by the roof insulation. In contrast, the minimum (5^{th} percentile) air temperature in the master bedroom with roof insulation is slightly higher than the base case which is about 0.2°C. This is probably because, the roof insulation prevented the heat from releasing to the night-sky.

Fig. 5.11 presents the resulting OT in the master bedroom and the living hall when the roof insulation is applied. As shown, the OT temperatures in the master bedroom and in the living hall ranges from 27.8-32.2°C and 27.9-31.0°C, respectively. The OT of the master bedroom was reduced by up to 1°C compared to the base night ventilation condition. Meanwhile, the reduction of OT in the living hall is minimal which is less than 0.2°C. Though the OT in both indoor spaces are reduced, they are still exceeding the 80% ACE upper limit by up to 64% during the daytime.

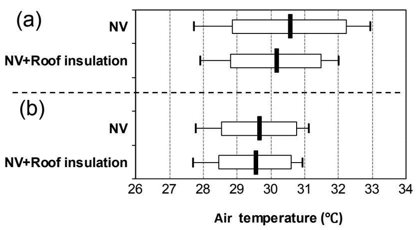


Figure 5.10. Statistical summary (5th and 95th percentiles, mean ± 1 standard deviation) of simulated air temperature under night ventilation with roof insulation in (a) master bedroom (b) living hall.

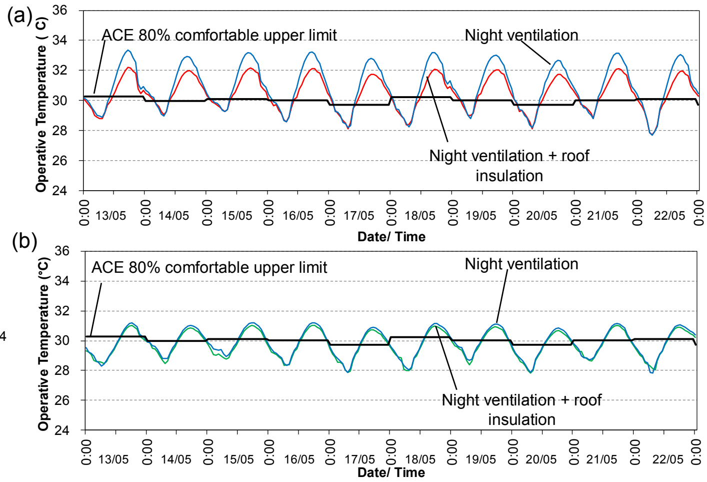


Figure 5.11. Temporal variations of simulated indoor OT with the corresponding temperature limits of thermal comfort under night ventilation with roof insulation in (a) Master bedroom and (b) living hall.

5.8.1.2 Effects of ceiling insulation

Figure 5.12 shows the shows the statistical summary of air temperature in the master bedroom and the living hall when the ceiling insulation is applied. In this case, the reduction of air temperature in the master bedroom is slightly lower compared to the previous case. The maximum and mean air temperature reduction in the master bedroom are about 0.7°C and 0.4°C lower than the base case during the daytime. There is almost no significant difference of in term of air temperature reduction in the living hall compared to the previous case. In the night-time, the air temperature in the master bedroom is almost the same with the base case where the reduction is only about 0.1°C.

The calculated OT in the master bedroom and the living hall are shown in Figure 5.13. Similar as the air temperature pattern, the reduction of OT in the master bedroom is smaller than the case of roof insulation. Meanwhile, the OT in the living hall is almost similar to that of the base case. The exceeding period in the master bedroom was slightly increase when the ceiling insulation is applied (about 65%). This indicates that the ceiling cooling effects of the ceiling insulation is slightly lower compared to that of roof insulation under the night ventilation condition.

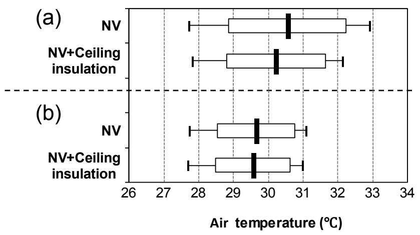


Figure 5.12. Statistical summary (5^{th} and 95^{th} percentiles, mean ± 1 standard deviation) of simulated air temperature under night ventilation with ceiling insulation in (a) master bedroom (b) living hall.

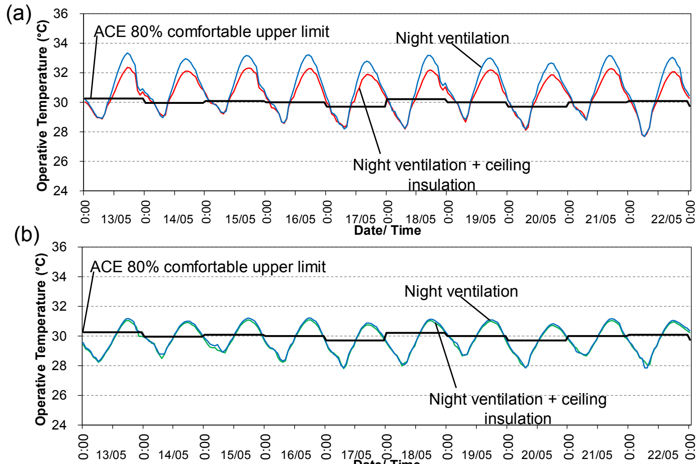


Figure 5.13. Temporal variations of simulated indoor OT with the corresponding temperature limits of thermal comfort under night ventilation with ceiling insulation in (a) master bedroom and (b) living hall.

5.8.1.3 Effects of high reflectivity roof coating

Figure 5.14 shows the shows the statistical summary of air temperature in the master bedroom and the living hall when the ceiling insulation is applied. In general, the air temperature reduction in both spaces are the largest in term of technique for the roof. The air temperature reduction can be seen not only in daytime, but also in night-time. The maximum air temperature reduction in the master bedroom and the living hall is about 0.9°C and 0.2°C lower than those in the base case. Meanwhile the nocturnal air temperature in both spaces are lower than the base case by about 0.1°C. This indicates that the high reflection of heat can reduce the heat transfer into the roof, thus slightly smaller rate of heat transferred to the master bedroom through the ceiling board.

The calculated OT of both spaces is shown in Figure 5.15. As shown, the resulting OT of the master bedroom ranges from 27.8-32.3°C, while in the living hall, it was ranges from 28-31°C. The exceeding period of both spaces are slightly reduced by up to 3-6% compared to the previous case. The exceeding period of the master bedroom is 57% while in the living hall is about 41%.

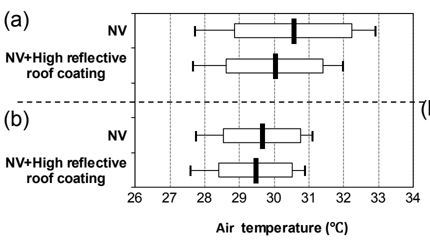


Figure 5.14. Statistical summary (5th and 95th percentiles, mean ± 1 standard deviation) of simulated air temperature under night ventilation with reflective roof coating in (a) master bedroom (b) living hall.

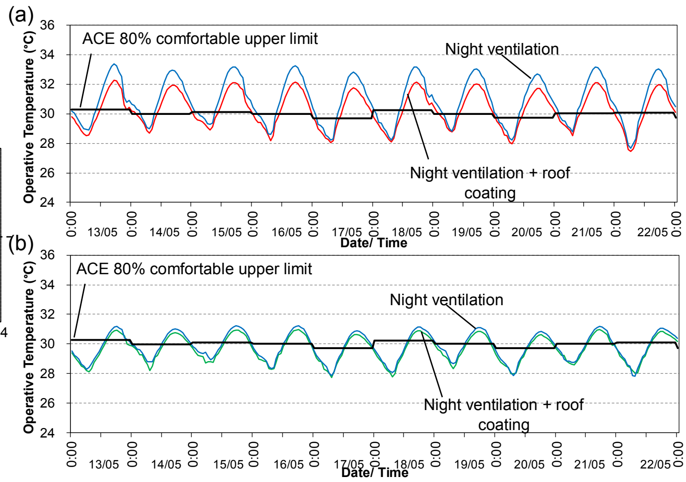


Figure 5.15. Temporal variations of simulated indoor OT with the corresponding temperature limits of thermal comfort under night ventilation with reflective coating in (a) master bedroom and (b) living hall.

5.8.1.4 Effects of external wall (outside surface) insulation

The statistical summary of air temperature in both indoor spaces are shown in Figure 5.16. It can be seen that the cooling effects of the insulation is larger in the living hall compared to the master bedroom, where the air temperature reduction was seen not only in daytime but also at night-time. The maximum and minimum air temperature reduction in the living hall is about 0.6°C and 0.2°C in daytime and night-time respectively. Meanwhile, the air temperature reduction in the master bedroom could only be seen on the daytime (95th percentile) which is about 0.3°C. In night-time, the air temperature in the master bedroom is higher than that of base case by about 0.1°C. This is simply because the living hall is not affected by the heat transfer from the warm attic roof during day and night-time. Thus, the resultant cooling effects could be maintained during the whole day.

Figure 5.17 shows the temporal variation of the calculated OT in the master bedroom and the living hall. The OT in the master bedroom is exceeded the 80% upper limit of ACE thermal comfort criteria by about 68%, which is higher than all previous cases. Meanwhile, the exceeding period in the living hall is reduced to about 38% after the application of the insulation.

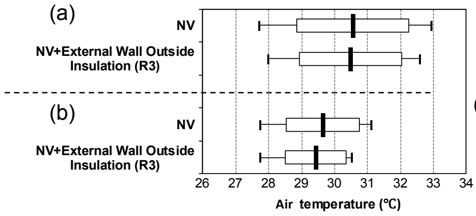


Figure 5.16. Statistical summary (5th and 95th percentiles, mean ± 1 standard deviation) of simulated air temperature under night ventilation with external wall (out) insulation in (a) master bedroom (b) living hall.

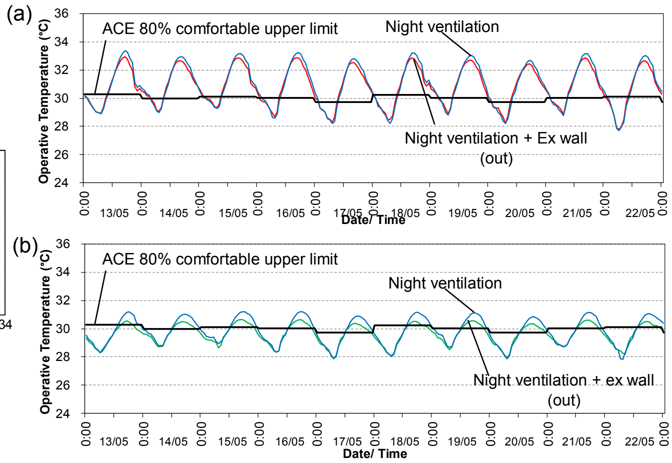


Figure 5.17. Temporal variations of simulated indoor OT with the corresponding temperature limits of thermal comfort under night ventilation with external wall (out) insulation in (a) master bedroom and (b) living hall.

5.8.1.5 Effects of external wall (inside surface) insulation

In this section, we investigate the effects of insulation located at the inside surface of the external wall. Figure 5.18 shows the statistical summary of air temperature in the master bedroom and the living hall after the installation of the insulation. In general, the cooling effects of the insulation located on the internal surface of external wall is slightly smaller than that of the external surfaces. The resultant of maximum air temperature reduction is about 0.1°C and 0.4°C in the master bedroom and living hall, respectively. Meanwhile, at the night-time, the air temperature reduction is almost similar to the case of external wall outside surface. The minimum air temperature in the master bedroom is about 0.2°C higher than the base case, while in the living hall, the air temperature was about 0.1°C lower than the base case. Thus, the resultant of mean air temperature in the master bedroom shows almost no reduction compared to the base case. Meanwhile, the mean air temperature of the living hall is slightly reduced by about 0.2°C compared to the based case. This is probably because the insulation likely retards the heat from inside to the outer layers of the wall.

Due to the slightly lower cooling effects resulted by the insulation at the inside surface, thus the exceeding period of both spaces is increased compared when the insulation of outside surface is applied. The exceeding period of the master bedroom in the master bedroom and the living hall is about 68% and 43%, respectively (Figure 5.19). This indicates that the insulation at the inside surface of external wall is less effective than those on outside surface.

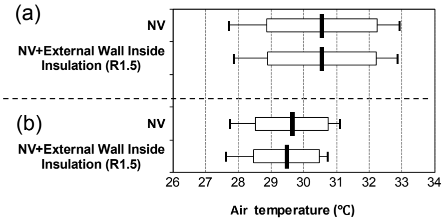


Figure 5.18. Statistical summary (5[th] and 95[th] percentiles, mean ± 1 standard deviation) of simulated air temperature under night ventilation with external wall (in) insulation in (a) master bedroom (b) living hall.

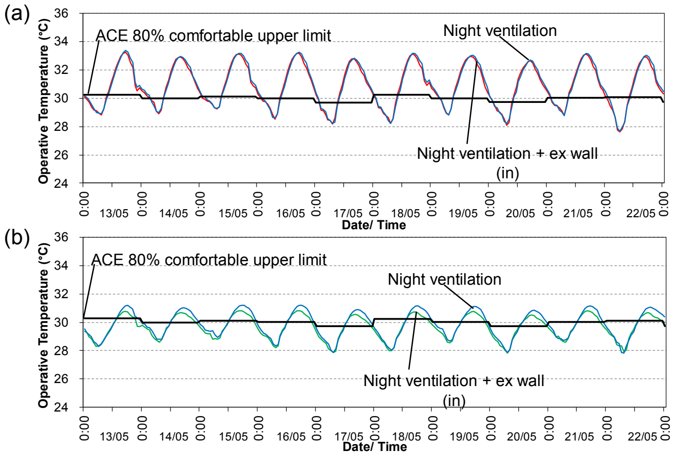


Figure 5.19. Temporal variations of simulated indoor OT with the corresponding temperature limits of thermal comfort under night ventilation with external wall (in) insulation in (a) master bedroom and (b) living hall.

5.8.1.6 Effects of external window shading

Figure 5.20 shows the statistical summary of air temperature in the master bedroom and the living hall when the external window shadings are applied. As shown, quite large reduction of maximum and mean air temperature observed in the master bedroom and the living hall. In the master bedroom, the maximum and mean air temperature reduction is about 0.9°C and 0.5°C, respectively. Meanwhile, the maximum and mean air temperature reduction in the living hall is about 0.8°C and 0.5°C respectively. This indicates that, the external shading successfully lowering the effects of solar radiation through the windows during the daytime. At the night-time, the cooling effects can only be seen in the living hall where the minimum air temperature is lower than the base case by about 0.2°C.

The evaluation of thermal comfort (OT) shows that the living hall almost fell within the ACE 80% comfort limit for most of the measurement period (Figure 5.21). In this case, the exceeding period of the living hall is about 25% in the whole simulation period. In contrast, the OT in the master bedroom is still largely exceed the limits by about 58%.

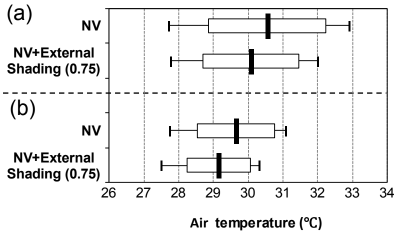


Figure 5.20. Statistical summary (5th and 95th percentiles, mean ± 1 standard deviation) of simulated air temperature under night ventilation with window shading (out)in (a) master bedroom (b) living hall.

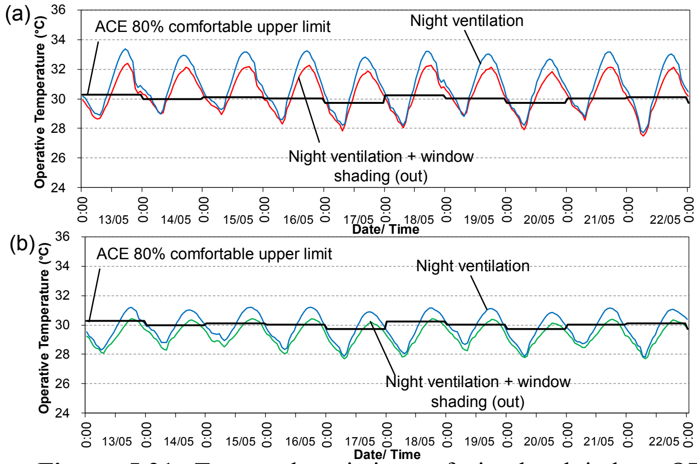


Figure 5.21. Temporal variations of simulated indoor OT with the corresponding temperature limits of thermal comfort under night ventilation window shading (out) in (a) master bedroom and (b) living hall.

5.8.1.7 Effects of internal window shading

Figure 5.22 shows the statistical summary of air temperature in the master bedroom and the living hall when the internal window shadings are applied. In general, the result shows that there are almost no cooling effects provided by the internal shading in the master bedroom and the living hall. The maximum, mean and minimum air temperature difference in those spaces are less than 0.1°C when compared to the condition of without shading (base case). This is because the solar radiation has already transmitted through the window before it is block by the internal shading. The solar radiation heat that enters between the glazing and the internal shading would then increase the room air.

As a result, the OT in the master bedroom and living hall largely exceed the comfort limits by about 66% and 43%, respectively (Figure 5.23). This indicates that external shading is prior than the internal shading.

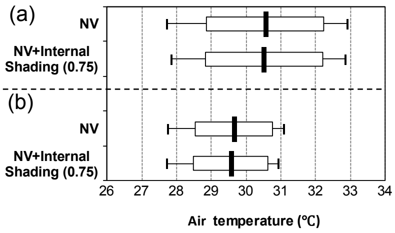


Figure 5.22. Statistical summary (5^{th} and 95^{th} percentiles, mean ± 1 standard deviation) of simulated air temperature under night ventilation with window shading (in) in (a) master bedroom (b) living hall.

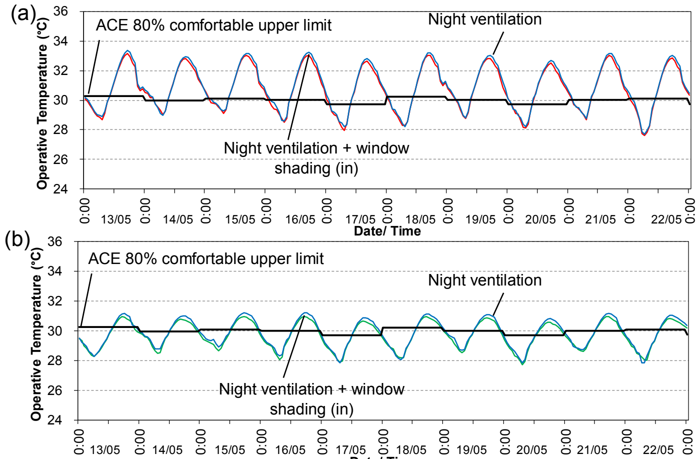


Figure 5.23. Temporal variations of simulated indoor OT with the corresponding temperature limits of thermal comfort under night ventilation with window shading (in) in (a) master bedroom and (b) living hall.

5.8.1.8 Effects of Low-E glass

In this section, the Low-E glass was applied to the simulation model as the last alternative techniques for the windows. Figure 5.24 shows the statistical summary of air temperature in the master bedroom and living hall after the application of the technique. The result show that the reduction of maximum and air temperature in both spaces were merely smaller than the case of external shading. In the master bedroom, the reduction of maximum and mean air temperature is 0.2°C and 0.3°C, respectively. Meanwhile, in the living hall, the reduction is about 0.3°C and 0.1°C, respectively. The are no significant improvement on the minimum air temperature in both rooms since they are almost the same as in the previous case (external and internal shading). This indicates that the low-e glass with the U value of 2.53m^2K/W and g-value of 0.44 is unable to provide sufficient thermal heat barrier as large as the external shading device. Probably, by increasing the specification of the glass could increase the cooling effects for the indoor spaces.

Figure 5.25 shows the temporal OT in the master bedroom and the living hall with the corresponding ACE 80% upper limits. In this case, the OT in the master bedroom exceeds the limit by about 67% along the measurement period. Meanwhile, as the OT in the living hall exceeds the limits by about 41%.

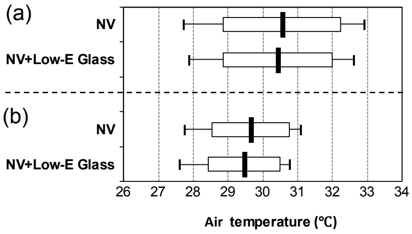


Figure 5.24. Statistical summary (5th and 95th percentiles, mean ± 1 standard deviation) of simulated air temperature under night ventilation with Low-E glass in (a) master bedroom (b) living hall.

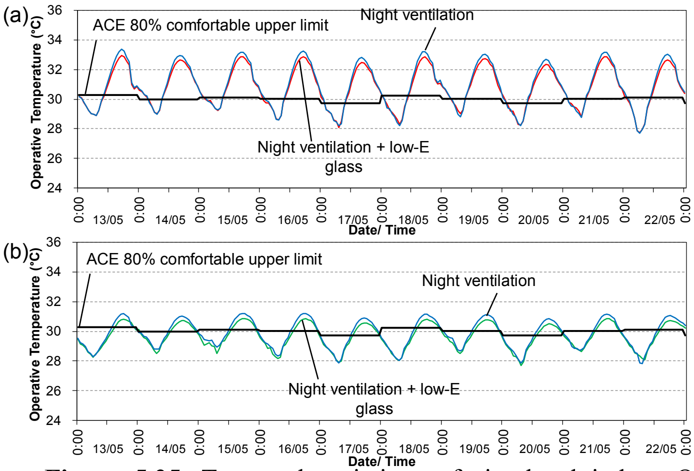


Figure 5.25. Temporal variations of simulated indoor OT with the corresponding temperature limits of thermal comfort under night ventilation with Low-E glass in (a) master bedroom and (b) living hall.

5.8.1.9 Effects of attic forced ventilation

From this section on, we investigate the effects of forced ventilation techniques on the thermal condition of the master bedroom and the living hall. Figure 5.26 shows the statistical summary of air temperature of both spaces when the attic fan is applied. As shown in the results, there are almost no improvement of indoor thermal condition in both spaces when compared to the condition without attic fan. This indicates that, the attic fan with 40 air change rate per hour (40) is not able to provide the cooling effects even for the master bedroom.

As a result, the resultant temporal variation of OT in both spaces are almost the same as the condition without attic fan. In this case, the thermal comfort of the master bedroom and the living hall exceeded the thermal comfort upper limit of ACE 80% by about 66% and 46%, respectively (Figure 5.27).

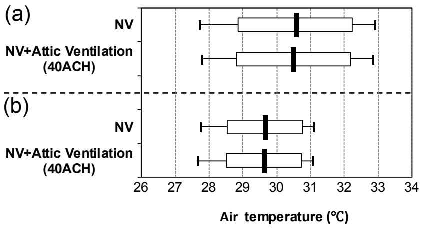


Figure 5.26. Statistical summary (5th and 95th percentiles, mean ± 1 standard deviation) of simulated air temperature under night ventilation with attic ventilation in (a) master bedroom (b) living hall.

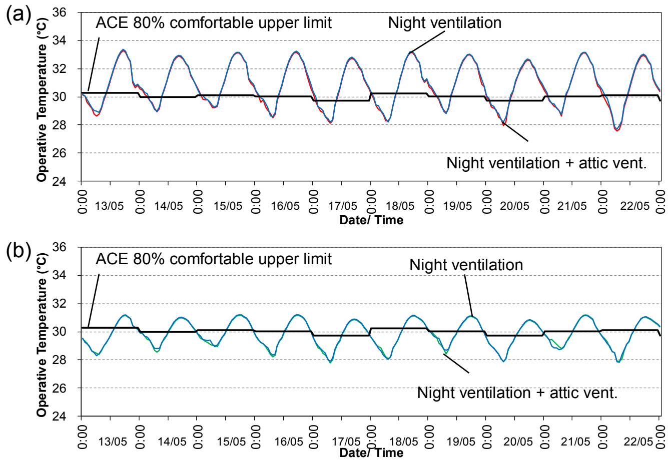


Figure 5.27. Temporal variations of simulated indoor OT with the corresponding temperature limits of thermal comfort under night ventilation attic ventilation in (a) master bedroom and (b) living hall.

5.8.1.10 Effects of master bedroom forced ventilation

The forced ventilation is applied with the assumption that it can directly strengthen the cooling effects of night ventilation in the master bedroom. In the model of simulation, the fan is being located at the external wall of the master bedroom. The forced master bedroom is applied at night-time (20:00 to 8:00) with the assigned speed of 40ACH. Figure 5.28 shows the statistical summary of air temperature in the master bedroom and the living hall during the simulation period. As shown, the mean and minimum air temperature of the master bedroom are reduced largely by about 0.9°C and 1.2°C compare to the case of without forced ventilation. This is simply because the cool outdoor air entered the room by the forced ventilation fan. However, the reduction of daytime air temperature is not as large as during night-time. The maximum air temperature in the master bedroom just only 0.3°C lower than the base case. Meanwhile, the cooling effects is not seen in the living hall. This is simply because the forced ventilation techniques are only improving the ventilation rate in the master bedroom. In the living hall, the maximum and minimum air temperature are just slightly lower than the base case by about 0.2°C and 0.1°C, respectively.

Figure 5.29 shows the temporal variation of OT in the master bedroom and the living hall. As shown, the techniques only reduce the nocturnal OT in the master bedroom. The resultant OT in the daytime is still high and closely follows the range of OT of the case without the forced ventilation fan. In this case, the exceeding period of OT in the master bedroom and the living hall is about 52% and 44% over the comfort limit.

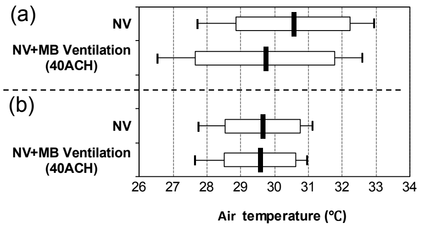


Figure 5.28. Statistical summary (5th and 95th percentiles, mean ± 1 standard deviation) of simulated air temperature under night ventilation with master bedroom ventilation in (a) master bedroom (b) living hall.

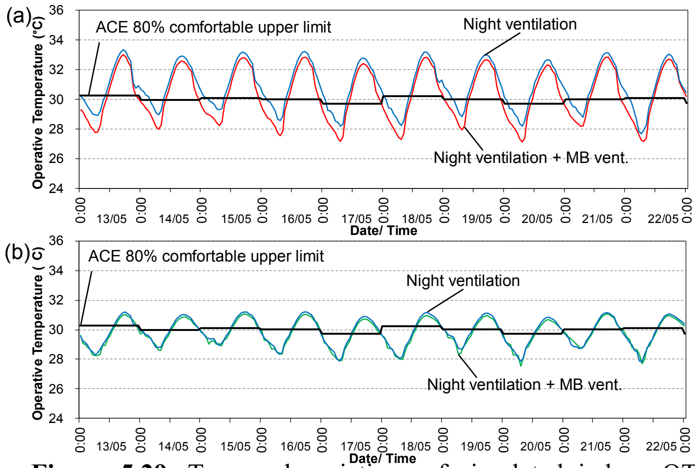


Figure 5.29. Temporal variations of simulated indoor OT with the corresponding temperature limits of thermal comfort under night ventilation with master bedroom ventilation in (a) master bedroom and (b) living hall.

5.8.1.11 Effects of whole house forced ventilation

In this section, the whole house ventilation is applied in the simulation model by using the large ventilation fan located above the staircase at the center of the house. The purpose of the techniques is to improve the cooling effects of night ventilation for the whole building by increasing the flow rate through the whole building. The fan is applied at night-time (20:00 to 8:00) with the assigned speed of 30ACH. As shown in Figure 5.30, the reduction of mean and minimum air temperature in the master bedroom are slightly larger than that in the case of master bedroom forced ventilation. The reduction of mean and minimum air temperature in the master bedroom is about 1.0°C and 1.3°C, respectively. However, similar to the previous case (master bedroom forced ventilation), the reduction of maximum air temperature is not as large as the mean and minimum air temperature. The reduction of the maximum air temperature in the master bedroom is only about 0.4°C. The cooling effects in the spaces on the ground floor is smaller than the room at the first floor. There is almost no reduction of mean air temperature in the living hall. Meanwhile the minimum air temperature is lower by only about 0.3°C compared to the base case. As for the maximum air temperature of the living hall, the reduction is about 0.2°C.

The temporal variations of OT in the master bedroom and the living hall is shown in Figure 5.31. Similar to the air temperature, the reduction of OT can be seen only in the night-time where the OT reduction is up to 1°C compared to the base case. In contrast, no significant reduction of OT in the living hall. As a result, the OT in the master bedroom and the living hall exceeds the comfort limit by about 51% and 44% respectively.

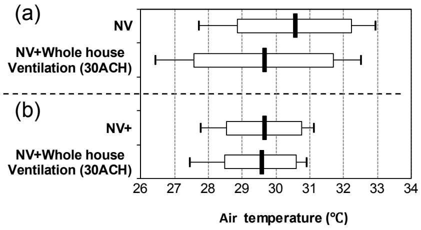


Figure 5.30. Statistical summary (5th and 95th percentiles, mean ± 1 standard deviation) of simulated air temperature under night ventilation with whole house ventilation in (a) master bedroom (b) living hall.

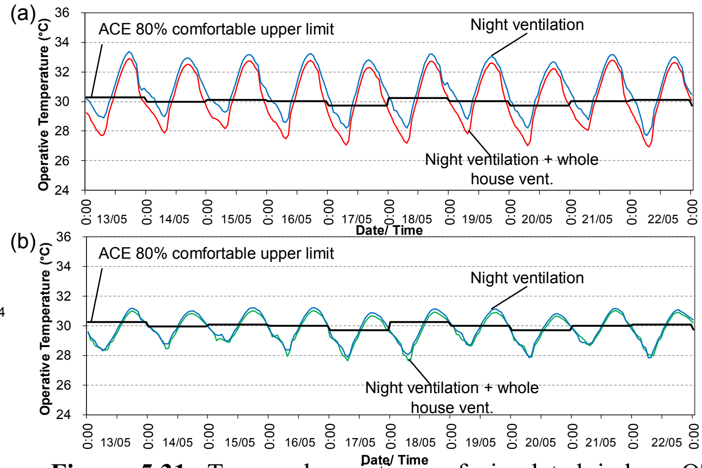


Figure 5.31. Temporal variations of simulated indoor OT with the corresponding temperature limits of thermal comfort under night ventilation with whole house ventilation in (a) master bedroom and (b) living hall.

5.8.1.12 Summary: comparison of different passive cooling techniques

Figure 5.32 present the statistical summary of simulated indoor OT in the master bedroom and the living hall with the corresponding thermal comfort (ACE) 80% upper limits under structural cooling strategy (night ventilation) each respective modification techniques. As shown in Figure 5.32a, the modifications for roof are generally highly effective in reducing the maximum temperature in the master bedroom. This is mainly because the master bedroom is located on the first floor below the roof. In particular, the high-reflective roof coating is found to reduce the maximum temperature the most by approximately 1.1°C, followed by roof insulation (1.0°C) and ceiling insulation (0.9°C). Meanwhile, the outside insulation for external wall merely reduces the maximum temperature by approximately 0.3°C though there is almost no cooling effect for the inside insulation. Among the modifications for windows considered in this analysis, the external shading gives the largest cooling effect for the maximum temperature, which is 0.9°C, followed by the low-E glass and internal shading. Forced ventilation techniques are effective in reducing nocturnal operative temperature in particular. As shown, the whole house ventilation reduces the minimum temperature by approximately 0.8°C, while it reduces maximum temperature of the next day due to the structural cooling effect by approximately 0.4°C.

Similar to the situation of the master bedroom, the application of roof coating show slightly better reduction of maximum operative temperature in the living hall compared to the other techniques for roof (Figure 5.32b). The maximum reduction of operative temperature is about 0.3°C. As for modification of the wall, the application of insulation at the outer surface of external wall shows better performance than that of internal surface where the reduction operative temperature is about 0.6°C. From all modification techniques, the application of external shading provided the most reduction of maximum and minimum operative temperature in the living hall. The daytime operative temperature reduction is about 0.8°C, while the nocturnal operative temperature reduction is about 0.3°C. In contrast to the condition of the master bedroom, there are almost no reduction of minimum operative temperature provided by the forced ventilation modification techniques. However, small reduction of maximum operative temperature is observed when the whole house ventilation is applied. The reduction is about 0.2°C.

In summary, it can be seen that several modification techniques are able to reduce the maximum and minimum operative temperature in both spaces. However, depending on single techniques alone is not sufficient to maintain the cooling effects in those spaces during the whole day. This is because some of techniques could only lowering the maximum operative temperature while the other could only lowering the minimum operative temperature. Therefore, the resultant of maximum operative temperature of master bedroom and the living spaces are largely exceeding the upper limit of thermal comfort ACE 80% upper limits). Therefore, the investigation to obtain the optimum combination between each modification techniques is required to improve the thermal comfort in the modern houses.

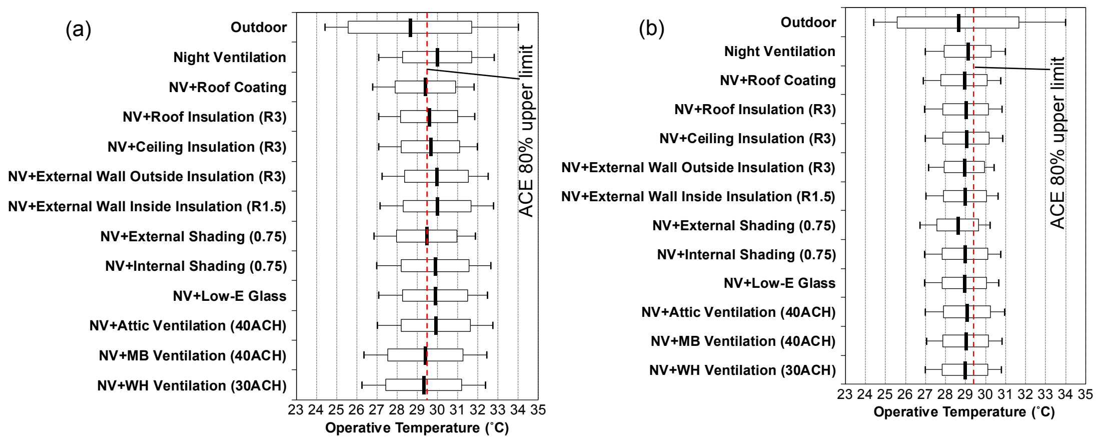


Figure 5.32. Statistical summary (5th and 95th percentiles, mean and ±one standard deviation) of simulated indoor operative temperatures under night ventilation in (a) master bedroom; (b) living hall

5.8.2 Combined techniques

As discussed in the previous section, it was found that it is difficult to achieve indoor thermal comfort by applying only a single passive cooling technique. Therefore, in this section, we determined the optimum combination of modification techniques that can provide an acceptable level of comfort in the modern urban houses. In general, the occupants in the Malaysian terraced houses tend to stay in the living hall (ground floor) during the daytime and uses bedroom during night-time. The optimum combinations were determined to reduce the nocturnal operative temperature in the master bedroom as much as possible, while minimizing the exceeding period in the living room, which is the duration when the resulting operative temperature exceeds the required adaptive comfort limit given by the Adaptive Comfort Equation (ACE). Based on the above assumption, we determined the optimum combinations by the means of Design of Experiment (DOE). The purpose of the Design of Experiment is to reduce the number of experiments (combinations) to a practical level.

The DOE is a body of knowledge and techniques that enables an investigator to conduct better experiments from the analysis and the original objectives of the investigation (Jeff Wu *et al.,* 2009). This technique was first proposed by R.A. Fisher in the 1930s at the Rothamsted Agricultural Experimental Station in the United Kingdom. Fisher's work and the notable contributions by F. Yates and D.J. Finney were motivated by problems in agriculture and biology. Since the nature of agricultural experiments tends to be in a large scale, it will take long time to be completed especially when considering the variations in the field. Such considerations led to the development of blocking, randomization, replication, orthogonality, and the use of analysis of variance and fractional factorial design.

There are several methods in the DOE analysis, i.e. one-way layout, two-way layout, multiple comparisons and orthogonal design. The orthogonal designs are often employed in industrial experiments to study the effects of several control factors. This technique stipulates the way of conducting the minimal number of experiments which could give the full information on all the factors that affect the performance parameter. Since we are considering various passive cooling techniques in this study, the resultant number of the possible combinations is more than 30 million cases. Therefore, we adopt orthogonal design as a method to select the most effective techniques.

Table 5.7 shows the orthogonal array of L32 (2^{31}) used for the experiments (L means Latin squares). The numerical simulations were conducted to obtain the nocturnal mean operative temperature of the master bedroom and the exceeding period in the living hall at the daytime are simulated based on the combinations of passive cooling techniques as shown in Table 5.6. In this analysis, we set the factor and levels, which is present or absent of the factor. For example, all factors are applied to simulation model in line No. 1.

Table 5.7. Orthogonal array of L32 (2^{31}) assigned passive cooling techniques.

Experiment	Column 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
3	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2
4	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1
5	1	1	1	2	2	2	2	1	1	1	1	2	2	2	2	1	1	1	1	2	2	2	2	1	1	1	1	2	2	2	2
6	1	1	1	2	2	2	2	1	1	1	1	2	2	2	2	2	2	2	2	1	1	1	1	2	2	2	2	1	1	1	1
7	1	1	1	2	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	1	1	1	1
8	1	1	1	2	2	2	2	2	2	2	2	1	1	1	1	2	2	2	2	1	1	1	1	1	1	1	1	2	2	2	2
9	1	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1	1	2	2
10	1	2	2	1	1	2	2	1	1	2	2	1	1	2	2	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1	1
11	1	2	2	1	1	2	2	2	2	1	1	2	2	1	1	1	1	2	2	1	1	2	2	2	2	1	1	2	2	1	1
12	1	2	2	1	1	2	2	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1	1	1	1	2	2	1	1	2	2
13	1	2	2	2	2	1	1	1	1	2	2	2	2	1	1	1	1	2	2	2	2	1	1	1	1	2	2	2	2	1	1
14	1	2	2	2	2	1	1	1	1	2	2	2	2	1	1	2	2	1	1	1	1	2	2	2	2	1	1	1	1	2	2
15	1	2	2	2	2	1	1	2	2	1	1	1	1	2	2	1	1	2	2	2	2	1	1	2	2	1	1	1	1	2	2
16	1	2	2	2	2	1	1	2	2	1	1	1	1	2	2	2	2	1	1	1	1	2	2	1	1	2	2	2	2	1	1
17	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
18	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1
19	2	1	2	1	2	1	2	2	1	2	1	2	1	2	1	1	2	1	2	1	2	1	2	2	1	2	1	2	1	2	1
20	2	1	2	1	2	1	2	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	1	2	1	2	1	2	1	2
21	2	1	2	2	1	2	1	1	2	1	2	2	1	2	1	1	2	1	2	2	1	2	1	1	2	1	2	2	1	2	1
22	2	1	2	2	1	2	1	1	2	1	2	2	1	2	1	2	1	2	1	1	2	1	2	2	1	2	1	1	2	1	2
23	2	1	2	2	1	2	1	2	1	2	1	1	2	1	2	1	2	1	2	2	1	2	1	2	1	2	1	1	2	1	2
24	2	1	2	2	1	2	1	2	1	2	1	1	2	1	2	2	1	2	1	1	2	1	2	1	2	1	2	2	1	2	1
25	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1
26	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1	2	1	1	2	2	1	1	2	2	1	1	2	2	1	1	2
27	2	2	1	1	2	2	1	2	1	1	2	2	1	1	2	1	2	2	1	1	2	2	1	2	1	1	2	2	1	1	2
28	2	2	1	1	2	2	1	2	1	1	2	2	1	1	2	2	1	1	2	2	1	1	2	1	2	2	1	1	2	2	1
29	2	2	1	2	1	1	2	1	2	2	1	2	1	1	2	1	2	2	1	2	1	1	2	1	2	2	1	2	1	1	2
30	2	2	1	2	1	1	2	1	2	2	1	2	1	1	2	2	1	1	2	1	2	2	1	2	1	1	2	1	2	2	1
31	2	2	1	2	1	1	2	2	1	1	2	1	2	2	1	1	2	2	1	2	1	1	2	2	1	1	2	1	2	2	1
32	2	2	1	2	1	1	2	2	1	1	2	1	2	2	1	2	1	1	2	1	2	2	1	1	2	2	1	2	1	1	2
Element	e	e	e	e	e	e	e	e	e	e	e	e	e	e	e	A	B	C	D	E	F	G	H	I	J	K	e	e	e	e	e

e = Error term
1: Presence
2: Absence

A: Roof Insulation (R=3)
B: Ceiling Insulation (R=3)
C: External Wall Insulation Outside Surface (R=3)
D: External Wall Insulation Inside Surface (R=1.5)
E: External Shading (SF=0.75)
F: Internal Shading (SF=0.75)
G: Low-E Glass
H: High Reflective Roof Coating
I: Attic Ventilation Fan (40ACH)
J: MB Ventilation Fan (40ACH)
K: Whole House Ventilation Fan (30ACH)

Basically, suitable orthogonal arrays for an experiment is selected by considering the number of factors and the number of experiments (L). However, if the orthogonal array of L16 (2^{15}) is used for eleven factors (number of passive cooling techniques), a mutual interaction between two factors and a main effect of factor are confounded. This condition tends to cause an inaccuracy of the analysis and confusion. In order to avoid this problem, instead, we use the orthogonal array of L32 (2^{31}) for the eleven factors. The factors were assigned in the latter halves of columns of the orthogonal arrays. This is because the mutual interaction was not observed based on the triangular table of two-level orthogonal arrays. As shown, the orthogonal arrays have 32 experiments (lines) which represents the study cases of one orientation under the night or full-day ventilation condition.

In general, by applying all techniques would be always the best combination to achieve the acceptable indoor thermal environment in the urban houses. However, this will cost a large usage of money and resources. Therefore, in this study, we adopted from the more effective modifications to the less effective modifications accumulatively on top of the respective natural ventilation techniques. As for the master bedroom, we adopted each technique until the operative temperature of the room reduce to at least 80% from the base natural ventilation case. Meanwhile, for the living hall, the technique was adopted cumulatively until the exceeding period is reduce to 100%. The effectiveness of each modification technique was determined based on the value of the variance of error from the DOE. The larger variance indicates that the factors (techniques) have more significance impact to the reduction of operative temperature in the respective spaces. In addition to this criterion, we only selecting the most effective techniques to represent each category of application. For instance, the whole house ventilation will be selected to represent the application of forced ventilation techniques if the variance is larger than the other types of forced ventilation techniques.

Figure 5.33a show the calculated variance from the DOE analysis in the master bedroom under the night ventilation condition. As shown, in the master bedroom, the whole house ventilation fan indicates the largest variance (1.890) compared to the other techniques. The list continues from the master bedroom ventilation fan (1.243) until the least effective techniques which is the internal shading with the variance of 0.014. In this case, the whole house ventilation, external shading and external wall insulation of internal surface were selected to represent the application of forced ventilation, techniques for the window and techniques for the wall respectively. Special consideration was given for the modification of roof where the roof insulation was selected instead of the high reflective roof coating. This is because the high reflective roof coating is believed to have low durability compared to the roof insulation (rock wool).

Figure 5.34a shows the result of combined passive cooling modifications and the cumulative proportion of the operative temperature reduction in the master bedrooms under the night ventilation condition. As shown, the nocturnal mean operative temperature of the master bedroom reduced by 0.86°C, which represents 44% of the cumulative reduction of all techniques after the whole house ventilation is applied. The application of the external shading device further reduces the operative temperature by 0.27°C and increase the cumulative reduction to 55%. The nocturnal operative temperature further reduces by up to 0.42°C when the external wall insulation of inside surface and the roof insulation are included in the combination. The low-e glass was added into the combination as the secondary modification for the windows to achieve the total reduction of cumulative proportion of 83%.

Figure 5.33b show the calculated variance from the DOE analysis in the living hall under the night ventilation condition. As shown, in the living hall, the external shading indicates the largest variance (1149.614) compared to the other techniques. The list continues from the internal shading device (403.104) until the least effective techniques which is the ceiling insulation with the variance of 3.074. In this case, the external shading and external wall insulation of outside surface were selected to represent the application for the window and for the wall respectively. In this case, the forced ventilation techniques are not selected due to their effects is not significant in reducing the exceeding period in the living hall. Similar to the condition of the master bedroom, special consideration was given for the modification of roof where the roof insulation was selected instead of the high reflective roof coating.

Figure 5.34b shows the result of combined passive cooling modifications and the cumulative proportion of the operative temperature reduction in the living hall under the night ventilation condition. As shown, the exceeding period reduced to 18% after the application of the external shading devices. The exceeding period reduce to almost none (0%) after the external wall insulation of outside surface and the roof insulation are included in the modification. This indicates that the exceeding period in the living hall can be reduced by 100% if these techniques are applied together.

As shown in Fig. 5.35a, the nocturnal operative temperature is reduced the most by adding the whole house ventilation to the night ventilation in the master bedroom with the reduction of up to 0.8°C at night and 0.4°C during daytime. The next option is the external shading, which reduces the nocturnal operative temperature further by 0.2°C as well as reduce the daytime peak operative temperature by 0.9°C, followed by external outside insulation and low-E glass. As for the living room, the external shading is better able to reduce the maximum operative temperature with the specific reduction of about 0.6°C (Fig. 5.35b). The external outside insulation was chosen as the next option, followed by the roof insulation

(a)

	Factor	(V)
1	Whole House Ventilation Fan(30ACH)	1.890
2	Master Bedroom Ventilation Fan(40ACH)	1.243
3	External Shading (SF=0.75)	0.808
4	High Reflective Roof Coating	0.162
5	External Wall Insulation Inside Surface(R=1.5)	0.124
6	External Wall Insulation Outside Surface(R=3)	0.092
7	Low-E Glass	0.083
8	Ceiling Insulation(R=3)	0.074
9	Roof Insulation(R=3)	0.058
10	Attic Ventilation Fan(40ACH)	0.042
11	Internal Shading (SF=0.75)	0.014

(b)

	Factor	(V)
1	External Shading (SF=0.75)	1149.614
2	Internal Shading (SF=0.75)	403.104
3	External Wall Insulation Outside Surface(R=3)	233.414
4	External Wall Insulation Inside Surface(R=1.5)	180.219
5	Low-E Glass	171.399
6	High Reflective Roof Coating	146.265
7	Whole House Ventilation Fan(30ACH)	39.050
8	Master Bedroom Ventilation Fan(40ACH)	21.910
9	Roof Insulation(R=3)	12.199
10	Attic Ventilation Fan(40ACH)	6.464
11	Ceiling Insulation(R=3)	3.704

Figure 5.33. Variance from design of experiments under the night ventilation condition in (a) master bedroom and (b) living room.

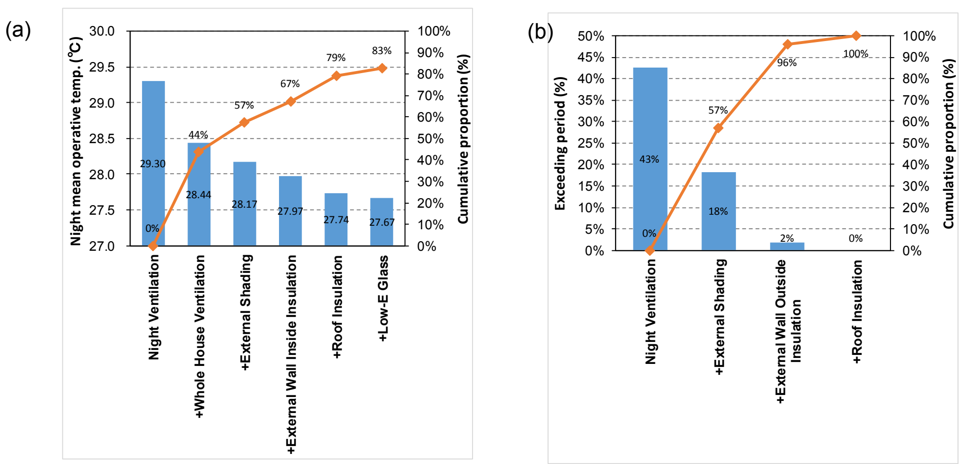


Figure 5.34. Effects of combined passive cooling techniques and cumulative proportion under the night ventilation condition in (a) master bedroom and (b) living room.

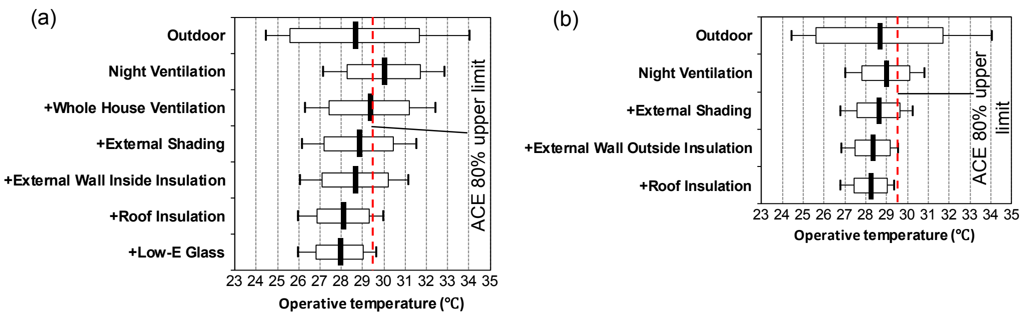


Figure 5.35. Statistical summary (5th and 95th percentiles, mean and ±one standard deviation) of simulated indoor operative temperatures under night ventilation in (a) master bedroom and (b) living hall.

5.9 Results: Comfort ventilation strategy (full-day ventilation)

5.9.1 Single techniques

The results of full-day natural ventilation can be seen in section 5.7. In general, indoor air temperature rise when full day was applied. However, in the same time the relative humidity will became relatively lower compared to that of night ventilation. Similar to the previous section, in this section, we investigate the effects of each techniques under full-day ventilation to investigate whether the operative temperature of the selected spaces is able to be reduced.

5.9.1.1 Effects of roof insulation

Figure 5.36 shows the statistical summary of air temperature in the master bedroom and the living hall under the full-day ventilation with and without the roof insulation techniques. As shown, the maximum air temperature of the master bedroom with the roof insulation is slightly lower than the base model by about 0.3°C. Similar to the case of night ventilation, the air temperature of the living hall is lower than that of master bedroom. There is almost no reduction of air temperature in the living hall when the roof insulation is applied. The maximum air temperature in the living hall is reduced by less than 0.2°C. Meanwhile, it was found that there is no significant reduction of nocturnal air temperatures in both spaces after the application of roof insulation.

Figure 5.37 shows the resultant of calculated operative temperature in the master bedrooms and living hall with and without the roof insulation. Similarly, to the results of air temperature, the maximum operative in the master bedrooms with the roof insulation is lower by up to 0.3°C compared to that of without the roof insulation. Meanwhile, there are almost no difference of operative temperature in the living hall during before and after the application of the roof insulation. The calculated exceeding period of the master bedroom and the living hall with the roof insulation strategy is about 67% and 55%, respectively.

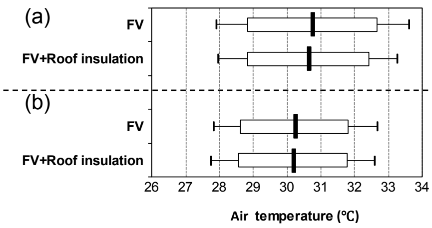


Figure 5.36. Statistical summary (5th and 95th percentiles, mean ± 1 standard deviation) of simulated air temperature under full-day ventilation with roof insulation in (a) master bedroom (b) living hall.

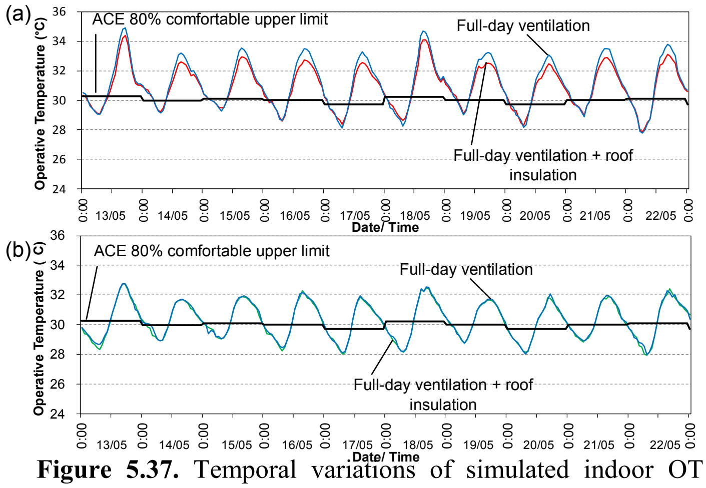


Figure 5.37. Temporal variations of simulated indoor OT with the corresponding temperature limits of thermal comfort under full-day ventilation with roof insulation in (a) master bedroom and (b) living hall.

5.9.1.2 Effects of ceiling insulation

Figure 5.38 shows the statistical summary of air temperature in the master bedroom and the living hall under the full-day ventilation with and without the ceiling insulation. As shown, the air temperature in the master bedroom and the living hall are almost similar with the case of roof insulation in daytime and night-time. The air temperature reduction only observed at the master bedroom during the daytime where the air temperature is about 0.3°C lower than the case without ceiling insulation.

Figure 5.39 shows the resultant of calculated operative temperature in the master bedrooms and living hall with and without the roof insulation. The calculated exceeding period in the master bedroom and the living hall with the ceiling insulation strategy is about 67% and 57%, respectively.

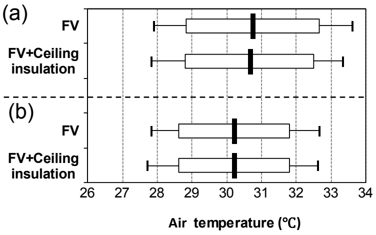


Figure 5.38. Statistical summary (5th and 95th percentiles, mean ± 1 standard deviation) of simulated air temperature under full-day ventilation with ceiling insulation in (a) master bedroom (b) living hall.

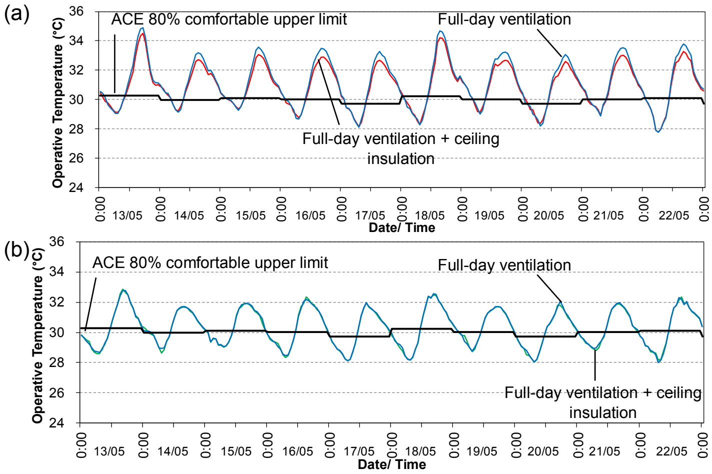


Figure 5.39. Temporal variations of simulated indoor OT with the corresponding temperature limits of thermal comfort under full-day ventilation with ceiling insulation in (a) master bedroom and (b) living hall.

5.9.1.3 Effects of high reflectivity roof coating

Figure 5.40 shows the statistical summary of air temperature in the master bedroom and the living hall under the full-day ventilation with and without the high reflectivity roof coating. Similar to the other techniques for the roof, the effects of roof coating can only be seen in the master bedroom where the maximum air temperature is reduced by about 0.4°C compare to the base case. The minimum air temperature of the master bedroom is also lower than the base case by about 0.2°C. As shown in the figure, there is no significant reduction of air temperature in the living hall during the daytime and night-time. The calculated exceeding period of the operative temperature in the master bedroom and the living hall with the high reflectivity roof coating is about 63% and 55%, respectively (Figure 5.41).

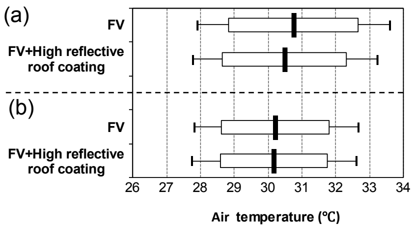


Figure 5.40. Statistical summary (5th and 95th percentiles, mean ± 1 standard deviation) of simulated air temperature under full-day ventilation with reflective roof coating in (a) master bedroom (b) living hall.

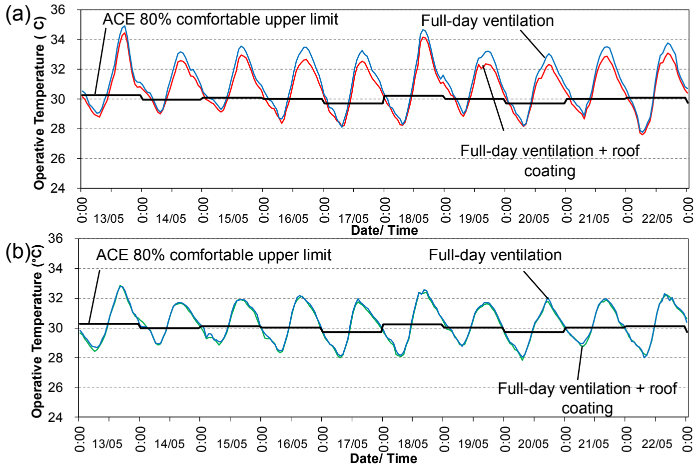


Figure 5.41. Temporal variations of simulated indoor OT with the corresponding temperature limits of thermal comfort under full-day ventilation with reflective roof coating in (a) master bedroom and (b) living hall.

5.9.1.4 Effects of external wall (outside surface) insulation

Figure 5.42 shows the statistical summary of air temperature in the master bedroom and the living hall under the full-day ventilation with and without the external wall insulation of the outside surface. In this case, it was found that there is only slight reduction of maximum air temperature in the master bedroom and the living hall. The maximum air temperature reduction in both spaces is about 0.1°C which is quite minimal. There is no difference of mean air temperature difference in both spaces compared to the condition without the external wall insulation. Meanwhile, at the night-time, the minimum air temperature of the master bedroom with the external insulation is slightly higher than the case without the insulation which is about 0.2°C. This is probably because the external wall insulation at the outside surface retards the heat transfer rate from the wall to outside air. Meanwhile, the nocturnal air temperature in the living hall with the external wall insulation of outside surface is almost the same with the base condition where the minimum air temperature is about 27.8°C.

Figure 5.43 shows the temporal variation of operative temperature in the master bedrooms and living hall with and without the external wall insulation of outside surface. The calculated exceeding period in the master bedroom and the living hall with this modification techniques is about 71% and 53%, respectively. This indicates that the exceeding period in the master bedroom has slightly increased compared to the case of roof modification techniques.

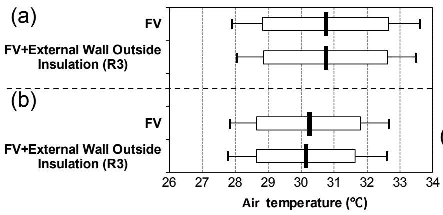


Figure 5.42. Statistical summary (5th and 95th percentiles, mean ± 1 standard deviation) of simulated air temperature under full-day ventilation with external wall (out) in (a) master bedroom (b) living hall.

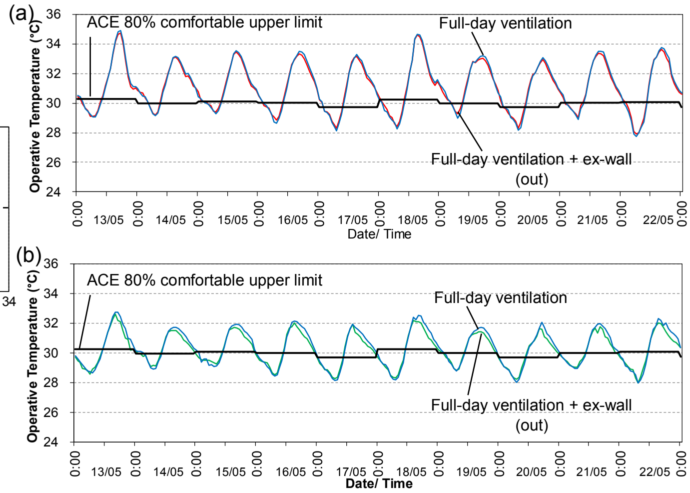


Figure 5.43. Temporal variations of simulated indoor OT the corresponding temperature limits of thermal comfort under full-day ventilation with external wall (out) in (a) master bedroom and (b) living hall.

