Doctoral Dissertation

Application of Passive Cooling Techniques to Improve Indoor Thermal Comfort of Modern Urban Houses in Hot-Humid Climate of Malaysia

Doris Hooi Chyee Toe

Graduate School for International Development and Cooperation
Hiroshima University

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Doris Hooi Chyee Toe

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We hereby recommend that the dissertation by Ms. Doris Hooi Chyee Toe entitled "Application of Passive Cooling Techniques to Improve Indoor Thermal Comfort of Modern Urban Houses in Hot-Humid Climate of Malaysia" be accepted in partial fulfillment of the requirements for the degree of Doctor of Engineering.

Committee on Final Examination:

T Kubota

KUBOTA Tetsu, Associate Professor
Chairperson

Junyi Zhang

ZHANG Junyi, Professor

H. Yamamoto

YAMAMOTO Haruyuki, Professor

D. Nishina

NISHINA Daisaku, Professor

O. Higashi

HIGASHI Osamu, Associate Professor

Date: 10 July 2013

Approved:

FUJIWARA Akimasa, Professor
Dean

Date: Sep. 6, 2013

Graduate School for International Development and Cooperation
Hiroshima University

To Malaysia
and UTM

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Abstract

The aim of this doctoral thesis was to evaluate and propose application of passive cooling techniques to existing terraced houses in Malaysian urban areas for improving the indoor thermal comfort in naturally ventilated condition towards reducing cooling energy use. In the current urban areas of Malaysia, majority (42% as of 2010) of the existing housing units are terraced houses, which are mostly constructed using bricks for their outer walls.

The review in Chapter 2 focused on ventilative cooling. In particular, night ventilation is effective for buildings of high thermal mass and might be useful for the brick terraced houses. 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. Both field measurement and numerical simulation were conducted in this study.

Chapter 3 covered occupants' thermal adaptation in naturally ventilated buildings in hot-humid climate. A review of previous field thermal comfort surveys showed that it might be inappropriate to use existing adaptive comfort standards that were not developed specifically for hot-humid climate. Subsequently, a meta-analysis of the ASHRAE RP-884 database was conducted to examine the thermal adaptation of occupants and to develop an adaptive thermal comfort equation for naturally ventilated buildings in this climate. The study confirmed that the thermal adaptation in hot-humid climate differed from the requirements mandated in existing standards including ASHRAE Standard 55-2010 and EN15251:2007, and those of hot-dry and moderate climates, in terms of the relationship between indoor comfort temperature and outdoor air temperature, the better characterization of the outdoor air temperature in the equation, the acceptable comfort temperature limits, and the effects of indoor air speed and indoor humidity on comfort temperature. The new equation developed in this study can be applied to tropical climates and hot-humid summer seasons of temperate climates. It was used to assess the passive cooling techniques studied in this thesis.

Chapter 4 explained the existing situation of terraced houses in two key aspects. Firstly, the current behaviour and energy consumption for cooling of households living in terraced houses were investigated through two questionnaire surveys, respectively. The result of the first survey showed that the common practice was daytime ventilation; few occupants applied night ventilation. The ownership levels of air conditioner were 62% from the first

survey and 65% from the second survey. From the second survey, the average yearly household energy consumption including electricity and gas among the respondents was 24.5 GJ/year. The total consumption by the respondents with air conditioner was 1.4 times that by non-owners. About a quarter, i.e. 24% or 6.71 GJ/year, of the total yearly energy consumption was attributed to air conditioning alone for the households with air conditioner. Air conditioning was mainly used in bedrooms, particularly master bedrooms, at night. Secondly, the cooling effects of night ventilation compared to other ventilation conditions were examined through a full-scale field experiment in two typical terraced houses. In all experimental cases, the indoor air and operative temperatures in the night ventilated master bedroom were lower than those of daytime ventilation, no ventilation and full-day ventilation throughout the day. Nevertheless, indoor operative temperatures in the night ventilated room did not meet the 80% comfortable temperature limits for 42% of the time on fair weather days. In comparison, the exceeding period for the daytime ventilated room was 91%; the low occurrence of comfortable temperature in the room might lead the actual households, who mostly practiced daytime ventilation, to use air conditioners at night.

Chapter 5 covered field measurement in traditional Malay houses and traditional Chinese shophouses. The objectives were to understand the traditional passive cooling techniques and to evaluate their potential application to the terraced houses. In case of the Malay houses, the results revealed that the evaluated spaces, i.e. the front living halls, were relatively cool when compared to other indoor spaces in the whole house. Nevertheless, their indoor air temperatures were higher than the corresponding outdoor air temperatures by about 1°C during daytime under open window conditions and 2°C at night under closed window conditions on average. Cooling of the lightweight Malay houses likely depended on cross ventilation, solar heat controls including shading of windows and walls by overhang and shade trees and the ceiling, and a cool microclimate. In case of the Chinese shophouses, the results showed that indoor air temperatures in the living halls that were adjacent to small courtyards were lower than the immediate outdoors during daytime by up to 5-6°C. At night, the indoor air temperatures maintained similar values to the outdoors, even though external doors and windows were closed at night. Moreover, the indoor operative temperatures were below the 80% comfortable upper limits almost throughout the day; the exceeding periods were only 7-8% and the temperature deviations above the limits were 0.5°C at most. It was found that the small courtyards functioned as a night ventilation cooling source, or heat sink, to the surrounding halls by virtue of their relatively small sky view factors that also provided good solar control. The courtyards also possibly contributed to the indoor humidity control throughout the day.

Chapter 6 discussed the results of a numerical simulation study. One of the field experiment terraced houses was modelled using the TRNSYS and COMIS programs. Several passive cooling techniques that might improve the cooling effectiveness of night ventilation were simulated using weather data that represented an urban climate and a rural climate. Empirical validation of the base model terraced house showed values of mean bias error and root mean square error that were satisfactory in terms of air and operative temperatures. With

regard to comfort temperatures, the 80% comfortable upper limits in the urban climate were raised by only about 1°C compared to the rural reference climate by considering thermal adaptation. On the other hand, thermal comfort in the rural reference climate was deemed more acceptable than that in the urban climate when the same passive cooling techniques were used. When applying only night ventilation through open windows, indoor operative temperatures during daytime in the urban climate were 1.4°C higher than those in the rural climate at the same outdoor air temperature. The results of the simulation test cases determined that the effective passive cooling techniques for the night ventilated master bedroom were roof insulation, ceiling insulation, external wall (outside surface) insulation, window external shading, room forced ventilation at night and whole house forced ventilation at night. The tested combinations of these passive cooling techniques provided thermal comfort in the night ventilated room in both climates. With the combined techniques, indoor operative temperatures in the urban climate were 2.4°C higher than those in the rural climate at the same outdoor air temperature during daytime; night-time indoor operative temperature difference also increased. The larger differences implied that it will be essential to lower the urban temperatures through mitigating urban heat islands and adopting the rural microclimatic controls to increase the effectiveness of passive cooling techniques in urban houses.

Chapter 7 compared the results related to the thermal performances of all the studied houses. The comparison confirmed that the basic passive cooling technique for the brick terraced houses was night ventilation. Potential techniques to obtain night ventilation in the terraced house include open external windows, open windows to small courtyards, and night-time forced ventilation either in the room of interest or in the central zone of the house if cooling more than one room is desired. Modifications to the existing typical terraced house were proposed to increase its adaptive capacity for passive cooling at three adaptation levels. It was expected that indoor thermal comfort requirements could be met through utilization of multiple passive cooling techniques. The potential cooling energy savings through eliminating the use of air conditioners was expected to total about 9.3 million GJ/year nationwide at the current air conditioner ownership level for the existing brick terraced houses. It was estimated that the likely financial savings for households nationwide will exceed RM0.97 billion/year at the current electricity tariff for domestic use. At an increased tariff without subsidy, the corresponding savings may exceed RM1.57 billion/year.

For final conclusions, 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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List of Acronyms

ACH	Air changes per hour
ACS	Adaptive comfort standard
AIJ	Architectural Institute of Japan
AIVC	Air Infiltration and Ventilation Centre
ANOVA	Analysis of variance
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BBU	*Bandar Baru Uda*
BSI	British Standards Institute
BUESA	Building and Urban Environmental Science in Asia
CFD	Computational fluid dynamics
CO_2	Carbon dioxide
COMIS	Conjunction of Multizone Infiltration Specialists
CSH	Chinese shophouse
CWB	Central Weather Bureau, Taiwan
C&CA	The Cement & Concrete Association of Malaysia
EN	European Standard
ET	Effective temperature

ET* New effective temperature

GBI Green Building Index

HVAC Heating, ventilating and air-conditioning

IPCC Intergovernmental Panel on Climate Change

ISO International Organization for Standardization

JMA Japan Meteorological Agency

LBNL Lawrence Berkeley National Laboratory

LPG Liquefied petroleum gas

MBAM Master Builders Association Malaysia

MBE Mean bias error

MH Malay house

MIMG Malaysian Insulation Manufacturers Group

MMD Malaysian Meteorological Department

MRT Mean radiant temperature

MTC Malaysian Timber Council

NAPIC National Property Information Centre

NCDC National Climatic Data Center

NOAA National Oceanic and Atmospheric Administration

NUS National University of Singapore

PLEA Passive and Low Energy Architecture

PMV Predicted mean vote

RH Relative humidity

RM *Ringgit Malaysia*

RMSE	Root mean square error
SCATs	Smart Controls and Thermal Comfort
SEL	Solar Energy Laboratory
SET*	Standard effective temperature
SF	Shading factor
TD	*Taman Daya*
TH	Terraced house
TMR	*Taman Mutiara Rini*
TMY	Typical meteorological year
TNB	*Tenaga Nasional Berhad*
TRNSYS	Transient Systems Simulation Program
TRY	Test reference year
TTCLC	Tun Tan Cheng Lock Centre for Asian Architectural and Urban Heritage
UNFCCC	United Nations Framework Convention on Climate Change
US	United States of America
UTM	*Universiti Teknologi Malaysia*
WMO	World Meteorological Organization
WP	*Wilayah Persekutuan* (Federal Territory)

Nomenclature

a	Y-intercept in regression model (-)
b	Slope in regression model (-)
c	Principal distance of fisheye lens (unknown)
C_Q	Volume flow coefficient (m^3/sPa^n)
d	Zero flow plane displacement height at building location (m)
d_{ref}	Zero flow plane displacement height at wind speed measurement location (m)
D	Diameter of black globe (m)
k	Break-point in segmented regression model (unit of the independent variable)
L_{im}	ith measured value (unit of the variable)
L_{is}	ith simulated value (unit of the variable)
n	Flow exponent (-)
N	Total number of observations or data pairs (-)
p	Barometric pressure (kPa)
p_a	Partial pressure of water vapour (kPa)
p_{as}	Saturated vapour pressure (kPa)
Q	Volume flow (m^3/s)
r'	Projected radius in fisheye lens image (-)

R^2	Coefficient of determination (-)
RH	Relative humidity (%)
T_a	Air temperature (°C)
T_g	Globe temperature (°C)
$\bar{T}_r$	Mean radiant temperature (°C)
T_{comf}	Indoor comfort temperature (°C)
T_{comfop}	Indoor comfort operative temperature (°C)
T_{lower}	Lower comfort operative temperature limit (°C)
T_{neutop}	Indoor neutral operative temperature (°C)
T_{op}	Operative temperature (°C)
T_{out}	Outdoor temperature (°C)
T_{outdm}	Daily mean outdoor air temperature (°C)
$T_{outdm-n}$	Daily mean outdoor air temperature for the n^{th} previous day (°C)
T_{outmm}	Monthly mean outdoor air temperature (°C)
T_{outrm}	Running mean outdoor air temperature (°C)
T_{upper}	Upper comfort operative temperature limit (°C)
v	Indoor air speed (m/s)
$v(z)$	Wind speed at z m height above ground (m/s)
$v(z_{ref})$	Wind speed at the wind speed measurement height (m/s)
W_a	Absolute humidity (g/kg')
x	Independent variable in regression model (unit of the variable)
x'	X-axis coordinate in the image coordinate system (-)
X	X-axis coordinate in the object coordinate system (-)

y	Dependent variable in regression model (unit of the variable)
y'	Y-axis coordinate in the image coordinate system (-)
Y	Y-axis coordinate in the object coordinate system (-)
z	Building height above ground (m)
z_{ref}	Reference height for wind speed measurement (m)
z_0	Roughness length at building location (m)
z_{0ref}	Roughness length at wind speed measurement location (m)
Z	Z-axis coordinate in the object coordinate system (-)
ΔP	Pressure difference (Pa)

Greek letter

β	Incidence angle (°)
γ	Solar altitude angle (°)
δ	Horizontal shadow angle (°)
ε	Vertical shadow angle (°)
ε_g	Emissivity of black globe (-)
θ	Solar azimuth angle (°)
λ	Thermal conductivity (kJ/hmK)
ρ_m	Density of material (kg/m^3)
ω	Azimuth angle of vertical building surface (°)

List of Publications and Awards

Refereed Journal Papers

Toe, D.H.C. and T. Kubota, 2013: Development of an adaptive thermal comfort equation for naturally ventilated buildings in hot-humid climates using ASHRAE RP-884 database. *Frontiers of Architectural Research* (accepted for publication).

Toe, D.H.C. and T. Kubota, 2013: Field measurement on thermal comfort in traditional Malay houses. *AIJ Journal of Technology and Design*, **19**(41), 219-224.

Kubota, T., S. Jeong, D.H.C. **Toe,** and D.R. Ossen, 2011: Energy consumption and air-conditioning usage in residential buildings of Malaysia. *Journal of International Development and Cooperation*, **17**(3), Special Issue, 61-69.

Refereed Conference Papers

Kubota, T. and D.H.C. **Toe,** 2012: Re-evaluating passive cooling techniques of traditional Malay houses in Malaysia. In: *Proceedings of the 4th International Network for Tropical Architecture Conference (INTA 2012)*, December 12-14, Singapore.

Toe, D.H.C. and T. Kubota, 2012: Reanalysing the ASHRAE RP-884 database to determine thermal comfort criteria for naturally ventilated buildings in hot-humid climate. In: *Proceedings of the 28th International Conference on Passive and Low Energy Architecture (PLEA 2012)*, November 7-9, Lima, Peru.

Toe, D.H.C., T. Kubota, and M.H. Ahmad, 2012: Analysis of outdoor microclimatic factors influencing indoor thermal environment of traditional Malay houses in Malaysia. In: *Proceedings of the 5th International Building Physics Conference (IBPC)*, May 28-31, Kyoto, Japan.

Kubota, T., K. Sakamoto, and D.H.C. **Toe,** 2012: The effects of thermal insulation and exhaust fan on indoor thermal environment in Malaysian terraced houses. In: *Proceedings of the 5th International Building Physics Conference (IBPC)*, May 28-31, Kyoto, Japan.

Kubota, T. and D.H.C. **Toe,** 2011: Local wisdom in Malaysian vernacular architecture: comparison of thermal environment between traditional and modern houses. In: *Proceedings of the 12th International Seminar on Sustainable Environment and Architecture (SENVAR)*, November 10-11, Malang, Indonesia (Keynote address).

Toe, D.H.C. and T. Kubota, 2011: A review of thermal comfort criteria for naturally ventilated buildings in hot-humid climate with reference to the adaptive model. In: *Proceedings of the 27th International Conference on Passive and Low Energy Architecture (PLEA 2011)*, July 13-15, Louvain-la-Neuve, Belgium.

Toe, D.H.C. and T. Kubota, 2010: A review of adaptive model of thermal comfort for naturally ventilated buildings in hot-humid climate. In: *Proceedings of the 8th International Symposium on Architectural Interchanges in Asia (ISAIA)*, November 9-12, Kitakyushu, Japan.

Kubota, T. and D.H.C. **Toe,** 2010: Passive cooling methods for modern houses in hot-humid climate of Malaysia with special focus on night ventilation technique. In: *Proceedings of the 8th International Symposium on Architectural Interchanges in Asia (ISAIA)*, November 9-12, Kitakyushu, Japan.

Kubota, T., S. Jeong, D.H.C. **Toe,** and D.R. Ossen, 2010: Energy consumption and air-conditioning usage in residential buildings of Malaysia. In: *Proceedings of the 11th International Seminar on Sustainable Environmental Architecture (SENVAR)*, October 14-16, Surabaya, Indonesia.

Non-Refereed Conference Papers

Sugiyama, S., D.H.C. **Toe,** and T. Kubota, 2013: Effects of natural ventilation and thermal insulation on indoor thermal environment in urban houses of Malaysia: potential of passive cooling houses under the influence of urban heat islands in the tropics. In: *Summaries of Technical Papers of Annual Meeting, AIJ, 2013*, August 30-September 1, Hokkaido, Japan (in Japanese) (forthcoming).

Yasufuku, S., T. Kubota, and D.H.C. **Toe,** 2013: Effects of courtyards on indoor thermal environment in traditional Chinese shophouses in Malacca. In: *Summaries of Technical Papers of Annual Meeting, AIJ, 2013*, August 30-September 1, Hokkaido, Japan (forthcoming).

Kubota, T. and D.H.C. **Toe,** 2012: Cooling effects of courtyards in traditional Chinese shop houses in Malacca. In: *Summaries of Technical Papers of Annual Meeting, AIJ, 2012*, September 12-14, Tohoku, Japan.

Toe, D.H.C., T. Kubota, and M.H. Ahmad, 2012: An evaluation of the passive cooling strategies of traditional Malay houses in hot-humid climate of Malaysia. In: *Proceedings of Annual Research Meeting Chugoku Chapter, AIJ, 2011*, March 3-4, Hiroshima, Japan.

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Sakamoto, K., T. Kubota, and D.H.C. **Toe,** 2011: Development of comprehensive passive cooling technique for terraced houses in hot-humid climate of Malaysia. In: *Summaries of Technical Papers of Annual Meeting, AIJ, 2011*, August 23-25, Tokyo, Japan (in Japanese).

Awards

Best Paper Award, 2012: Toe, D.H.C. and T. Kubota, Reanalysing the ASHRAE RP-884 database to determine thermal comfort criteria for naturally ventilated buildings in hot-humid climate. *28th International Conference on Passive and Low Energy Architecture (PLEA 2012)*, November 7-9, Lima, Peru.

2012 Hiroshima University Excellent Student Scholarship, 2012: Toe, D.H.C., *Graduate School for International Development and Cooperation, Division of Development Science*, June 29, Hiroshima University, Japan.

1

Introduction

Modern societies are living on the Earth's resources at an increasingly rapid pace to satisfy certain needs and desires. In face of the present global climate change and related anthropogenic carbon emissions, the use of energy from fossil fuels becomes a main concern. At least three pathways to reduce energy consumption are at hand: first is to simply lower the demand and use less energy; second is to be more energy-efficient in our energy-based technology and systems; and third is to substitute fossil fuels with renewable energy sources to meet the demand. The same approaches apply to buildings. This thesis takes the first pathway as a fundamental approach towards energy-saving in buildings. Its focus is on passive cooling to fulfill indoor comfort needs.

1.1 General Context

Changes in our climate system today in the form of global average surface temperature increase, global average sea level increase and snow cover decrease are understood to be driven more by human activities than natural processes. These drivers, including atmospheric concentrations of greenhouse gases and aerosols, land surface properties and solar radiation, individually alter the energy balance of the climate system by imposing either a warming effect or a cooling effect known as radiative forcing. According to the IPCC Fourth Assessment Report (IPCC, 2007a), the global average net effect of human activities since 1750 has been one of warming with a radiative forcing of +1.6 W/m^2 in 2005. In detail, carbon dioxide contributed most among the studied factors to this warming effect (Figure 1.1). The total increase in global average surface temperature from 1850-1899 to 2001-2005 was 0.76°C (IPCC, 2007a).

Due to the vulnerability of land and living to the impacts of climate change, UNFCCC-participating governments agreed in 2010 that emissions need to be reduced so as to limit the

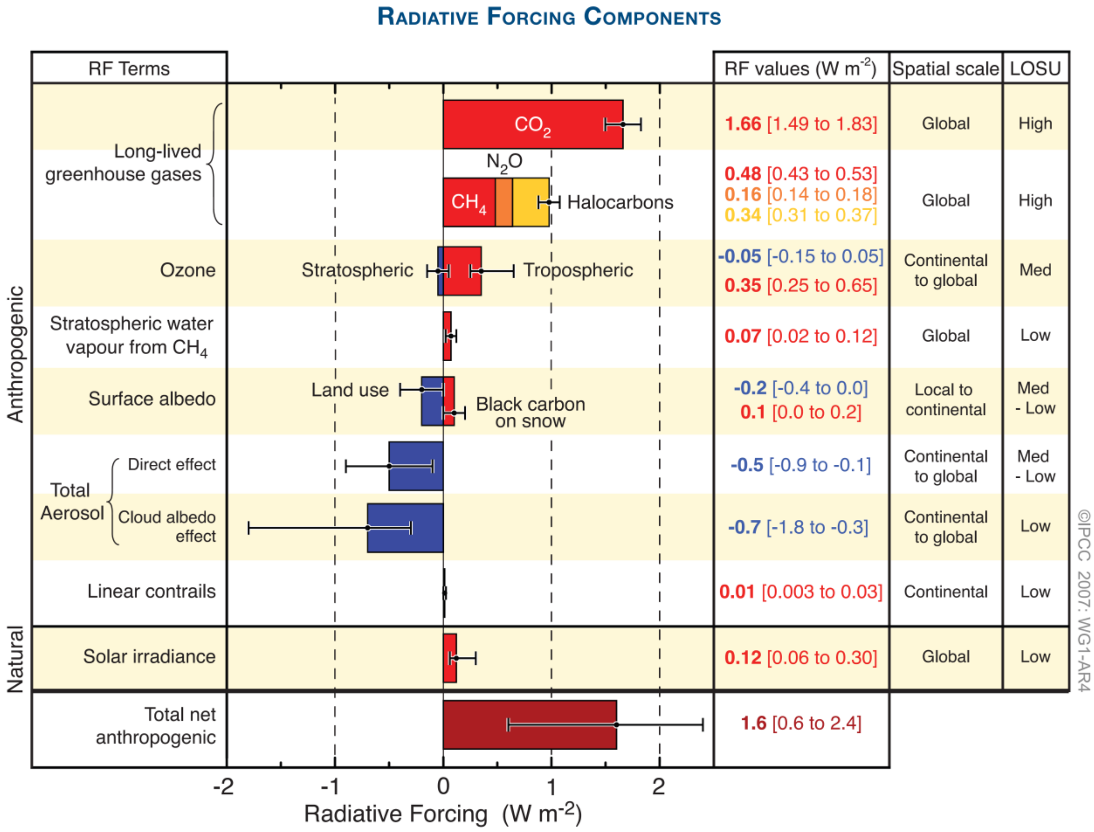


Figure 1.1. Global average radiative forcing estimates and ranges in 2005 for anthropogenic and natural drivers. RF: radiative forcing; LOSU: level of scientific understanding. Source: IPCC, 2007a.

increase in global average temperature below 2°C above pre-industrial levels (UNFCCC, 2011). This consensus implies that CO_2 emissions will need to peak and decline by 2015 and the mitigation target of CO_2 emissions in 2050 is 50-85% below the level of 2000 at the very least (IPCC, 2007b) (Figure 1.2). It will be necessary to implement mitigation strategies across sectors and countries, in particular sectors that depend heavily on fossil fuel use and where their consumption is foreseen to rise quickly if without similar efforts.

Even if energy is to be debated as a sole issue, the finite amount of fossil fuels warrants energy-saving concerns.

1.1.1 Energy Use in Buildings

Buildings are known major energy consumers. Their operational energy is commonly supplied in the form of electricity which is generated from fossil fuels. Overall, studies

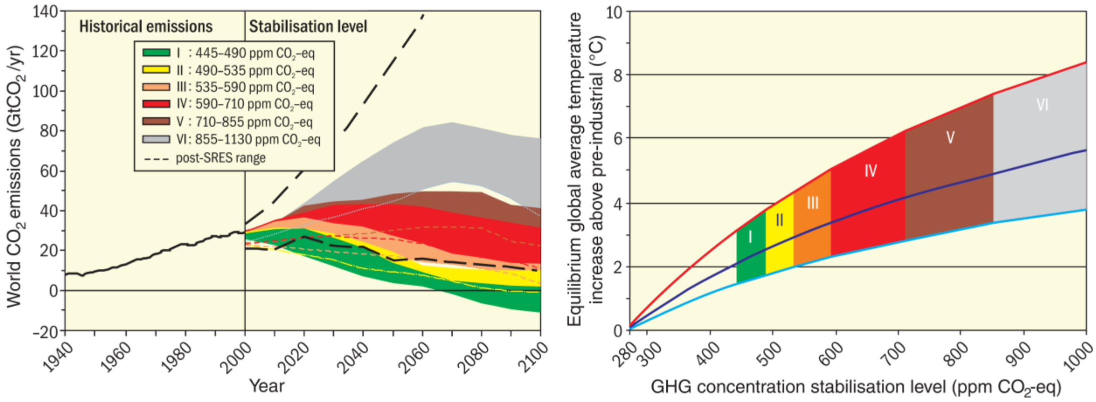


Figure 1.2. Actual global CO_2 emissions from 1940-2000 and projected emission ranges from 2000-2100 for different stabilization scenarios (left), with the corresponding equilibrium global average temperature increase (right). Scenario I (green band) represents a global average temperature increase of 2.0-2.4°C above pre-industrial at equilibrium. Source: IPCC, 2007b.

reported that buildings energy use constitutes about one third of the global final energy use (Liu *et al.*, 2010). This was equivalent to almost a quarter of the global CO_2 emissions in 2004 (Levine *et al.*, 2007). These statistics vary from region to region. In Europe, the households and services sector consumed 39.8% of the continent's final energy use in 2010 (European Commission, 2012). Meanwhile, 41% of the US primary energy use in 2010 was attributed to buildings, out of which 47% was used for space heating and cooling (US Department of Energy, 2012). Their high shares reflect a high standard of living.

By considering the development stage of respective regions, studies predict that buildings related CO_2 emissions resulting from energy use will rise sharply in the coming two decades in developing nations, especially Developing Asia (Levine *et al.*, 2007) (Figure 1.3). The increase will be driven by population growth, urbanization, increased and expanded wealth, and likely climate variability. Cooling demand in residential buildings in particular is highly sensitive to these factors (Liu *et al.*, 2010; Sivak, 2009; Wong *et al.*, 2012). It is likely to cause the increase at large as much of the developing world lies in the hot tropical belt.

1.1.2 Energy-Saving Opportunities in Buildings

According to the IPCC Fourth Assessment Report (IPCC, 2007b), the buildings sector has the highest potential to mitigate carbon emissions; other sectors considered were energy supply, transport, industry, agriculture, forestry and waste. Approximately 29% reduction below the projected baseline of 2020 can be achieved in residential and commercial buildings at relatively low costs (Levine *et al.*, 2007).

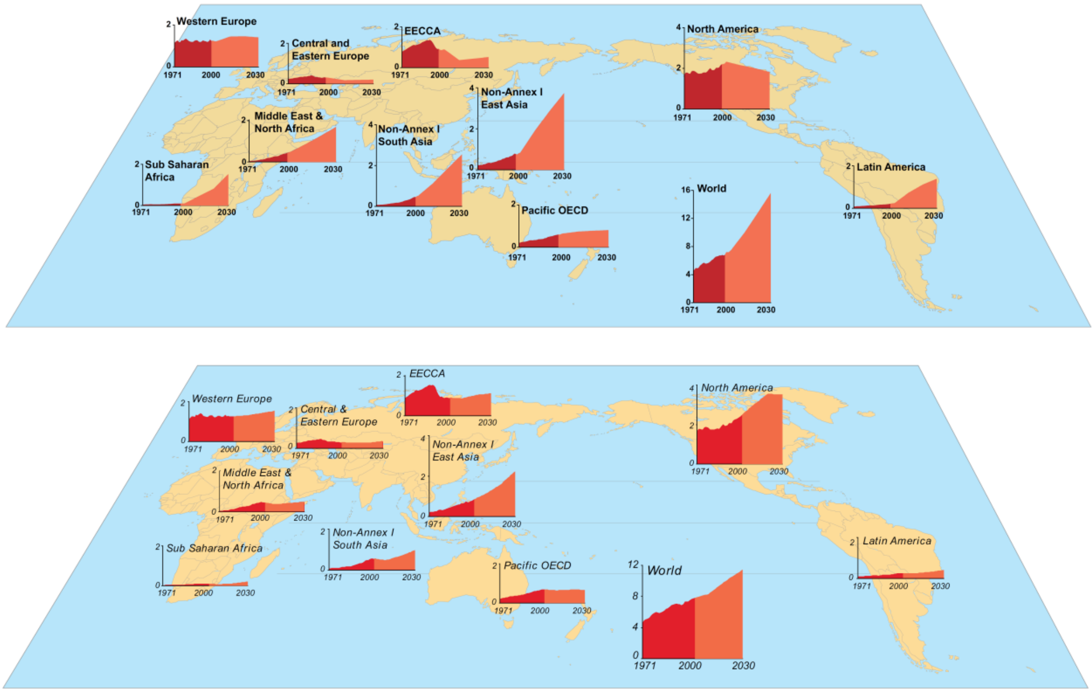


Figure 1.3. Actual (1971-2000) and projected (2001-2030) CO_2 emissions resulting from energy use (including electricity) in buildings for two IPCC scenarios by region. Source: Levine *et al.*, 2007.

To this end, measures aimed at operational energy saving in buildings are seen as the most diverse, largest and cost-effective mitigation opportunities. They fall into three categories: reducing the energy load; using efficient (active) systems to serve the load; and substituting renewable energy where possible (Liu *et al.*, 2010). Since the load in buildings is usually '*locked-in*' and dominated by space cooling or heating, reducing the load through climate-responsive passive techniques becomes imperative to achieve low-energy and low-carbon buildings.

Over the entire building stock, the largest portion of potential carbon and energy savings (by 2030 through 2050) is in retrofitting existing buildings. This is due to the slow turnover of the stock, their conditions of being less energy efficient compared to new buildings and their potential to stimulate the sector's change (Levine *et al.*, 2007; Rode, 2012).

1.1.3 Thermal Adaptation of Building Occupants

Human needs can be subjective matters. This is, in part, thanks to our ability to adjust ourselves to cope with prevailing circumstances. Recent studies showed that through thermal adaptation, our comfort temperature can vary with changing outdoor conditions, thus reducing indoor-outdoor temperature differences and required cooling loads of buildings (de Dear and Brager, 2002; Nicol *et al.*, 2012). Energy-saving measures in the form of passive cooling techniques will enhance the adaptive capacity of buildings, which is necessary to support this kind of occupants' adaptation (Kwok and Rajkovich, 2010).

1.2 The Study Context and Problem Statement

Malaysia is a developing economy in the Southeast Asian region. In tandem with rapid development, the proportion of urban population in Malaysia grew from 34.2% in 1980 to 71.0% in 2010 (Department of Statistics Malaysia, 2011a). Following more rapidly is the increase in final energy demand, which in 2007 was more than threefold that of 1990 level and close to sevenfold that of 1980 level (Ministry of Energy, Communications and Multimedia Malaysia, 2002; Ministry of Energy, Water and Communications Malaysia, 2009) (Figure 1.4). In parallel, final energy use in the residential and commercial sector escalated more than sevenfold between 1980 and 2007, which was at a higher rate than the

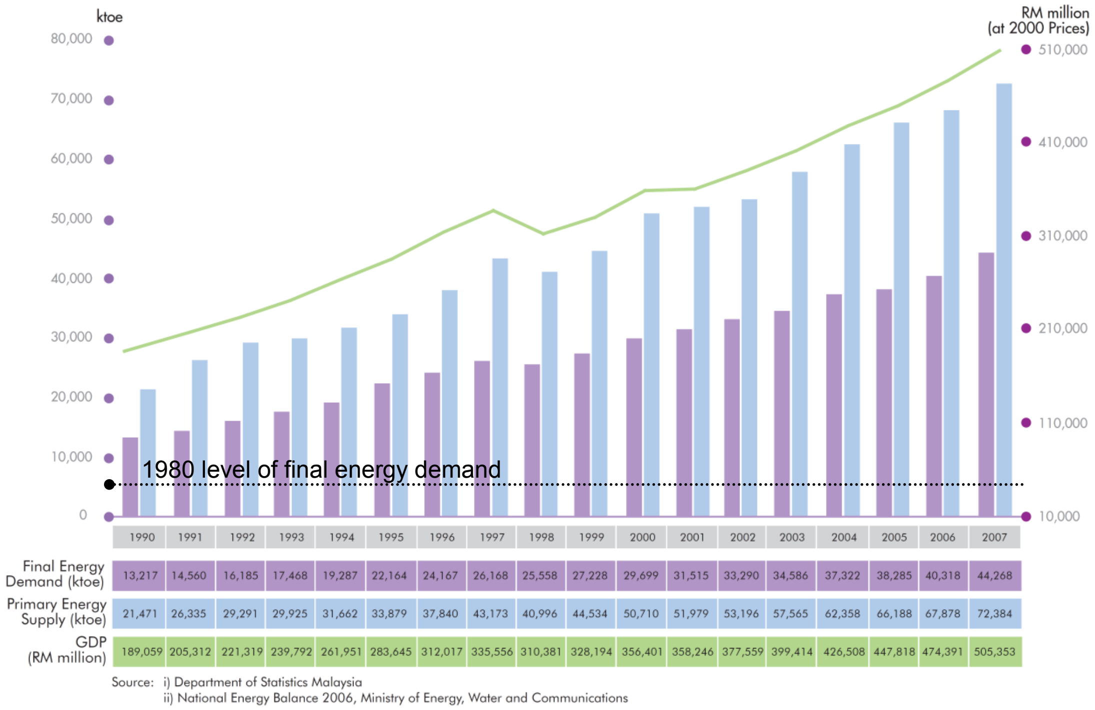


Figure 1.4. Trends in gross domestic product, primary energy supply and final energy demand from 1990-2007 in Malaysia. Source: Ministry of Energy, Water and Communications Malaysia, 2009.

Table 1.1. Residential electricity consumption and air conditioner ownership in Malaysia. Source: Mahlia *et al.*, 2004; Department of Statistics Malaysia, 2005.