5.9.1.5 Effects of external wall (inside surface) insulation

In this case, the insulation is applied on the internal surface of the external insulation. Figure 5.44 shows the statistical summary of air temperature in the master bedroom and the living hall under the full-day ventilation with and without the insulation. As shown, there are almost no significant difference between the air temperature of before and after the insulation is applied in both spaces. The only reduction is observed on the night-time in the living hall where the minimum air temperature is lower than the base case by about 0.2°C. This indicates that the internal insulation could not contribute in lowering the maximum and mean air temperature in both spaces.

Figure 5.45 shows the temporal variation of operative temperature in the master bedrooms and living hall with and without the external wall insulation of inside surface. The calculated exceeding period in the master bedroom and the living hall with this modification techniques is about 68% and 53%, respectively. It should be noted that the exceeding period of the master bedroom in this case is slightly lower than that of previous case which using the external wall insulation of the outer surface.

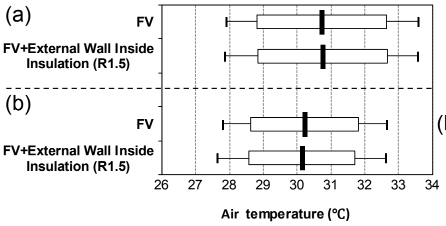


Figure 5.44. Statistical summary (5th and 95th percentiles, mean ± 1 standard deviation) of simulated air temperature under full-day ventilation with external wall (in) in (a) master bedroom (b) living hall.

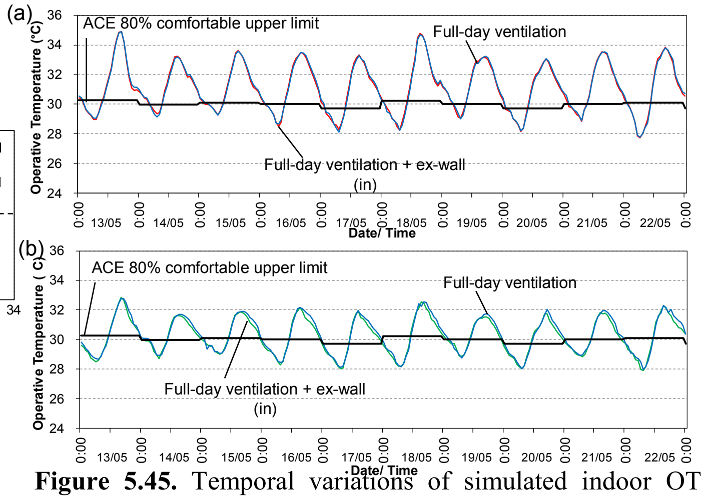


Figure 5.45. Temporal variations of simulated indoor OT with the corresponding temperature limits of thermal comfort under full-day ventilation with external wall (in) in (a) master bedroom and (b) living hall.

5.9.1.6 Effects of external window shading

In this case, the external shading device for window is applied to the simulation model in addition to the full-day ventilation condition. Figure 5.46 shows the statistical summary of air temperature in the master bedroom and the living hall under the full-day ventilation with and without the external shading device. The result shows that the maximum air temperature in master bedroom and the living hall are slightly reduced after the application of the external shading device. The maximum air temperature reduction is about 0.3°C and 0.4°C in the master bedroom and the living hall, respectively. The mean air temperature in both spaces are also reduced by about 0.1°C. Meanwhile in the night-time, the minimum air temperature reduction could only be seen in the living hall where the reduction is about 0.1°C lower than the base case.

The exceeding period of operative temperature in the master bedroom and the living hall after the application of the external shading device is about 64% and 51%, respectively (Figure 5.47).

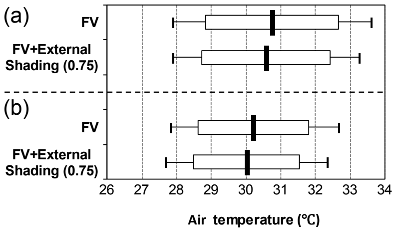


Figure 5.46. Statistical summary (5^{th} and 95^{th} percentiles, mean ± 1 standard deviation) of simulated air temperature under full-day ventilation with window shading (out)in (a) master bedroom (b) living hall.

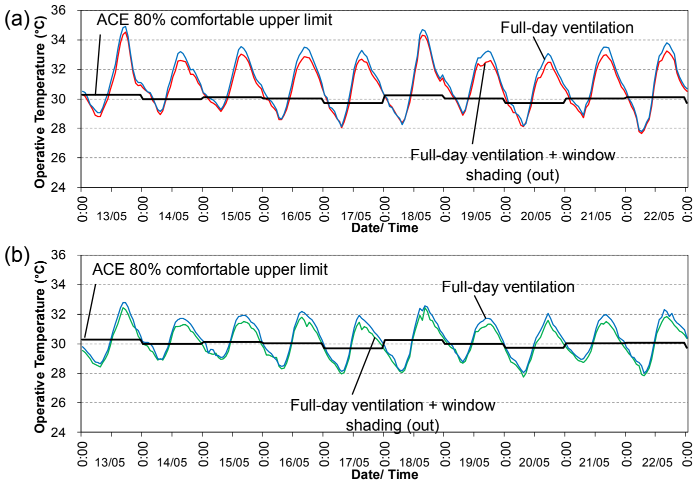


Figure 5.47. Temporal variations of simulated indoor OT with the corresponding temperature limits of thermal comfort under full-day ventilation with window shading (out) in (a) master bedroom and (b) living hall.

5.9.1.7 Effects of internal window shading

Figure 5.48 shows the statistical summary of air temperature in the master bedroom and the living hall under the full-day ventilation with and without the internal shading device. As shown, there are no cooling effects observed in both spaces during the daytime and night-time after the application of the internal shading. This is because the solar radiation has already transmitted through the windows opening before it is block by the internal shading. In addition, the infiltrations of warm air during the daytime increase the air temperature in both spaces. On the daytime, the maximum air temperature in the master bedroom and the living hall is about 33.6°C and 32.6°C, respectively.

In this case, the calculated exceeding period in the master bedroom and the living hall is slightly larger than that of when external shading device is applied. The operative temperature in the master bedroom and the living hall exceeds the 80% upper limits of ACE thermal comfort by about 66% and 54%, respectively (Figure 5.49).

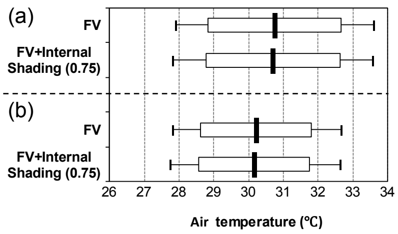


Figure 5.48. Statistical summary (5th and 95th percentiles, mean ± 1 standard deviation) of simulated air temperature under full-day ventilation with window shading (in) in (a) master bedroom (b) living hall.

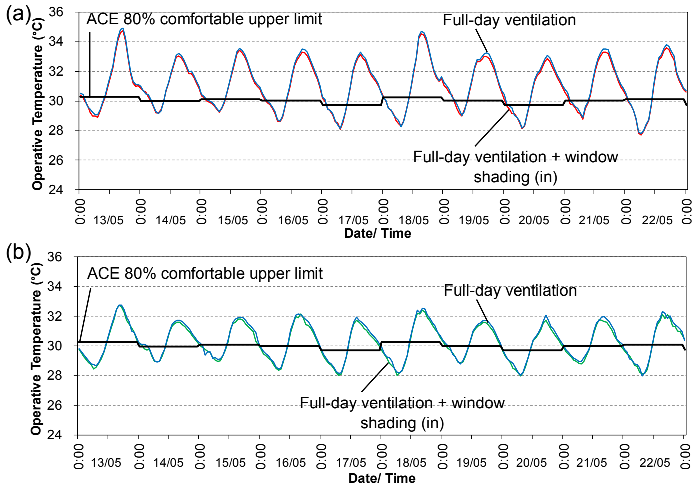


Figure 5.49. Temporal variations of simulated indoor OT with the corresponding temperature limits of thermal comfort under full-day ventilation with window shading (in) in (a) master bedroom and (b) living hall.

5.9.1.8 Effects of Low-E glass

Figure 5.50 shows the statistical summary of air temperature in the master bedroom and the living hall under the full-day ventilation with and without the internal shading device. As expected, there are no cooling effects provide by the low-e glass. This is simply because the windows are opened during the full-day ventilation condition. Therefore, the solar radiation is not filtered by the low-e glass windows. There is also no difference of operative temperature between the case of with and without the low-e glass windows (Figure 5.51).

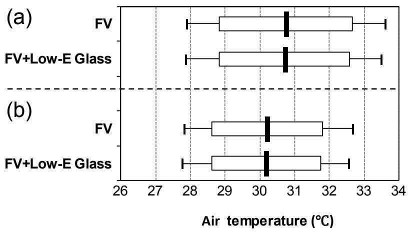


Figure 5.50. Statistical summary (5th and 95th percentiles, mean ± 1 standard deviation) of simulated air temperature under full-day ventilation with Low-E glass in (a) master bedroom (b) living hall.

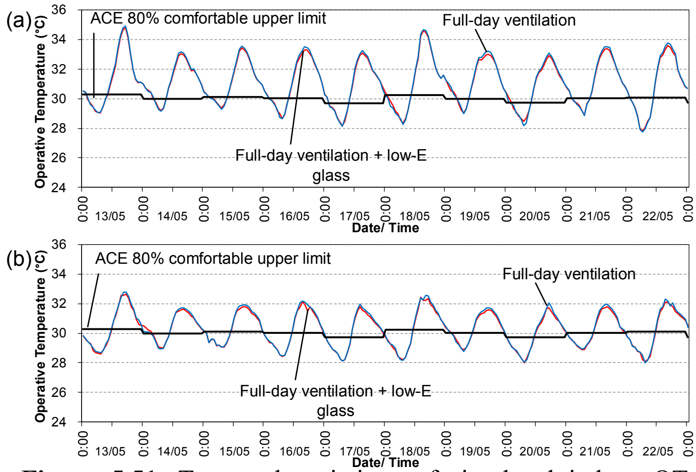


Figure 5.51. Temporal variations of simulated indoor OT with the corresponding temperature limits of thermal comfort under full-day ventilation with Low-E glass in (a) master bedroom and (b) living hall.

5.9.1.9 Effects of attic forced ventilation

From this section on, the forced ventilation modification is applied to strengthen the structural cooling effects during the night-time. Figure 5.52 shows the statistical summary of air temperature in the master bedroom and the living hall under the full-day ventilation with and without the attic ventilation. As shown, there are almost no reduction of minimum air temperature in the master bedroom and the living hall after the application of the attic ventilation. The minimum air temperature of the master bedroom and the living hall with the attic ventilation is almost the same with the condition of without attic ventilation which is about 27.8°C. Therefore, the daytime air temperature reduction by the structural cooling effects is not observed in the following day.

Figure 5.53 shows the temporal variation of operative temperature in the master bedrooms and living hall with and without the external wall insulation of inside surface. As shown, the operative temperature of the master bedroom and the living hall with the modification are similar to that of without the modifications. The exceeding period of operative temperature in the master bedroom and the living hall after the application of the attic ventilation is about 66% and 57%, respectively.

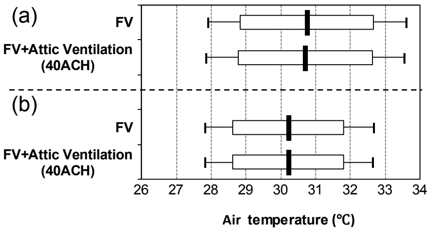


Figure 5.52. Statistical summary (5th and 95th percentiles, mean ± 1 standard deviation) of simulated air temperature under full-day ventilation with attic ventilation in (a) master bedroom (b) living hall.

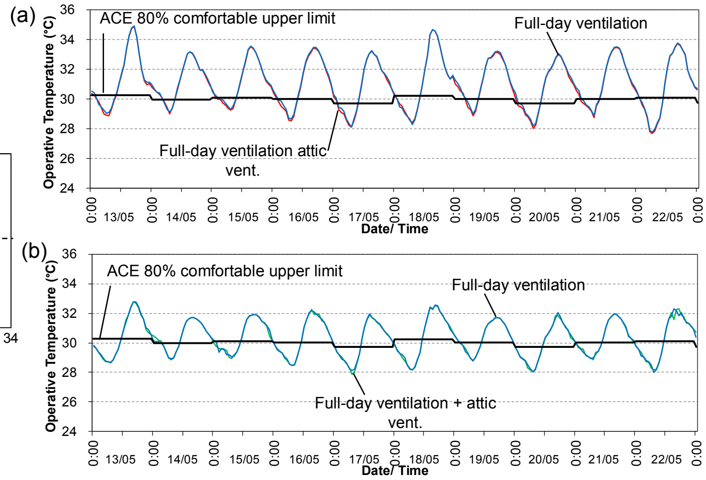


Figure 5.53. Temporal variations of simulated indoor OT with the corresponding temperature limits of thermal comfort under full-day ventilation with attic ventilation in (a) master bedroom and (b) living hall.

5.9.1.10 Effects of master bedroom forced ventilation

Figure 5.54 presents the statistical summary of air temperature in the master bedroom and the living hall under the full-day ventilation with and without the master bedroom ventilation fan. In contrast to the case with the attic ventilation, the reduction of minimum air temperature of master bedroom and the living hall can be seen when the master bedroom ventilation fan is applied. In the master bedroom, the reduction of the minimum air temperature is about 1.3°C compared to the base case. Meanwhile, the reduction of minimum air temperature in the living hall is smaller which is about 0.1°C. This is simply because the fan is located at the master bedroom and directly improve the nocturnal air temperature in that spaces. However, the reduction of maximum air temperature in the master bedroom is not large as observed in the night-time. The maximum air temperature of the master bedroom with the ventilation fan is only 0.2°C lower than the base case. This indicates that the effects of direct solar radiation and the infiltration of warm air can easily reduce the effectiveness of the structural cooling effects that was obtain through the ventilation fan. Nevertheless, the mean air temperature in the master bedroom with the ventilation fan still largely lower than the base case by about 0.7°C.

Figure 5.55 shows the temporal variation of operative temperature in the master bedrooms and living hall with and without the master bedroom ventilation under the full-day ventilation. As shown, the master bedroom fan is mostly effective in the reduction of nocturnal operative temperature in the master bedroom. The reduction of the operative in the master bedroom is up to 1.3°C compared to the base case (only with full day ventilation). However, no significant reduction observed on the daytime. Thus, the resultant exceeding period in the master bedroom is about 55%. Meanwhile, the exceeding period in the living hall is about 57% higher than the 80% upper limit of ACE thermal comfort.

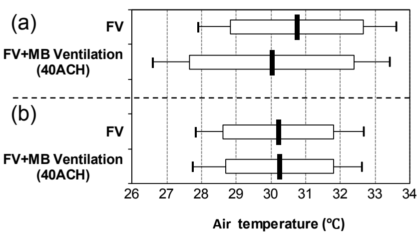


Figure 5.54. Statistical summary (5th and 95th percentiles, mean ± 1 standard deviation) of simulated air temperature under full-day ventilation with master bedroom ventilation in (a) master bedroom (b) living hall.

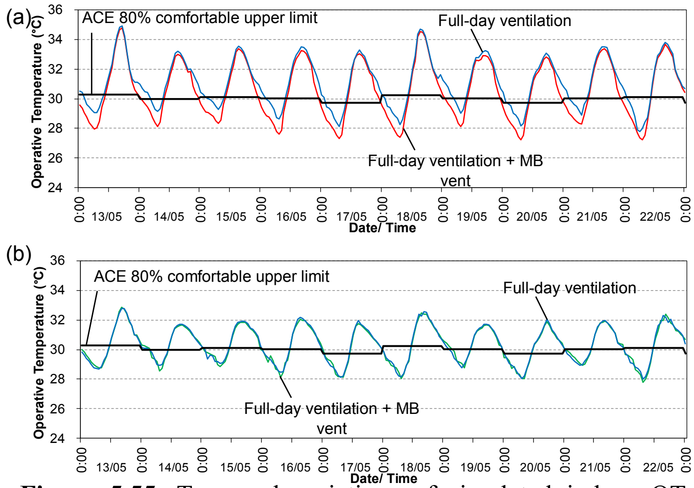


Figure 5.55. Temporal variations of simulated indoor OT with the corresponding temperature limits of thermal comfort under full-day ventilation with master bedroom ventilation in (a) master bedroom and (b) living hall.

5.9.1.11 Effects of whole house forced ventilation

Figure 5.56 presents the statistical summary of air temperature in the master bedroom and the living hall under the full-day ventilation with and without the whole house ventilation fan. As shown, the minimum air temperature in the master bedroom is largely reduce by about 1.5°C after the application of the whole house ventilation fan. Meanwhile, the cooling effects in the living hall is smaller compared to that of the master bedroom, where the minimum air temperature reduction is only about 0.1°C. Similar to the case of with the master bedroom ventilation, the maximum air temperature reduction in the master bedroom is only about 0.2°C during the daytime. Meanwhile, the maximum air temperature reduction in the living hall is about 0.1°C. This indicates that, even with the whole house ventilation being applied at the night-time, larger reduction of maximum air temperature could not be expected due to the open window condition during the daytime. Nevertheless, the average air temperature in the master bedroom is lower by about 0.5°C when the whole house ventilation is applied. Meanwhile, no reduction observed on the average air temperature in the living hall.

Figure 5.57 shows the temporal variation of operative temperature in the master bedrooms and living hall with and without the whole house ventilation under the full-day ventilation. Similar to the condition of the previous case (master bedroom ventilation), the reduction of operative temperature only occurred at the night-time in the master bedroom when the whole house ventilation is applied. In this case, the calculated exceeding period in the master bedroom and the living hall is 55% and 56%, respectively.

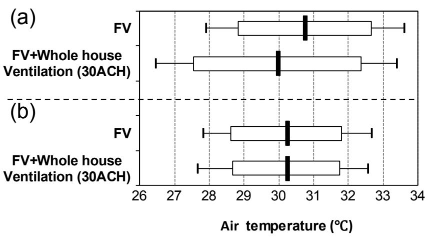


Figure 5.56. Statistical summary (5th and 95th percentiles, mean ± 1 standard deviation) of simulated air temperature under full-day ventilation with whole house ventilation in (a) master bedroom (b) living hall.

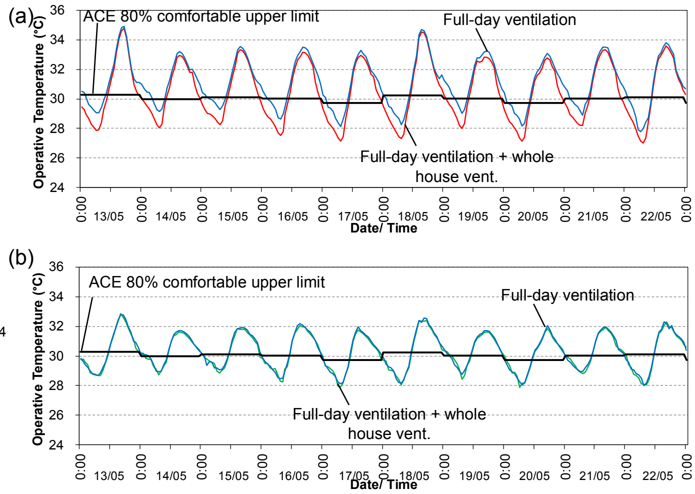


Figure 5.57. Temporal variations of simulated indoor OT with the corresponding temperature limits of thermal comfort under full-day ventilation with whole house ventilation in (a) master bedroom and (b) living hall.

5.9.1.12 Summary: comparison of different passive cooling techniques

Figure 5.58 present the statistical summary of simulated indoor operative temperature in the master bedroom and the living hall with the corresponding thermal comfort (ACE) 80% upper limits under comfort ventilation strategy (night ventilation) each respective modification techniques. Similar to the case of night ventilation, the modifications for roof are generally highly effective in reducing the maximum temperature in the master bedroom. In particular, the high-reflective roof coating and the roof insulation are found to reduce the maximum temperature the most by approximately 0.6°C, followed by ceiling insulation (0.5°C). As for the modification for the walls, the external wall of outside surface shows a slightly reduction of maximum air temperature which is about 0.2°C. Meanwhile, no reduction of maximum operative temperature observed in the case of external wall insulation of internal surface. Among the modifications for windows considered in this analysis, the external shading gives the largest cooling effect for the maximum temperature, which is 0.5°C, followed by the internal shading and low-e glass. Forced ventilation techniques are effective in reducing nocturnal operative temperature in particular. As shown, the whole house ventilation reduces the minimum temperature by approximately 0.7°C, while it reduces maximum temperature of the next day due to the structural cooling effect by approximately 0.3°C.

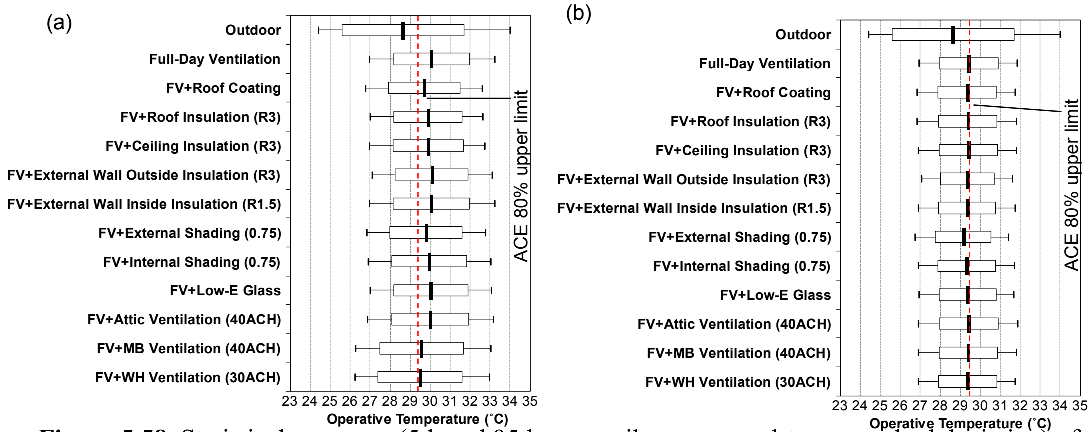


Figure 5.58. Statistical summary (5th and 95th percentiles, mean and ±one standard deviation) of simulated indoor operative temperatures under the full-day ventilation in (a) master bedroom; (b) living hall.

In the living hall, it was found that the most effective modification is by applying the external shading device. By applying this technique, the reduction of the operative temperature in the living hall is not only can be seen in the daytime but also in the night-time. The reduction of maximum and minimum operative temperature is about 0.5°C and 0.2°C, respectively. The second largest reduction is by the application of the external wall of outside insulation where the reduction is about 0.3°C. Meanwhile, the application of roof coating and low-e glass reduced the maximum operative temperature by about 0.1°C and 0.2°C, respectively. The forced ventilation techniques show almost no effects on the reduction of nocturnal operative temperature in the living hall. Nevertheless, the maximum operative temperature of the living hall is reduced by about 0.1°C when the whole house ventilation is applied

In summary, it can be seen that several modification techniques are able to reduce the maximum and minimum operative temperature in both spaces under the full-day ventilation condition. However, the effects are smaller than that of night ventilation condition. In the next section, we will investigate the optimum combination between each modification techniques are required to improve the thermal comfort in the modern houses.

5.9.2 Combined techniques

In this section, we investigate the optimum combination of the modification techniques under the full day ventilation condition. The procedure is similar to that of the night ventilation condition.

Figure 5.59a show the calculated variance from the DOE analysis in the master bedroom under the full-day ventilation condition. As shown, in the master bedroom, the whole house ventilation fan indicates the largest variance (1.269) compared to the other techniques. The list continues with the master bedroom ventilation fan (1.243) until the least effective techniques which is the low-e glass with the variance of 0.000. In this case, the whole house ventilation, external shading and external wall insulation of internal surface were selected to represent the application of forced ventilation, techniques for the window and techniques for the wall respectively. Similar to the case of night ventilation, special consideration was given for the modification of roof where the roof insulation was selected instead of the high reflective roof coating.

Figure 5.60a shows the result of combined passive cooling modifications and the cumulative proportion of the operative temperature reduction in the master bedrooms under the night ventilation condition. As shown, the nocturnal mean operative temperature of the master bedroom is reduced by 0.82°C, which represents 58% of the cumulative reduction of all techniques after the whole house ventilation is applied. The application of the external shading further reduces the operative temperature by 0.16°C and increase the cumulative reduction to 69%. The nocturnal mean operative temperature further reduces by up to 0.21°C when the external wall insulation of inside surface and the roof insulation are included in the combination. The final reduction of cumulative proportion of the operative temperature is at 84%.

Figure 5.59b show the calculated variance from the DOE analysis in the living hall under the full-day ventilation condition. As shown, in the living hall, the external shading indicates the largest variance (570.212) compared to the other techniques. The list continues from the external wall insulation of outside surface (139.449) until the least effective techniques which is the ceiling insulation with the variance of 0.028. In this case, the external shading and external wall insulation of outside surface were selected to represent the modification for the window and for the wall respectively. In this case, the whole house ventilation is selected as the third modification. Similar to the condition of the master bedroom, special consideration was given for the modification of roof where the roof insulation was selected instead of the high reflective roof coating.

Figure 5.60b shows the result of combined passive cooling modifications and the cumulative proportion of the operative temperature reduction in the living hall under the night ventilation condition. As shown, the exceeding period reduced to 43% after the application of the external shading devices. The exceeding period reduce to almost none (0%) after the external wall insulation of outside surface, whole house ventilation and the roof insulation are included in the modification. This indicates that the exceeding period in the living hall can be reduced by 100% if these techniques are applied together.

(a)

	Factor	(V)
1	Whole House Ventilation Fan(30ACH)	1.857
2	Master Bedroom Ventilation Fan(40ACH)	1.269
3	External Shading (SF=0.75)	0.184
4	High Reflective Roof Coating	0.071
5	External Wall Insulation Inside Surface(R=1.5)	0.062
6	Attic Ventilation Fan(40ACH)	0.032
7	Internal Shading (SF=0.75)	0.016
8	External Wall Insulation Outside Surface(R=3)	0.009
9	Roof Insulation(R=3)	0.007
10	Ceiling Insulation(R=3)	0.003
11	Low-E Glass	0.000

(b)

	Factor	(V)
1	External Shading (SF=0.75)	570.212
2	External Wall Insulation Outside Surface(R=3)	139.449
3	External Wall Insulation Inside Surface(R=1.5)	56.018
4	Whole House Ventilation Fan(30ACH)	35.003
5	Low-E Glass	20.595
6	Internal Shading (SF=0.75)	19.742
7	Master Bedroom Ventilation Fan(40ACH)	12.534
8	Roof Insulation(R=3)	5.989
9	High Reflective Roof Coating	5.759
10	Attic Ventilation Fan(40ACH)	0.692
11	Ceiling Insulation(R=3)	0.028

Figure 5.59. Variance from design of experiments under the full-day condition in (a) master bedroom and (b) living room

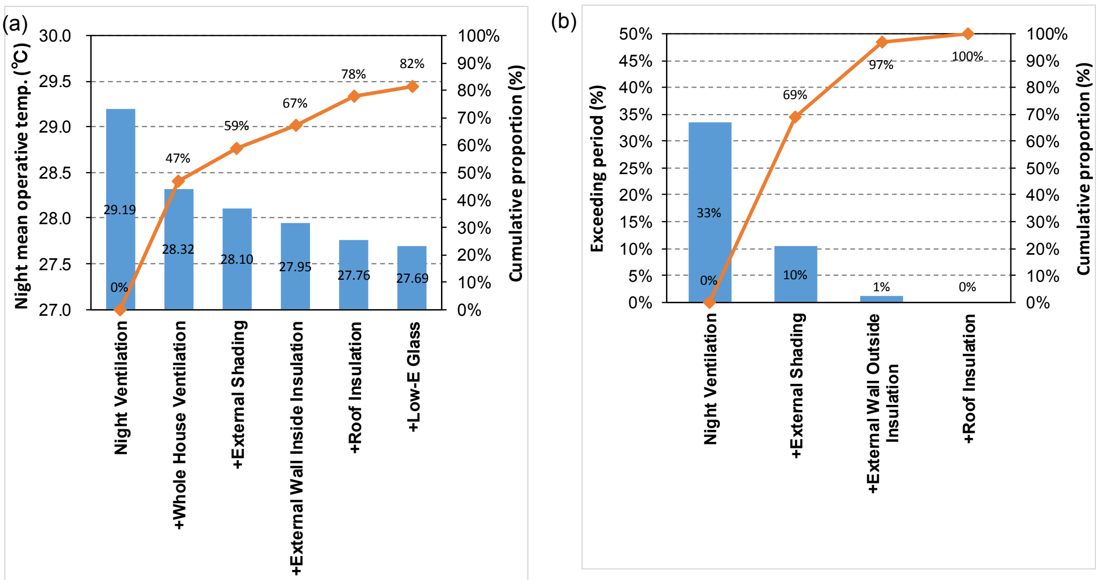


Figure 5.60. Effects of combined passive cooling techniques and cumulative proportion under the full-day ventilation condition in (a) master bedroom and (b) living room.

As shown in Figure 5.61a, the nocturnal operative temperature is reduced the most by adding the whole house ventilation to the night ventilation in the master bedroom with the reduction of up to 0.7°C at night. By the application of this modification, the maximum operative temperature is also reducing by about 0.4°C during daytime. The next option is the external shading, which reduces the nocturnal operative temperature further by 0.1°C as well as reduce the daytime peak operative temperature by 0.5°C, followed by external wall insulation of outside surface and low-E glass. As for the living room, the external shading is better able to reduce the maximum operative temperature with the specific reduction of about 0.7°C (Fig. 5.61b). The external outside insulation was chosen as the next option, followed by the roof insulation

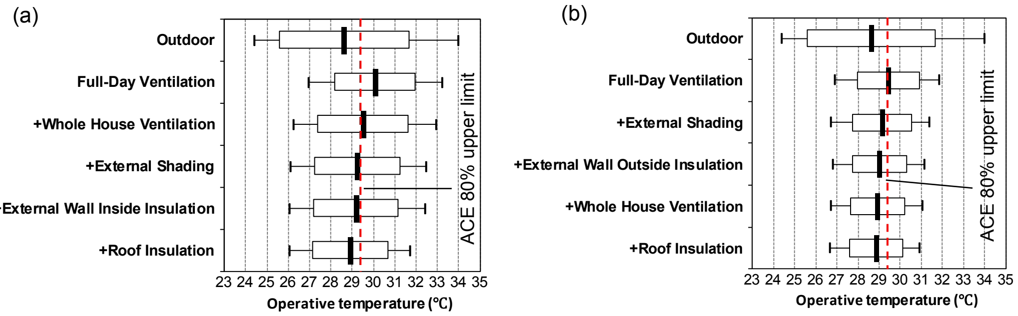


Figure 5.61. Statistical summary (5th and 95th percentiles, mean and ±one standard deviation) of simulated indoor operative temperatures under full-day ventilation in (a) master bedroom and (b) living hall.

5.10 Proposed energy-saving modifications

As shown in section 5.8.1.12 and 5.9.1.12, several modifications are relatively effective to reduce the air and operative temperature under the night and full-day ventilation condition. However, relying on the single modification alone is not enough to achieved the acceptable thermal comfort condition. Meanwhile, in section 5.8.2 and 5.9.2, the effects of combined modifications showed that the indoor operative temperature could be reduced to an acceptable comfort level. However, the results suggested a different combination of modifications in the master bedroom and the living hall. Therefore, in this section, we consider a reasonable and practical combinations of passive cooling techniques for the urban houses in Malaysia.

In the master bedroom, the optimum combination of modifications under both ventilation condition is almost similar except for the low-e glass. This is because the low-e glass is not effective to be used during the full-day ventilation condition. In general, the modifications are 1) the whole house ventilation, 2) external shading for window, 3) external wall insulation of inside surface and 4) the roof insulation. Meanwhile, in the living hall, the optimum modifications under the night and full-day ventilation are 1) external shading, external wall insulation of outside insulation and roof insulation. In addition, whole house ventilation is required for the living hall under the full-day ventilation condition.

Since both spaces are constructed as a unit of house, we combined the modification techniques between the master bedroom and the living hall. As a result, the combination of four modification techniques, including roof insulation was proposed to improve indoor thermal comfort in the Malaysian terraced houses not only for night-ventilation condition but also for full-day ventilation condition. Figure 5.62 shows the conceptual of the proposed modification techniques for the modern terraced houses in Malaysia. To be noted that the external wall insulation of outside surface was chosen instead of the internal surface because the cooling effects of the former was larger than the latter, especially in the living hall. The low-e glass can be an optional modification in addition to the above-mentioned modification since it is only affective under the night-time ventilation condition.

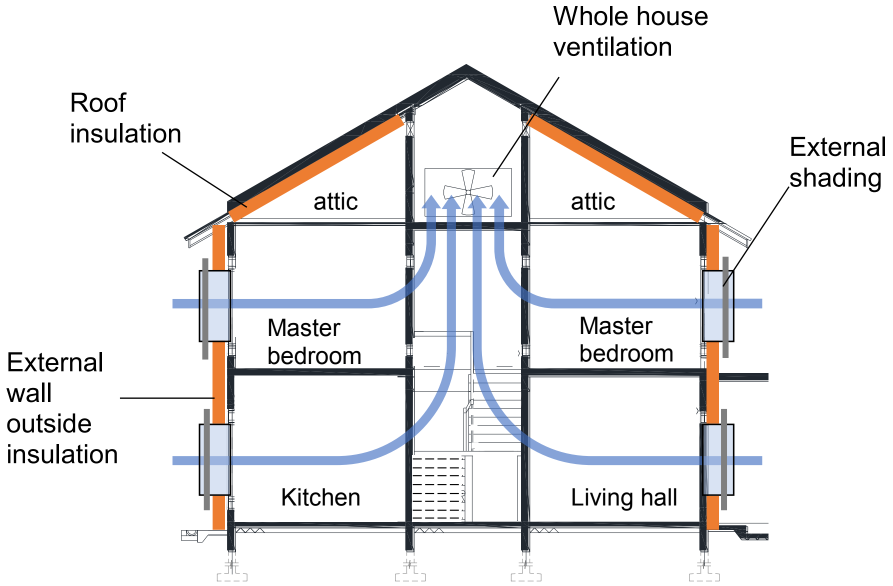


Figure 5.62. Conceptual illustration of combination of proposed passive cooling techniques for experimental houses

5.11 Summary

In this chapter, the numerical simulation programs were employed to examine the optimum combinations of modification techniques for the urban houses in the hot-humid climate of Malaysia. Two types of numerical simulation program were used which is TRNSYS and COMIS.

The simulation has been conducted to investigate the effects of the modification techniques under structural cooling (night-ventilation) and comfort ventilation (full-day ventilation) strategy. Meanwhile, the modifications techniques that were considered in the study cases covered the application of passive cooling strategies on the roof, wall, windows and the forced ventilation system. The simulation has been conducted to investigate the effect of modifications on the thermal condition of indoor spaces (i.e. master bedroom and living hall) as a single and combined techniques.

In the results of the single techniques of structural cooling strategies, it was found that the modifications for roof are generally highly effective in reducing the maximum temperature. This is mainly because the master bedroom is located on the first floor below the roof. In particular, the high-reflective roof coating is found to reduce the maximum temperature the most by approximately 1.1°C, followed by roof insulation (1.0°C) and ceiling insulation (0.9°C). Meanwhile, the outside insulation for external wall was found to be more effective than the internal insulation in reducing the maximum temperature in the master bedroom. Among the modifications for windows considered in this analysis, the external shading gives the largest cooling effect for the maximum temperature, which is 0.9°C, followed by the low-E glass and internal shading. Forced ventilation techniques by whole house ventilation is the most effective in reducing nocturnal operative temperature. The whole house ventilation reduces the minimum temperature by approximately 0.8°C, while it reduces maximum temperature of the next day due to the structural cooling effect by approximately 0.4°C.

Meanwhile, in the case of full-day ventilation, the cooling effects of respective modifications on the maximum temperatures are reduced to approximately 0.1-0.6°C compared to the former ventilation strategy. Among the techniques considered in this analysis, the external shading is found to be the most effective in reducing the maximum temperature, which records an average reduction of 0.5°C.

The simulation of combined techniques was conducted to find the optimum combinations of modification techniques to reduce the nocturnal operative temperature as much as possible in the master bedroom, whereas to minimize the exceeding period of operative temperature in the living room. For this purpose, the analysis of Design of Experiment (DOE) has been employed to simplified the number of the study cases (combination). As a result, the simulation cases has been reduced to only 32 cases in each natural ventilation condition, i.e. structural cooling and comfort ventilation strategies. In the case of structural cooling strategy, the optimum combination to reduce the nocturnal operative temperature in the master bedroom is by the application of whole house ventilation, external shading of window, external outside insulation and low-E glass where the total reduction is about 1.2°C. As for the living room, the external shading is better able to reduce the maximum operative temperature with the specific reduction of about 0.6°C. The external outside insulation was chosen as the next option, followed by the roof insulation.

In the case of comfort ventilation, the whole house ventilation is found to be the most effective in reducing the nocturnal operative temperature in the master bedroom just like the case of night ventilation, followed by the external shading, external wall outside insulation and roof insulation. As for the living room, the external shading is found to be the most effective, followed by the external wall outside insulation, the whole house ventilation and roof insulation.

The optimum combinations of energy-saving modifications for the experimental houses were determined by combining the optimum combinations for the master bedroom and the living room. As a result, the proposed modifications include roof insulation, external wall outside insulation, external shading, and whole house ventilation. This combination would be effective not only for night ventilation condition but also for full-day ventilation condition.

6.

Full-scale experiment on energy-saving modifications for urban houses: Methods and results

6.1 Objectives

The purpose of the full-experiment is to confirm the resulting effects of the proposed energy-saving modification techniques derived from the previous simulation studies (Chapter 5). The investigation includes the evaluation of thermal comfort level of the indoor environment by standard effective temperature (SET*) which is not available in the simulation program. In order to meet the objective, the full-scale experiment was conducted in the experimental houses (two adjacent terraced houses) located in the main campus of Universiti Teknologi Malaysia (UTM), in the city of Johor Bahru (as described in Chapter 4).

6.2 Methods

The full-scale experiment was conducted in two units of the above-mentioned experimental houses from June to September 2016. In the field measurement, one of the houses (House 2) was equipped with the proposed modifications (i.e. measurement unit), while the other house (House 1) was remained unchanged as a control unit. Figure 6.1 presents the picture and the plan of the experimental houses including the location of the measurement equipment. The proposed modifications include i) roof insulation, ii) external wall insulation (outside), iii) external shading devices, and iv) forced ventilation (for the whole house and for attic spaces). Roof insulation was installed underneath the roof board of north- and south-facing master bedrooms of House 2. Meanwhile, the external wall insulation was installed on the outer surfaces of the external wall of the master bedrooms. Both insulations were of 100 mm thick rock wool form with a thermal resistance of 3 (m^2K)/W. Furthermore, the external shading devices were installed on all windows in House 2 except for the window located in the washroom. The shading factor was set to be 0.75. The windows were shaded during the daytime (8:00-20:00) and unshaded during the night-time (20:00-08:00). As for the forced ventilation, a large exhaust fan was utilized at 30 air change rates per hour (ACH) for the entire house, master bedroom fan at 40 ACH, while the attic fan was at 40 ACH. The forced ventilation system was applied only during night-time to reinforce the effect of night ventilation (structural cooling). In this measurement, the Low-E glass for windows were not included as the modification techniques. This is due to the limitation of the current design of the window's frame which is not suitable to be used with the thick Low-E glass. The summary of the modification techniques is as shown in Table 6.1.

Table 6.1. Description of the energy-saving modification strategies

Modification techniques	Details
1) Roof insulation	100mm thick of rock wool insulation, R value=3
2) External wall insulation	100mm thick of rock wool insulation, R value=3
3) External shading devices	Shading factor of 0.75 Material: Polyethylene fabric Thickness = 1 mm
4) Forced ventilation	a) Whole house ventilation fan at the speed of 30 ach b) Master bedroom supply fan at the speed of 40 ach c) Attic exhaust fan at the speed of 40 ach

(a)

(b)

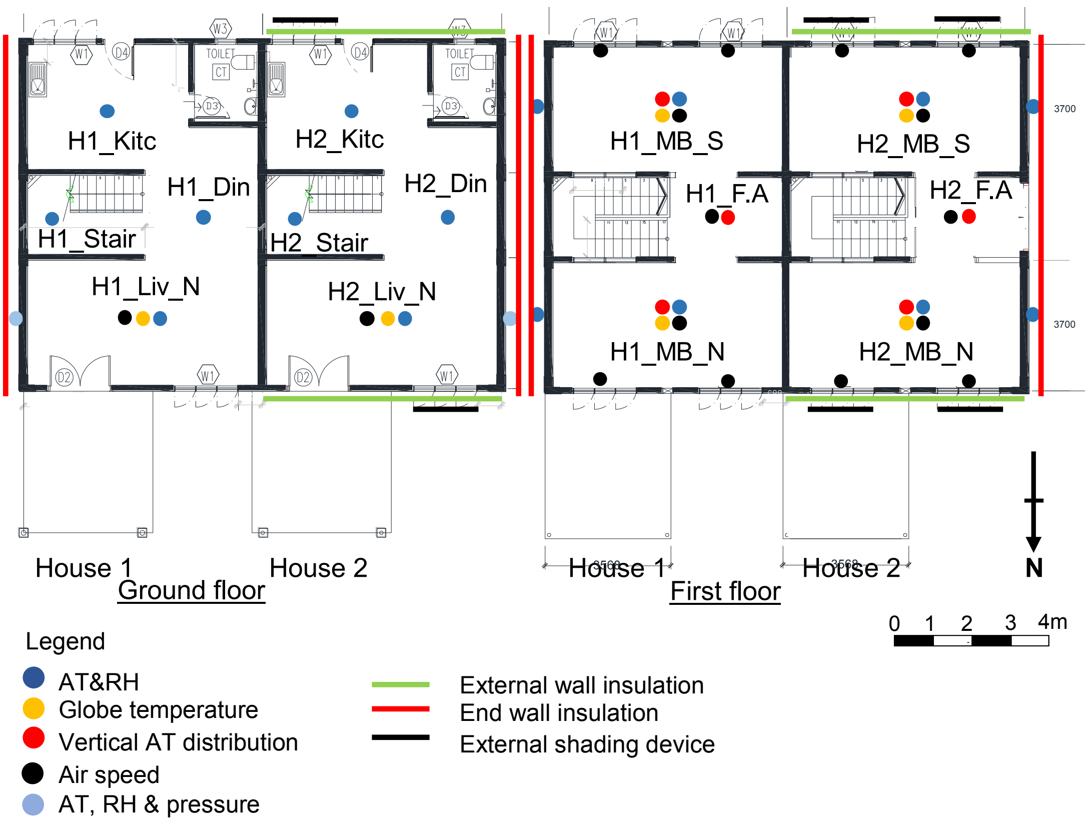


Figure 6.1. (a) Exterior views of the experimental houses (b) The floor plans of the experimental houses and the location of the measurement equipment.

Note: H1= House 1; H2=House 2; MB= Master bedrooms; N= North; S=South; F. A= Family area; Liv_N= Living hall North; Din=Dining; Kitc=Kitchen; Stair=Staircase

The main variables for the thermal comfort assessment were measured in the master bedrooms (first floor) of the two units at 1.1 m above the floor. The measured variables were air temperature, relative humidity, wind speed and globe temperature. The surface temperatures were also measured in the bedrooms. In addition, air temperature and relative humidity were measured in the attic spaces and at the other spaces located on the ground floor, i.e., dining halls, kitchens and staircases of both units. The outdoor weather data were recorded by a weather station located in an open space approximately 40 m away from the units. The buildings were unoccupied during the measurement period except during the changing of the experimental case and data collection by one or two researchers. Both houses were equipped with minimum furniture on the ground floor and totally unfurnished at the first floor. The measurement instruments used and the accuracy level are presented in Table 6.2.

Table 6.2. Description of measurement equipment

Measured variable	Instrument model	Accuracy
Air temperature and RH	T&D TR-72WF	±0.3°C, ±2.5%RH (10 to 85%RH), ±3.5%RH (0 to 10, 85 to 99%)
	Vaisala HMP155-A	±0.1°C, ±1% at 0 to 90%RH
	T&D TR-72U	±0.3°C, ±5%RH
Globe temperature	Type T thermocouple and Globe ball 75 mm	±0.1%+0.5°C plus ±0.5°C for cold junction compensation
	T&D TR-52 and ping pong ball 25 mm	±0.3℃ (0 to 50°C)
Air velocity	Kanomax sensors (0965-03)	0.1-4.99m/s: ±0.15m/s, 5.00-9.99m/s: ±0.3m/s, 10.0-25.0m/s: ±0.6m/s
	Hobo T-DCI-F900-L-P	± 0.05m/s
Vertical air temperature distribution	Type T thermocouple and Graphtec GL820	±0.1%+0.5°C plus ±0.5°C for cold junction compensation
Surface temperature	Type T thermocouple and Graphtec GL820	±0.1%+0.5°C plus ±0.5°C for cold junction compensation
Heat flux	Eto Denki S11A and Graphtec GL820	N. A
Weather station (outdoor) (Air temperature, RH, Wind speed, Wind direction, Solar radiation, Rain fall and Air pressure)	HOBO Pro V2 U23-001	±0.21°C (0 to 50°C); ±2.5% (10-90% RH) ±3.5 (to a maximum); ±0.5m/s; ±5°; ±10 W/m2 or ±5° (Whichever is greater); ±1.0% at up to 20 mm/hr.; ±3.0 mbar (= 1hPa)

6.3 Weather conditions

Figure 6.2 presents the weather condition during the period of the experiment. As shown, the maximum and minimum outdoor air temperature were ranges from 32.1-32.6°C and 22.8-23.8°C. The highest maximum air temperature was recorded in July and the lowest minimum air temperature was in September. Nevertheless, the average air temperature between all months is about 26.9°C. The level of maximum solar radiation increased from about 650 to 800 W/m^2 in June to September. During the measurement period, the minimum outdoor relative humidity was ranges from 60-65%. Meanwhile, the maximum relative humidity reaches 100% for most of night-time. In average, the outdoor relative humidity was ranges from 85-90%. The occurrence of rain was about 1.5-3.5% of the total measurement period in each month.

The outdoor wind speeds are varied between each month. The average outdoor wind speed in each month was about 0.2 m/s. The highest outdoor wind speed was recorded in September which is up to 5 m/s while the lowest wind speed was in July which was about 2.4 m/s. For most of the measurement period, the outdoor wind flow was from south-west to south-southeast direction.

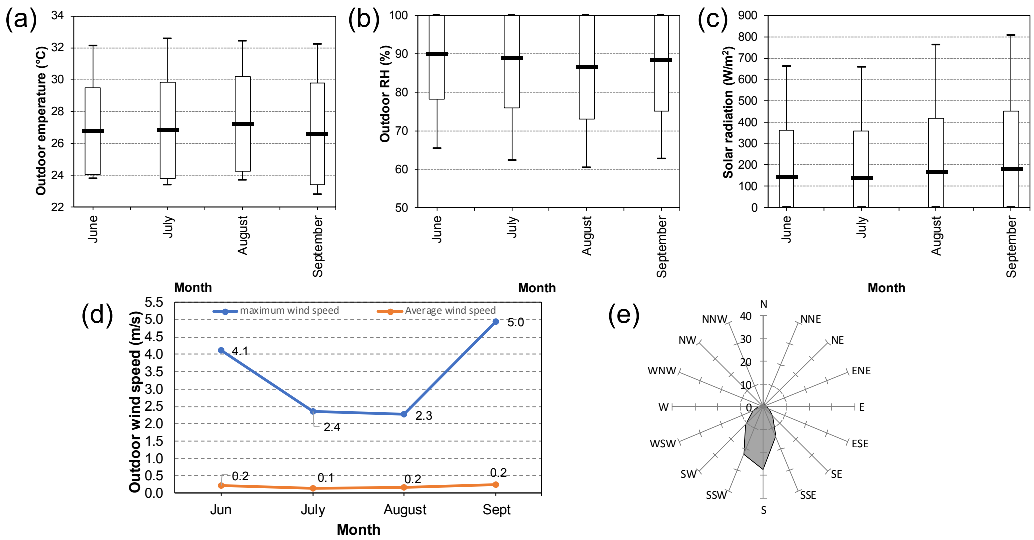


Figure 6.2. Monthly outdoor weather conditions. (a) Air temperature; (b) relative humidity; (c) solar radiation; (d) wind speed and (e) wind direction.

6.4 Experimental cases

In this study, seven cases of field measurement were conducted to fulfill the objective of the experiment. The conditions for the experimental cases (Cases 1-7) are described in Table 6.3. As shown, Case 1 to 3 investigate the effects of modifications under the structural cooling condition (night ventilation) while Case 4 to 6 investigate the effects of modifications under the comfort ventilation condition (full-day ventilation). Case 7 investigates the effects of structural cooling effects through window opening positions under the night ventilation condition. In Case 1 to 3, the number of modification techniques were applied cumulatively, started from three modifications in case 1 to full modifications (i.e. five modifications) in case 3. In detailed, Case 1 investigates the effects of solar gain protection on the building. In case 2, the whole house ventilation was adopted (at night-time) in addition to the three techniques to enhance the nocturnal structural cooling effects of the building. In Case 3, the master bedroom and attic ventilation fan was adopted (in night-time) on top of all previous techniques to investigate the effects of the increase of ventilation rate and cooler attic spaces on the thermal environment in the master bedroom. The same experimental cases were conducted under the full-day ventilation condition in Case 4 to 6. In Case 7, three types of window-opening position (i.e. main windows (Case 7-a), slit windows (Case 7-b) and all windows (Case 7-c)) were applied in the master bedroom of the measurement unit (House 2) to investigates the effects of window-opening position on the indoor thermal environments in the master bedroom. Structural cooling condition (night ventilation) was obtained by opening the window from 8 p.m.to 8 a.m. and closing them from 8 a.m. to 8 p.m. In contrast, the windows were opened for the whole day in the comfort ventilation condition (full-day ventilation).

Table 6.3. Experimental cases of full-scale measurement

Study cases	Natural ventilation	House 1 (control)	House 2
Case 1	Night ventilation	• Opening: All windows • Techniques: No	• Opening: All windows • Techniques: Roof and external wall (out) insulation + external shading
Case 2	Night ventilation	• Opening: All windows • Techniques: No	• Opening: All windows • Techniques: Roof and external wall (out) insulation + external shading + whole house fan
Case 3	Night ventilation	• Opening: Main windows • Techniques: No	• Opening: Slit windows • Techniques: Roof and external wall (out) insulation + external shading + whole house fan + attic fan
Case 4	Full-day ventilation	• Opening: All windows • Techniques: No	• Opening: All windows • Techniques: Roof and external wall (out) insulation + external shading
Case 5	Full-day ventilation	• Opening: Main windows • Techniques: No	• Opening: Main windows (day)/ slit windows (night) • Techniques: Roof and external wall (out) insulation + external shading + whole house fan
Case 6	Full-day ventilation	• Opening: Main windows • Techniques: No	• Opening: Main windows (day)/ slit windows (night) • Techniques: Roof and external wall (out) insulation + external shading + whole house fan + attic fan
Case 7	Night ventilation	• Opening: Main windows • Techniques: No	• Opening types: a) Main windows b) Slit windows c) All windows • Techniques: Roof and external wall (out) insulation + external shading + whole house fan

6.5 Results

6.5.1 Effects of natural ventilation

Before analyzing the seven experimental cases, this section preliminary investigates the indoor thermal conditions under various natural ventilation conditions. Figure 6.3 shows the results of daily average air temperature, relative humidity (RH) and absolute humidity under daytime ventilation, night ventilation and full-day ventilation conditions.

Daytime ventilation represents the common ventilation practice in residential house in Malaysia. As shown in Fig. 6.3a, air temperatures in the two spaces (master bedroom and living hall) increased with the increases of outdoor temperature during daytime. Meanwhile, at night, the two spaces became warmer due to closed window condition especially in the master bedroom where the air temperature was increased by up to 3.8°C compared with the outdoors.

In contrast, the daytime air temperatures in the two spaces were lower than the outdoors by up to 2.3°C and 3.8°C respectively when the windows were closed, i.e. night ventilation (Fig. 6.3b). Furthermore, the indoor air temperatures were lower during night-time by about 1.0°C and 1.4°C in the master bedroom and the living hall respectively, compared with the previous daytime ventilation. Nevertheless, the RH level of the two spaces in this case was always higher than 70%.

Meanwhile, the nocturnal air temperatures of the two spaces under full-day ventilation are similar with the night ventilation condition, whereas the daytime air temperatures tend to be higher than that of night ventilation condition just like daytime ventilation condition, with relatively lower RH levels of approximately 65%.

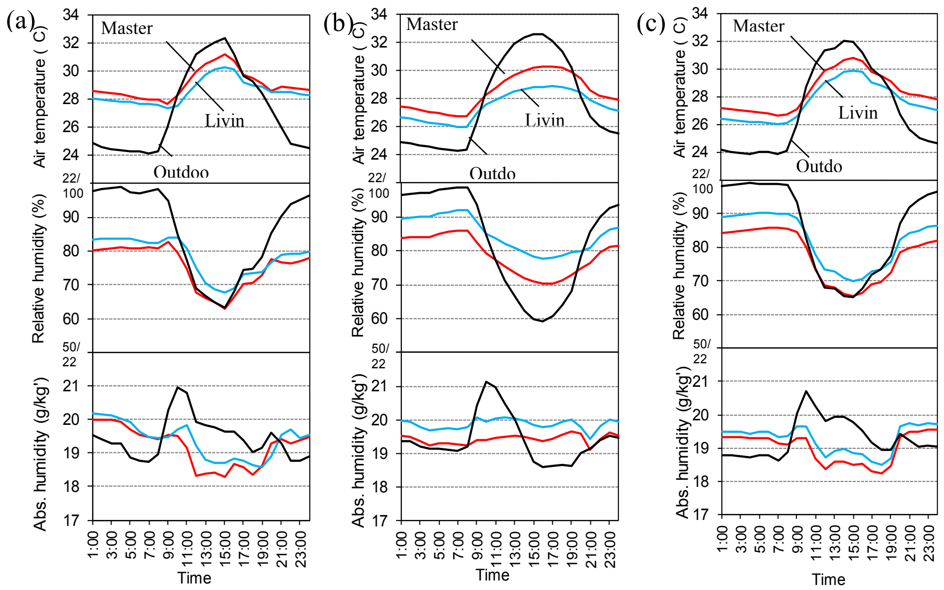


Figure 6.3. Daily average air temperature, relative humidity and absolute humidity in (a) day ventilation; (b) night ventilation and (c) full-day ventilation.

6.5.2 Measurement of air change rates

The purpose of the measurement is to investigate the actual ventilation rates in the master bedroom with different window opening conditions under natural and forced ventilation techniques. The experiment has been conducted by using gas tracer method, i.e. concentration decay. In this experiment, the depletion rates of the tracer gas inside the master bedroom represents the ventilation rates in that space. This method is the most commonly accepted since its implement is the easiest. In this measurement, the carbon dioxide (CO_2) gas was used due to widely available and cost effective. The detailed description of this methods can be found in the international standard ISO 12569 (2013).

6.5.2.1 Method

The level of CO_2 gas was measured in the experimental room and outdoor. The gas was measured in term of particle per millions (ppm). In this measurement, the CO_2 gas was injected and mixed into the air in the master bedroom (test room). The injection was stopped after the gas concentration was uniform across the spaces in the room. The measurement started after the corresponding window and ventilation conditions has been applied. The decreasing of CO_2 concentration was recorded and monitored until it reached stable condition.

The air changes rates were estimated based on the following equation (Cui *et al.*, 2015):

$$N = \frac{ln\frac{C_0 - C_{bg}}{C_f - C_{bg}}}{\Delta t} = \frac{1}{\Delta t}\left[\ln\left(C_0 - C_{bg}\right) - ln\left(C_f - C_{bg}\right)\right] \quad (1)$$

where, N is the air change rate, C_{bg} is the background concentration, C_0 is the initial point, C_f is the final point and t is time.

6.5.2.2 Result

Five test conditions were conducted in this measurement. Table 6.4 presents the test conditions and the resulted air change rates. To be noted that, all condition in the test cases will be adopted in the study cases in Section 6.5.4-6.5.5. As shown, the resulted air change rate per hour (ACH) in the master bedroom were ranges from 6.2-28.4 ACH. The application of main windows in daytime (Case-a) generated about 7.8 ACH inside the master bedroom. In Case-b, whole house was adopted in addition to the slit windows. As a result, the generated ACH is about 6.5 which is the smallest among the other case. This is simply because it has the smallest opening size compared to others. The ACH was increased to 11.5 when the main windows were applied together with the whole house ventilation (Case-c). In Case-d, the master bedroom ventilation was adopted on top of the condition of Case-b. As a result, the ACH of the master bedroom is 7.5 which is 1.3 higher than that of Case-b. In Case-e, all windows were open during night-time and the master bedroom was ventilated by natural ventilation. The estimated ACH for this case is 28.4. As shown, the resulted ACH was the largest compared to the other cases. The detailed results of the experiment of each case are available in Appendix A.

Table 6.4: Experimental cases and results of CO_2 test

Case	ACH	Average ACH
a. Main window (daytime)	Test 1: - Test 2: 7.8 Test 3: 7.5	7.8
b. Slit windows +Whole house (30 ACH) at night-time	Test 1: 6.8 Test 2: 5.4 Test 3: 6.3	6.2
c. Main windows + whole house (30 ACH) at night-time	Test 1: 12.1 Test 2: 11.8 Test 3: 10.5	11.5
d. Slit windows +whole house (30 ACH) +MB fan (40 ACH) at night-time.	Test 1: 7.8 Test 2: 7.1 Test 3: 7.7	7.5
e. Open all windows at night-time	Test 1: - Test 2: 27.8 Test 3: 28.9	28.4

Note: (-) means the result has been excluded due to overestimation (error in measurement).

6.5.3 Effects of ceiling fan

In this section, we investigate the effects of the ceiling fan on the thermal comfort in the master bedroom and the living hall during the daytime. As discussed in section 6.5.1, during daytime, the indoor air temperature in the master bedroom and living hall increases with the increase of outdoor temperature under daytime or full-day ventilation. This is due to the inflow of warm air into the indoor spaces. Therefore, in this analysis, we investigate the thermal comfort condition of both spaces during daytime when the indoor wind speed is increased by the ceiling fan. The analysis is based on the SET* thermal comfort indices. Indoor wind speed of 1.9 m/s was applied in the calculation of SET* from 8:00 to 20:00. The assigned indoor wind speed was obtained from the field measurement which is the average indoor wind speed under maximum speed of typical ceiling fan. The detailed results of the measurement is available in Appendix B.

Figure 6.4 presents the results of SET* in the master bedroom and living hall with and without the ceiling fan under the full-day ventilation condition. As shown, the SET* in both spaces reduce when the ceiling fan was applied. SET* in the master bedroom was reduced by up to 4.0°C. Meanwhile, in the living hall, the SET* was reduced by up to 5°C. This indicates that the thermal comfort of indoor spaces during daytime could be improved if the wind speed increases.

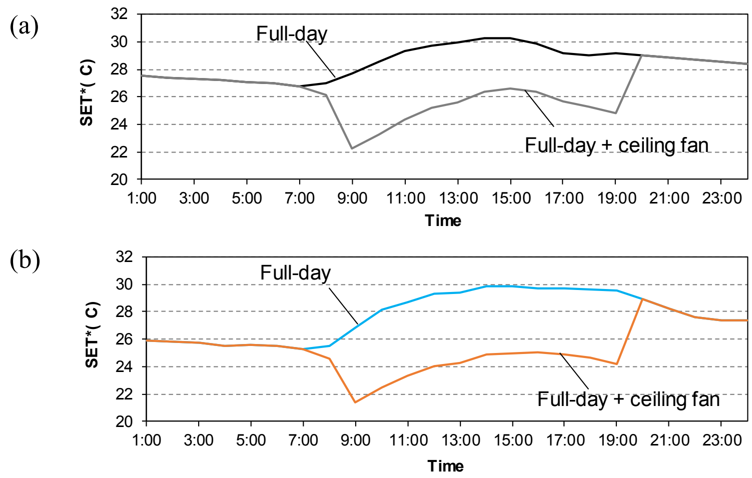


Figure 6.4. Daily average SET* with and without ceiling fan (in daytime) under full day ventilation condition in (a) master bedroom; (b) living hall.