Year	Electricity consumption (GWh)	Number of households having room air conditioner
1970	326	13,251
1980	1348	57,340
1990	3897	229,187
2000	9471	764,416

total final energy demand growth rate. In residential buildings, the increase could be attributed to electricity consumption for air conditioning as air conditioner ownership expanded among households (Table 1.1). This proportion is expected to rise further as Malaysia improves her economy to a developed status.

Modernization and mass construction of residential buildings have occurred alongside the economic development. In the current urban areas of Malaysia, majority (42% as of 2010) of the existing housing units are terraced houses, which are mostly constructed using bricks for their outer walls (Department of Statistics Malaysia, 2012). The high thermal mass building envelope of these houses might be difficult to be cooled in the hot-humid climate at night, especially under occurrence of (night-time) urban heat islands. During this modernization process, there has been little scientific reference about passive cooling techniques and thermal performance of past vernacular houses to inform the modern house designs. Building regulations in Malaysia (Legal Research Board, 2012) to date do not specify any requirement of thermal performance and thermal comfort in houses, except requiring natural ventilation openings of at least 5% of the clear floor area in each room. Based on our review, scientific studies that attempt to improve thermal performance of urban terraced houses remain few and fragmented, thus may explain the lack of proper building regulations and practice that can also help save energy. On the other hand, there is growing interest towards green residential buildings in the national vision, as evidenced by the recent introduction of the Green Building Index (GBI, 2011). These mean that together with updated knowledge of the human adaptive comfort processes, there is wide potential to apply contextual passive cooling techniques and further exploit the adaptive capacity of the largest housing stock through building modification and behavioural adjustment for natural ventilation.

A previous full-scale field experiment performed in two existing terraced houses showed that night ventilation provided more acceptable operative temperature than other ventilation conditions, including the current household behaviour of daytime ventilation (Kubota *et al.*, 2009; Kubota and Toe, 2010). Consequently, in this work, the laboratory of Building and Urban Environmental Science in Asia (BUESA) at Hiroshima University initiates a joint project with *Universiti Teknologi Malaysia* (UTM) to propose comprehensive passive cooling strategies to be applied to existing Malaysian terraced houses. Two of the final goals of the project are to construct experimental houses in the local main campus of UTM for real monitoring of thermal performance of passive cooling techniques and to propose an energy-saving building standard for Malaysia.

1.3 Research Purpose

The main goal of this thesis is to evaluate and propose application of passive cooling techniques to existing terraced houses in Malaysian urban areas for improving the indoor thermal comfort in naturally ventilated condition towards reducing cooling energy use. The priority here is not creating novel techniques. The novelty of this thesis lies in its breadth, i.e. an attempt to *unite* several key related aspects using scientific approaches, in order to deepen the understanding and open pathways towards solving an 'old but overlooked' problem.

We work to reach this goal through the following objectives:

1. To examine the thermal adaptation of building occupants in hot-humid climate and to determine their thermal comfort requirements in naturally ventilated buildings. These thermal comfort requirements will serve dual functions, i.e. as the main assessment criteria to evaluate the performance of the passive cooling techniques studied in this work, and as an integral part of an energy-saving building standard to be proposed in the future.

2. To understand the existing situation of terraced houses in two key aspects, i.e. current behaviour related to cooling and energy consumption among households, and effects of ventilative cooling on indoor thermal environments of existing terraced houses. Primary data are collected through questionnaire-based surveys for the former and a full-scale field experiment for the latter.

3. To evaluate indoor thermal environments of vernacular houses and to find out their passive cooling techniques that can be useful for the terraced houses. Since climate has a major influence on thermal adaptation of occupants and also effectiveness of passive cooling techniques, it is most logical to firstly make scientific references to past local buildings. This aspect has not been addressed sufficiently in scientific research and thus field measurement is our main method.

4. To initiate a numerical model of a typical terraced house and to simulate selected passive cooling techniques to improve the indoor thermal comfort of the house. At this point, it is possible to begin employing computer simulations to provide feedback

results that build on the field data. The basic questions, which passive cooling technique is effective and how well the passive cooling techniques work in urban climate compared to rural climate, are investigated.

5. To evaluate the cooling potential of the different passive cooling techniques attained through Objectives 3 and 4 compared to the thermal performance of the existing terraced house (Objective 2) and to propose modifications to the terraced house design to incorporate the effective passive cooling techniques. The cooling energy saving benefits from the proposed modifications are estimated.

2

Passive Cooling of Buildings: A Literature Review

This chapter provides a literature review of relevant studies of passive cooling in naturally ventilated buildings. We firstly explain some fundamental principles of passive cooling including use of terminologies (Section 2.1). Since modern air conditioning was not available until its first introduction in 1902 (Carrier, 2013), we particularly look into studies of vernacular buildings in Section 2.2. Section 2.3 covers recent studies which dealt with ventilative cooling techniques. Two aspects of interest are: (1) current knowledge of their thermal performances, i.e. cooling effects that were achieved by applying certain cooling techniques; and (2) current methods used to develop the techniques. Finally, we consider the status of passive cooling developments in hot-humid climate from the review (Section 2.4).

2.1 Fundamentals of Passive Cooling

The term '*passive*' was adopted to describe space conditioning systems that are driven primarily by *natural phenomena*, i.e. without power driven mechanical devices, in the early 1970s by US researchers (Cook, 1989). An oil embargo occurred at that time. International acceptance of the term since then can be seen for example in the organization called PLEA (PLEA, 2013). A '*passive*' building may include the use of a low-energy fan or a pump when its application might enhance the performance (Balaras, 1996; Givoni, 1994). This is seen as a good opportunity in the study context of this work where the use of ceiling fans is very common in the Malaysian houses (see Chapter 4: Section 4.2.3). Cooling is the transfer of energy from the space or the air supplied to the space, in order to achieve a lower temperature and/or humidity level than those of the natural surroundings (Balaras, 1996).

Although the term '*passive cooling*' is relatively new, its practice could be as old as time worldwide. From a wide viewpoint, it is inseparable from the concepts of bioclimatic design (Givoni, 1976; Hyde, 2008; Olgyay, 1963), tropical architecture (in the context of the tropics) (Bay and Ong, 2006; Koenigsberger *et al.*, 1974; Lauber, 2005; Tzonis *et al.*, 2001), ecohouse (Roaf, 2013) and green buildings (Bauer *et al.*, 2010; Bonta and Snyder, 2008), whose aims include energy-saving and sustainability. Comprehensive references on passive cooling can be found in Cook (1989), Givoni (1994), Santamouris and Asimakopoulos (1996) and Santamouris (2007). In their generalities, these books focused on the climates of America, Israel, Europe and the Mediterranean climate (see Figure 2.3). Recent review papers (Givoni, 2011; Santamouris and Kolokotsa, 2013) which collated individual studies from a broader spectrum of climatic regions are also available.

The above references are all in agreement that cooling strategies for buildings should be designed at three levels: (1) prevention of heat gains in the building; (2) modulation of heat gains; and (3) rejection of heat from the building to heat sinks by ventilation, evaporative cooling, radiative cooling or earth cooling (Dimoudi, 1996) (Figure 2.1). The natural heat sinks are the upper atmosphere (sky), the atmosphere (air) and the earth (ground and water). Examples of heat prevention strategies are use of microclimate and proper site design, building form and layout, shading, use of light colours or reflective surfaces on the exterior, use of insulated envelopes and control of internal heat gains (Balaras, 1996; Cook, 1989; Dimoudi, 1996; Givoni, 1994). Heat modulation is associated with high thermal mass materials, like brick and concrete, in building structures that act as a storage for heat during daytime and cold at night. It is considered to be useful for buildings in continuous occupation such as houses (Dimoudi, 1996). Further, the role of heat rejection is to dissipate indoor heat to the heat sinks so that indoor temperature is possibly lower than the outdoors.

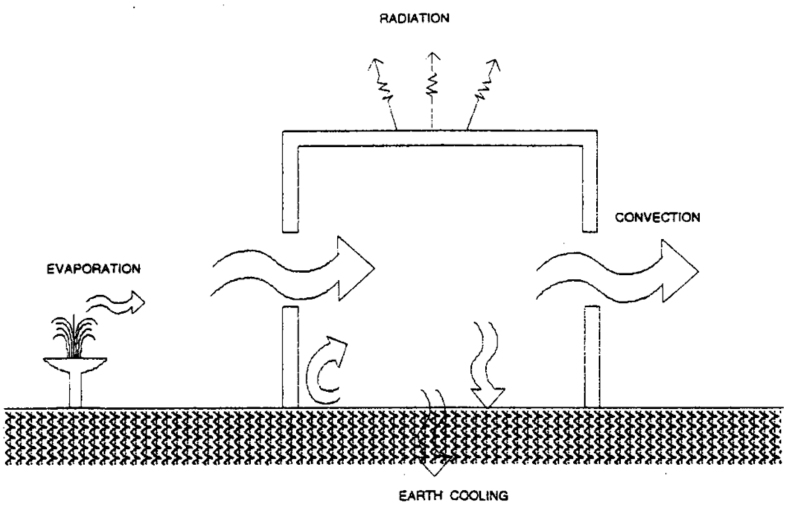


Figure 2.1. Modes of heat transfer to heat sinks in buildings. Source: Dimoudi, 1996.

The heat sinks and heat transfer mechanisms thus play an important role as cooling sources. This is the exact idea of passive cooling that differentiates it from bioclimatic design, which emphasizes the first level, although both are interrelated as mentioned above (see Givoni, 1994).

In environments where cooling is required, the purpose is to increase heat losses from the body or to reduce the sensation of heat discomfort including discomfort resulting from skin wetness (Cook, 1989; Givoni, 1998a). Thermal comfort is dealt with in Chapter 3 of this thesis.

2.2 Passive Cooling of Vernacular Buildings

Vernacular buildings are the architecture of the people – designed and customarily built by the owner, family or community using available resources and traditional technologies within their environmental contexts to meet specific needs (May and Reid, 2010; Oliver, 1997). Since passive cooling is driven by natural phenomena, it has and requires a close association with the environmental conditions. Reference to vernacular buildings has become invaluable in recent passive cooling studies (Kimura, 1994). This is because it is generally

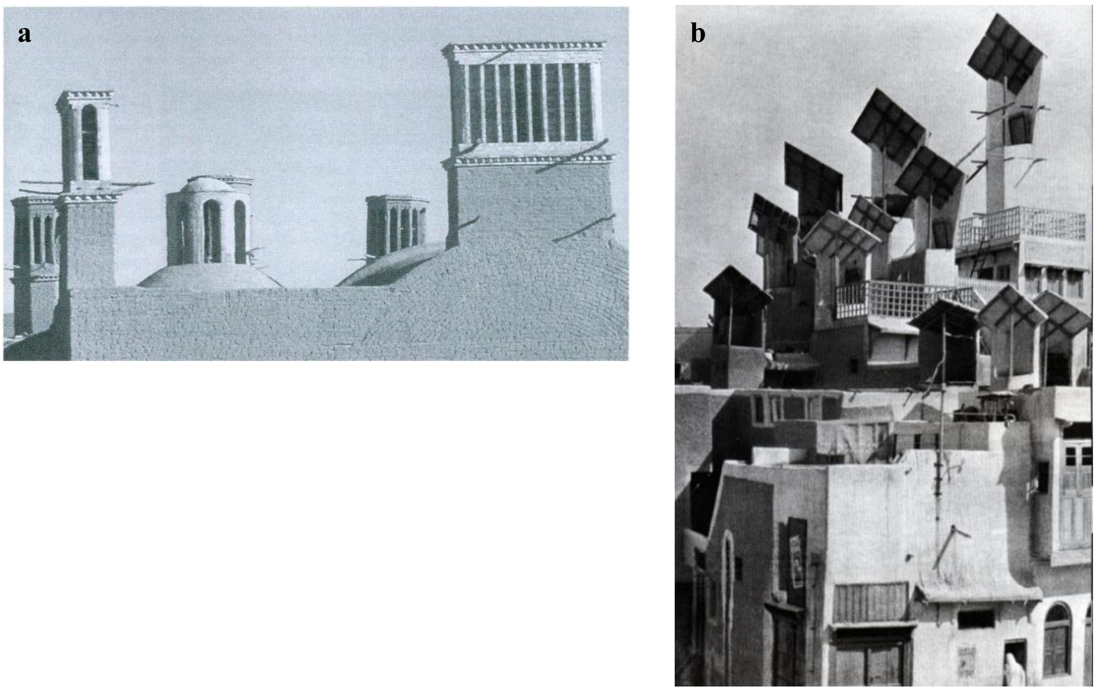


Figure 2.2. Windcatchers in two hot-dry locations. (a) Yazd, Iran; (b) Hyderabad, Pakistan. Source: Meir and Roaf, 2006; Rudofsky, 1964.

believed that vernacular buildings have already withstood time and are subtly crafted over generations in response to experience of conditions and use including the local climate and human comfort needs; also, vernacular buildings are culturally rooted to each study context (Oliver, 2006). The same reasons produce place-identifiable structures, for example the two different forms of windcatchers found in Yazd, Iran and Hyderabad, Pakistan that perform a similar function, i.e. to channel wind into buildings in a dense, hot-dry area (Figure 2.2). It is noted that the exact definition of vernacular buildings does not attach a specific period of time to them. We place our study interest in traditional vernacular buildings that still exist based on the assumption that they have matured and are available for study.

On the other hand, any passive cooling system employed in vernacular buildings is an outcome of series of trial and error usually without proper documentation. Lessons to be learned are to be unearthed and understood. Recent researches were devoted to analyse the performance or effectiveness of traditional techniques using scientific methods exemplified in Meir and Roaf (2006). As using a systematic and rigorous approach is relatively new to problem-centred vernacular research (Rapoport, 2006), both qualitative and quantitative studies continue to be seen recently in various parts of the world, for example in Vietnam (Nguyen *et al.*, 2011), India (Dili *et al.*, 2010) and Europe (Oikonomou and Bougiatioti, 2011). The qualitative approach involves overall assessments of multiple climatic aspects or environmental strategies while the quantitative approach entails real performance evaluations of thermal environmental variables usually collected from field measurement.

In-depth quantitative studies with regard to cooling techniques of vernacular buildings remain few, including in Malaysia (Hassan and Ramli, 2010). A detailed study that examined a specific traditional passive cooling system was conducted by Ryu *et al.* (2009). The said study analysed naturally driven wind turbulence data measured at the *Daechung* in a traditional Korean house to explain the effects of turbulence characteristics on thermal comfort in the space. Another study explained the thermal mechanism of warm in winter and cool in summer that was controlled by the inner surface temperature of loess walls with specific thickness in a type of traditional Chinese house known as *Yaodong* (Liu *et al.*, 2011).

One obvious benefit of scientific, especially quantitative, methods is that learning can take place not by means of copying but through analysis to derive generalizations, principles and so on for the intended use (Rapoport, 2006). In particular, two studies pointed out some misconceptions about the actual functions of traditional cooling techniques believed to work otherwise in non-scientific texts. Meir and Roaf (2006) highlighted that the high thermal mass of vernacular houses in the desert regions of the Middle East was, in fact, excessive. The extreme thermal inertia was counter-productive due to its inability to take advantage of solar gains in winter and of night cooling by ventilation in summer, primarily due to their limited fenestration size which was the result of limited construction technology. Indoor conditions were uncomfortably hot in summer and uncomfortably cold in winter especially in the lowlands and more humid coastal plains. The other study by Lin *et al.* (2004) clarified that the ventilation strategy of traditional Wannan houses in Anhui, China was actually to restrain natural ventilation during daytime and to boost it at night by a dooryard. Shading and insulation were important while cross ventilation was just an auxiliary approach.

It is derived that a significant task of this study would be to initiate analytical learning through field measurement in Malaysian traditional houses for a scientific evaluation of their indoor thermal environments and passive cooling techniques. Further details about the studied types of Malaysian traditional houses are given in Chapter 5: Section 5.1.

2.3 Recent Developments in Ventilative Cooling Techniques

This thesis, hence this section of the review, focuses on passive cooling by ventilation, also known as ventilative cooling, for two reasons. First, natural ventilation is a well-accepted passive cooling technique by tradition in hot-humid climate. Second, it is the most elementary practice of heat dissipation from buildings and can be as simple as opening a window (Cook, 1989). These mean that ventilative cooling techniques could be readily applied to the existing houses of this study through occupants' behavioural adjustment and/or building modification. Reference study of vernacular buildings could be made.

2.3.1 Night Ventilation

Night ventilation, also known as nocturnal ventilative cooling, is most useful to reduce temperatures of indoor air and building structures by utilizing the cooler ambient air as a natural cooling source (Abrams, 1986; Balaras, 1996; Evans, 1980). The effects of cooled building structures are most pronounced in buildings with high thermal mass, where the peak indoor air temperature of the following day is also maintained lower and delayed especially if the building is closed during daytime (Givoni, 1994). It is relevant to examine the effects of this ventilative cooling technique in the brick terraced houses with fairly high thermal mass.

The subject of night ventilation has been studied profoundly by many researchers in the past four decades. Givoni (1991, 1994, 1998b) provided significant sources to experimental studies of night ventilation using full-scale measurement in naturally ventilated test buildings mainly in Israel and California. The test buildings were high mass with light external colours, shaded windows, and insulated externally on walls and ceiling. In Israel, indoor daytime temperature drop for the night ventilated room compared to an unventilated room was about 2°C or 15% of the outdoor temperature range. During the hot-humid summer season in California, night ventilation was preferred and provided better comfort than full-day ventilation, especially in the high mass test building. When ventilated continuously day and night, the high mass test building had lower indoor daytime temperature than the low mass one.

Night ventilation application for office building use in moderate climate has advanced considerably. Studies in the European continent included full-scale measurement in actual buildings and numerical simulations to analyze building and technical parameters for optimizing the application of night ventilation. Some of the recent extensive studies in occupied office buildings were reported in Pfafferott *et al.* (2003, 2004, 2005, 2007) and Voss *et al.* (2007). These studies investigated the reduction of cooling load in air-conditioned, naturally ventilated and hybrid ventilated offices as a result of applying night ventilation in summer-cool, moderate and summer-hot climate zones. According to Pfafferott *et al.* (2003, 2005), night ventilation efficiency could be quantified by the thermodynamically cause (energy balance or heat flow) and by its effect (temperature and comfort performance). Some important factors that influenced night ventilation efficiency were the ventilation rate at night, thermal energy storage of the building mass, difference between indoor and outdoor temperatures as well as solar and internal heat gains (Pfafferott *et al.*, 2003). User behaviour and meteorological conditions influenced the short-term and long-term dynamics of its efficiency too (Pfafferott *et al.*, 2005). In Pfafferott *et al.* (2007) and Voss *et al.* (2007), various European standards were used to evaluate the comfort performances of the monitored offices during occupancy hours (8 a.m.-5 p.m.). The studies generally agreed that thermal comfort criteria of each standard were exceeded for less than 5% of the occupancy hours, unless in extreme weather conditions such as the summer heat wave of 2003.

In an earlier full-scale experiment, Blondeau *et al.* (1997) found that night ventilation reduced diurnal indoor air temperatures between 1.5-2°C even though the average outdoor temperature range was only 8.4°C and was considered unfavourable. The study applied night ventilation at a rate of 8 ACH between 9 p.m. and 8 a.m. as soon as the outdoor air was 2°C cooler than the indoor air.

Few studies of night ventilation have been done in the hot-humid tropics. One of the skepticisms maintained that the outdoor diurnal temperature swing should be more than 15°C with outdoor daytime temperatures between 32-36°C and night temperatures around or below 20°C for night ventilation (Givoni, 1998a). Nevertheless, some studies explored the implementation of night ventilation in hot-humid climate and produced various findings. For example, Aynsley (1999) did not find sufficient wind at night for thermal comfort compared to daytime ventilation in the warm humid tropical region in Australia.

On the other hand, Sreshthaputra (2003) produced some promising results on night ventilation cooling in the hot-humid tropics based on thermal and computational fluid dynamics (CFD) simulations. The case study buildings were temples in Bangkok, Thailand. The study showed that even without any modification to existing high mass temples, maximum temperature in the afternoon was reduced by 1°C compared to daytime ventilation when night ventilation was applied with an estimated maximum airflow rate of 20 ACH. The simulation results showed that the cooling effect on peak indoor temperature was improved by another 1.3°C when a ceiling insulation of R-30 value (5.3 m^2K/W) was installed in the high mass temples. However, Sreshthaputra (2003) conceded that humidity level increased by 20% RH in the night ventilated condition and might cause mold growth problems.

It was only recently that night ventilation was adopted by Malaysian researchers for residential buildings. Davis *et al.* (2006) performed a simulation study of the *Universiti Putra Malaysia* experimental house based on meteorological data for Kuala Lumpur, Malaysia. The experimental house was a one-storey freestanding building with concrete and brick structures, a low pitched roof and louvered windows. The study reported that by reducing daytime ventilation from 3 ACH to 0.5 ACH, the peak daytime temperature was reduced by 0.4°C. When mechanical night ventilation at 28 ACH was applied to the same house, a reduction of 1.0°C was seen in the night-time temperature compared to unventilated condition.

Another simulation study in Malaysia by Sh. Ahmad (2005) compared four window opening schedules in a ten-storey apartment building. The study also used meteorological data for Kuala Lumpur station to evaluate the Kelvin hours of overheating as a result of the different ventilation conditions. Kelvin hours is the cumulative hourly temperature in excess of the upper comfort limit, which was taken as 28.6°C in still air condition and 33.6°C at 1.5 m/s indoor air speed in the study. When windows were closed, the air change rate was assumed to be 0 ACH. The study concluded that opening windows at night and closing it during daytime gave the least Kelvin hours of overheating followed by opening windows permanently. Daytime ventilation performed third while no ventilation was the worst case.

2.3.2 Ventilative Cooling by Courtyards

Ventilative cooling by courtyards in traditional Chinese shophouses is one of the study interests of this thesis (see Chapter 5: Sections 5.1 and 5.4). Courtyard houses are a generic vernacular building form that can be found in vast regions across the world (Edwards *et al.*, 2006; Knapp, 1999; Rapoport, 2007). The courtyards exist in different scales and configurations, which are believed to suit local climates not only for heating but also for cooling in hot climates. In southern China, where the courtyards in Malaysia and other parts of Southeast Asia originated, small courtyards are most common.

Numerous studies related to the thermal and airflow effects induced by courtyards have been conducted in hot-dry climate. One of the studies concerned yard-to-yard convective flows in multiple large courtyards in a relatively large building complex (Ernest, 2011). Transitional spaces were flanked by a cool garden courtyard and a warm courtyard. In this kind of courtyard configuration and climate, the study stated that the convective flow occurred when the denser air from the cool courtyard replaced the hotter air in the warm courtyard. The process transferred cool air through the transitional spaces for ventilative cooling.

In Japan, Ishida *et al.* (1990) studied the thermal characteristics of traditional Japanese townhouse with a small courtyard and a backyard through field measurement during the hot-humid summer season. These yards were open to the sky and living spaces. The study found fluctuating but small changes in air pressure differences between the two yards so that warmed air was removed naturally upwards through the yards and cooled air from under the floor filled the living spaces.

Nevertheless, cooling effects and mechanism inside courtyards of traditional Chinese shophouses in hot-humid climate remain unknown.

2.3.3 Methods of Development

As reviewed above, several methods of developing and evaluating passive cooling techniques were employed in the existing studies. The methods can be broadly categorized as field experiment and measurement, and computer simulation. Chen (2009) reviewed the contribution and merits of each method including these in predicting ventilation performance for buildings in recent researches and found that the CFD models were the most popular. While computer simulation appears to be an efficient tool for testing many conditions or multiple conditions simultaneously, field works are useful to obtain the necessary data for validating computer models (Chen, 2009; Jankovic, 2012). Field measurement is also frequently used to evaluate the performance of existing buildings including vernacular buildings (Chen, 2009; Meir and Roaf, 2006).

The methods chosen in this thesis are to conduct field measurement in existing houses followed by numerical simulation for further tests and feedbacks. The complexity level of simulation that is possible is dynamic simulation using multi-zone thermal and airflow models (see Chapter 6: Section 6.2).

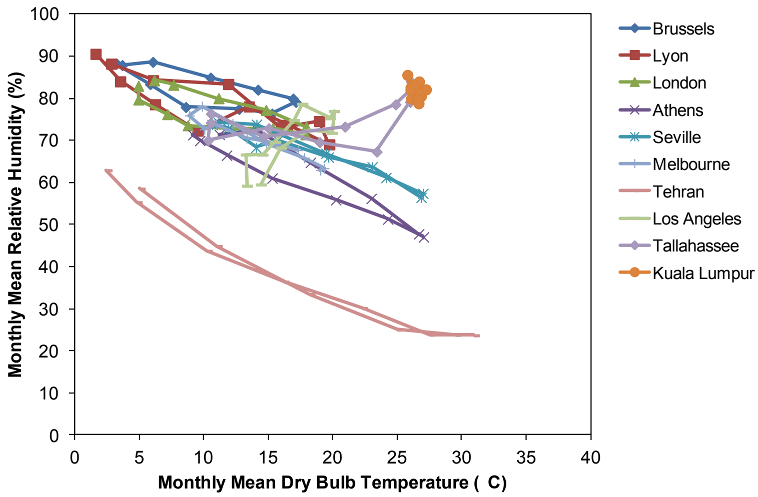


Figure 2.3. Scatter diagram of monthly mean outdoor air temperatures and relative humidity in a typical meteorological year for various locations. Source: Data from Meteonorm and TMY2 files in TRNSYS (Klein *et al.*, 2012).

2.4 Status of Passive Cooling Developments in Hot-Humid Climate

The above review shows that passive cooling techniques in both old and new buildings have been actively studied and developed in moderate and hot-dry climatic regions. The recent studies are making integrated, detailed and advanced improvements, especially in more developed regions (Allard, 1998; Givoni, 2011; Mumovic and Santamouris, 2009; Santamouris, 2007; Santamouris and Wouters, 2006; Yannas *et al.*, 2006). A number of studies are also available in the developing tropics. Nevertheless, there is still lack of basic field data in many cases so that progress is difficult to be made.

Passive cooling basically requires an elaborate information base to rationalize the interfaces with natural phenomena (Cook, 1989). Some of the main climatic factors affecting the efficiency of the different cooling approaches are high night ambient temperature, cloud cover, high humidity and insufficient wind speeds (Dimoudi, 1996). These conditions are usually prevalent in hot-humid climate. Figure 2.3 gives a plot of the monthly mean outdoor air temperatures and relative humidity in a typical meteorological year for several locations where the reviewed studies were conducted. It is clear that the climatic condition of Kuala Lumpur, which represents year-round hot-humid climate, differs from the other locations. Both basic and comprehensive studies in hot-humid climate will be useful to help the application and development of passive cooling techniques for the region.

3

Thermal Comfort Assessment Criteria

The primary function of passive cooling is to cool a building's structure and its indoor space so as to provide thermal comfort to the occupants. It is clear that conditions for thermal comfort would form the main assessment criteria of the performance of the passive cooling techniques studied in this work. In broad terms, thermal comfort has a subjective definition, '*that condition of mind that expresses satisfaction with the thermal environment*' (ASHRAE, 2010). It is well known that *that condition* is contextually dynamic. Since this thesis deals with naturally ventilated buildings, adaptive comfort standards and field studies of thermal comfort are of main interest. The heat balance model pioneered by Fanger (1972) is thus not discussed in-depth here.

In this chapter, we begin with an overview of current thermal comfort standards (Section 3.1) and a review of thermal comfort studies in the tropics (Section 3.2). We find a mismatch between the available standards and the reviewed field findings. We then develop a new adaptive thermal comfort equation and its related criteria for assessing naturally ventilated buildings in hot-humid climate by conducting a meta-analysis of the ASHRAE RP-884 database (Section 3.3). The proposed criteria that we use in this study are summarized at the end (Section 3.3.6).

3.1 The Adaptive Model and Current Standards

Thermal comfort is one of the most essential aspects of user satisfaction and energy consumption in buildings (Milne, 1995; Nicol *et al.*, 2012). Standards on indoor thermal environment are also important factors considered in building designs. In view of the current energy challenges, such standards must balance reductions in cooling/heating energy requirements of a building with improvements in occupant comfort.

Current standards are essentially based on either heat balance or adaptive models. The most notable example of the former is the predicted mean vote (PMV) model developed by Fanger (1972), which is applied in ISO 7730 (BSI, 2006) and ASHRAE Standard 55 (ASHRAE, 2010). The latter model is also used in ASHRAE Standard 55 (ASHRAE, 2010) as the code for naturally conditioned spaces and in EN15251 (BSI, 2008) for buildings without mechanical cooling systems during cooling season. Naturally conditioned spaces are defined by ASHRAE (2010) as those spaces where the thermal conditions of the space are regulated primarily by the occupants through opening and closing of windows. Mechanical ventilation with unconditioned air is allowed in such spaces (ASHRAE, 2010). In addition, there may be other low-energy methods of personally controlling the indoor environment such as fans, shutters and night ventilation (BSI, 2008). All these descriptions are synonymous with the definition of passive cooling (see Chapter 2: Section 2.1).

In principle, the heat balance model analyses thermal physiology in detail by assuming controlled steady-state conditions and high accuracy for all analysed variables such as activity level, thermal resistance of clothing, air temperature, mean radiant temperature, relative air velocity and water vapour pressure in ambient air (Fanger, 1972). In contrast, the adaptive model investigates the dynamic relationship between occupants and their general environments based on the principle that people tend to react to changes that produce discomfort by seeking methods of restoring their comfort levels (Humphreys and Nicol, 1998). Such adaptation encompasses physiological, psychological and behavioural adjustments simultaneously (Brager and de Dear, 1998; Humphreys and Nicol, 1998; Humphreys *et al.*, 2007). Therefore, the adaptive model provides greater flexibility in matching optimal indoor temperatures with outdoor climate, particularly in naturally ventilated buildings (de Dear and Brager, 2002; Deuble and de Dear, 2012; Humphreys, 1981; Nicol and Humphreys, 2010). Adaptive standards are thus considered more appropriate for supporting comfort in low-energy buildings (de Dear and Brager, 2002; Humphreys *et al.*, 2007; Kwok and Rajkovich, 2010; Nicol and Humphreys, 2002; Nicol *et al.*, 2012).

The adaptive model was formalized in a standard for the first time in ASHRAE Standard 55-2004 (ASHRAE, 2004; de Dear and Brager, 2002). 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 (ASHRAE, 2010; BSI, 2008).

3.2 Review of Thermal Comfort Studies in the Tropics

We reviewed studies related to general thermal comfort in the tropics in two phases, i.e. early phase studies (pre-1990) and recent phase studies (1990-2010). Our purpose is to analyse the appropriateness of the pioneering adaptive comfort standard (ACS) in ASHRAE Standard 55-2004 (ASHRAE, 2004) for application to naturally ventilated buildings in hot-humid climate based on the review. Later revisions (ASHRAE, 2010) and the European Standard EN15251 (BSI, 2008) are considered in Section 3.3. The review includes studies conducted in air-conditioned spaces. It should be noted that we did not draw a strict climatic boundary in this general review. Few surveys that were done in hot-dry area or during the dry season are included. The terms 'tropics' and 'hot-humid climate' are used interchangeably in this section. We later applied climatic classification to the meta-analysis (see Section 3.3.1).

3.2.1 Early Phase Studies

Early thermal comfort studies in the tropics were conducted mainly to understand the thermal comfort requirements of occupants and examine the relationship of the physical variables, i.e. air temperature, mean radiant temperature, air speed and humidity, to thermal sensation. Among the earliest surveys performed were those by Webb (1952; 1959) and Ellis (1953) in the 1950s, followed by Wyndham (1963), Rao and Ho (1978) and Sharma and Ali (1979; 1986). All the surveys were carried out in naturally ventilated buildings under the subjects' normal daily routine and clothing. Particular interest was given to analyse the prevailing outdoor climate, adequacy of indoor air movement, occupants' behaviour and feeling of skin wetness. It is evident that research on thermal comfort in naturally ventilated buildings is not new in the tropical region. However, relatively few studies could be found in the literature before 1990.

Some thermal indices were developed as a result of the above studies. These include the Singapore Index (Webb, 1959), Equatorial Comfort Index (Chrenko, 1974), Thermal Stress Index (Sharma and Ali, 1979) and Tropical Summer Index (Sharma and Ali, 1986). Prior to the development of these indices, comfort temperatures were indicated using the effective temperature (ET) (Ellis, 1953; Webb, 1952). It should be noted that all the above early indices evaluate the effects of air movement and humidity on thermal sensation. However, the early tropical indices were not widely used after their establishment and not developed further to produce a more comprehensive index, as the standard effective temperature (SET^*) was from the ET by Gagge *et al.* (1986).

3.2.2 Recent Phase Studies

Relatively many thermal comfort studies could be seen in the tropical region in the recent two decades (1990-2010). These studies can be generally classified into climate chamber studies and field studies. Although some climate chamber studies (Abdul Shukur, 1993; de Dear *et al.*, 1991a, 1991b; Kubo *et al.*, 1997; Shimura *et al.*, 1996; Zainal, 1993) were conducted under hot and humid conditions, our review found that field studies were still by far more popular than climate chamber studies in the tropics. This is probably because emerging researchers during the recent period were more attracted to the adaptive model, which calls for field studies.

In particular, this period coincided with the commencement of ASHRAE RP-884 (de Dear *et al.*, 1997), the project which contributed to the development of the adaptive comfort standard in ASHRAE (2004). Some of the recent field studies (Busch, 1995; de Dear *et al.*, 1991c; de Dear and Fountain, 1994; Karyono, 2000; Nicol *et al.*, 1999) in the tropics participated in ASHRAE RP-884 and were included in the meta-analysis that produced the standard. Each study surveyed both naturally ventilated and air-conditioned buildings for comparison purposes except for the study by de Dear and Fountain (1994). The trend to compare both building operation modes arose out of consciousness of energy use in building cooling. This group of studies signifies the beginning of such trend in hot-humid climate.