6.5.4 Structural cooling strategy (night ventilation)

6.5.4.1 Case 1: Effects of 3 techniques

6.5.4.1.1 Effects on indoor thermal environment of the master bedrooms

In the first case, three modifications techniques, i.e. roof insulation, external wall outside insulation and external shading devices were applied in the measurement unit (house 2). The opening condition for both control (house 1) and measurement unit is by using all windows (main windows and slit windows). Figure 6.5 shows the temporal variations of air temperatures, relative humidity and absolute humidity in north and south facing rooms of both houses under in Case 1. During the measurement period, the outdoor air temperature was ranges from 23.5-33°C with the average of 26.8°C. Meanwhile, the outdoor relative humidity and absolute humidity were ranges from 69-100% and 17.8-23 g/kg', respectively. The average wind speed during daytime is about 0.23 m/s, while in the night-time, it was less than 0.1 m/s.

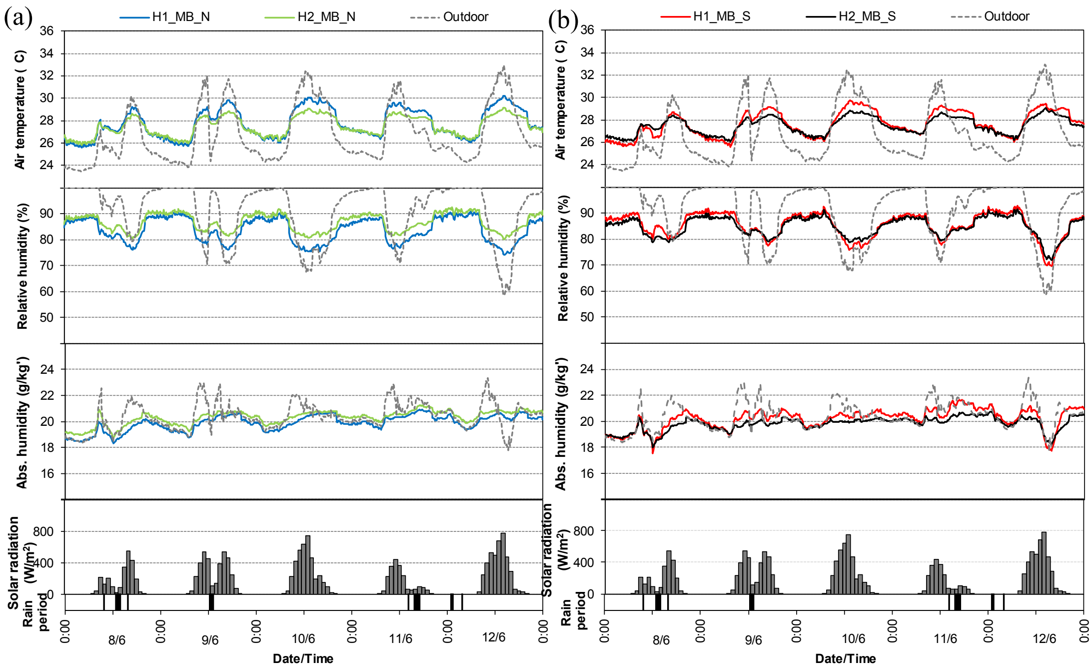


Figure 6.5. Temporal variations of air temperatures, RH and absolute humidity in the master bedrooms of House 1 and House 2 with the corresponding outdoor solar radiation and rain period in Case 1. (a) North facing master bedroom (H1/H2_MB_N) (b) South facing master bedroom (H1/H2_MB_S)

In general, the air temperatures in the master bedrooms were lower than outdoor during daytime and higher than that of outdoor at night-time. The air temperature difference between indoor (master bedrooms) and outdoor was ranges from 2-3.5°C during the daytime. Meanwhile, in the night-time, the air nocturnal air temperatures in the master bedrooms were higher than that out outdoor by about 2-2.5°C. This indicates that lower indoor thermal condition can be obtained at daytime under night-ventilation condition even in the control house (without modification). During the night-time, the air temperature in the master bedroom could not be reduced as low as the outdoor, probably due to large thermal heat in the structure. To be noted that, the air temperature in the south facing master bedroom was slightly lower than the north facing side. This is due to the solar incident angle was slightly towards the northern side during the period of measurement. Therefore, the north facing master bedroom received slightly higher rate of direct solar radiation during daytime compared to the south facing side.

The result also shows that the air temperature in the master bedrooms in the measurement unit were lower than the control in daytime. In the north facing rooms, the air temperature in the master bedroom of house 2 (H2_MB2_N) was lower than that of house 1 (H1_MB_N) by up to 1.1°C. Meanwhile, in the south facing rooms, the air temperature reduction is up to 0.9°C (H2_MB_S-H1_MB_S) after the application of the modifications. In average, the air temperature in the north and south facing rooms of the measurement unit is lower than that of control by about 0.8°C and 0.6°C respectively (Figure 6.6). This indicates that the modification techniques successfully reduced the impact of direct solar radiation to the building during the daytime under night-time ventilation. In contrast, there are no significant of air temperature reduction observed in the measurement unit during the night-time. The air temperature in the north master bedroom of measurement unit was slightly higher than the control unit by about 0.1°C in average. Meanwhile, in the south master bedrooms, the reduction of air temperature was almost none. This is believed due to the effect of insulations which retarding the heat transfer from the wall and attic spaces to the outside during the night-time. Calm indoor wind speed observed at the night-time was not able to remove warm air inside the room and increase the convective heat transfer rate on the building structure (House 2).

In this case, the relative humidity in the master bedrooms in the measurement unit ranges from 78-85% while in the control unit, it was ranges from 75-80%. During daytime, the relative humidity in the north and south facing rooms of the measurement unit were higher than that of control rooms by up to 6% and 3% respectively. In average, they were higher than the control rooms by about 5% and 1% in north facing and south facing room. This is due to the slightly lower air temperatures in both master bedrooms in the measurement unit. Meanwhile, at night-time, the relative humidity in the north facing room of the measurement unit continues to be higher than that of the control room. In contrast, the relative humidity in the south facing room of the measurement unit was lower than the control unit for most of night-time period. Nevertheless, the difference can be considered relatively small since the nocturnal air temperatures between the rooms in both houses were almost the same.

Meanwhile, the difference of the absolute humidity between the rooms in the measurement and the control unit were also relatively small during the measurement. In general, the differences in the rooms of both houses were less than 0.5 g/kg' during day and night-time. Nevertheless, the absolute humidity recorded in the south facing room of the measurement unit was always lower than that of control unit for most of the time.

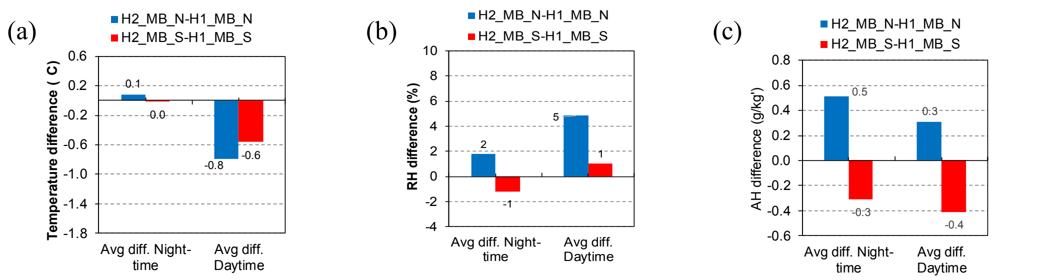


Figure 6.6. Average difference between master bedroom in House 1 and House 2 (House 2-House1) for north and south direction in daytime and night-time in Case 1. (a) Air temperature; (b) relative humidity; and (c) absolute humidity.

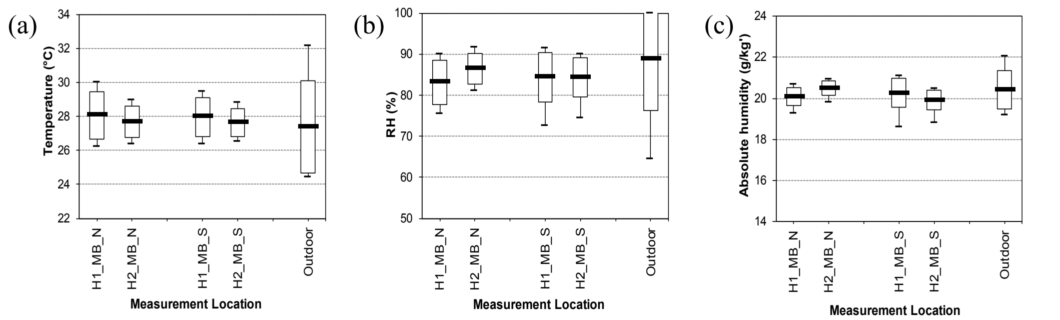


Figure 6.7. Statistical summary (5th and 95th percentiles, mean and ±one S.D.) of measurements (at 1.5 m above floor) in the master bedrooms in Case 1. (a) Air temperature; (b) relative humidity; and (c) absolute humidity.

6.5.4.1.2 Heat fluxes and surface temperature in the master bedrooms

Figure 6.8 shows the results of heat fluxes on the inside surface of the external wall, end wall and the ceiling of the master bedrooms. Meanwhile, Figure 6.9 shows the average surface temperature difference between the master bedrooms in the measurement and control unit (measurement-control unit). As shown in Figure 6.8, the external wall of both rooms in the measurement unit absorbed lower heat than that of the control unit by up to 5-6 W/m^2. This is simply because of the heat reduction provided by the insulation on the external wall and lower indoor air temperature in the master bedrooms of the measurement unit. As a result, the average difference of surface temperature on the external wall is about 0.4 °C and 1.1°C, lower than the control rooms in the north and the south facing room respectively (Figure 6.9).

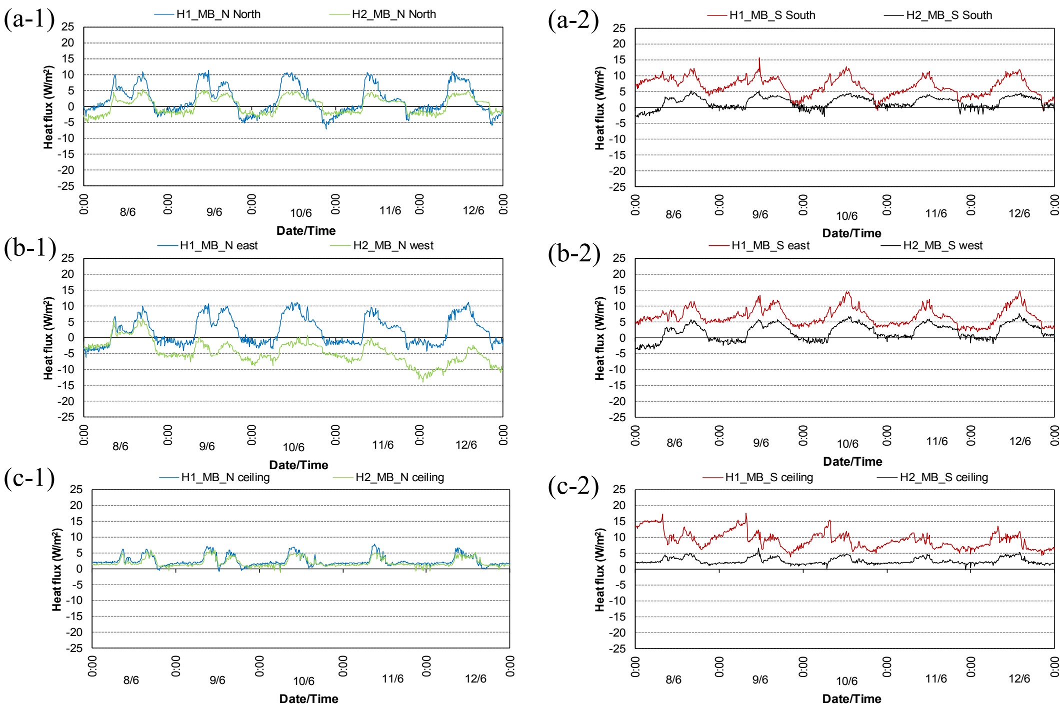


Figure 6.8. Heat fluxes on (a) external wall (inside); (b) end wall (inside) and (c) ceiling surfaces in north and south facing master bedrooms of both houses in Case 1.

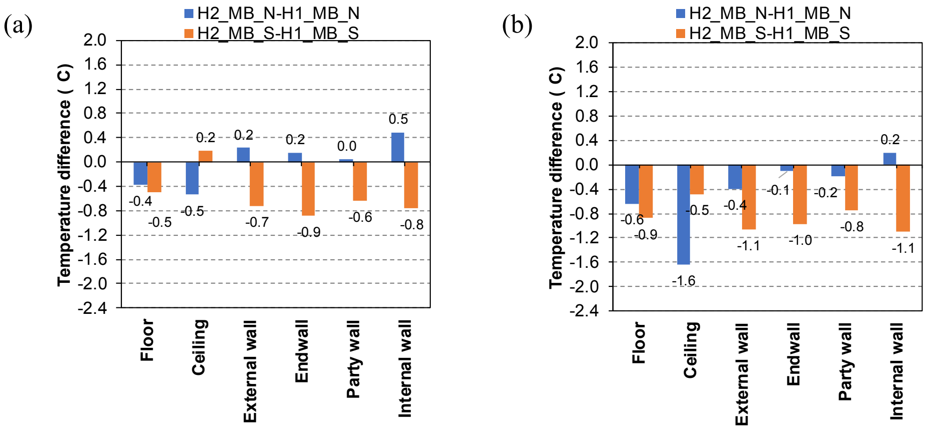


Figure 6.9. Average surface temperature difference between master bedroom in House 2 and House1 (House2 – House 1) during (a) night-time and (b) daytime in Case 1.

Meanwhile, in night-time, the external wall in the north facing master bedroom of the control unit has slightly better rate of heat release where the heat fluxes were larger than that of measurement unit by up to 2.5 W/m^2. At this time, the surface temperature of the external wall in the control unit is lower by about 0.2°C in average. In contrast, there are almost no heat fluxes observed on the surface of external wall of the south facing room in the measurement unit while positive heat fluxes (absorption) occurred in the control unit. To be noted that the surface temperature of the external wall in the measurement unit is lower than that of control unit by about 0.7°C on average. This indicates that the surface temperature of the external wall in the measurement unit was reduced to nearly the same as its indoor air temperature.

Almost the same phenomenon observed for the heat fluxes on the surface of end wall. In this case, we will discuss the results of the south facing rooms since the result in the north facing room is believed containing errors (H2_MB1_N). Using the south facing room as reference, the heat fluxes on the end wall of the measurement unit were lower than the control room by about 5-10 W/m^2 during the daytime. Meanwhile, similar to the situation of the external wall, there are no heat release during the night-time in the measurement unit.

It was found that almost similar amount of heat fluxes was recorded on the surface of ceiling in the north facing room of both houses even in the measurement unit which has roof insulation. In contrast, the south facing room in the measurement unit recorded lower heat fluxes value compared to the control rooms by about 5-8 W/m^2. Nevertheless, all ceilings recorded positive value of heat fluxes which indicates absorption process occurred in the night-time. This mean the ceiling surface were lower than the indoor air temperature.

As shown in Figure 6.9, the surface temperature of walls in the master bedrooms of the measurement unit were lower than that of control unit except for the internal wall of north facing rooms in daytime. In average, the surface temperature of floor, ceiling and the external wall of the north facing room in the measurement unit are lower than that of the control room by about 0.6°C, 1.6°C and 0.5°C, respectively. Meanwhile, small temperature difference observed on the surface of end wall, party wall and internal wall where the surface temperature in the measurement room were lower than that of control room by about 0.2°C in average. In contrast, larger reduction of surface temperature observed in the south facing room of the measurement unit where the average reduction is about 0.6°C. This indicates that the application of modification not only lowering the air temperature in the master bedroom, but also their surface temperature during daytime. Meanwhile, in the night-time, the surface temperature of the north facing room in the measurement unit were mostly similar compared to that of the control room except for the floor and the ceiling surface. The average surface temperature difference is about 0.3°C. In contrast, almost all surfaces in the south facing room of the measurement unit were lower than that of control unit in night-time with the average difference of 0.6°C. Nevertheless, the cool surface of wall in south facing master bedroom in the measurement unit did not affects its air temperature condition to be lower than that of control unit.

6.5.4.1.3 Thermal comfort in the master bedrooms

Operative temperature (OT) and SET* are used as indices to evaluate thermal comfort in the master bedroom. The 80% adaptive comfort upper limit from ACE is used for the evaluation (Toe and Kubota, 2013). Meanwhile, a metabolic rate of 1.0 met and a clothing value of 0.4 clo was applied in the calculation of SET*. Figure 6.10 shows the result of calculated OT and SET* in the master bedrooms including the respective indoor wind speed.

During the measurement, the recorded indoor air speed in all master bedroom were lower than 0.2 m/s for most of the time. As shown, the operative temperature in the master bedrooms of the measurement unit fall under the 80% ACE upper limit for most of the time. In contrast, the master bedrooms in the control unit exceeded the upper limit by about 45%. This indicates that the combination of the three modifications together with night ventilation condition successfully providing better indoor thermal condition in term of operative temperature especially in daytime.

Meanwhile, in term of SET*, it was ranges from 26-30°C in the north facing room of the measurement unit during daytime. The SET* was lower than that of the control unit by about 1-1.8°C. Almost similar range of SET* observed in the south facing room (measurement unit) which is about 26.2-29.8°C, and they were lower than the control room by about 1-2°C. In this case, lower air and mean radiant temperature in the measurement units contributes in lowering their SET* value during daytime since the wind speed is very low. In the night-time, the SET* in the north facing master bedrooms recorded almost the same value in both houses. In contrast, slightly higher SET* observed in the control room in the south facing room compared to the measurement unit. On average, the SET* difference is about 0.5°C in the south facing room. This is probably because the measurement room has lower air temperature and slightly larger wind speed.

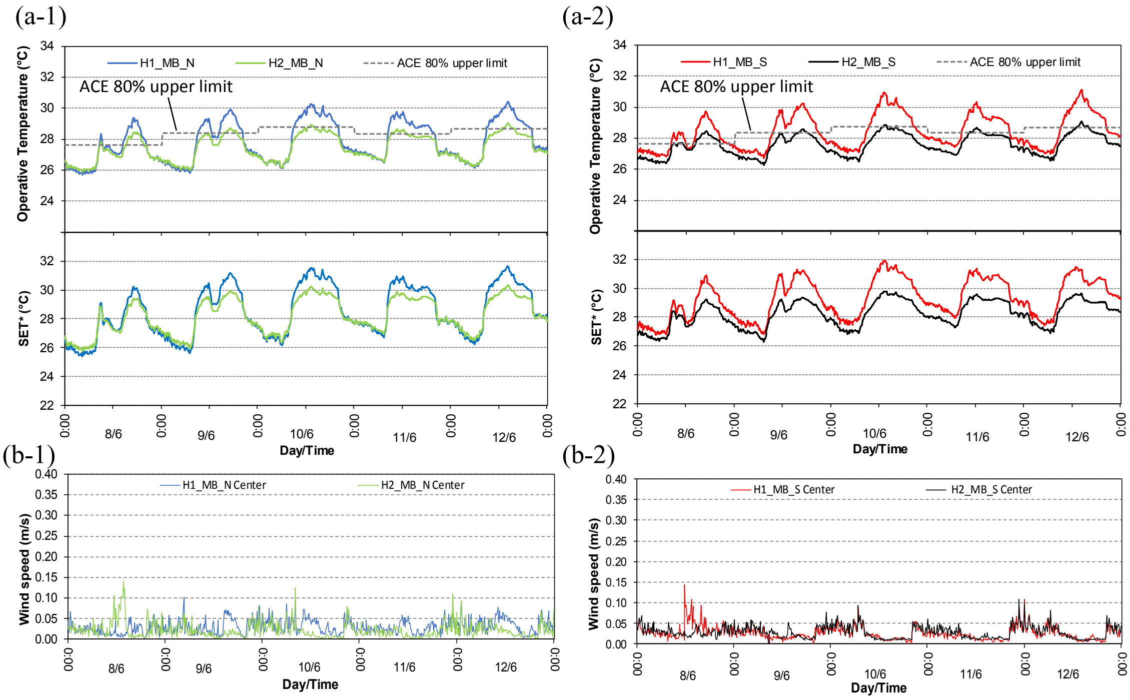


Figure 6.10. (a) Operative temperature (top) and SET* (bottom) in the master bedrooms of both houses in Case 1. (b) Wind speed in the living halls in Case 1

6.5.4.1.4 Thermal comfort in the living halls

Figure 6.11 presents the temporal variations of air temperature, relative humidity and absolute humidity in the living hall of both houses. As shown, the daytime air temperature in the measurement unit ranges from 25.8- 28.1°C while in the control unit ranges from 25.8-29.0°C. In average, the air temperature reduction in the living hall of the measurement unit is about 0.4°C during daytime. In this case, relatively small air temperature reduction observed in the living hall compared to the rooms on the first floor. This is because, the spaces in the ground floor were cooler than that of first floor due to less exposed to the direct solar radiation and not directly located under the roof. Meanwhile, in the night-time, it was found that the recorded air temperatures in both living halls was almost the same.

The level of relative humidity was almost similar in both living hall for most of the time, where they are ranges from 85-98%. Therefore, the resulted absolute humidity is also the same between both living halls which was ranges from 19-22 g/kg'.

Figure 6.12 shows the results of calculated operative temperature and SET* in the living halls including the respective indoor wind speed. As shown, both living halls have a good thermal comfort condition where their operative temperatures were almost fall within the 80% ACE upper limits for most of the time. The operative temperature in the living hall of the control unit exceeded the limit by only 11%, while the living hall in the measurement unit was always under the limits during the measurement period. Based on the evaluation by using SET* indices, the result shows that the living halls in the measurement unit was always lower than that of control unit by about 0.5-1.0°C for the whole days. To be noted that the temperature reduction by SET* was larger than that of air temperature. This is probably because the radiant effects form the surrounding were larger in the control unit than in the measurement unit.

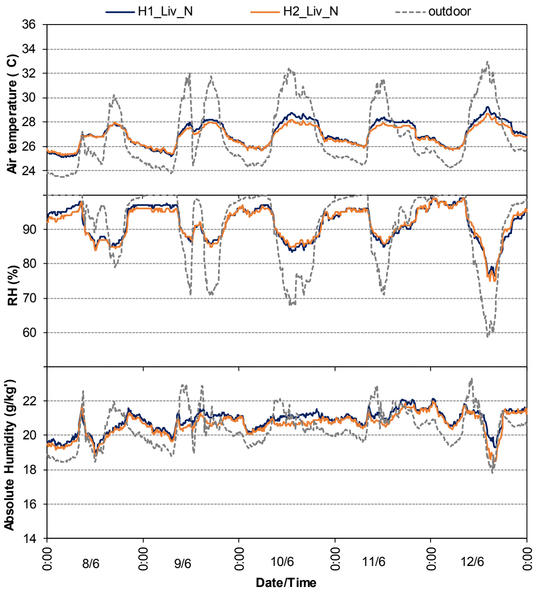


Figure 6.11. Temporal variations of air temperatures, RH and absolute humidity in the living hall of both houses in Case 1.

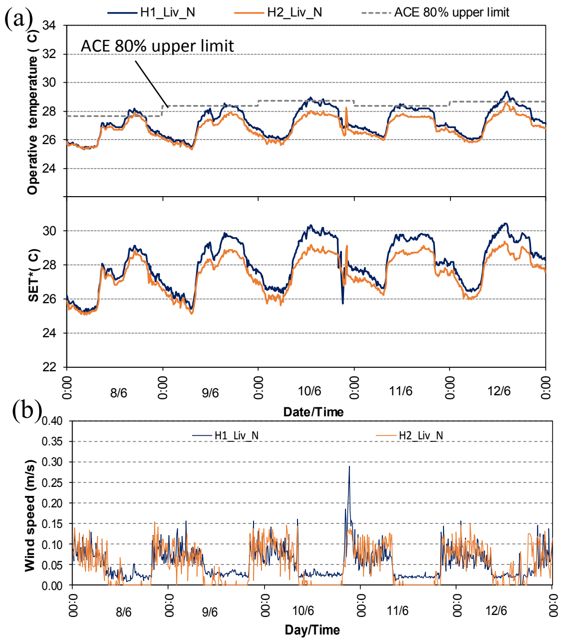


Figure 6.12. (a) Operative temperature (top) and SET* (bottom) in the living hall of both houses in Case 1. (b) Wind speed in the living halls in Case 1

6.5.4.1.5 Thermal environment variations of the whole house

Figure 6.13 shows the air temperature variations of the whole house during daytime (15:00) and night-time (00:00). As shown, during daytime (15:00), the air temperatures increased with the increases of height. The lowest air temperatures observed on the ground floor of both houses (measurement and control unit). In the ground floor, the lowest air temperature recorded at the dining hall where the average temperature is about 28.1°C and 27.9°C in the control and the measurement unit, respectively. The highest air temperature was recorded at the living hall which is about 28.8°C and 28.3°C of the control and the measurement unit, respectively. The dining room is the coolest place because they are located deep at the center of house and less exposure to solar radiation from the windows. In general, the ground floor spaces in the measurement unit have slightly lower air temperatures compared to the control unit. The temperature average difference in the living hall, dining and kitchen spaces is 0.5°C, 0.2°C and 0.3 °C, respectively.

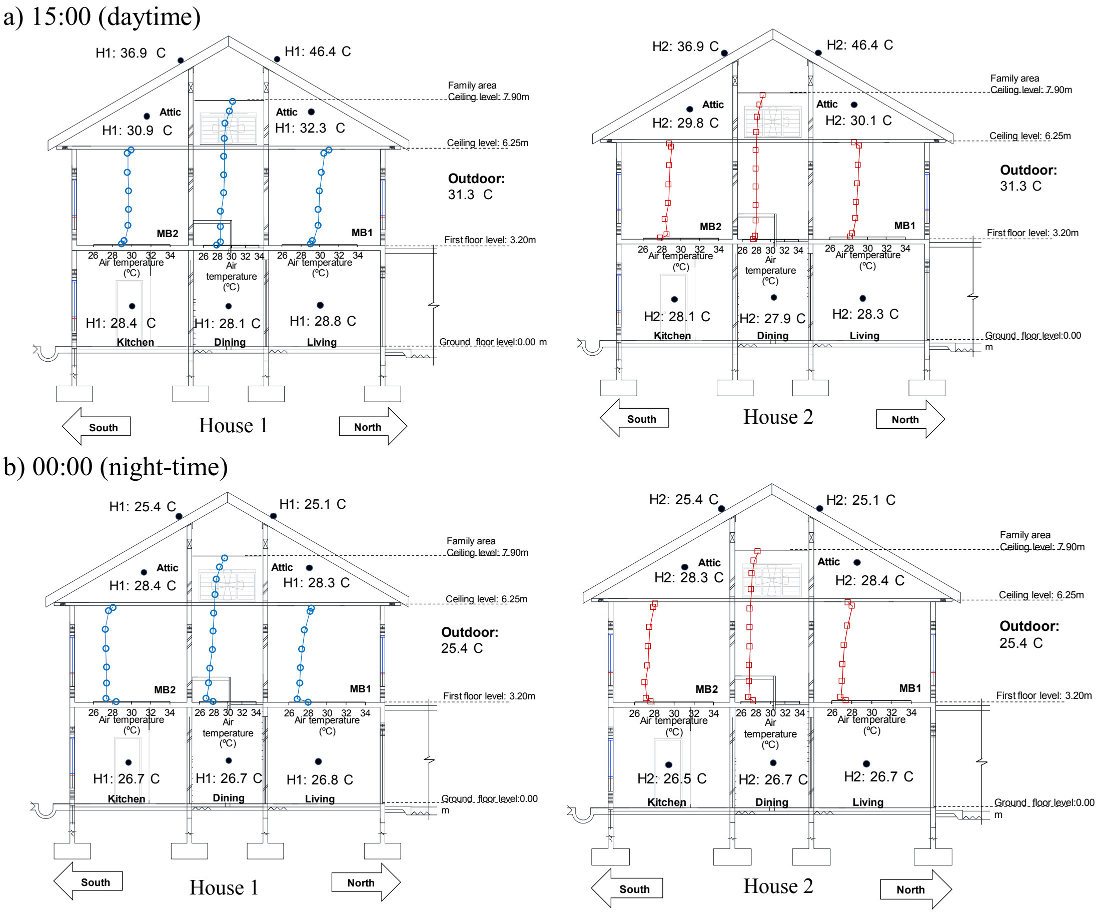


Figure 6.13. Whole house air and surface temperature distribution in House 1 (control unit) and House 2 (measurement unit) at (a) 15:00 (daytime) and (b) 00:00 (night-time) in Case 1.

Meanwhile, in the first floor, the air temperature in the master bedrooms increased with the increase of height from floor to the ceiling. Slightly large gradient of air temperatures observed in the control unit. Large gradient means bigger air temperature differences between floor and ceiling level. In the control unit, the temperature difference from floor to ceiling level was about 2°C while in the measurement unit, they were less than 1°C. This is simply because of high air temperature in the attic spaces above the rooms in the control unit. For instance, the air temperature in the attic of north facing room in the control unit was about 2.2°C higher than that of the measurement unit. Same effects observed in the south facing rooms but with a slightly lower magnitude of reduction due to a lower value of temperature. This indicates that the roof insulation successfully reduces the attic air temperature during daytime. The lowest air temperature recorded on the first floor is at the family area. However, the air temperature begins to rise from the level of ceiling of the master bedroom until the ceiling of the family area due to no insulation installed above the family area.

During night-time (00:00), it was found that the air temperatures in the ground floor were almost similar in both houses which ranges from 26.5-26.8°C in the living hall to the kitchen spaces. On the first floor, the attic temperatures were also similar in both houses which was about 28.4°C. The vertical air temperatures of master bedrooms in both houses showed almost the same gradient during the night-time. In the north facing rooms, the air temperature difference between each vertical height in both master bedrooms were less than 0.3°C. Meanwhile, in the family areas, the air temperatures at 1.1 m height of both houses were almost similar which is about 27°C. This indicates that there is no significant reduction of air temperature in the measurement unit at the night-time even with the installation of modifications techniques.

Figure 6.14 presents the statistical summary of air temperature, relative humidity and absolute humidity in all spaces of both houses. As discussed above, the ground floor spaces of both houses recorded the lowest value of air temperature compared to the other level. However, they also have a higher level of relative and absolute humidity compared to the spaces on the first floor. As shown, the range of relative humidity on the ground floor was from 92-95% compared to the first floor which is about 84-87% in both houses. In general, the average of air temperature of all spaces in the measurement unit were lowered than that of control unit (without techniques). This indicates that the techniques effectively reduce the air temperature by reducing the effects of direct solar radiation to the building especially during the daytime. However, the indoor spaces in the measurement unit have slightly higher air temperature than the control unit at the night-time, especially in the master bedroom. As shown in Figure 6.14a, almost all spaces in the measurement unit have slightly higher minimum air temperature compared to the control unit. This indicates that the proposed modifications (3 techniques) were not able to improve the nocturnal structural cooling effects in the building. The presence of high indoor wind speed is required during night-time to assist in the thermal heat transfer from indoor to outdoor environment.

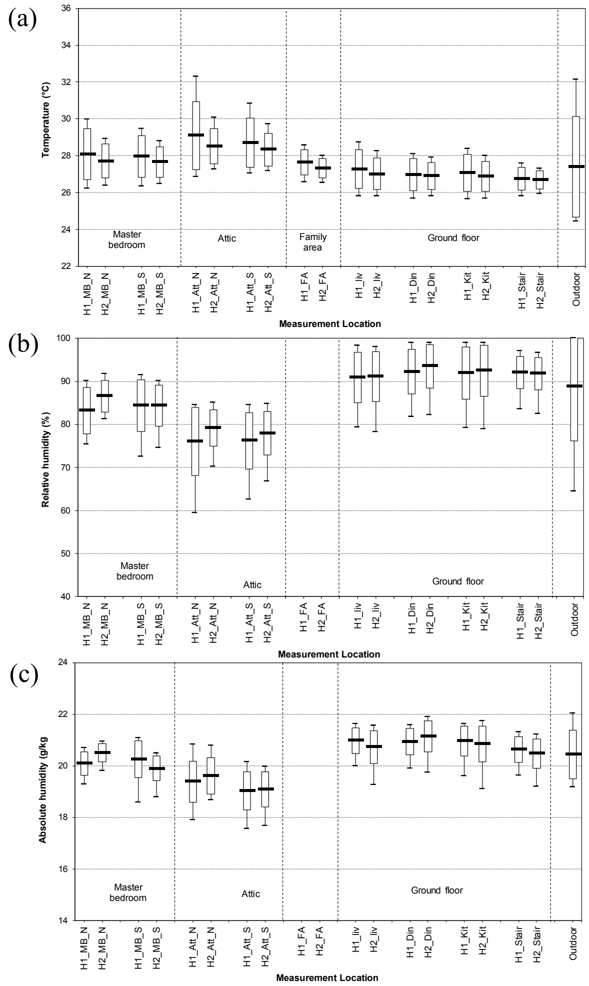


Figure 6.14. Statistical summary (5th and 95th percentiles, mean and ±one S.D.) of measurements (at 1.5 m above floor) of whole house in both House 1 and House 2 in Case 1. (a) Air temperature; (b) relative humidity; and (c) absolute humidity.

6.5.4.2 Case 2: Effects of 3 techniques and whole house ventilation

6.5.4.2.1 Effects on indoor thermal environment of the master bedrooms

In this case, the whole house ventilation was adopted at night in addition to the three modifications techniques, i.e. roof insulation, external wall outside insulation and external shading devices in the measurement unit (house 2). The opening condition for houses were remain the same for both houses (main windows and slit windows). Figure 6.15 shows the temporal variations of air temperatures, relative humidity and absolute humidity in the north and south facing rooms of both houses in Case 2. During the measurement period, the outdoor air temperature ranges from 24.5-35°C with the average of 26.8°C. Meanwhile, the outdoor relative humidity and absolute humidity ranges from 51-100% and 17.3 -23.5 g/kg' respectively. The average wind speed during daytime is about 0.50 m/s, while in the night-time, it was less than 0.1 m/s.

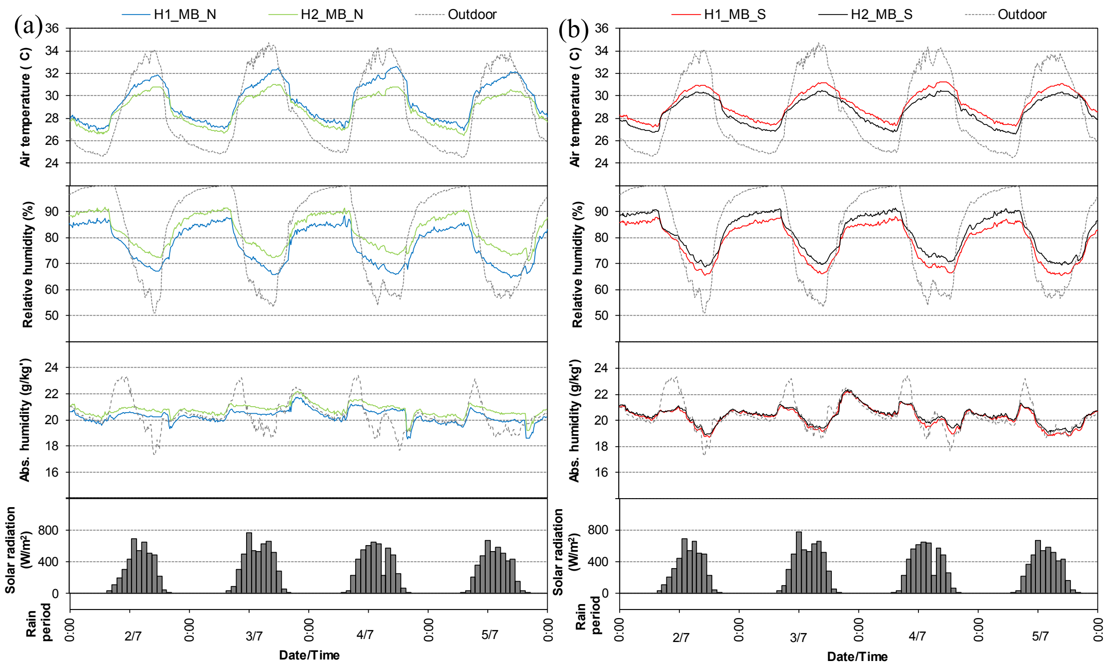


Figure 6.15. Temporal variations of air temperatures, RH and absolute humidity in the master bedrooms of House 1 and House 2 with the corresponding outdoor solar radiation and rain period in Case 2. (a) North facing master bedroom (H1/H2_MB_N) (b) South facing master bedroom (H1/H2_MB_S)

As shown in the figure, the air temperature in the master bedrooms in the measurement unit were lower than the control during daytime. In the north facing rooms, the air temperature in the master bedroom of house 2 (H2_MB2_N) was lower than that of house 1 (H1_MB_N) by up to 1.8°C. Meanwhile, in the south facing rooms, the air temperature reduction is up to 0.8°C (H2_MB_S-H1_MB_S) after the application of the modifications. In average, the air temperature in the north and south facing rooms of the measurement unit is lower than that of control unit by about 1.0°C and 0.6°C respectively (Figure 6.16). Similar to the previous case, this is simply because the effects of the modifications techniques which prevent the effect of direct solar radiation on the building. In this case, the air temperature reduction was observed not only in daytime, but also during the night-time. The air temperature reduction in the master bedrooms of the measurement unit were about 0.1-0.6°C. In average, the nocturnal air temperature difference in the north and south facing master bedrooms were about 0.4°C and 0.6°C, respectively. This indicates that the application of the whole house ventilation is effective in reducing nocturnal air temperature, but the resulting indoor temperatures were still higher than the outdoors by about 2°C. The whole house fan successfully increases the air flow in the master bedrooms and this improving the rate of heat transfer on the building structure. Therefore, the structural cooling effects observed in the north facing master bedroom in the measurement unit was larger than that of Case 1.

The relative humidity in the master bedrooms of the measurement unit was found to be increased accordingly after the modifications compared to that of control unit for the whole day. In daytime, the relative humidity in the north and south facing rooms of the measurement unit were higher than that of control rooms by up to 8% and 6% respectively. In average, they were higher than the control rooms by about 6% and 3% in north facing and south facing room. Meanwhile, at night-time, the nocturnal relative humidity in the north and south facing room were higher than that of in control rooms by up to 5% and 4 %, respectively. This is probably because the humid outdoor air entered the room by the whole house ventilation. Meanwhile, absolute humidity level in the master bedrooms of the measurement unit maintained higher value than that of the control rooms by about 0.4-0.5 g/kg' and 0.1-0.2 g/kg' in the north and south master bedroom, respectively.

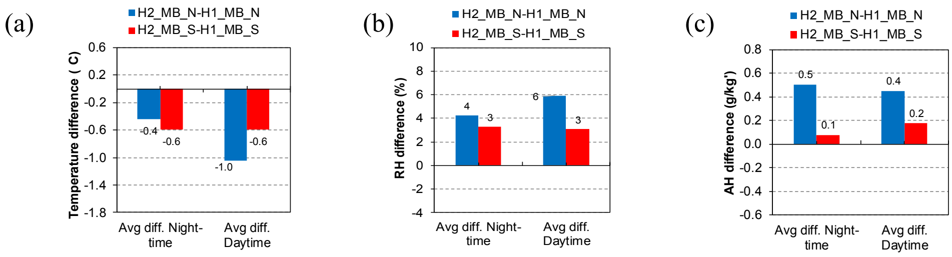


Figure 6.16 Average difference between master bedroom in House 1 and House 2 (House 2-House1) for north and south direction in daytime and night-time in Case 2. (a) Air temperature; (b) relative humidity; and (c) absolute humidity.

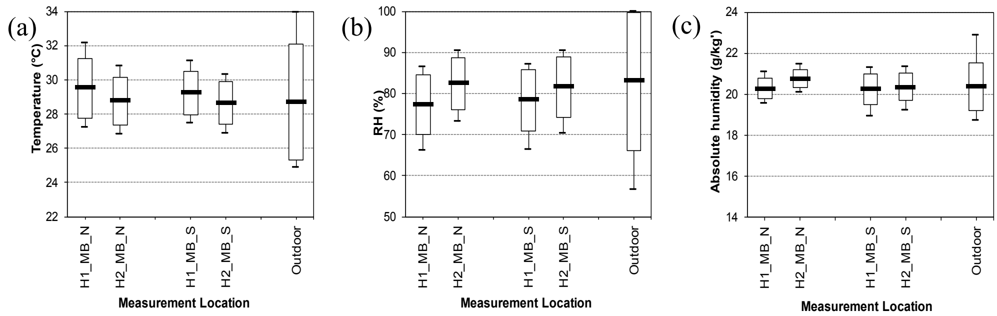


Figure 6.17. Statistical summary (5th and 95th percentiles, mean and ±one S.D.) of measurements (at 1.5 m above floor) in the master bedrooms in Case 2. (a) Air temperature; (b) relative humidity; and (c) absolute humidity.

6.5.4.2.2 Heat fluxes and surface temperature in the master bedrooms

Figure 6.18 shows the results of heat fluxes on the inside surface of the external wall, end wall and the ceiling in the master bedrooms. Meanwhile, Figure 6.19 shows the average surface temperature difference between the master bedrooms in the measurement and control unit (measurement-control unit). Similar to the previous case, the external wall of both rooms in the measurement unit absorbed lower heat than that of the control unit by up to 5-6 W/m^2 (Figure 6.18). This is simply because of the heat reduction provided by the insulation on the wall and the lower indoor air temperature in the master bedrooms of the measurement unit. As a result, the average difference of surface temperature on the external wall is about 0.4 °C and 0.7°C, lower than the control rooms in the north and the south facing room respectively (Figure 6.19). Meanwhile, in the night-time, the external wall in the north facing master bedroom in the control unit shows slightly better rate of heat release where the heat fluxes are larger than that of measurement unit by up to 5.0 W/m^2. At this time, the surface temperature of the external wall in the north facing master bedroom of the control unit was about the same as the measurement unit. Meanwhile, the external wall surface of south facing room in the measurement unit was lower than that of control unit by about 0.4°C in average.

Similar situation observed on the surface of end wall. Slightly lower heat absorption occurred in the master bedrooms of the measurement unit. For instance, the heat flux on the end wall of measurement unit (south facing master bedroom) was lower than that of control room by about 2.5-5 W/m^2. Meanwhile, the heat fluxes on the surface of end walls of both houses are quite similar during the night-time. The surface temperature of the end wall in the measurement unit was higher than that of control unit by about 0.3°C in the north facing master bedroom. In contrast, the surface temperature of the end wall in the south facing master bedroom of the measurement unit was lower than that of the control unit by about 0.4°C on average. It was found that heat fluxes values on the ceiling are almost the same between all rooms. Nevertheless, the surface temperature of the ceiling in the measurement unit were always lower than in the control unit where the average difference is ranges from 0.6-1.8°C and 0.5-1.5°C in the north and south facing master bedrooms respectively.

As shown in Figure 6.19, the surface temperature of the walls in the master bedrooms in the measurement unit were lower than that of control unit for most of daytime. The surface temperature difference was ranges from 0.2-1.8°C. The largest reduction was on the ceiling (1.5-1.8°C), followed by floors (0.8°C) and the external wall (0.4-0.7°C). In the night-time, most of the surfaces in master bedrooms of the measurement unit were lower than that of the control unit except for the external wall, end wall and the internal wall in the south facing room. Nevertheless, they are not affecting the air temperature of the room.

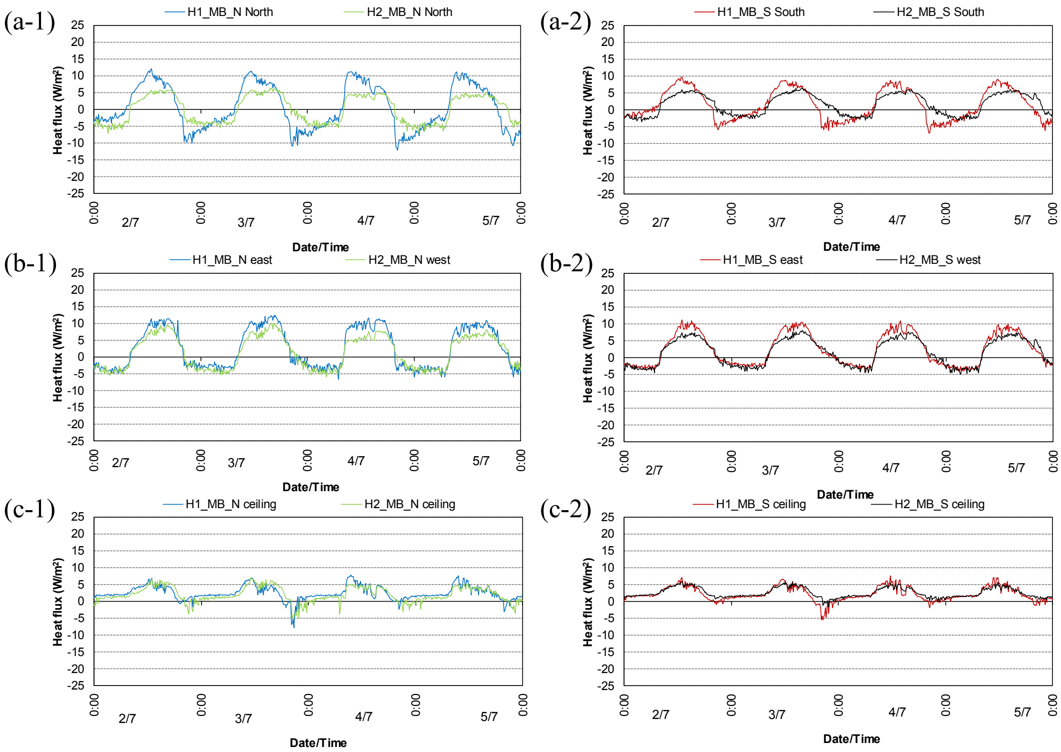


Figure 6.18. Heat fluxes on (a) external wall (inside); (b) end wall (inside) and (c) ceiling surfaces in north and south facing master bedrooms of both houses in Case 2.

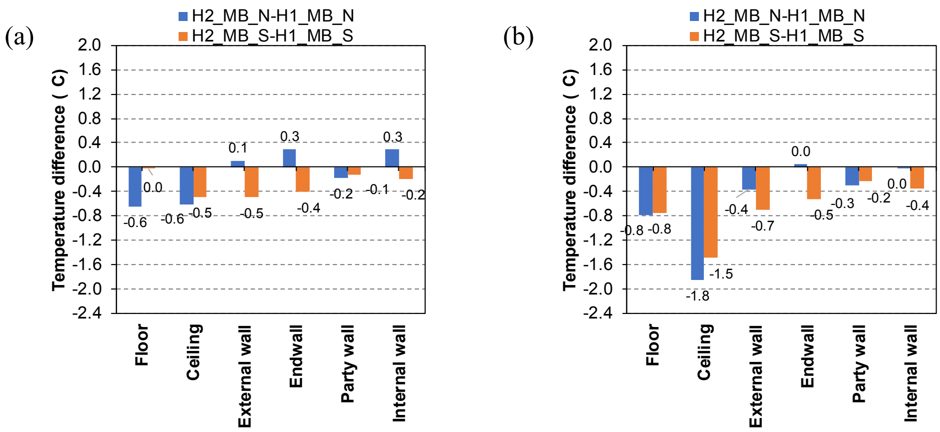


Figure 6.19. Average surface temperature difference between master bedroom in House 2 and House1 (House2 – House 1) in Case 2 during (a) night-time and (b) daytime.

6.5.4.2.3 Thermal comfort in the master bedrooms

Figure 6.20 shows the result of calculated operative temperature and SET* in the master bedrooms including the respective indoor wind speed in case 2. During the measurement, the recorded indoor wind speed in all master bedroom were about 0.1-0.2 m/s for most of the time. The wind speed in the master bedroom of the measurement unit were slightly higher than that of the control unit due to the application of the whole house ventilation, but they are still not exceeding 0.2 m/s. Despites there are significant reduction of air temperatures provided by the modification techniques, the operative temperature in the master bedrooms in the measurement unit exceed the 80% of ACE upper limit as that of in the control unit. The operative temperatures exceed the limit for over 46% and 40% of the measurement period in the control and the measurement unit, respectively. This probably due to relatively higher outdoor air temperature during the measurement period. Nevertheless, it can be seen that the operative temperature in the rooms without the modifications was far higher than the limits by about 2-`3°C. In contrast, the operative temperature in the measurement rooms exceeds the just about 1-1.3°C.

The SET* in the north facing room of the measurement unit was ranges from 27.5-32.2°C, which was about 1-2°C and 0.3°C lower than the control room during daytime and night-time, respectively. The reduction of SET* was also observed in the south facing room where the reduction is about 0.5°C during daytime and 0.2-0.3°C during night-time compared to the control room. The results indicate that the reduction of SET* was not only in the daytime, but also in the night-time due to the increase of wind flow by the whole house ventilation.

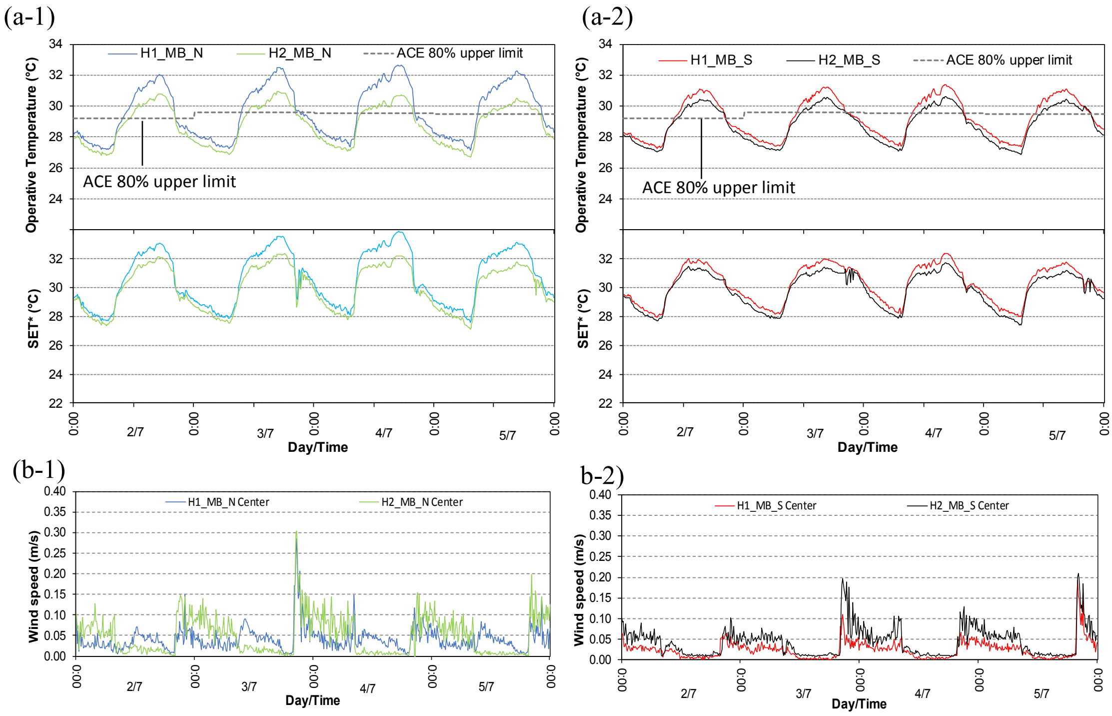


Figure 6.20. (a) Operative temperature (top) and SET* (bottom) in the master bedrooms of both houses in Case 2. (b) Wind speed in the living halls in Case 2.

6.5.4.2.4 Thermal comfort in the living halls

Figure 6.21 presents the temporal variations of air temperature, relative humidity and absolute humidity in the living hall of both houses. As shown, the daytime air temperature in the measurement unit ranges from 22.6- 28.9°C while in the control unit it was ranges from 26.8-30.2°C. In average, the air temperature reduction in the living hall of the measurement unit is about 0.3°C during daytime. In this case, relatively small air temperature reduction observed in the living hall compared to the rooms on the first floor. Meanwhile, at the night-time, it was found that the recorded air temperatures in both living halls was almost the same where the difference was less than 0.2°C even with the whole house ventilation has been applied. The relative humidity was almost similar in both living halls for most of the time, where they were ranges from 72-95%. In this case, the absolute humidity in both living halls which was ranges from 19-22 g/kg'.

Figure 6.22 presents the variations of operative temperature and SET* in the living halls including the respective indoor wind speed. As shown, the operative temperature in the measurement unit was slightly exceed the 80% of ACE upper limit by about 10% of the measurement period. In contrast, the living hall in the control unit largely exceed the limit by about 40% of the measurement period. In term of SET*, the result showed that the living hall in the measurement unit was always lower than that of control unit by about 0.6-1.0°C for the whole days. This is probably because slightly higher mean radiant temperature in the living hall of the control unit compared to the measurement unit.

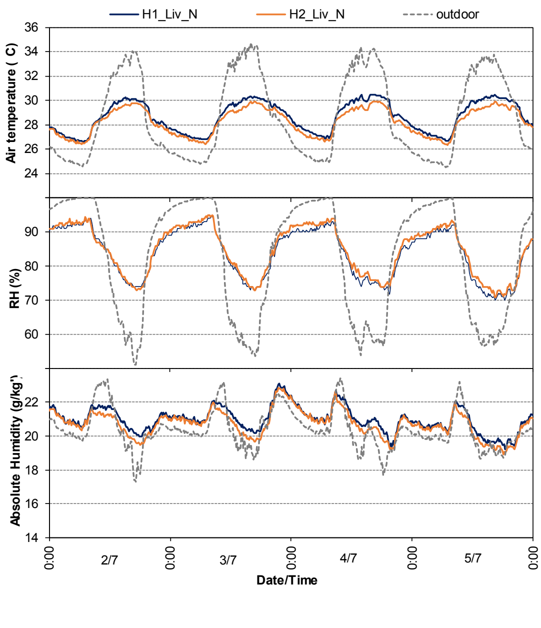


Figure 6.21. Temporal variations of air temperatures, RH and absolute humidity in the living hall of both houses in Case 2.

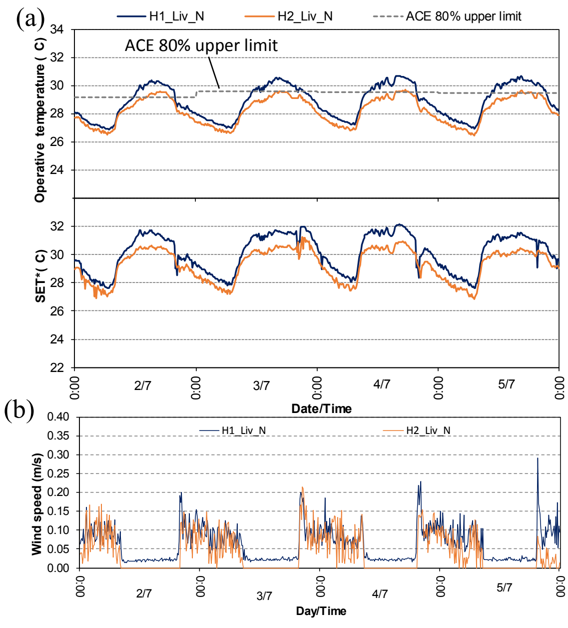


Figure 6.22. (a) Operative temperature (top) and SET* (bottom) in the living hall of both houses in Case 2. (b) Wind speed in the living halls in Case 2.

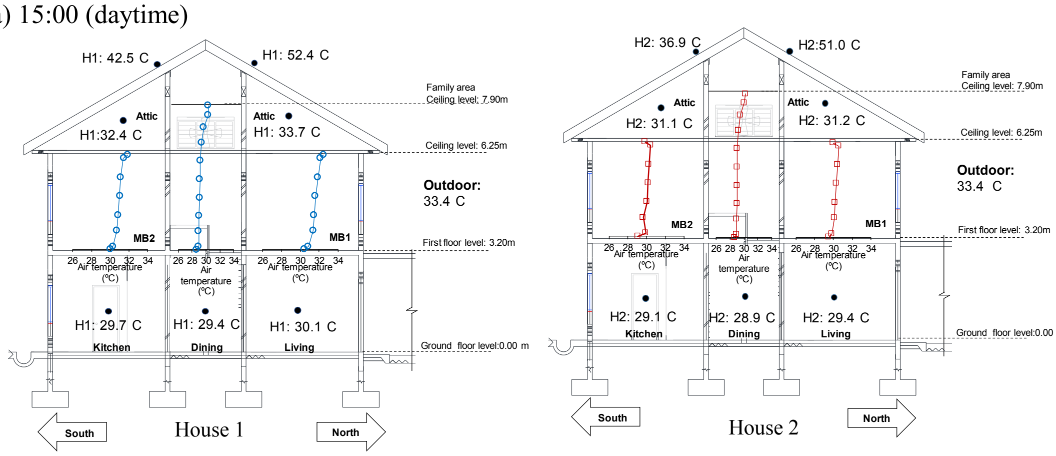
6.5.4.2.5 Thermal environment variations of the whole house

Figure 6.23 shows the air temperature variations of the whole house during daytime (15:00) and night-time (00:00). As shown, during daytime (15:00), the air temperatures increased with the increases of height. The lowest air temperatures observed on the ground floor of both houses (measurement and control unit). In the ground floor, the lowest air temperature recorded at the dining hall where the average temperature is about 29.4°C and 28.9°C in the control and the measurement unit, respectively. The highest air temperature was recorded at the living hall which is about 30.1°C and 29.4°C in the control and the measurement unit, respectively. In general, the ground floor spaces in the measurement unit have slightly lower average air temperature in all spaces compared to the control unit. The temperature difference between both houses in living hall, dining and kitchen spaces is 0.5°C, 0.5°C and 0.6°C, respectively.

Meanwhile, in the first floor, the air temperature in the master bedrooms increased with the increases of height from floor to the ceiling level. Slightly large gradient of air temperatures observed in the control unit. Large gradient means bigger air temperature differences between the floor and ceiling level. In the control unit, the temperature difference from floor to ceiling level was about 2°C while in the measurement unit, they were less than 1°C. This is simply because of high air temperature in the attic spaces above the rooms in the control unit. Nevertheless, the vertical air temperatures increased linearly from floor to the ceiling level in all rooms (control and measurement unit). In this case, the air temperature in the attic of north and south facing master bedrooms in the measurement unit was about 2.5°C and 1.3°C lower than that of in the control unit. This indicates that the roof insulation successfully reduces the attic air temperature during daytime.

During night-time (00:00), it was found that the air temperatures in the ground floor were almost similar in both houses. Moreover, the attic temperatures were found similar in both houses which was about 30°C. There was almost no gradient of vertical air temperatures in the master bedrooms of the measurement unit from the height of 0.1 m to 1.7 m above floor level. However, the vertical air temperature increase when the height is over 1.7 m until the ceiling. This is probably due the increased wind speed by the whole house ventilation was not uniformly distributed from the floor to the ceiling level. Nevertheless, the vertical air temperature in the measurement rooms were always lower than that of the living hall by about 0.3-0.5°C.

a) 15:00 (daytime)



b) 00:00 (night-time)

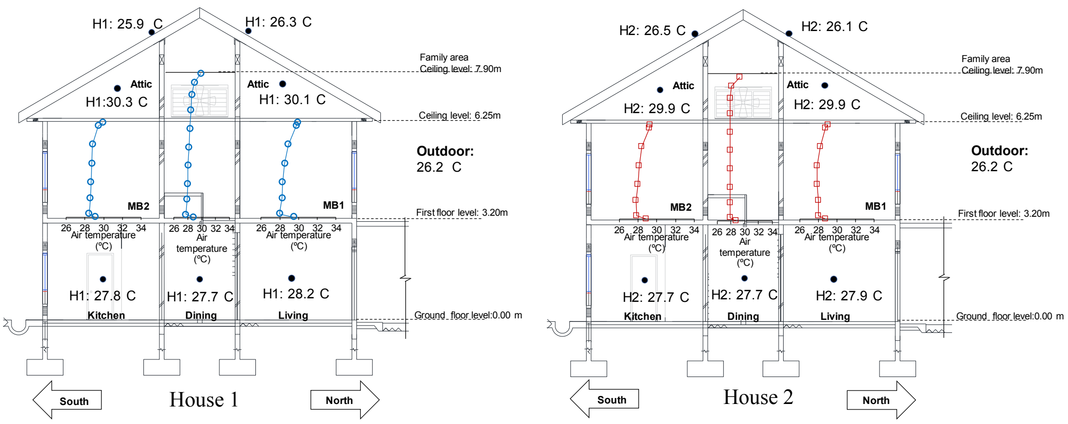


Figure 6.23. Whole house air and surface temperature distribution in House 1 (control unit) and House 2 (measurement unit) at (a) 15:00 (daytime) and (b) 00:00 (night-time) in Case 2.