Numerous other field studies were carried out in naturally ventilated buildings (Abdul Rahman and Kannan, 1997; Cândido *et al.*, 2010a; Djongyang and Tchinda, 2010; Feriadi and Wong, 2004; Gomez-Azpeitia *et al.*, 2009; Ibrahim and Hidayat, 2001; Indraganti, 2010; Khedari *et al.*, 2000; Mallick, 1996; Memon *et al.*, 2008; Ogbonna and Harris, 2008; Tablada *et al.*, 2009; Wijewardane and Jayasinghe, 2008; Wong and Khoo, 2003; Wong *et al.*, 2002), air-conditioned buildings (Atthajariyakul and Lertsatittanakorn, 2008; Cheong *et al.*, 2003; Hwang *et al.*, 2007, 2008; Mui and Chan, 2003; Mui and Wong, 2007; Nakano *et al.*, 2002; Yamtraipat *et al.*, 2005; Zainal and Keong, 1996) and combination of both in the same study (Han *et al.*, 2007; Hwang *et al.*, 2006, 2009; Jitkhajornwanich and Pitts, 2002; Kwok, 1998; Kwok and Chun, 2003; Rangsiraksa, 2006; Yang and Zhang, 2008; Zainal and Adnan, 1997). The field studies in naturally ventilated buildings in a way can be seen as a continuation of the early studies to further determine the thermal comfort requirements of occupants (Section 3.2.1). They were also performed under the occupants' ordinary daily activities, clothing and environment. Nevertheless, they did not continue to utilize the tropical indices developed from those early surveys. Measurements of all physical variables were taken in the major studies, yet recent researchers are mostly found to report comfort conditions using simple indices such as air temperature, operative temperature and globe temperature. One of the reasons given was these indices provided higher correlations with the subjective assessments (Mallick, 1996). Another reason was to compare their results with other recent field studies and existing thermal comfort standards (Memon *et al.*, 2008; Tablada *et al.*, 2009).

In all, studies which encountered higher air speeds reported that comfort temperatures voted by respondents also increased accordingly (Atthajariyakul and Lertsatittanakorn, 2008; Cândido *et al.*, 2010a; Khedari *et al.*, 2000; Mallick, 1996; Rangsiraksa, 2006; Wijewardane and Jayasinghe, 2008). One of the studies by Mallick (1996) claimed that the cooling effect of air movement was observed only at air speeds greater than 0.3 m/s. The highest recommended air speed found in this review is 3 m/s in the study by Khedari *et al.* (2000). Although absolute values of the air speeds and the corresponding comfort temperatures differ among the studies, it is agreeable that poor ventilation is probably the most important reason for the discomfort of occupants in naturally ventilated buildings in the humid tropics (Yang and Zhang, 2008).

3.2.3 Trend of the Studies

The early phase studies concentrated on two fundamental aspects: (1) understanding the thermal comfort requirements of occupants in the naturally ventilated buildings; and (2) developing thermal indices. Together with the recent phase studies, it has been clarified that occupants require higher air speeds at higher air temperatures to expedite sweat evaporation and still feel comfortable in hot-humid climate. However, for the latter aspect few early studies were found, thus resulting in limited development of tropical indices to assess the effects of evaporative heat loss.

We analysed the share of the reviewed studies according to their thermal index usage based on thermal indices that include (early indices and SET^*) and exclude evaporative heat loss (other indices). Figure 3.1 shows that only about 12% of the studies used the early indices, i.e. ET, Singapore Index, Equatorial Comfort Index and Tropical Summer Index. Combining both early indices and SET^*, it is found that less than 20% of the studies applied thermal indices which account for the effect of evaporative heat loss at high air movement. More than 80% of the studies applied other indices that do not evaluate evaporation, i.e. air temperature, operative temperature, globe temperature, ET^* and equivalent temperature.

The recent phase studies emerged as a continuation of the former aspect of the early phase studies and also out of curiosity to examine the closeness of thermal perceptions in hot-humid climate compared to major standards including ASHRAE Standard 55, ISO 7730 (BSI, 2006) and the adaptive comfort standard (ASHRAE, 2004). On the whole, recent studies were greatly influenced by and, in turn, supported the adaptive model. Although

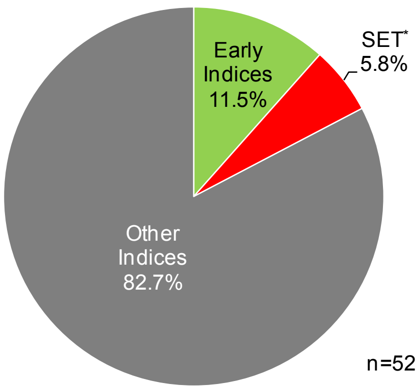


Figure 3.1. The share of thermal comfort studies which include (early indices and SET^*) and exclude evaporative heat loss (other indices).

there are increasing concern and efforts to develop thermal comfort criteria for hot-humid climate, the process to standardize a set of thermal comfort criteria in this region has not taken place. Furthermore, considering that thermal comfort is achieved in diverse environments in naturally ventilated buildings, there is still a weak area in terms of development and validation works for a comprehensive standard that can be applied across a wide range of thermal conditions.

3.2.4 Appropriateness of the Adaptive Comfort Standard

The adaptive comfort standard in ASHRAE (2004) applied a simple thermal index, i.e. operative temperature, to characterize the indoor comfort temperature. The simpler temperature index is sufficient and very useful when indoor thermal environment is close to the standard environment, which is at low air speed and 50% RH (Humphreys *et al.*, 2007). However, the conditions might not be so in hot-humid climate, especially when high air speed is essential and promoted by the adaptive model to aid evaporative heat loss by sweat. This deficiency is observed in two ways. First is the use of a thermal index which considers only convective and radiative heat exchanges, i.e. operative temperature, as explained above. Second is not specifying the acceptable (and required) range of air speed for the corresponding comfort temperature, even though the adaptive comfort standard in ASHRAE (2004) did not restrict air speed to any limit. To be used as a standard particularly for hot-humid climate, this may bring two implications – under provision of the required air speed to building occupant and underestimation of the potential for higher comfort temperature under increased air speed.

To discuss the above deficiency further, comfort temperatures from the reviewed studies were clustered in groups according to the thermal index used and the corresponding mean air speed for the comfort condition. Figure 3.2 shows the comfort temperatures from studies which provided air speed data as a function of mean monthly outdoor air temperatures. They are presented separately for the naturally ventilated buildings (Figure 3.2a) and the air-conditioned buildings (Figure 3.2b). The mean monthly outdoor air temperatures were obtained from the respective papers and if not given, they were sourced from WMO (2010), JMA (2010) and CWB (2010) according to the survey month and location reported in the papers. In Figure 3.2a, the adaptive comfort standard 80% and 90% acceptability limits are indicated for evaluating the criteria for naturally ventilated buildings while in Figure 3.2b, the ASHRAE (2004) 0.5 clo comfort zones are shown for the same purpose for air-conditioned buildings.

Figure 3.2a illustrates that the ACS acceptability limits generally agree well with the neutral temperatures reported from the field studies in the naturally ventilated buildings under air speeds below 0.3 m/s. This can be said of the early indices and also other indices, although there was no comfort temperature using the SET^* to be compared. Nevertheless, some upper limits from the same air speed group, particularly other indices, are 2-3°C above

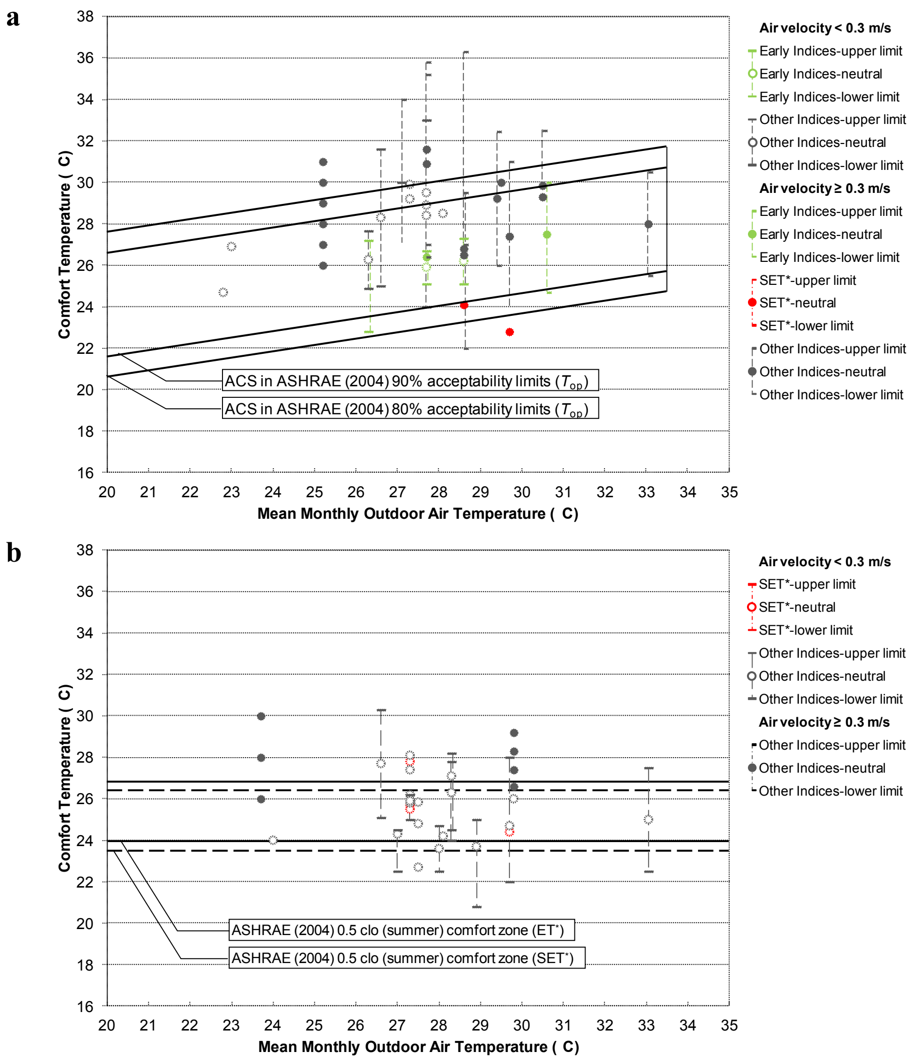


Figure 3.2. Comfort temperatures from the reviewed studies in the tropics. (a) Naturally ventilated building; (b) Air-conditioned building.

the ACS upper limit. Under higher air speeds, some of the neutral temperatures which used other indices exceed the ACS upper limit by about 2°C while some of the corresponding comfort limits are up to 6°C above and 1°C below the ACS acceptability limits. In comparison, both neutral temperatures and comfort limits which applied the early indices are within the ACS acceptability limits while neutral SET* are near the ACS lower limit, even under air speeds of 0.3 m/s or more (Figure 3.2a).

Although different expectation and acclimatization of occupants might have contributed to the diversity in comfort temperatures, the difference seen between the two air speed groups for other indices is most likely due to the effects of different levels of air movement on evaporative heat loss. The analysis implies that the said ACS, given in operative temperature, might be applicable to naturally ventilated buildings in hot-humid climate in low air movement conditions. Even that, the neutral temperatures using other indices fall in the upper half of the ACS comfort band (Figure 3.2a). A new adaptive comfort equation that considers the effects of indoor air speed and higher comfort temperature allowance under increased air speed may be necessary for hot-humid climate. It is noted that although the SET^* evaluates air speed and humidity, it does not include the concept of thermal adaptation as implied in Brager and de Dear (1998); hence, the SET^* is not used to develop the adaptive comfort equation in Section 3.3.

For the air-conditioned buildings, Figure 3.2b shows that the comfort temperatures found in this review are less spread out than those for the naturally ventilated buildings, even though the range of mean monthly outdoor air temperature is similar (cf. Figure 3.2a). This is quite logical as the air-conditioned buildings mostly encountered relatively constant indoor environments regardless of the outdoor climate. Nevertheless, some of the neutral temperatures under air speeds below 0.3 m/s using other indices exceed above and below the ASHRAE comfort zone for ET^* by more than 1°C, and the corresponding comfort limits by more than 3°C. This could be partly due to the clothing worn with insulation lower and higher than 0.5 clo. Neutral temperatures applying SET^* also fall within and above the ASHRAE comfort zone for SET^* (Figure 3.2b). Under higher air speeds, most of the temperatures, which were all reported in other indices, are above the ASHRAE comfort zone for ET^*. In general, the above analysis supports the distinction between thermal comfort criteria for naturally ventilated and air-conditioned buildings as proposed by the adaptive model.

Given that the variability of comfort temperatures are different for the naturally ventilated and air-conditioned buildings, Figures 3.3 and 3.4 compare their frequency distributions of neutral temperatures and comfort bands, respectively. For the naturally ventilated buildings, the neutral temperatures average about 28°C with a standard deviation of 1.96°C on the whole (Figure 3.3a). The corresponding comfort bands average about 6°C with a standard deviation of 2.43°C (Figure 3.4a). These statistical values are higher than those of the air-conditioned buildings (cf. Figures 3.3b and 3.4b). It should be carefully noted that the present analysis is highly dominated by other indices. For the naturally ventilated buildings, the average neutral temperature in early indices and SET^* combined is 3°C lower while the average comfort band in early indices is almost 3.5°C narrower than those of other indices, respectively (Figures 3.3a and 3.4a). These differences are probably due to the effects of evaporative heat loss provided by air movement that are considered in early indices and SET^*, but not in other indices. On the other hand, average neutral temperature in SET^* is quite close with that of other indices for the air-conditioned buildings (Figure 3.3b). This analysis further implies the need to reconsider an adaptive comfort standard that can better evaluate the effects of evaporative heat loss on thermal comfort for naturally ventilated buildings in hot-humid climate.

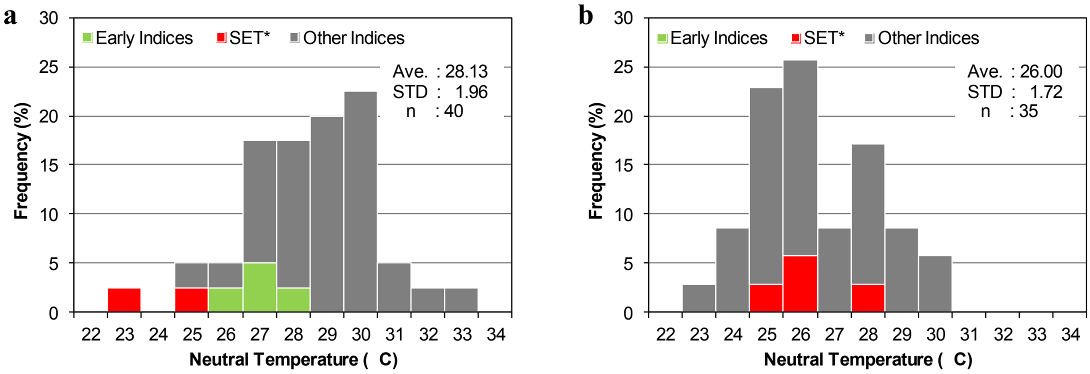


Figure 3.3. Frequency distribution of neutral temperatures from the reviewed studies in the tropics. (a) Naturally ventilated building; (b) Air-conditioned building.

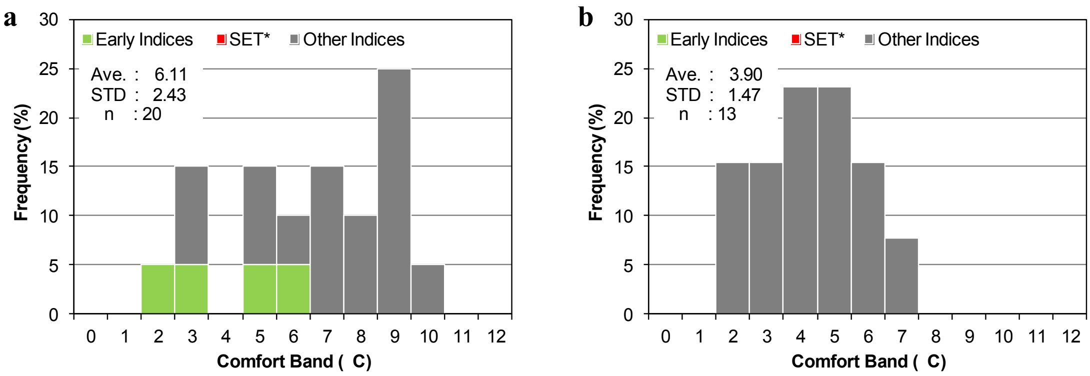


Figure 3.4. Frequency distribution of comfort bands from the reviewed studies in the tropics. (a) Naturally ventilated building; (b) Air-conditioned building.

3.3 Development of an Adaptive Thermal Comfort Equation for Naturally Ventilated Buildings in Hot-Humid Climate

Previous studies have shown that the PMV model covers narrow ranges of moderate climatic conditions and is not applicable to warm environments in buildings (Humphreys and Nicol, 2002). Because climatic context is a primary consideration in the adaptive model, it is imperative to evaluate the comfort requirements of people worldwide, particularly in tropical regions that lack comprehensive standards (Nicol, 2004). The review in Section 3.2 raises the question that general standards may not be appropriate for all climates.

In a Brazilian study, Cândido *et al.* (2010b, 2011) demonstrated that although thermal acceptability was determined to be within the ASHRAE adaptive standard (ASHRAE, 2010), occupants required more air velocity. They proposed minimum air velocity at three ranges of operative temperature including 0.4 m/s at 24-27°C, 0.41-0.8 m/s at 27-29°C, and >0.81 m/s at 29-31°C (Cândido *et al.*, 2011). In addition, they determined that neutral operative temperatures were nearly the same as mean daily outdoor air temperatures at Brazil's northeast coast (Cândido *et al.*, 2011). This relationship had a higher gradient than those specified in the existing adaptive standards (ASHRAE, 2010; BSI, 2008).

On the contrary, Nguyen *et al.* (2012) determined that the adaptive algorithm of EN15251 (BSI, 2008) was appropriate to their adaptive comfort equation derived from Southeast Asian studies in naturally ventilated buildings. They indicated that air velocity and humidity were negligible factors in comfort temperature (Nguyen *et al.*, 2012). However, their database and analysis also contained data of mild cold-dry seasons (Nguyen *et al.*, 2012). These conflicting results warrant further investigation through collective analysis of larger regions that share a *clearly defined* similar climate.

One of the main methods applied to form the adaptive model is meta-analysis of a larger database that includes several thermal comfort field surveys. Several such resources include the Humphreys 1975-81 database (Humphreys, 1981); the ASHRAE RP-884 database (de Dear, 1998; de Dear *et al.*, 1997), which was used to develop the ASHRAE adaptive standard (ASHRAE, 2004, 2010); and the European Smart Controls and Thermal Comfort (SCATs) Project database (McCartney and Nicol, 2002), which was used to develop the EN15251 adaptive standard (BSI, 2008). Among these well-established resources, the comprehensive ASHRAE RP-884 database, which consistently covers several climatic zones including hot-humid, has been analysed by numerous researchers including Arens *et al.* (2009, 2010), de Dear *et al.* (1997), de Dear and Brager (1998), Farghal and Wagner (2010), Humphreys *et al.* (2007, 2010), Humphreys and Nicol (2000a, 2000b, 2002, 2004), Nicol (2004), Schweiker and Shukuya (2012), and Toftum (2004). However, with the exceptions of Nicol (2004) and Farghal and Wagner (2010), none of these studies explored climatic classification; that is, data from different climates were not analysed separately. To examine the relationship between comfort and humidity, Nicol (2004) classified the data from ASHRAE RP-884 into three datasets according to mean outdoor relative humidity. His study suggested that occupants may require comfort temperatures approximately 1°C lower than that specified by the overall data when the outdoor relative humidity is greater than 75%.

In addition, Farghal and Wagner (2010) used the ASHRAE RP-884 database to classify naturally ventilated buildings into seven climatic zones among which significant differences were noted in thermal neutralities. Their analysis utilized only a mean neutral temperature for each building and did not include raw database values. Moreover, they conducted field surveys in Cairo and proposed a steeper adaptive comfort equation for hot-dry climate than those of existing adaptive standards (ASHRAE, 2010; BSI, 2008). They did not suggest equations for other climatic zones.

Based on these previous studies, we hypothesized that reanalysis of the ASHRAE RP-884 database according to climate would clarify any differences in thermal adaptation among climates. We determined that it is relevant to identify climates in defining the adaptive model because this approach considers typical environment and adaptive actions that are useful in particular sets of circumstances (Brager and de Dear, 1998; Humphreys and Nicol, 1998). Climate significantly affects such factors. In particular, the typical conditions of warm environments generally differ from those of moderate environments; in response to heat, the former require adaptive actions such as sweating and increased air movement. Accordingly, the adaptive model should also differ under warm conditions. Considering this factor, the adaptive model can more effectively explain discrepancies between predicted and actual thermal responses among climates.

We conducted a statistical meta-analysis of the ASHRAE RP-884 database by sorting the data according to climate to examine the thermal adaptation of occupants and to develop an adaptive thermal comfort equation to be used as a standard for naturally ventilated buildings in the hot-humid climate. With reference to the two major adaptive standards (ASHRAE, 2010; BSI, 2008), the main criteria for discussion include formulation of an adaptive comfort equation, temporal characterization of outdoor air temperature in the equation, acceptable comfort limits, and allowance for increased comfort temperature by considering the effects of indoor air speed and humidity. Although the study focuses on hot-humid climate, the results of hot-dry and moderate climates are also discussed for comparison. However, the effects of indoor air speed and humidity are considered for only hot climates.

3.3.1 Meta-Analysis of the ASHRAE RP-884 Database

Data Classification by Climate

The first step in the data preparation was to classify each data file supplied in the ASHRAE RP-884 database (The University of Sydney, 2010) into one of three climate groups including hot-humid, hot-dry, and moderate according to survey location and season. The widely employed Köppen-Geiger climate classification map updated by Peel *et al.* (2007) was used to define the three groups. In this classification system, five climates including tropical (A), arid (B), temperate (C), cold (D), and polar (E) are categorized into 30 climate types on the basis of quantitative criteria for temperature and precipitation (Peel *et al.*, 2007).

In the present analysis, all locations with A climate types were regarded as hot-humid climate. However, it should be noted that the database did not contain data during the driest month in the tropical savannah climate, which is considered to be a transition between hot-humid and hot-dry climates. Moreover, the Cfa type summer season (temperate; hot summer with no dry season) was also classified as hot-humid.

Conversely, all locations with B climate types were considered to be hot-dry climate, except for the winter season with seasonal mean outdoor air temperatures below 18°C. (Seasonal mean outdoor air temperature was determined on the basis of meteorological data in the Supplementary Material Section in Peel *et al.*, 2007.) Similarly, the summer seasons of Csa (temperate; dry and hot summer) and Cwa (temperate; dry winter and hot summer) climate types were included in this group. All other files in the database were in locations with C climate types; these and the winter exceptions were classified as moderate climate in this study.

Table 3.1 shows that of the 10,065 observations for naturally ventilated buildings in the database, 1682 represent hot-humid climate while 4339 represent hot-dry climate. The remaining 4044 observations apply to moderate climate. Both residential buildings and offices were surveyed in each climate. Previous research conducted by de Dear and Brager (2002) to establish the ASHRAE adaptive standard (ASHRAE, 2010) excluded the data files of Kwok (1998), which are available in the database downloader and would had been classified as hot-humid. Similarly, these files were not used in the present study. The Kwok survey involved mainly young high school students and was not representative of adult occupants (Kwok, 1998). Despite the unequal sample sizes among climates, the number of hot-humid observations was considered as sufficient to facilitate a reliable statistical analysis.

Data Consistency and Refinement

The second step involved checking the consistency of each variable to be analysed and refining the data where necessary. Variables analysed in the regression models were determined on the basis of three groups in the database including a thermal questionnaire containing subjective votes and personal variables; calculated indices including averaged physical variables and thermal indices; and outdoor meteorological observations (de Dear, 1998; de Dear *et al.*, 1997).

Table 3.1. Classification of the ASHRAE RP-884 database for naturally ventilated buildings according to climate.

Climate	Survey location and season where applicable	Number of observations	
		Original database	Refined database
Hot-humid	Bangkok; Jakarta; Brisbane summer; Singapore	1682	1673
Hot-dry	Karachi summer and winter; Multan summer; Peshawar summer; Quetta summer; Saidu Sharif summer; Athens summer	4339	2776
Moderate	Melbourne summer; Peshawar winter; Quetta winter; Saidu Sharif winter; Oxford summer; San Francisco summer and winter; Liverpool summer and winter	4044	3213
All		10065	7662

There was no strong justification to suspect error in or by checking other variables against the subjective votes. Detection of vote error would have involved the difficult process of thoroughly tracing each original field survey. Moreover, the adaptive principle underlying our analysis implies the ability to adapt according to situation; hence, thermal responses of the subjects could be varied and subjective in each environment. Nonetheless, one observation with a subjective vote outside its scale, which might have been a data entry error, was omitted.

Data standardization for personal variables and all calculated indices has been conducted by de Dear (1998) and de Dear *et al.* (1997). Such variables included clothing and chair insulation, operative temperature, and standard effective temperature (SET^*). A further check for random error in individual physical measurements resulted in the removal of 27 observations from the database; these were mainly outliers.

A main focus of this study was to determine the statistical relationship between indoor comfort temperature, T_{comf}, and outdoor temperature, T_{out}. The expected linear equation (Eq. 3.1) has outdoor temperature as its independent variable.

$$T_{comf} = bT_{out} + a \qquad (3.1)$$

The original outdoor meteorological data in the database were obtained from various resources and therefore contained a mixture of daily observations and long-term averages (de Dear, 1998; de Dear *et al.*, 1997). We attempted to standardize the outdoor temperature for all observations by using the daily (24-hour) mean outdoor air temperature for each exact survey date and station in the survey location. These data were obtained from Global Surface Summary of Day Data Version 7, which has undergone quality control by the US NOAA National Climatic Data Center (NCDC, 2012). Weather data for Saidu Sharif in addition to several survey dates in Multan, Peshawar, Quetta and Melbourne were not available. Moreover, adaptive equations developed by using the original and newly attached outdoor data differed in some cases due to inconsistency in the original outdoor temperature data. The standardization further allowed us to calculate and examine the various characterizations of outdoor temperature (see Section 3.3.3) from the same data source. For this purpose, outdoor air temperature data of seven sequential days prior to respective survey days and entire survey months were also obtained from NCDC (2012).

The final refined database for analysis consisted of 7662 observations (Table 3.1). Each observation contained both indoor operative temperature and standardized daily mean outdoor air temperature data; other variables may have been missing. The scatter diagram of indoor conditions is illustrated in Figure 3.5, which clearly shows that the indoor conditions in the hot-humid climate were concentrated at indoor operative temperatures higher than 25°C and indoor relative humidity greater than 45% (Figure 3.5). A summary of their descriptive statistics is also given in Table 3.2. Most of the statistical characteristics from the original database were maintained in the refined database for hot-humid and hot-dry climates despite the reduction in observation number.

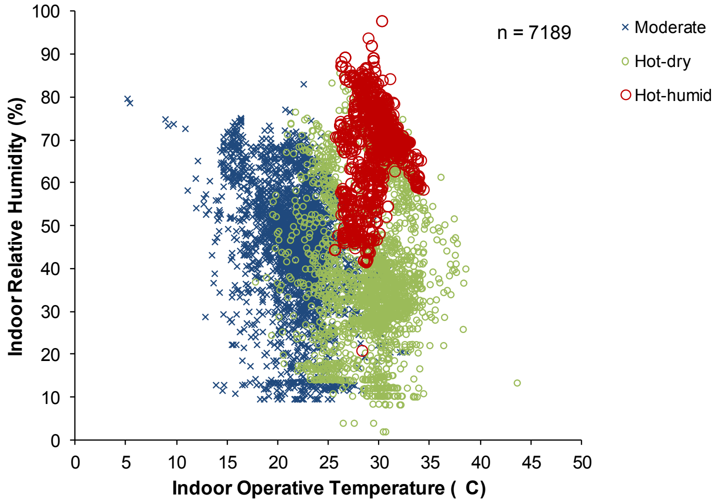


Figure 3.5. Scatter diagram of indoor operative temperatures and indoor relative humidity in the refined database.

Data Analysis

The refined database was then analysed mainly by employing two types of regression models including linear regression and probit regression. Both models used the least-squares method.

The linear regression model related indoor comfort temperatures and outdoor temperatures to provide an adaptive equation that could predict indoor comfort from outdoor conditions (Eq. 3.1). This type of model is commonly used in adaptive comfort analysis for naturally ventilated buildings. However, representations of indoor comfort temperature, generally denoted as T_{comf} in Eq. 3.1, varied among previous studies partly due to its subjectivity, thus yielding no single superior method. For example, de Dear and Brager (1998, 2002), in developing the existing standards, used a binning method and calculated neutral temperature by solving each building’s regression model for a mean sensation of zero. They also used the binning method and fitted probit models to obtain a preferred temperature for each building. Both temperatures were the same in case of naturally ventilated buildings (de Dear and Brager, 2002). However, Nicol and Humphreys (2010) used the Griffiths method to estimate a neutral temperature for every comfort vote that was not zero.

Table 3.3 outlines the available subjective votes in the refined database, which include thermal sensation, thermal preference, and thermal acceptability votes. No thermal acceptability vote was given for hot-humid climate. The indoor temperature at thermal neutrality, which is the observed indoor temperature with a thermal sensation vote equaling zero on the ASHRAE scale, was applied as the indoor comfort temperature in this analysis. This measure was conducted so that the regression line would predict the neutral temperature

Table 3.2. Descriptive statistics of the refined database.

Variable	Hot-humid climate				Hot-dry climate				Moderate climate			
	Min	Max	Mn	SD	Min	Max	Mn	SD	Min	Max	Mn	SD
Indoor air temp. (°C)	24.7	34.2	29.3	1.7	17.4	42.5	29.4	3.1	6.2	31.5	21.9	2.9
Indoor RH (%)	20.9	97.8	67.6	10.5	2.0	85.7	40.5	17.6	9.6	83.1	45.2	13.9
Indoor air speed (m/s)	0.05	2.25	0.27	0.19	0.00	3.72	0.31	0.34	0.00	1.47	0.12	0.17
Indoor MRT (°C)	23.2	34.5	29.4	1.9	17.8	44.7	29.3	3.0	3.7	34.1	21.9	3.1
Indoor operative temp. (°C)	25.6	34.4	29.4	1.8	17.7	43.6	29.4	3.0	5.1	32.7	21.9	3.0
Indoor ET* (°C)	25.4	36.1	30.6	2.4	17.6	37.8	28.9	3.1	5.2	30.9	21.8	2.8
Indoor SET* (°C)	22.8	36.1	29.5	2.6	11.8	38.3	28.6	3.0	10.7	34.5	24.1	2.8
Metabolic rate (met)	0.8	2.6	1.2	0.2	0.6	3.8	1.2	0.4	0.6	3.8	1.2	0.4
Clothing and chair insulation (clo)	0.2	1.1	0.6	0.2	0.2	2.0	0.6	0.3	0.2	2.4	0.9	0.4
Daily mean outdoor air temp. (°C)	19.4	30.5	26.7	2.3	19.1	34.5	26.2	3.7	2.0	27.7	13.5	4.1

Min: minimum; Max: maximum; Mn: mean; SD: standard deviation.

without further data treatment that may have modified thermal adaptation and regression. The Griffiths method (Nicol *et al.*, 2012) was not used because a correct Griffiths coefficient could not be determined with certainty in the present study or in previous research (Humphreys *et al.*, 2007; Nguyen *et al.*, 2012). However, this coefficient would have significantly affected the adaptive equation.

Acceptable comfort limits were analysed with the probit regression model by considering thermal sensation and thermal preference votes. Probit regression analysis is a widely employed statistical method used for data forming a sigmoid response curve such as thermal comfort assessments with unequal increments between scale points (Ballantyne *et al.*, 1977). This method was used in recent studies (Nicol and Humphreys, 2007) for a purpose similar to that of the present study, which was to predict probability of comfort or discomfort as a function of temperature deviation from the comfort temperature. As previously stated, the

Table 3.3. Statistical summary of subjective votes in the refined database.

Climate	Thermal sensation vote, *tsv*[a]			Thermal preference vote, *tpv*[b]			Thermal acceptability vote, *tav*[c]		
	All *tsv*		"Neutral"	All *tpv*		"No change"	All *tav*		"Acceptable"
	n	Mean	n (%)	n	Mean	n (%)	n	Mean	n (%)
Hot-humid	1671	+0.9	332 (20)	992	1.3	207 (21)	0	-	-
Hot-dry	2767	+0.6	1205 (44)	2776	1.6	1223 (44)	1600	1.8	1224 (77)
Moderate	3193	+0.1	1300 (41)	2837	2.0	1617 (57)	374	1.6	213 (57)

[a] *tsv* scale: -3 "cold"; -2 "cool"; -1 "slightly cool"; 0 "neutral"; +1 "slightly warm"; +2 "warm"; +3 "hot".
[b] *tpv* scale: 1 "want cooler"; 2 "no change"; 3 "want warmer".
[c] *tav* scale: 1 "unacceptable"; 2 "acceptable".

definition of comfort temperature differed among existing studies; therefore, the term was used as a general notation in this thesis, particularly when referring to such research. It should be clarified that in the present study, neutral temperature refers to temperatures with neutral thermal sensation votes of zero, and comfortable temperature refers to temperatures with thermal sensation votes of ±1 in the three central categories of the ASHRAE scale. Comfortable temperatures were used to define comfort limits (see Section 3.3.4).

Analyses of both regression models were conducted at the individual observation level with raw data used as a single unit. It was assumed that climate is the major factor influencing occupants' thermal adaptation, which considers location and season as applied to the above data classification. Thus, no further data grouping was determined for statistical analysis. It should be noted that points of grouped bins were plotted in Figures 3.7 and 3.8 only to clarify the illustration. All transverse and longitudinal surveys in the database were treated similarly.

3.3.2 The Adaptive Thermal Comfort Equation

A scatter diagram of observed indoor operative temperatures at thermal neutrality and the corresponding daily mean outdoor air temperatures is presented in Figure 3.6. The existing major adaptive standards (ASHRAE, 2010; BSI, 2008) utilize operative temperature. It is clear that data for each climate have a distinguishable range of daily mean outdoor air temperatures. For hot-humid and hot-dry climates, their daily mean outdoor air temperatures are higher than approximately 20°C and extend to approximately 30°C and 35°C, respectively (Figure 3.6). In contrast, most of the data for moderate climate appear below the daily mean outdoor air temperature of 20°C (Figure 3.6).

The adaptive thermal comfort equations used for predicting neutral temperatures in respective climates are illustrated by discontinuous linear regression lines in Figure 3.6. The comfort temperature lines for naturally ventilated buildings prescribed in ASHRAE Standard 55 (ASHRAE, 2010) and EN15251 (BSI, 2008) are also compared in the figure. The adaptive comfort equations underlying ASHRAE and EN15251 standards are:

$$T_{\text{comfop}} = 0.31T_{\text{outmm}} + 17.8 \quad (3.2)$$

$$T_{\text{comfop}} = 0.33T_{\text{outrm}} + 18.8 \quad (3.3)$$

respectively, where T_{comfop} is indoor comfort operative temperature (°C), T_{outmm} is monthly mean outdoor air temperature (°C), and T_{outrm} is running mean outdoor air temperature (°C) (de Dear and Brager, 2002; Nicol and Humphreys, 2010). Both equations share nearly the same regression coefficients (gradient). It is considered that both standards suggest a change in indoor comfort temperature per unit change of the outdoor temperature at a similar rate. The EN15251 equation consistently predicts a higher comfort temperature than that of the ASHRAE equation by 1°C (Figure 3.6).

The regression lines for hot-humid, hot-dry and moderate climates are defined by the following equations, respectively:

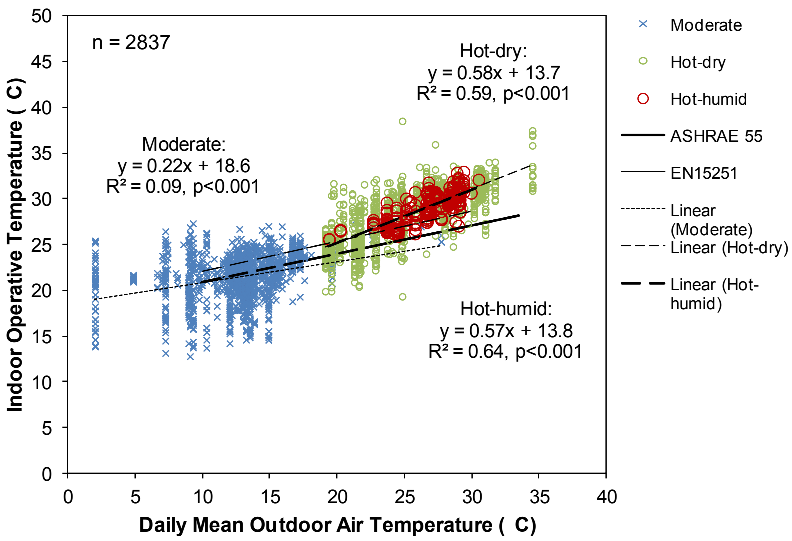


Figure 3.6. Scatter diagram of indoor operative temperatures at thermal neutrality and daily mean outdoor air temperatures. Discontinuous lines denote linear regression models used in this study and represent adaptive equations for predicting neutral temperatures.

$T_{neutop} = 0.57T_{outdm} + 13.8$ (3.4)

$T_{neutop} = 0.58T_{outdm} + 13.7$ (3.5)

$T_{neutop} = 0.22T_{outdm} + 18.6$ (3.6)

where T_{neutop} is indoor neutral operative temperature (°C) and T_{outdm} is daily mean outdoor air temperature (°C) (Figure 3.6). All are significant at the 0.1% level. As indicated, these regression lines differ among themselves and from those of the standards in terms of their gradients and the outdoor temperature ranges (Figure 3.6). Compared with the ASHRAE adaptive equation, the regression lines for hot-humid and hot-dry climates are nearly twice as steep with regression coefficients close to 0.6. The regression line for moderate climate, which covers lower outdoor air temperatures, shows a slightly lower regression coefficient than that of ASHRAE (Figure 3.6). Within the observed daily mean outdoor air temperature ranges, these equations predict neutral operative temperatures of 24.9-31.2°C, 24.8-33.7°C and 19.0-24.7°C for hot-humid, hot-dry and moderate climates, respectively. The analysis of variance (ANOVA) reveals a significant mean difference of $F(2, 2834) = 2525.12$, $p<0.001$. This result supports our hypothesis such that climate is a major influence on the thermal adaptation of occupants in naturally ventilated buildings.

This result also implies that people living in hot climates, particularly regions with daily mean outdoor air temperatures higher than 20°C, adapt to a wider and higher range of indoor operative temperatures relative to the same magnitude of outdoor air temperature increases than those living in colder climates. These statistical findings reveal that the ability of adapting to obtain thermal neutrality in naturally ventilated buildings differs among climatic zones, likely due to different adaptation needs and opportunities. In particular, the adaptive equations for hot-humid and hot-dry climates differ markedly from current major adaptive standards (ASHRAE, 2010; BSI, 2008), which implies that the standards predict neutral operative temperature that do not match the occupants' thermal neutrality in warm conditions. The predicted neutral operative temperatures appear to be analogous in hot-humid and hot-dry climates. Nevertheless, the contributory thermal adaptation processes of occupants in both climates may differ. This aspect is investigated further in Section 3.3.5 by considering the varied effects of indoor air speed and humidity.

3.3.3 Characterization of Outdoor Air Temperature

Three methods of characterizing the outdoor air temperature in the adaptive equations, noted in Section 3.3.2, include monthly mean outdoor air temperature (ASHRAE, 2010), running mean outdoor air temperature (BSI, 2008) and daily mean outdoor air temperature (present analysis). Researchers' interest of these characterizations is related to the role of past thermal experiences on occupants' responses. The sensitivity of these temporal averaging techniques and the recently introduced prevailing mean outdoor air temperature (ASHRAE, 2012) to the above adaptive equations is analysed in Table 3.4. Equations for the daily mean are obtained from Figure 3.6 and Eqs. 3.4-3.6.

As described in Section 3.3.1, the daily mean is the 24-hour average of the observed outdoor air temperatures for each day with a minimum of four observations per day (NCDC, 2012). The monthly mean follows the definition given by ASHRAE (2010), which is the average of the mean daily minimum and mean daily maximum outdoor air temperatures for the survey month. The running and prevailing means are calculated by using the above-mentioned daily mean outdoor air temperatures of seven sequential days prior to the survey date. The prevailing mean is a simple arithmetic mean of the temperatures (ASHRAE, 2012). The running mean is defined as an exponentially weighted average of previous days' daily mean air temperatures in a series (Nicol and Humphreys, 2010). This value puts greater weight on the temperature for days closer to the present by assuming that more recent experiences are more influential in a person's thermal history. In this study, the running mean is calculated by using the formula given in EN15251 (BSI, 2008) at 0.8 exponential weight:

$$T_{outrm} = (T_{outdm-1} + 0.8T_{outdm-2} + 0.6T_{outdm-3} + 0.5T_{outdm-4} + 0.4T_{outdm-5} + 0.3T_{outdm-6} + 0.2T_{outdm-7}) / 3.8 \quad (3.7)$$

where $T_{outdm-1-7}$ is the daily mean outdoor air temperature for the first previous day through the last seven days.

Table 3.4 reveals all equations predict similar neutral operative temperatures for hot-humid climate. The adaptive equation based on the daily mean outdoor air temperature shows the highest coefficient of determination (R^2) and predicts at least 10% more variability in the neutral operative temperature compared with other characterizations. For hot-dry and moderate climates, the adaptive equations based on all outdoor air temperature characterizations show similar coefficients of determination (Table 3.4). These results imply that consideration of acclimatization to outdoor air temperatures of previous days is not necessarily superior to predicting thermal responses of occupants in all climates. This finding is in agreement with two statements reported in previous studies. The first is that the process of acclimatization is slow and less influential than other adaptive processes; however, expectations based on past thermal experiences occur on time scales of weeks to months that translate into seasonal processes (Brager and de Dear, 1998). The second is that adaptive comfort equations and the strength of the equations are not very sensitive to the exponential weight of the running mean outdoor temperature, which was determined by Nicol and Humphreys (2010) through statistical analysis of the SCATs database. These statements imply that adaptation related to thermal history is covered more effectively in the climate classification that considers season than in that considering the previous week's outdoor temperatures. The dependence on previous days' acclimatization in the hot-humid climate is

Table 3.4. Adaptive equation for different characterizations of the outdoor air temperature.

Outdoor air temperature	Hot-humid climate			Hot-dry climate			Moderate climate		
	Adaptive equation	R^2	Sig.[a]	Adaptive equation	R^2	Sig.[a]	Adaptive equation	R^2	Sig.[a]
Daily mean, T_{outdm}	$T_{neutop} = 0.57T_{outdm} + 13.8$	0.64	***	$T_{neutop} = 0.58T_{outdm} + 13.7$	0.59	***	$T_{neutop} = 0.22T_{outdm} + 18.6$	0.09	***
Monthly mean, T_{outmm}	$T_{neutop} = 0.53T_{outmm} + 14.5$	0.51	***	$T_{neutop} = 0.56T_{outmm} + 14.3$	0.60	***	$T_{neutop} = 0.18T_{outmm} + 19.3$	0.08	***
Running mean, T_{outrm}	$T_{neutop} = 0.55T_{outrm} + 14.2$	0.54	***	$T_{neutop} = 0.63T_{outrm} + 12.4$	0.59	***	$T_{neutop} = 0.33T_{outrm} + 17.4$	0.09	***
Prevailing mean, T_{outpm}	$T_{neutop} = 0.54T_{outpm} + 14.6$	0.53	***	$T_{neutop} = 0.60T_{outpm} + 13.0$	0.58	***	$T_{neutop} = 0.35T_{outpm} + 17.1$	0.09	***

Sig.: significant level.

[a] ***0.1% significant level; **1% significant level; *5% significant level.

even likely less due to the small changes in its daily outdoor weather conditions over the entire year.

These results imply that the choice of an appropriate outdoor air temperature length and averaging technique for predicting thermal neutrality in naturally ventilated buildings for most climates can be based on practical factors such as data availability and application. The daily mean and monthly mean may be used in standards that guide building design and post-occupancy evaluation because a time lapse is required to gather the day's or month's data. The running mean and prevailing mean would be useful for real-time monitoring of buildings such as those involving adaptive controls. Nonetheless, the daily mean outdoor air temperature has been used throughout this study because the study objective is to develop an equation that can be used as a standard for hot-humid climate.

3.3.4 Acceptable Comfort Limits

An acceptable range of temperature deviation from the predicted neutral operative temperature (Eqs. 3.4-3.6) for each climate is analysed in Figures 3.7 and 3.8 by using probit models in consideration of the thermal sensation votes and thermal preference votes, respectively. For thermal sensation votes, probit analysis is first used to predict the proportion of thermal sensation votes for each category less than a particular value (left side of Figure 3.7). The proportion of occupants voting "neutral" (0) is then taken as the difference between the proportions of votes of 0 or less and less than 0. The proportion of occupants voting “comfortable” (±1) is the difference between the proportions of votes of 1 or less and less than -1 (right side of Figure 3.7).

Figure 3.7a shows that the proportion of occupants voting “neutral” does not exceed 30% and peaks at approximately 1°C lower than the neutral operative temperature for hot-humid climate. The probit line for “comfortable” thermal sensation, which includes “slightly cool," “neutral,” and “slightly warm,” or -1, 0, +1, respectively, is one-tailed and has no symmetry within the observed temperature range (Figure 3.7a). The proportion of occupants who voted “comfortable” increases from 30% at 2.5°C higher than the predicted neutral temperature to 86% at 2°C below the predicted neutral temperature (Figure 3.7a). Eighty percent “comfortable” votes are predicted at 0.7°C less than the neutral temperature for hot-humid climate.

In comparison, at least 80% of the occupants voting “comfortable” appear within temperature deviations of approximately 2°C above and 6°C below the predicted neutral temperature for hot-dry climate (Figure 3.7b) and approximately 1.5°C above and 2.5°C below that for moderate climate (Figure 3.7c). The results show that the acceptable comfort ranges are asymmetric and lean toward operative temperatures below thermal neutrality for all climates. Ninety percent “comfortable” votes are not predicted by the probit models in all climates (Figure 3.7). The comfortable temperature range is largest for hot-dry climate, at 8°C for 80% of “comfortable” votes, likely because adapting to a wider temperature range is easier when humidity is low.

Analysis of the thermal preference votes in Figure 3.8 provides similar results. In the figure, preferred temperature is observed at the intersection of the two probit lines that represent “want cooler” and “want warmer” votes. Preferred temperatures for hot-humid and hot-dry climates appear at 2.5°C and 3.5°C below the neutral operative temperatures, respectively (Figure 3.8ab). The highest proportions of occupants voting “no change” also occur at temperatures below thermal neutrality for both climates (Figure 3.8ab). The result clearly agrees with the concept such that although occupants adapt to higher neutral temperatures in hot climates, as discussed previously, they prefer cooler conditions (Humphreys and Nicol, 2004). Figure 3.8c indicates that the preferred temperature nearly matches the neutral temperature for moderate climate, which is similar to the findings reported by de Dear and Brager (2002). Nevertheless, the probit line fitted to the “no change” votes shows a slightly skewed curve similar to that of the “comfortable” sensation votes, albeit at a lower proportion (Figures 3.8c and 3.7c).

We have inferred from the analysis that the upper and lower comfort limits must be considered separately for each climate. These limits could be determined on the basis of thermal sensation votes; thermal preference votes show similar patterns. Currently, both the ASHRAE and EN15251 adaptive standards provide symmetrical limits of ±2-4°C away from the comfort temperature for various categories of occupant acceptability or buildings (ASHRAE, 2010; BSI, 2008). The comfort limits for each climate could be determined from Figure 3.7a-c for the respective percentages of “comfortable” votes. In particular, a lower comfort limit is not observed for naturally ventilated buildings in hot-humid climate. The

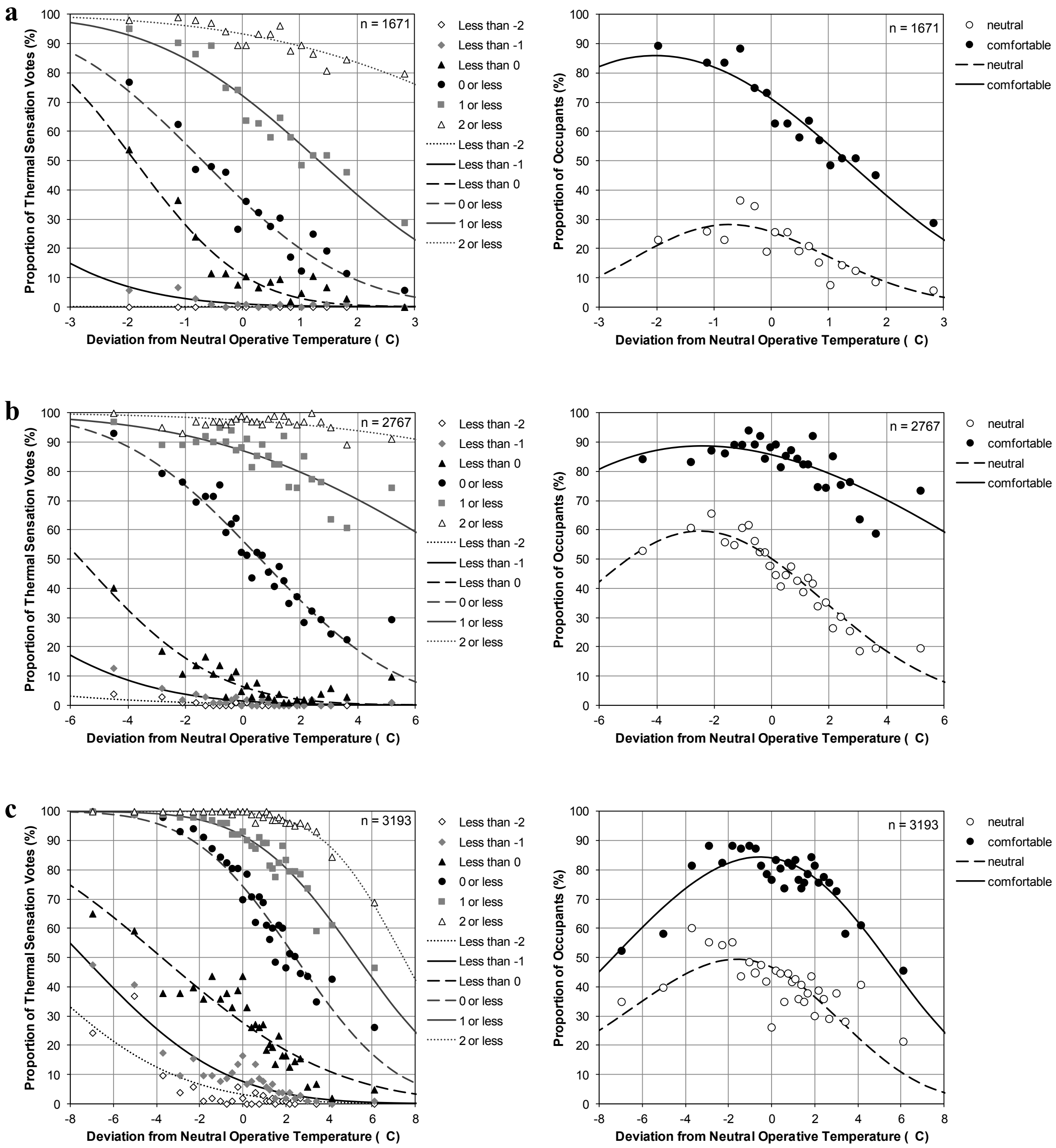


Figure 3.7. Proportion of thermal sensation votes (left) and proportion of occupants voting "neutral" (0) and "comfortable" (±1) (right) as a function of deviation from the predicted neutral operative temperature. (a) Hot-humid climate; (b) Hot-dry climate; (c) Moderate climate. Lines indicate probability predicted by probit regression models. Points represent observed values for equal bins of the temperature deviation (102-105 data per bin). In the left figure, dashed lines and black points represent "neutral" votes (0); continuous lines and grey points represent "comfortable" votes (±1).

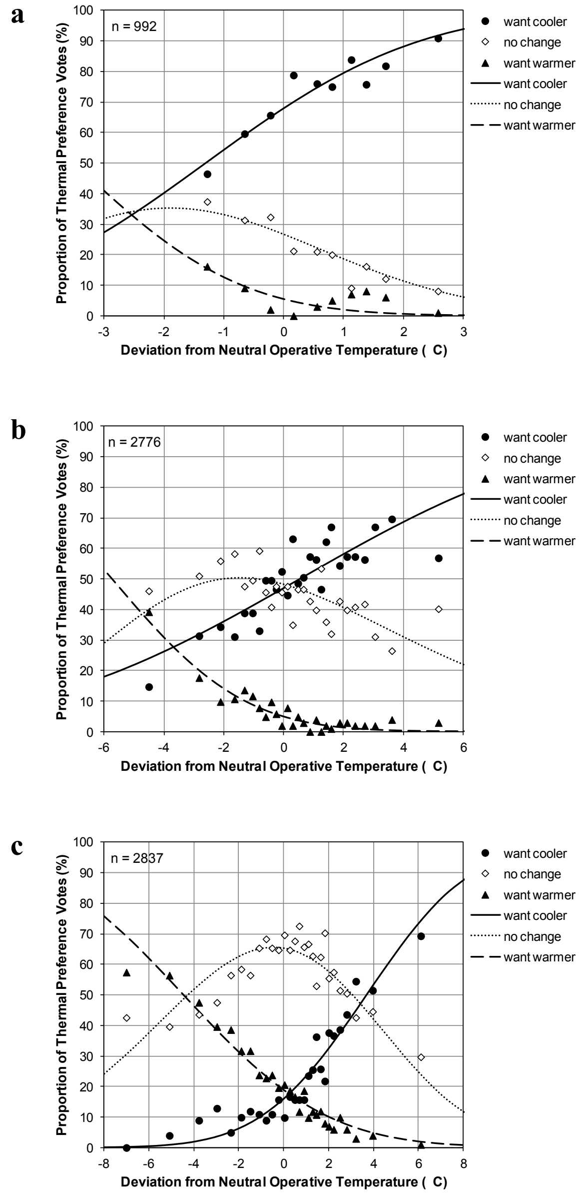


Figure 3.8. Proportion of thermal preference votes as a function of deviation from the predicted neutral operative temperature. (a) Hot-humid climate; (b) Hot-dry climate; (c) Moderate climate. Lines indicate probability predicted by probit regression models. Points represent observed values for equal bins of the temperature deviation (99-103 data per bin).

upper comfort limit for this climate is recommended to not exceed 0.7°C below the predicted neutral operative temperature so that at least 80% of the occupants would be in comfort. The 80% "comfortable" votes follow the acceptability level for typical applications in the ASHRAE adaptive standard (ASHRAE, 2010). Further studies to confirm whether 80% acceptability is appropriate for the adaptive model in various climates are encouraged.

3.3.5 Effects of Indoor Air Speed and Humidity

As discussed in Section 3.3.2, the adaptive thermal comfort equations for hot-humid and hot-dry climates are steeper than that for moderate climate. Previous studies of naturally ventilated buildings in hot-humid climate indicate that comfort temperatures voted by respondents increase with higher indoor air speeds (Cândido *et al.*, 2011; Khedari *et al.*, 2000; Mallick, 1996; Wijewardane and Jayasinghe, 2008) (see Section 3.2.2). As previously mentioned, Nicol (2004) has suggested that outdoor relative humidity influences indoor comfort temperatures. In this section, we analyse the indoor air speed and indoor humidity levels as two possible factors affecting the thermal adaptation in hot-humid and hot-dry climates.

The effects of indoor air speed on the adaptive equations are analysed in Figure 3.9. In the figure, the data are categorized into three groups of indoor air speeds including low (<0.3 m/s), moderate (0.3 to <0.65 m/s) and high (≥0.65 m/s). As mandated in the ASHRAE addendum (ASHRAE, 2012) and in EN15251 (BSI, 2008), increased air speed may be applied to elevate the upper comfort temperature limit when indoor operative temperatures exceed 25°C. This temperature marks the lower end of the regression lines for the hot climates in Figure 3.6. The air speed allowance is obviously targeted to hot climates, although no distinction between hot-humid and hot-dry climates is mentioned in the standards.

Figure 3.9a shows similar linear regression lines for low and moderate air speeds that maintain regression coefficients at 0.5-0.6 for hot-humid climate. These regression lines predict that moderate air speed has little to no effect on neutral temperatures compared with low air speed. Still air conditions (0 m/s) do not generally occur in naturally ventilated buildings in hot-humid climate (Table 3.2). The regression line for high air speed is steeper and higher than that for low air speed by up to approximately 2°C at 29°C daily mean outdoor air temperature (Figure 3.9a). The analysis of variance also reveals a significant mean difference of $F(2, 309) = 4.52$, $p<0.05$. These results imply that air movement is likely a possible factor for increasing the gradient of the adaptive equation for hot-humid climate. Occupants in the hot-humid climate likely adapt to neutral temperatures by making use of air movement at all times to aid evaporative heat loss in indoor high-humidity conditions.

For hot-dry climate, the analysis of variance shows a significant mean difference among the air speed groups. Nevertheless, the regression lines predict no constant increase in indoor neutral operative temperature at moderate and high air speeds when compared with low air

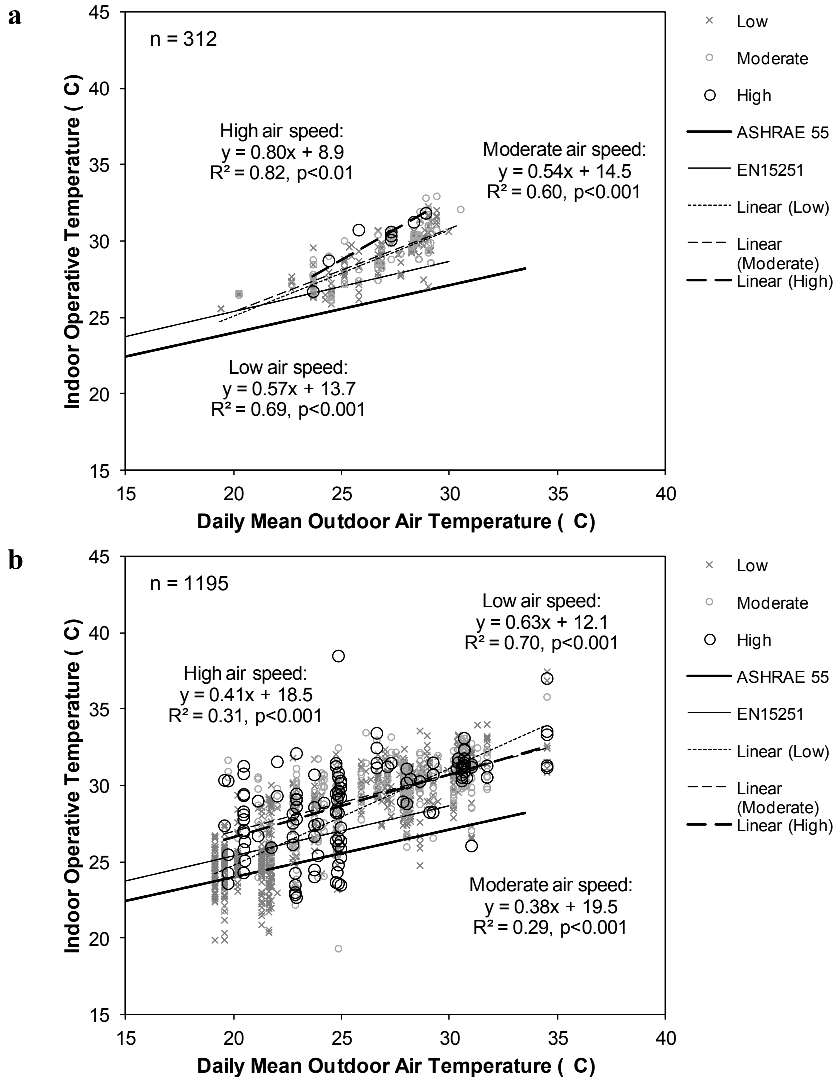


Figure 3.9. Scatter diagram of indoor operative temperatures at thermal neutrality and daily mean outdoor air temperatures at various indoor air speeds. (a) Hot-humid climate; (b) Hot-dry climate.

speed (Figure 3.9b). This result emphasizes that the thermal adaptation processes of occupants in dry air conditions differ in humid air conditions at high temperatures. Increased air speed allowance is not applicable to hot-dry climate.

Figure 3.10 further illustrates the effects of indoor relative humidity on the adaptive equations for the two hot climates. Low relative humidity represents values below 60%; high relative humidity represents the remaining values. Figure 3.10b shows that for hot-dry climate, the regression line for low relative humidity predicts higher neutral operative

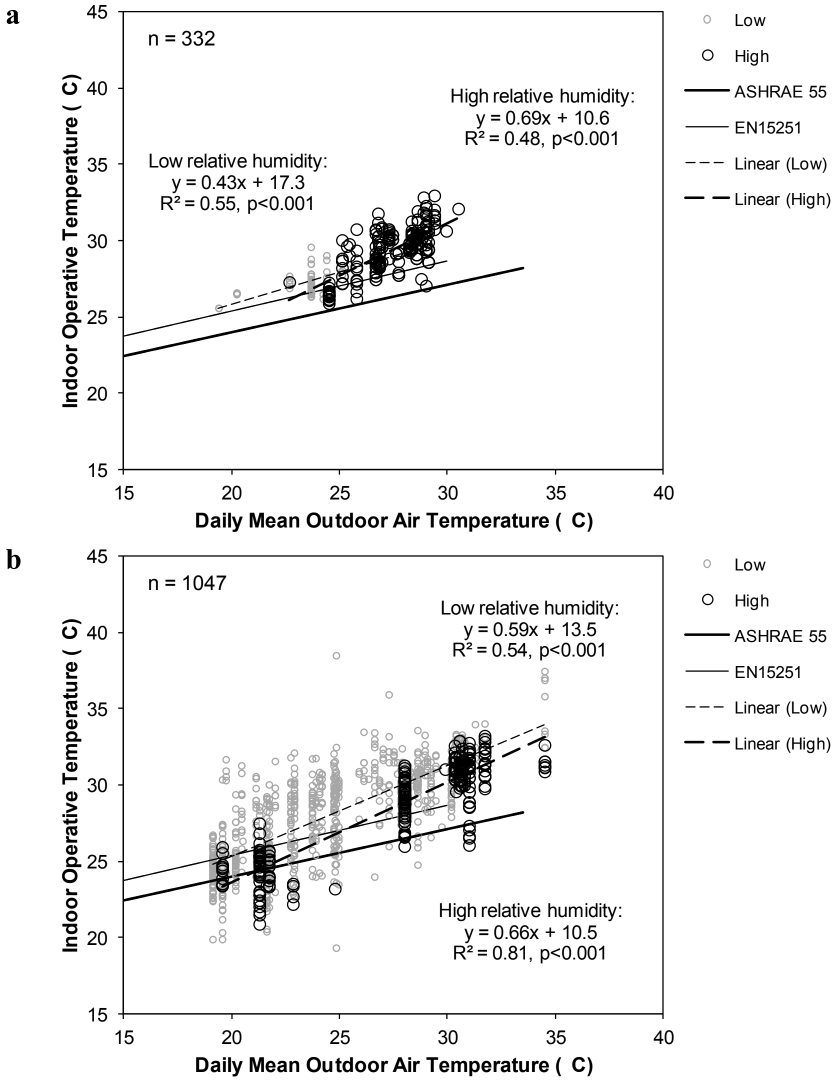


Figure 3.10. Scatter diagram of indoor operative temperatures at thermal neutrality and daily mean outdoor air temperatures at various percentages of indoor relative humidity. (a) Hot-humid climate; (b) Hot-dry climate.

temperatures than for high relative humidity by 0.6-1.7°C. The analysis of variance shows a significant mean difference of $F(1, 1045) = 9.29$, $p<0.01$. The indoor relative humidity values show these effects likely because they are evaluated at respective temperatures and indirectly account for the effect of water vapour pressure on evaporation. A similar effect is not apparent in the regression lines for hot-humid climate (Figure 3.10a), although a significant mean difference is obvious. Indoor relative humidity is high (≥60%) more than

75% of the time in hot-humid climate. This result indicates that humidity influences the predicted neutral temperature in hot-dry climate but not in hot-humid climate.

It is concluded that a thermal comfort standard for naturally ventilated buildings in hot-humid climate should consider occupants' thermal adaptation to various indoor air speeds. Within the limitation of the study analysis, the adaptive equation developed in Section 3.3.2, Eq. 3.4, is proposed because of its closeness to the regression lines for low and moderate air speeds, which are dominant values in the database. It is considered that a minimum indoor air speed of 0.65 m/s is required to increase the neutral operative temperature predicted by this adaptive equation. Further research to develop an increased air speed allowance for hot-humid climate will be useful.

3.3.6 The Proposed Thermal Comfort Criteria and Concluding Remarks

The statistical meta-analysis of the ASHRAE RP-884 database by climate highlights several key differences in the thermal adaptation of occupants in naturally ventilated buildings among climates and the existing standards (ASHRAE, 2010; BSI, 2008). These differences are summarized in the following points:

1. The adaptive equations for hot-humid and hot-dry climates are analogous with regression coefficients of approximately 0.6, which are nearly twice those of existing standards. The adaptive equation for moderate climate has a slightly lower regression coefficient than those of the existing standards. Moreover, people in hot climates adapt to higher neutral operative temperatures.

2. The adaptive equation based on the daily mean outdoor air temperature has the highest coefficient of determination for hot-humid climate. For hot-dry and moderate climates, the adaptive equations based on all outdoor air temperature characterizations show similar coefficients of determination. Acclimatization of previous days is less important in predicting occupants' thermal responses in hot-humid climate.

3. The proportion of occupants voting "comfortable" increases from 30% at 2.5°C above the predicted neutral temperature to 86% at 2°C below the predicted neutral temperature for hot-humid climate. A lower comfort limit is not observed in hot-humid climate. Acceptable comfort ranges also show asymmetry and lean towards operative temperatures below thermal neutrality for hot-dry and moderate climates.

4. Air movement is a possible factor for increasing the gradient of the adaptive equation for hot-humid climate. In contrast, indoor relative humidity influences the adaptive equation for hot-dry climate.

The proposed adaptive thermal comfort criteria for naturally ventilated buildings in hot-humid climate based on the present study findings are summarized in Table 3.5. The proposed criteria are used throughout this thesis to evaluate thermal performance of passive cooling techniques. This study also anticipates that the proposed criteria can be used as a thermal comfort standard for tropical climates and hot-humid summer seasons of temperate climates and may form an energy-saving building standard for Malaysia. Further studies are recommended, particularly to determine suitable percentages of occupants in comfort, to develop an increased air speed allowance and to verify the applicability of these criteria to the driest month in the tropical savannah climate.

Table 3.5. Proposed adaptive thermal comfort equation and related criteria for naturally ventilated buildings in hot-humid climate.

No.	Aspect	Criterion	Note
(i)	Climate type	All A climate types; and Summer season of Cfa climate type.	Climate type refers to the Köppen-Geiger climate classification system.
(ii)	Neutral operative temperature, T_{neutop} (°C)	$T_{neutop} = 0.57T_{outdm} + 13.8$	T_{outdm} is daily mean outdoor air temperature (°C), i.e. the 24-hour arithmetic mean for the day in question.
(iii)	Daily mean outdoor air temperature, T_{outdm} (°C)	Range from 19.4 to 30.5.	Recommended applicable range for criterion no. (ii).
(iv)	Lower comfort operative temperature limit, T_{lower} (°C)	No required limit.	-
(v)	Upper comfort operative temperature limit, T_{upper} (°C)	$T_{upper} = T_{neutop} - 0.7$ for 80% comfortable thermal sensation votes.	Graphical representation can be referred in Figure 3.7a (continuous line in the right figure) for a different percentage of comfortable thermal sensation votes.
(vi)	Indoor air speed, v (m/s)	<0.65 at and below neutral operative temperature; ≥0.65 above neutral operative temperature.	Recommended to provide non-still air and occupants' control to adjust the indoor air speeds according to their preferences.
(vii)	Indoor humidity, RH (%)	No required limit.	-

4

Existing Terraced Houses in Malaysia

In this chapter, we look into some aspects of the existing housing situation in Malaysian urban areas. We begin with an overview of the existing housing stock based on national data and analyses of typical terraced house plans and construction materials based on design documents (Section 4.1). Results from two social surveys conducted in terraced housing areas reveal current behaviour related to cooling and energy consumption among households (Section 4.2). We conducted a full-scale field experiment in two existing typical terraced houses to evaluate effects of ventilative cooling on the indoor thermal environments. The cooling potential of night ventilation for the terraced house is shown based on the results of this field experiment (Section 4.3).