Figure 6.24 presents the statistical summary of air temperature, relative humidity and absolute humidity in all spaces in both houses. In general, the nocturnal air temperature reduction was slightly improved due to the application of the whole house ventilation at night. However, the humidity level was also increased for the whole day. The maximum relative humidity in the living hall of the measurement unit was higher than the control unit by about 2-3% while in the master bedrooms, it was higher by about 5-7%. Meanwhile, the minimum relative humidity in the living hall increase by about 3% while in the master bedrooms, it was about 5-8%. As shown in the figure, the average absolute humidity in the measurement room were always lower than that of the control unit in the first floor. In contrast, the average absolute humidity in most of ground floor spaces were lower than that of the control unit.

(a)

(b)

(c)

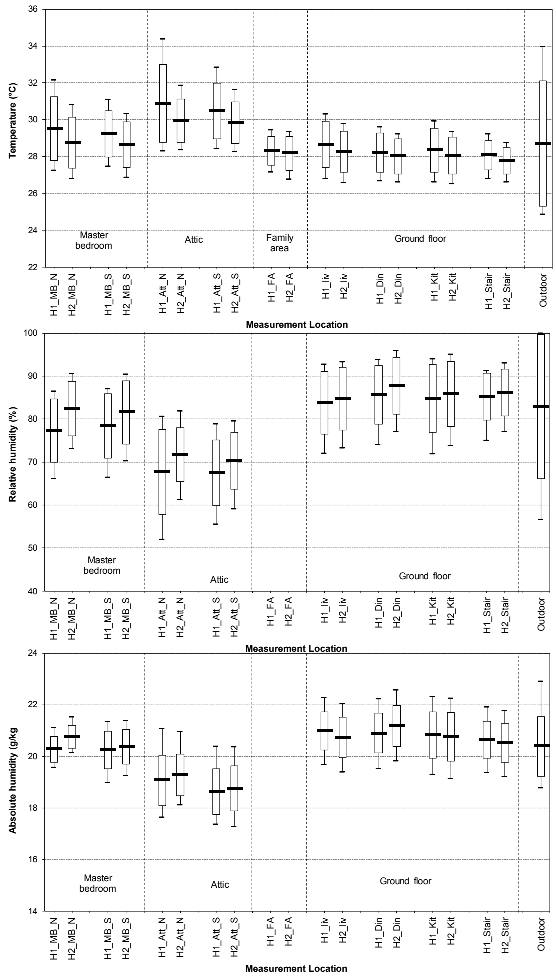


Figure 6.24. Statistical summary (5th and 95th percentiles, mean and ±one S.D.) of measurements (at 1.5 m above floor) of whole house in both House 1 and House 2 in Case 2. (a) Air temperature; (b) relative humidity; and (c) absolute humidity.

6.5.4.3 Case 3: Effects of 3 techniques, whole house ventilation and attic ventilation

6.5.4.3.1 Effects on indoor thermal environment of the master bedrooms

In case 3, the master bedroom fan (Case 3a) and attic ventilation fan (Case 3b) was adopted at night in addition to all modifications techniques of case 2. The purpose is to investigate the effect of the increase of ventilation rate in the master bedroom and cooler attic condition at the night-time. Moreover, the opening condition in both houses were different. In the control unit, the main windows were opened while in the measurement unit, only the slit windows were opened at the night-time. The opening condition in the control unit represents the typical opening condition in the modern houses. Meanwhile, in the measurement houses, the slit windows were opened to direct the wind flow near to the building structure, i.e. ceiling and floor with the purpose to enhance the structural cooling effects. Figure 6.25 shows the temporal variations of air temperatures, relative humidity and absolute humidity in the north and south facing rooms of both houses in case 3 under night ventilation condition. During the measurement period, the outdoor air temperature ranges from 23.8-32.5°C with the average of 27.8°C. Meanwhile, the outdoor relative humidity and absolute humidity ranges from 55-98% and 16.4 -20.8 g/kg' respectively. The average wind speed during daytime is about 0.30 m/s, while in the night-time, it was less than 0.1 m/s.

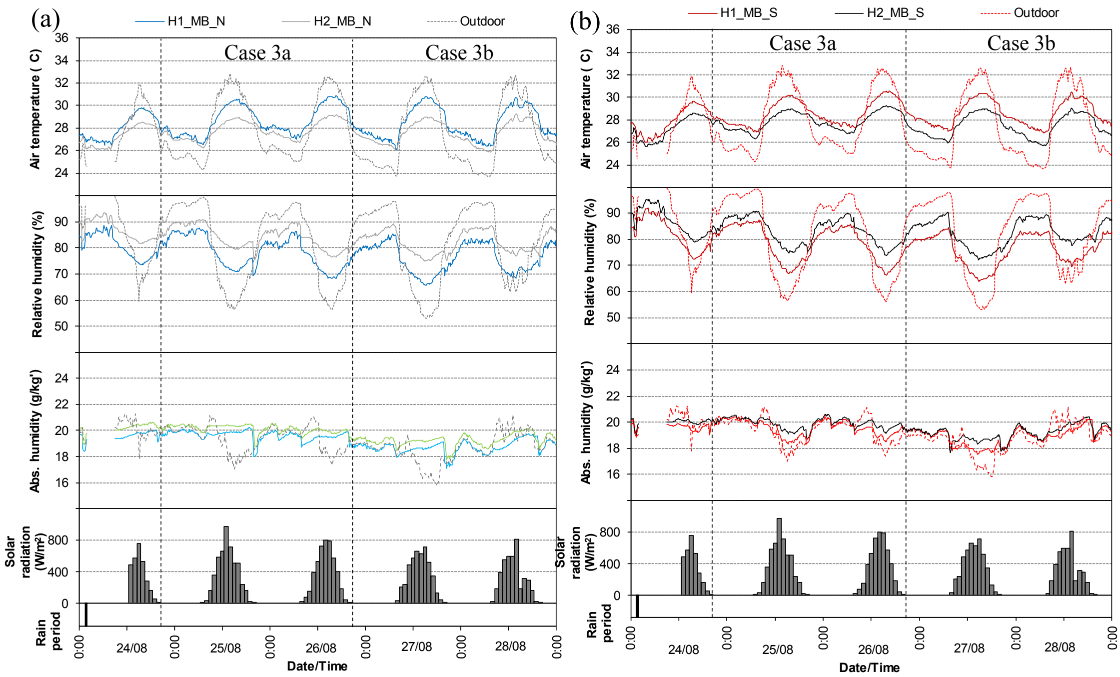


Figure 6.25. Temporal variations of air temperatures, RH and absolute humidity in the master bedrooms of House 1 and House 2 with the corresponding outdoor solar radiation and rain period in Case 3a and 3b. (a) North facing master bedroom (H1/H2_MB_N) (b) South facing master bedroom (H1/H2_MB_S)

In the case of master bedroom ventilation, the air temperature in the master bedrooms of the measurement unit were lower than the control unit during daytime by up to 1.7°C and 1.3°C in the north and south facing room, respectively. In average, the reduction is about 1.3°C and 1.0°C in both master bedrooms, respectively (Figure 6.26). Meanwhile, in the case of attic ventilation, the air temperature in the master bedrooms of the measurement unit were lower than the control unit during daytime by up to 1.8°C and 1.3°C in the north and south facing room, respectively. In average, the reduction is about 1.3°C and 1.2°C in both master bedrooms. In general, the daytime air temperature reduction in the master bedroom in both forced ventilation condition is about the same. In the night-time, the nocturnal air temperature in the master bedroom with the master bedroom ventilation was lower than that of the control room by about 0.4°C and 0.5°C in average in the north and south master bedroom, respectively. Meanwhile, in the case of attic fan ventilation, larger air temperature reduction observed in the south facing master bedroom which is about 1.1°C in average. In the same ventilation case, the average nocturnal air temperature reduction in the north facing master bedrooms is about 0.5°C. It was found that the air temperature reduction in this case was slightly larger than the previous two cases (case 1 and case 2). However, it should be noted that the opening position in both houses was different from the previous cases where the slit windows were opened in the measurement unit compared to the previous cases in which all windows were opened.

The relative humidity in the master bedrooms of the measurement unit were almost similar in both ventilation cases despites large volumes of air were introduced to the master bedroom by the master bedroom fan. In both ventilation cases, the recorded relative humidity in the measurement room was higher than that of the control unit. In the case of master bedroom ventilation, the average relative humidity in the master bedroom of the measurement unit was about 83-84%. On average, the relative humidity in the master bedroom of the measurement unit was higher than that of the control unit by about 6-7% during daytime and about 3-6% during the night-time. The average absolute humidity was about 20 g/kg'. Meanwhile in the case of attic ventilation, the average relative humidity in the master bedrooms of the measurement unit was about 82%. In average, the relative humidity in the master bedroom of the measurement unit was higher than that of the control unit by about 7-8% during daytime and about 4% during the night-time. The average absolute humidity was about 20 g/kg'.

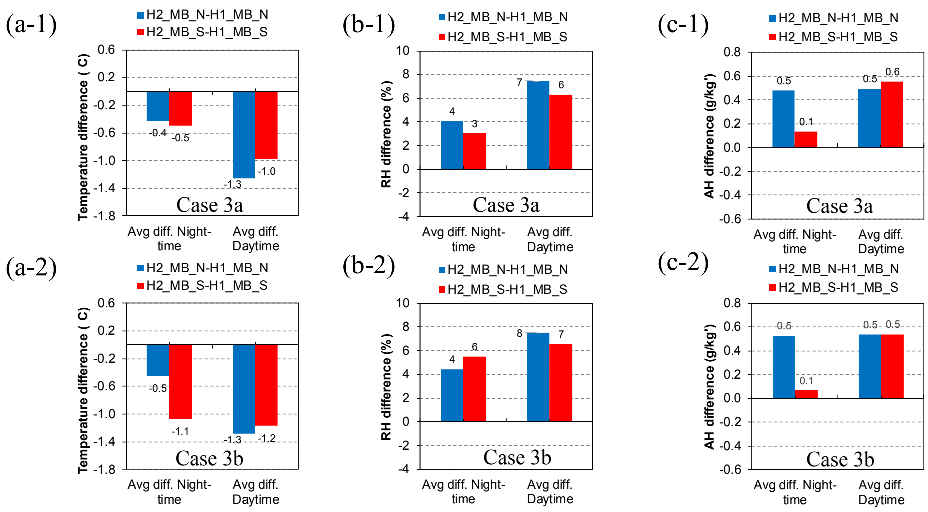


Figure 6.26. Statistical summary (5th and 95th percentiles, mean and ±one S.D.) of measurements (at 1.5 m above floor) in the master bedrooms in Case 3a and 3b. (a) Air temperature; (b) relative humidity; and (c) absolute humidity.

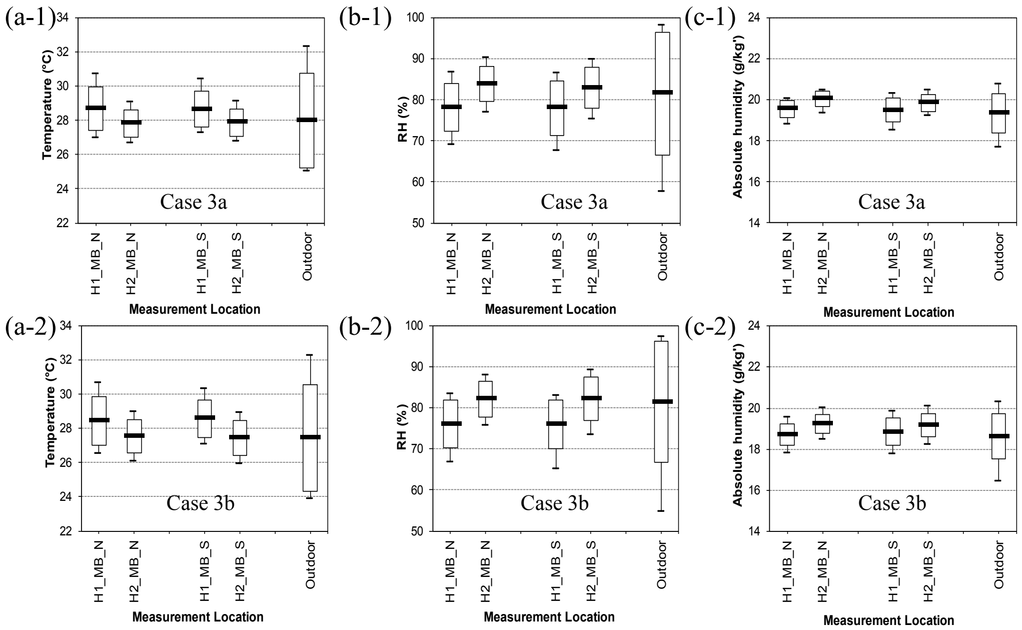


Figure 6.27. Statistical summary (5th and 95th percentiles, mean and ±one S.D.) of measurements (at 1.5 m above floor) in the master bedrooms in Case 3a and 3b. (a) Air temperature; (b) relative humidity; and (c) absolute humidity.

6.5.4.3.2 Heat fluxes and surface temperature in the master bedrooms

Figure 6.28 shows the results of heat fluxes on the inside surface of the external wall, end wall and the ceiling in the master bedrooms. Meanwhile, Figure 6.29 shows the average surface temperature difference between the master bedrooms in the measurement and control unit (measurement-control unit). In both ventilation cases, the daytime heat fluxes on the surface of the external walls in the measurement rooms was about 5 W/m^2 lower than that of the control unit. Meanwhile, in the night-time, the average heat flux was about 4 W/m^2 in the north facing master room and about 2.5 W/m^2 in the south facing master room in both ventilation cases.

As for the surface of the end wall, the daytime heat fluxes in the case of master bedroom ventilation (in the measurement unit) was about 5W/m^2 lower than that of in the control unit. Meanwhile, during night-time, the heat fluxes in the control unit was almost none while in measurement unit, they were about 3-5 W/m^2 of negative heat flows (heat release). In the case of attic ventilation, the heat flux in the measurement rooms was also lower than that of the control unit by about 5 W/m^2 during daytime. At the night-time, the heat fluxes in the measurement unit were almost the same as in the control unit.

In both ventilation cases, the heat fluxes on were on the positive side (absorbing) in for the ceiling of the master bedrooms in the control unit. In contrast, the heat fluxes of ceiling in the measurement master bedrooms were always in the negative side (heat release). This is because, the master bedrooms in the measurement unit were always cooler than that of in the control unit.

As shown in Figure 6.29, the surface temperature of the walls in the master bedrooms in the measurement unit were always lower than that of control unit for the whole day. In both cases, the highest reduction was on the surface of floor and ceiling (in the measurement unit). In the case of master bedroom ventilation, the temperature reduction on the ceiling was about 1.7°C and 1.9°C in the north and the south master bedroom. Meanwhile the reduction on the surface of the floor was about 1.1°C in average. On the other surrounding surfaces, the reduction was ranges from 0.2-1.2°C. In the night-time, the surface temperature of the master bedrooms in the measurement unit remained lower than the control unit by about 0.2-1.3°C.

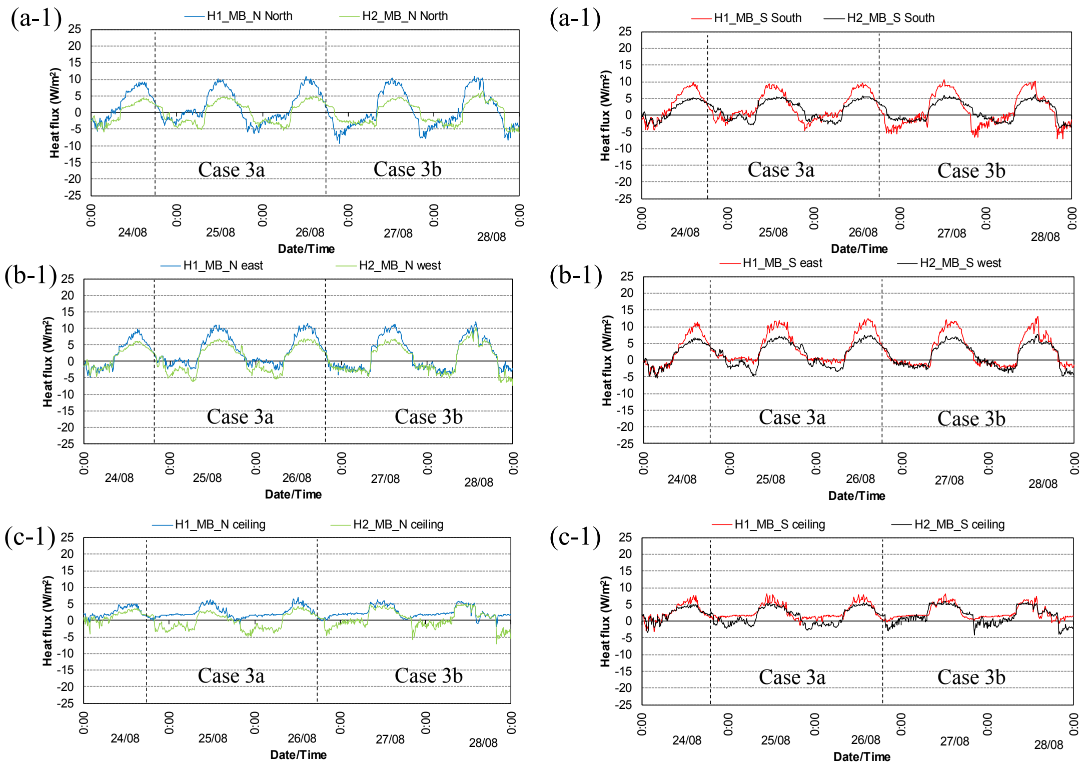


Figure 6.28. Heat fluxes on (a) external wall (inside); (b) end wall (inside) and (c) ceiling surfaces in north and south facing master bedrooms of both houses in Case 3a and 3b.

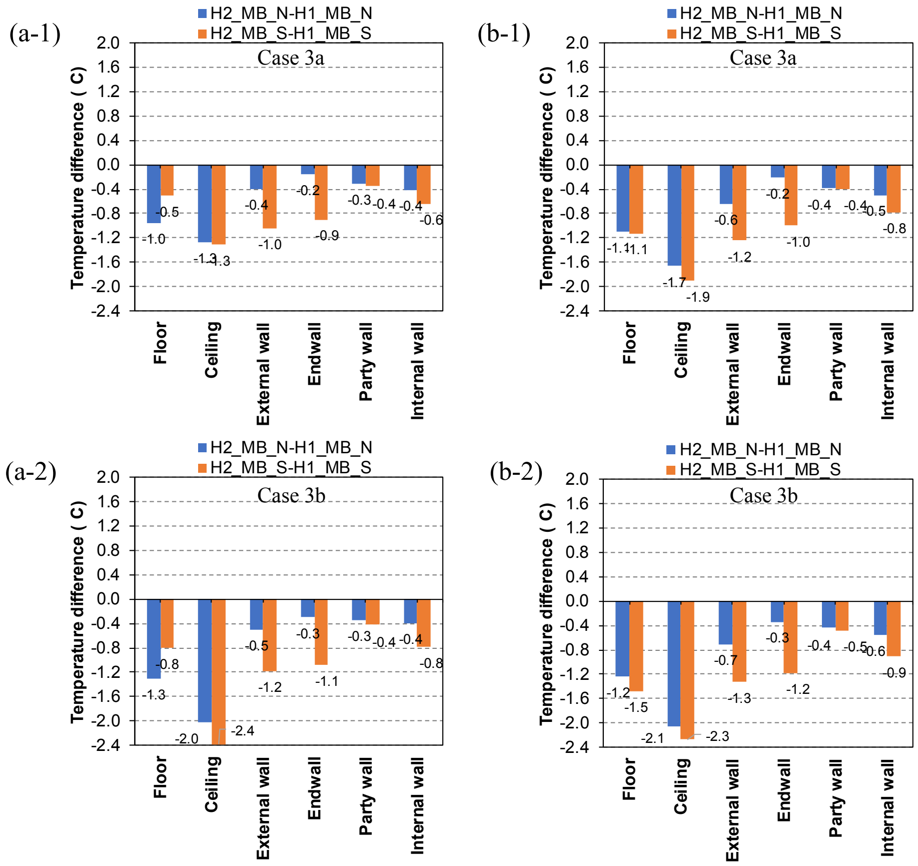


Figure 6.29. Average surface temperature difference between master bedroom in House 2 and House1 (House2 – House 1) in Case 3a and 3b during (a) night-time and (b) daytime.

In the attic ventilation case, the temperature reduction on the ceiling and floor surface were slightly larger than the former case (master bedroom ventilation). In daytime, the reduction on the ceiling surface can be as large as 2.3°C. Meanwhile the reduction on the surface of floor was about 1.2-1.5°C. In the night-time, the largest reduction was still on the ceiling surface which was about 2.0 and 2.4°C in the north and south facing master bedroom, respectively. The reduction of the floor surface temperature was ranges from 0.8-1.3°C. In this case, the reduction on the surrounding walls were lower than the former case especially in the south facing master bedroom. The reduction of surface temperature in the attic ventilation case was larger than that of the master bedroom ventilation case despites lower indoor wind speed at the night-time.

6.5.4.3.3 Thermal comfort in the master bedrooms

Figure 6.30 shows the result of calculated operative temperature and SET* in the master bedrooms including the respective indoor wind speed in case 3. During the measurement, the indoor wind speed in the master bedrooms with the ventilation fan were largely improved where the wind speed was larger than that of the control room by about 0.4 m/s and 0.5 m/s in the north and south master bedroom, respectively. This is simply because the direct wind supply from the master bedroom ventilation fan. Meanwhile, in the case of attic fan, the wind speed in the master bedrooms of the measurement unit were slightly larger than that of control room by about 0.1 m/s.

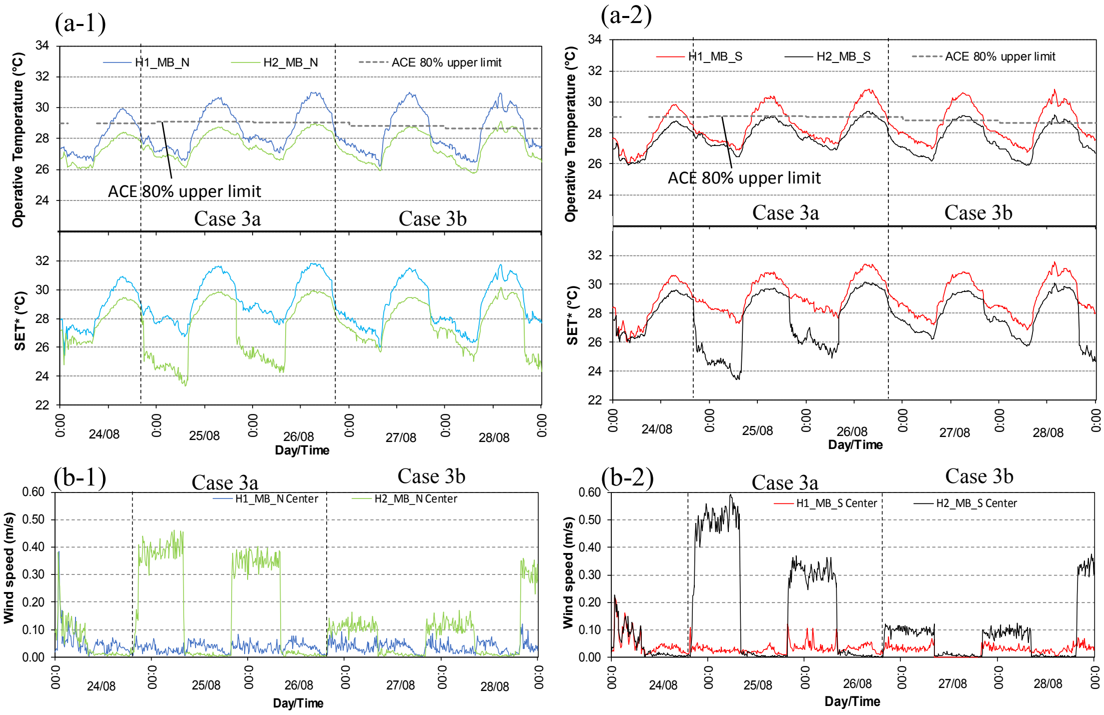


Figure 6.30. (a) Operative temperature (top) and SET* (bottom) in the master bedrooms of both houses in Case 3a and 3b. (b) Wind speed in the living halls in Case 3a and 3b.

In both cases (master bedroom and attic ventilation), the operative temperature in the master bedrooms of the measurement unit fall under the 80% of ACE upper limit for most of the time. In contrast, the operative temperatures of the master bedrooms in the control unit exceed the limits for about 40% of the measurement period. This indicates that the modification techniques successfully lowering the operative temperature of the master bedrooms.

As shown in the figure, the SET* in the master bedroom ventilation case were much lower than that of control unit during night-time. Due to the direct inflow of wind, the SET* of the master bedroom was reduced by up to 4°C lower than the control unit. Meanwhile, in the case of attic ventilation, the reduction was only about 0.5°C. This indicates that the increase of indoor wind speed is important to reduce the SET* value.

6.5.4.3.4 Thermal comfort in the living halls

Figure 6.31 presents the temporal variations of air temperature, relative humidity and absolute humidity in the living hall of both houses. As shown, the daytime air temperature in the measurement unit ranges from 26.0- 28.2°C while in the control unit it was ranges from 26.0-29.0°C. In both cases, the living hall air temperature were lower than that of the control unit by about 0.8°C in average, during the daytime. Meanwhile, in the night-time the air temperature in the living hall of the measurement unit was almost similar as in the control unit. In this case, the relative humidity in the living hall of both houses were also similar which were ranges form 72-93%. As for the absolute humidity, the value in the measurement unit was lower than the control room during daytime by 0.6 g/kg' in average.

Figure 6.32 presents the variations of operative temperature and SET* in the living halls including the respective indoor wind speed. As shown, the operative temperatures in the living hall of the measurement unit always fall under the 80% of ACE upper limit in both cases. Unlike in the master bedroom, the SET* in the living hall in the case of master bedroom ventilation was almost the same as in the control room. The SET* was ranges from 26.5-30.2°C. This is simply because the wind condition in the living hall is not affected by the increase of wind speed in the master bedroom. Similar situation observed in the case of attic ventilation where the SET* between living halls in both house was almost the same which were ranges from 26.0-30.0°C.

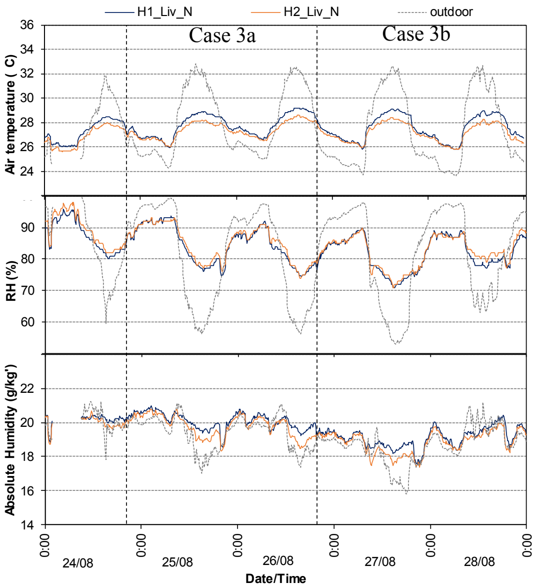


Figure 6.31. Temporal variations of air temperatures, RH and absolute humidity in the living hall of both houses in Case 3a and 3b.

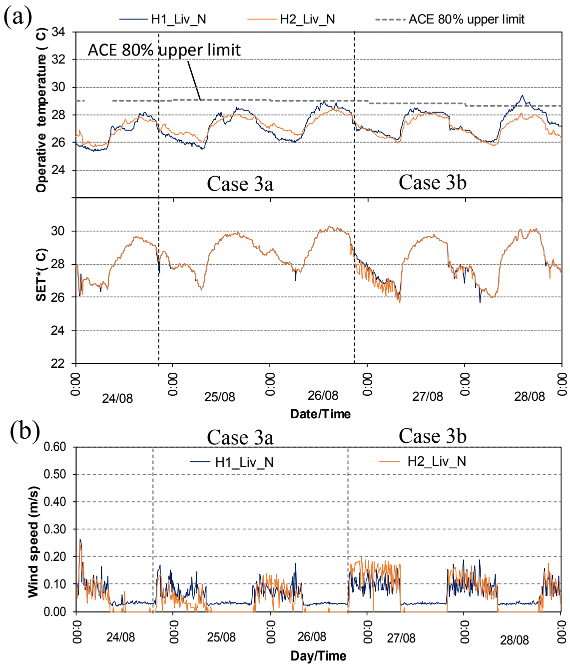
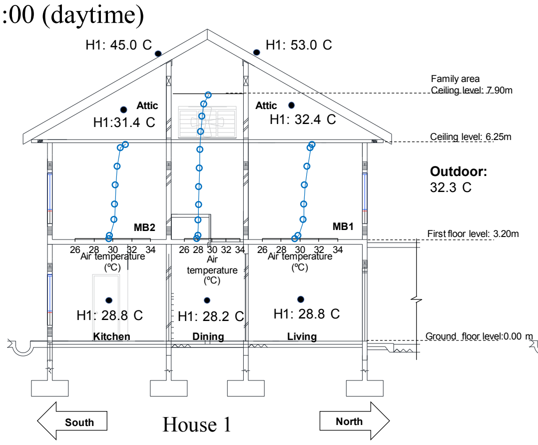


Figure 6.32. (a) Operative temperature (top) and SET* (bottom) in the living hall of both houses in Case 3a and 3b. (b) Wind speed in the living halls in Case 3a and 3b.

6.5.4.3.5 Thermal environment variations of the whole house

Figure 6.33 shows the air temperature variations of the whole house during daytime (15:00) and night-time (00:00) in the case of master bedroom ventilation. As shown, in the daytime (15:00), the air temperatures in all spaces in the ground floor of the measurement unit were always lower than that of the control unit by about 0.4-0.7°C. Meanwhile, in the master bedrooms, the vertical air temperature distribution in the master bedrooms of the measurement unit were almost lower than that of the control room by about 2°C. In the night-time (00:00), the air temperature in the ground floor of both houses were almost the same where the difference was less than 0.3°C. In the first floor, the vertical distribution of air temperature in the master bedroom of the measurement unit was almost vertical with no gradient. This indicates that the air temperatures were uniformly reduced from the floor to the ceiling level. Meanwhile in the control room, the gradient of vertical temperature distribution was occurred and the difference from the floor to the ceiling level was up to 1°C.

a) 15:00 (daytime)



b) 00:00 (night-time)

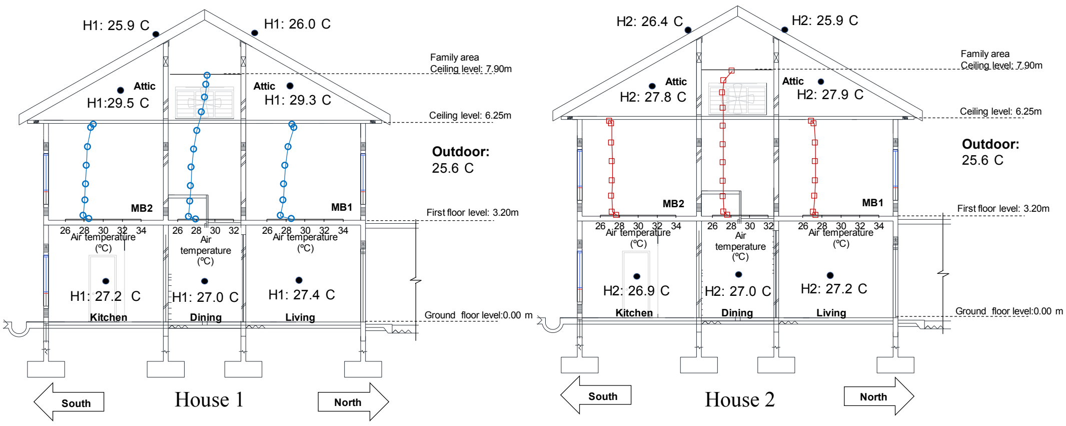
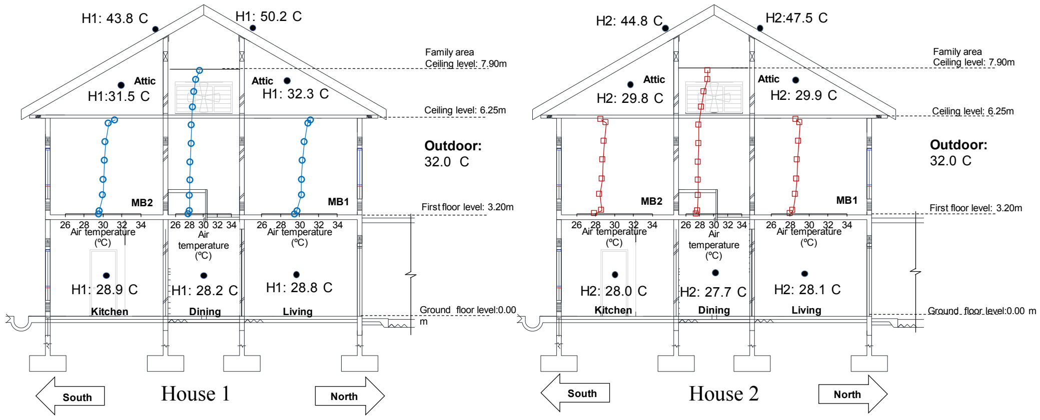


Figure 6.33. Whole house air and surface temperature distribution in House 1 (control unit) and House 2 (measurement unit) at (a) 15:00 (daytime) and (b) 00:00 (night-time) under the case of master bedroom ventilation in Case 3a.

In the case of attic fan (Figure 6.34), large reduction observed on the ground floor during the daytime (15:00) especially in the kitchen which was about 0.9°C. In first floor, vertical air temperature gradient was observed in both houses. In the measurement unit, the vertical temperature gradient was about 1°C from the floor to the ceiling. Meanwhile, in the control unit, the vertical temperature gradient was slightly larger which is about 1.5°C from the floor to the ceiling. In the night-time (00:00), the air temperature reduction in the ground floor was ranges from 0.1-0.3°C. Similar to the previous case, the vertical distribution of air temperatures in the master bedroom of the measurement unit was almost have no gradient. Meanwhile in the control room, the gradient of vertical temperature distribution was occurred and the difference from floor to the ceiling level was about 1-1.5°C.

a) 15:00 (daytime)



b) 00:00 (night-time)

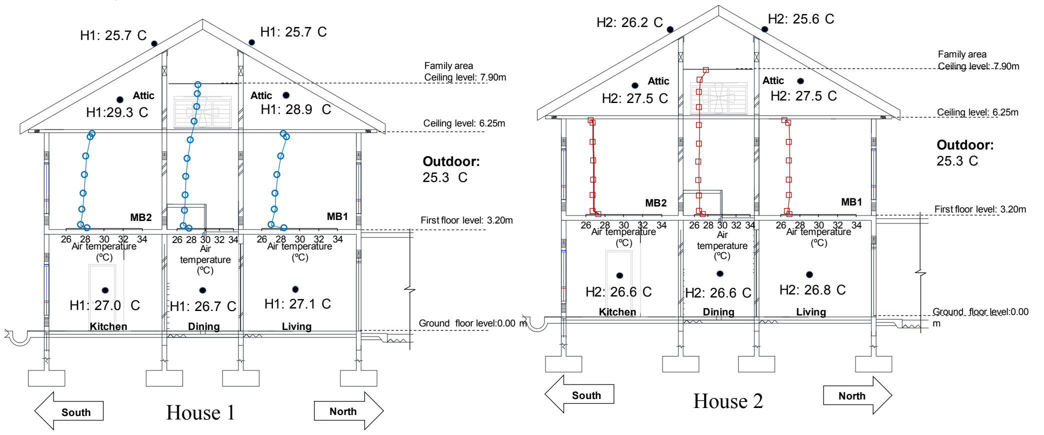


Figure 6.34. Whole house air and surface temperature distribution in House 1 (control unit) and House 2 (measurement unit) at (a) 15:00 (daytime) and (b) 00:00 (night-time) under the case of attic ventilation in Case 3b.

Figure 6.35 presents the statistical summary of air temperature, relative humidity and absolute humidity in all spaces in both houses with the master bedroom and the attic fan. In general, the performance of the modifications in both cases were almost the same in all aspects. The main difference was on the SET* results in the master bedroom. The master bedrooms in the measurement unit have much lower SET* due to direct ventilation provided the master bedroom ventilation fan. In term of air temperature, slightly lower values observed in all spaces during night-time in the case of attic ventilation. This is probably due to the lower nocturnal outdoor condition during the measurement. The air temperature reduction was about the same in both cases. The average air temperature reduction in the master bedrooms was about 0.8°C and in the living hall was about 0.5°C in average. Average relative humidity in both cases is about 80% while the average absolute humidity in the master bedroom and the living hall was about 20 g/kg’ in the case of master bedroom ventilation and about 19 g/kg’ in the case of attic fan ventilation.

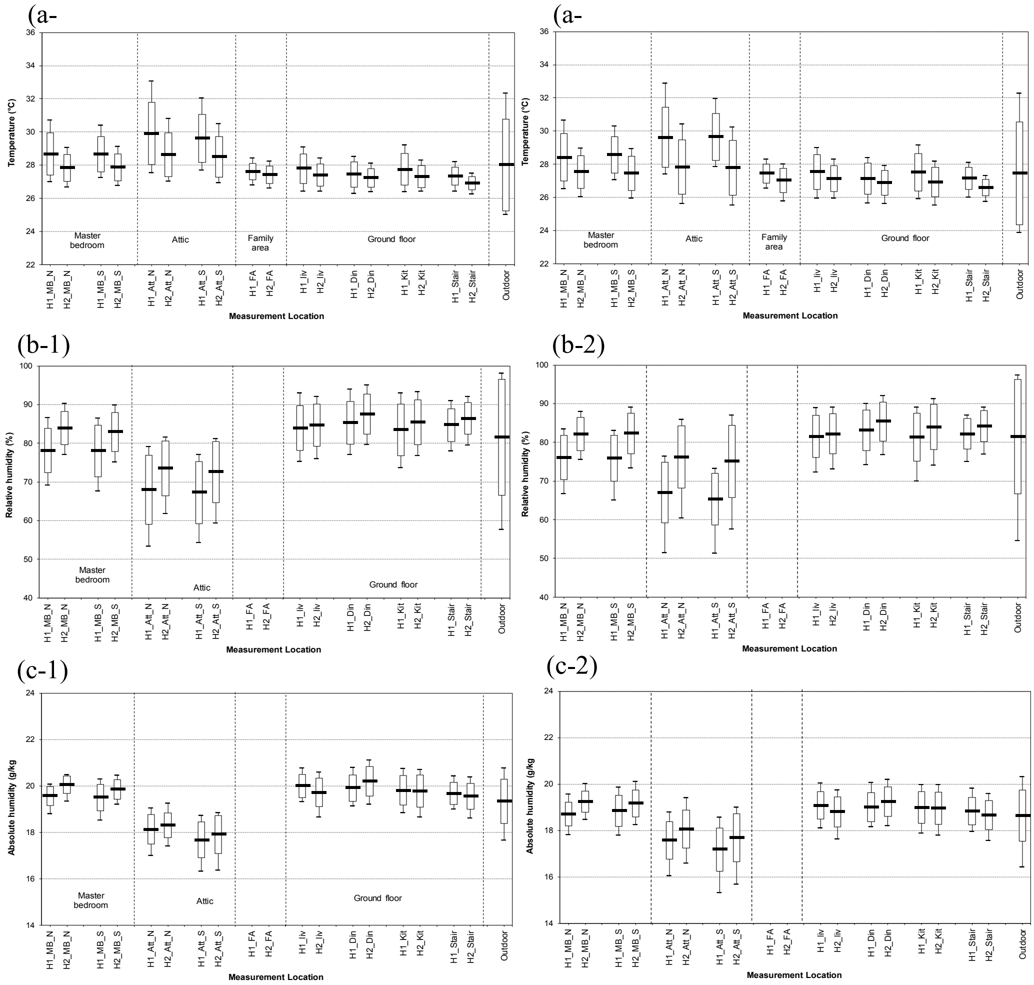


Figure 6.35. Statistical summary (5th and 95th percentiles, mean and ±one S.D.) of measurements (at 1.5 m above floor) of whole house in both House 1 and House 2 in Case 3a and 3b. (a) Air temperature; (b) relative humidity; and (c) absolute humidity under the case of master bedroom (left) and attic ventilation (right).

6.5.5 Comfort ventilation strategy (full-day ventilation)

6.5.5.1 Case 4: Effects of 3 techniques

6.5.5.1.1 Effects on indoor thermal environment of the master bedrooms

Similar to Case 1, the modification techniques in Case 4 were roof insulation, external wall outside insulation and external shading devices. In this case, the opening condition in both houses was the same. In both houses, all windows were opened throughout the measurement period.

Figure 6.36 shows the temporal variations of air temperatures, relative humidity and absolute humidity in north and south facing rooms of both houses in Case 4. The result of solar radiation and rain period of outdoor are also included. During the measurement period, the outdoor air temperature ranges from 22.7-34.2°C with the average of 27.2°C. Meanwhile, the outdoor relative humidity and absolute humidity ranges from 50-100% and 16.2-23.2 g/kg' respectively. The average wind speed during daytime is about 0.25 m/s, while in the night-time, it was less than 0.1 m/s.

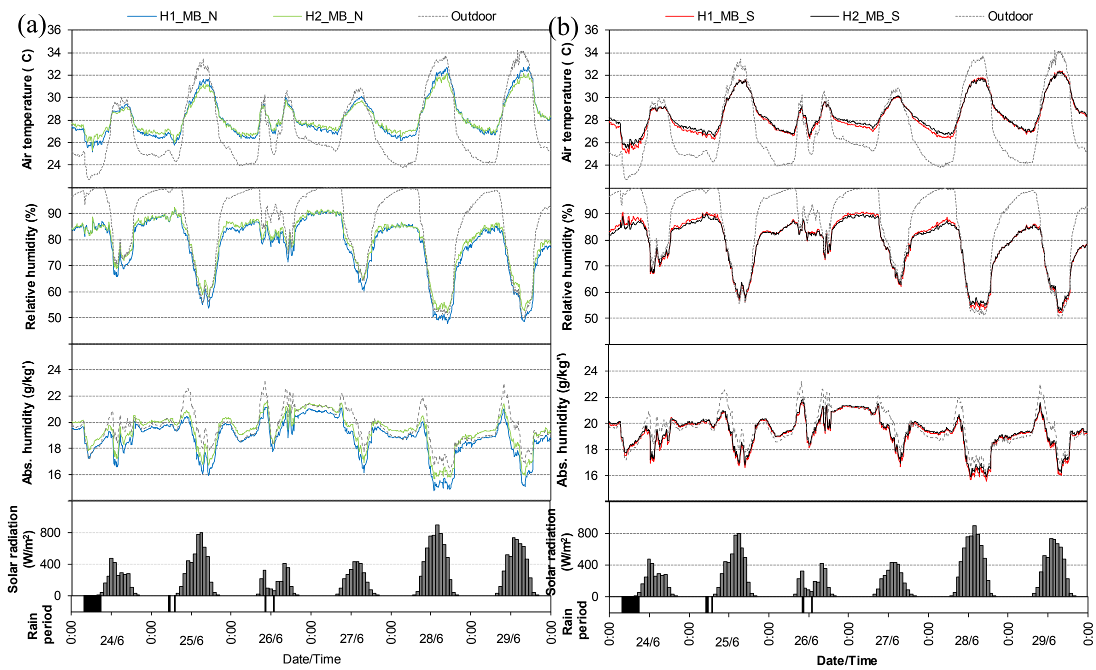


Figure 6.36. Temporal variations of air temperatures, RH and absolute humidity in the master bedrooms of House 1 and House 2 with the corresponding outdoor solar radiation and rain period in Case 4. (a) North facing master bedroom (H1/H2_MB_N) (b) South facing master bedroom (H1/H2_MB_S).

As shown in Figure 6.37, the air temperature in the master bedrooms in the measurement unit were lower than the control during daytime but only with a small difference. In the north facing master bedroom the reduction was about 0.3°C while no significant reduction in the south facing master bedroom. This is simply because the inflow of warm air into the room and reduce the effects of the modifications techniques. Meanwhile, in the night-time, the air temperature in the master bedrooms of the measurement unit were higher than that of the control unit by up to 0.5°C and 0.3°C in the north and south facing master bedroom, respectively. In average, the air temperature in the measurement unit were higher by about 0.3°C and 0.2°C in the north and south facing master bedroom, respectively. This is probably because the roof insulation prevented the heat from releasing to the night-sky.

In this case, the indoor relative humidity in the measurement unit was almost the same as in the control unit for the whole day. The relative humidity in the in the master bedroom of the measurement unit ranges from 50-90%. In daytime, the average relative humidity in the north facing room in the measurement unit was larger than that of the control unit by about 1.3% while in the south facing room, it was larger by about 1 %. In the night-time, the relative humidity difference between the houses was smaller which is about 1%. Meanwhile, the absolute humidity in measurement house always higher than the control room during day and night which is about 0.2-0.7 g/kg'.

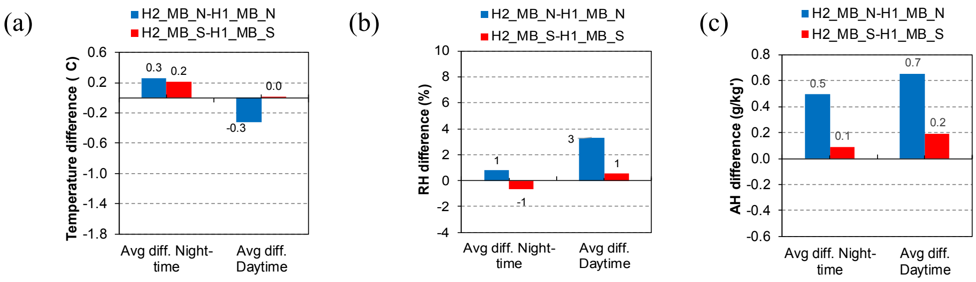


Figure 6.37. Average difference between master bedroom in House 1 and House 2 (House 2-House1) for north and south direction in daytime and night-time in Case 4. (a) Air temperature; (b) relative humidity; and (c) absolute humidity.

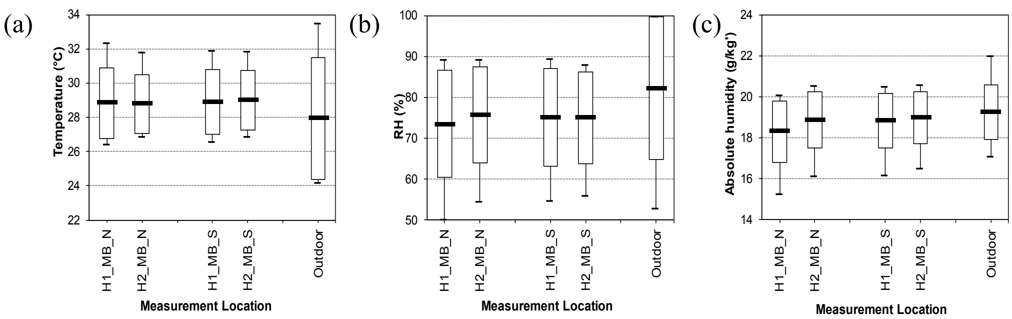


Figure 6.38. Statistical summary (5th and 95th percentiles, mean and ±one S.D.) of measurements (at 1.5 m above floor) in the master bedrooms in Case 4. (a) Air temperature; (b) relative humidity; and (c) absolute humidity.

6.5.5.1.2 Heat fluxes and surface temperature in the master bedrooms

Figure 6.39 shows the results of heat fluxes on the inside surface of the external wall, end wall and the ceiling in the master bedrooms. Meanwhile, Fig 6.40 shows the average surface temperature difference between the master bedrooms in the measurement and control unit (measurement-control unit). As shown, the heat fluxes on the external wall in the measurement unit increased closely to the level of heat fluxes in the control unit during daytime. The maximum heat fluxes in the measurement unit were lower than the control unit by only 3-6 W/m^2 in fine weather days. This indicates the effects of insulation was smaller in the full-day ventilation case. In the night-time, the external wall in the control unit showed slightly better heat released compared to the measurement unit where the difference was up to 5 W/m^2 in the north facing master bedroom and up to 2.5 W/m^2 in the south facing master bedroom.

The heat fluxes on the end wall of both houses were almost similar during the whole day. For instance, in the north facing master bedroom (measurement unit), the heat fluxes increased to as high as 24 W/m^2 during daytime. Meanwhile, in the night-time the negative heat fluxes was as high as 5 W/m^2. Even though the heat fluxes in both rooms are quite similar, the average surface temperature on the end wall in measurement room was slightly higher than that of the control unit by about 0.7°C and 0.8°C during daytime and night-time in the north facing room. In contrast, the surface temperature on the end wall of the south facing master bedroom was almost the same in both houses. The average surface temperature difference was about 0.1 difference during day and night-time.

In the north facing room of the measurement unit, the heat fluxes on the ceiling was slightly larger than that of control unit during daytime by up to 5W/m^2. Meanwhile, in the night-time, the heat fluxes on that ceiling of was almost the same between both houses which ranges from -2 W/m^2 to 2 W/m^2. Meanwhile, the heat fluxes on the ceiling on the south facing master bedroom was almost the same between both house for the whole day. They were ranges from -5 W/m^2 to -15 W/m^2.

As shown in Figure 6.40, the surface temperature of the walls in the master bedrooms in the measurement unit were lower than that of control unit for most of daytime except for the end wall in the north facing room and the internal wall of both rooms in the measurement unit. The largest surface temperature reduction was on the ceiling of the master bedrooms. The average reduction is 1.2°C and 0.8°C in the north and south facing master bedroom, respectively. This is probably because the thermal reduction in the attic space was provided by the roof insulation (almost the same as Case 1). Moreover, the floor surfaces were also cooler than that of the control unit by about 0.2°C and 0.4°C in the north and south facing room, respectively.

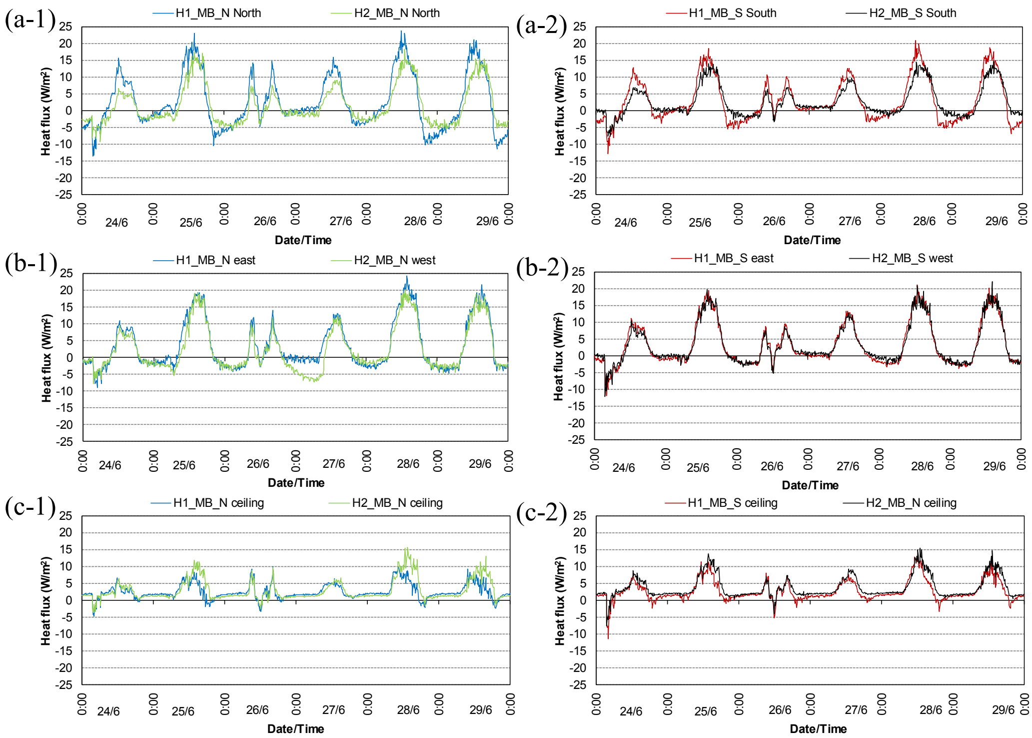


Figure 6.39. Heat fluxes on (a) external wall (inside); (b) end wall (inside) and (c) ceiling surfaces in north and south facing master bedrooms of both houses in Case 4.

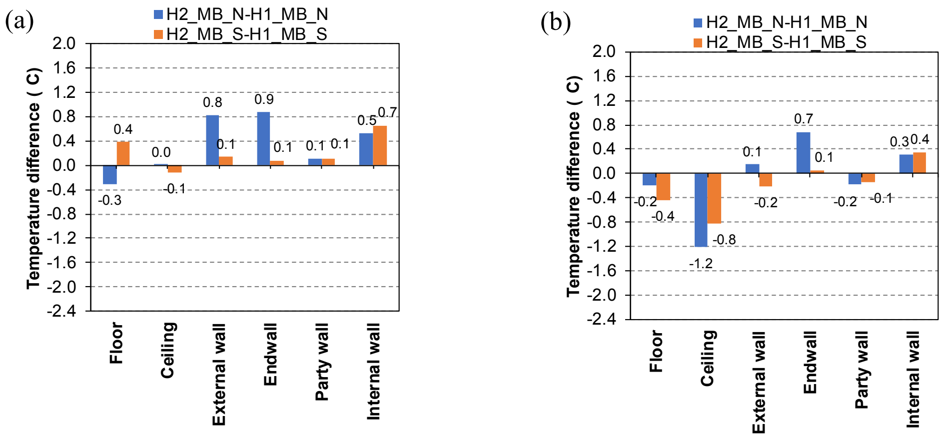


Figure 6.40. Average surface temperature difference between master bedroom in House 2 and House1 (House2 – House 1) in Case 4 during (a) night-time and (b) daytime.

6.5.5.1.3 Thermal comfort in the master bedrooms

Figure 6.41 shows the result of calculated operative temperature and SET* in the master bedrooms including the respective indoor wind speed in case 4. During the measurement period, the recorded indoor wind speed in all master bedroom were about 0.1-0.3m/s for most of the time. To be noted that in this case, the wind speed during daytime was higher than that of night-ventilation by about 0.2 m/s due to opened window condition. Meanwhile, at night-time, the wind speed was less than 0.1 m/s which is quite similar to that of Case 1.

In this case, the operative temperature in the master bedrooms of the measurement unit were almost similar to that of the control unit for the whole day. As a result, the operative temperature in both master bedrooms in the measurement unit exceed the 80% ACE upper comfort limit by about 40% of the measurement period. Meanwhile, the calculated SET* in the master bedroom of the measurement unit were almost the same as in the control unit where the they were ranges from 26-32°C. This indicates that, even with the modification techniques, the operative temperature and the SET* in the master bedrooms of the measurement unit could not be lower than that of the control unit under the full-day ventilation condition.

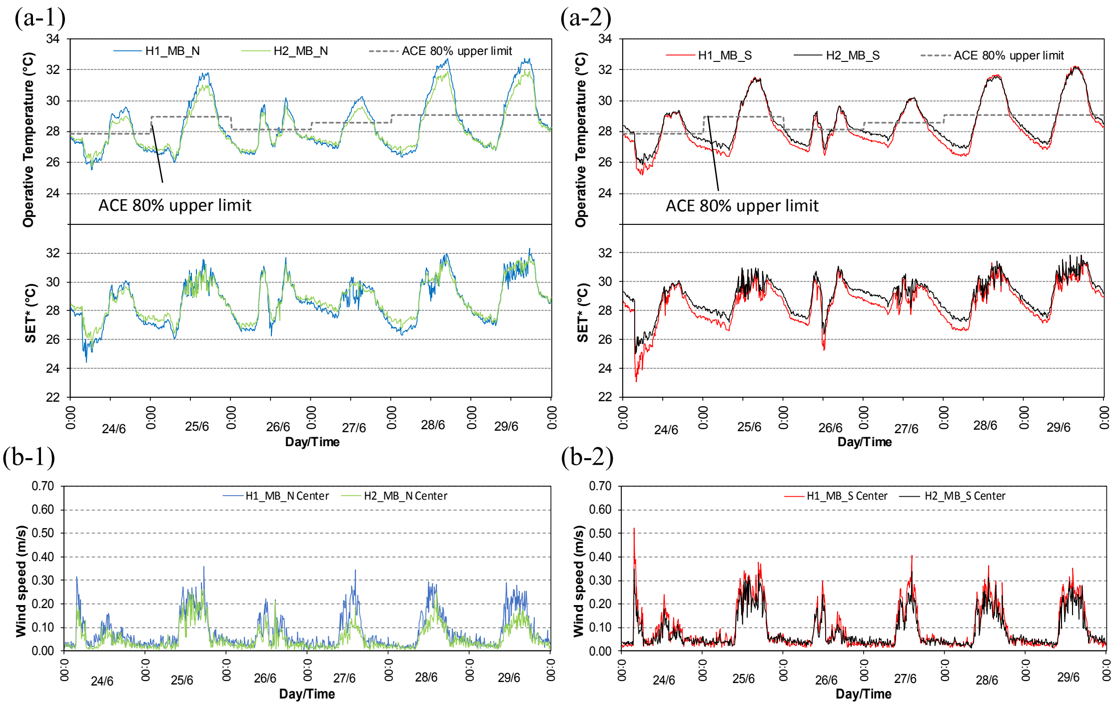


Figure 6.41. (a) Operative temperature (top) and SET* (bottom) in the master bedrooms of both houses in Case 4. (b) Wind speed in the living halls in Case 4.

6.5.5.1.4 Thermal comfort in the living halls

Figure 6.42 presents the temporal variations of air temperature, relative humidity and absolute humidity in the living hall of both houses. Due to the full-day ventilation, the air temperatures in the living hall of both houses were almost the same which ranges from 26.0-31.3°C. There was almost no air temperature reduction observed during the daytime. Meanwhile, in the night-time, the air temperature in the living hall of the measurement unit was slightly higher than that of control unit by about 0.1-0.2°C due to same reason as in Case 1.

The relative humidity was almost similar in both living halls for most of the time, where they were ranges from 55-95%. In the daytime, the relative humidity in the measurement unit was slightly lower than that of control unit by about 3%. Meanwhile, almost the same level of relative humidity observed in both houses during the night-time. In this case, the absolute humidity in both living halls was ranges from 16-22 g/kg'.

Figure 6.43 presents the variations of operative temperature and SET* in the living halls including the respective indoor wind speed. As shown, the operative temperature in the measurement unit was increased and closely follows that of in the control unit. In the fine weather days, the operative temperature in the measurement unit was slightly lower than the control unit by about 0.4°C during the daytime. Thus, the exceeding period in the living hall of the measurement unit exceeds the thermal comfort limit by about 32% of the measurement period. Meanwhile, the SET* in both living halls were almost similar which is ranges from 25-31.5°C.

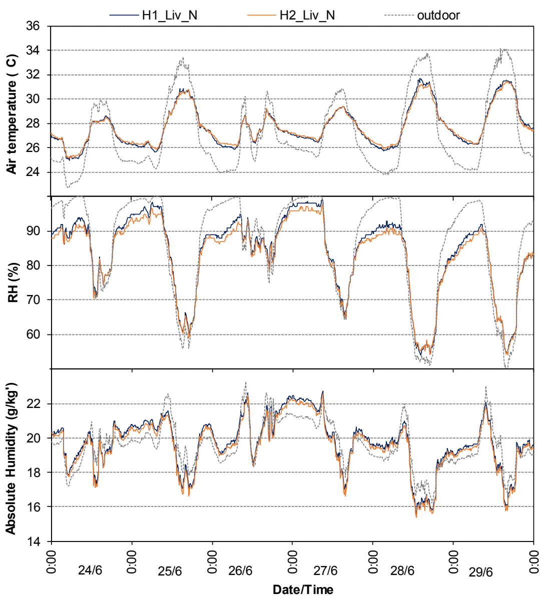


Figure 6.42. Temporal variations of air temperatures, RH and absolute humidity in the living hall of both houses in Case 4.