4.1 The Existing Housing Stock

4.1.1 National Distribution and Trends

Most urban residential areas in Malaysia are composed of homogenous large-scale housing estates and terraced houses are the most common housing type (Figure 4.1). According to the most recent nationwide census conducted in 2010, terraced houses accounted for 42% of all housing units in urban areas (Department of Statistics Malaysia, 2012) (Figure 4.2). Its existing stock totaled close to 2.3 million units as of 2010 (Department of Statistics Malaysia, 2012). A terraced house refers to any residential building designed as a single dwelling unit and forming part of a row or terrace of not less than three such residential buildings (Legal Research Board, 2012). It usually has a narrow frontage and shares party walls with adjacent houses. The same census revealed that 93% or more than 2.1 million units of these urban terraced houses were constructed using bricks for their

Figure 4.1. Typical modern terraced houses in Malaysia. (a) Double-storey; (b) Single-storey.

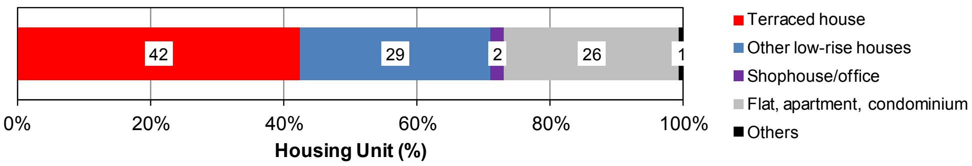


Figure 4.2. Housing unit by house type in the urban areas of Malaysia in 2010. Source: Department of Statistics Malaysia, 2012.

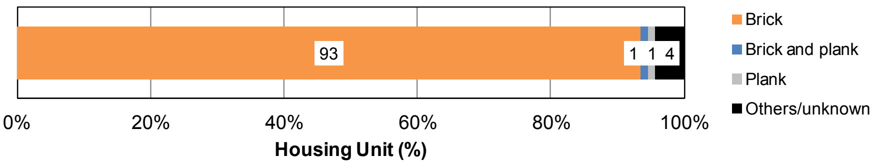


Figure 4.3. Housing unit by construction material of outer walls for terraced houses in the urban areas of Malaysia in 2010. Source: Department of Statistics Malaysia, 2012.

outer walls (Figure 4.3). Overall, 85% of all types of housing units in urban areas used bricks and another 5% used brick and plank for their outer walls (Department of Statistics Malaysia, 2012). Brick and concrete are modern building construction materials that have replaced timber, which was used in the wall construction of almost two-thirds of the living quarters in Peninsular Malaysia back in 1970 (Chander, 1979).

The national distribution of housing units by house type and state in 2010 showed that terraced houses formed the majority of the urban housing stock in most states (Department of Statistics Malaysia, 2012) (Figure 4.4). Its percentage was highest in Negeri Sembilan (62%) followed by Johor (60%). Johor Bahru, which is the capital city of Johor, is considered to have huge number of terraced houses and offers us a good location for studying this house type. Exceptional cases where medium and high-rise residential buildings including flats, apartments and condominiums outnumbered terraced houses were

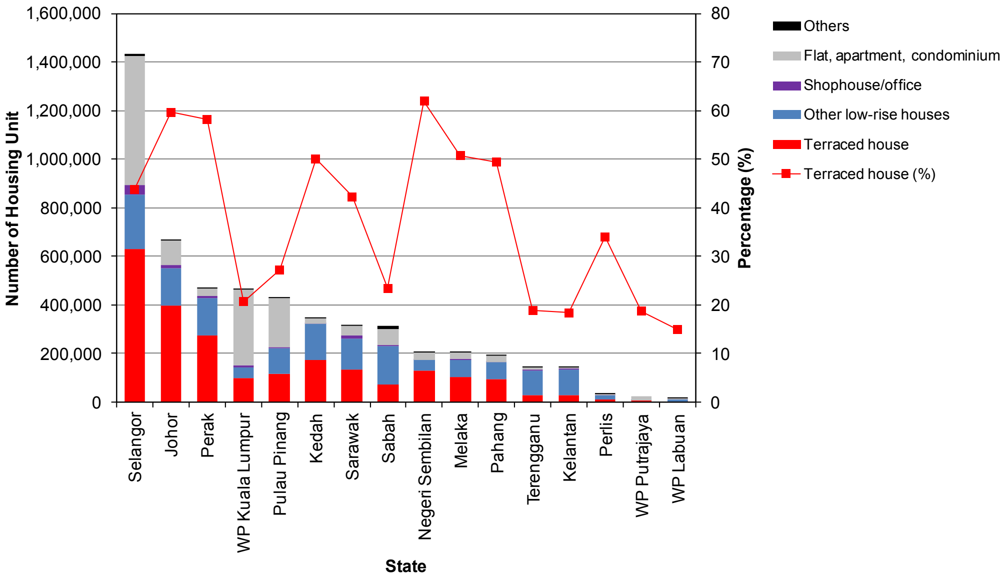


Figure 4.4. Distribution of the urban housing units and percentage of terraced houses in the states of Malaysia in 2010. Source: Department of Statistics Malaysia, 2012.

seen only in WP Kuala Lumpur, Pulau Pinang and WP Putrajaya (Figure 4.4). The population densities in these states at 6891, 1490 and 1478 persons/km^2, respectively, were clearly much higher than the national average of 86 persons/km^2 for the same year (Department of Statistics Malaysia, 2011a). More than half (53%) of the terraced houses in Malaysia were 2-3 storey buildings and the remaining terraced houses were single-storey buildings as of the first quarter of 2012 (NAPIC, 2012).

4.1.2 Classification of Typical House Plans

In this study, we analysed typical terraced houses according to their floor plans which were collected in two phases, i.e. in January-February 2007 (Toe, 2008) and May-September 2012. The sample plans were obtained from major housing developer offices and websites in Johor and Selangor, local authorities in Johor, and national housing magazines (Housing and Property, 1975-1978). The sample comprised 219 plans in the following composition by their development years: 1960s (1%); 1970s (21%); 1980s (8%); 1990s (17%); and 2000 onwards (53%). We were unable to locate the housing stock distribution by development year based on national data. Nevertheless, the sample spread from probably the earliest modern terraced houses up to new terraced houses scheduled to be constructed in the coming two years. In general, it is known that modern terraced houses have existed in Malaysia for about more than fifty years (Sudin, 2012).

Two methods of house classification were attempted in this study. The first method was similar to that documented in Toe (2008). The classification focused on the internal layout and total floor area of each plan. Total floor area was defined as the gross floor area, i.e. the total internal space area including stairs, hallways, thickness of internal walls or other interior features, as measured from the inside surface of the external walls (Harris, 2006). It was found that there was no significant difference in the building structure and construction materials used in the sample. In Figure 4.5, the internal layout is organized into four types for single-storey terraced houses and another five types for double-storey terraced houses. Few plans were three-storey terraced houses from recent developments. They had relatively large floor areas. They are not drawn in this figure. The typical layout type for the double-storey terraced houses has total floor areas between about 90 and 230 m^2 per house unit (Figure 4.5). Both typical layout groups for the single-storey and double-storey terraced houses contained plans from various development years. It should be noted that the low-cost terraced house and the one and a half-storey terraced house are variations of the single-storey and double-storey terraced houses.

The second classification method was done with interest in courtyard application. Our field observation and collection of floor plans revealed that the small courtyard, also known

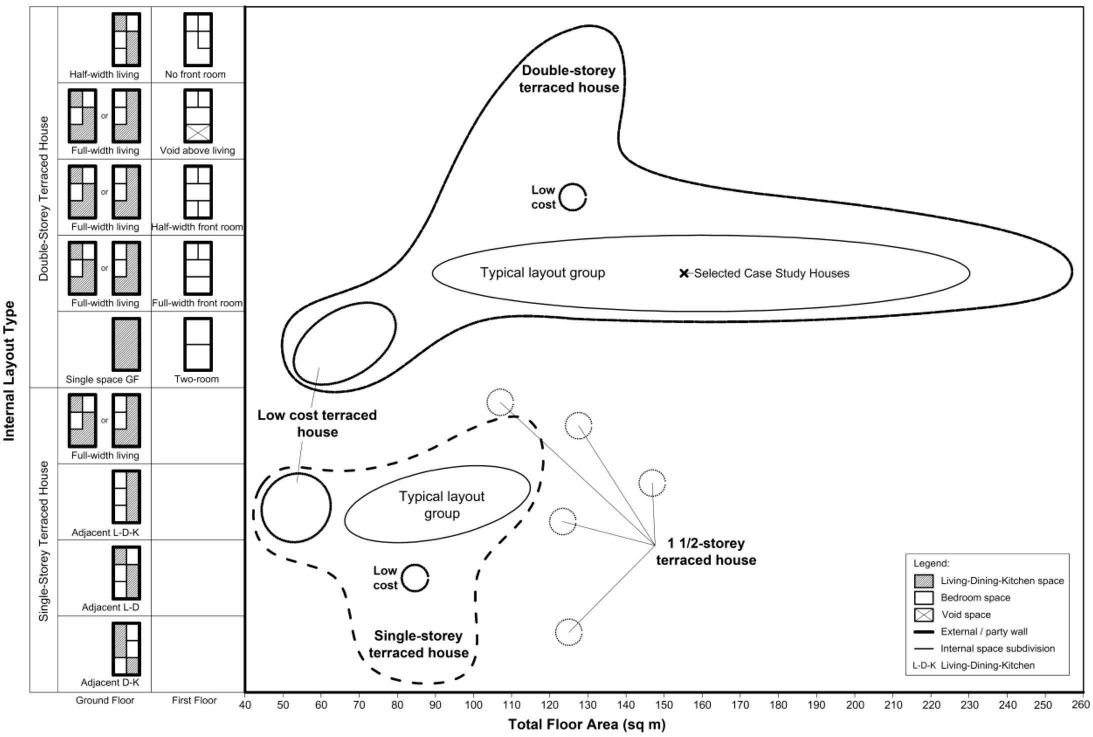


Figure 4.5. Classification of Malaysian terraced houses by internal layout and total floor area. Source: Updated from Toe (2008).

as air-well, was used in the past particularly in single-storey terraced houses. Its main function was to provide middle rooms with daylighting and ventilation opening as required by the building by-law (Sudin, 2012). It is less commonly used nowadays. Unlike the traditional Chinese shophouse (see Chapter 5: Section 5.1), few of the double-storey and three-storey terraced houses were designed with an internal courtyard. Details of this classification are explained further in Chapter 7: Section 7.2.1 after we examine the thermal performance of the courtyards in the traditional Chinese shophouses.

4.1.3 Common Building Materials and Material Data

According to the specifications given in the same sample plans that we used for the analysis in Section 4.1.2, most of the terraced houses were constructed of similar building materials which included reinforced concrete structures and brick walls. As expected, the information is consistent with the national data shown in Figure 4.3. Table 4.1 outlines these common building materials used for the main building structures. Other less common materials are also listed. On the other hand, we could find very little information on the thermal properties of the materials used for the terraced houses even from the material companies. Available data were mainly material densities in most cases. Our interest in

Table 4.1. Common building materials for the existing terraced houses in Malaysia.

Building structure	Material	
	Common material	Other material
Column, beam and floor structures	Reinforced concrete	-
Walls	Clay brick and cement/sand brick with cement plaster and paint	Reinforced concrete
Roof structures	Timber (hardwood) truss	Steel truss
Roofing	Concrete roof tile (main roof)	Clay roof tile, metal deck (main roof); Reinforced concrete flat roof, corrugated roof sheet, polycarbonate roof sheet (usually portion of roof only)
Ceiling	Asbestos free fibre-cement board	Plasterboard
Windows	Glass window with aluminium frame	Metal and timber frames
Flooring	Ceramic tile and cement screed	Mosaic, parquet, terrazzo, vinyl tile (for early terraced houses); timber flooring

knowing the material thermal properties is in part to assist our numerical modelling of the case study typical modern terraced house (see Chapter 6: Section 6.3.2) and experimental houses in the near future.

In order to fill this data gap, we collated data on the thermal conductivity, density and specific heat capacity of eight categories of the common building materials, namely brick, mortar, cement plaster, cement screed, ceramic tile, concrete slab, timber and fibre-cement board, from several reference books (AIJ, 1978, 1984, 1995, 2001, 2007, 2011; ASHRAE, 2009; Bradshaw, 1993; Chrenko, 1974; Givoni, 1976, 1998a; Hassid and Geros, 2006; Koch-Nielsen, 2002; Krigger and Dorsi, 2009; Lechner, 2009; Littlefield, 2012; Markus and Morris, 1980; McMullan, 2002; Miyano, 1981; Shimazu *et al.*, 2001; Szokolay, 2008; Ward-Harvey, 2009; Watson, 2000). In general, it is known that the conductivity increases with the density of the material except for very lightweight insulating materials (Givoni, 1998a). Figure 4.6 shows that the relationship between the thermal conductivity and the density of the selected materials in this study is:

$$\lambda = 0.2351 \exp 0.0014\rho_m \qquad (4.1)$$

where λ is thermal conductivity (kJ/hmK) and ρ_m is density of material (kg/m^3). This relationship is in close agreement with that given in Givoni (1998a) for masonry materials.

Figures 4.7 and 4.8 summarize the density and specific heat capacity data of the same material sample. In addition, densities of Malaysian materials that we gathered from various measured or official data (Arman Ali, 2005; Firebrick Industries, 2012; Kim Hin Industry,

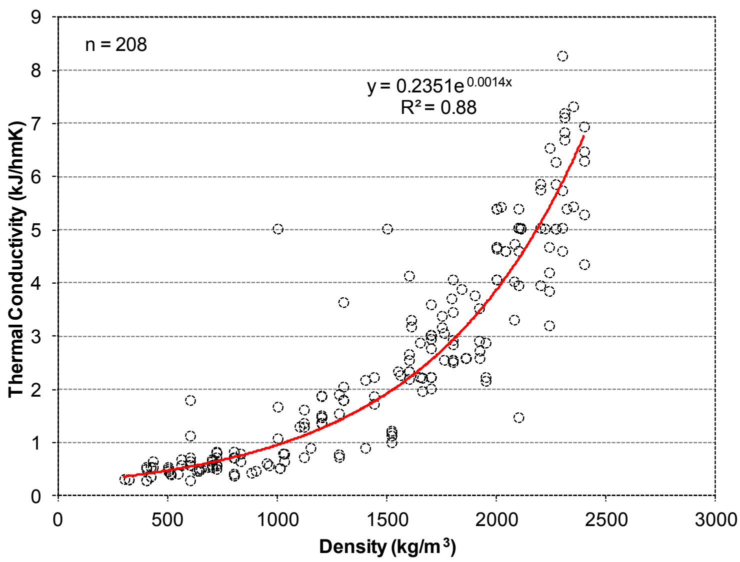


Figure 4.6. Relationship between thermal conductivity and density of the selected building materials from reference books.

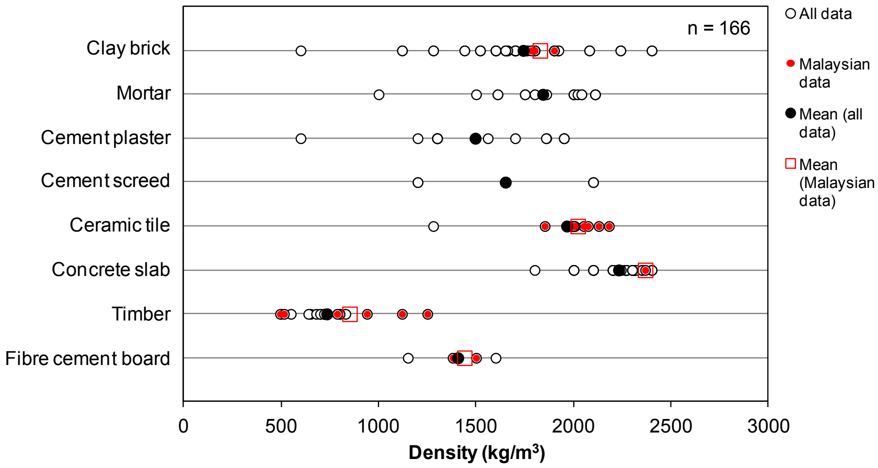


Figure 4.7. Density of the selected building materials from reference books and Malaysian data.

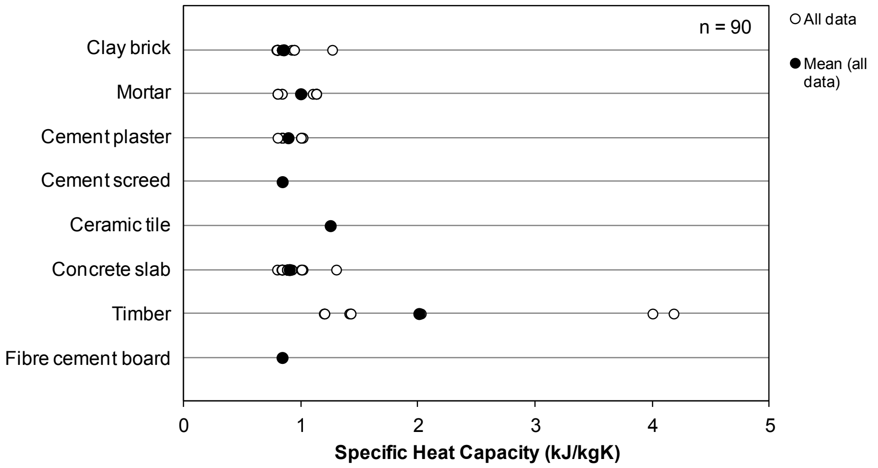


Figure 4.8. Specific heat capacity of the selected building materials from reference books.

2012; MBAM, 2012; MTC, 2012; Nichias, 2012; Shafigh *et al.*, 2012; UAC, 2012; Venus Ceramic Industry, 2012) are also plotted in Figure 4.7. There were no Malaysian data on density for mortar, cement plaster and cement screed because on-site cement mixtures were less documented (C&CA, 2012). It appears that the densities of the Malaysian materials average slightly higher than overall mean values, though we could not confirm the validity of this result due to the small sample size (Figure 4.7). On the other hand, the specific heat capacities of most materials average between 0.8-1.0 kJ/kgK except ceramic tile and timber, which have values above 1.0 kJ/kgK (Figure 4.8).

4.2 Current Behaviour Related to Cooling Among Households

In this study, we conducted two surveys in the city of Johor Bahru, Malaysia in different years. The first survey (Survey 1) was carried out from September to October 2004 in order to understand the occupants' behaviour related to air conditioner usages in typical modern urban houses (Kubota *et al.*, 2009). The second survey (Survey 2) was carried out in October 2009 to reveal the household energy consumption structure in the same residential areas (Jeong *et al.*, 2010). Johor Bahru is located in the southernmost part of Peninsular Malaysia. It was ranked the second biggest city in Malaysia in terms of population size after Kuala Lumpur in 2000 (Department of Statistics Malaysia, 2005). Its population including the conurbation was about 1.3 million in 2010 (Department of Statistics Malaysia, 2011b).

Both surveys were conducted in the same housing estates in Johor Bahru. Three typical housing estates, namely Bandar Baru Uda (BBU), Taman Daya (TD) and Taman Mutiara Rini (TMR), were selected for the surveys in consideration of their locations relative to the city centre and establishment years (Table 4.2). These surveys were carried out through face-to-face interviews using questionnaire forms. A total of 366 responses were obtained with an average response rate of 45% in Survey 1 while 388 responses were recorded with an average response rate of 34% in Survey 2 (Table 4.2). The households were selected to cover a wide range of income groups in each survey.

Questions related to the following aspects were asked in Survey 1: (1) usage patterns of air conditioners; (2) usage patterns of windows; and (3) usage patterns of ceiling fans. Meanwhile, the following items were investigated in Survey 2: (1) ownership and usage time of household electrical appliances; (2) the electric capacity of the appliances; and (3) household electricity and gas consumption. Since climatic conditions in Malaysia are relatively uniform throughout the year, the respondents were questioned on their annual average usage and consumption patterns. All of the surveyed houses were terraced houses.

Table 4.2. Summary of Survey 1 and Survey 2 on cooling and energy consumption in terraced houses.

	BBU	TD	TMR	Total
Established year	1970s	1980s	1990s	-
Distance from the city centre	7 km	10 km	15 km	-
Survey 1				
No. of responses	144	147	75	366
Response rate (%)	44	45	47	45
Survey 2				
No. of responses	136	103	99	338
Response rate (%)	41	24	45	34

4.2.1 Household Characteristics

In Survey 1, 64% of the respondents were Malays, 28% were Chinese and 7% were Indians. The average household size was 5.4 persons. The age of household head was 45 years old on average. The average number of workers in each household was 2.1. The respondents had an average of 2.4 children per household. About 70% of the respondents answered that at least one of the household members stayed at home during daytime on weekdays while the corresponding frequency for weekends was about 80% (Figure 4.9). 40% of the respondents' houses were single-storey terraced houses and 60% were double-storey terraced houses. The average number of bedrooms in each house was 3.5.

The demographic profile of the respondents in Survey 2 showed similar information with that of Survey 1. In Survey 2, 67% of the respondents were Malays, 24% were Chinese and 8% were Indians. These percentages correspond to the nationwide population distribution by ethnic group (Department of Statistics Malaysia, 2011a). The average household size was 4.6 persons. The average staying at home duration of households was 15.4 hours per day on weekdays while it was 20.4 hours per day on weekends. With regard to the respondents' houses, 51% of them were single-storey terraced houses and 49% were double-storey terraced houses. The average number of bedrooms in each house was 3.3.

4.2.2 Energy Consumption for Cooling

Figure 4.10 indicates the ownership level of household electrical appliances from Survey 2. Almost all of the respondents owned at least one unit of the first 5 items: television (100%); refrigerator (99%); washing machine (96%); rice cooker (95%); and ceiling fan (93%). The air conditioner ownership level is 65%. About 57% of the respondents owned stand or wall fans on the other hand. Figure 4.11 shows the average daily usage time of respective appliances. The usage time of ceiling fan is about 8 hours per day and the usage time of air conditioner is about 6 hours per day. Incandescent lamps were found to be installed in bathrooms and therefore the usage time is shorter compared with other types of lamps.

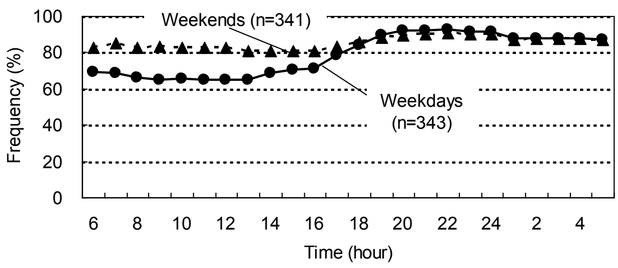


Figure 4.9. Hourly frequency of staying at home during a day (Survey 1).

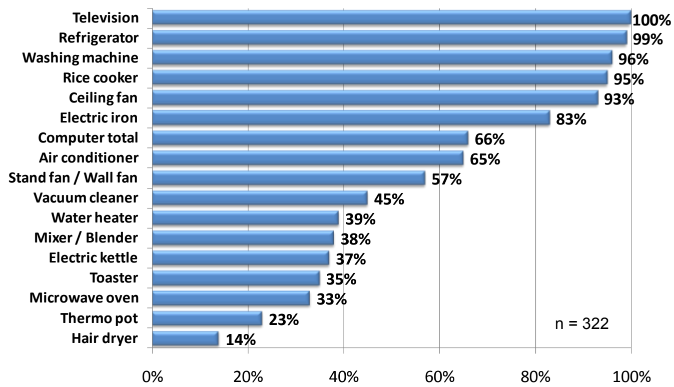


Figure 4.10. Ownership level of household electrical appliances (Survey 2).

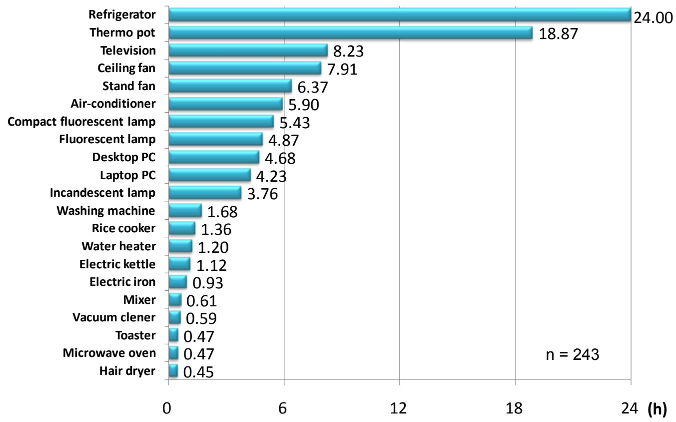


Figure 4.11. Average daily usage time of household electrical appliances (Survey 2).

The average yearly electricity consumption was calculated for each appliance based on the number, daily usage time and electric capacity of the item. The results are summarized in Figure 4.12. As mentioned earlier, the usage patterns of household appliances were assumed to be constant throughout the year. Monthly mean air temperatures and humidity are almost constant all the year round in most of the towns in Malaysia. Figure 4.12 reveals air conditioner is the biggest contributor with a yearly electricity consumption of 1,167 kWh/year per household on average.

It should be noted that the above electricity consumption caused by air conditioner was averaged among the air conditioner owners (65%) and non-owners (35%). The high electricity consumption for air conditioning is due to not only its ownership level but also the high electric capacity, which is 581W on average, and the long usage time (6 hours). Another important factor is probably the temperature setting of the air conditioner. As shown in Figure 4.13, the average temperature setting is 20.8°C. More than 15% of the respondents

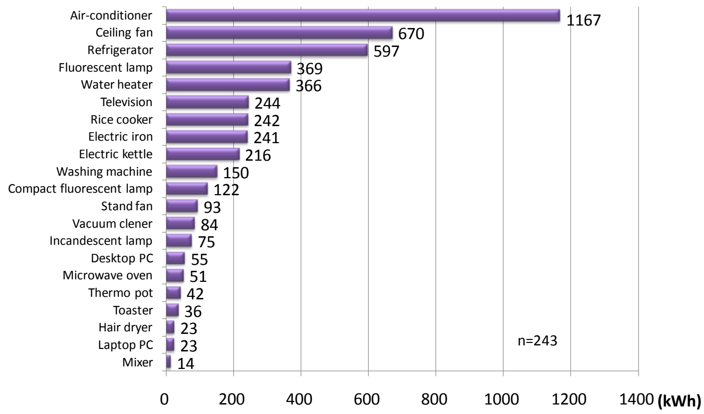


Figure 4.12. Average yearly electricity consumption by household electrical appliances (Survey 2).

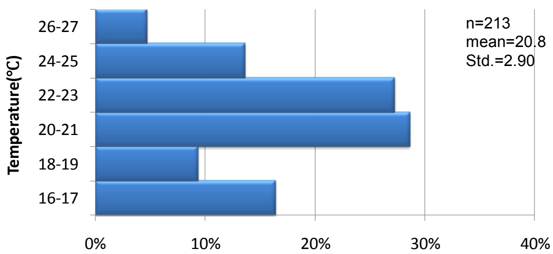


Figure 4.13. Frequency of temperature setting of air conditioner (Survey 2).

set the temperature for 16-17°C, which might be the lowest available temperature setting for the air conditioner.

The average yearly household energy consumption including electricity and gas was estimated in joule. Gas (LPG) consumption was estimated based on the frequency of refilling cooking gas cylinder. None of the households used gas for water heating; some of them used electric water heater (Figures 4.10 and 4.11). The average yearly household energy consumption among the respondents is 24.5 GJ/year (Figure 4.14). As revealed in the figure, cooking gas (27%) is the largest contributor, followed by air conditioner (17%), ceiling fan (10%) and refrigerator (9%). The energy consumption for cooking accounts for 45% in total while that for cooling is 29%.

Figure 4.15 analyses the difference in yearly energy consumption between the households with air conditioner and those without air conditioner. As expected, the average yearly household energy consumption by the respondents with air conditioner is 1.4 times that by non-owners in total. About a quarter, i.e. 24% or 6.71 GJ/year, of the total yearly energy consumption is attributed to air conditioning alone for the households with air conditioner.

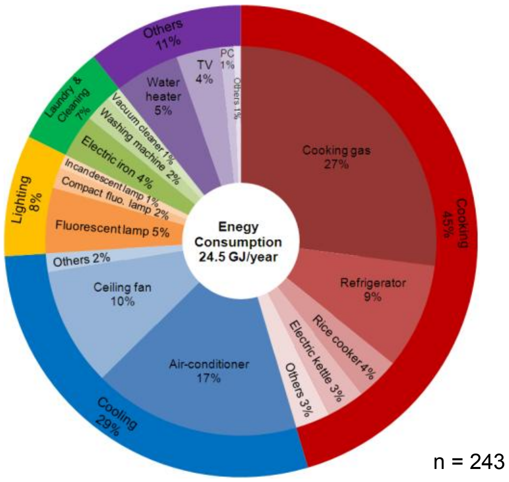


Figure 4.14. Average yearly household energy consumption by use (Survey 2).

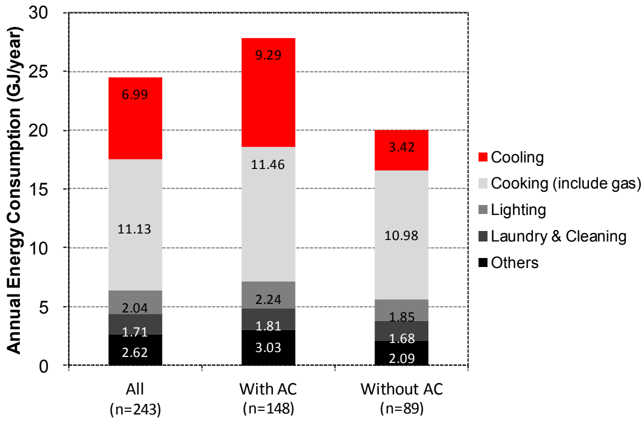


Figure 4.15. Average yearly energy consumption by households with and without air conditioner (Survey 2).

This clearly indicates that reduction in the air conditioner usage would be one of the most effective means for achieving energy-saving objectives in the modern Malaysian houses.

In Figure 4.16, we further analyse the yearly household energy consumption by household size. It is found that the household energy consumption increases with the increase in household size except for the households with 2 and 7 persons. In this figure, it is interesting to see that the energy consumption by single-person households is slightly higher than that by households of 2 persons. This is probably because relatively large houses with more than two bedrooms are resided even by single-person households in Malaysia.

4.2.3 Usage Patterns of Windows, Ceiling Fans and Air Conditioners

The ownership level of air conditioner observed in Survey 1 is 62%, which is a little lower than the level found in Survey 2. Figure 4.17 shows that almost all (99%) of the households with air conditioner also owned ceiling fan. The survey result shows that there is a clear relationship between the monthly household income and air conditioner ownership. The higher the income the more air conditioners they have. The average number of air conditioner among the owners is 2.3 units per household. The air conditioners were installed mainly in bedrooms (Figure 4.18). About 94% of the respondents installed air conditioner in the master bedroom, followed by 52% in other bedrooms.

Figure 4.19a indicates the hourly frequency of operating air conditioner during a day by the respondents. As indicated, only 10% of the owners operated air conditioner during daytime. However, its percentage increases from 7 p.m. and reaches 80% by 11 p.m. More than 50% of the owners continued to use air conditioner throughout the night until 5 a.m. The average usage time of air conditioner is 7.6 hours per day, which shows slightly longer time than the result of Survey 2 (6.0 hours). As described above, most of the owners installed the air conditioners in bedrooms and used them at night. Therefore, it is implied that most of them use air conditioner during sleep.

In Survey 1, it is found that the ceiling fan ownership level is 98% (Figure 4.17). It is 93% in Survey 2 (see Figure 4.10). Almost all (96%) of the respondents in Survey 1 installed ceiling fan in the living room, followed by 73% in the master bedroom, 58% in other bedrooms and 39% in the dining room. The average number of ceiling fan among the owners is 3.9 units per household. Figure 4.19b illustrates the hourly frequency of using ceiling fan during a day. As shown in the figure, there is a difference in the usage patterns between the air conditioner owners and non-owners. More than 60% of the non-owners continued to operate ceiling fan throughout the night until 5 a.m. while only 40% of the air conditioner owners used ceiling fan during the same period. The average usage time of ceiling fan is 14 hours for air conditioner owners while that for the non-owners is 15 hours.

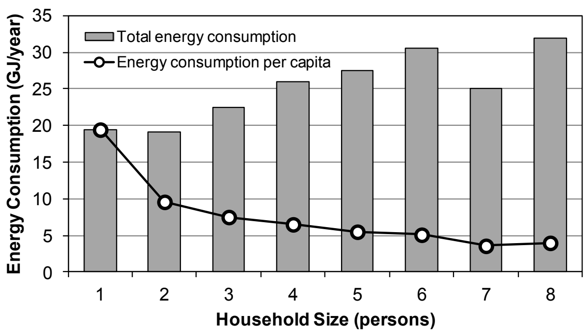


Figure 4.16. Average yearly household energy consumption by household size (Survey 2).

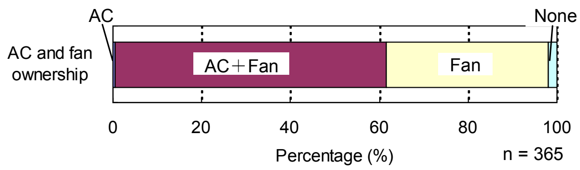


Figure 4.17. Air conditioner and ceiling fan ownership (Survey 1).

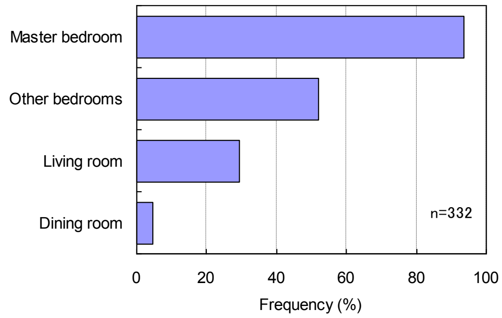


Figure 4.18. Rooms in which air conditioners were installed (Survey 1).

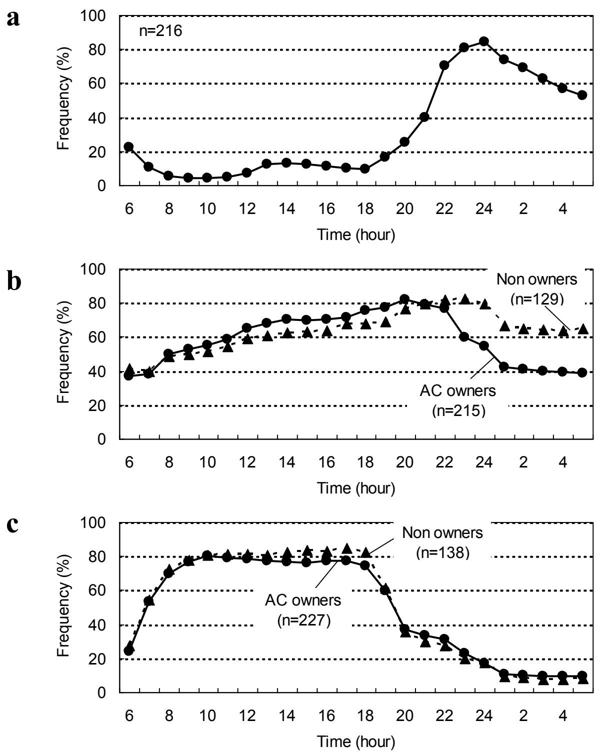


Figure 4.19. Hourly frequency of using (a) air conditioner; (b) ceiling fan; and (c) window during a day (Survey 1).

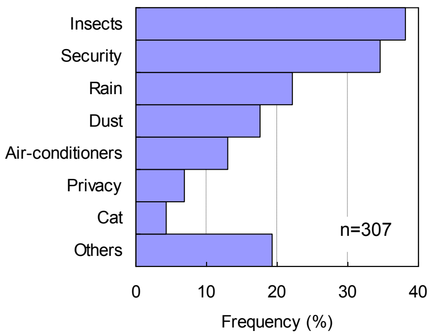


Figure 4.20. Reasons for not opening windows (Survey 1).

Figure 4.19c presents the hourly frequency of opening windows during a day. The two lines show the respective results for air conditioner owners and non-owners. Interestingly, an evident difference is not seen in the usage pattern of windows between the two groups. About 80% of the respondents practiced opening windows from 10 a.m. to 6 p.m. The frequency gradually declines from 7 p.m. and drops to about 10% from 1 a.m. to 5 a.m. It is found that most of the occupants opened windows during the daytime and closed them during the night-time regardless of the air conditioner ownership. This result is an indication that few occupants applied night ventilation in the terraced houses.

Further result shows that the main reasons for not opening windows are the entry of insects (38% of the respondents), security (35%), rain (22%) and dust (18%) (Figure 4.20). Although 'insects' was recorded as the most significant reason, it was found that insect screen was installed by only 1% of the respondents.

4.3 The Field Experiment in Existing Terraced Houses

4.3.1 The Case Study Houses

We conducted a full-scale field experiment in two selected adjacent terraced houses (TH 1 and TH 2) in one of the previous survey areas (TMR) in Johor Bahru, Malaysia from June to August 2007 (Figures 4.21 and 4.22). The work was documented in Kubota and Toe (2010) and Kubota *et al.* (2009), although we make new analyses in this thesis. Our purpose was to examine the effects of various ventilation strategies on the indoor thermal environments in the houses. The selected case study houses are representative of average sized houses in the typical layout group for double-storey terraced house (see Figure 4.5) and were also constructed using the common materials listed in Table 4.1. They were identical, unoccupied and unfurnished during the experiment.

The total floor area of each house is 155 m^2. The reinforced concrete structures were infilled with plastered brick walls that are 240mm thick for the party walls and 140mm thick for the other walls. The concrete roof tiles were laid with a thin layer of double-sided aluminium foil underneath as radiant barrier (Monier, 2012). The ceiling on the first floor was fibre-cement boards of 6mm thick and 3.2mm thick in the master bedroom and other bedrooms, respectively, without insulation (UAC, 2012). The floors were reinforced concrete slabs of 100mm thick and finished with ceramic tiles on the ground floor and timber

Figure 4.21. Exterior view of the case study terraced houses.

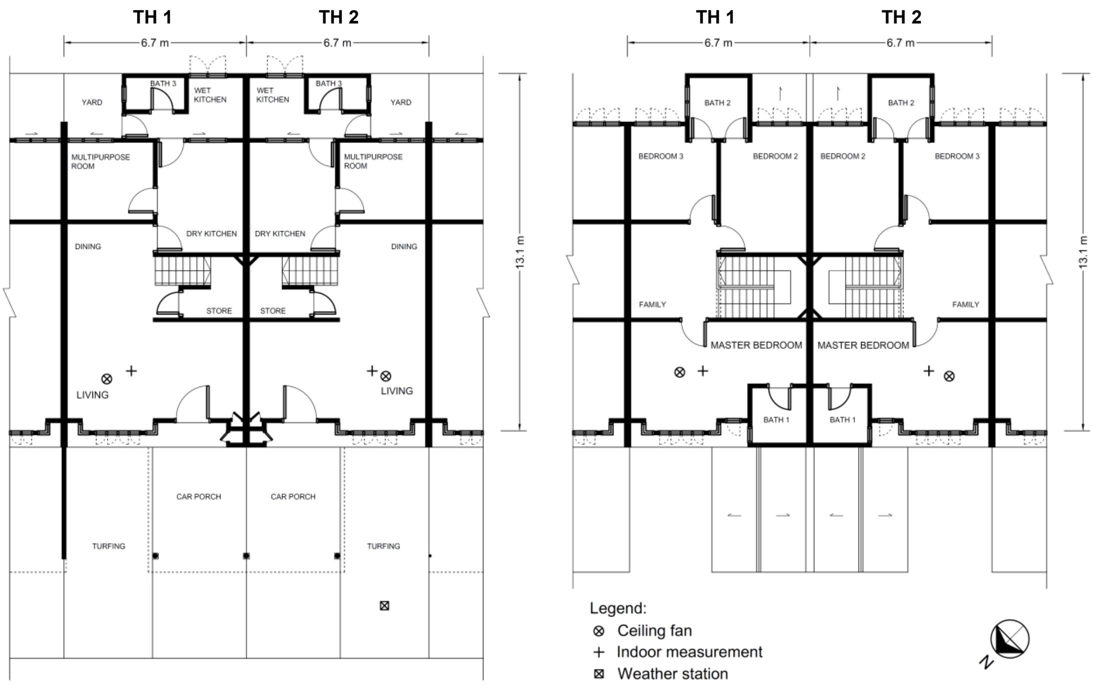


Figure 4.22. Floor plans of the case study terraced houses. Note: Drawn based on architectural drawings with permission of Arkitek MAA (2010).

strips on the first floor. All windows were casement or sliding type of 6mm thick single layer light tinted glass with aluminium frame. A clerestory window of fixed glass louvers with timber frame was available above the family area on the first floor. These data were obtained from the architectural drawings (Arkitek MAA, 2010) and verified on site.

4.3.2 The Experimental Setup and Measurement Methods

The experimental cases were conducted as outlined in Table 4.3. Cases 1-3 compared night ventilation with daytime ventilation, no ventilation and full-day ventilation, respectively. Daytime ventilation was obtained by opening all windows from 8 a.m.-8 p.m. and closing them from 8 p.m.-8 a.m. to emulate the households' window opening behaviour that was found in the previous survey (see Figure 4.19c). In contrast, all windows were closed from 8 a.m.-8 p.m. and opened from 8 p.m.-8 a.m. for night ventilation. Case 4 further analysed the conditions of Case 3 with the additional use of ceiling fans. On the day before each case, all windows in both houses were opened equally from 8 a.m.-8 p.m. for 24h so that their indoor thermal conditions would be similar at the start of the respective cases.

Measurements of indoor thermal environment were taken in the master bedrooms (first floor) and living rooms (ground floor) of the two houses (Figure 4.22). The floor-to-ceiling heights of the rooms are 3.05m. The measured variables at 1.5m height above floor in the master bedrooms were air temperature, relative humidity, air speed and globe temperature for the purpose of thermal comfort assessment. In addition, air temperature measurements were taken at 0.6m, 2.4m and 2.9m in the master bedrooms and 0.6m, 1.5m and 2.4m in the living rooms for vertical thermal distribution analysis. Floor and ceiling surface temperatures were also recorded on both floors. All indoor measurements were logged automatically at 10-minute intervals. The measurement instruments used are outlined in Table 4.4. A weather station (Environdata EASIDATA Mark 4) was placed in the immediate outdoor of TH 2 to record the outdoor air temperature, relative humidity, wind speed and direction, global horizontal solar radiation and rainfall throughout the experiment (Figure 4.22). Due to the technical setting of the weather station, outdoor data were logged at 15-minute intervals. Barometric pressure data from the nearest meteorological station, i.e. Senai Station, were obtained from the Malaysian Meteorological Department (MMD, 2011).

Table 4.3. Ventilation conditions of the field experiment in the terraced houses.

Case	Terraced house 1	Terraced house 2
1	Daytime ventilation	Night ventilation
2	No ventilation	Night ventilation
3	Full-day ventilation	Night ventilation
4	Full-day ventilation + ceiling fan	Night ventilation + ceiling fan

Table 4.4. Description of measurement instruments used in the terraced houses.

Measured variable	Instrument model	Accuracy
Master bedrooms		
Air temperature and RH at 1.5m above floor	Delta Ohm HP472AC and T&D TR-72U	±0.30°C; ±2% RH and ±0.3°C; ±5% RH
Air speed	Delta Ohm AP471S2 and Innova MM0038	±0.02m/s and ±5% plus ±0.05m/s
Globe temperature	Type T thermocouple inside 150mm diameter black globe and Innova MM0030	±0.1°C plus probe's error and ±0.5°C
Vertical thermal distributions		
Air temperature	T&D TR-72U, T&D TR-52, Dickson D200, Dickson TP120 and Innova MM0034	±0.3°C, ±0.3°C, ±0.28°C, ±1°C and ±0.2°C
Surface temperature (floor and ceiling)	T&D TR-52 and Innova MM0035	±0.3°C and ±0.5°C
Weather station		
Air temperature	Environdata TA10	±0.3°C
Relative humidity	Environdata RH21	±2% RH
Wind speed	Environdata WS30	±0.2m/s or ±1% of reading (whichever is greater)
Wind direction	Environdata WD32	±5°
Global horizontal solar radiation	Environdata SR10	±5% of reading
Rainfall	Environdata RG12	±0.2mm or ±2% of reading (whichever is greater)

4.3.3 Thermal Comfort in the Master Bedrooms

Figures 4.23-4.26 show the temporal variations of the thermal variables measured in the master bedrooms at 1.5m height above floor with the corresponding outdoor conditions for Cases 1-4, respectively. The data processing is made to be consistent throughout this thesis. Indoor absolute humidity is calculated from the measured air temperature, relative humidity and barometric pressure based on ISO 7726 (BSI, 2002):

$$W_{\mathrm{a}} = \left(0.6220 \frac{p_{\mathrm{a}}}{p - p_{\mathrm{a}}}\right) \times 1000 \quad (4.2)$$

$$p_{\mathrm{a}} = 0.01 \times p_{\mathrm{as}} \times \mathrm{RH} \quad (4.3)$$

$$p_{\mathrm{as}} = 0.611 \times \exp\left(\frac{17.27T_{\mathrm{a}}}{T_{\mathrm{a}}+237.3}\right) \quad (4.4)$$

where W_{a} is absolute humidity (g/kg'), p_{a} is partial pressure of water vapour (kPa), p is barometric pressure (kPa), p_{as} is saturated vapour pressure (kPa), RH is relative humidity (%) and T_{a} is air temperature (°C). The same standard provides two expressions to calculate mean radiant temperature based on the globe temperature, which are in case of natural convection and in case of forced convection (BSI, 2002). We apply the expression by forced convection, which is most frequently used in practice:

$$\bar{T}_{\mathrm{r}} = \left[\left(T_{\mathrm{g}} + 273\right)^4 + \frac{1.1\times10^8\times v^{0.6}}{\varepsilon_{\mathrm{g}}\times D^{0.4}}\left(T_{\mathrm{g}} - T_{\mathrm{a}}\right)\right]^{1/4} - 273 \quad (4.5)$$

where $\bar{T}_{\mathrm{r}}$ is mean radiant temperature (°C), T_{g} is globe temperature (°C), v is air speed (measured at the level of the globe) (m/s), ε_{g} is emissivity of the black globe (-) and D is diameter of the globe (m). The emissivity of the black globe is taken as 0.98 in all the calculations in this thesis.

In all experimental cases, it is found that indoor air temperatures in the night ventilated master bedroom are lower than that of the other ventilation conditions throughout the day, especially on fair weather days (Figures 4.23a, 4.24a, 4.25a and 4.26a). For example, in Case 1, night ventilation lowers the maximum indoor air temperatures by 3.4-5.0°C and also delays the occurrence of the peak air temperatures by 1-3 hours compared to the outdoors on fair weather days (Figure 4.23a). This is due to the nocturnal ventilative cooling through open windows and thermal mass effect of the cooled building structures from the respective previous nights.

On the other hand, when daytime ventilation was applied in Case 1, the maximum indoor air temperatures are 2.0-3.4°C higher than the night ventilated room and only 0.9-1.7°C lower than the outdoors (Figure 4.23a). The daytime air temperatures are closer to the outdoors mainly due to its open window condition which allows hot outdoor air to ventilate the house. Further, the heat from the outdoor air is stored in the building structures and radiates to the indoor spaces at night. Since windows are closed during night-time, the heat is confined inside the house and nocturnal indoor air temperature in the daytime ventilated room maintains 2.2°C higher than the night ventilated room on average (Figure 4.23a).

When no ventilation was applied in Case 2, the nocturnal indoor air temperature is also maintained 1.8° higher than the night ventilated room on average, which is almost as high as that of the daytime ventilated room (Figure 4.24a). It is found that without night cooling, maximum indoor air temperatures in the unventilated room are 1.1-1.2°C higher than the night ventilated ones on fair weather days, although windows were closed during daytime.

When full-day ventilation was applied in Case 3, diurnal indoor air temperature is similar to the pattern of the daytime ventilated one while nocturnal indoor air temperature is still 0.7°C higher than that of the night ventilated room on average (Figure 4.25a). As explained

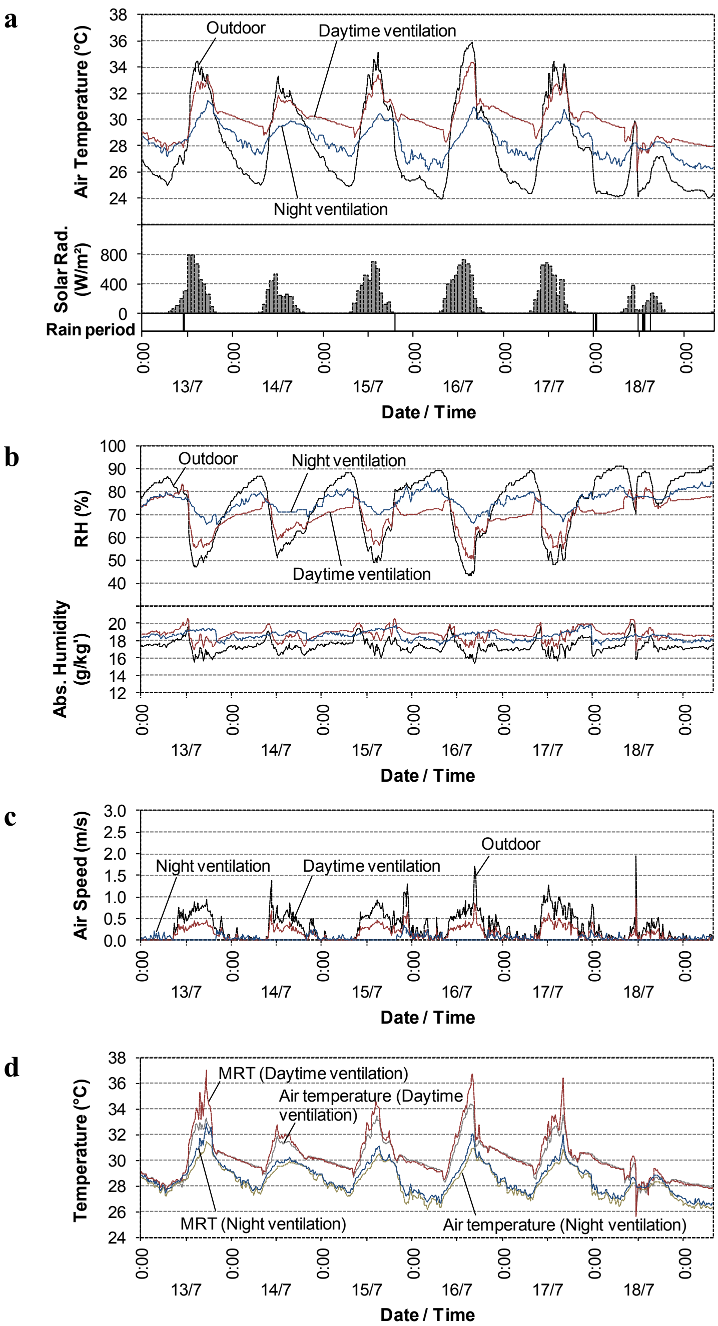


Figure 4.23. Temporal variations of the measured thermal variables at 1.5m above floor in the master bedrooms of terraced houses and the outdoors for Case 1: daytime ventilation vs. night ventilation. (a) Air temperature and solar radiation; (b) Relative humidity and absolute humidity; (c) Air speed; (d) Mean radiant temperature.

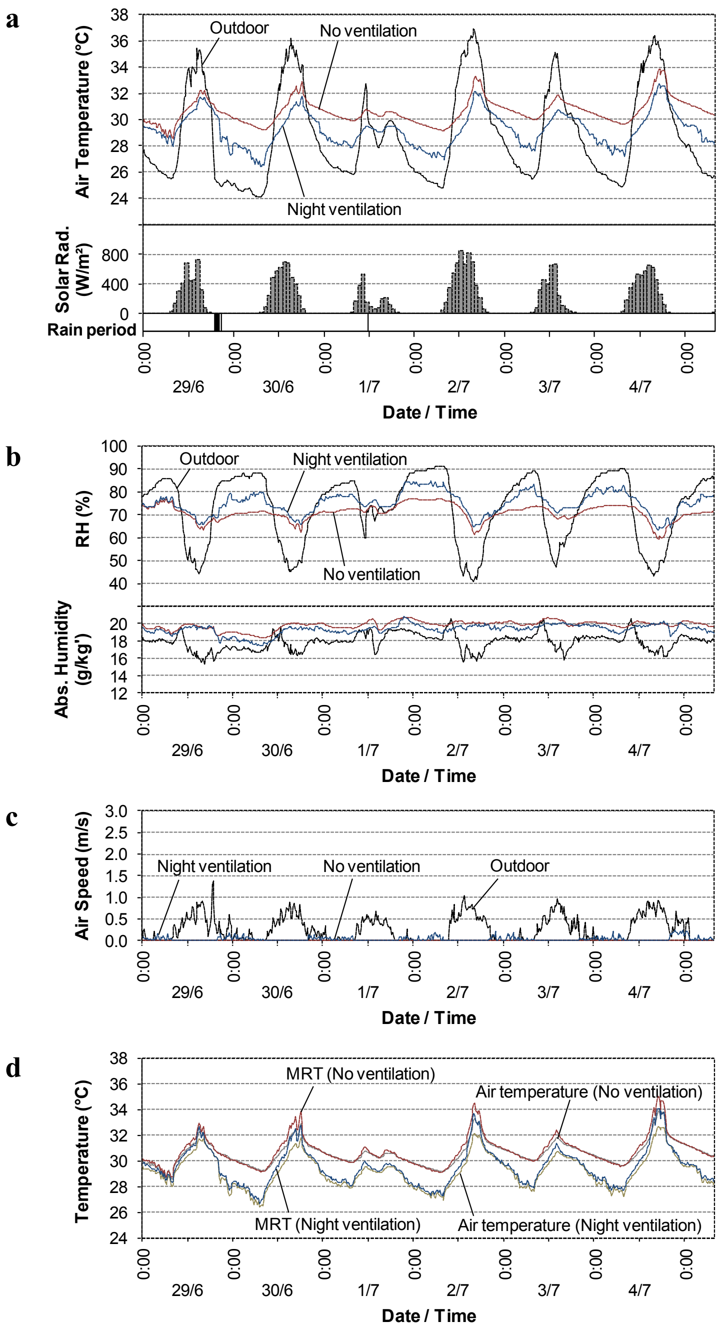


Figure 4.24. Temporal variations of the measured thermal variables at 1.5m above floor in the master bedrooms of terraced houses and the outdoors for Case 2: no ventilation vs. night ventilation. (a) Air temperature and solar radiation; (b) Relative humidity and absolute humidity; (c) Air speed; (d) Mean radiant temperature.

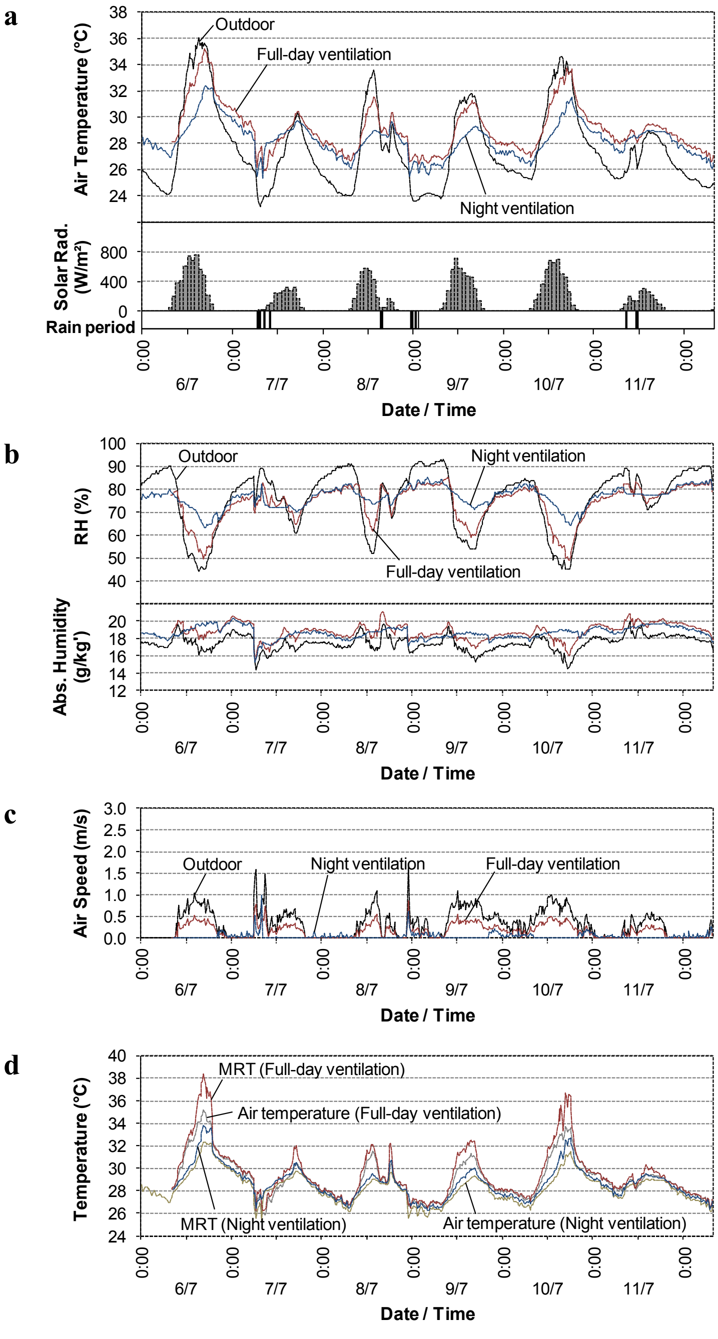


Figure 4.25. Temporal variations of the measured thermal variables at 1.5m above floor in the master bedrooms of terraced houses and the outdoors for Case 3: full-day ventilation vs. night ventilation. (a) Air temperature and solar radiation; (b) Relative humidity and absolute humidity; (c) Air speed; (d) Mean radiant temperature.

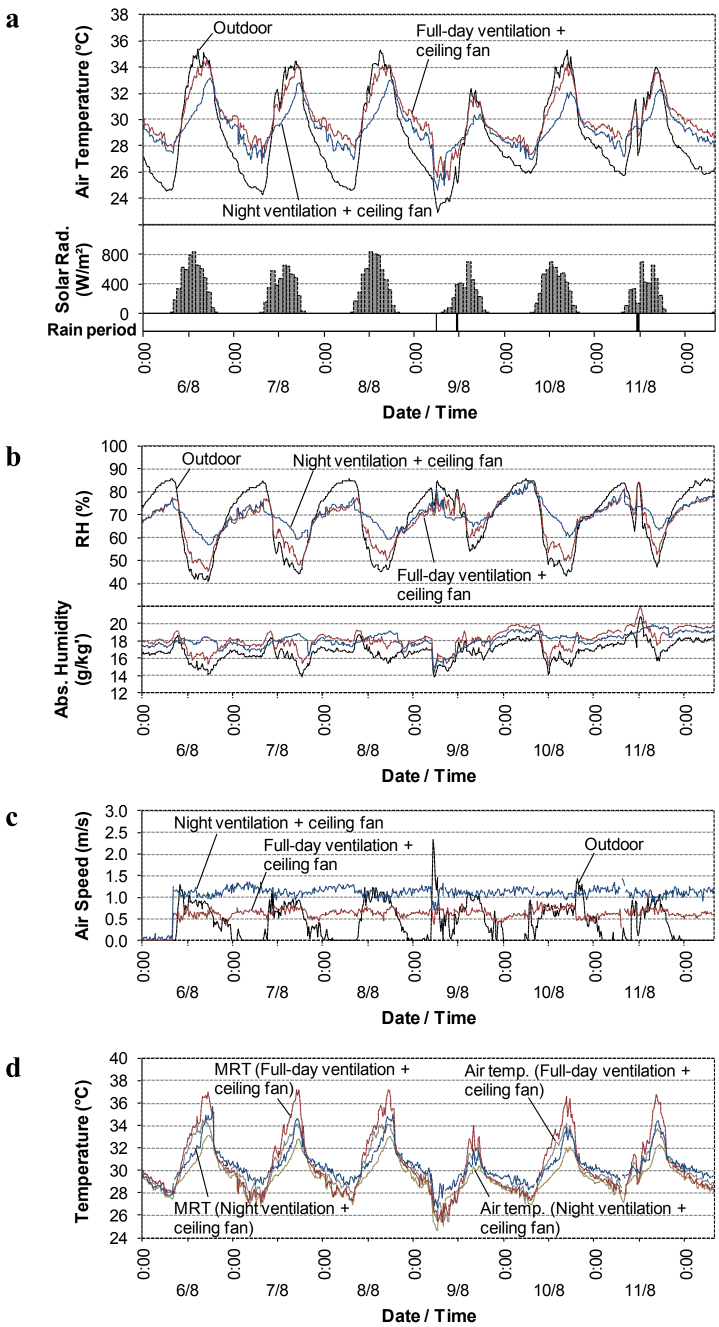


Figure 4.26. Temporal variations of the measured thermal variables at 1.5m above floor in the master bedrooms of terraced houses and the outdoors for Case 4: full-day ventilation + ceiling fan vs. night ventilation + ceiling fan. (a) Air temperature and solar radiation; (b) Relative humidity and absolute humidity; (c) Air speed; (d) Mean radiant temperature.

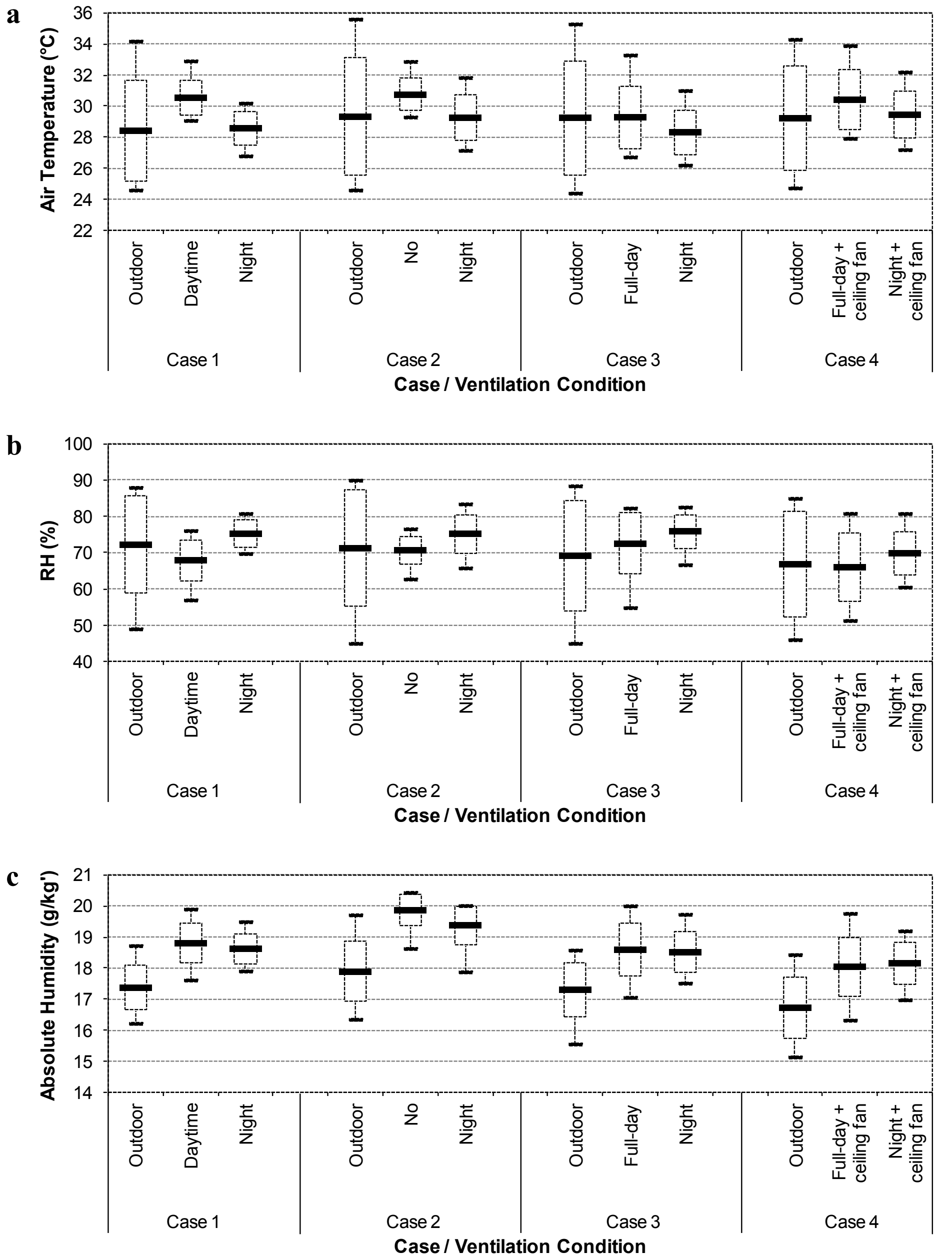


Figure 4.27. Statistical summary (5th and 95th percentiles, mean and ± one standard deviation) of measurements at 1.5m above floor in the master bedrooms of terraced houses and the outdoors for Cases 1-4. (a) Air temperature; (b) Relative humidity; (c) Absolute humidity.

before, the building structures are heated more when windows are open during daytime. As the mean outdoor wind speeds drop from about 0.6-0.7 m/s during the day to about 0.0-0.3 m/s at night, the night-time ventilation rate might be insufficient to cool the heated structure of the full-day ventilated house properly at night due to its high thermal capacity (Figure 4.25c).

It should be noted that nocturnal air temperatures in the night ventilated room are still 1.7-2.0°C higher than the outdoors on average in Cases 1-3 probably due to the same reasons of low ventilation rate at night and high thermal capacity (Figures 4.23a, 4.24a and 4.25a).

On the other hand, the measurement results reveal that the air temperature reductions obtained in the night ventilated room are accompanied by increase in relative humidity compared to the other ventilation conditions (Figures 4.23b, 4.24b and 4.25b). The minimum relative humidity during daytime in the room is about 65-70% while its nocturnal relative humidity is about 75-85%. Full-day ventilation and daytime ventilation are able to control diurnal humidity level to 10-15% RH lower than night ventilation, but at the expense of the aforementioned cooling effects. Indoor absolute humidity is also higher under closed window conditions than open window conditions, whether during daytime or night-time, by about 0.5 g/kg' on average.

Ceiling fans were used in both full-day ventilated and night ventilated rooms throughout the experimental period of Case 4. Figure 4.26ab show that the air temperature and humidity profiles are similar with those of Case 3 (same open window conditions without using ceiling fans). Nocturnal indoor air temperature in the night ventilated room is still 1.9°C higher than the outdoors on average. The result implies that the ceiling fans likely do not affect the room air exchange with the outdoor air very much, though they are effective to increase the indoor air speed. The mean indoor air speeds measured at the centre of the full-day ventilated and night ventilated rooms are 0.65 m/s and 1.13 m/s, respectively (Figure 4.26c).