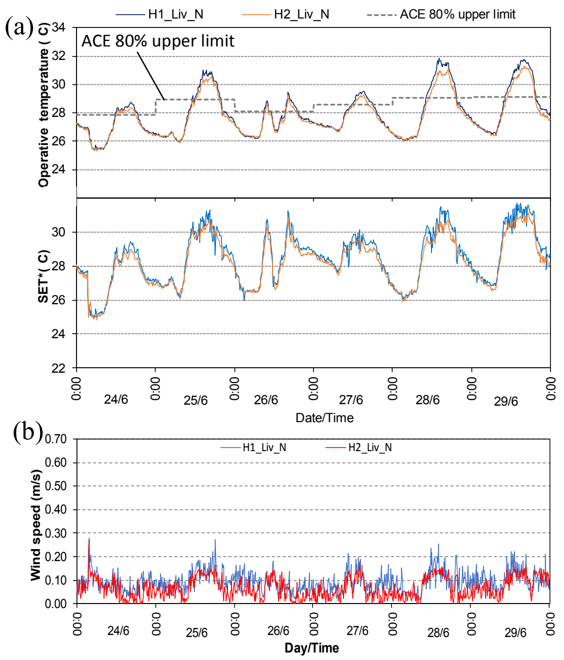
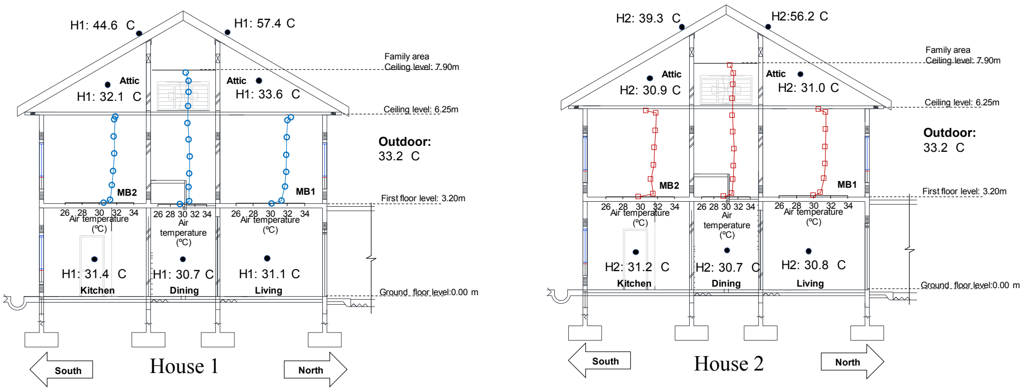


Figure 6.43. (a) Operative temperature (top) and SET* (bottom) in the living hall of both houses in Case 4. (b) Wind speed in the living halls in Case 4.

6.5.5.1.5 Thermal environment variations of the whole house

Figure 6.44 shows the air temperature variations of the whole house during daytime (15:00) and night-time (00:00). As shown, during daytime (15:00), the air temperatures increased with the increases of height. The lowest air temperatures observed on the ground floor of both houses (measurement and control unit). In general, during daytime (15:00), the roof surface of north facing side were hotter than the south facing side. In north facing side, the surface temperature range 57.4-56.2°C while on the south facing side, it was ranges from 44.6 -39.3°C. This indicates that the solar radiation is more intense on the northern side. Due to the roof insulation, the attic temperature in measurement unit was is lower than that of control unit by about 2.6°C in the north facing room. Meanwhile, in the south facing room, the attic space was lower than the control unit by about 1.2°C. However, due to the opened window condition, the air temperature in the master bedrooms in both houses were almost

a) 15:00 (daytime)



b) 00:00 (night-time)

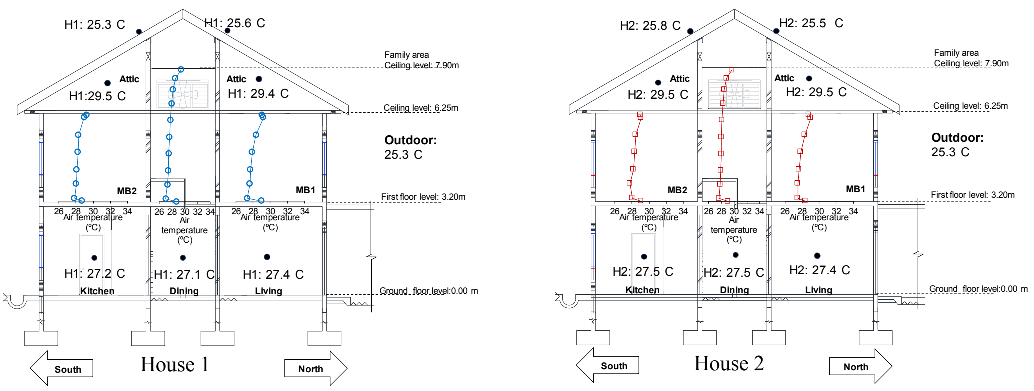


Figure 6.44. Whole house air and surface temperature distribution in House 1 (control unit) and House 2 (measurement unit) at (a) 15:00 (daytime) and (b) 00:00 (night-time) in Case 4.

the same. It can be seen from vertical temperature distribution where all rooms recorded almost the same vertical air temperature which is about 32°C. Nevertheless, the ceiling in the master bedroom of the measurement unit were slightly cooler than that of the control unit due to slightly cool attic condition. In the ground floor, small air temperature reduction was observed. The air temperature in the living hall and kitchen in the measurement unit were slightly lower than that of control unit by about 0.3°C and 0.2°C respectively. Meanwhile no reduction observed in the dining hall.

During night-time (00:00), the temperature of the roof surfaces was almost the same between each room where it ranges from 25.3-25.6°C. It can be seen that, even though the measurement unit were equipped with the roof insulation, the air temperature of the attic spaces was almost the same compared to the control unit. In the master bedrooms, the air temperature increase with the increase of height. This is because the attic spaces were hotter than that of the master bedroom. In both houses, the vertical temperature in the master bedroom were almost have the same values. This indicates that not much difference of air temperature between the master bedroom with 3 techniques and without techniques. In ground floor, the dining and the kitchen of the measurement unit recorded slightly higher air temperature that the control unit. The air temperature in dining and kitchen of the measurement unit was higher by about 0.4 and 0.3°C than that of in the control unit. Meanwhile no air temperature difference observed in the living hall. This is probably because of slightly higher ventilation rate in the ground floor of the control unit which helps to remove the heat from the building.

Figure 6.45 presents the statistical summary of air temperature, relative humidity and absolute humidity in all spaces in both houses. In general, it can be seen that the average air temperature in in both houses were almost similar in the master bedrooms as well as in the ground floor. On the ground floor, the air temperature in the indoor spaces were between 28-28.2°C. The average air temperature in the first floor was slightly higher than the ground floor which was ranges about 28.8-29°C in average. Most of the time, the maximum air temperature in all spaces in the measurement unit were either similar or slightly lower than the control unit during the daytime. In contrast, the minimum air temperatures in the control unit were always lower than that of measurement unit during the night-time. This indicates that without proper ventilation during the night-time, the nocturnal indoor air temperatures in the building tends to increase if the building insulation was applied.

Meanwhile, due to the increase of air temperature during the daytime, the relative humidity was also reduced to as low as 55% in master bedroom and the living hall of the measurement unit. On average, the relative humidity was 75% and 80% in the master bedroom and in the living hall of the measurement unit.

The recorded relative humidity is lower than that of Case 1. In contrast, not much difference of absolute humidity observed between both houses. The average absolute humidity was ranges from 18.8-19.2 g/kg in ground floor and about 19 g/kg' on the first floor.

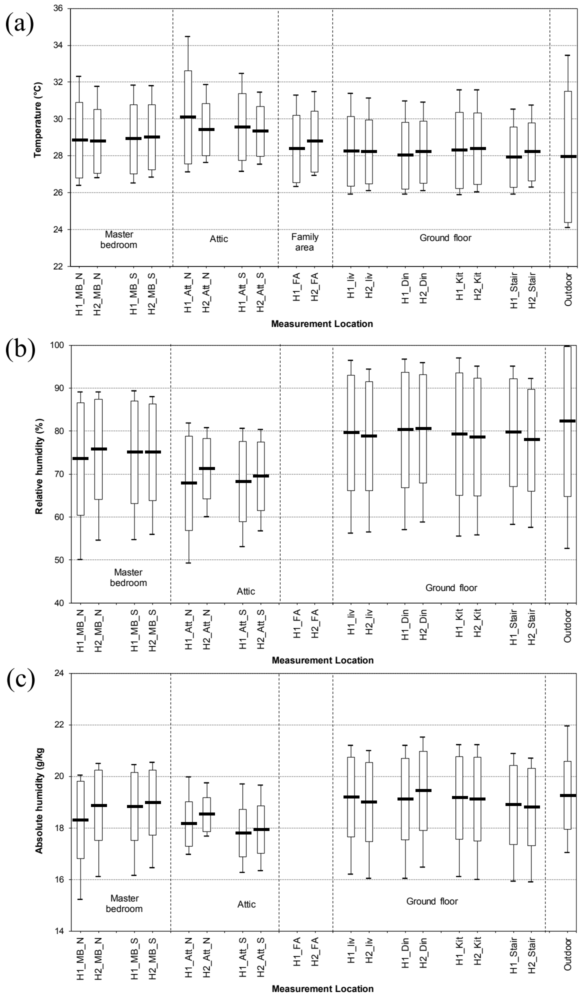


Figure 6.45. Statistical summary (5th and 95th percentiles, mean and ±one S.D.) of measurements (at 1.5 m above floor) of whole house in both House 1 and House 2 in Case 4. (a) Air temperature; (b) relative humidity; and (c) absolute humidity.

6.5.5.2 Case 5: Effects of 3 techniques with the whole house ventilation fan

6.5.5.2.1 Effects on indoor thermal environment of the master bedrooms

In this case, the whole house ventilation was applied in the measurement unit (House 2) addition to the modifications in Case 4. From this case and on (under full-day ventilation), the window opening condition in both houses was the different. In the control house (house 1), the main windows were opened for all measurement period. Meanwhile, in the measurement unit (house 2), the main windows were open in daytime, while at the night-time, only the slit windows were opened.

Figure 6.46 shows the temporal variations of air temperatures, relative humidity and absolute humidity in north and south facing rooms of both houses in Case 5. The result of solar radiation and rain period of outdoor are also included. During the measurement period, the outdoor air temperature was ranges from 23.0-33.5°C with the average of 26.3°C. Meanwhile, the outdoor relative humidity and absolute humidity was ranges from 55-100% and 16.2-23.2 g/kg', respectively. The average outdoor wind speed during daytime is about 0.20 m/s, while in the night-time, it was less than 0.1 m/s.

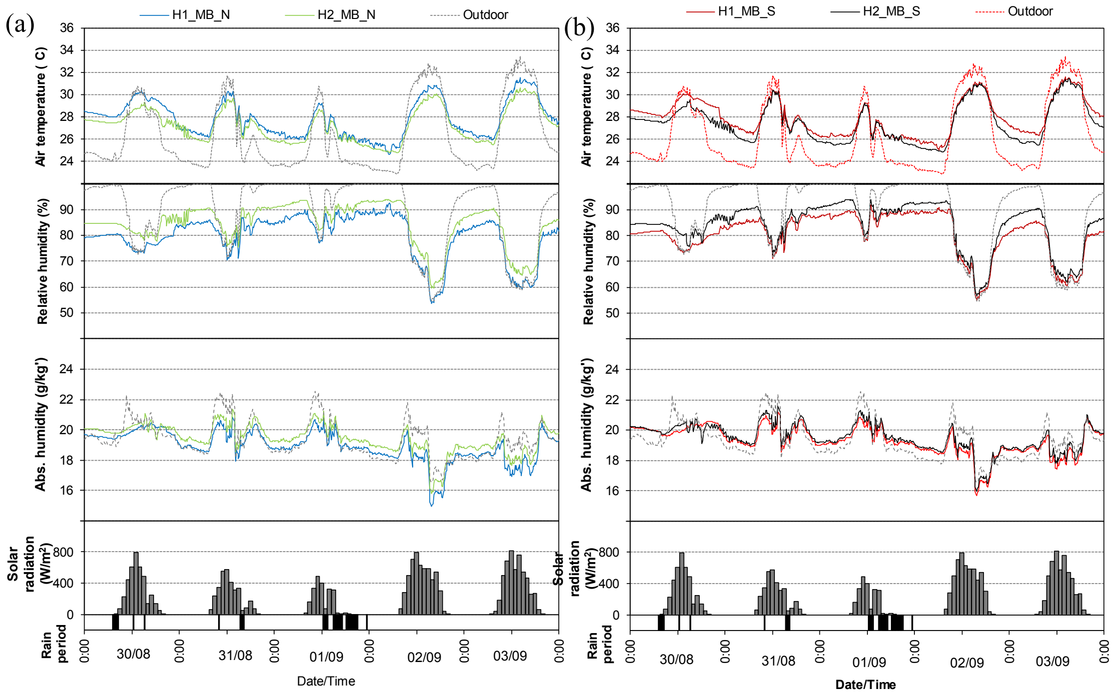


Figure 6.46. Temporal variations of air temperatures, RH and absolute humidity in the master bedrooms of House 1 and House 2 with the corresponding outdoor solar radiation and rain period in Case 5. (a) North facing master bedroom (H1/H2_MB_N) (b) South facing master bedroom (H1/H2_MB_S).

As shown in the Figure 6.47, the air temperature in the north facing master bedrooms in the measurement unit were lower than the control unit not only during daytime but also in night-time. In the daytime, the air temperature reduction in the north facing master bedroom in the measurement unit was about 0.7°C in average. Meanwhile, the air temperature in the night-time was about 0.4°C in average. In contrast, the temperature reduction in the south facing master bedroom (measurement unit) was only during night-time which is about 0.7°C while on the daytime, the air temperature difference was relatively small which is about

0.2°C in average. This is because the air temperatures in that master bedroom increased closely to the level of the control room during the daytime due to the inflow of warm air.

In this case, the indoor relative humidity in the measurement unit was reduced to as low as 55-60% during the daytime. This is simply because the increase of air temperature due to open window condition. In average, the relative humidity in the north facing room of the measurement unit was slightly higher than that of the control unit by about 5% during the daytime. Meanwhile, the relative humidity in the south facing master bedroom in both houses was almost the same where the difference is less than 2%. During night-time, the relative humidity in both master bedrooms in the measurement unit were larger than that of the control unit. This is probably because the humid outdoor air entered the room by the whole house ventilation.

In general, there are not much difference in term of absolute humidity level in the master bedrooms of both houses. The absolute humidity in the north facing master bedroom of the measurement unit was always slightly higher than that of control by at least 0.5 g/kg’ for the whole day. Meanwhile, in the south facing master bedroom, the absolute humidity in the measurement unit was almost similar to that of the control unit during the daytime but slightly higher in the night-time by about 0.5 g/kg’.

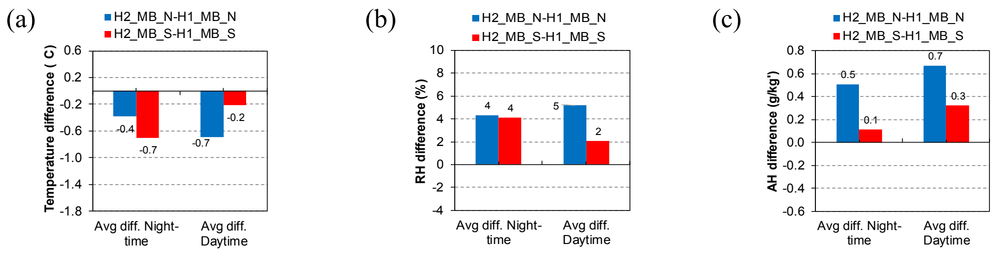


Figure 6.47. Average difference between master bedroom in House 1 and House 2 (House 2-House1) for north and south direction in daytime and night-time in Case 5. (a) Air temperature; (b) relative humidity; and (c) absolute humidity.

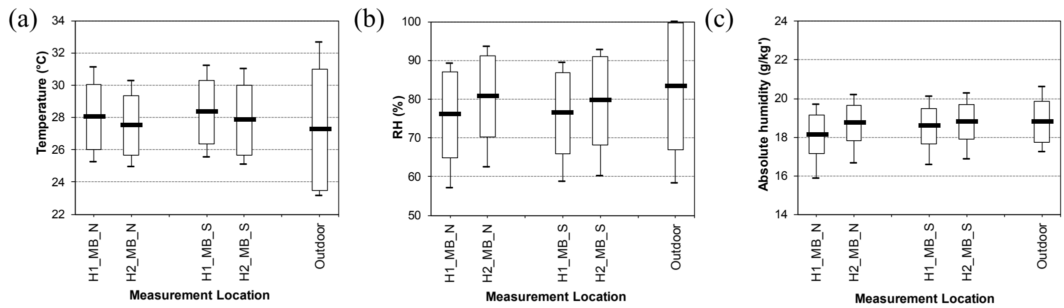


Figure 6.48. Statistical summary (5th and 95th percentiles, mean and ±one S.D.) of measurements (at 1.5 m above floor) in the master bedrooms in Case 5. (a) Air temperature; (b) relative humidity; and (c) absolute humidity.

6.5.5.2.2 Heat fluxes and surface temperature in the master bedrooms

Figure 6.49 shows the results of heat fluxes on the inside surface of the external wall, end wall and the ceiling in the master bedrooms. Meanwhile, Figure 6.50 shows the average surface temperature difference between the master bedrooms in the measurement and control unit (measurement-control unit). As shown, the external wall of both master bedrooms in the measurement unit have the almost the same range of heat fluxes level with the control room. The heat fluxes on the external wall of both houses increased by up to 20 W/m^2 during the daytime. However, the increase of heat fluxes in the measurement unit was slightly delayed compared to the control unit because of wall insulation. In night-time, both master bedrooms in the measurement unit has lower heat fluxes compared to the control unit by about 2.5 W/m^2. This is probably because of the insulation installed on the external wall retarding the heat transfer to outside.

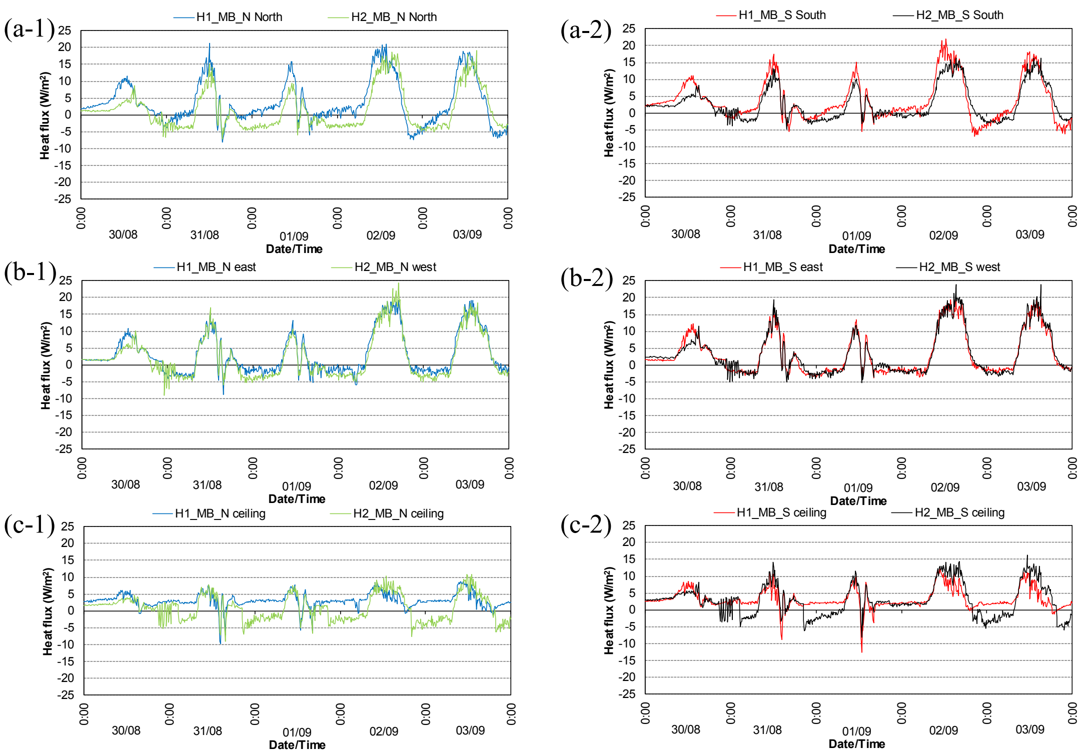


Figure 6.49. Heat fluxes on (a) external wall (inside); (b) end wall (inside) and (c) ceiling surfaces in north and south facing master bedrooms of both houses in Case 5.

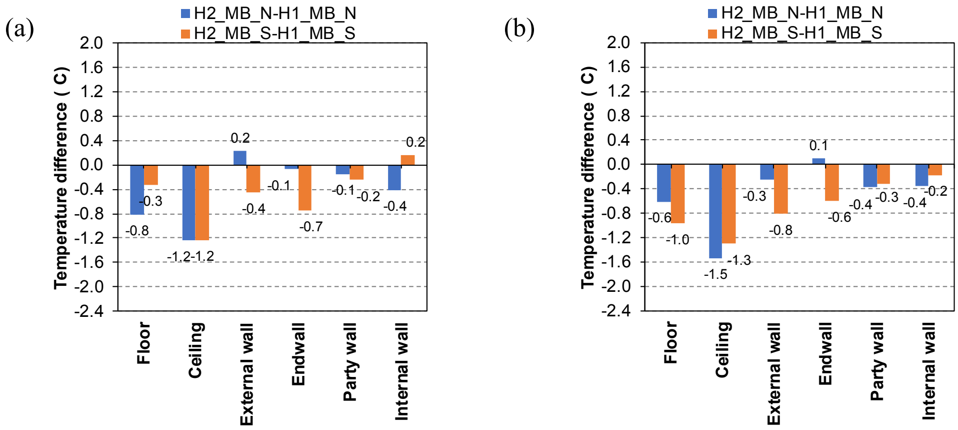


Figure 6.50. Average surface temperature difference between master bedroom in House 2 and House1 (House2 – House 1) in Case 5 during (a) night-time and (b) daytime.

On the end wall, similar heat fluxes range observed during daytime and night-time between measurement and the control unit. In the daytime, the absorbed heat fluxes were up to 20 W/m^2 while in night-time the negative heat fluxes ranges from 2.5-5 W/m^2.

On the ceiling surface, the master bedrooms in the measurement and the control unit have almost the same magnitude of maximum heat flux where it reaches up to 10 W/m^2. Meanwhile in night-time, it was found that the master bedrooms in the measurement unit have negative heat flux flows compared to the control unit. This indicates that indoor air temperatures of the master bedrooms were cooler than the surfaces during the night-time because of whole house ventilation. Thus, heat from ceiling could be transferred to the indoor air.

Despites almost similar magnitude of heat fluxes observed on the external wall of both houses, the surface temperature on external wall of the measurement unit were lower than that of the control unit. The surface temperature reduction was about 0.3 and 0.8°C in the north and south facing master bedroom, respectively. Most of the surfaces in the master bedrooms in the measurement unit were lower than that of control during the daytime. The largest reduction was on the ceiling which is about 1.5°C and 1.3°C in the north and south facing master bedroom, respectively. The second-largest reduction is on the floor surface. The reduction was about 0.6°C and 1.0°C in the north and south facing master bedroom, respectively. In the night-time, the surface temperature in the master bedrooms of the measurement unit remained cooler than that of the control unit during night-time. Similar to the result on the daytime, the largest reduction in night-time is on the ceiling surface which is about 1.2°C in average, followed by the reception on the floor's surface which is about 0.8°C and 0.3°C in the north and south facing master bedroom, respectively. This indicates that the whole house ventilation can reduce the surface temperature not only in night-time but also in daytime under the full-day ventilation condition.

6.5.5.2.3 Thermal comfort in the master bedrooms

Figure 6.51 shows the result of calculated operative temperature and SET* in the master bedrooms including the respective indoor wind speed in case 4. During the measurement, the recorded indoor wind speed in the master bedrooms of the measurement unit was almost similar to that of in the control room for most of daytime where they were ranges from 0.1-0.3 m/s. In night-time, the wind speed in the master bedrooms of the measurement unit were higher than control unit by about 0.1 m/s due to the application of the whole house ventilation fan.

As shown, the operative temperatures in the north facing master bedrooms of the measurement unit were not only lower than that of control unit during night-time but also in the daytime. The reduction of nocturnal operative temperatures is about 0.5°C and about 1°C in daytime. Meanwhile, slightly larger reduction of operative temperatures observed in south facing master bedrooms of the measurement unit where the reduction is about 0.6°C compared to that of control unit. In daytime, there are almost no reduction observed due to high infiltration of warm air into that room. However, the operative temperatures in both master bedrooms still exceed the 80% ACE thermal comfort upper limits by about 40 % of the measurement period.

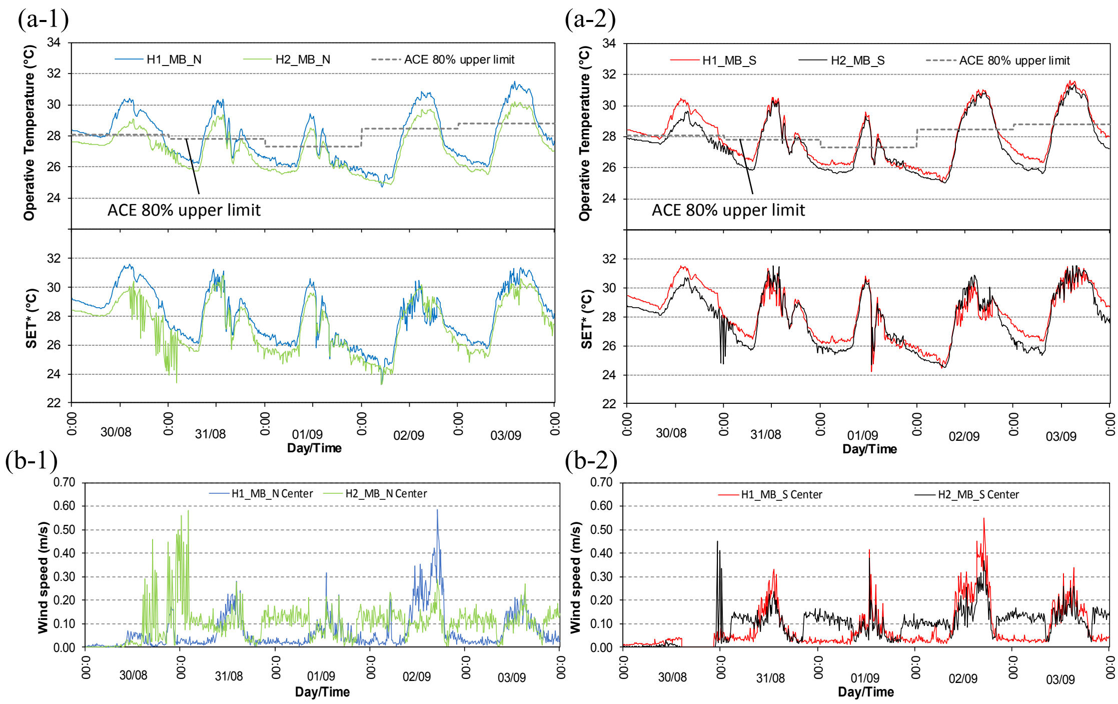


Figure 6.51. (a) Operative temperature (top) and SET* (bottom) in the master bedrooms of both houses in Case 5. (b) Wind speed in the living halls in Case 5.

Meanwhile, the calculated SET* in the north facing master bedroom of the measurement unit was ranges from 25-30°C which was lower than that of the control room by about 0.4°C during daytime and night-time. Meanwhile, in the south facing master bedroom of the measurement unit, the SET* increased as high as that of in the control unit during the daytime (31.5°C) and slightly cooler in night-time by up to 1°C.

6.5.5.2.4 Thermal comfort in the living halls

Figure 6.52 presents the temporal variations of air temperature, relative humidity and absolute humidity in the living hall of both houses. As shown, the air temperature in the living hall of the measurement unit increased closely as in the control unit in daytime. Thus, the reduction of air temperature was relatively small which is about 0.4°C in average. Meanwhile, at night-time, the air temperatures in the living halls of both houses were almost the same which can be as low as 24.5°C. However, they were still higher than the corresponding outdoor air temperature by about 2°C. This indicates that almost no reduction of nocturnal air temperature occurred in the living hall of the measurement unit despites the whole house ventilation was adopted at night-time. As shown in Figure 6.53b, indoor wind speed in the living hall of both houses was almost the same.

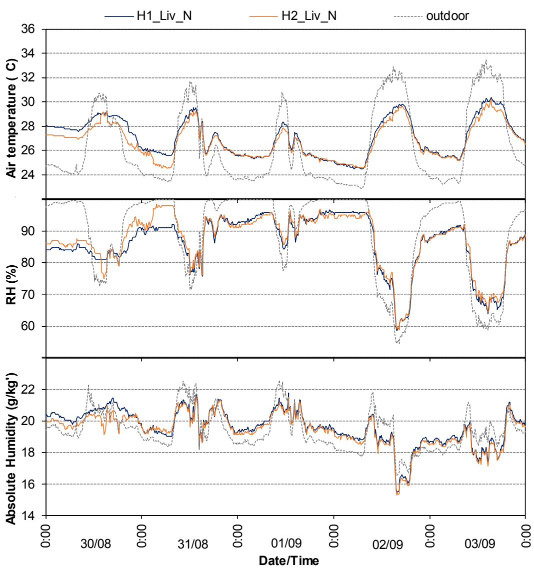


Figure 6.52. Temporal variations of air temperatures, RH and absolute humidity in the living hall of both houses in Case 5.

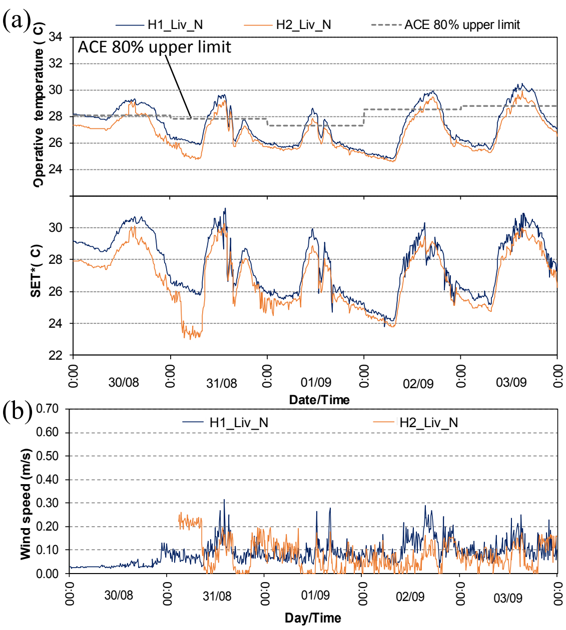


Figure 6.53. (a) Operative temperature (top) and SET* (bottom) in the living hall of both houses in Case 5. (b) Wind speed in the living halls in Case 5.

On the fine weather days, the maximum relative humidity recorded in the living hall was about 90% in the night-time. Meanwhile in daytime, the RH in both spaces were reduced to as low as 60%. In this case, the absolute humidity in both living halls were ranges from 16-21 g/kg'.

Figure 6.53a presents the variations of operative temperature and SET* in the living halls including the respective indoor wind speed. As shown, the maximum operative temperature in the measurement unit was lower than that of the control unit by about 0.5°C. Thus, the operative temperature in the living hall of the measurement unit exceeds the 80% ACE upper limit by about 20% of the measurement period, which is about 12% lower than that of in the control unit.

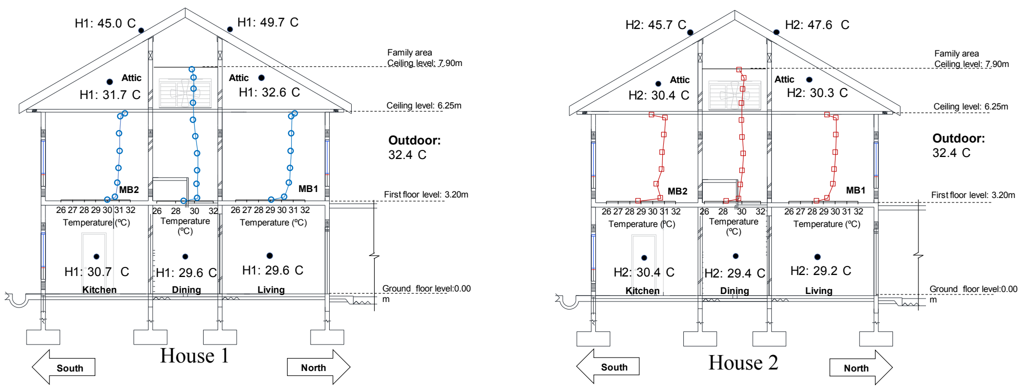
The calculated SET* in the living hall of the measurement unit was lower than that of in the control unit by about 0.5°C for the whole day. In the measurement unit, the SET* was ranges from 24.5-29.5°C. Though the wind speed was lower in living hall of the measurement unit at night time, the calculated SET* was still lower than that of in the control unit. This is probably due to the lower air temperatures in the living hall in the night-time.

6.5.5.2.5 Thermal environment variations of the whole house

Figure 6.54 shows the air temperature variations of the whole house during daytime (15:00) and night-time (00:00). In this case, it was found that the solar angle was almost equal between each side of houses (north and south) during daytime (15:00). The surface temperatures of the roof tiles on the north side was about 49.7-47.6°C while on the south side, surface temperatures of the roof tiles were about 45.0-45.7°C. Nevertheless, the temperature of attic in the measurement unit were lower than of control unit by about 2.3°C and 1.3°C in the north facing and south facing master bedroom, respectively. This is simply because the effects of the roof insulation. Similar as in Case 5, the ceiling of the master bedrooms in the measurement unit were slightly cooler than that of in the control unit during the daytime. In this case, the air surface temperature difference of the ceiling is about 2°C lower than in the control unit. The vertical distribution of air temperature in the master bedrooms of both houses showed almost no gradient from the 1.1 m above the floor level up to 0.1 m below ceiling surface. This indicates that the indoor air temperature increases uniformly along the height in all master bedrooms. Nevertheless, the vertical distribution of air temperature in the master bedroom of measurement unit were lower than that that of the control rooms by about 0.5°C in average. In the ground floor, the temperature in all spaces is almost the same, where the reduction is about 0.2-0.3°C between house 2 and house 1.

During night-time (00:00), the temperature of the roof surfaces was almost the same between each room where it was about 24.2°C in average. The air temperature in the attic spaces in the measurement unit remained lower than that of the control unit. The air temperature in the attic is about 0.8°C and 0.9°C in the north and south facing master bedroom, respectively. Due to the whole house ventilation, the vertical air temperature in the master bedrooms of the measurement unit reduced uniformly along the height (no gradient) to about 26.5°C and 26.3°C in the north and south facing master bedroom, respectively. In contrast, in the control house, both rooms (north and south) showed a steep temperature gradient from 0.1 m above floor up to the ceiling. This indicates that the combination of whole house and slit windows successfully reduced the air temperatures near the ceiling surface (structural cooling). In the ground floor, the air temperature of all spaces in both houses were almost similar where the average air temperature was about 26.3°C.

a) 15:00 (daytime)



b) 00:00 (night-time)

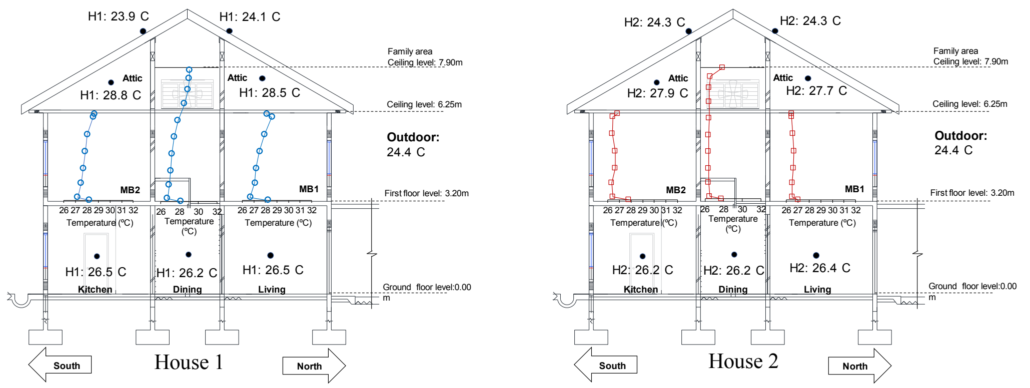


Figure 6.54. Whole house air and surface temperature distribution in House 1 (control unit) and House 2 (measurement unit) in Case 5 at (a) 15:00 (daytime) and (b) 00:00 (night-time).

Figure 6.55 presents the statistical summary of air temperature, relative humidity and absolute humidity in all spaces in both houses. In this case, the average air temperature in the master bedrooms in the measurement unit were lower than that of in the control house despites the increased of maximum air temperature during daytime. Thanks to the whole house ventilation, the reduction of average air temperature in the south and north master bedroom was about 0.5°C and 0.3°C respectively. In addition, the nocturnal air temperatures were also reduced to about 0.3°C in both master bedrooms. The average temperature of the living hall in the measurement unit is also slightly lower compared to the control unit. However, the reduction is not significant during night-time. This is because the wind flow in both living halls was almost the same during the night-time.

Average relative humidity in the north facing master bedrooms of the measurement unit is about 82% while in the south facing room is about 82%. The relative humidity was relatively higher than that of the control house by about 5% and 3 %, respectively. Nevertheless, minimum relative humidity in those master bedrooms can be as low as 60% during daytime. In ground floor, the relative humidity in al spaces were about 84% in average. During daytime, minimum relative humidity in the ground floor can be as low as 60%.

Average absolute humidity in the master bedrooms of the measurement unit were slightly higher than that of in the control unit. The absolute humidity in the north facing and south facing master bedroom were about 6 g/kg' and 2 g/kg' higher than that of in the control unit. In the ground floor, the absolute humidity in all spaces were almost the same which is about 18.5 g/kg' in average.

(a)
(b)
(c)

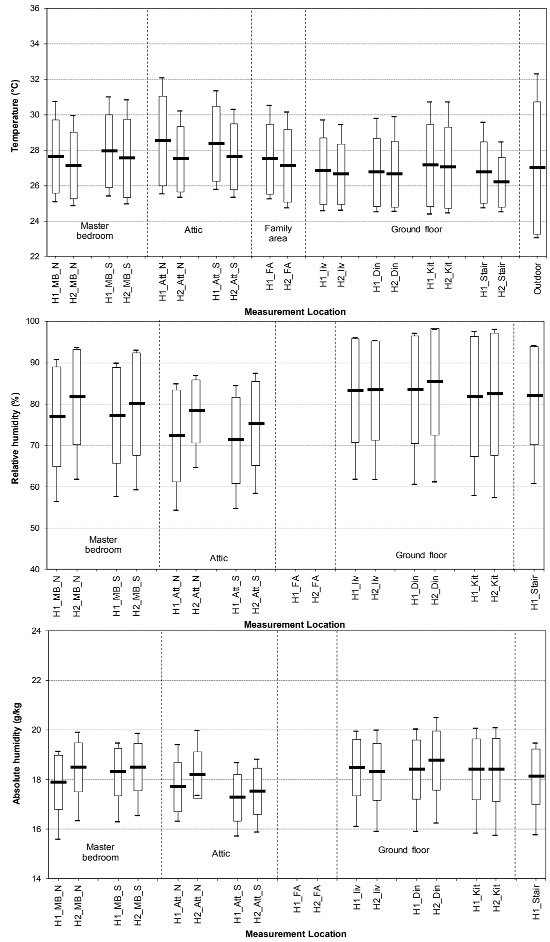


Figure 6.55. Statistical summary (5th and 95th percentiles, mean and ±one S.D.) of measurements (at 1.5 m above floor) of whole house in both House 1 and House 2 in Case 5. (a) Air temperature; (b) relative humidity; and (c) absolute humidity.

6.5.5.3 Case 6: Effects of 3 techniques, whole house ventilation fan and attic ventilation fan

6.5.5.3.1 Effects on indoor thermal environment of the master bedrooms

In this case, the attic ventilation fan was applied in the measurement unit (House 2) in addition modifications in Case 5. The opening conditions in both houses were remained as the same as in the previous case (Case 5). Figure 6.56 shows the temporal variations of air temperatures, relative humidity and absolute humidity in north and south facing rooms of both houses in Case 6. The result of solar radiation and rain period of outdoor are also included. During the measurement period, the outdoor air temperature was ranges from 23.3-33.1°C with the average of 26.9°C. Meanwhile, the outdoor relative humidity and absolute humidity was ranges from 60-100% and 17.6-22.7 g/kg', respectively. The average outdoor wind speed during daytime is about 0.50 m/s, while in the night-time, it was less than 0.1 m/s.

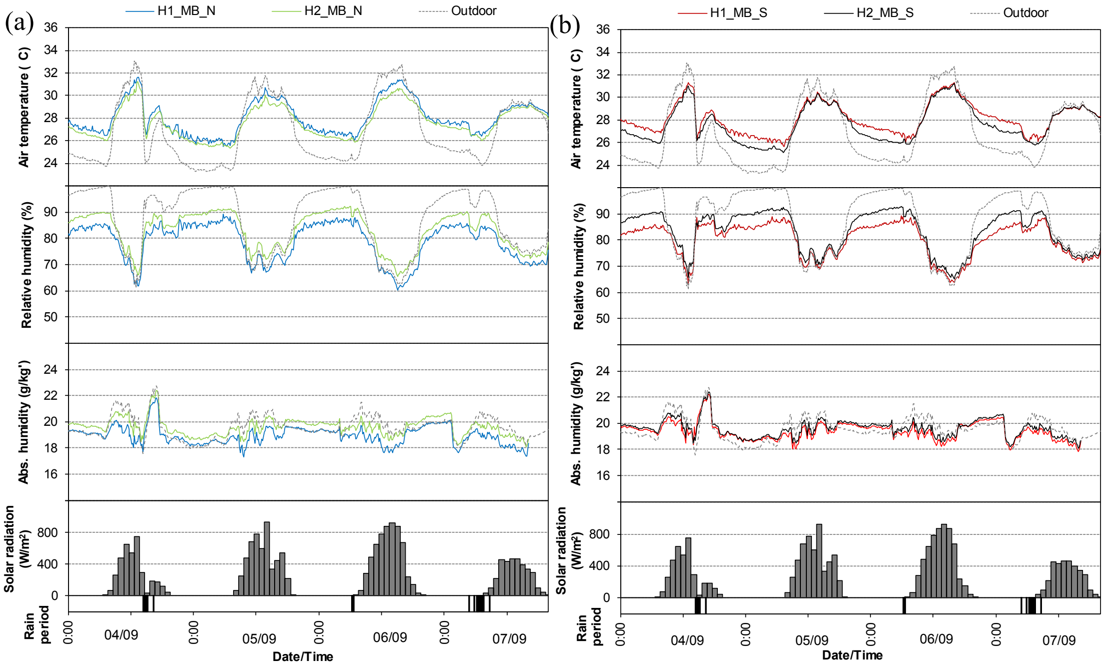


Figure 6.56. Temporal variations of air temperatures, RH and absolute humidity in the master bedrooms of House 1 and House 2 with the corresponding outdoor solar radiation and rain period in case 6. (a) North facing master bedroom (H1/H2_MB_N) (b) South facing master bedroom (H1/H2_MB_S).

As shown, the nocturnal air temperature in the north facing master bedrooms of the measurement unit were lower than that of in the control unit by about 0.4°C in average (Figure 6.57). Meanwhile, in the daytime, the air temperature reduction in that room was about 0.6°C in average. In the south facing master bedroom (measurement unit), the nocturnal and daytime air temperature reduction is about 0.8°C and 0.6°C, respectively. It should be noted that the reduction of nocturnal air temperature in this case is almost the same as that in case 5. This implies that the air temperature reduction seen in Case 3 was not because of attic ventilation but due to the position of windows (slit windows).

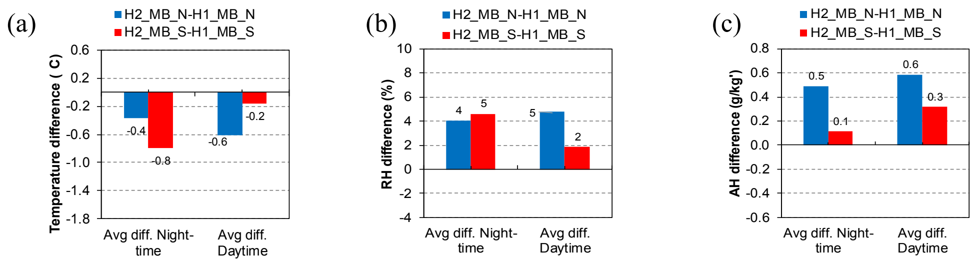


Figure 6.57. Average difference between master bedroom in House 1 and House 2 (House 2-House1) for north and south direction in daytime and night-time in case 6. (a) Air temperature; (b) relative humidity; and (c) absolute humidity.

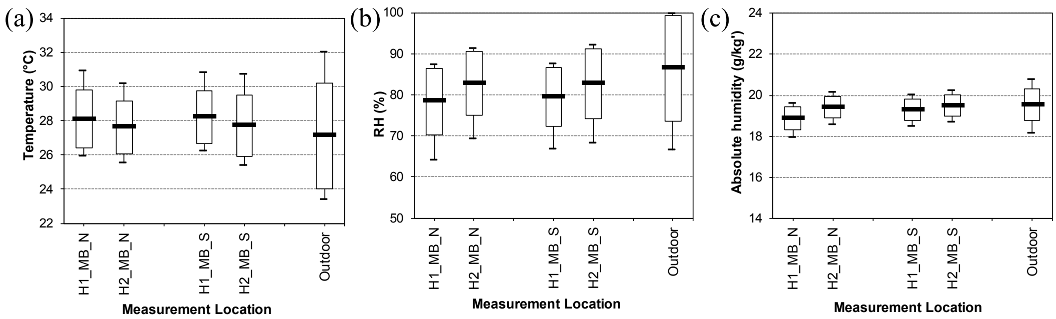


Figure 6.58. Statistical summary (5th and 95th percentiles, mean and ±one S.D.) of measurements (at 1.5 m above floor) in the master bedrooms in case 6. (a) Air temperature; (b) relative humidity; and (c) absolute humidity.

In this case, the relative humidity in the master bedrooms of the measurement unit were always higher than that of control unit by about 4-5% during night-time while about 2-5% during daytime. The lowest relative humidity recorded in the master bedrooms was as low as 68%. It should be noted that the measured relative humidity was slightly higher than the other full-day ventilation cases. This is because the measured minimum outdoor relative humidity was higher in this case.

As the discussed in the other cases, there are not much difference observed in the result of absolute humidity where both master bedrooms in the measurement unit were higher than that of control unit by up to 0.5 g/kg'. In average, the nocturnal difference of absolute humidity is 0.5 g/kg' and 0.1g/kg' in the north and south facing master bedroom, respectively. Meanwhile the average difference of daytime absolute humidity is about 0.6 g/kg' and 0.3 g/kg' in the north and south facing master bedroom, respectively, respectively.

6.5.5.3.2 Heat fluxes and surface temperature in the master bedrooms

Figure 6.59 shows the results of heat fluxes on the inside surface of the external wall, end wall and the ceiling in the master bedrooms. Meanwhile, Figure 6.60 shows the average surface temperature difference between the master bedrooms in the measurement and control unit (measurement-control unit). As shown, the maximum heat flux measured on the external wall of master bedrooms in the control unit were slightly larger than that of measurement unit by about 2.5-5 W/m^2. Moreover, the heat flux in the control unit also reached the maximum value earlier than that of measurement unit. This is simply because the air temperature in the master bedrooms in the control unit is warmer than that of measurement unit during daytime, thus more heat absorbed by the wall. During daytime, the surface temperature of external wall in the master bedrooms of the measurement unit is lower than that of control unit by about 0.2°C in average.

In the night-time, the negative heat fluxed (heat release) on the external wall of master bedrooms in the control unit was larger than that of measurement unit by about 2.5 W/m^2 and reach the maximum value earlier (negative). This is simply because the surface temperature of external wall in that rooms were higher than its air temperature, thus the heat transferred rapidly from the wall to the indoor air.

As shown in Figure 6.59, the heat fluxes on the end wall of the master bedrooms in the measurement unit was almost similar to that of control unit for the whole day, which ranges from 5W/m^2 during the night-time (negative heat flux) to about 20 W/m^2 during the daytime in the fine weather days. From the results, this indicates that the end wall in each direction received similar heat flux during day and night-time.

It was found that the heat fluxes on the ceiling of the master bedrooms in the measurement unit were slightly higher than that of control unit by about 2.5 W/m^2 during daytime. However, it didn't increase the temperature of the ceiling to be higher than that of control house. In this case, the daytime surface temperature of the ceiling in the master bedrooms of the measurement unit is about 1.4-1.6°C lower than the control room during the daytime. This indicates that the air temperature in the daytime in the measurement room is much lower thus the ceiling absorbing much heat during the daytime. Meanwhile in the night-time, the heat flux on the ceiling of north facing master bedroom in the control unit is always in positive value (absorbing) while that of in the measurement unit is negative value (releasing). This indicates that the indoor air temperature in the master bedrooms of the measurement unit were reduced much lower than that of control room. Similar pattern of heat fluxes observed on the ceiling of the south facing master bedroom but with a smaller value.

As shown in the Figure 6.60, most of the surfaces in the master bedrooms of the measurement unit were lower than that of control room during day and night-time. The largest reduction is on the ceiling of the master bedrooms. In the daytime, the reduction of ceiling temperature was about 1.6 and 1.4 °C in north and south facing master bedroom, respectively. In the night-time, the reduction is about 1.6 and 1.9°C in north and south facing master bedroom, respectively. Moreover, slightly higher reduction observed on the surface of the floor in the north master bedroom in the measurement unit compared to that of control unit during the night-time. The reduction was about 1°C in average. This is probably due to the ventilation effect by the slit windows. The reduction of the other surfaces is between 0.2-1.0°C during the day and night-time.

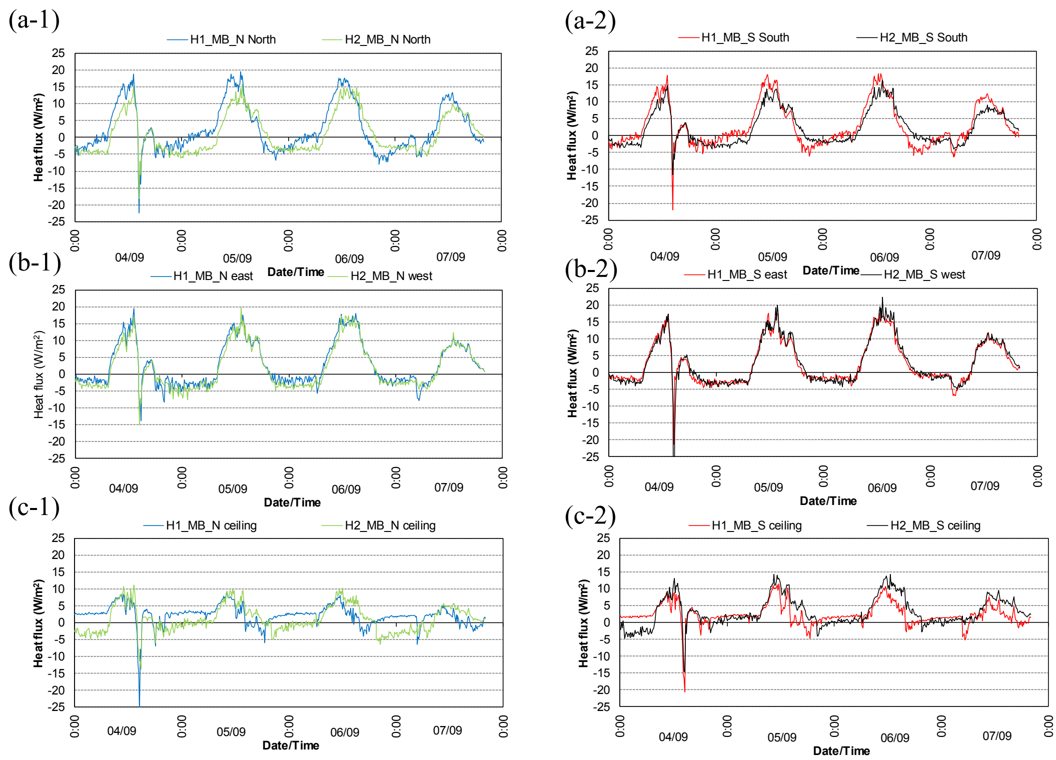


Figure 6.59. Heat fluxes on (a) external wall (inside); (b) end wall (inside) and (c) ceiling surfaces in north and south facing master bedrooms of both houses in case 6.

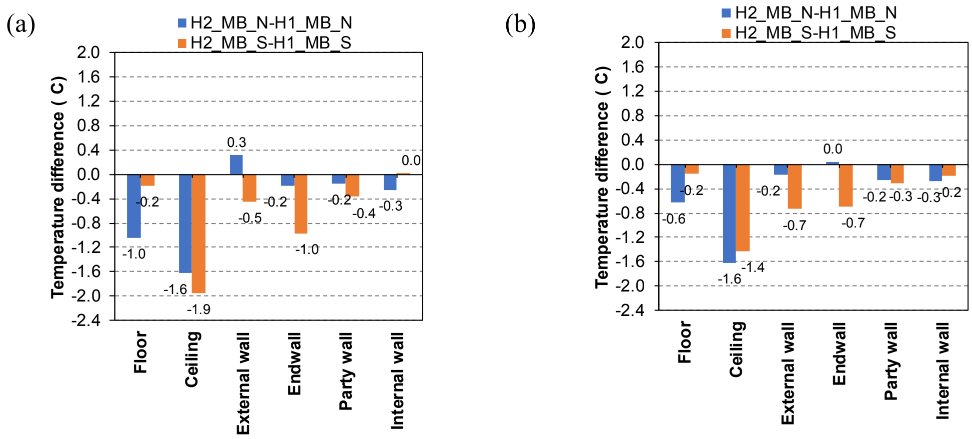


Figure 6.60. Average surface temperature difference between master bedroom in House 2 and House1 (House2 – House 1) in case 6 during (a) night-time and (b) daytime.

6.5.5.3.3 Thermal comfort in the master bedrooms

Figure 6.61 shows the result of calculated operative temperature and SET* in the master bedrooms including the respective indoor wind speed in case 6. During the measurement, the recorded indoor wind speed in the master bedrooms of the control unit was slightly larger than that of measurement unit for most of daytime. The difference is as large as 0.1 m/s. In contrast, the wind speed in the master bedrooms of the measurement unit were higher than control unit by about 0.1 m/s due to the application of the whole house ventilation fan in night-time.

As shown, the operative temperatures in the north facing master bedrooms of the measurement unit were not only lower than that of control unit during night-time but also in the daytime. The reduction of nocturnal operative temperatures is about 1.0°C while in daytime, the reduction is about 0.5°C. Meanwhile, slightly larger reduction of nocturnal operative temperatures observed in the south facing master bedrooms of the measurement unit where the reduction is about 1.0°C compared to that of control unit. In daytime, the reduction of operative temperature in that room is about 0.3°C. Nevertheless, the operative temperatures in both master bedrooms in the measurement unit exceed the 80% ACE thermal comfort upper limits by about 38-44% of the measurement period.

As for north facing master bedroom, the SET* in the measurement unit was range from 25.8-30.2 which is lower than that of control unit by about 0.3°C and 0.6°C during day and night-time, respectively. Meanwhile, in the south facing master bedroom, the SET* in the measurement unit was range from 24.8-31.0°C which is lower than that of control unit by about 0.2°C and 0.1°C during day and night-time, respectively.

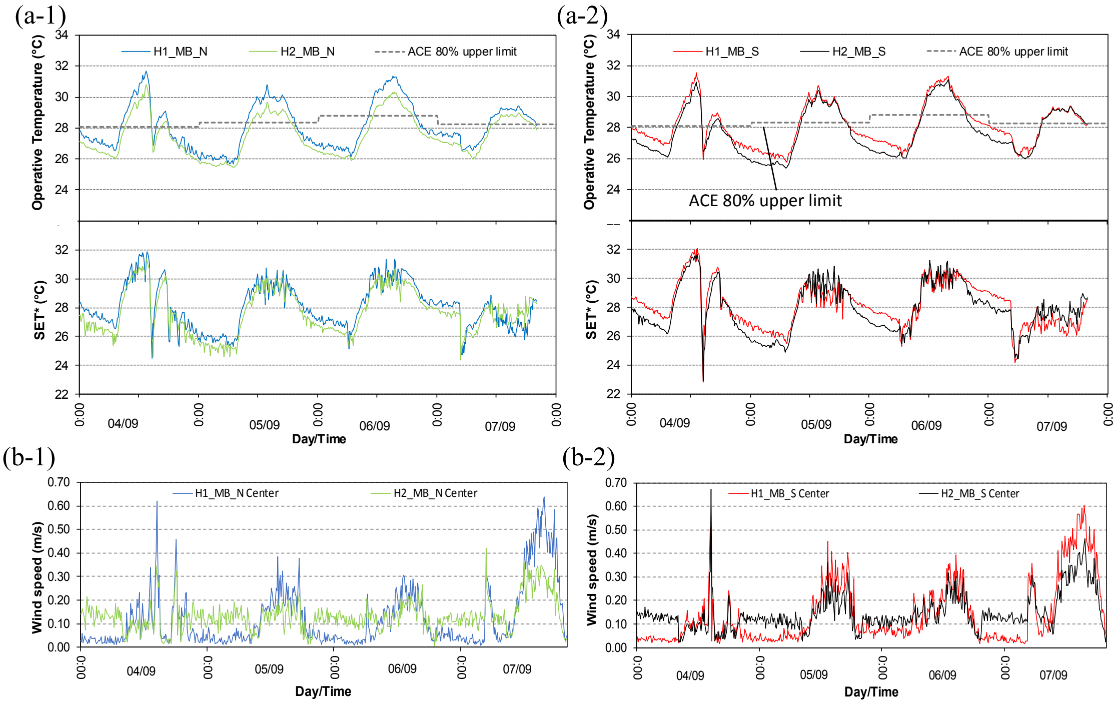


Figure 6.61 (a) Operative temperature (top) and SET* (bottom) in the master bedrooms of both houses in case 6. (b) Wind speed in the living halls in case 6.

6.5.5.3.4 Thermal comfort in the living halls

Figure 6.62 presents the temporal variations of air temperature, relative humidity and absolute humidity in the living hall of both houses. As shown, the air temperature in the living hall of the measurement unit was increased and closely as in the control unit in daytime. Thus, the reduction of air temperature was relatively small which is about 0.2°C in average. Meanwhile, at night-time, the air temperatures in the living halls of both houses were almost no temperature reduction. However, they were still higher than the corresponding outdoor air temperature by about 2°C. This indicates that that the increase of air flow during night-time by the whole house ventilation didn't reduce the air temperature in the living hall in the measurement unit.

In this case, the range of relative and absolute humidity between the living hall both houses were almost similar which is about 68-92% and 18-20.5 g/kg' in the fine weather days, respectively.

Figure 6.63 presents the variations of operative temperature and SET* in the living halls including the respective indoor wind speed. As shown, the operative temperature in the measurement unit was lower than that of the control unit by about 0.5°C during daytime and night-time. Thus, the operative temperature in the living hall of the measurement unit exceeds the 80% ACE upper limit by about 21% of the measurement period, which is about 14% lower than that of in the control unit. The calculated SET* in the living hall of the measurement unit was lower than that of in the control unit by about 0.5°C for the whole day. In the measurement unit, the SET* of the living hall was ranges from 25.0-30.2°C.

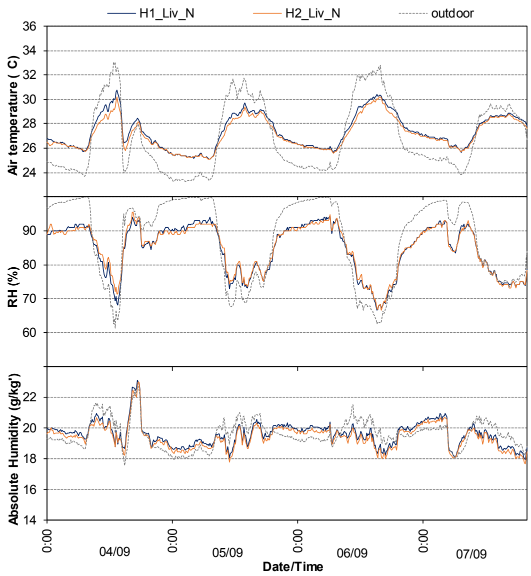


Figure 6.62. Temporal variations of air temperatures, RH and absolute humidity in the living hall of both houses in case 6.