Figure 4.27 further presents a statistical summary of the measured air temperature and humidity in the master bedrooms on fair weather days for Cases 1-4. In terms of air temperature, Figure 4.27a confirms that night ventilation shows lower statistical values than the other ventilation conditions for all cases. The mean indoor air temperatures in the night ventilated room are almost similar to or lower than the mean outdoor air temperatures. Figure 4.27b determines that night ventilation shows higher statistical values in terms of relative humidity on the other hand. Nonetheless, mean indoor absolute humidity in the night ventilated room is almost similar to those of daytime ventilation and full-day ventilation (Cases 1, 3 and 4) and lower than that of no ventilation (Case 2) (Figure 4.27c). Overall, indoor absolute humidity shows higher statistical values than the outdoors for all ventilation conditions in the terraced houses (Figure 4.27c).

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 non-uniform environment (ASHRAE, 2010). The relative weight or influence of the radiation and convection heat exchanges is a function of the indoor air speed. We estimate the indoor operative temperature according to an equation given in ISO 7726 (BSI, 2002), which is applicable over a wide range of indoor air speed:

$$T_{\mathrm{op}} = \frac{T_{\mathrm{a}}\sqrt{10v}+\bar{T}_{\mathrm{r}}}{1+\sqrt{10v}} \tag{4.6}$$

where T_{op} is operative temperature (°C), v is indoor air speed (m/s) and $\bar{T}_{\mathrm{r}}$ is the mean radiant temperature (°C) that is calculated earlier.

We plot the indoor operative temperatures and humidity of the two master bedrooms on a psychrometric chart in Figure 4.28. The data in the night ventilated room are mostly concentrated between 26-34°C indoor operative temperature and absolute humidity of 17-20 g/kg'. In comparison, the data are more spread out in terms of both operative temperature and absolute humidity in daytime ventilation and full-day ventilation conditions. In the latter two conditions, the indoor absolute humidity is lowered at high indoor operative temperature, as discussed above.

Basically, we would evaluate the indoor thermal comfort based on the adaptive model since the rooms were naturally ventilated. Nonetheless, the graphic comfort zone recommended by ASHRAE (2010) for typical indoor environments at 0.5 clo level is also drawn as a reference point in Figure 4.28. It should be noted that the upper humidity limit of 0.012 kg/kg' applies only to the graphical compliance method of the standard and where a system designed to control humidity is in place (ASHRAE, 2010; Olesen and Brager, 2004). It was proposed to avoid mold growth and other moisture related phenomena in earlier versions of ASHRAE Standard 55 (Berglund, 1995). On the other hand, there is no humidity limit for the computer model method that uses the PMV comfort equation (ASHRAE, 2010). Another criterion allowed in the same standard is the use of elevated air speed to increase the maximum operative temperature for acceptability (ASHRAE, 2010). In Figure 4.28, the dashed line indicates the cooling effect of elevated air speed of 0.8 m/s, which is the maximum acceptable air speed in compliance with the graphical method (ASHRAE, 2010). Figure 4.28 reveals none of the data in both rooms under all the tested ventilation conditions falls within the illustrated comfort zone.

Temporal variations of the same indoor operative temperatures are plotted in Figure 4.29 for thermal comfort evaluation. This evaluation is made based on the thermal comfort criteria that are developed in this study (see Chapter 3: Section 3.3.6). In Figure 4.29, the 80% comfortable upper limit is drawn for each day based on the measured outdoor air temperatures. The 80% comfortable upper limits range between 27.6-29.4°C, 29.0-30.1°C, 28.3-29.9°C and 28.6-30.0°C for Cases 1-4, respectively. The evaluation is also summarized in terms of indoor operative temperature deviations from the 80% comfortable upper limits and the exceeding periods on fair weather days in Table 4.5.

Overall, the evaluation reveals that night ventilation is able to provide more comfortable indoor operative temperature than the other ventilation conditions (Figure 4.29). The period of exceeding the upper limit and the magnitude of temperature above the limit are less in the

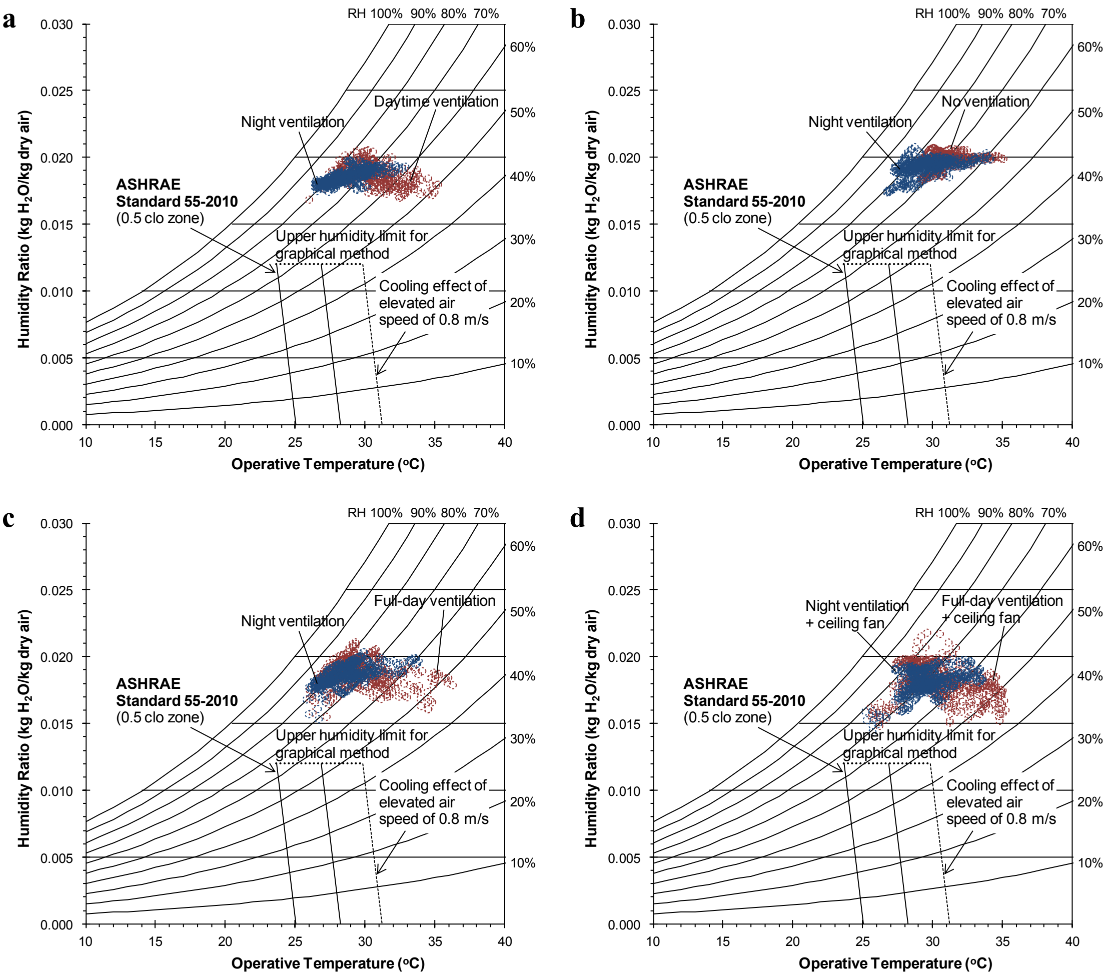


Figure 4.28. Scatter diagram of indoor operative temperatures and indoor humidity in the master bedrooms of terraced houses on a psychrometric chart. (a) Case 1; (b) Case 2; (c) Case 3; (d) Case 4.

night ventilated room for all cases (Table 4.5). For example, in Case 1, the period that indoor operative temperatures in the night ventilated room exceeds the 80% comfortable upper limit is 37% while it is 91% in the daytime ventilated room (Table 4.5). On average, the exceeding period for night ventilation in Cases 1-3 is 42%. It is noted that the exceeding periods for night ventilation in Cases 3 and 4 are slightly higher compared to Cases 1 and 2 (Table 4.5). The reasons are probably due to the unavailable operative temperature data on the first night for Case 3 so that there were unequal daytime and night-time data and the effect of ceiling fan which likely increases the air temperature at 1.5m height for Case 4 (see Section 4.3.4). The latter also probably reduces the difference in the exceeding periods between night ventilation and full-day ventilation in Case 4 compared to Case 3 (Table 4.5).

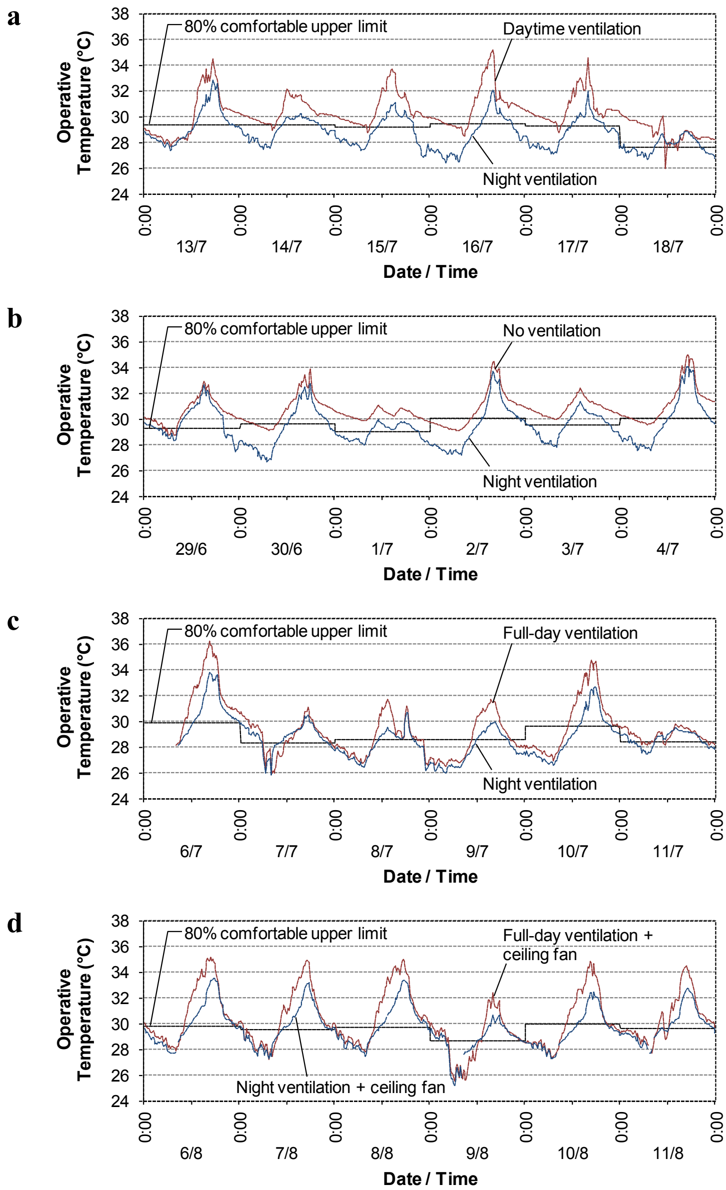


Figure 4.29. Temporal variations of indoor operative temperatures in the master bedrooms of terraced houses and the corresponding temperature limits for thermal comfort. (a) Case 1; (b) Case 2; (c) Case 3; (d) Case 4.

Daily maximum indoor operative temperatures in the night ventilated room are higher than the 80% comfortable upper limits by 0.9-4.0°C on the afternoons of fair weather days in Cases 1-3 (Figure 4.29abc and Table 4.5). This is likely caused by the incoming solar

Table 4.5. Summary of thermal comfort evaluation in the master bedrooms of terraced houses on fair weather days.

Ventilation condition	Deviation of indoor operative temperature from the 80% comfortable upper limits (°C)[a]		Exceeding period (%)
	Daily maximum	Daily minimum	
Case 1			
Daytime ventilation	2.9 to 5.8	-0.4 to -1.0	91
Night ventilation	0.9 to 2.8	-1.8 to -3.1	37
Case 2			
No ventilation	2.9 to 5.0	0.5 to -1.0	76
Night ventilation	1.9 to 4.0	-1.7 to -2.9	45
Case 3			
Full-day ventilation	5.1 to 6.4	-1.7 to -2.7	65
Night ventilation	3.0 to 3.9	-1.8 to -3.1	49
Case 4			
Full-day ventilation + ceiling fan	4.9 to 5.4	-1.9 to -2.6	55
Night ventilation + ceiling fan	2.5 to 3.6	-2.3 to -2.7	47
Cases 1-3			
Night ventilation	0.9 to 4.0	-1.7 to -3.1	42

[a] Positive values indicate indoor operative temperatures above the 80% comfortable upper limits and negative values indicate indoor operative temperatures below the 80% comfortable upper limits.

radiation through the windows, which were on the northwest façade, in the afternoons as well as heat through the ceiling (see Section 4.3.4). As presented in Figures 4.23d, 4.24d, 4.25d and 4.26d, the maximum mean radiant temperatures in the night ventilated room are 0.4-2.0°C higher than its maximum air temperatures on fair weather days.

The radiant and convective heat through daytime ventilation further increases the maximum indoor operative temperatures in the daytime ventilated and full-day ventilated rooms. Their maximum operative temperatures exceed the 80% comfortable upper limits by 2.9-6.4°C on the afternoons of fair weather days (Figure 4.29ac and Table 4.5). It is of interest to find that indoor operative temperature in the daytime ventilated room is above the 80% comfortable upper limit not only during the daytime but also almost throughout the night (Figure 4.29a). As noted above, the exceeding period is 91% (Table 4.5). The low occurrence of comfortable operative temperature in the daytime ventilated room for the whole day might thus lead the actual households, who mostly practiced daytime ventilation, to use air conditioners at night (see Figure 4.19). However, it should be noted that thermal comfort for night-time sleep environments is not evaluated.

The evaluation of no ventilation condition in Case 2 shows that the exceeding period is 76%, which is about 30% more than night ventilation (Table 4.5). This is mainly because the night-time indoor operative temperature is kept high without ventilation.

4.3.4 Vertical Thermal Distributions on Two Floors

The vertical temperature measurements on the two floors of the terraced houses allow us to examine the effect of heat through the ceiling on the first floor. Figures 4.30-4.33 show the average surface and air temperatures at respective measurement heights that represent daytime (12 p.m.-8 p.m.) and night-time (12 a.m.-8 a.m.) conditions on fair weather days for Cases 1-4, respectively.

The windows in the night ventilated house were closed between 12 p.m.-8 p.m. Figures 4.30a, 4.31a, 4.32a and 4.33a show that the ceiling surface temperature on the first floor in the night ventilated house is similar to the average outdoor air temperature during this period, even though the temperatures at all other measurement points in the house are much lower. It is 1.4-2.8°C higher than the floor surface and air temperatures of the same room. In fact, the first floor ceiling surface temperatures are almost the same in both houses under the different ventilation conditions. Air temperature in the attic space was measured in Case 4. Both attic spaces were not ventilated. As an example, attic air temperature in the night ventilated house averages 35.0°C, which is about 2°C higher than the outdoors (Figure 4.33a). The result implies that the attic space is heated by solar radiation received on the roof during daytime. Consequently, the ceiling is heated and passes the heat into the master bedroom via convection and radiation. This process likely increases the indoor air temperature, mean radiant temperature and operative temperature that are evaluated in the previous section.

It is observed that the ground floor was cooler than the first floor when windows were closed during daytime, i.e. in the night ventilation and no ventilation conditions. The air temperature at 1.5m on the ground floor is 0.9-1.4°C lower than that of the first floor on average in the night ventilated house (Figures 4.30a, 4.31a, 4.32a and 4.33a). This air temperature difference between floors is likely due to the heat coming through the ceiling on the first floor, as discussed above. In comparison, in addition to the heated ceiling, ventilation with the hot outdoor air further increases the air temperatures in the daytime ventilated and full-day ventilated house on both floors, thus air temperature differences between floors are less pronounced (Figures 4.30a and 4.32a).

Further, in Case 4, air temperature gradient is not seen on the first floor in both houses during daytime (Figure 4.33a). The ceiling fans possibly enhance convection in the rooms including stirring the hotter air downwards, which otherwise might have stayed near the ceiling surface, especially when windows are closed as in the night ventilated room, and increase the air temperatures at the lower points.

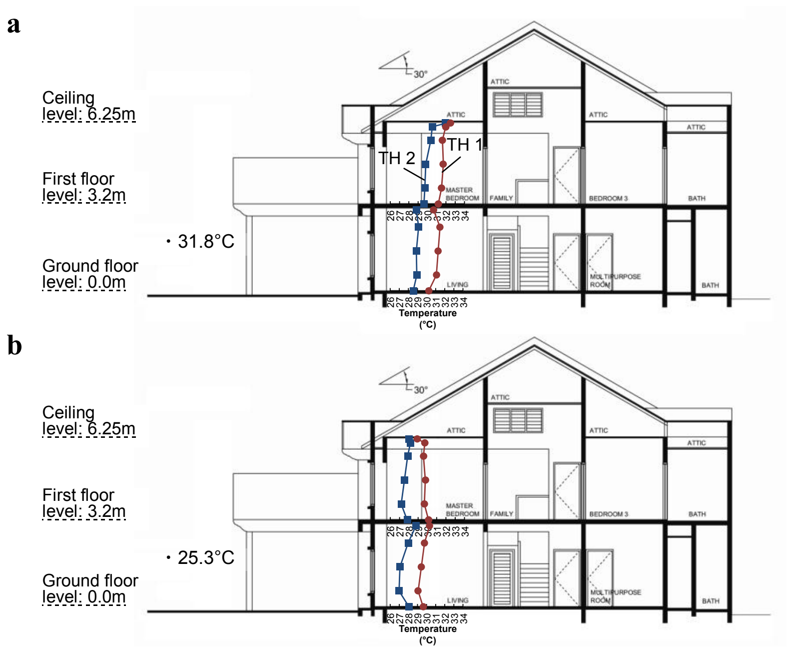


Figure 4.30. Vertical temperature distributions in the master bedrooms (first floor) and living rooms (ground floor) of terraced houses for Case 1. (a) 12 p.m.-8 p.m.; (b) 12 a.m.-8 a.m. Note: Section drawn based on architectural drawings with permission of Arkitek MAA (2010).

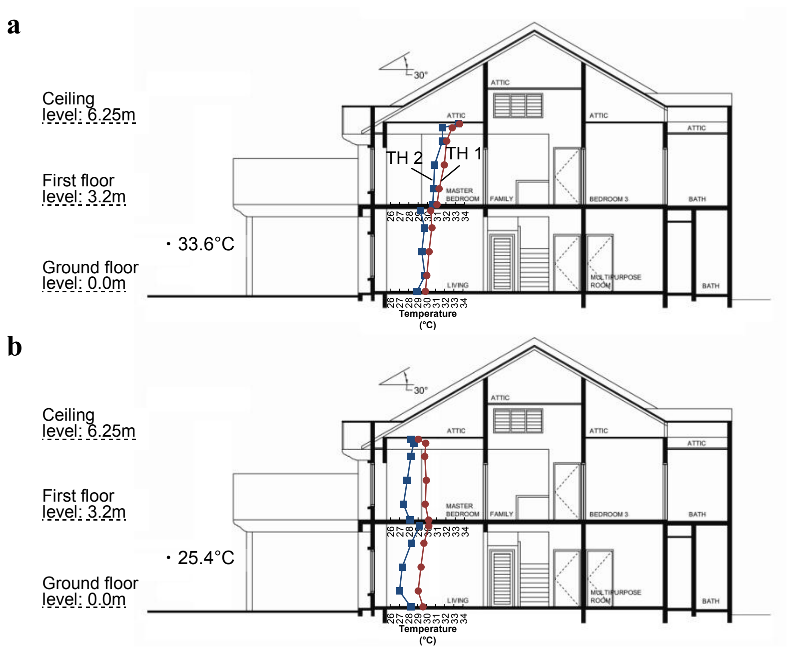


Figure 4.31. Vertical temperature distributions in the master bedrooms (first floor) and living rooms (ground floor) of terraced houses for Case 2. (a) 12 p.m.-8 p.m.; (b) 12 a.m.-8 a.m. Note: Section drawn based on architectural drawings with permission of Arkitek MAA (2010).

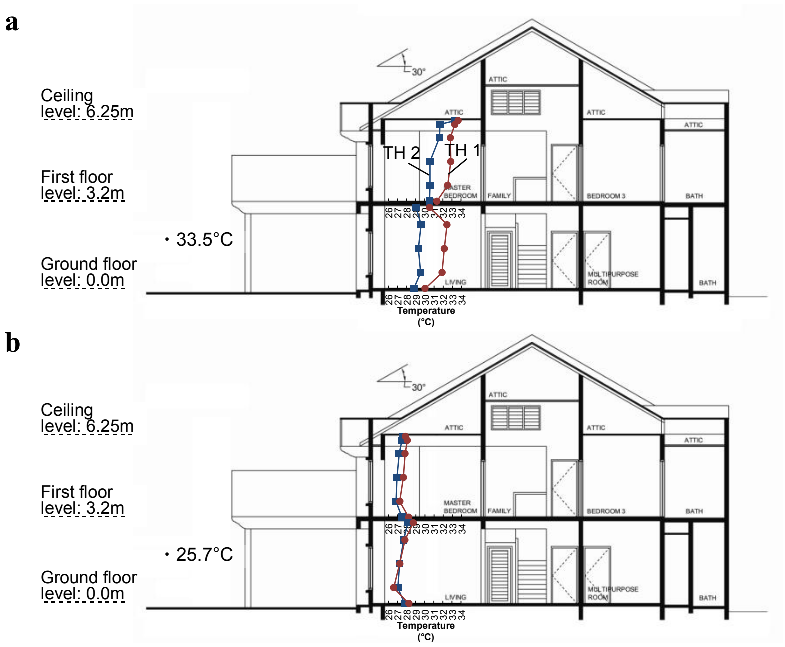


Figure 4.32. Vertical temperature distributions in the master bedrooms (first floor) and living rooms (ground floor) of terraced houses for Case 3. (a) 12 p.m.-8 p.m.; (b) 12 a.m.-8 a.m. Note: Section drawn based on architectural drawings with permission of Arkitek MAA (2010).

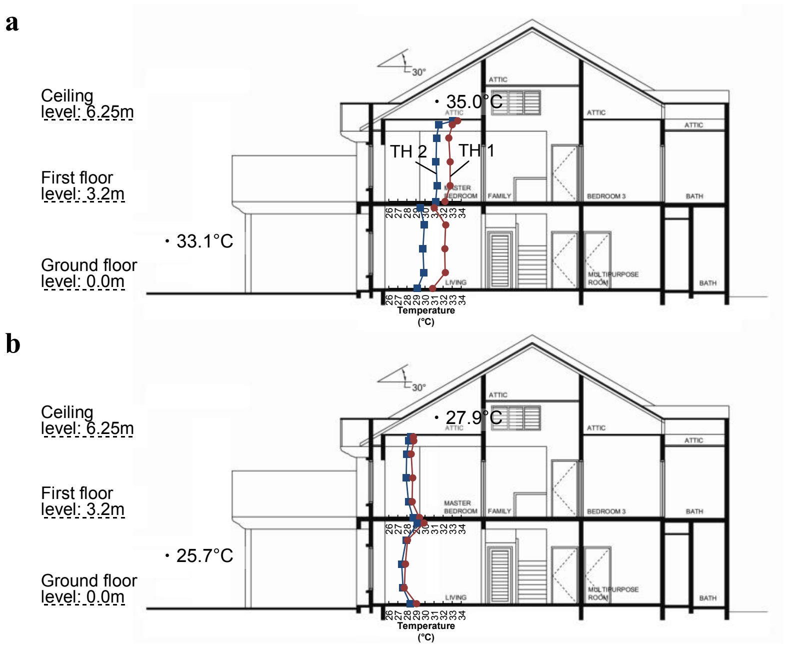


Figure 4.33. Vertical temperature distributions in the master bedrooms (first floor) and living rooms (ground floor) of terraced houses for Case 4. (a) 12 p.m.-8 p.m.; (b) 12 a.m.-8 a.m. Note: Section drawn based on architectural drawings with permission of Arkitek MAA (2010).

Between 12 a.m.-8 a.m., the ceiling surface temperatures reduce and the air temperature differences between floors that are seen in the daytime diminish (Figures 4.30b, 4.31b, 4.32b and 4.33b). The first floor ceiling surface temperature in the night ventilated room is about 1°C lower than the daytime ventilated and unventilated room, i.e. closed window condition at night. Overall, surface temperatures of the building structures are higher than the air temperatures during night-time due to the thermal storage effect of the heavyweight materials.

4.3.5 Cooling Potential of Night Ventilation in Relation to Outdoor Conditions

It is generally expected that indoor thermal conditions follow the outdoor conditions in naturally ventilated buildings. In fact, this is an underlying principle in the theory of adaptive thermal comfort that explains the relatively obvious relationship between indoor comfort temperature and outdoor air temperature in naturally ventilated buildings compared to air-conditioned buildings (see for example Humphreys *et al.*, 2007). On the other hand, a precise relationship between indoor and outdoor conditions in naturally ventilated buildings will be governed by the thermal capacity of the building and open window conditions, among others.

We analyse the relationship between indoor and outdoor thermal conditions on fair weather days in the night ventilated room compared to the other ventilation conditions in Figures 4.34-4.37, respectively, based on the results presented in Section 4.3.3. We consider the indoor operative temperature as a thermal comfort index in addition to relative humidity and absolute humidity conditions.

For Case 1 (daytime ventilation vs. night ventilation), Figure 4.34a shows that the relationships between outdoor air temperatures and indoor operative temperatures in both master bedrooms are almost linear but segmented clearly at a certain point each. This kind of regression model, known as segmented, piecewise or broken-line regression, is commonly used in the medical field, for example to see the effect of some risk factor on the response to change before and after some threshold value (Muggeo, 2003). It is also used in physical phenomena studies, for example to fit a diffuse radiation fraction against clearness index model for estimating hourly diffuse solar radiation at the surface (Furlan *et al.*, 2012). The value of the independent variable, x, where the response changes is called break-point, k. We apply a method given in Ryan and Porth (2007) to estimate the break-point, slopes and Y-intercepts of each segmented regression model:

$$y = a_1 + b_1x \qquad \text{for } x \leq k \qquad (4.7)$$

$$y = a_2 + b_2x \qquad \text{for } x > k \qquad (4.8)$$

In a continuous regression, when x equals k:

$$a_1 + b_1k = a_2 + b_2k \qquad (4.9)$$

and by replacing one of the parameters, say a_2, Eqs. 4.7 and 4.8 can be rearranged as:

$$y = a_1 + b_1x \qquad \text{for } x \leq k \qquad (4.10)$$
$$y = \{a_1 + k(b_1 - b_2)\} + b_2x \qquad \text{for } x > k \qquad (4.11)$$

An Excel spreadsheet tool based on the above method was available (Process Trends, 2013).

The result shows that the break-point for daytime ventilation is 31.5°C, which is higher than the break-point for night ventilation at 26.9°C (Figure 4.34a). The regression line is steeper and higher *after* the break-point for daytime ventilation whereas the regression line is steeper and lower *before* the break-point for night ventilation. These parts of the regression lines represent open windows during daytime and night-time, respectively. The gradients are relatively close to 1 but indoor temperatures are not equal to the outdoor temperatures in these open window conditions – the reasons are discussed in Section 4.3.3. The other parts of both regression lines are almost parallel with gradients around 0.2 (Figure 4.34a). They represent closed window conditions together with heat modulation by thermal mass in the brick terraced houses. The regression line after the break-point for night ventilation is 2°C lower than the regression line before the break-point for daytime ventilation. It should be noted that the values of the break-points are probably influenced by the time that we changed the window states between open and closed, i.e. 8 a.m. and 8 p.m., and thus we do not emphasize their exact values for other opening/closing periods. Nevertheless, the empirical regression lines summarize the thermal behaviour, i.e. indoor-outdoor relationship, of a night ventilated room in the typical terraced house when it is ventilated for the whole night (or vice versa for a daytime ventilated room) in a simple and flexible statistical way.

In general, relative humidity condition has an inverse relationship with the air temperature if the absolute humidity does not differ much. Figure 4.34b shows that the regression models between indoor and outdoor relative humidity for both daytime ventilation and night ventilation are also segmented and show inverse patterns compared to each temperature relationship. The break-points occur at 67% RH and 73% RH for daytime ventilation and night ventilation, respectively. The indoor relative humidity maintain almost constant values around 70% RH in closed window conditions, i.e. before the break-point for night ventilation and after the break-point for daytime ventilation. The regression line for night ventilation shows that indoor relative humidity is always higher than the daytime ventilated room and higher than the outdoors before the break-point.

The relationships between indoor and outdoor absolute humidity differ from those of temperature and relative humidity. Figure 4.34c shows that the relationship is linear in case of daytime ventilation. Indoor absolute humidity is always higher than the outdoors. On the other hand, the indoor absolute humidity in the night ventilated room has a weak relationship with the outdoors overall. In detail, two patterns can be seen, i.e. a positive correlation similar to daytime ventilation and a flat correlation. The indoor absolute humidity values in the night ventilated room mostly scatter between 18-20 g/kg' across the outdoor humidity range. The control of indoor humidity through daytime ventilation is less obvious when absolute humidity is considered.

On the other hand, a clear segmented regression is not seen between outdoor air temperatures and indoor operative temperatures when no ventilation was applied (Figure 4.35a). The gradient of the linear regression line for no ventilation is almost similar to that of night ventilation after the break-point. The latter line is 0.8-1.0°C lower than the former line. It signifies the nocturnal ventilative cooling effect in similar closed window condition during daytime.

As before, the regression models between indoor and outdoor relative humidity show inverse patterns compared to each temperature relationship (Figure 4.35b). The regression line for no ventilation has a similar gradient compared to that of night ventilation before the break-point. It is about 3% RH lower than the latter due to the temperature difference.

The relationship between indoor and outdoor absolute humidity in the unventilated room is weak, which is similar to that of the night ventilated room (Figure 4.35c). The indoor absolute humidity values in no ventilation condition scatter slightly higher than those of the night ventilation condition, although the indoor relative humidity is lower as shown above.

A clear segmented regression is also not seen between outdoor air temperatures and indoor operative temperatures when full-day ventilation was applied (Figure 4.36a). The linear regression line for full-day ventilation predicts slightly higher indoor operative temperatures even when compared to the regression line before the break-point for night ventilation. The indoor temperatures in the two rooms are not equal at night, as discussed in Section 4.3.3.

The linear regression line between indoor and outdoor relative humidity for full-day ventilation shows inversely that the indoor relative humidity is lower than that of night ventilation (Figure 4.36b).

Figure 4.36c further shows that the relationship between indoor and outdoor absolute humidity is linear in case of full-day ventilation. The regression line resembles that of daytime ventilation while the coefficient of determination is higher for full-day ventilation (see Figure 4.34c). The scatter of the indoor absolute humidity follows the outdoor absolute humidity more closely since the windows are always open in the full-day ventilated room.

When ceiling fan was used for Case 4, Figure 4.37a reveals that the gradients of the segmented regression line for night ventilation are relatively close before and after the break-point compared to the earlier cases. In particular, the gradient before the break-point, which represents open window condition at night, is reduced from about 0.6-0.8 to less than 0.5 (Figures 4.34a, 4.35a, 4.36a and 4.37a). The result implies that indoor operative temperature in the night ventilated room relative to the outdoor air temperature is increased in Case 4. This could be due to the convection effect of the ceiling fan that is seen in the vertical distribution analysis in Section 4.3.4. We inferred that if solar heat gain through the roof and ceiling was reduced so that air near the ceiling surface was not warmed, the change in the indoor-outdoor temperature relationship would not be seen when the ceiling fan was used.

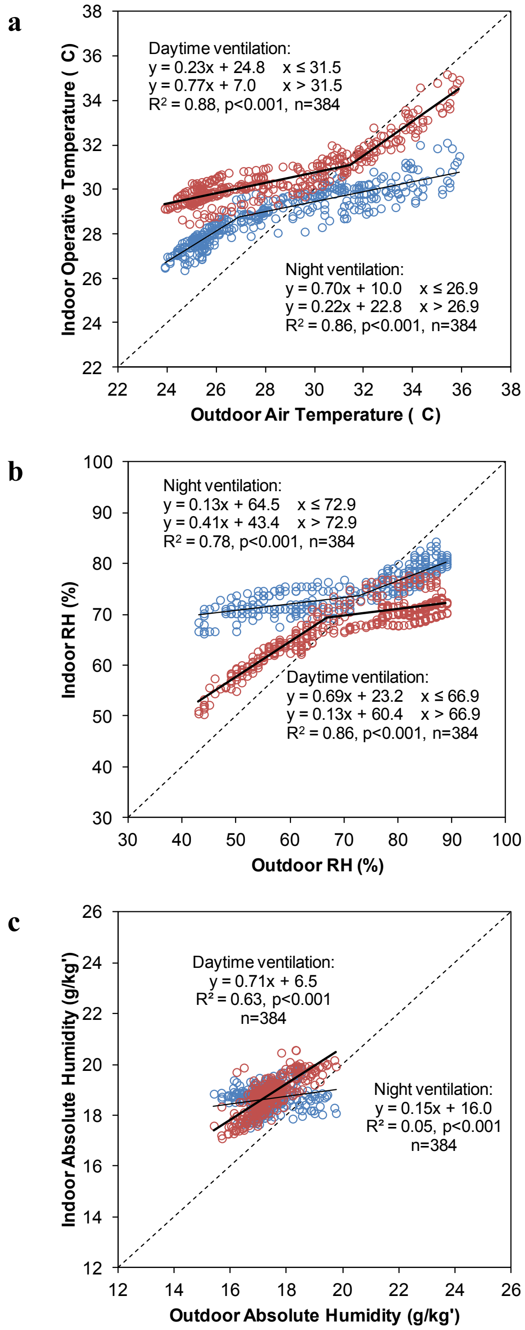


Figure 4.34. Relationships between outdoor conditions and indoor conditions at 1.5m above floor in the master bedrooms of terraced houses for Case 1. (a) Operative temperature; (b) Relative humidity; (c) Absolute humidity. Red points and thick regression lines represent daytime ventilation while blue points and thin regression lines represent night ventilation. Dashed lines represent indoor conditions equaling outdoor conditions.