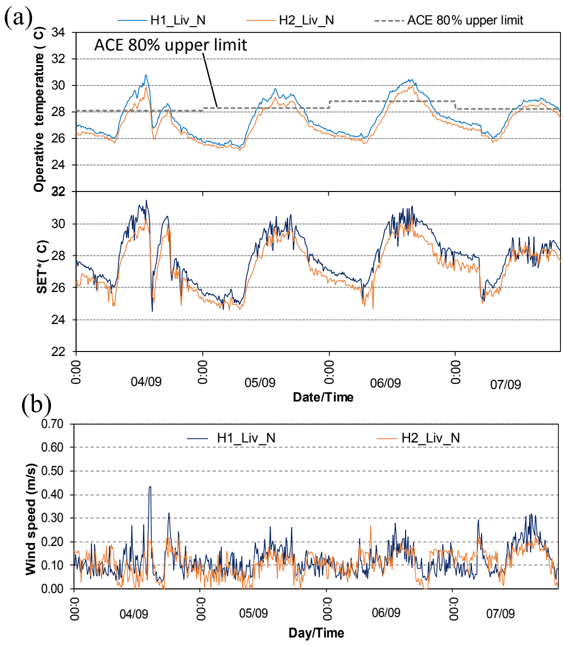
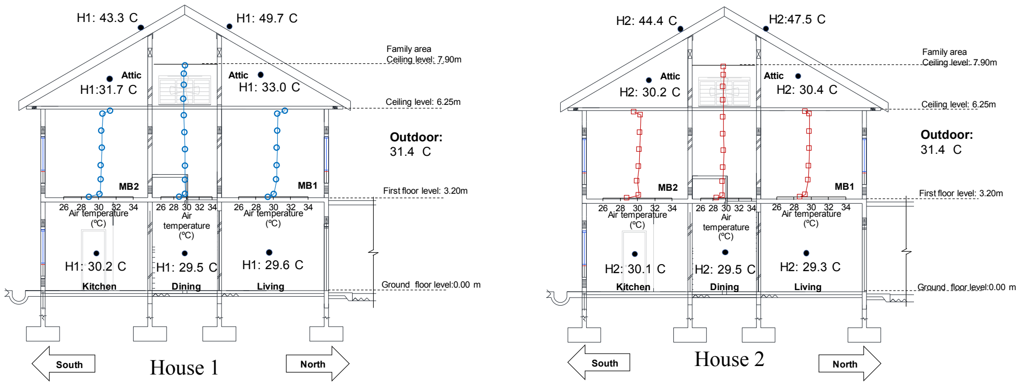


Figure 6.63. (a) Operative temperature (top) and SET* (bottom) in the living hall of both houses in case 6. (b) Wind speed in the living halls in case 6.

6.5.5.3.5 Thermal environment variations of the whole house

Figure 6.64 shows the air temperature variations of the whole house during daytime (15:00) and night-time (00:00). As shown, the surface temperatures of the roof tiles on the north side was about 49.7-47.5°C while on the south side, surface temperatures of the roof tiles were about 43.3-44.4°C. Nevertheless, the temperature of attic in the measurement unit were lower than of control unit by about 1.6°C and 1.5°C in the north facing and south facing master bedroom, respectively. Similar to Case 5 and Case 6, the ceiling of the master bedrooms in the measurement unit were slightly cooler than that of in the control unit during the daytime by about 2°C in average. The vertical distribution of air temperature in the master bedrooms of both houses showed almost no gradient from the 1.1 m above the floor level up to 0.1m below ceiling surface. Nevertheless, the vertical distribution of air temperature in the master bedroom of measurement unit were lower than that of the control rooms by about 0.5°C in average. In the ground floor, the temperature in all spaces is almost the same, where the reduction is about 0.1-0.6°C between the measurement and the control unit.

a) 15:00 (daytime)



b) 00:00 (night-time)

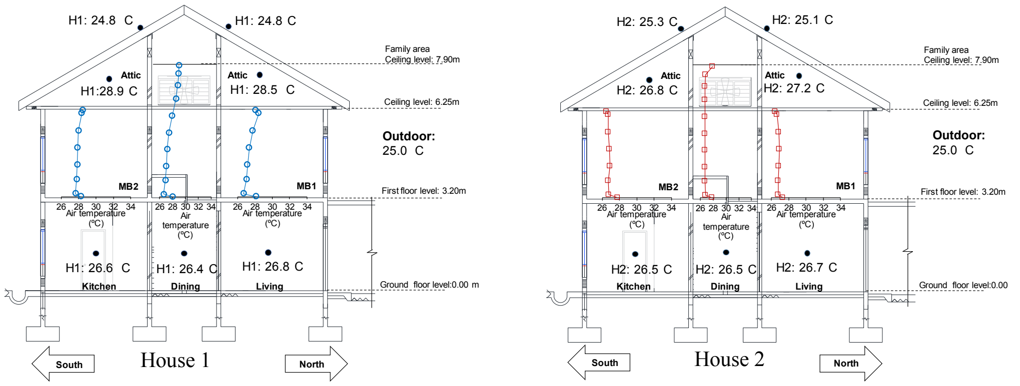


Figure 6.64. Whole house air and surface temperature distribution in House 1 (control unit) and House 2 (measurement unit) in case 6 at (a) 15:00 (daytime) and (b) 00:00 (night-time).

During night-time (00:00), the temperature of the roof surfaces was almost the same between each room where it was about 25.0°C in average. The air temperature in the attic spaces in the measurement unit remained lower than that of the control unit by about 1.3°C and 2.1°C in the north and south facing master bedroom, respectively. However, the cooler condition in the attic did not affect the air temperature in the master bedrooms in the measurement unit. The air temperature difference at 1.1 m above floor level is nearly the same as the previous case (Case) i.e. without the attic fan. At 1.1 m height, the temperature difference is about 0.4 and 0.8 in the north and south facing master bedroom, respectively. In this case, a steep gradient of vertical air temperature was observed in the master bedroom in the control unit. In the ground floor, the at temperature of all spaces are almost similar between both house where the average difference is about 0.1°C.

Figure 6.65 presents the statistical summary of air temperature, relative humidity and absolute humidity in all spaces in both houses. Similar to the previous case 5, the air temperature in the master bedroom was reduced not only on the night-time but also in the daytime. As shown, the minimum nocturnal air temperature in the north and south master bedroom of the measurement unit was lower than that of control unit by about 0.5 and 0.7°C, respectively. Meanwhile, the maximum air temperature of the same rooms was reduced by about 0.9 and 0.2°C, respectively. Small reduction of air temperature observed in south facing room probably because of slightly large infiltration of warm air during daytime. In the living hall, the air temperature reduction is about 0.2°C in average. Maximum and minimum air temperature of the living hall in the measurement unit was nearly the same as that of control unit. This indicates that the effects of the modifications are not significant in the ground floor spaces under the full-day ventilation condition.

Meanwhile, the average relative humidity in the in the master bedrooms and living hall of the measurement unit were ranges from 82-86%. During the daytime, the relative humidity in the master bedrooms can be as low as 68% while in the living hall, the minimum relative humidity is about 72%.

As shown, the average absolute humidity in the master bedrooms of the measurement unit were slightly higher than that of the control unit. The absolute humidity in the north and south facing master bedroom were higher than that of control unit by about 0.6 g/kg' and 0.3 g/kg', respectively. Meanwhile, in the ground floor, the absolute humidity is about 19.3 g/kg' in average.

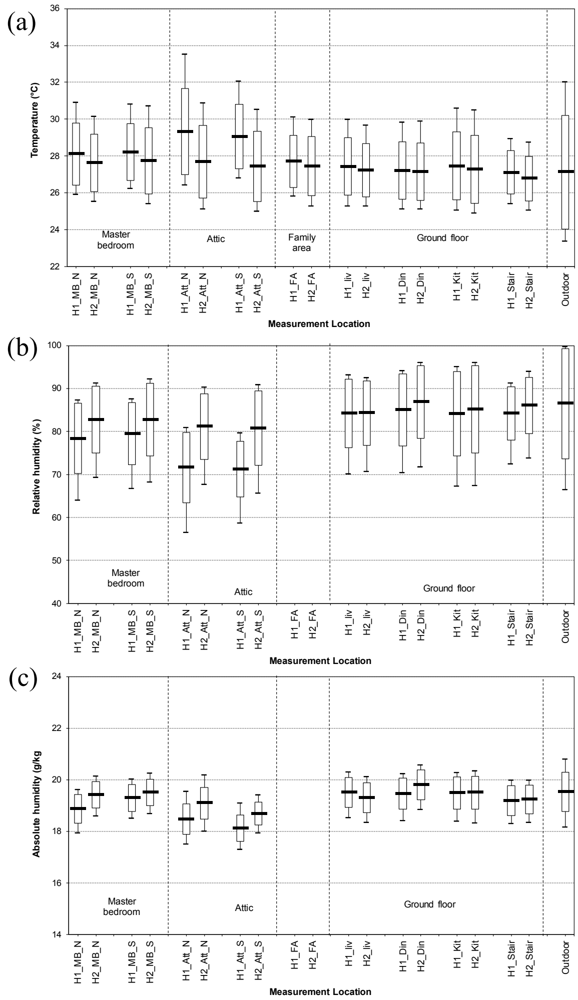


Figure 6.65. Statistical summary (5th and 95th percentiles, mean and ±one S.D.) of measurements (at 1.5 m above floor) of whole house in both House 1 and House 2 in case 6. (a) Air temperature; (b) relative humidity; and (c) absolute humidity.

6.5.6 Influence of window positions

This section investigates the effects of window-opening position on the indoor thermal environments in the master bedroom (Case 7). Three types of window-opening position (i.e. main windows, slit windows and all windows) were applied in the master bedroom of the measurement unit (House 2), whereas the main window was used in the control unit (House 1). To be noted that only the main windows are normally used in urban houses of Malaysia. Case 7 was conducted under the same modification conditions, i.e., roof insulation, external wall insulation, external shading and the whole house ventilation.

6.5.6.1 Case 7-a Main windows (Night ventilation, 3 techniques and whole house fan)

6.5.6.1.1 Effects on indoor thermal environment of the master bedrooms

In this case, the main windows of both houses were opened during night-time (20:00-08:00). Figure 6.66 shows the temporal variations of air temperatures, relative humidity and absolute humidity in north and south facing rooms of both houses of Case 7-a under night ventilation condition. During the measurement period, the outdoor air temperature ranges from 22.7-34°C with the average of 27.8°C. Meanwhile, the outdoor relative humidity and absolute humidity ranges from 51-100% and 16.5-22.8 g/kg', respectively. The average wind speed during daytime is about 0.34 m/s, while almost calm wind speed during night-time (less than 0.1 m/s).

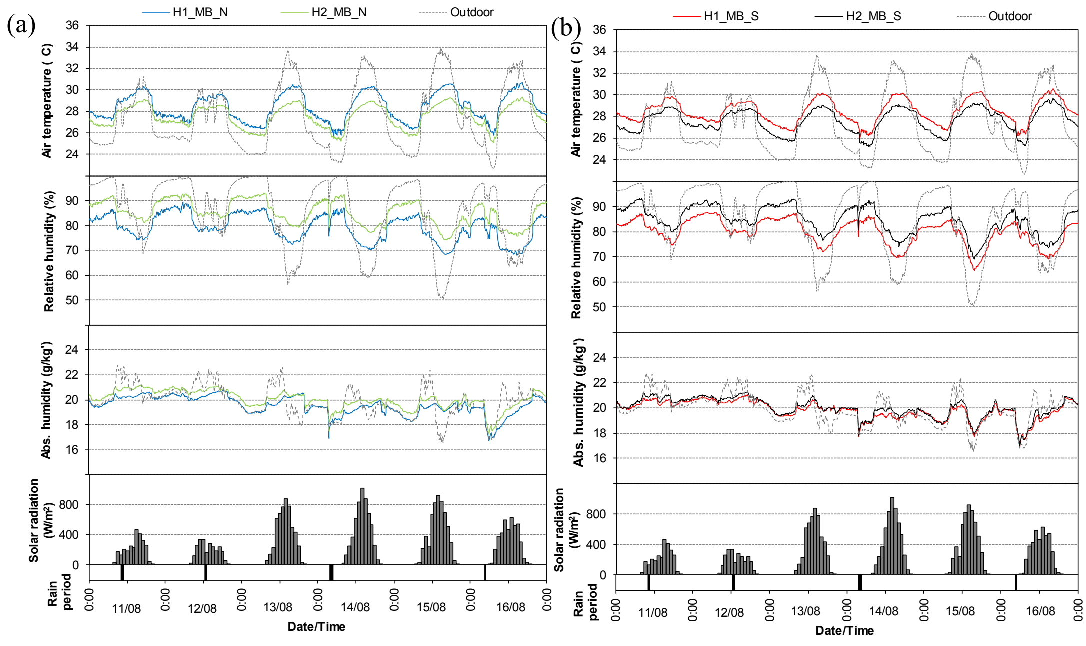


Figure 6.66. Temporal variations of air temperatures, RH and absolute humidity in the master bedrooms of House 1 and House 2 with the corresponding outdoor solar radiation and rain period in Case 7-a. (a) North facing master bedroom (H1/H2_MB_N) (b) South facing master bedroom (H1/H2_MB_S).

As shown, the air temperature in the master bedrooms in the measurement unit were lower than the control in daytime. In the north facing rooms, the air temperature in the master bedroom of house 2 (H2_MB2_N) was lower than that of house 1 (H1_MB_N) by up to 1.5°C. Meanwhile, in the south facing rooms, the air temperature reduction is up to 1.2°C (H2_MB_S-H1_MB_S). In average, the air temperature in the north and south facing rooms of the measurement unit is lower than that of control by about 1.2°C and 0.9°C respectively (Figure 6.67). This is simply because the modification techniques successfully reduced the effect of direct solar radiation to the building during the daytime. In the night-time, the nocturnal air temperature in the north and south facing master bedrooms in the measurement unit was lower than that of control unit by about 0.7°C and 0.9°C, respectively. Similar to the other case of night-ventilation with the whole house ventilation, this indicates that the application of the whole house ventilation is effective in reducing nocturnal air temperature. The relative humidity in the master bedrooms of the measurement unit are found to be increased accordingly after the modifications compared to that of control unit for the whole day. At the daytime, the relative humidity in the north and south facing rooms of the measurement unit were higher than that of control rooms by up to 8% and 6% respectively. In average, they were higher than the control rooms by about 6% and 5% in north facing and south facing room, respectively. Meanwhile, at night-time, the nocturnal relative humidity in the north and south facing room were higher than that of in control rooms by up to 6.5% and 5.5 %, respectively. The absolute humidity in the north master bedrooms of the measurement unit were higher than that of the control rooms by about 0.4 g/kg' and 0.5 g/kg' during daytime and night-time, respectively. In contrast, the absolute humidity in the south master bedrooms of the measurement unit were almost the same with that of the control rooms where the difference was less than 0.2 g/kg' during day-time and night-time respectively.

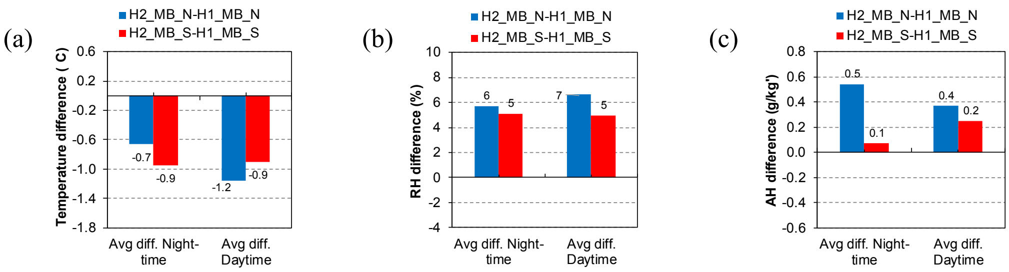


Figure 6.67. Average difference between master bedroom in House 1 and House 2 (House 2-House1) for north and south direction in daytime and night-time in Case 7-a. (a) Air temperature; (b) relative humidity; and (c) absolute humidity.

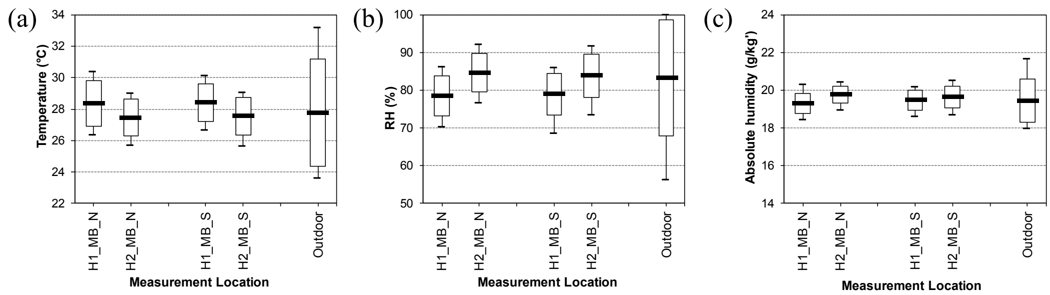


Figure 6.68. Statistical summary (5th and 95th percentiles, mean and ±one S.D.) of measurements (at 1.5 m above floor) in the master bedrooms in Case 7-a. (a) Air temperature; (b) relative humidity; and (c) absolute humidity.

6.5.6.1.2 Heat fluxes and surface temperature in the master bedrooms

Figure 6.69 shows the results of heat fluxes on the inside surface of the external wall, end wall and the ceiling in the master bedrooms. Meanwhile, Figure 6.70 shows the average surface temperature difference between the master bedrooms in the measurement and control unit (measurement-control unit). The external wall of both rooms in the measurement unit absorbed lower heat than that of the control unit by up to 10 W/m^2 (Figure 6.69). This is simply because the air temperature in master bedroom in the control unit was warmer than that of measurement unit. Meanwhile, in the night-time, the external wall in the north facing master bedroom in the control unit shows slightly better rate of heat release where the heat fluxes are larger than that of measurement unit by up to 5.0 W/m^2.

Similar situation observed on the surface of end wall. Slightly lower heat absorption occurred in the master bedrooms of the measurement unit during daytime. The heat flux on the end walls of measurement unit was lower than that of control room by about 3-4 W/m^2. Meanwhile, the heat fluxes on the surface of end walls of both houses are quite similar during the night-time. For most of the time, the ceiling in all master bedrooms always absorb the heat (daytime and night-time) (positive). This indicates that the surface temperature of the ceiling always lower than the air temperature in the master bedroom for most of the day. In average, the heat fluxes of ceiling were about 5 W/m^2 in daytime and about 2.5 W/m^2 in night time.

As shown in Figure 6.70, the surface temperature of the walls in the master bedrooms in the measurement unit were lower than that of control unit for the whole day. In daytime, the highest difference is on the floor and ceiling which is about 0.9-1.1°C and 1.8-2.0°C, respectively. In the night-time, the ceiling and floor surfaces remained as the largest reduction where temperature difference is about 1.0°C and 0.4-0.8°C, respectively.

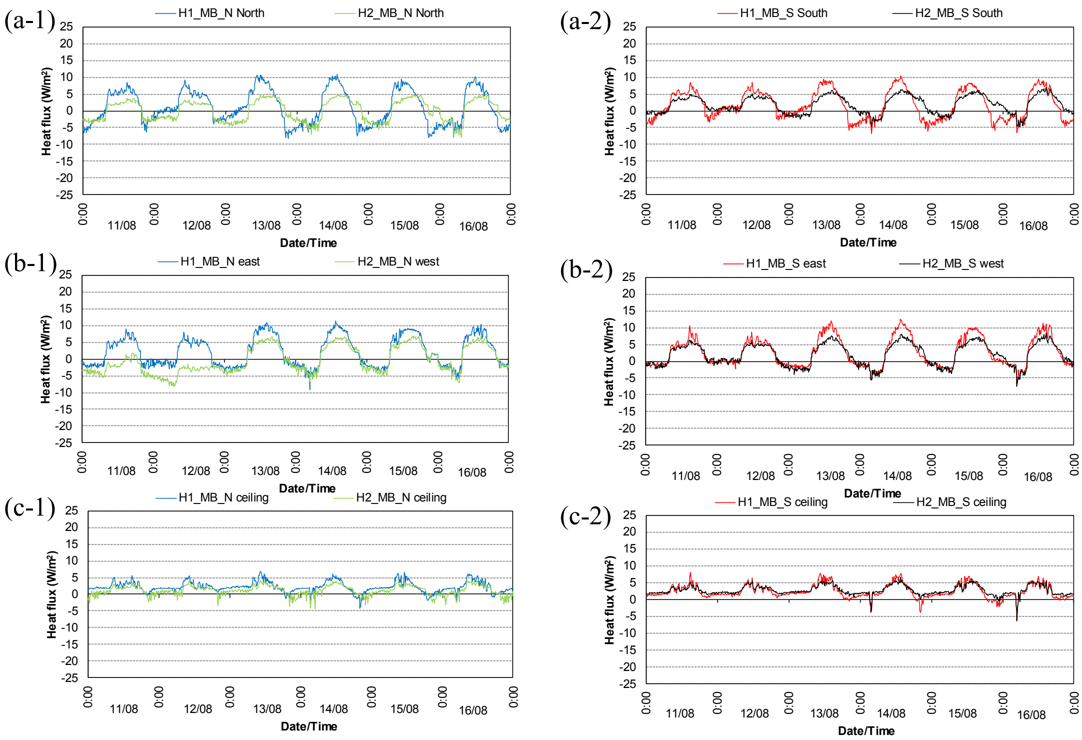


Figure 6.69. Heat fluxes on (a) external wall (inside); (b) end wall (inside) and (c) ceiling surfaces in north and south facing master bedrooms of both houses in Case 7-a.

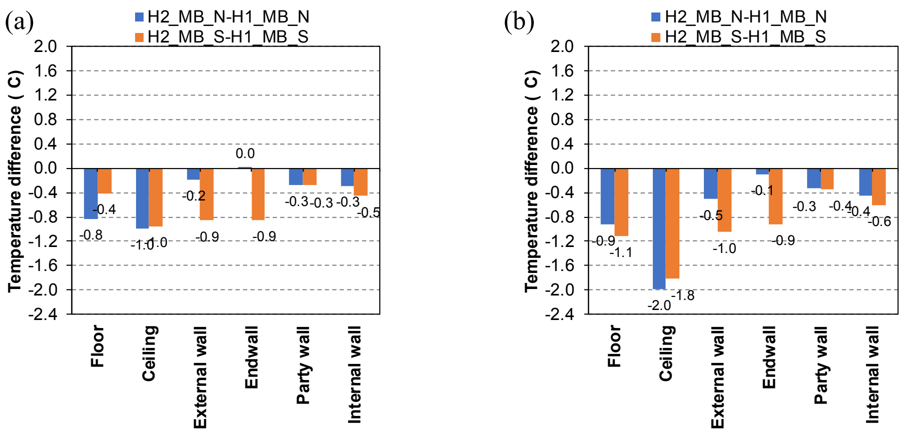


Figure 6.70. Average surface temperature difference between master bedroom in House 2 and House1 (House2 – House 1) in Case 7-a during (a) night-time and (b) daytime.

6.5.6.1.3 Thermal comfort in the master bedrooms

Figure 6.71 shows the result of calculated operative temperature and SET* in the master bedrooms including the respective indoor wind speed in Case 7-a. During the measurement, the recorded indoor wind speed in the north facing master bedroom of the measurement unit were slightly higher than that of the control unit by about 0.1m/s in average during night-time. Meanwhile, in the south facing master bedrooms, the indoor wind speed in both houses were almost similar. As shown, the calculated operative temperature in the north facing master bedroom of the measurement unit was completely fall under the 80% ACE upper limits during the whole measurement period. Meanwhile, the operative temperatures in the south facing master bedroom of the measurement unit was slightly exceed the limits by about 16% of the measurement period. Meanwhile, the operative temperature in the master bedrooms of the control unit exceed the limit for more than 40% of the measurement period. To be noted that the above results are almost similar to that of Case 7-a.

The SET* in the north facing room of the measurement unit was ranges from 25.0-30.2°C, which was about 1.3°C and 0.8°C lower than the control room during daytime and night-time, respectively. The reduction of SET* was also observed in the south facing room where the reduction is about 1.2°C during daytime and 0.9°C during night-time compared to the control room. The SET* in the south facing room of the measurement unit was ranges from 24.0-30.5°C. The results indicate that the reduction of SET* was not only in the night-time, but also in the daytime.

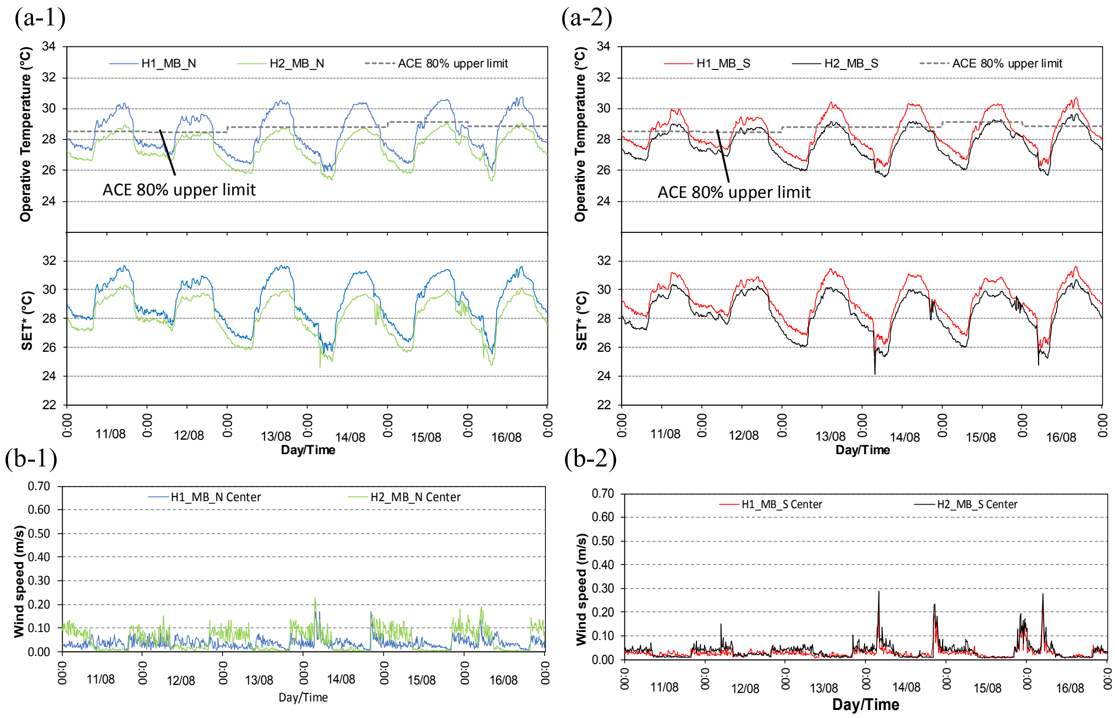


Figure 6.71. (a) Operative temperature (top) and SET* (bottom) in the master bedrooms of both houses in Case 7-a. (b) Wind speed in the living halls in Case 7-a.

6.5.6.1.4 Thermal comfort in the living halls

Figure 6.72 presents the temporal variations of air temperature, relative humidity and absolute humidity in the living hall of both houses. As shown, the daytime air temperature in the measurement unit ranges from 25.5- 28.0°C while in the control unit it was ranges from 25.5-29.0°C. In average, the air temperature reduction in the living hall of the measurement unit is about 0.5°C during daytime. Meanwhile, at the night-time, there are no significant reduction of air temperature observed in the living hall of the master bedroom in the measurement unit. The relative humidity in the living hall of the measurement was slightly higher than that of the control unit in the daytime by about 5%. Meanwhile, the relative humidity in both living halls is almost similar during the night-time. In this case, the absolute humidity in living halls of the measurement was slightly lower than that of the control unit in the daytime by about 0.2 g/kg' while in night-time, it was almost similar in both living halls.

Figure 6.73 presents the variations of operative temperature and SET* in the living halls including the respective indoor wind speed. As shown, the operative temperature of both living halls were fall under the comfortable upper limit (ACE) for whole measurement period. Nevertheless, the maximum operative temperatures of the living hall in the control unit was larger than that of the measurement unit by about 1°C. The result showed that the calculated SET* in the living hall of the measurement unit was ranges from 24-30°C. The SET* of the living hall in the measurement unit was always lower than that of control unit by about 0.9-1.1°C for the whole days.

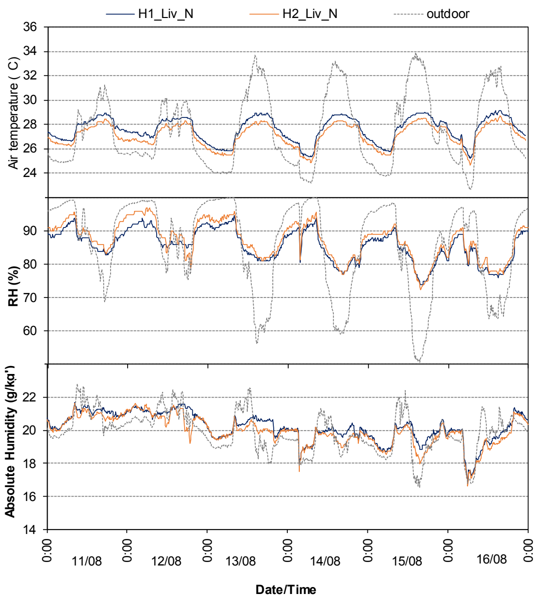


Figure 6.72. Temporal variations of air temperatures, RH and absolute humidity in the living hall of both houses in Case 7-a.

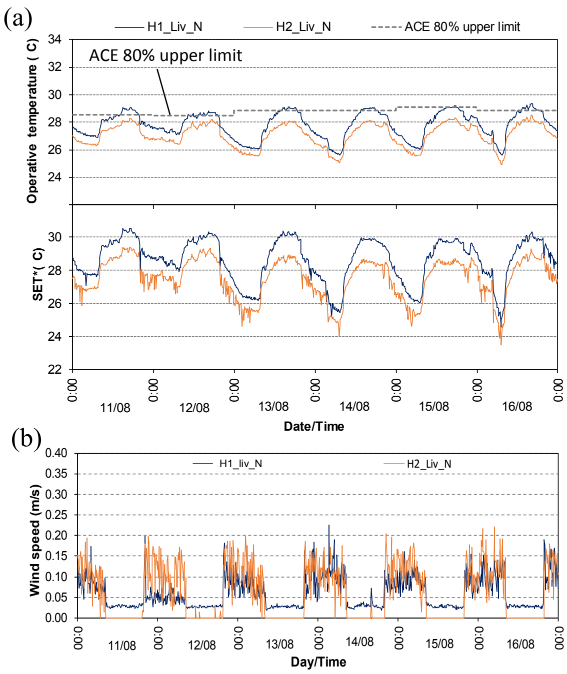


Figure 6.73. (a) Operative temperature (top) and SET* (bottom) in the living hall of both houses in Case 7-a. (b) Wind speed in the living halls in Case 7-a.

6.5.6.1.5 Thermal environment variations of the whole house

Figure 6.74 shows the air temperature variations of the whole house during daytime (15:00) and night-time (00:00). As shown, during daytime (15:00), the air temperatures increased with the increases of height. The lowest air temperatures observed on the ground floor of both houses (measurement and control unit). In general, the ground floor spaces in the measurement unit have slightly lower average air temperature compared to that of control unit. The temperature difference between both houses in living hall, dining and kitchen spaces is 0.8°C, 0.4°C and 0.7°C, respectively.

a) 15:00 (daytime)

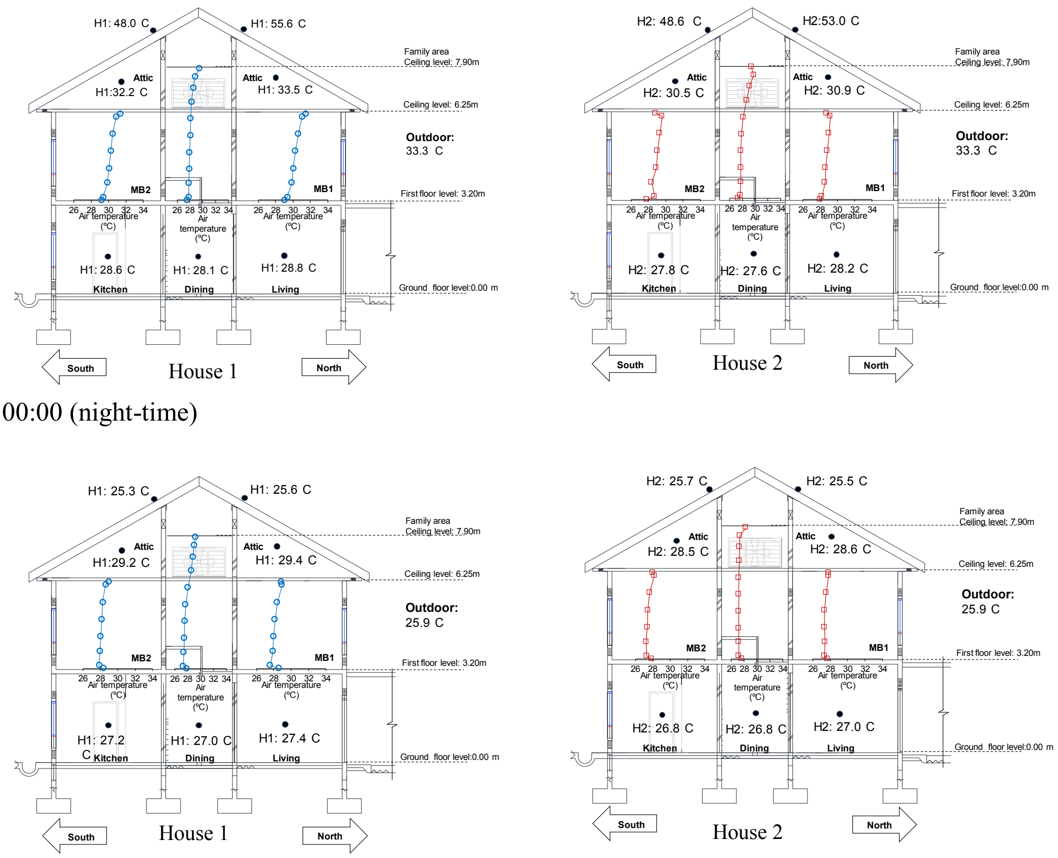


Figure 6.74. Whole house air and surface temperature distribution in House 1 (control unit) and House 2 (measurement unit) in Case 7-a at (a) 15:00 (daytime) and (b) 00:00 (night-time).

Meanwhile, in the first floor, the air temperature in the master bedrooms increased with the increase of height from floor to the ceiling. Slightly large gradient of air temperatures observed in the control unit. Large gradient means bigger air temperature differences between floor and ceiling level. In the control unit, the temperature difference from floor to ceiling level was about 2.2-2.3°C while in the measurement unit, they were about than 0.8-1.2°C. In this case, the air temperature in the attic of north and south facing master bedrooms in the measurement unit was about 2.2°C and 1.3°C lower than that of in the control unit. This indicates that the roof insulation successfully reduces the attic air temperature during daytime.

During night-time (00:00), it was found that the air temperatures in the ground floor in the measurement unit were lower than that of in the control unit by about 0.2-0.3°C. Moreover, the attic temperatures in the measurement unit were lower than that of the control unit by about 0.5-0.9°C.

In the control unit, the gradient of vertical air temperatures (from 0.1m above floor to the ceiling) is up to 1.5°C and 1.1°C in north and south master bedroom, respectively. Meanwhile, in the measurement house, the gradient of vertical air temperatures (from 0.1m above floor to the ceiling) is up to 04°C and 0.8°C in north and south master bedroom, respectively.

Figure 6.75 presents the statistical summary of air temperature, relative humidity and absolute humidity in all spaces in both houses. In general, the nocturnal air temperature reduction was improved due to the application of the whole house ventilation at night. In average, the air temperature in the master bedrooms of the measurement unit are lower than that of control unit by about 1.0°C. Meanwhile, the living hall of the measurement unit is lower than that of the control unit by about 0.5°C in average. The average humidity in the master bedrooms is about 87%. Meanwhile, average absolute humidity in the master bedroom of measurement unit were always higher than that of the control unit by about 0.5 g/kg'. In the ground floor, the average absolute humidity in most of ground floor spaces were almost similar to that of in the control unit except for the living hall where the difference is about 0.5 g/kg'.

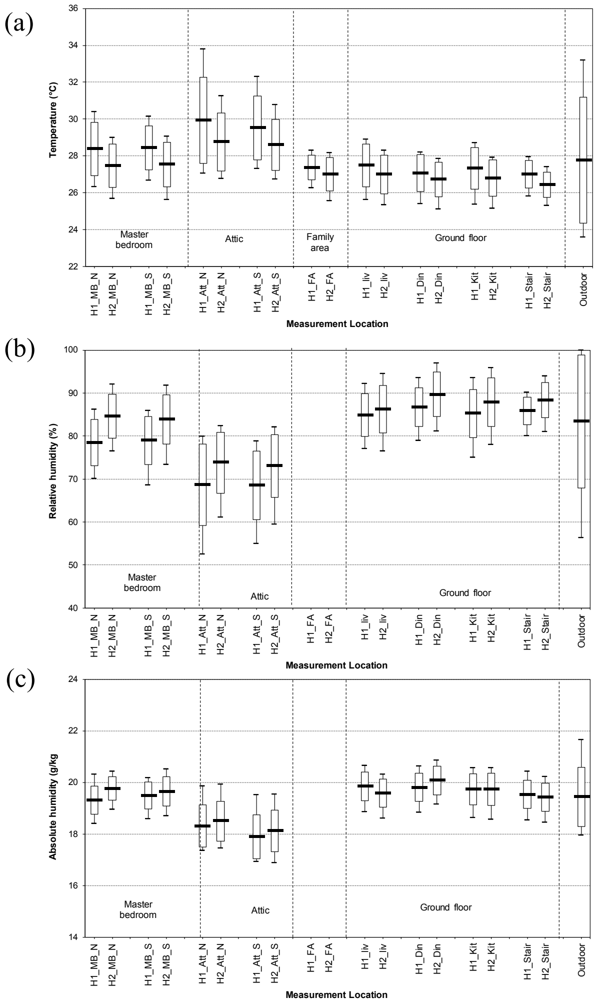


Figure 6.75. Statistical summary (5th and 95th percentiles, mean and ±one S.D.) of measurements (at 1.5 m above floor) of whole house in both House 1 and House 2 in Case 7-a. (a) Air temperature; (b) relative humidity; and (c) absolute humidity.

6.5.6.2 Case 7-b: Slit windows (Night ventilation, 3 techniques and whole house fan)

6.5.6.2.1 Effects on indoor thermal environment of the master bedrooms

In this case, the opening condition during night-time in the control unit was by the main windows while in the measurement unit, the slit windows were applied. The purpose is to investigate the effect wind flow near the building structure (i.e. floor and ceiling) during night-time in addition to the three modification techniques (i.e. roof insulation, external wall insulation and external window shading). Figure 6.76 shows the temporal variations of air temperatures, relative humidity and absolute humidity in north and south facing rooms of both houses of Case 7-b under night ventilation condition. During the measurement period, the outdoor air temperature ranges from 23.0-33.8°C with the average of 27.7°C. Meanwhile, the outdoor relative humidity and absolute humidity ranges from 57-100% and 17.2-22.2 g/kg', respectively. The average wind speed during daytime is about 0.30 m/s, while almost calm wind speed during night-time (less than 0.1 m/s).

As shown in Figure 6.76, the air temperature in the master bedrooms in the measurement unit were lower than the control in daytime. In the north facing rooms, the air temperature in the master bedroom of the measurement unit (H2_MB2_N) was lower than that of control unit (H1_MB_N) by up to 1.8°C. Meanwhile, in the south facing rooms, the air temperature reduction is up to 1.3°C (H2_MB_S-H1_MB_S). In average, the air temperature in the north and south facing rooms of the measurement unit is lower than that of control by about 1.3°C and 1.1°C respectively (Figure 6.77). The results show that the air temperature reduction in the master bedrooms of the measurement unit were slightly larger than that of Case 7-a during daytime. Probably, the structural cooling effects was larger in this case due to the wind flow near to the building structure in the night-time. Meanwhile, in the night-time, the average nocturnal air temperature in the north and south facing master bedrooms in the measurement unit was lower than that of control unit by about 0.4°C and 0.9°C, respectively. The resulted air temperature reduction was slightly lower than that of Case 7-a. This is probably because the cool night-time air flows did not flow directly at the center of the room and resulted to slower heat transfer to outside compared to the previous case (Case 7-a).

The relative humidity in the master bedrooms of the measurement unit was always higher than that of control unit for the whole day. At the daytime, the relative humidity in the north and south facing rooms of the measurement unit were higher than that of control rooms by up to 10% and 8% respectively. In average, they were higher than the control rooms by about 7% and 6% in north facing and south facing room, respectively. Meanwhile, at night-time, the nocturnal relative humidity in the north and south facing room were higher than that of in control rooms by up to 5% and 6%, respectively. The absolute humidity in the north master bedrooms of the measurement unit were higher than that of the control rooms by about 0.5 g/kg' during daytime and night-time. Meanwhile, the absolute humidity in the south master bedrooms of the measurement unit was higher than that of the control rooms in daytime by about 0.4 g/kg'. In contrast, the absolute humidity in both south facing room was almost similar where the average difference is about 0.1 g/kg' in nigh-time.

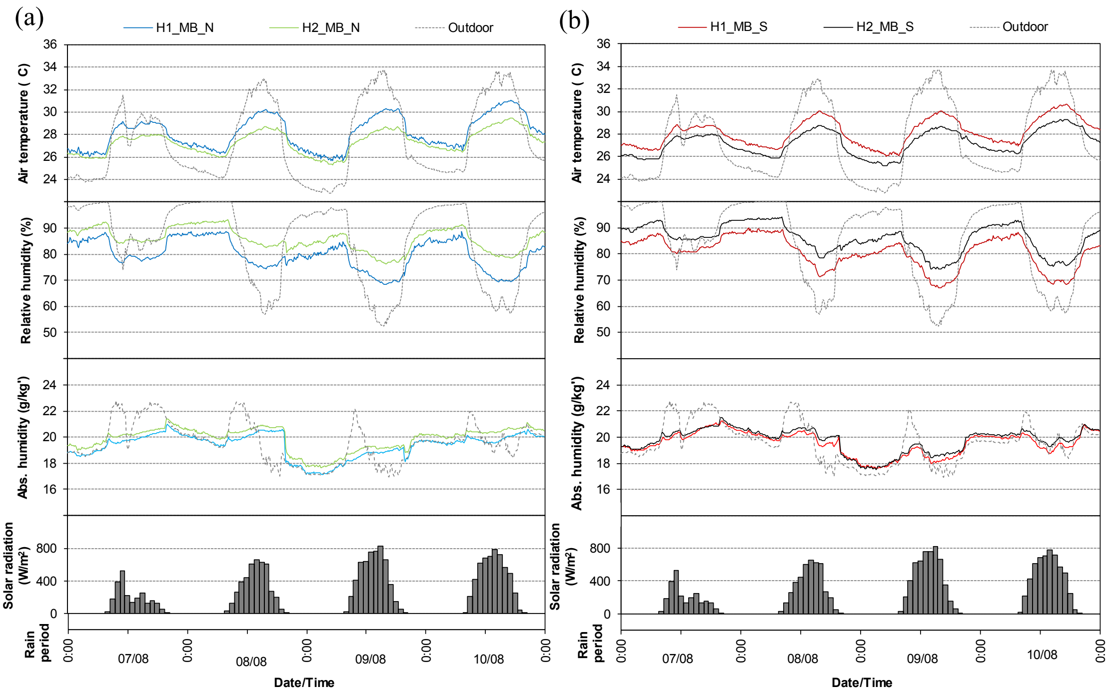


Figure 6.76. Temporal variations of air temperatures, RH and absolute humidity in the master bedrooms of House 1 and House 2 with the corresponding outdoor solar radiation and rain period in Case 7-b. (a) North facing master bedroom (H1/H2_MB_N) (b) South facing master bedroom (H1/H2_MB_S).

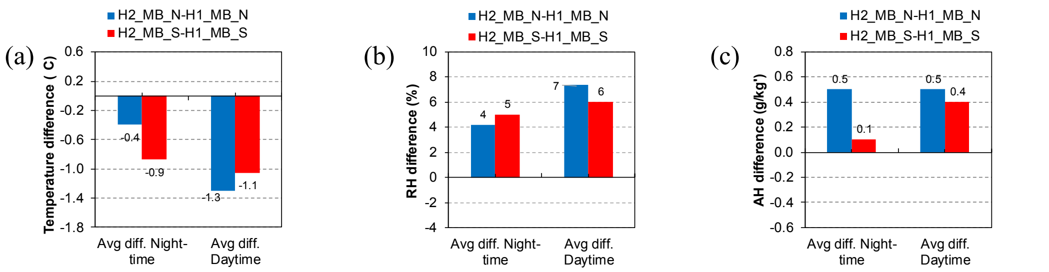


Figure 6.77. Average difference between master bedroom in House 1 and House 2 (House 2-House1) for north and south direction in daytime and night-time in Case 7-b. (a) Air temperature; (b) relative humidity; and (c) absolute humidity.

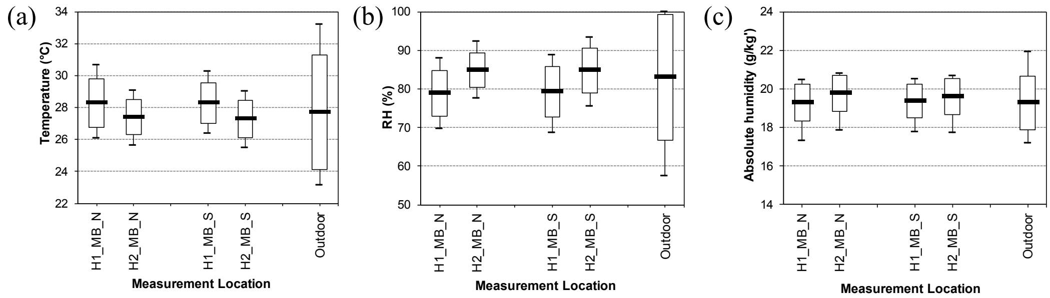


Figure 6.78. Statistical summary (5th and 95th percentiles, mean and ±one S.D.) of measurements (at 1.5 m above floor) in the master bedrooms in Case 7-b. (a) Air temperature; (b) relative humidity; and (c) absolute humidity.

6.5.6.2.2 Heat fluxes and surface temperature in the master bedrooms

Figure 6.79 shows the results of heat fluxes on the inside surface of the external wall, end wall and the ceiling in the master bedrooms. Meanwhile, Figure 6.80 shows the average surface temperature difference between the master bedrooms in the measurement and control unit (measurement-control unit). The external wall of both rooms in the measurement unit absorbed lower heat than that of the control unit by about 5-7 W/m^2 (Figure 6.79). This is simply because the air temperature in master bedroom in the control unit was warmer than that of measurement unit. Meanwhile, in the night-time, the external wall in the north facing master bedroom in the control unit shows slightly better rate of heat release in the early night-time where the heat fluxes (negative value) are larger than that of measurement unit by up to 5.0 W/m^2. The heat fluxes in the master bedroom of the measurement unit improved at the mid-night where the heat fluxes became the same as in the control unit.

Similar situation observed on the surface of end wall. Slightly lower heat absorption occurred in the master bedrooms of the measurement unit during daytime. The heat flux on the end walls of measurement unit was lower than that of control room by about 2.5-5 W/m^2 in both master bedrooms. Meanwhile, the heat fluxes on the surface of end walls of south facing master bedroom in both houses are almost equal in the night-time. In the north facing master bedroom, the heat fluxes in measurement unit was larger than that of in the control unit by about 5 W/m^2. For most of the time, the ceiling in the master bedrooms of the control unit was always absorbing the heat (positive heat fluxes). This indicates that the surface temperature of the ceiling in those master bedrooms were always lower than the air temperature for most of the day. Meanwhile, the heat fluxes of the ceiling in the measurement unit was almost similar to that of the control unit during the daytime. In the night-time, the heat was released from the ceiling surface with the heat fluxes value of 5 W/m^2. This indicates that the ceiling in the master bedrooms of the measurement unit was cooler the air temperature during daytime while in night-time, the cool air flow near the ceiling surface, enhance the thermal heat transfer from the surface to the air.

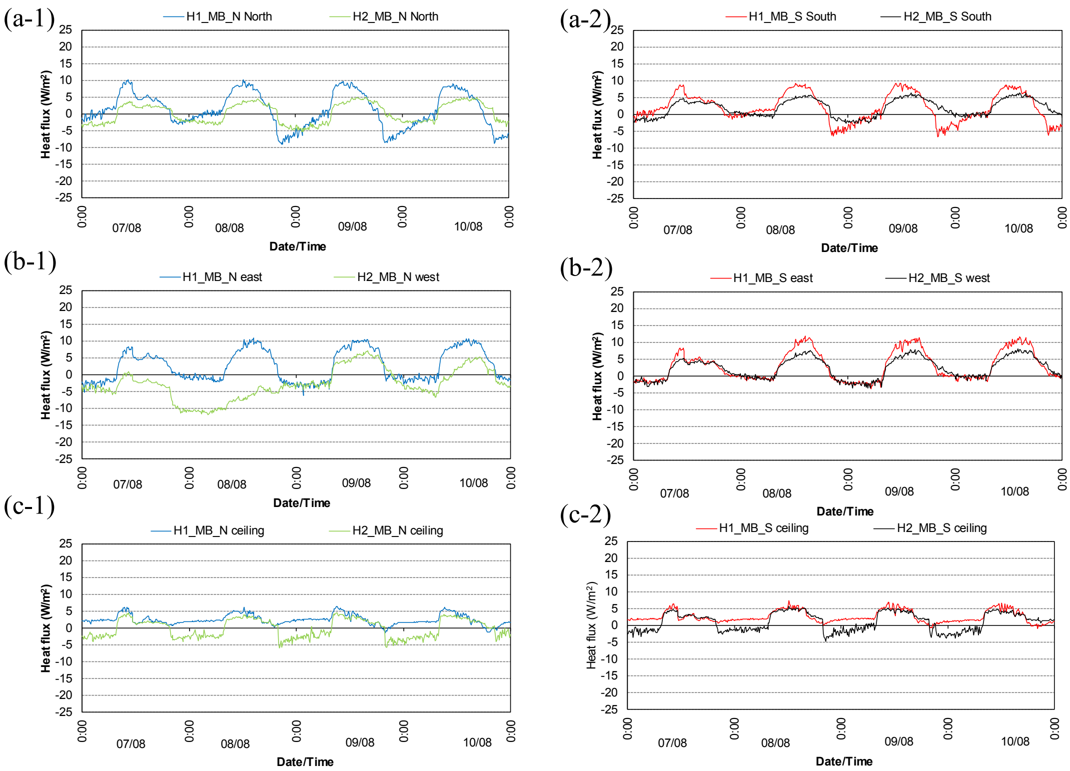


Figure 6.79. Heat fluxes on (a) external wall (inside); (b) end wall (inside) and (c) ceiling surfaces in north and south facing master bedrooms of both houses in Case 7-b.

As shown in Figure 6.80, the surface temperature of the walls in the master bedrooms in the measurement unit were always lower than that of control unit for the whole day. In daytime, the highest difference is on the floor and ceiling which is about 1.1-1.3°C and 2.0-2.3°C, respectively. In the night-time, the temperature reduction on the ceiling and floor surfaces remained as the largest where reduction is about 0.6-1.1°C on the floor and 1.5-1.7°C on the ceiling. The reduction of both surfaces was found slightly larger than that of Case 7-a.

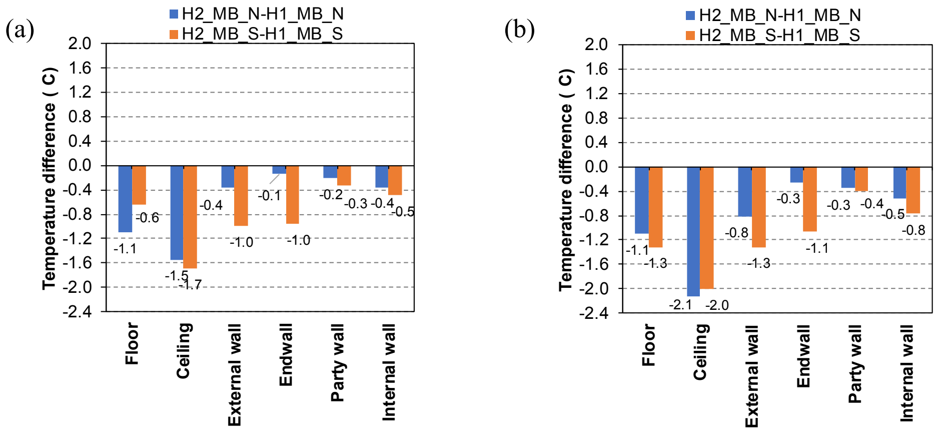


Figure 6.80. Average surface temperature difference between master bedroom in House 2 and House1 (House2 – House 1) in Case 7-b during (a) night-time and (b) daytime.

6.5.6.2.3 Thermal comfort in the master bedrooms

Figure 6.81 shows the result of calculated operative temperature and SET* in the master bedrooms including the respective indoor wind speed in Case 7-b. During the measurement, the recorded indoor wind speed in the master bedrooms of the measurement unit were slightly higher than that of the control unit by about 0.1m/s during night-time. As shown, the calculated operative temperature in both master bedrooms of the measurement house was under the 80% ACE comfortable upper limits during the whole measurement period. Meanwhile, the operative temperature in the master bedrooms of the control unit exceed the limit for more than 40% of the measurement period.

The SET* in the north facing room of the measurement unit was ranges from 25.0-30.2°C, which was about 2°C and 0.4°C lower than the control room during daytime and night-time, respectively. The reduction of SET* was also observed in the south facing room. The reduction is about 1.0°C during daytime and 0.5°C during night-time compared to the control room. Thus, the SET* in the south facing room of the measurement unit was ranges from 25.0-30.2. The results indicate that the reduction of SET* was not only in the night-time, but also in the daytime.

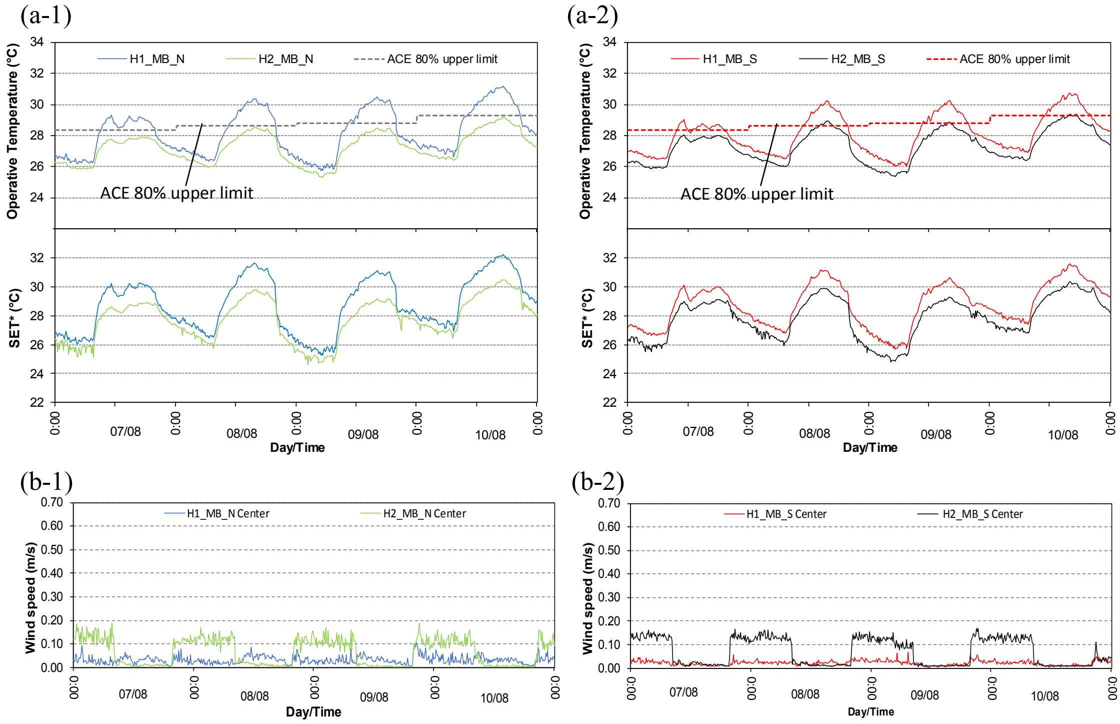


Figure 6.81. (a) Operative temperature (top) and SET* (bottom) in the master bedrooms of both houses in Case 7-b. (b) Wind speed in the living halls in Case 7-b.

6.5.6.2.4 Thermal comfort in the living halls

Figure 6.82 presents the temporal variations of air temperature, relative humidity and absolute humidity in the living hall of both houses. As shown, the daytime air temperature in the measurement unit ranges from 25.2- 28.5°C while in the control unit it was ranges from 25.2-29.0°C. In average, the air temperature reduction in the living hall of the measurement unit is about 0.6°C during daytime. Meanwhile, at the night-time, it was found that the recorded air temperatures in both living halls was almost the same for most of the measurement period. The relative humidity in both living halls was almost the same for the whole day and they were ranges from 75-95%. Meanwhile, the absolute humidity in both living halls was about 17.3-22 g/kg'.

Figure 6.83 presents the variations of operative temperature and SET* in the living halls including the respective indoor wind speed. As shown, the operative temperature in both living halls fall within the measurement unit was completely fall under the comfortable upper limit of the measurement period. In contrast, the living hall in the control unit exceed the limit by about 10% of the measurement period. The result showed that the calculated SET* in the living hall of the measurement unit was ranges from 24-29°C. The SET* of the living hall in the measurement unit was always lower than that of control unit by about 1.2-1.5°C for the whole days.

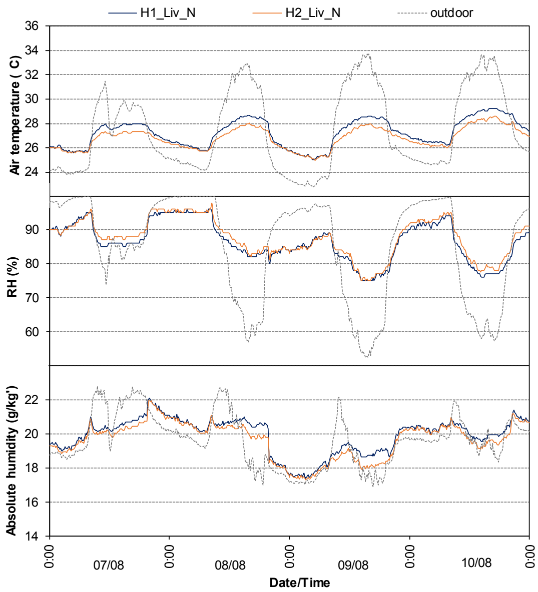


Figure 6.82. Temporal variations of air temperatures, RH and absolute humidity in the living hall of both houses in Case 7-b.

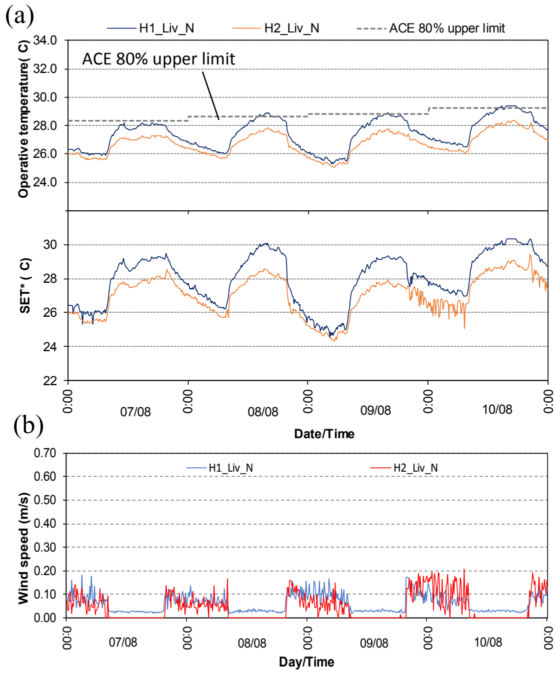


Figure 6.83. (a) Operative temperature (top) and SET* (bottom) in the living hall of both houses in Case 7-b. (b) Wind speed in the living halls in Case 7-b.

6.5.6.2.5 Thermal environment variations of the whole house

Figure 6.84 shows the air temperature variations of the whole house during daytime (15:00) and night-time (00:00). As shown, during daytime (15:00), the air temperatures increased with the increases of height. The lowest air temperatures observed on the ground floor of both houses (measurement and control unit). In the ground floor, the lowest air temperature recorded at the dining hall where the average temperature is about 27.5°C and 28.0°C in the control and the measurement unit, respectively. The highest air temperature was recorded at the living hall which is about 28.7°C and 28.0°C in the control and the measurement unit, respectively. In general, the ground floor spaces in the measurement unit have slightly lower average air temperature in all spaces compared to the control unit. The temperature difference between both houses in living hall, dining and kitchen spaces is 0.7°C, 0.5°C and 0.9°C, respectively.

a) 15:00 (daytime)

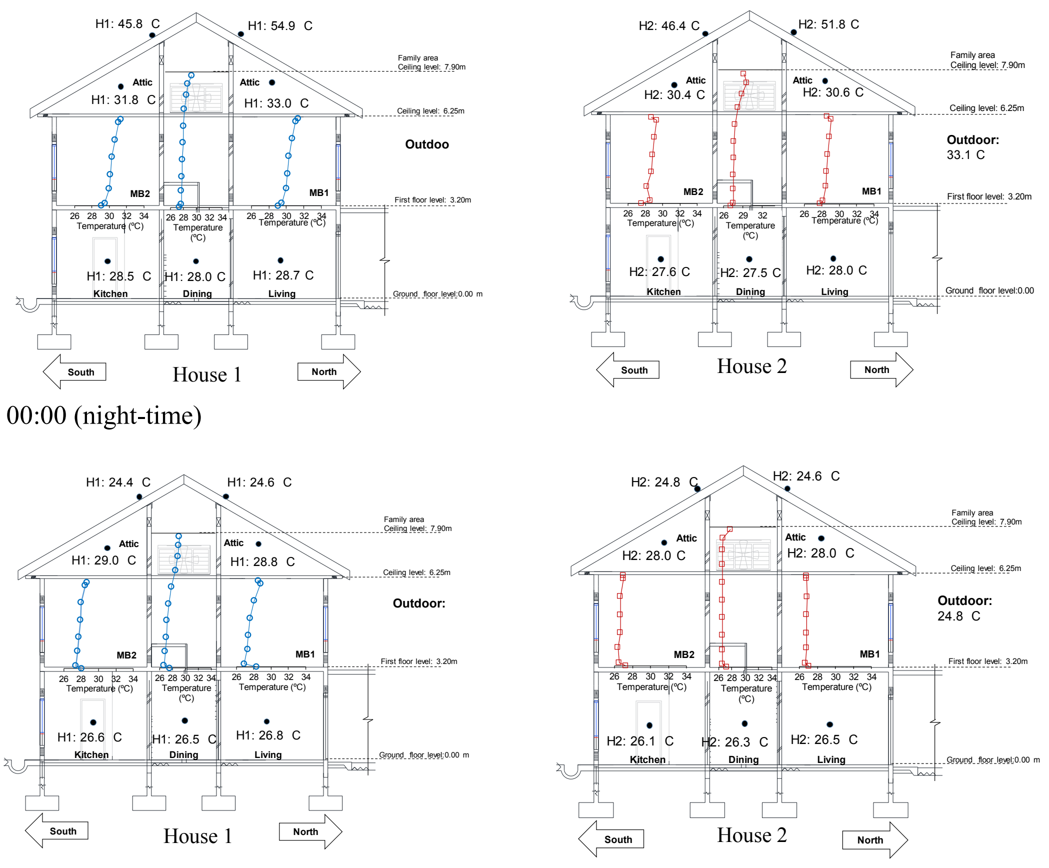


Figure 6.84. Whole house air and surface temperature distribution in House 1 (control unit) and House 2 (measurement unit) in Case 7-b at (a) 15:00 (daytime) and (b) 00:00 (night-time).

Meanwhile, in the first floor, the air temperature in the master bedrooms increased with the increase of height from floor to the ceiling. Slightly large gradient of air temperatures observed in the control unit. In the control unit, the temperature difference from floor to ceiling level was about 2-2.3°C while in the measurement unit, they were less than 1°C. Nevertheless, the vertical air temperatures increase linearly from floor to the ceiling level in all rooms (control and measurement unit) during the daytime. In this case, the air temperature in the attic of north and south facing master bedrooms in the measurement unit was about 2.4°C and 1.4°C lower than that of in the control unit. This indicates that the roof insulation successfully reduces the attic air temperature during daytime.

During night-time (00:00), it was found that the air temperatures in the ground floor in both houses were almost similar except for the living hall. The living hall in the measurement unit was lower than that of the control unit by about 0.3°C. Moreover, the attic temperatures in the measurement unit were lower than that of the control unit by about 0.7-0.8°C. In the control unit, the gradient of vertical air temperatures (from 0.1m above floor to the ceiling) is up to 1.6°C and 1.3°C in north and south master bedroom, respectively. Meanwhile, in the measurement house, the gradient of vertical air temperatures (from 0.1m above floor to the ceiling) is up to 0.1°C and 0.5°C in north and south master bedroom, respectively. This indicates that the nocturnal air temperature in the master bedrooms in the control unit were cooled uniformly from the floor to the ceiling level.

Figure 6.85 presents the statistical summary of air temperature, relative humidity and absolute humidity in all spaces in both houses. In average, the air temperature in the master bedrooms of the measurement unit are lower than that of control unit by about 0.9-1.0°C. Nevertheless, the average humidity in the master bedrooms can be considered quite high which about 85%. Meanwhile, average absolute humidity in the measurement unit were slightly higher than that of the control unit in the first floor by about 0.3-0.6 g/kg'. In the ground floor, the average absolute humidity in most of ground floor spaces were lower than that of control by about 0.4 g/kg'.

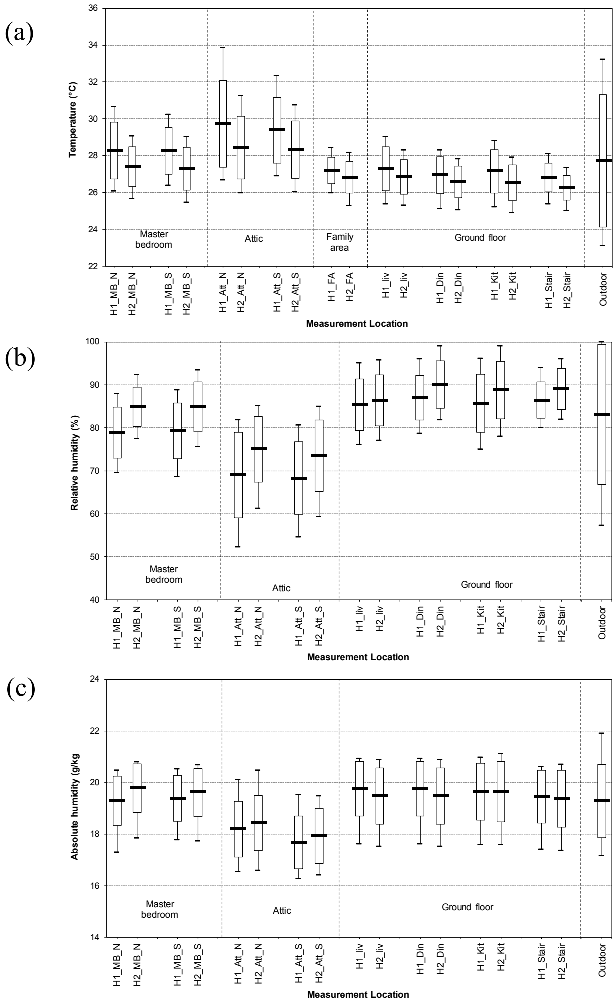


Figure 6.85. Statistical summary (5th and 95th percentiles, mean and ±one S.D.) of measurements (at 1.5 m above floor) of whole house in both House 1 and House 2 in Case 7-b. (a) Air temperature; (b) relative humidity; and (c) absolute humidity.

6.5.6.3 Case 7-c: All windows (Night ventilation, 3 techniques and whole house fan)

6.5.6.3.1 Effects on indoor thermal environment of the master bedrooms

In this case, the opening condition during night-time in the control unit was by the main windows while in the measurement unit, all windows were applied (i.e. main windows and slit windows). The purpose is to investigate the effect maximum window opening (i.e. floor and ceiling) during night-time in addition to the three modification techniques (i.e. roof insulation, external wall insulation and external window shading). Figure 6.86 shows the temporal variations of air temperatures, relative humidity and absolute humidity in north and south facing rooms of both houses of Case 7-c under night ventilation condition. During the measurement period, the outdoor air temperature ranges from 23.0-33.7°C with the average of 28.0°C. Meanwhile, the outdoor relative humidity and absolute humidity ranges from 58-100% and 17.0-23.5 g/kg', respectively. The average wind speed during daytime is about 0.50 m/s, while almost calm wind speed during night-time (less than 0.1 m/s).

As shown in Figure 6.86, the air temperature in the master bedrooms in the measurement unit were lower than the control in daytime. In the north facing rooms, the air temperature in the master bedroom of the measurement unit (H2_MB2_N) was lower than that of control unit (H1_MB_N) by up to 1.5°C. Meanwhile, in the south facing rooms, the air temperature reduction is up to 1.2°C (H2_MB_S-H1_MB_S).

In average, the air temperature in the north and south facing rooms of the measurement unit is lower than that of control by about 1.1°C and 0.9°C respectively (Figure 6.87). The results show that the air temperature reduction in the master bedrooms of the measurement unit were almost similar to that of Case 7-a during daytime. Meanwhile, in the night-time, the average nocturnal air temperature in the north and south facing master bedrooms in the measurement unit was lower than that of control unit by about 0.6°C and 1.0°C, respectively. The resulted air temperature reduction during night-time were also similar to that of Case 7-a. This is probably because the cool night-time air flows directly at the center of the room and resulted to similar cooling as in Case 7-a.

The relative humidity in the master bedrooms of the measurement unit was always higher than that of control unit for the whole day. At the daytime, the relative humidity in the north and south facing rooms of the measurement unit were higher than that of control rooms by up to 9%. In average, they were higher than the control rooms by about 7% and 5% in north facing and south facing room, respectively. Meanwhile, at night-time, the nocturnal relative humidity in the north and south facing room were higher than that of in control rooms by 6% in average. The absolute humidity in the north master bedrooms of the measurement unit were higher than that of the control rooms by about 0.5 g/kg' during daytime and night-time. The absolute humidity in the south master bedrooms of the measurement unit was also higher than that of the control rooms in daytime and night-time by about 0.4 g/kg' and 0.2 g/kg', respectively.

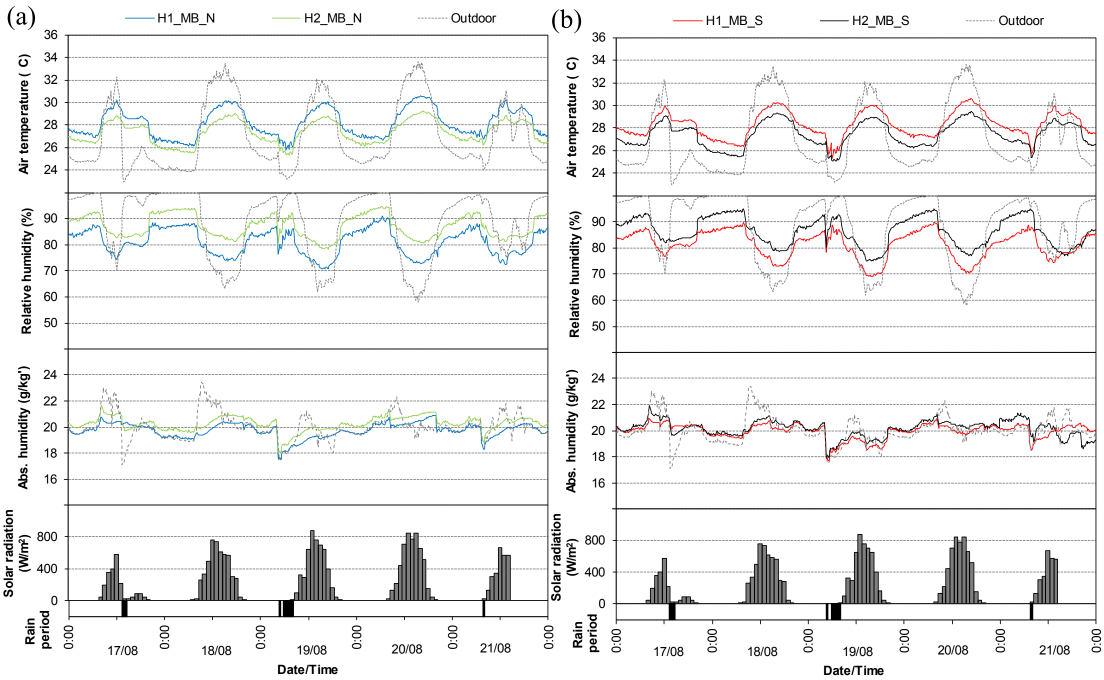


Figure 6.86. Temporal variations of air temperatures, RH and absolute humidity in the master bedrooms of House 1 and House 2 with the corresponding outdoor solar radiation and rain period in Case 7-c. (a) North facing master bedroom (H1/H2_MB_N) (b) South facing master bedroom (H1/H2_MB_S).

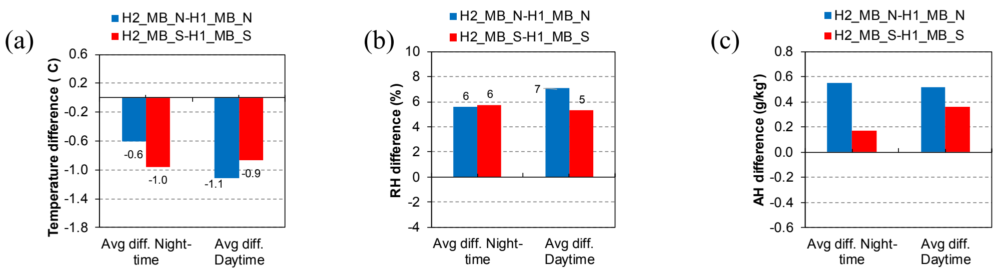


Figure 6.87. Average difference between master bedroom in House 1 and House 2 (House 2-House1) for north and south direction in daytime and night-time in Case 7-c. (a) Air temperature; (b) relative humidity; and (c) absolute humidity.

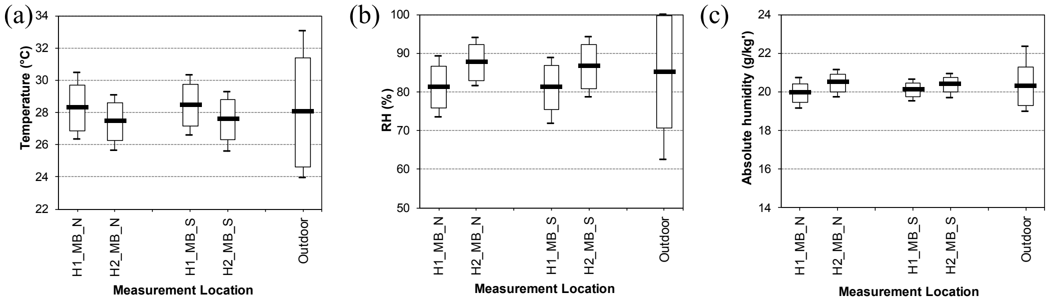


Figure 6.88. Statistical summary (5th and 95th percentiles, mean and ±one S.D.) of measurements (at 1.5m above floor) in the master bedrooms in Case 7-c. (a) Air temperature; (b) relative humidity; and (c) absolute humidity.

6.5.6.3.2 Heat fluxes and surface temperature in the master bedrooms

Figure 6.89 shows the results of heat fluxes on the inside surface of the external wall, end wall and the ceiling in the master bedrooms. Meanwhile, Figure 6.90 shows the average surface temperature difference between the master bedrooms in the measurement and control unit (measurement-control unit). The external wall of both rooms in the measurement unit absorbed lower heat than that of the control unit by about 3-5 W/m^2 (Figure 6.89a). This is simply because the air temperature in master bedroom in the control unit was warmer than that of measurement unit. Meanwhile, in the night-time, the external wall in the north facing master bedroom in the control unit shows slightly better rate of heat release in the early night-time where the heat fluxes (negative value) are larger than that of measurement unit by up to 5.0 W/m^2. Similar as in Case 7-b, the heat fluxes in the master bedroom of the measurement unit improved at the mid-night where the heat fluxes became the same as in the control unit.

Similar situation observed on the surface of end wall. Slightly lower heat absorption occurred in the master bedrooms of the measurement unit during daytime. The heat flux on the end walls of measurement unit was lower than that of control room by about 2.5-5 W/m^2 in both master bedrooms. Meanwhile, the heat fluxes on the surface of end walls in the master bedrooms of both houses are almost equal in the night-time. For most of the time, the ceiling in the master bedrooms of the control unit was always absorbing the heat (positive heat fluxes). This indicates that the surface temperature of the ceiling in those master bedrooms were always lower than the air temperature for most of the day. Meanwhile, the heat fluxes of the ceiling in the measurement unit was almost similar to that of the control unit during the daytime. In the night-time, the heat fluxes in the north facing master bedroom of the measurement unit were slightly lower than that in the control unit by about 2.5 W/m^2. In contrast, the heat fluxes in the south facing master bedroom of the measurement unit remain similar to that of in the control unit during the night-time. In general, this indicates that the ceiling in the master bedrooms of both house was cooler than their air temperature during daytime while in night-time and night-time.

As shown in Figure 6.90, the surface temperature in the master bedrooms of the measurement unit were always lower than that of control unit for the whole day except for the external wall in the north facing master bedroom. In daytime, the highest difference is on the floor and ceiling which is about 0.9-1.1°C and 1.9-1.8°C, respectively. In the night-time, the temperature reduction on the ceiling and floor surfaces remained as the largest where reduction is about 0.4-0.7°C on the floor and 0.9°C on the ceiling. The reduction of both surfaces was almost similar to that of Case 7-a, but lower than that of Case 7-b.

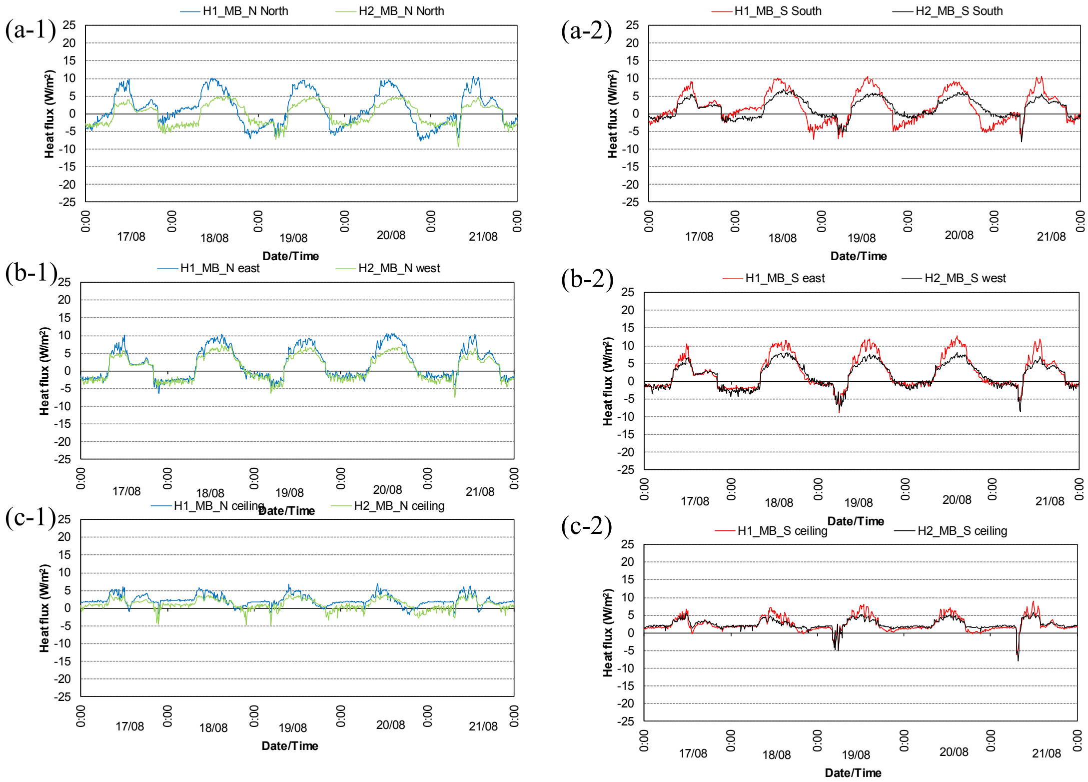


Figure 6.89. Heat fluxes on (a) external wall (inside); (b) end wall (inside) and (c) ceiling surfaces in north and south facing master bedrooms of both houses in Case 7-c.

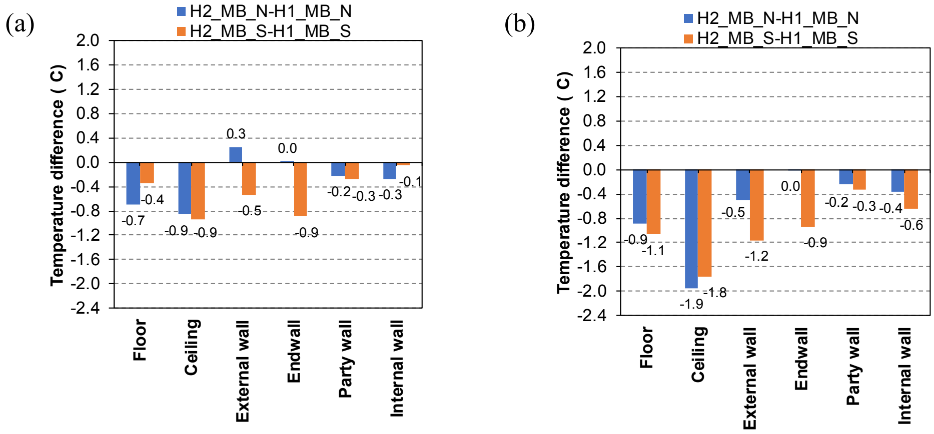


Figure 6.90. Average surface temperature difference between master bedroom in House 2 and House1 (House2 – House 1) in Case 7-c during (a) night-time and (b) daytime.

6.5.6.3.3 Thermal comfort in the master bedrooms

Figure 6.91 shows the result of calculated operative temperature and SET* in the master bedrooms including the respective indoor wind speed in Case 7-c. During the measurement, the recorded indoor wind speed in the master bedrooms of the measurement unit were slightly higher than that of the control unit by about 0.1m/s during night-time. As shown, the calculated operative temperature in both master bedrooms of the measurement house was under the 80% ACE comfortable upper limits during the whole measurement period. Meanwhile, the operative temperature in the master bedrooms of the control unit exceed the limit for more than 40% of the measurement period. The SET* in the north facing room of the measurement unit was ranges from 25.0-30.2°C, which was about 2°C and 0.4°C lower than the control room during daytime and night-time, respectively. The reduction of SET* was also observed in the south facing room. The reduction is about 1.0°C during daytime and 0.5°C during night-time compared to the control room. Thus, the SET* in the south facing room of the measurement unit was ranges from 25.0-30.2. The results indicate that the reduction of SET* was not only in the night-time, but also in the daytime.

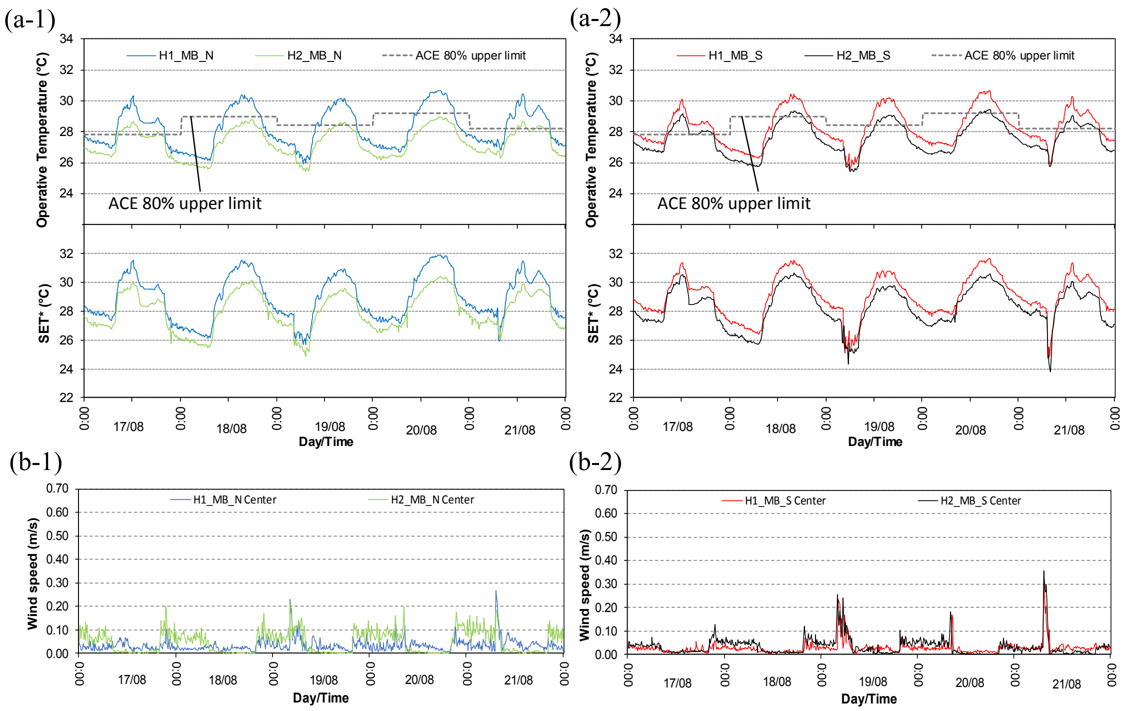


Figure 6.91. (a) Operative temperature (top) and SET* (bottom) in the master bedrooms of both houses in Case 7-c. (b) Wind speed in the living halls in Case 7-c.

6.5.6.3.4 Thermal comfort in the living halls

Figure 6.92 presents the temporal variations of air temperature, relative humidity and absolute humidity in the living hall of both houses. As shown, the daytime air temperature in the measurement unit ranges from 25.2- 28.5°C while in the control unit it was ranges from 25.2-29.0°C. In average, the air temperature reduction in the living hall of the measurement unit is about 0.6°C during daytime. Meanwhile, at the night-time, it was found that the recorded air temperatures in both living halls was almost the same for most of the measurement period. The relative humidity in both living halls was almost the same for the whole day and they were ranges from 75-95%. Meanwhile, the absolute humidity in both living halls was about 17.3-22 g/kg'.

Figure 6.93 presents the variations of operative temperature and SET* in the living halls including the respective indoor wind speed. As shown, the operative temperature in both living halls fall within the measurement unit was completely fall under the comfortable upper limit of the measurement period. In contrast, the living hall in the control unit exceed the limit by about 10% of the measurement period. The result showed that the calculated SET* in the living hall of the measurement unit was ranges from 24-29°C. The SET* of the living hall in the measurement unit was always lower than that of control unit by about 1.2-1.5°C for the whole days.

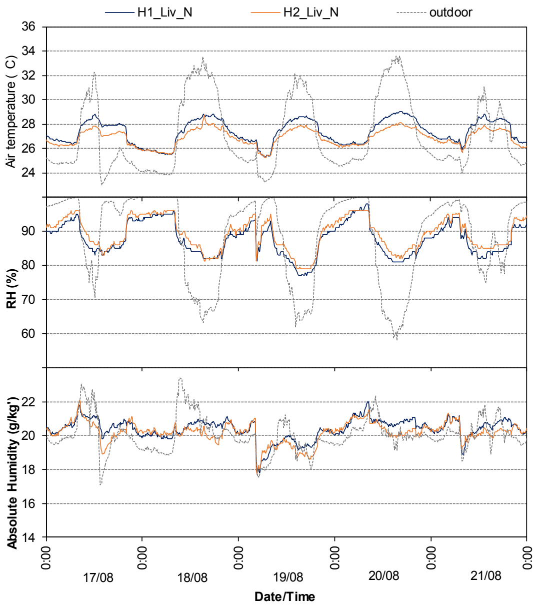


Figure 6.92. Temporal variations of air temperatures, RH and absolute humidity in the living hall of both houses in Case 7-c.

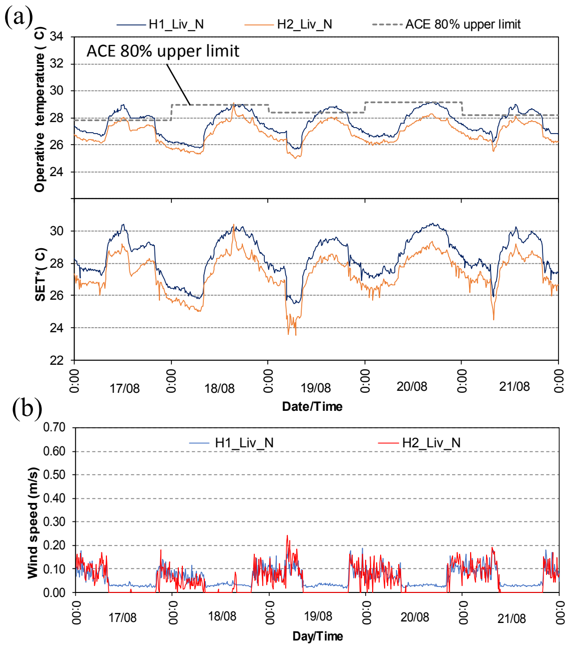
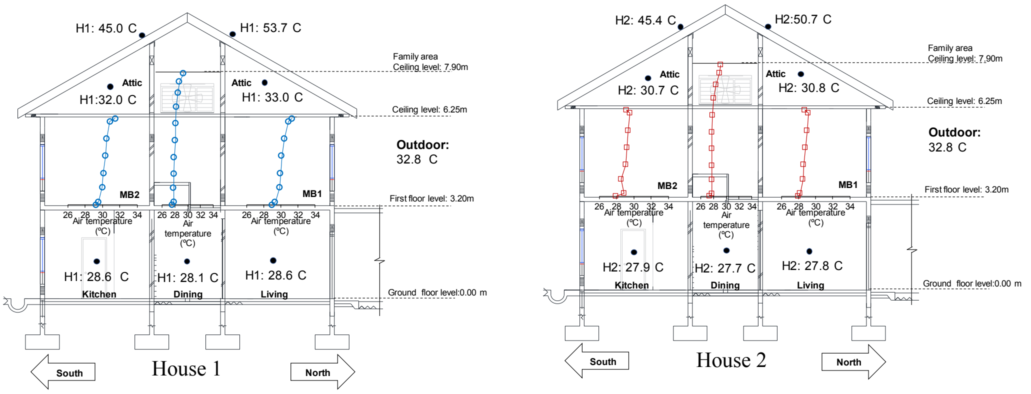


Figure 6.93. (a) Operative temperature (top) and SET* (bottom) in the living hall of both houses in Case 7-c. (b) Wind speed in the living halls in Case 7-c.

6.5.6.3.5 Thermal environment variations of the whole house

Figure 6.94 shows the air temperature variations of the whole house during daytime (15:00) and night-time (00:00). As shown, during daytime (15:00), the air temperatures increased with the increases of height. The lowest air temperatures observed on the ground floor of both houses (measurement and control unit). In the ground floor, the lowest air temperature recorded at the dining hall where the average temperature is about 27.5°C and 28.0°C in the control and the measurement unit, respectively. The highest air temperature was recorded at the living hall which is about 28.7°C and 28.0°C in the control and the measurement unit, respectively. In general, the ground floor spaces in the measurement unit have slightly lower average air temperature in all spaces compared to the control unit. The temperature difference between both houses in living hall, dining and kitchen spaces is 0.7°C, 0.5°C and 0.9°C, respectively.

a) 15:00 (daytime)



b) 00:00 (night-time)

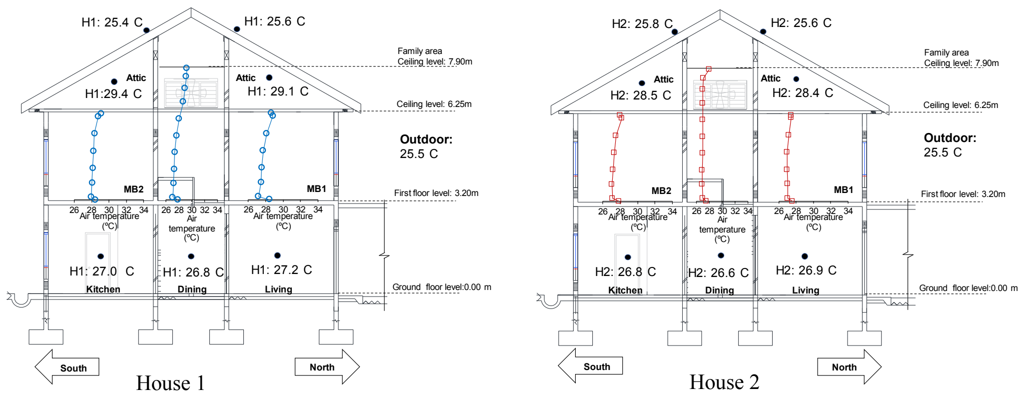


Figure 6.94. Whole house air and surface temperature distribution in House 1 (control unit) and House 2 (measurement unit) in Case 7-c at (a) 15:00 (daytime) and (b) 00:00 (night-time).

Meanwhile, in the first floor, the air temperature in the master bedrooms increased with the increase of height from floor to the ceiling. Slightly large gradient of air temperatures observed in the control unit. In the control unit, the temperature difference from floor to ceiling level was about 2-2.3°C while in the measurement unit, they were less than 1°C. Nevertheless, the vertical air temperatures increase linearly from floor to the ceiling level in all rooms (control and measurement unit) during the daytime. In this case, the air temperature in the attic of north and south facing master bedrooms in the measurement unit was about 2.4°C and 1.4°C lower than that of in the control unit. This indicates that the roof insulation successfully reduces the attic air temperature during daytime.

During night-time (00:00), it was found that the air temperatures in the ground floor in both houses were almost similar except for the living hall. The living hall in the measurement unit was lower than that of the control unit by about 0.3°C. Moreover, the attic temperatures in the measurement unit were lower than that of the control unit by about 0.7-

0.8°C. In the control unit, the gradient of vertical air temperatures (from 0.1m above floor to the ceiling) is up to 1.6°C and 1.3°C in north and south master bedroom, respectively. Meanwhile, in the measurement house, the gradient of vertical air temperatures (from 0.1m above floor to the ceiling) is up to 0.1°C and 0.5°C in north and south master bedroom, respectively. This indicates that the nocturnal air temperature in the master bedrooms in the control unit were cooled uniformly from the floor to the ceiling level.

Figure 6.95 presents the statistical summary of air temperature, relative humidity and absolute humidity in all spaces in both houses. In average, the air temperature in the master bedrooms of the measurement unit are lower than that of control unit by about 0.9-1.0°C. Nevertheless, the average humidity in the master bedrooms can be considered quite high which about 85%. Meanwhile, average absolute humidity in the measurement unit were slightly higher than that of the control unit in the first floor by about 0.3-0.6 g/kg'. In the ground floor, the average absolute humidity in most of ground floor spaces were lower than that of control by about 0.4 g/kg'.

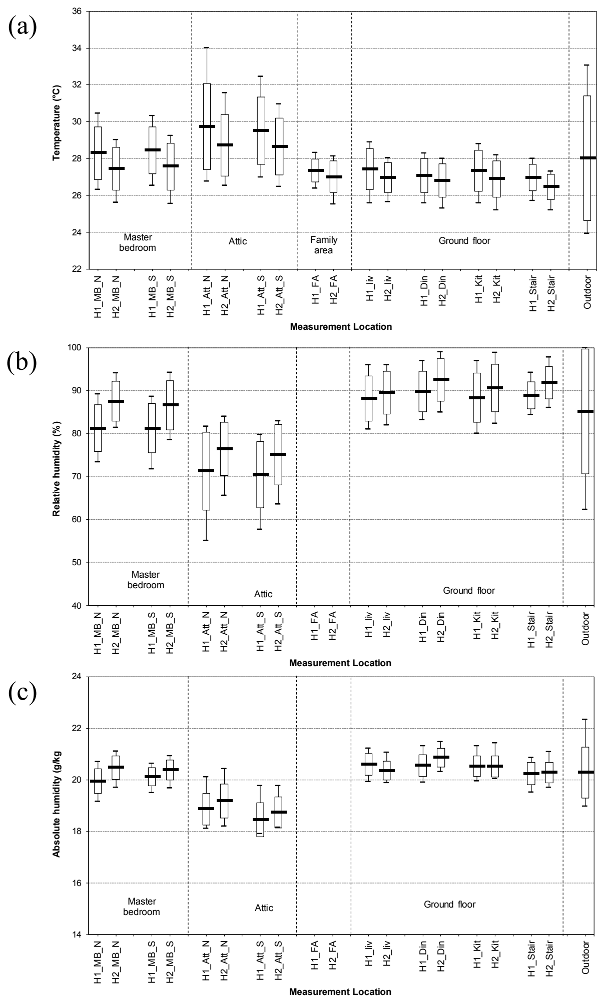


Figure 6.95. Statistical summary (5th and 95th percentiles, mean and ±one S.D.) of measurements (at 1.5 m above floor) of whole house in both House 1 and House 2 in Case 7-c. (a) Air temperature; (b) relative humidity; and (c) absolute humidity.

6.6 Summary

Full-scale measurement was conducted in the experimental houses located in UTM, Johor Bahru Malaysia from June to September 2016 to confirm the resulting effects of the proposed energy-saving modification techniques derived from the previous simulation studies (Chapter 5). Seven study cases have been conducted to investigate the effects of the proposed passive cooling modification techniques under the structural cooling and comfort ventilation strategies. The investigation of the effects of window position is also included. Based on the results of the full-scale experiment, we draw the following:

- The application of proposed modifications, i.e. roof insulation, external wall insulation, external shading and whole house ventilation successfully reduced indoor air temperatures by about 0.8°C during the day and night under structural cooling strategy. In the case of comfort ventilation strategy, the temperature reduction during the night-time is about 0.7°C while only small reduction observed in the daytime. Nevertheless, the whole house ventilation was not able to reduce the nocturnal indoor air temperatures as low as outdoor in both cooling strategies.
- In term of relative humidity, it was found that the application comfort ventilation strategies could provide lower indoor humidity level than that of structural cooling strategy as low as about 55%. This is due to the increased of ventilation rate and indoor air temperature during daytime. Nevertheless, the indoor temperature of the house with the proposed techniques still lower than that of the control unit (without passive cooling strategies).
- Ventilation through the slit window provided slightly larger reduction of indoor air temperature in the master bedrooms at night. The result also showed that the temperatures of indoor surfaces, especially the ceiling of the master bedroom, was cooler by up to 1.7°C when the slit windows were opened instead of the main windows at night.
- The resultant indoor thermal comfort of two different cooling strategies, i.e., structural cooling and comfort ventilation was evaluated by using OT and SET*. Based on the results of OT in the master bedroom and living hall in structural cooling showed lower values than those of comfort ventilation. Nevertheless, the value of SET* in those spaces in both cooling strategies were almost the same during the daytime (approximately 30.0°C and 30.3°C SET*).

The detail discussion on the effects of the energy-saving modification techniques is provided in the next chapter.

7.

Discussion: Results and passive cooling strategy for urban houses in the hot-humid climate

7.1 Effect of the proposed passive cooling strategies and the thermal comfort evaluation for indoor environment

This section evaluates the resulting thermal comfort under two proposed cooling strategies respectively, i.e. structural cooling and comfort ventilation. Figure 7.1 shows the daily average of indoor thermal environments in the master bedroom and the living hall under the two cooling strategies equipped with the proposed modifications, i.e. roof insulation, external wall insulation, external shading and whole house ventilation.

As shown in Figure 7.1 a-1, by the application of structural cooling (night ventilation) strategy, the air temperature in the master bedroom and the living hall tended to be lower than the corresponding outdoor temperature by up to 4.0-4.5°C during the daytime. Meanwhile, the air temperature in both spaces were about 2°C higher than the corresponding outdoor temperature during the night-time. In this case, the RH was always above 75% for the whole day. The reason of large reduction of air temperatures observed during the daytime are mainly because the closed window condition in addition to the effects of direct solar radiation prevention strategies (modification techniques). Due to closed window condition during day-time, the inflow of warm air was prevented and indoor condition can be maintained much lower than the corresponding outdoor. In this case, the heat gain to the indoor condition is mainly from the building envelop and window. However, this strategy resulted to high indoor relative humidity (RH) during the daytime, where the minimum RH is almost 80%. This is because the lack of ventilation in addition to low indoor air temperature. As showed in the previous chapter, the indoor air flow during daytime in the night-ventilation case is almost less than 0.1 m/s. In contrast, in the case of comfort ventilation (full-day ventilation), the reduction of air temperature during daytime in the two spaces was smaller than those of the previous strategy due to inflow of warm air during daytime (Figure 7.1 b-1). The air temperature of the master bedroom and living hall were about 2°C and 3°C lower than the corresponding outdoor temperature. However, it should be noted that the RH of the indoor spaces was lower than that of the previous strategy as expected, which can be as low as 65% in the daytime. In the night-time, the air temperature difference between indoor and outdoor was almost the same as that of the former strategy, which is about 2°C higher than the corresponding outdoor temperature. To be noted that daytime indoor air wind speed in most of full-day ventilation case is about 0.2-0.3 m/s.

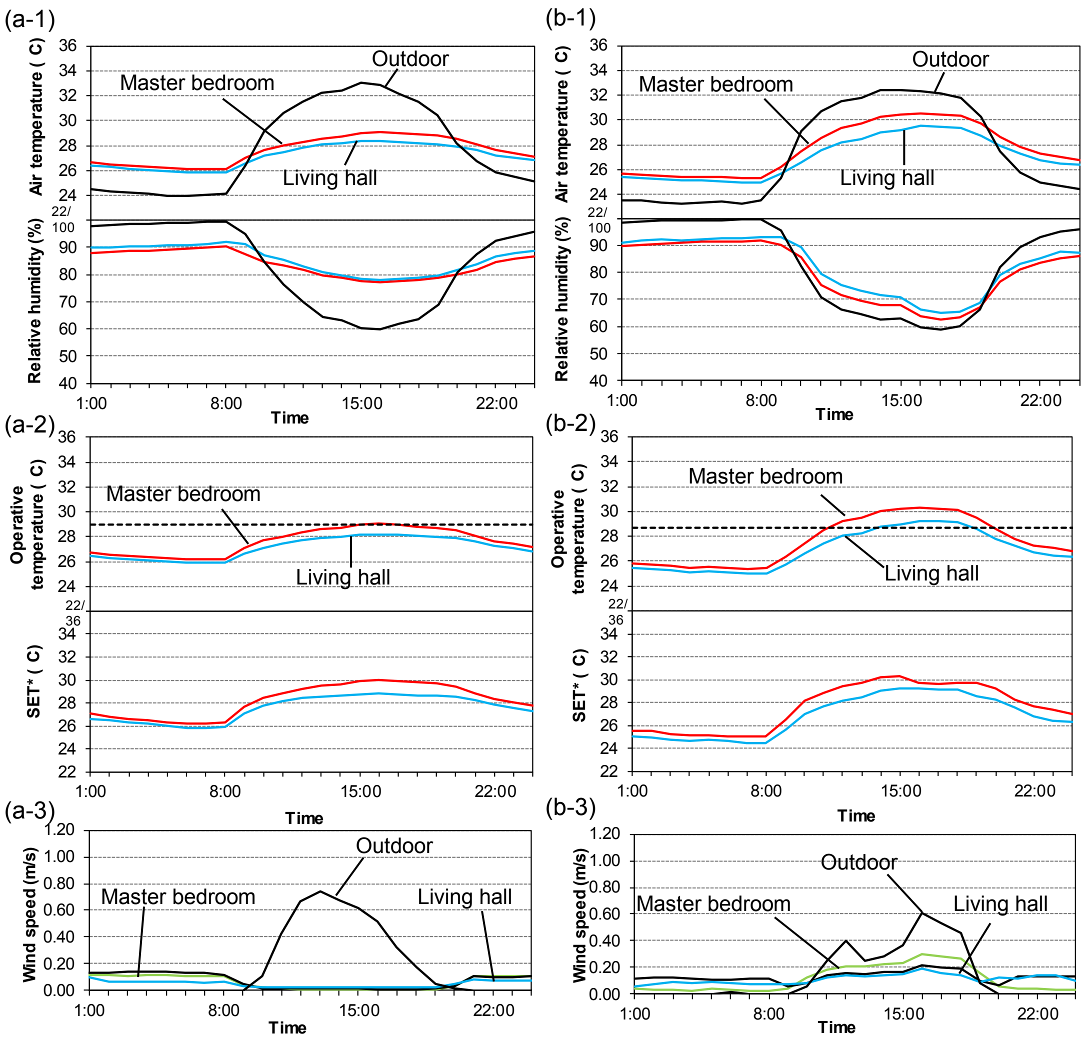


Figure 7.1. Indoor thermal environment of master bedroom and living hall of the proposed energy-saving strategy. (a) Structural cooling strategy and (b) comfort ventilation strategy.

Figure 7.2a shows the relationship of average air temperature between outdoor and master bedroom air for night ventilation, full-day ventilation and the day ventilation case. Day ventilation represents the current practice of most occupant in the terraced house in Malaysia (Kubota *et al.*, 2009). As shown, by the application of night-ventilation together with the proposed modifications, the maximum indoor air temperature can be reduced by up to 3°C compared to day ventilation case. Meanwhile in night-time, the air temperature can be reduced by up to 2.2°C. The result also showed that the air temperature reduction is also can be achieved when utilizing full-day ventilation with the modification techniques compared to day ventilation. By the application of full-day ventilation with the modification techniques, the maximum and minimum air temperature in the master bedroom were reduced by up to 1°C and 2.2°C, respectively, when compared to day ventilation. As discussed above, night ventilation strategy provides slightly lower daytime air temperature compared to full-day ventilation. As shown, the reduction can be up to 1.5°C. Meanwhile, at night-time similar indoor condition can be obtained. In addition, due to closed window condition, the air

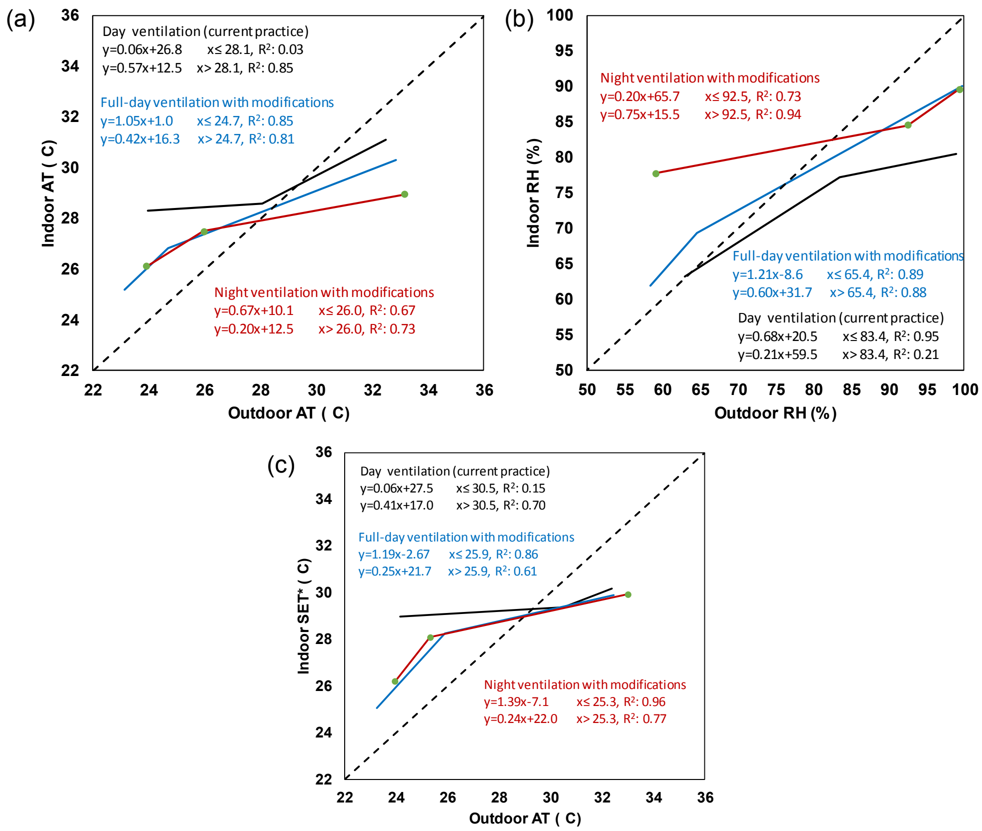


Figure 7.2. Relationship between indoor and outdoor environmental condition under various natural ventilation strategies in term of (a) air temperature; (b) relative humidity and (c) thermal comfort (SET*).

temperature break-point at night-ventilation (before increase of air temperature) was slightly higher than the full-day ventilation by about 1.3°C (26.0°C).

Figure 7.2b shows relationship of average RH between outdoor and master bedroom for night ventilation, full-day ventilation and the day ventilation case. As shown, the maximum RH of night ventilation and full-day ventilation are almost the same during the night-time. This is because of natural ventilated condition during the night-time. In contrast, the minimum RH of full-day ventilation were lowered by about 15% compared to night-ventilation on daytime. Meanwhile, the day-time ventilation has the lowest minimum and maximum RH level compared to both proposed ventilation strategies. This is because of warmed indoor condition during daytime and night-time.

Figure 7.1 a-2 and b-2 present the result of thermal comfort evaluation by operative temperature (OT) and SET* in master bedroom and living hall under both cooling strategies. As shown, with respect to the OT, the master bedroom and the living hall in structural cooling recorded lower values (28.0 to 29.0ºC) than those in comfort ventilation (29.0 to 30.0ºC) during daytime. The calculated OT of master bedroom and living hall in structural cooling generally fell within the limits, while those in comfort ventilation exceeded the limit over 30% of the measurement period. Nevertheless, when SET* was used for the evaluation, those in the two spaces during daytime in the two cooling strategies show almost the same values (approximately 30.0ºC and 30.3 SET*). This indicates that if the effect of sweat evaporation is taken into account by using SET*, the resulting thermal comfort levels in the two cooling strategies are considered almost equal. This result is almost similar to the condition of ventilated Chinese shophouse with courtyard where the cross ventilation between courtyard provided almost the same SET* with the non-ventilated courtyard (Chapter 3). Clear relationship between outdoor and indoor SET* are shown in Figure 7.2c. As shown, the SET* of night ventilation and full-day ventilation are almost similar from minimum to maximum outdoor temperature. The break-point of night ventilation was slightly earlier than the full-day ventilation which is at 25.3 ºC. This is probably due to the effect of increase RH in the master bedroom. Both proposed ventilation strategies offered lower SET* than the day-ventilation when the outdoor air temperature is below approximately 31ºC. Above that outdoor temperature, the SET* of day ventilation will increase higher than the proposed ventilation strategies when the outdoor air temperature increased.

Table 7.1 shows the summary of preferred indoor air temperature (neutral) and the comfortable air temperature range based on the previous study. As shown, the neutral for naturally ventilated building in hot-humid climate temperature ranges from 28.0-30.0 ºC and 25.4-28.8 temperature ranges from 28.0-30.0ºC in term of air temperature and operative temperature, respectively. Meanwhile, the comfortable indoor air temperature can be as high as 30ºC and 32.5ºC in term of operative temperature and air temperature, respectively. The maximum indoor air temperature observed in this study in the case of night ventilation and full-day ventilation with the proposed modifications is 29ºC and 30.2ºC, respectively. Meanwhile, the maximum operative temperature is also about 29ºC and 30.2ºC, respectively. Based on these values, it can be said that both resulted indoor air and operative temperature of night-ventilation and full-day ventilation strategies almost within the preferred comfort range suggested from the previous study in the hot-humid climate.

Table 7.1: Comfort temperature from previous study

Reference	Country	Thermal Indices	Neutral temperature (°C)	Comfort range (°C)
Djamila *et al*., 2013	Malaysia	Air temperature	30.0	27.0-32.5
Zhang *et al*., 2010	China (hot-humid region)	Operative temperature	25.4	22.1-28.7
Hwang *et al*., 2009	Taiwan (hot-humid)	Operative temperature	n.a	17.6-30.0
Feriadi and Wong, 2004	Indonesia	Operative temperature	29.2	n.a
Feriadi and Wong, 2003	Singapore	Operative temperature	28.8	n.a
Wong *et al*., 2002	Singapore	Air temperature	28.9	n.a
Khedari, 2000	Thailand	Air temperature	28.0	n.a
De Dear *et al*., 1991	Singapore	Operative temperature	28.5	n.a

Furthermore, when comparison was made between the proposed ventilation strategies (night and full-day ventilation), the results showed that the structural cooling strategies (night-ventilation) is not necessary the superior technique despites providing lower indoor air temperature during daytime. This is because, in daytime, the level of humidity will also increase and did not receive any wind velocities under the structural cooling ventilation strategies. In contrast, the indoor humidity level dropped lower than 70% and the air velocities reached about 0.3 m/s when the windows were opened during daytime. Thus, the effect of lower humidity level and relatively high indoor wind speed offset the effect of air temperature reduction obtained by structural cooling during daytime. In this case, especially in the hot-humid climate, continuous ventilation since the elevated air movement can produce a physical cooling effects and enhancing indoor thermal perception (Prajongsan and Sharples, 2012; Djamila *et al*., 2014). The effect of convective heat transfer and evaporative heat lost from human body will increases with the increased-on air velocity and will prevent thermal discomfort due to moist skin (Feriadi and Wong, 2004; Givoni, 1994). In addition, based on Szokolay's model, the minimum air speed of 0.2 m/s is required for creating cooling effect on human body (Prajongsan and Sharples, 2012). Meanwhile, it has been reported that high indoor RH (>70%) can bring an impact on human response (Jin *et al*., 2017), feeling tired (Tsutsumi *et al*., 2007) and humidity sensation (Damiati *et al*., 2016; Sekhar, 2016). It was suggested that, low humidity level is required to improve sweat evaporative cooling (Givoni *et al*., 2006). Therefore, several studies and thermal comfort standard suggested that the upper limit of relative humidity in building should be in ranges of 65-70% (ASHRAE 55, 2013; ASHRAE 62.1, 2016; He *et al*., 2016).

Moreover, it can be said that the relatively lower RH in comfort ventilation is more tolerable than that in structural cooling since constantly high humidity condition (>70%) would cause mold growth (Johansson *et al.,* 2012) and health related problems (Sterling *et al.,* 1985). Hence, it can be concluded that the cooling strategy of comfort ventilation is probably preferable than that by the structural cooling for the hot-humid climate of Malaysia.

7.2 Effects of passive techniques

The effects of passive techniques can be divided into two aspects, i.e. 1) reducing the indoor daytime air temperature by blocking the heat entering the building and 2) improving the nocturnal indoor air temperature and structural cooling by increasing the indoor wind speed and remove the internal heat to the outside.

There are various techniques to prevent direct solar radiation and to improve nocturnal indoor air temperature in the building. The current modifications in this study are based on the availability of the techniques in the Malaysia local market (easy to purchase). The selected strategies for reducing the direct solar radiation on daytime are the roof insulation, external wall insulation and external shading devices. Meanwhile, the whole house ventilation was applied to represent the second aspects of passive cooling with the purpose to enhance the structural cooling effects at night-time.

Roof insulation

The purpose of roof insulation is to reduce the heat transfer from the roof tile to the attic spaces. This is because the reduction of heat transfer from roof to the occupied space is essential because solar heat gain in the attic could increase the indoor air temperature and caused thermal discomfort to the occupants (Chungloo and Limmeechokchai, 2009). There are various methods for reduce the solar heat gain on the rood such as the application of cool ceiling and solar chimney (Chungloo and Limmeechokchai, 2009), roof solar collector (Khedari *et al.*, 1997), roof insulation (Soubdan *et al.*, 2005), radiative cooling roof (Hanif *et al.*, 2014) and others. In this study, roof insulation was selected for the heat gain prevention for the roof spaces.

Figure 7.3 shows the results of air and surface temperature in the attic and master bedroom of the measurement house (with modification) and the control house (without techniques) of the north facing master bedrooms under night and full-day ventilation condition. The result of north facing master bedroom was selected in this discussion because the solar radiation was higher at the northern side of the houses during the field measurement period. To be noted that during the full-scale measurement, all modifications were applied as a combined technique (at the same time). Therefore, the air temperature reduction in the master bedroom of the measurement house represented the result of combined effects of roof insulation, external wall insulation and external shading device. As shown in Figure 7.3a, in the case of structural cooling strategy (night-ventilation), the maximum temperature of attic in the measurement house was lower than that of the control house by about 2.5°C due to the application of the attic insulation. As a result, the maximum surface temperature of attic in the measurement house was lower than that of control unit by about 2.9°C. The result also showed that the air temperature at 0.1m under the ceiling of the measurement unit was lower than that of the control unit by about 2°C. In the case of roof insulation, it can be seen that the temperature of attic tends to be higher that the corresponding outdoor. The temperature difference was up to 0.4°C. The result also showed that the ceiling temperature was higher than indoor air temperature by about 0.4°C. In this case, the heat can be transferred from attic to indoor spaces (master bedroom) through the ceiling. Meanwhile, in the case of with roof insulation, the attic temperature was always lower than that of corresponding outdoor. Moreover, the surface temperature of ceiling was lower than the air temperature of the master bedroom by about 0.5 °C during daytime. In this case, there is a possibility that no heat transfer will occurred from the attic to the master bedroom. In contrast, the surface temperature of attic was higher than that of master bedroom at night-time (measurement house). However, the air temperature of the master bedroom can be maintained at lower value due to the application of whole house ventilation.

As shown in Figure 7.3b, in the case of comfort ventilation strategy (full-day), the maximum temperature of attic in the measurement house was lower than that of the control house by about 2.1°C due to the application of the attic insulation. As a result, the maximum surface temperature of attic in the measurement house was lower than that of control unit by about 2.2°C. The result also showed that the air temperature at 0.1m under the ceiling of the measurement unit was lower than that of the control unit by about 0.8°C. In this case, the air temperature reduction in the master bedroom was lower than that of structural cooling strategy due to the inflow of warm air to the indoor spaces. However, in the case with roof insulation, the surface of ceiling was always lower than that of air temperature in the master bedroom during daytime. Similar to the case of structural cooling, there is a possibility that no heat will be transferred from the attic to the indoor spaces during the daytime. Based on both results, it can be concluded that the roof insulation successfully preventing the heat gain in the master bedroom during the daytime. Therefore, the roof insulation strategy is suitable to be incorporated with both natural ventilation strategy.

Scientific report on the effects of roof insulation in the tropics region is very limited. Recent development of direct solar radiation strategies was report by Chungloo and Limmeechokchai (2009) where they investigate the effect of solar chimney and cool ceiling which is more complicated that the installation of insulation. Based on their techniques, the surface of ceiling temperature can be reduced by about 2-4°C. The result of this study, i.e. reduction of ceiling temperature (2°C) is comparable with theirs especially when the simplicity of technique is taken into consideration. Other techniques were report by Chungloo and Bundit (2007) and Hanif *et al.* (2014). Chungloo and Bundit (2007) investigate the effects of wetted roof and solar chimney and the techniques can reduce indoor air temperature by up to 3°C compared to the control case (without techniques). Meanwhile, Hanif *et al.* (2014) claims that the application of radiative cooling system can reduce the energy consumption by up to 25%. Compared to the other cooling strategies, it seems that the application of roof insulation is more practical for residential house since the application is less complicated.

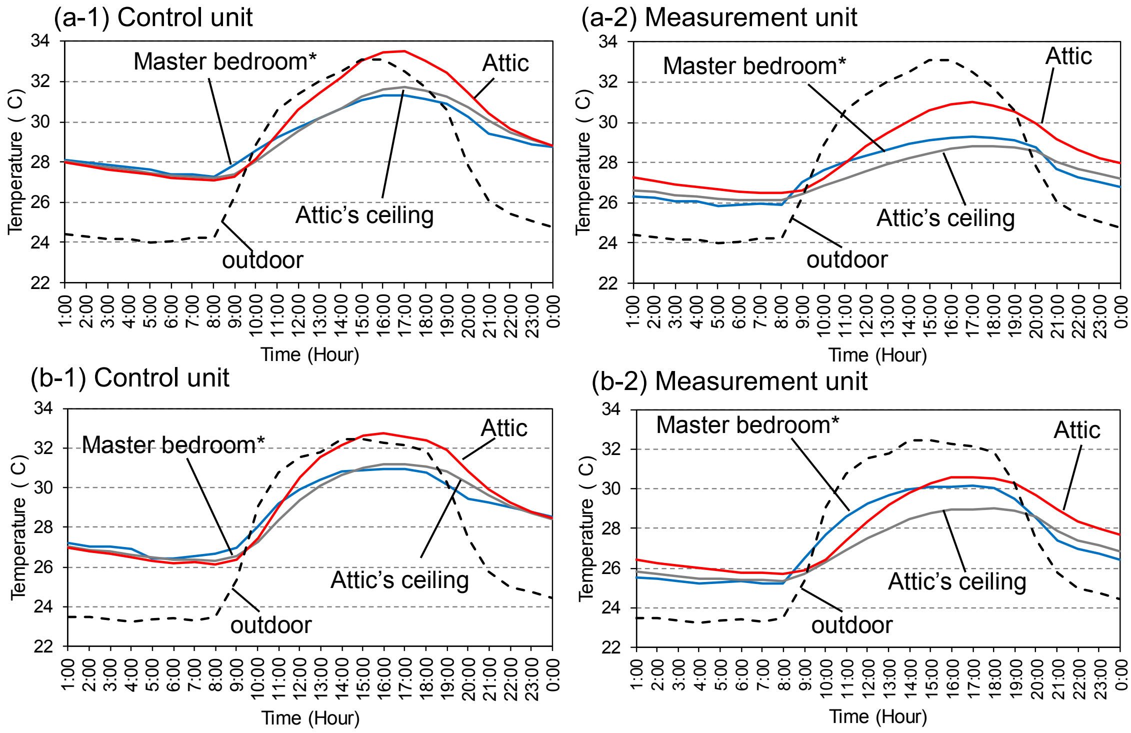


Figure 7.3. Temperature of air and surface in the attic and the north-facing master bedrooms with and without modification techniques (a) structural cooling strategy and (b) comfort cooling strategy. Note: Master bedroom* represent the air temperature at 0.1m below the ceiling level.

External wall insulation

Figure 7.4 shows the results of indoor air and surface temperature of external wall (inside) in the north-facing master bedroom of control and measurement houses with and without external wall insulation under structural cooling and comfort ventilation strategy. As shown in Figure 7.4a, the surface temperature of external wall in the measurement unit (with external wall insulation) was lower than that of control unit (without external wall insulation) by up to 1.8°C. This indicates that the external wall insulation successfully reduced the surface temperature of external wall (inside) of the master bedroom. Moreover, it can be seen that, when the insulation was not applied (in control unit), the maximum surface temperature of the external wall (inside) tends to be higher than the indoor air temperature of the master bedroom especially at the late evening. This indicates that there is a possibility that the heat can be transferred from wall to the indoor air during daytime. The result also showed that surface temperature of the external wall was relatively higher that the indoor air temperature during early night-time by up to 2°C. This high air temperature difference could reduce the effectiveness of structural cooling effects at night-time. Meanwhile, the surface temperature of the external wall (inside) in the measurement unit was always lower than indoor air temperature during daytime. In the night-time, the temperature different between the surface temperature and indoor air was relatively small which is less than 1°C. The result indicates that the external wall insulation is probably required to be installed in the case of structural cooling strategy in order to prevent the heat transfer from the wall to indoor spaces during daytime.

Figure 7.4b shows the surface and indoor air temperature of the master bedrooms under comfort ventilation strategies with and without the application of external wall insulation. As shown, the maximum surface temperature of external wall in the measurement unit was lower than that of control unit by about 1.3°C. In this case, the indoor air temperature of master bedroom of measurement unit was lower than that of control unit by about 0.9°C. However, it can be seen that the surface temperature of external wall (inside) in both houses were lower than their indoor air temperature during daytime. This indicates that, the inflow of warm air largely affecting the indoor air temperature in the master bedroom. In this case, there will be no heat transferred from the external wall to the indoor air even in the case of no insulation. As conclusion, it can be said that, the application of external wall insulation is probably not necessary to be used in full-day ventilation condition since the heat transfer by convection through natural ventilation is larger during daytime.

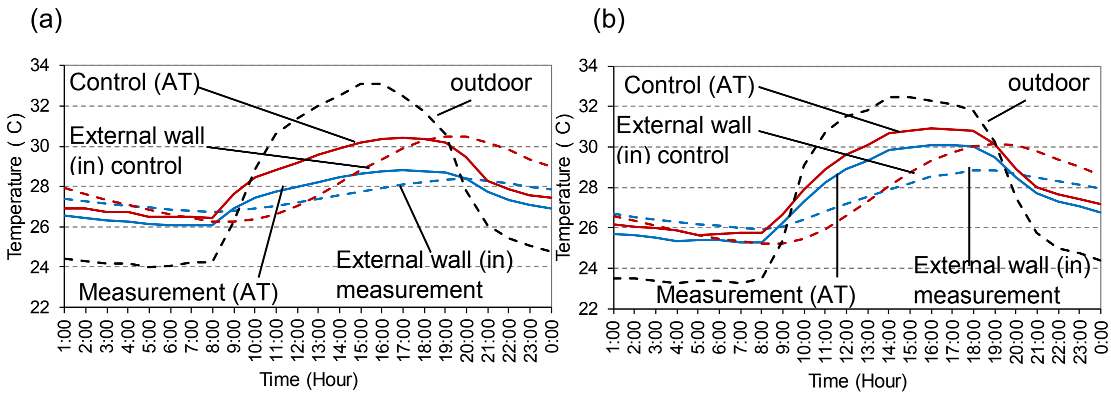


Figure 7.4. Temperature of air and the external wall surface (inside) in the master bedrooms with and without modification techniques (a) structural cooling strategy and (b) comfort cooling strategy. Note: (AT) represent air temperature measured at the center of room.

External shading devices

Shading for windows is an important passive cooling strategy especially for hot climate. Emphasis must be given to shading devices because glazed windows are the main components which allow the penetration of incoming heat and consequently increases the risk of overheating. Based on the above results, it seems that the heat gain in the experimental house is mainly from the windows besides from the roof. However, since the modifications were tested as a combined technique, it is difficult to investigate the effects of the other techniques on the indoor air temperature as in the simulation study. Based on the results of the field measurement, the proposed techniques including external shading devices successfully reduced the daytime air temperature of the master bedroom and the living hall under both ventilation conditions (i.e. structural cooling and comfort ventilation). The combination of the above modifications reduced the daytime air temperature in master bedroom and living hall by about 1.5-2.0°C compared to that of control unit (without techniques) under the structural cooling strategies. Meanwhile the reduction in the living hall was about 0.5-1.0°C. In the comfort ventilation strategies, the effects of the proposed techniques are reduced to about 0.2-0.8°C in both master bedroom and the living hall.

Whole house ventilation

The application of forced ventilation (i.e. whole house ventilation, master bedroom ventilation and attic ventilation) represents the passive cooling techniques for the second aspect. The application of whole house ventilation significantly reduced the nocturnal air temperature in the master bedroom which is up to 1.2°C in both ventilation strategies. The effects of the whole house ventilation compensate the negative effects of the insulation techniques at night-time. The application of whole house ventilation improves the ventilation rate in the master bedroom and remove warm air to outside. However, the effects are smaller in the living hall. The air maximum reduction recorded in the living hall is about 0.5°C. This probably because the air flow in the living hall was not significantly improved after the application of the whole house ventilation. To be noted that the level of relative humidity will be increased when the whole house ventilation is applied. This is probably because the humid outdoor air entered the room by the whole house ventilation. Meanwhile, the application of master bedroom ventilation and attic ventilation were not significantly reduced the nocturnal air temperature in the master bedroom.

7.3 Effects of window opening patterns

Three types of window-opening position (i.e. main windows, slit windows and all windows) were applied in the master bedroom of the measurement unit (House 2) to investigate the effects of window-opening position under night-time ventilation. Figure 7.5 shows the relationship of air temperature and relative humidity between indoor and outdoor with different window opening pattern under the case of night-ventilation.

As shown in Figure 7.5a, the daytime air temperature of master bedroom was almost similar in all opening condition which is ranges from 27.6-29.0°C. In contrast, the nocturnal air temperature of master bedroom with all window opened recorded the lowest value compared to the other opening condition. This is simply because the large opening introduces more cool air into the indoor spaces at night. However, this strategy resulted to high indoor relative humidity level during day and night-time compared to the other opening pattern (Figure 7.5b). In contrast, the nocturnal air temperature of the master bedroom with slit window recorded the highest value compared to other strategy. However, the difference was relatively small which is less than 0.5°C. The level of relative humidity was also lower than the other strategy which is up to 3%. Moreover, the surface temperature of the ceiling can be reduced by up 1.7°C, which is the highest reduction compared to the other strategies (Chapter 6). This indicates that the ventilation through the slit windows successfully improved the structural cooling effects of the building by enable the flow of cooled air near to the building structure at night-time. It was reported that concern of security and insects are the main limitation of the application night-ventilation in Malaysia (Kubota et. al, 2009). Since the cooling effect of night-ventilation by the slit windows was almost similar compared to the other bigger window opening, thus this strategy is recommended to be used for ventilation at night. Moreover, the small opening of the slit window is much more secured than the big opening of the other strategies and the cost of insect protection (net) will be much cheaper.

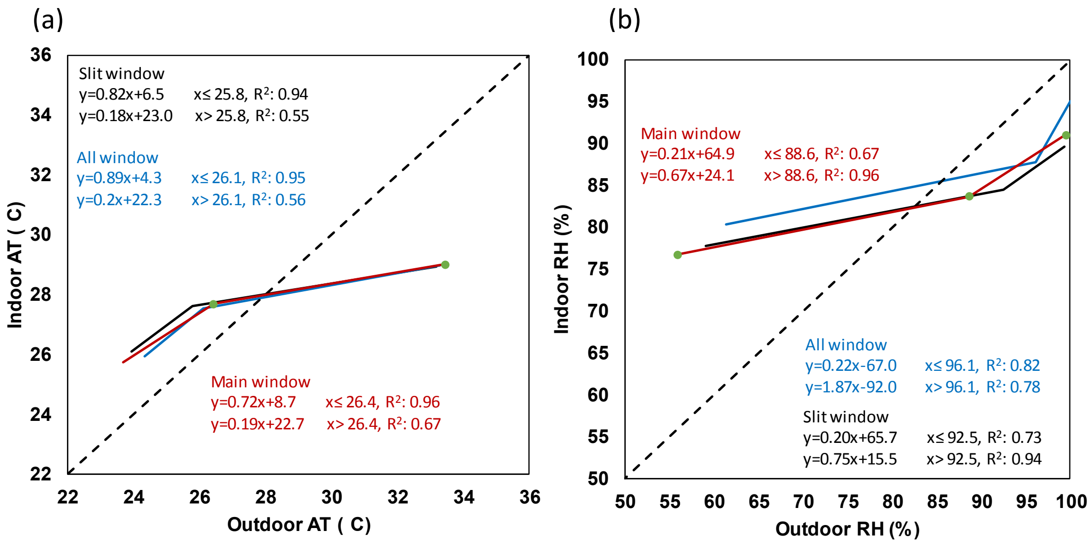


Figure 7.5. Relationship between indoor and outdoor environmental condition under various window opening strategies under night-time ventilation (a) air temperature and (b) relative humidity.

7.4 Cost analysis

Based on the above discussion, the proposed passive cooling strategies can be divided into two options. The first option is the application of comfort ventilation with roof insulation, external shading and the whole house ventilation. The second option is by the application of structural cooling with roof insulation, external shading, external wall insulation and the whole house ventilation. The difference between both techniques is the application of natural ventilation mode and the application of external wall insulation. In order to select the most suitable strategy, the cost for each technique should be taken into account. Based on the current price of the modification in Malaysia, the cost of installation for external wall insulation, external shading device, roof insulation and whole house ventilation is about RM21300, RM 2940, RM 1200 and RM 6500, respectively.

In the case of comfort ventilation, the total cost of this techniques is about RM10,640. Meanwhile the cost for the structural cooling techniques is RM 31,940 which is higher by about three-folds. This is due to the application of external wall insulation which is the most expensive compared to the other techniques. This indicates that the cost for comfort ventilation is much more cheaper and probably affordable. Therefore, in the case of passive cooling strategy for urban houses in Malaysia, the comfort ventilation strategy can be the main option rather than the structural cooling strategy. The reason is, the comfort ventilation can provide relative the same indoor thermal comfort as the structural cooling strategy with much more lower cost.

However, the structural cooling strategy still can be an option in case of the application of air-conditioner (AC) is required especially during day-time. With lower air temperature during daytime, the cooling load of the AC can be reduced compared to the house without the application of the selected passive cooling strategy. Moreover, the application of AC could overcome the problem of high relative humidity problem during daytime under structural cooling strategy by mechanically control the level of relative humidity. Meanwhile, it has been reported that the air temperature of urban area will be increase in the future due to global warming and land use changes. Therefore, this passive strategy can be use if the application of comfort ventilation is not able to offset the effect of urban air temperature increase in the future.

7.5 Recommendations: Guidelines of energy-saving modifications for urban houses

Based on the study findings, modifications to the existing terraced house to incorporate passive cooling techniques are proposed as follows:

Natural ventilation techniques

The recommended natural ventilation strategy is by using comfort ventilation (full-day ventilation). By applying the full-day ventilation, the indoor thermal comfort can be achieved not only in night-time but also in daytime with lower humidity level and high indoor air speed. This may be realized through occupants by open windows for the whole day. Opening the windows during daytime is the current practice of occupants in the Malaysian terraced houses. Therefore, the recommended practice is to remain window to be opened at the night-time to represent full-day ventilation. It may require minor installations of insect screens and security grilles in order to solve some of the problems of night-time open windows. Slit windows can be used at night if opening the large window is not preferred due to security reason.

Main modification techniques for modern terraced houses

a) Comfort ventilation strategy

The modifications consider using multiple passive cooling techniques so that the indoor thermal conditions can be enhanced in addition to the natural ventilation techniques. The recommended passive cooling techniques for the modern terraced house are:

- *Roof insulation*
  Roof insulation is affective to reduce the attic temperature at daytime. Since the master bedroom directly located under the roof, it can reduce the attic temperature during daytime and less heat transfer to the master bedroom through the ceiling. The suggested insulation level is R 3, i.e. a thermal resistance of 4 m^2K/W, based on the available range of insulation products in Malaysia. It should be noted that a layer of water barrier, such as zinc plate, under the roof tiles may be required to prevent leakage of rainwater into the thermal insulation.

- *External shading device for windows*
  External shading is recommended than the internal shading. A higher shading factor, i.e. lower solar transmission, improves the cooling effects. External shading may be provided by roof overhang, devices such as operable louvers or shade trees. In particular, shade trees are also useful to shield the building structures and indoor spaces from diffuse solar radiation and lower the ambient air temperature for a cooler microclimate.

- *Forced ventilation at night*
  Whole house ventilation is more effective than the master bedroom and attic ventilation. The whole house ventilation may be applied by installing the ventilation fan in the central zone of the house.

- *Slit windows*
  Slit windows can be installed on top or bottom of the main window. It is also recommended to be installed on the internal wall to ensure cross ventilation within the indoor spaces. The combination of slit windows and whole house ventilation can increase the structural cooling effects of the building and improving night-time indoor air temperature. However, major modification for the wall of the building is required for the installation.

b) Structural cooling strategy

- *All the above-mentioned strategies*
- *External wall insulation at outside surface*
  Since the effects of external insulation is not as large as the roof insulation and external shading, this can be as an additional option for the occupants. Insulating the outside surface of external walls reduces the daytime indoor operative temperature but increases the night-time indoor operative temperature slightly. Insulation with a thermal resistance of i.e. 3 m^2K/W is suggested. The application of external insulation is recommended to be used along with the whole house ventilation at night to improve the nocturnal indoor operative temperature.

Secondary option of modification techniques for modern terraced houses

- Small courtyard
  Small courtyard functions as a night ventilation cooling source to adjacent indoor spaces that are open to it. The cooling effects rely on maintaining a stable thermal stratification during daytime (with vertical air temperature gradient) and an unstable one at night (without vertical air temperature gradient). External windows may be kept closed at night. On the other hand, it is suggested that openings to the courtyard may be open throughout the day on the ground floor and open only at night on the first floor (because the air temperature inside the courtyard increases with height during daytime). The courtyard may also assist mass transfer of water vapor for humidity control of the adjacent indoor spaces throughout the day. For this purpose, upper ventilation openings on walls adjacent to the courtyard may be useful.

Figure 7.6 illustrates the proposed strategies that can be applied in the modern urban houses in hot-humid climate, especially in Malaysia.

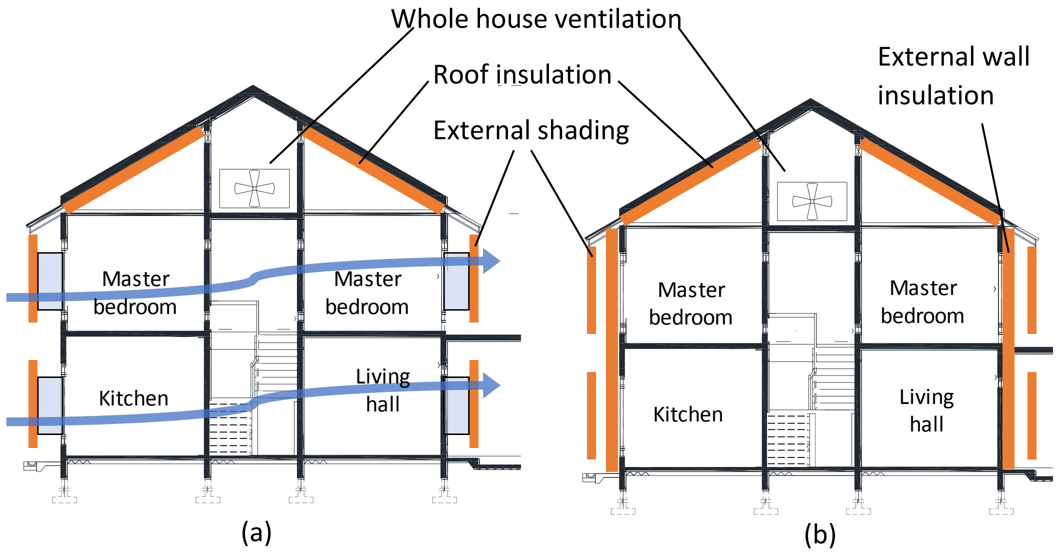


Figure 7. 6. Passive cooling strategies for modern urban houses in Malaysia (a) Comfort ventilation strategy and (b) Structural ventilation strategy.

7.6 Summary

In this chapter, the discussion focuses on the thermal comfort evaluation of the indoor spaces (i.e. master bedroom and the living hall), the effects of the modification techniques and the effects of window opening pattern. The recommendations of passive modification for the modern terraced house is included in the last section.

Based on the results of full-scale field measurement, it was found that the cooling strategy of comfort ventilation is probably preferable than that by the structural cooling for the hot-humid climate of Malaysia. This is because the effect of lower humidity level and relatively high indoor wind speed can offset the effect of air temperature reduction obtained by structural cooling during daytime.

Meanwhile the effects of passive cooling modification techniques have been discussed in two aspects, i.e. in term of heat reduction during daytime and improving the nocturnal indoor air temperature and structural cooling at night-time. The application of roof insulation and external window shading successfully reduced the daytime air temperature in the master bedroom and the living hall. Meanwhile, the application of whole house ventilation is effective in providing lower nocturnal indoor air temperature in the respective indoor spaces (i.e. master bedroom and the living hall) compared to the master bedroom and attic ventilation. As for the strategy of external (outside surface) insulation, it was found that the cooling effect is not significant to be apply for the comfort ventilation strategy. On the other hand, the strategy seems more appropriate to be use with the structural cooling strategy.

In term of window opening position, the application slit windows with the whole house ventilation under the night-time ventilation is found can reduce not only nocturnal air temperature of the master bedroom but also the surface temperature of the floor and ceiling.

In the last section, the recommendation of energy-saving modifications for urban houses was discussed. As for natural ventilation strategy, the comfort ventilation strategy is recommended for urban houses in the hot-humid climate. Meanwhile, the recommended modification techniques to be applied with the comfort ventilation strategy includes the roof insulation, external wall (outside) insulation, external shading devices and the whole house ventilation.

8.

Conclusions

The aim of this doctoral thesis is to is to develop comprehensive energy-saving modification techniques through passive cooling for existing urban houses in the hot-humid climate of Malaysia. To achieve this goal, we investigate the passive cooling techniques applied in the traditional Chinese shophouses, the effects of natural ventilation in the modern houses and the potential modification techniques to be applied in the modern urban houses. We evaluate the cooling effects of passive cooling techniques and the resultant indoor thermal comfort using data from field measurement and numerical simulation. The findings are compared in order to determine effective passive cooling techniques for the typical terraced house. The final combinations of some techniques were evaluated in the full-scale field measurement and the results confirmed the effects of the proposed techniques obtained by the numerical simulation.

Section 8.1 summarizes these key findings. Section 8.2 highlighted the contribution of this study. Section 8.3 explained several limitations of this study. Moreover, further studies that can be continued from this project and beyond are recommended in Section 8.4.

8.1 Key findings of this study

Passive Cooling Techniques in Traditional Chinese shophouse

The unique feature of the CSHs is its internal courtyard. Field measurement was carried out in 16 CSHs in order to identify the thermal functions of internal courtyards of CSHs with the aim of providing useful passive cooling strategies for modern urban houses. The main findings are:

The effects of courtyard form on their indoor thermal environment

- The degree of exposure of the courtyard to the outdoor is a key factor that influence the profiles of indoor air temperature in the courtyards during day and night-time. Specifically, the daily maximum air temperature in internal courtyards is affected by the sky view factor (SVF) and the height of the courtyard. In contrast, the daily minimum air temperature is determined by the difference in the heights of the building and walls that form the courtyard. Hence, the daily mean air temperature in courtyard areas is the result of the SVF and the heights of the surrounding walls and buildings.
- Small and staggered courtyards tended to provide lower nocturnal air temperatures. In contrast, deep and closed (with a low SVF (<2%)) courtyards exhibited a substantial reduction in peak air temperatures.
- In term of humidity, the height of the courtyard and the opening area of the courtyard influenced the minimum value of the relative humidity. Meanwhile, the difference in the heights of a courtyard affected the daily maximum relative humidity. the ratio of the courtyard area to the entire building area was one of the key variables affecting the levels of absolute humidity in the courtyards.

The effects of courtyard on indoor thermal comfort

- Different types of courtyards performed different functions with respect to improving the indoor thermal comfort in the adjacent living halls. The living hall of CSH 1 was located next to the deep, closed courtyard of Type 5 (SVF: 0.2%). The air temperatures in the courtyard and the adjacent living hall maintained relatively low values that were approximately 4.0ºC lower than the corresponding outdoor temperature, although the indoor air flow was almost absent even during the day (<0.2 m/s).
- The other living hall (CSH 3) was situated between the two courtyards of Types 5 and 2 without a wall partition. The indoor wind speeds of approximately 0.2 to 0.4 m/s were generated due to the circulating air flow between the two courtyards during

the day. Though this inflow increased indoor wind speeds, it simultaneously increased indoor air temperatures. The daytime air temperature in the living hall was only 1.5ºC lower, on average, than the outdoor temperature.

- Based on the thermal comfort evaluation by operative temperature (OT) indices, the living hall of CSH 1 was considered superior to that of CSH 3 because of its lowered air temperatures. Nevertheless, when the evaporative cooling effect was taken into account by using SET*, the condition of CSH 3 was similar to that of CSH 1 because of its higher indoor wind speeds. Meanwhile, the relative humidity in the living hall of CSH 3 was lower by up to 10% compared to that in CSH 1. Therefore, it was concluded that the condition of high wind speed and lower humidity level in the living hall of CSH 3 was more tolerable than that in CSH 1.
- For elongated row houses of high thermal mass structure in hot-humid climates, it is suggested that closed (with a low SVF), cross-ventilated courtyards be embedded to achieve indoor thermal comfort and avoid excessive humidity. Hence, the wind orientation should be more important than the solar orientation for the elongated row houses in the tropics. Meanwhile, it is also recommended that a staggered form courtyard with V-shaped roofs should be designed at the corner of the house as a nocturnal cooling source.

Numerical Simulation of modern urban houses in Malaysia

The experiment terraced houses was modelled using the TRNSYS and COMIS programs. Several passive cooling techniques including thermal insulation, window shading and forced ventilation were simulated using weather data that represented an urban climate in Malaysia under the structural cooling (night ventilation) and full-day ventilation condition. The main finding from this study are:

- In the structural cooling condition, the high-reflective roof coating is found to reduce the maximum temperature the most by approximately 1.1°C, followed by roof insulation (1.0°C) and ceiling insulation (0.9°C). Meanwhile, the outside insulation for external wall was found to be more effective than the internal insulation in reducing the maximum temperature in the master bedroom. Among the modifications for window, the external shading gives the largest cooling effect for the maximum temperature, which is 0.9°C, followed by the low-E glass and internal shading. Forced ventilation techniques by whole house ventilation is the most effective in reducing nocturnal operative temperature. The whole house ventilation reduces the minimum temperature by approximately 0.8°C, while it reduces maximum temperature of the next day due to the structural cooling effect by approximately 0.4°C.
- Meanwhile, in the case of full-day ventilation, the cooling effects of respective modifications on the maximum temperatures are reduced to approximately 0.1-0.6°C compared to the former ventilation strategy. Among the techniques considered in this

analysis, the external shading is found to be the most effective in reducing the maximum temperature, which records an average reduction of 0.5°C.

- Based on the results of combined modification techniques under the structural cooling strategies, it was found that the optimum combination to reduce the nocturnal operative temperature in the master bedroom is by the application of whole house ventilation, external shading of window, external outside insulation and low-E glass, where the total reduction is about 1.2°C. As for the living room, the external shading is better able to reduce the maximum operative temperature with the specific reduction of about 0.6°C. The external outside insulation was chosen as the next option, followed by the roof insulation.
- In the case of comfort ventilation, the whole house ventilation is found to be the most effective in reducing the nocturnal operative temperature in the master bedroom just like the case of night ventilation, followed by the external shading, external wall outside insulation and roof insulation. The total reduction of the nocturnal air temperature is about 0.9°C. As for the living room, the external shading is found to be the most effective, followed by the external wall outside insulation, the whole house ventilation and roof insulation. By the application of these techniques, the total reduction of maximum air temperature in the living hall is about 0.9°C.
- The optimum combinations of energy-saving modifications for the experimental houses were determined by combining the optimum combinations for the master bedroom and the living room. As a result, the proposed modifications include roof insulation, external wall outside insulation, external shading, and whole house ventilation. This combination would be effective not only for night ventilation condition but also for full-day ventilation condition.

Full-scale experiment on the proposed energy-saving modifications for the urban houses

Full-scale measurement was conducted in the experimental houses located in UTM, Johor Bahru Malaysia from June to September 2016 to confirm the resulting effects of the proposed energy-saving modification techniques derived from the previous simulation studies. The main findings are:

- The application of roof insulation, external wall insulation and external shading successfully reduced the daytime air temperature of the master bedroom and the living hall under both ventilation conditions (i.e. structural cooling and comfort ventilation). The combination of the above modifications reduced the daytime air temperature in master bedroom and living hall by about 1.5-2.0°C compared to that of control unit (without techniques) under the structural cooling strategies. Meanwhile the reduction in the living hall was about 0.5-1.0°C. In the comfort ventilation strategies, the effects of the proposed techniques are reduced to about 0.2-0.8°C in both master bedroom and the living hall.

- The application of roof insulation reduced the attic temperature by up to 2.7°C compared to the control unit during daytime. Meanwhile, the application of external wall and the window shading device contributes in lowering the daytime air temperature in the master bedroom and the living hall by limiting the effect of solar radiation on the structure and transmitted through the window. However, the application of the insulation tends to increase the nocturnal air temperature of the building during if proper ventilation strategies is not provided.
- The application of proposed modifications, i.e. roof insulation, external wall insulation, external shading and whole house ventilation successfully reduced indoor air temperatures by about 0.8°C during the day and night under the structural cooling strategy in average. In the comfort ventilation strategy, the temperature reduction during the night-time is about 0.7°C while only small reduction observed in the daytime.
- The application of whole house ventilation significantly reduced the nocturnal air temperature in the master bedroom which by up to 1.2°C. The effects of the whole house ventilation compensate the negative effects of the insulation techniques at night-time. Nevertheless, the whole house ventilation was not able to reduce the nocturnal indoor air temperatures as low as outdoor in both cooling strategies. In addition, the humidity level increased at night-time during when the whole house ventilation is applied. The application of master bedroom ventilation and attic ventilation were not significantly reduced the nocturnal air temperature in the master bedroom
- Ventilation through the slit window provided slightly larger reduction of indoor air temperature in the master bedrooms at night. It was also seen that the surface temperatures of inner walls, especially the ceiling, was cooler by up to 1.7°C when the slit windows were opened instead of the main windows at night.
- The resultant indoor thermal comfort of two different cooling strategies, i.e., structural cooling and comfort ventilation was evaluated by using operative temperature (OT) and SET*. Based on the results of OT in the master bedroom and living hall in structural cooling showed lower values than those of comfort ventilation. However, the SET* of these spaces in both cooling strategies was almost the same during the daytime (approximately 30.0°C and 30.3°C SET*).
- It was found that the structural cooling strategies (night-ventilation) is not necessary the superior technique despites providing lower indoor air temperature during daytime. This is because, in daytime, the level of humidity will be increased and did not receive any wind velocities under the structural cooling ventilation strategies. In contrast, the indoor humidity level dropped lower than 70% and the air velocities reached about 0.3 m/s when the windows were opened during daytime. Thus, the effect of lower humidity level and relatively high indoor wind speed offset the effect of air temperature reduction obtained by structural cooling during daytime. The finding is quite similar as in the Chinese shophouses with cross ventilation between two courtyards.

- Hence, in addition to the modification techniques for the urban houses, it can be concluded that the cooling strategy by comfort ventilation is probably preferable than that by the structural cooling for the hot-humid climate of Malaysia.
- By considering the effects of modifications techniques and the cost of installation, the main strategy of passive cooling is by the application of comfort ventilation with roof insulation, external shading devices and the whole house ventilation. The strategy of structural cooling can be a secondary option. However, dehumidification strategy should be considered to reduce the humidity level during daytime. In this strategy, the modification techniques that required to be installed is the roof insulation, external shading device, external wall insulation and the whole house ventilation.

8.2 Contribution of research

The contributions of this research are summarized as follows:

1. This research comprehensively investigates the suitable natural ventilation strategy for urban houses in hot-humid climate especially by comparing the performance of indoor thermal condition under structural cooling (night-ventilation) and comfort ventilation (full-day) strategy. This study revealed the advantages and disadvantages of each strategy. As the outcome, the study showed that the structural cooling is not necessary superior than the comfort ventilation strategy for urban houses in hot-humid climate. In contrast, indoor thermal condition of full-day ventilation is probably more suitable or preferable in this climate especially when the aspect of thermal comfort, human health and durability of building material were taken into consideration. The result of this study is also can be as a contribution to the current literatures in the field of natural ventilation by comfort ventilation strategy (full-day) which is quite scarce especially for the hot-humid climate.

2. This study comprehensively investigates the optimum combination for energy-saving techniques for urban houses in hot-humid climate especially in Malaysia. Compared to the other studies which investigates the effects of a single passive cooling techniques on indoor thermal environment, this study considered the optimum combination of the available passive cooling techniques to be applied in the modern urban houses. In order to achieved this goal, this study explores the possibility to use the analysis of Design of experiment (DOE) analysis to reduce the number of combination of the study cases for the numerical simulation study. In this case, the number of possible combination cases has been significantly reduced from 30 million to 32 cases. By this technique of analysis,

the optimum combination of passive-cooling modifications for modern urban houses in Malaysia is possible to be obtained.

3. This study has the opportunity to investigate the actual effects of the proposed modification techniques in the actual scale model. The data from the full-scale field measurement is very valuable and can be referred by others.

8.3 Limitation of study

Despites providing in-depth analysis and interesting outcome, this study is also having its limitation especially in the full-scale experiment. The experimental houses were constructed in an open area with less wind obstruction. This condition probably will improve the effect of wind flow on the indoor spaces under the natural ventilation condition and could not represent the actual condition of the urban houses. Nevertheless, during the experiment, both houses (control and measurement unit) were compared directly under the same condition and the improvement of indoor thermal condition in the house with the proposed techniques is still can be observed. This indicates that the proposed strategies have the potential to be applied in the actual situation and still can effectively provide relatively better indoor thermal condition compared to the normal urban houses.

8.4 Further studies

In this thesis, we do not deal with thermal comfort responses by the occupants on the proposed modification strategy. The thermal comfort evaluation in this thesis was estimated by using the mathematical equation provided by the international standard, i.e. ASHRAE and BSI (ISO 7726). It will be useful to understand the actual response from the occupants especially in term of thermal adaptation in naturally ventilated building.

In addition, economic studies are encouraged to evaluate the actual energy consumption of the houses with the proposed strategies. Moreover, further study of energy-saving strategies for modern urban houses with air-conditioning system is also suggested.

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Appendix A: Measurement and result of air change rate in the master bedroom.

A field measurement has been conducted to investigate the air change rate in the master bedroom of the experimental houses under the natural and forced ventilation condition. The detail explanation and the method of experiments were explained in Section 6.5.2 and 6.2.5.1. Figure A.1 presents the position of measurement equipment and the pictures during the field measurement.

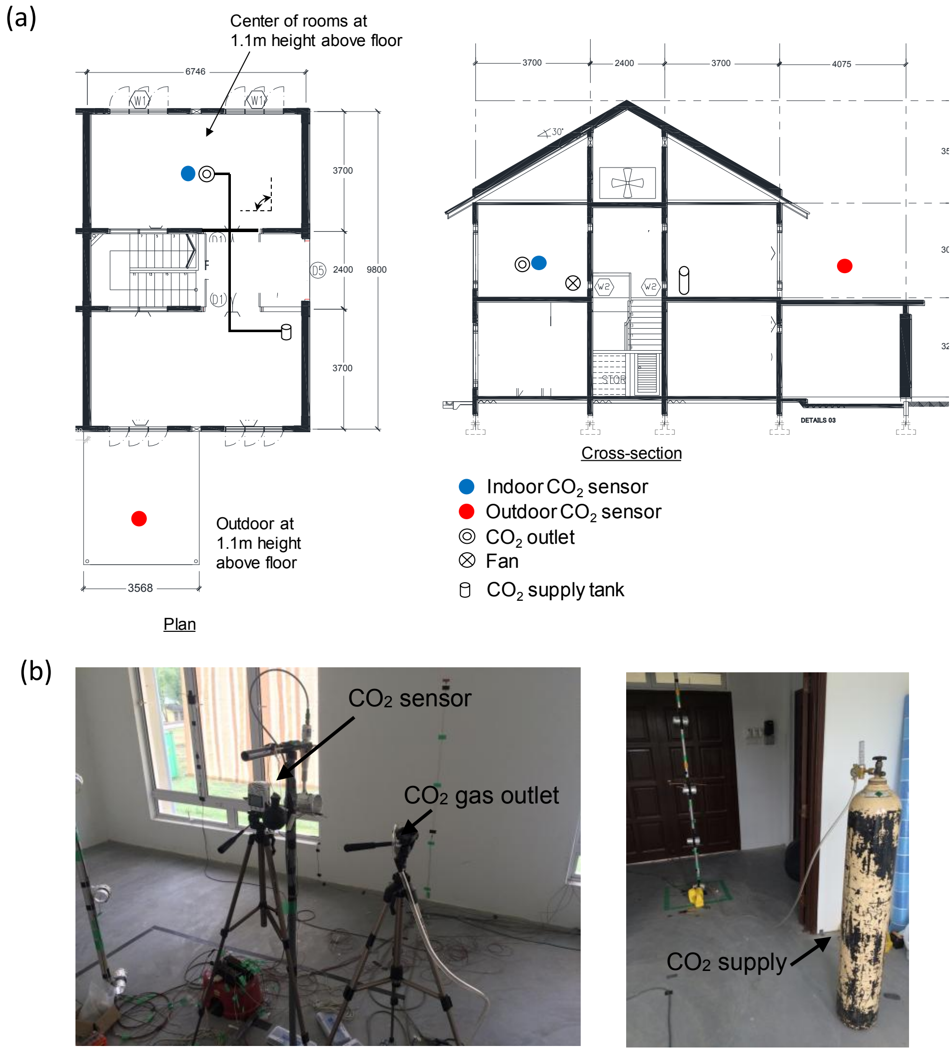

Figure A.1 (a) Position of sensors for the measurement (b) Picture of the equipment during the measurement.

As shown in the results in Section 6.5.2.2, the experiment has been conducted under 5 ventilation cases. The measurement was repeated for three time for each case to obtain the average value. The following figures (A.2 – A.6) present the result of air change rate of each measurement for each case.

a) Case 1: Main windows (opened) at daytime.

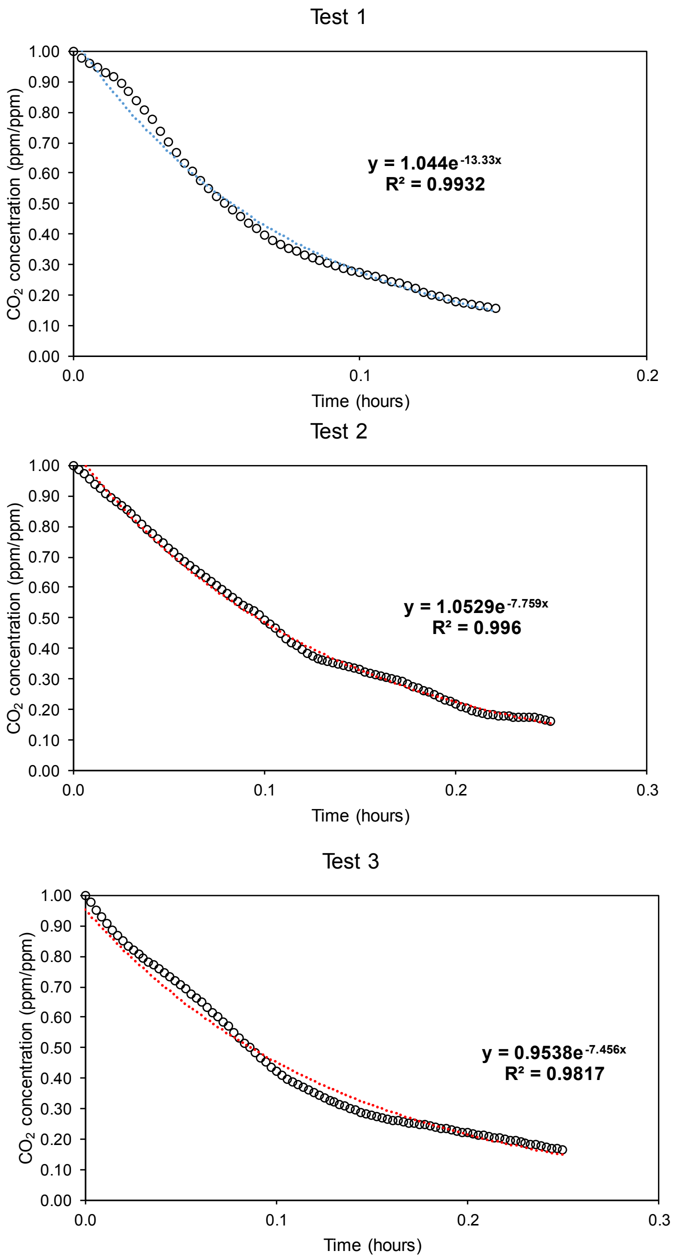

Figure A.2 (a) Estimation of air change rate per hour (ACH) in the master bedroom in Case 1.

a) Case 2: Slit windows (opened) with whole house ventilation (30 ACH) at night-time.

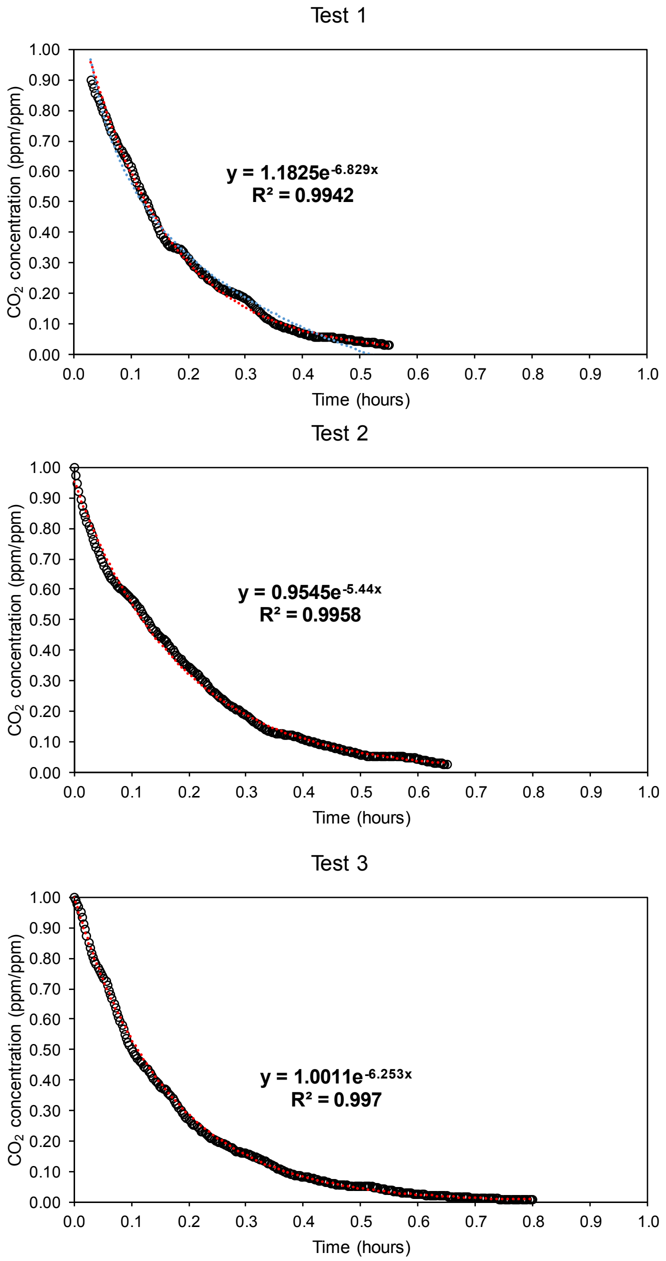

Figure A.3 (a) Estimation of air change rate per hour (ACH) in the master bedroom in Case 2.

a) Case 3: Main windows (opened) with whole house ventilation (30ACH) at night-time.

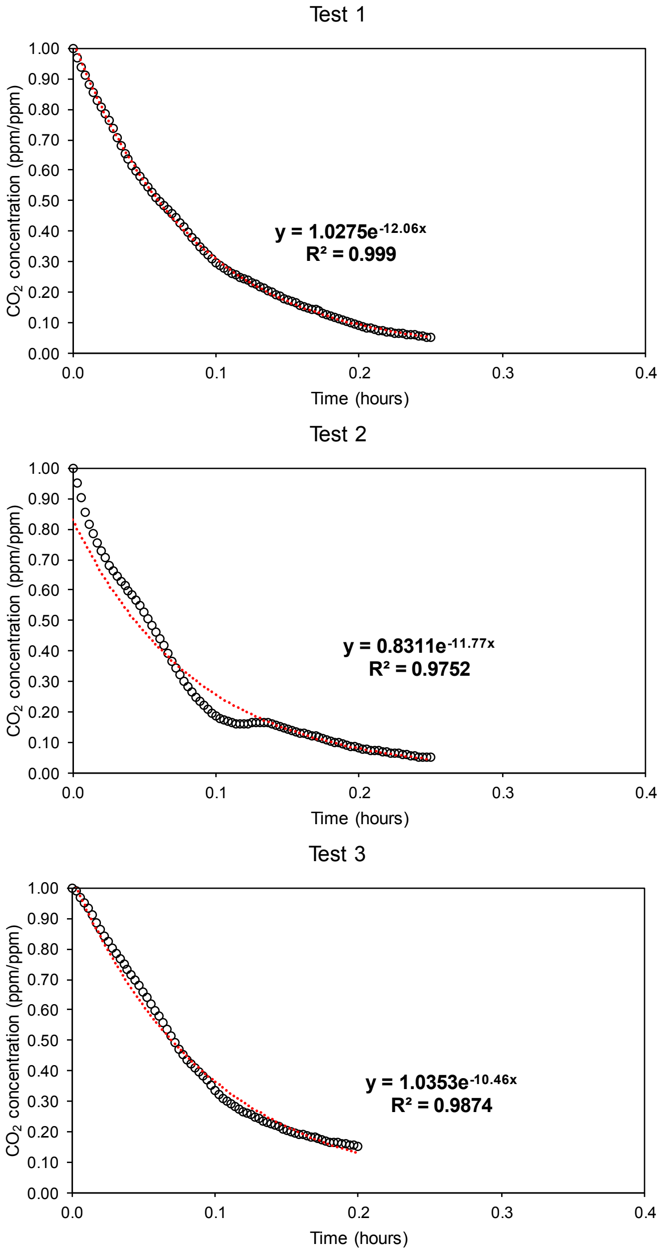

Figure A.4 (a) Estimation of air change rate per hour (ACH) in the master bedroom in Case 3.

a) Case 4: Main windows (opened) with whole house ventilation (30 ACH) and MB fan (40 ACH) at night-time

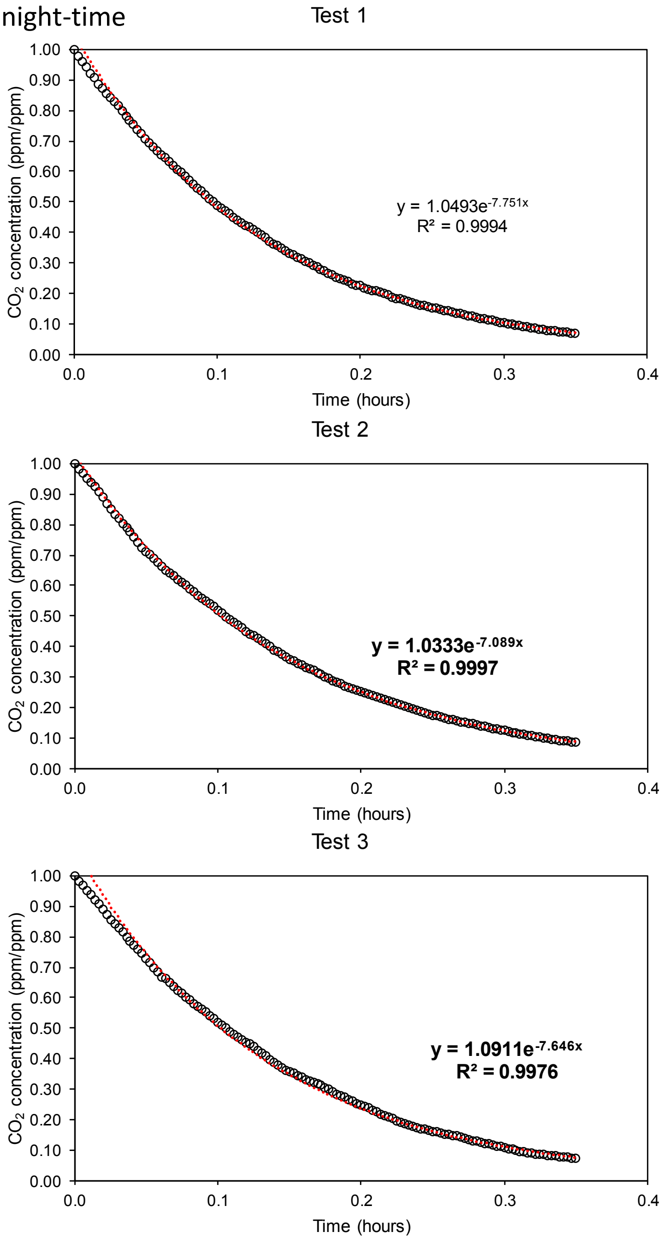

Figure A.5 (a) Estimation of air change rate per hour (ACH) in the master bedroom in Case 4.

a) Case 5: All windows (opened) at night-time

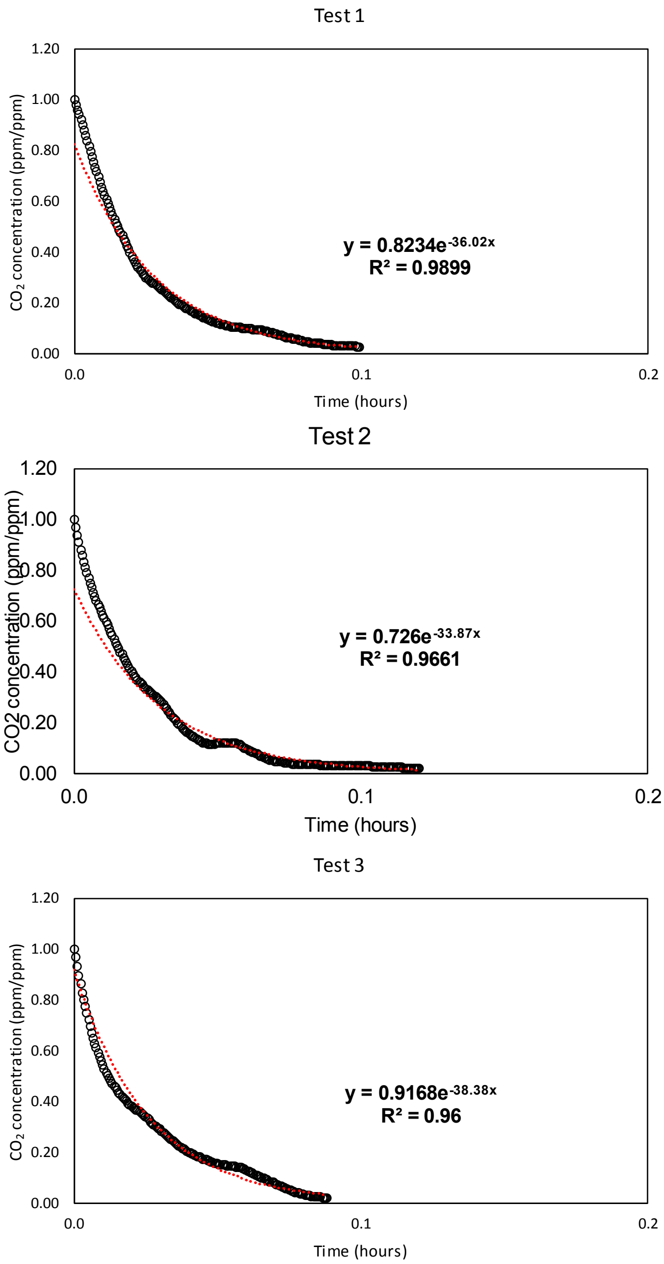

Figure A.6 (a) Estimation of air change rate per hour (ACH) in the master bedroom in Case 5.

Appendix B: Measurement of fan speed

B.1 Speed of master bedroom fan and whole house ventilation

Field experiment has been conducted to investigate the required ‘preset’ speed of the whole house and the master bedroom fan to provide the required air change rate for the purpose of full-scale experiment (Chapter 6). Based on the study cases of numerical simulation (Chapter 5), the whole house fan should be able to provide the speed that equal to 30 air change rates per hour (ACH), while for the master bedroom fan, the speed is about 40 ACH. Figure B.1 shows the measurement setup during the field measurement of both fans.

(a) Master bedroom fan

(b) Whole house fan

Figure B.1 Master bedroom fan and the whole house fan with the customized ducting system.

Customized ducting system has been constructed for both fans based on BS 848-1 (Fans for general purposes Part 1, Method of testing). In the full-scale experiment, the master bedroom fan will be used as a supply fan. In order to measure the supplied air speed, the total length of the ducting system is $5D_e$. D_e is 2 L*W/(L+W), where L and W is the length and width of the duct, respectively. The air speed measurement was taken at the length of $4.5D_e$ away from the fan, at 9 different points. The measurement was repeated for 3 times to obtain the average value.

Meanwhile, the whole house fan will be used as an exhaust fan. For an exhaust fan, the length of the ducting system is 2.75D_e. The air speed measurement was taken at the length of 1.5D_e away from the fan. Similar to the previous case, the measurement was taken at 9 different points and repeated 3 times. The equipment used for the measurement is TSI Velocicalc plus (multi-parameter ventilation meter 8386) with the accuracy of ±0.015 m/s and the resolution of 0.01 m/s. Figure B.2 shows the temporal air speed at 9 measurement points under several preset speeds of the fan.

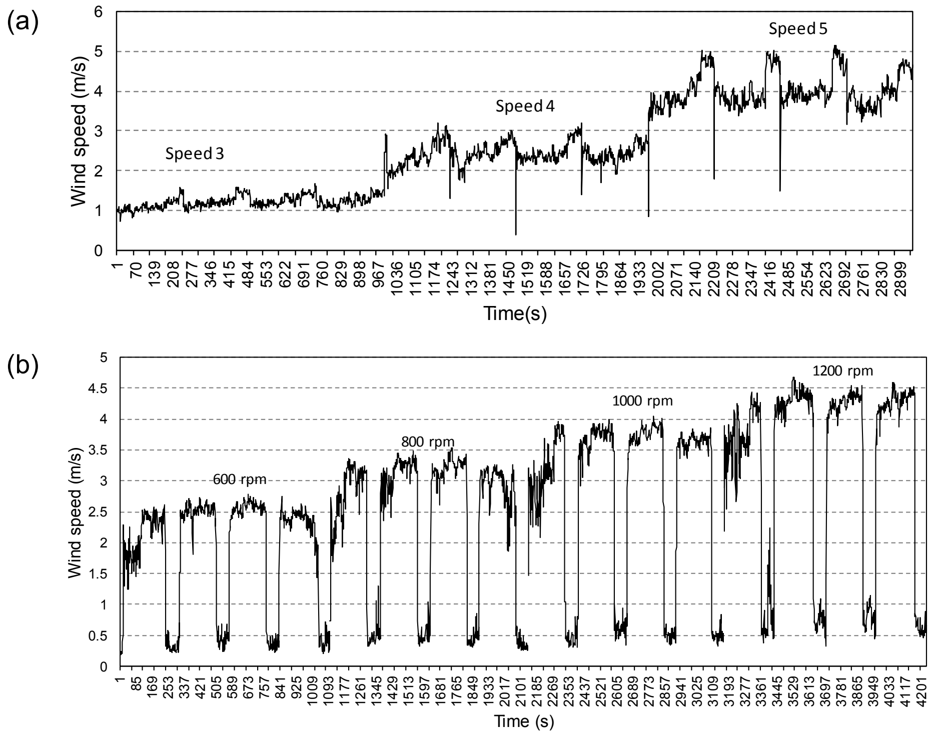

Figure B.2 Temporal air speed at different preset speed of fan. (a) Master bedroom fan (b) Whole house fan.

Based on the data above, the ACH was estimated for each fan. Figure B.3 presents the relationship between the ACH and the fan speed (preset) for each fan. As shown, for the master bedroom fan, the supplied ACH of 40 can be obtained by using the preset speed at number 5. Meanwhile, for the whole house fan, the ACH of 30 can be obtained at the speed of 800 rpm (revolution per minute).

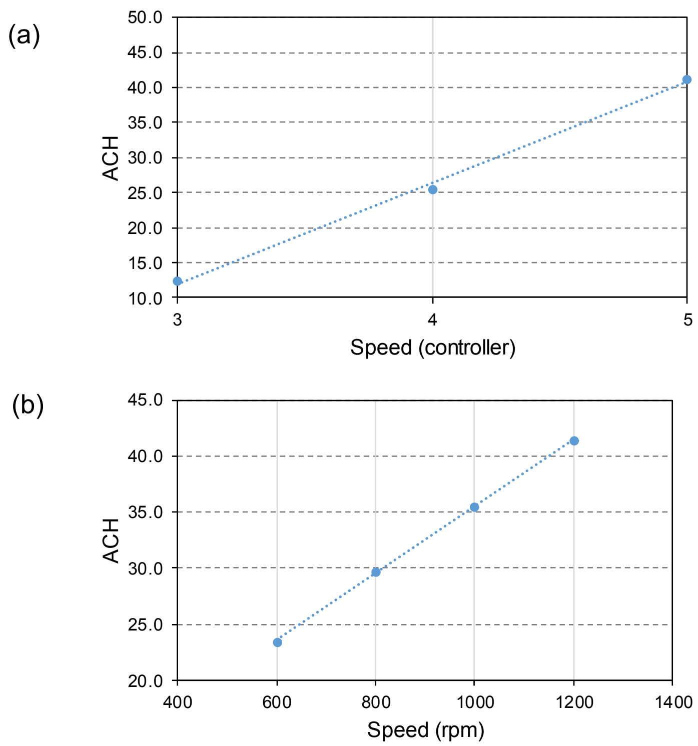

Figure B.3 Relationship between ACH and the preset speed of fan. (a) Master bedroom fan (b) Whole house fan.

B.2 Speed of the ceiling fan in the master bedroom

The measurement has been conducted to estimate the average air speed in the master bedroom under different preset speed of ceiling fan. For each preset speed, the measurement was taken for one-hour with the interval of one minute. The air speed was taken at 1.1 m above the floor level, at the center of the master bedroom. Figure B.4 shows the temporal variations of air speed in the master bedroom under different preset speed of ceiling fan. Meanwhile, Table B.1 presents the average air speed in the master bedroom under different speed of ceiling fan.

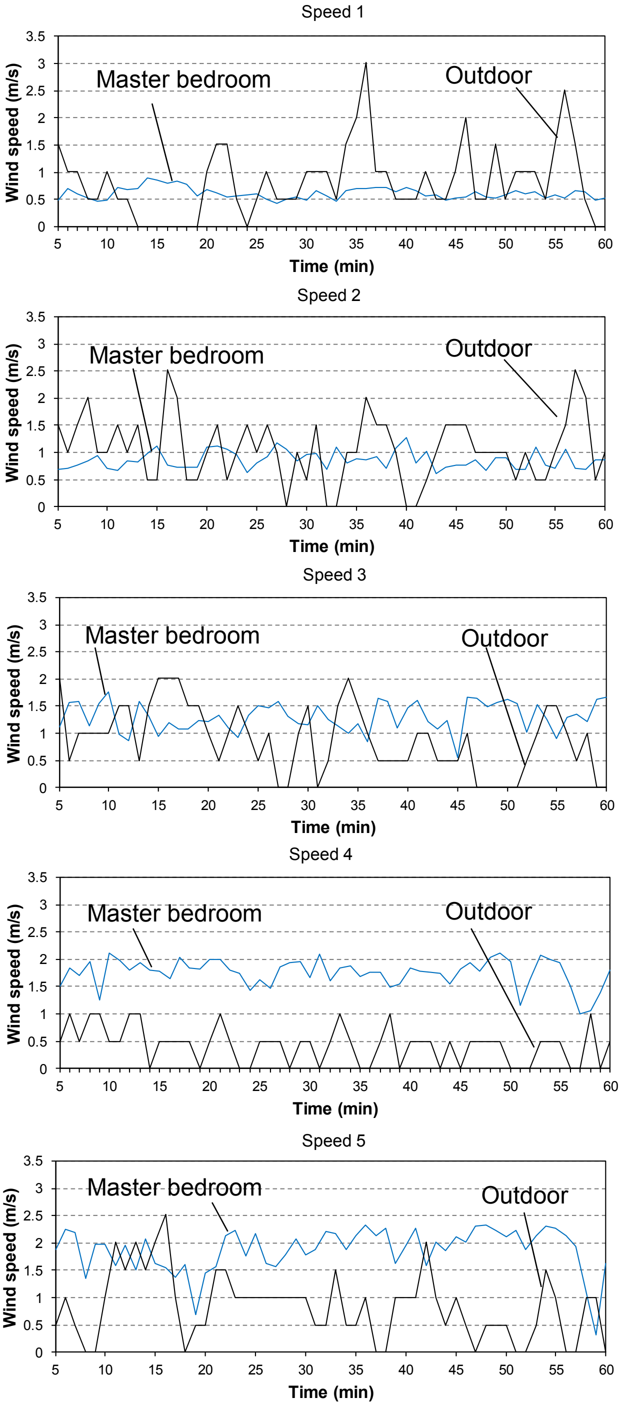

Figure B.4 Temporal variations of air speed at 1.1 m above floor level in the master bedroom at different preset speed of the ceiling fan and outdoor.

Table B.1 Average air speed at 1.1 m above floor in the master bedroom under different preset speed of the ceiling fan and outdoor.

Speed of ceiling fan	1	2	3	4	5
Master bedroom (m/s)	0.6	0.9	1.3	1.8	1.9
Outdoor (m/s)	0.8	1.1	0.9	0.4	0.8