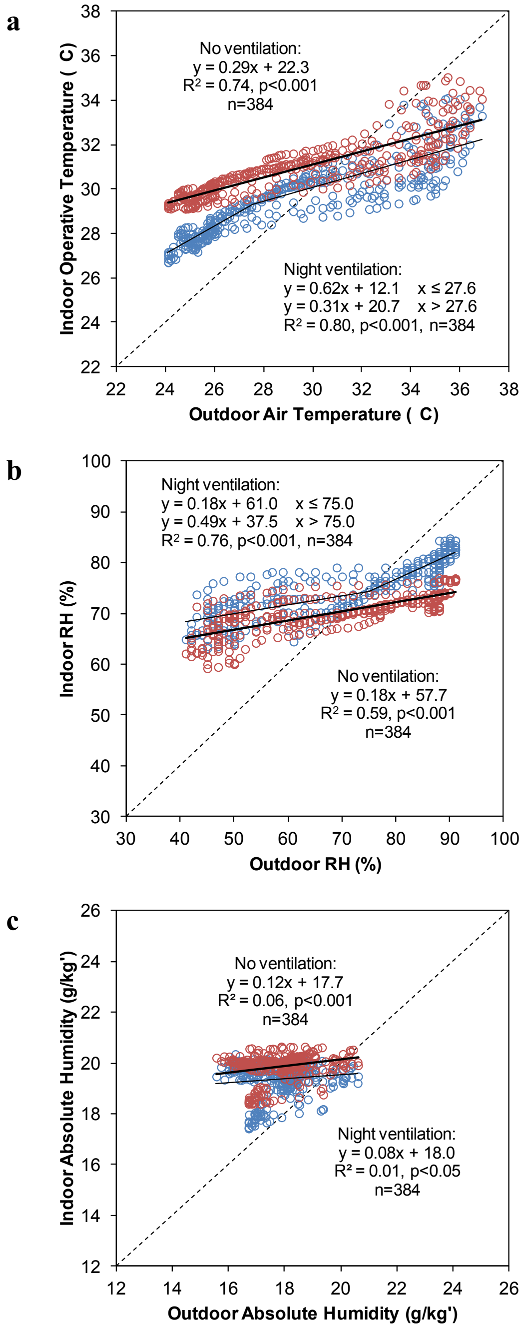


Figure 4.35. Relationships between outdoor conditions and indoor conditions at 1.5m above floor in the master bedrooms of terraced houses for Case 2. (a) Operative temperature; (b) Relative humidity; (c) Absolute humidity. Red points and thick regression lines represent no ventilation while blue points and thin regression lines represent night ventilation. Dashed lines represent indoor conditions equaling outdoor conditions.

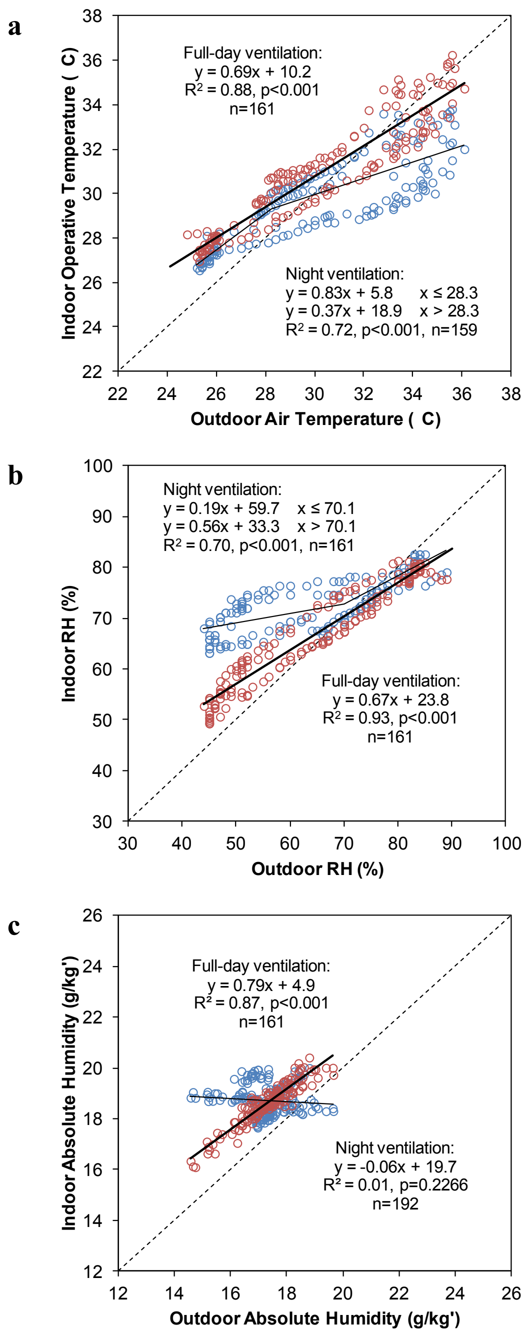


Figure 4.36. Relationships between outdoor conditions and indoor conditions at 1.5m above floor in the master bedrooms of terraced houses for Case 3. (a) Operative temperature; (b) Relative humidity; (c) Absolute humidity. Red points and thick regression lines represent full-day ventilation while blue points and thin regression lines represent night ventilation. Dashed lines represent indoor conditions equaling outdoor conditions.

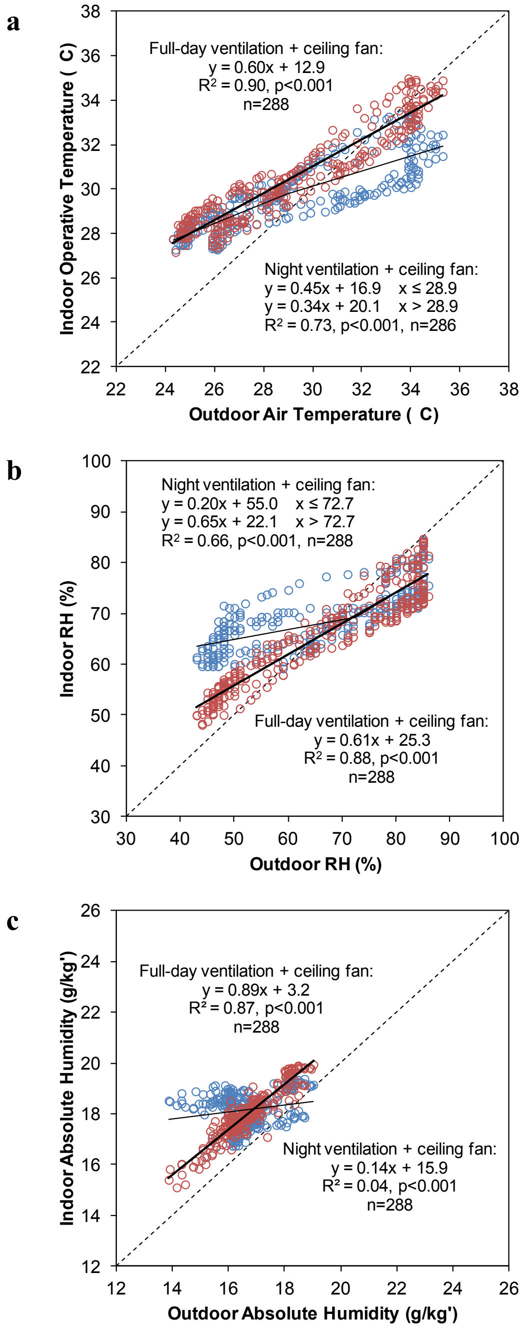


Figure 4.37. Relationships between outdoor conditions and indoor conditions at 1.5m above floor in the master bedrooms of terraced houses for Case 4. (a) Operative temperature; (b) Relative humidity; (c) Absolute humidity. Red points and thick regression lines represent full-day ventilation + ceiling fan while blue points and thin regression lines represent night ventilation + ceiling fan. Dashed lines represent indoor conditions equaling outdoor conditions.

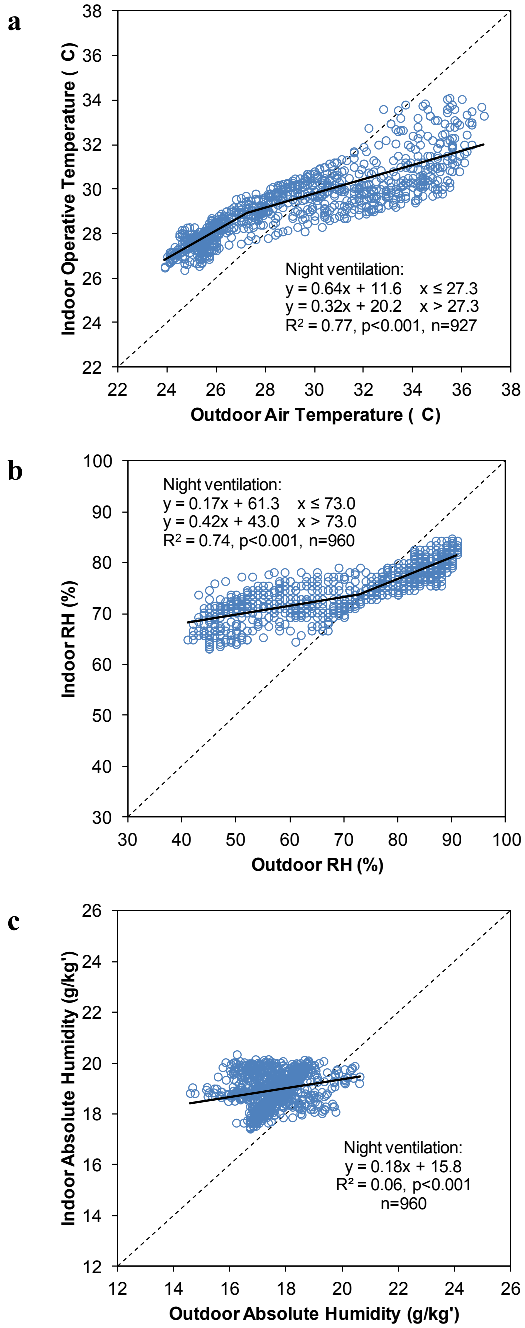


Figure 4.38. Relationships between outdoor conditions and indoor conditions at 1.5m above floor in the master bedrooms of terraced houses for night ventilation (Cases 1-3). (a) Operative temperature; (b) Relative humidity; (c) Absolute humidity. Dashed lines represent indoor conditions equaling outdoor conditions.

The gradient of the linear regression line for full-day ventilation is also probably reduced slightly in this case compared to the case without ceiling fan (Figures 4.37a and 4.36a).

The results of relative humidity and absolute humidity show almost similar patterns for Case 4 compared to Case 3 (Figures 4.37bc and Figures 4.36bc).

We combine the data set on fair weather days for night ventilation by including Cases 1-3 in Figure 4.38. The data for Case 4 is excluded due to the possible effect of ceiling fan, as explained above. The mean break-points in terms of temperature and relative humidity are 27.3°C and 73% RH, respectively (Figure 4.38ab). The gradients of the temperature regression line before and after the break-point are 0.32 and 0.64, respectively (Figure 4.38a). Besides weather variability, the scatter of the indoor operative temperature at higher values at the upper end of the outdoor air temperature is likely caused by the increase in indoor heat (mainly radiant heat) from solar radiation through unshaded parts of the windows and ceiling, as discussed in Sections 4.3.3 and 4.3.4. As before, the indoor absolute humidity values mostly scatter between 18-20 g/kg' across the outdoor humidity range (Figure 4.38c).

5

Field Measurement in Vernacular Houses

In the previous chapter, we evaluate the thermal comfort conditions in existing modern terraced houses based on a full-scale field experiment. The main interest of this chapter is investigating passive cooling techniques of vernacular houses that may be useful for the terraced houses. In this study, we extend our field measurement works in two kinds of traditional vernacular houses in Malaysia. They are the traditional Malay house and the traditional Chinese shophouse. Section 5.1 introduces them. The objectives of the field measurement are outlined in Section 5.2. Sections 5.3 and 5.4 present the methods and results of the measurement in detail.

5.1 The Traditional Malay House and the Traditional Chinese Shophouse

The traditional Malay house and the traditional Chinese shophouse are two fine examples of Malaysian vernacular architecture (Chen, 1998). Both houses are low-rise buildings. On the other hand, both houses originate from different cultural roots and exist in different locations. They are likely to offer different passive cooling techniques for our study.

The Malay house is usually a well-ventilated detached building of timber structure with raised floor. It can be seen mostly in rural villages. Its climatic adaptation techniques were described by Lim (1987) as follows: (1) raised-on-stilts lightweight construction (with open under floor space) using low thermal conductivity materials such as timber and thatch; (2) having full-height operable windows, upper ventilation grilles and minimal internal partitions for adequate cross ventilation; (3) having large roof eaves and low walls to control direct solar radiation and protect against rain; and (4) arranged sparsely with adequate natural vegetation in the surroundings for shade and a cooler microclimate. Despite receiving much praise for its environmental qualities especially in socio-cultural texts, for example

Oliver (2006), indoor thermal conditions of traditional Malay houses have not been studied in great detail. In a recent study, Hassan and Ramli (2010) conducted field measurement in a Malay house but the thermal measurement was not taken for the whole day. Its outdoor conditions are also less studied. Especially as urban environments become warmer, studies on modifying the microclimate with trees and grass were pursued in order to lower the ambient temperature (Bowler *et al.*, 2010) and cool buildings better (Mochida *et al.*, 2006). Generally, planted areas can be as much as 6-8°C cooler than built-up areas due to a combination of evapotranspiration, reflection, shading and storage of cold (Brown and DeKay, 2000). On the other hand, humidification may occur due to the vegetation.

The traditional Chinese shophouse is a narrow and deep-plan brick building situated in rows in relatively dense urban areas. The emergence of the Chinese shophouse in Malaysia can be traced to the influx of Chinese immigrants who came from the densely populated southern coastal provinces of China in the 19th century until World War II (Chen, 1998). By the early 20th century, the Chinese shophouse could be seen along main streets in every major town in Malaysia. One of the important features of the Chinese shophouse is having one or more courtyards in its internal space (Chen, 1998; Home, 1997). Originally, courtyard houses are typical of residences all over China, but their composition and scale differ to a specific degree across the country as influenced by the climatic conditions (Knapp, 1999). In general, the proportion of open space (courtyard) to structural space diminishes significantly from northeast to southeast China in order to restrict infiltration of intense direct rays of the sun and to facilitate ventilation (Knapp, 1999). Therefore, the above-mentioned author differentiated the term '*skywell*' for a relatively small courtyard, which is seen typically in southeast China, from a large northern courtyard. Most of the courtyards seen in Malaysian Chinese shophouses are considered as '*skywell*' in terms of their spatial configurations and functions. Since '*skywell*' is a substitution of the corresponding Chinese word (天井), the common term 'courtyard' is used in this thesis.

5.2 Objectives of the Field Measurement

The primary objectives of the field measurement in the vernacular houses are to understand traditional passive cooling techniques employed in and around the buildings and to evaluate their potential application to the modern terraced houses through comparative analysis. In order to meet these objectives, traditional houses in good thermal environmental conditions were selected as case study houses for the measurement. In particular, their indoor thermal comfort conditions would be evaluated to assist our understanding. The main living space that might benefit more from the passive cooling of each house, in other words the cooler spot in the house, was used for the detailed measurement and this evaluation. Most other spaces were also included in our measurement so that we could see the thermal environment variations in the whole house. These measurements confirmed our selection of the main measurement space. Each measurement was conducted for about 1-2 weeks to include several fair weather days. Additionally, in the traditional Malay house we considered the outdoor microclimate of the house while in the traditional Chinese shophouse our measurement was aimed at investigating the cooling effects of the courtyards.

5.3 The Field Measurement in Traditional Malay Houses

5.3.1 The Case Study Houses

The field measurement was conducted in two selected traditional Malay houses (MH 1 and MH 2) in Pontian, Malaysia consecutively from March to April 2011 (Figure 5.1). Pontian is located about 40km to the west of the city of Johor Bahru in Peninsular Malaysia. Pontian, like most Malaysian towns and villages, experiences year-round hot and humid climate with high rainfall. Both houses shared the typical Malaysian rural village setting with many trees in their surroundings.

Both selected houses, which were considered typical traditional Malay houses, had timber structure elevated more than 1m above the ground for the front part of the houses (front living hall and all bedrooms). The rear part of both houses was of brick-and-timber structure on the ground (rear living hall, dining, kitchen and bathroom) (Figure 5.2). The roofing material was zinc. As noted, traditional Malay houses used to apply thatch roof made from local palm leaves. However, thatch roof is gradually being replaced by modern materials such as zinc for easy maintenance and other reasons. Both MH 1 and MH 2 installed ceiling in the front living halls and master bedrooms.

Windows in the two houses comprised full-height timber panel windows, half-height timber panel windows and half-height glass louver windows, with upper ventilation openings (permanently open) above some of the windows, doors and walls. Total floor areas of MH 1 and MH 2 are 130 m^2 and 178 m^2, respectively. Their household sizes were 7 persons for MH 1 and 5 persons for MH 2. Both houses were occupied throughout the measurement period. Household behaviour regarding room occupancy, opening windows and ceiling fan usage was recorded hourly throughout the measurement period.

5.3.2 The Measurement Methods

Detailed measurements of physical thermal comfort variables were taken at 1.5m height above floor in the front living halls of the two houses (Figure 5.2). The floor-to-ceiling heights of the halls are 2.7m in MH 1 and 2.9m in MH 2. The measurement instruments used are given in Table 5.1. Air temperature and relative humidity were also measured in all other rooms of both houses (Table 5.1). A weather station (HOBO U30-NRC and HOBO Pro v2 U23-001) was placed on the grass area in front of each house to record the ambient weather conditions during respective measurement (Figure 5.2). Outdoor air temperatures were also measured at various locations around each house (Figure 5.2 and Table 5.1). All measurements were logged automatically at 10-minute intervals.

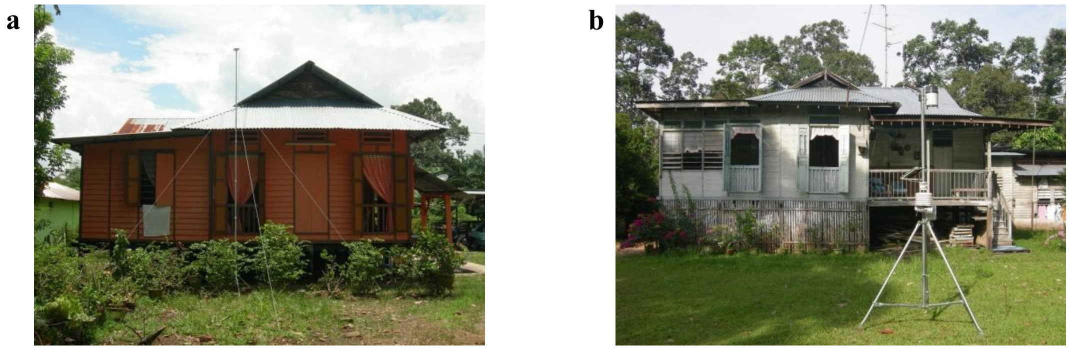


Figure 5.1. Exterior view of the case study Malay houses. (a) MH 1; (b) MH 2.

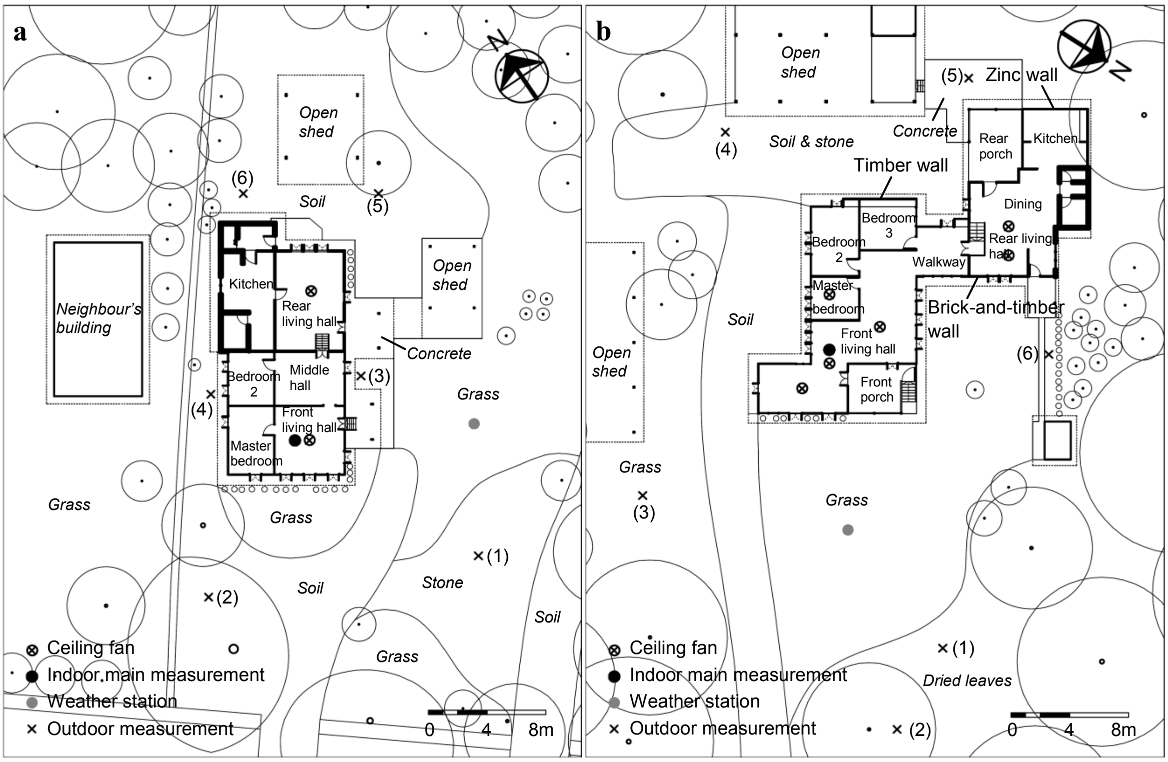


Figure 5.2. Plan of the case study Malay houses. (a) MH 1; (b) MH 2.

Table 5.1. Description of measurement instruments used in the Malay houses.

Measured variable	Instrument model	Accuracy
Front living halls		
Air temperature and RH	Vaisala HMP155	±0.10°C; ±1.0% RH at 0-75% RH
Air speed	Innova MM0038	±5% plus ±0.05m/s
Globe temperature	Type T thermocouple inside 75mm diameter black globe	±0.1%+0.5°C plus ±0.5°C for cold junction compensation
Other rooms		
Air temperature and RH	T&D TR-72U and HOBO U12-011	±0.3°C; ±5% RH and ±0.35°C; ±2.5% RH
Weather station		
Air temperature and RH	HOBO Pro v2 U23-001	±0.2°C; ±2.5% RH at 10-90% RH
Wind speed and wind direction	Onset S-WCA-M003	±0.5m/s; ±5°
Global horizontal solar radiation	Onset S-LIB-M003	±10 W/m^2 or ±5% (whichever is greater) plus ±0.38 W/m^{2}K for additional temp. induced error at 25°C and above
Barometric pressure	Onset S-BPB-CM50	±3.0 mbar
Rainfall	Onset S-RGB-M002	±1.0% at up to 20 mm/hr
Outdoor		
Air temperature	T&D TR-52 and T&D TR-51A	±0.3°C and ±0.5°C

5.3.3 Thermal Comfort in the Front Living Halls

Measurement results on fair weather days, i.e. from 23-28 March 2011 and 31 March-6 April 2011, are analysed for MH 1 and MH 2, respectively. Figures 5.3 and 5.4 present the measured thermal variables in the front living halls with the corresponding outdoor conditions measured by the weather station during the respective periods. As shown, maximum outdoor air temperatures are 31-33°C (Figures 5.3a and 5.4a) while outdoor relative humidity is always above 60% (Figures 5.3b and 5.4b). Daily global horizontal solar radiation ranges from about 4000-5900 Wh/m^2 on these days.

In general, it is observed that indoor air temperatures in both halls follow the pattern of the outdoor air temperatures, as expected for the lightweight timber structures with low airtightness (Figures 5.3a and 5.4a). No time lag between indoors and outdoors in terms of daily maximum and minimum air temperatures is seen. Indoor air temperatures are higher than the corresponding outdoor air temperatures throughout the day except for a few hours around 9 a.m. until 11 a.m. (Figures 5.3a and 5.4a). Indoor air temperature elevations are

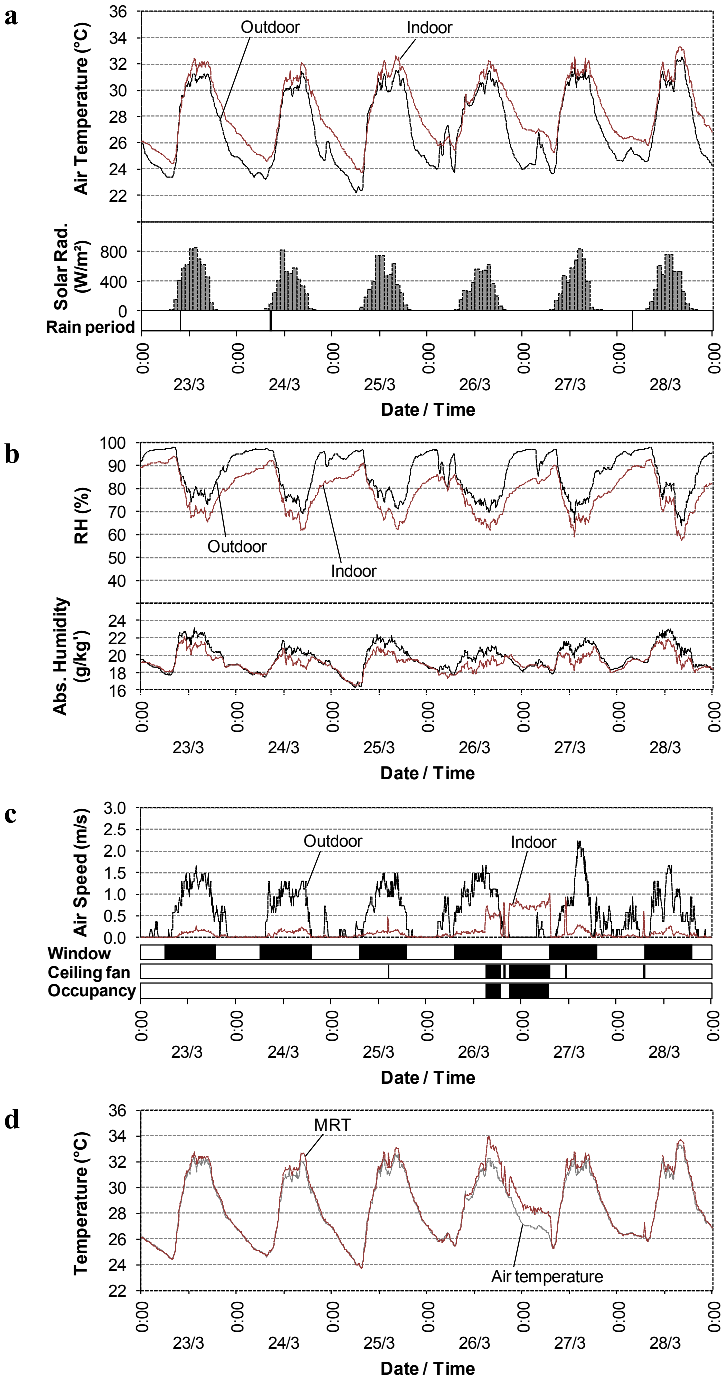


Figure 5.3. Temporal variations of the measured thermal variables in the front living hall of MH 1 and the outdoors. (a) Air temperature and solar radiation; (b) Relative humidity and absolute humidity; (c) Air speed and occupant's behaviour; (d) Mean radiant temperature. In figure (c), black bars indicate open for "window", used for "ceiling fan" and occupied for "occupancy".

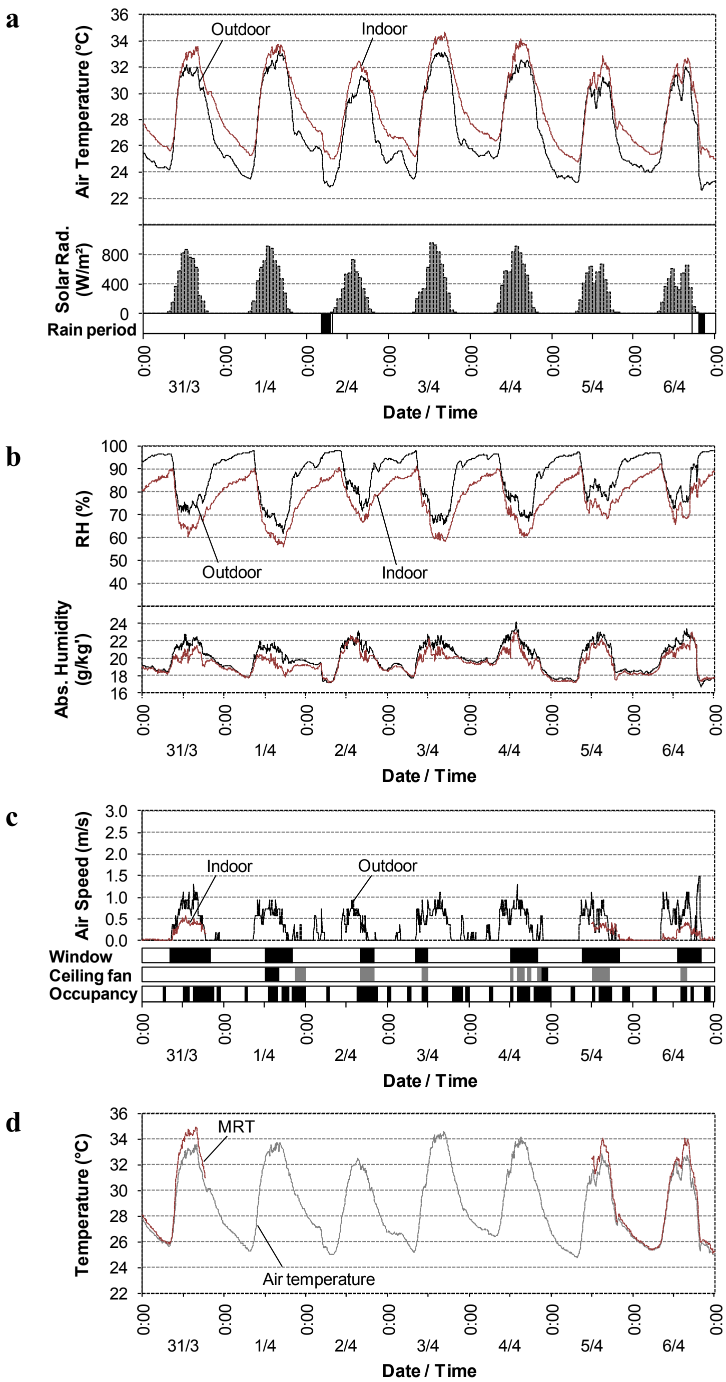


Figure 5.4. Temporal variations of the measured thermal variables in the front living hall of MH 2 and the outdoors. (a) Air temperature and solar radiation; (b) Relative humidity and absolute humidity; (c) Air speed and occupant's behaviour; (d) Mean radiant temperature. In figure (c), black bars indicate open for "window", used for "ceiling fan" and occupied for "occupancy". Indoor air speed and MRT on 1-4 April are not shown/analysed due to possible data error.

higher under closed window conditions than open window conditions (see window usage in Figures 5.3c and 5.4c).

As seen in Figure 5.3a, indoor-outdoor air temperature differences in the front living hall of MH 1 average 0.7°C during daytime under open window conditions and 1.9°C during night-time under closed window conditions. In MH 2, the same differences in the front living hall average 1.0°C during daytime under open window conditions and 2.0°C during night-time under closed window conditions (Figure 5.4a). The period between 8 a.m. and 8 p.m. is considered as daytime while the period between 8 p.m. and 8 a.m. is considered as night-time.

The mean radiant temperature is calculated according to ISO 7726 (BSI, 2002) (see Eq. 4.5 in Chapter 4). It is observed that maximum indoor mean radiant temperatures at the measurement point are higher than the maximum indoor air temperatures by 0.6°C in MH 1 and 1.3°C in MH 2 on average (Figures 5.3d and 5.4d). The higher mean radiant temperatures seen in the front living hall of MH 2 imply that the radiant heat might cause its slightly higher indoor air temperatures compared to MH 1. The radiant heat might heat the indoor air most and causes the indoor air temperature elevations above the outdoors, although it is possible that some heat is also stored in the building structures. Further, under closed window conditions, ventilation to remove or cool the heated indoor air would become slower. Thus, indoor air temperature elevations are higher in this condition despite the presence of permanent ventilation openings.

During night-time, the indoor mean radiant temperatures are similar or only slightly higher than the indoor air temperatures (Figures 5.3d and 5.4d). The result signifies that the lightweight structures cool quickly at night. As indicated in the occupancy bar in Figure 5.3c, it seems that the front living hall of MH 1 was rarely used due to two possible reasons: the household occupied the rear living hall mostly in the daytime; and short occupancy of less than one hour might not be recorded. The said front living hall was occupied and its ceiling fan was used on the night of 26 March until the next morning (Figure 5.3c). These probably elevate the corresponding mean radiant temperature to be 1-2°C higher than the air temperature during the period (Figure 5.3d).

It is anticipated that proper prevention of solar heat gain through walls, window openings and roof/ceiling by shading and thermal insulation would be rather important, together with natural ventilation to remove indoor heat, to lower the indoor air temperatures to the outdoor level. Nevertheless, indoor air temperatures below the outdoors are not anticipated for these lightweight timber structures which are without thermal mass effect.

In terms of humidity, Figures 5.3b and 5.4b show that outdoor absolute humidity increases during daytime by up to 3-6 g/kg' higher than the daily minima. This reflects the high evapotranspiration of plants, moist soil and dew in the rural area after sunrise as the outdoor air temperature increases (Oke, 1987). Indoor absolute humidity values in both front living halls are lower than the outdoors by 1 g/kg' on average during daytime. It is implied that indoor moisture production during daytime from the likely sources including occupants, moisture desorption of hygroscopic surfaces (e.g. timber, fabric) and ventilation is lower than the outdoor evapotranspiration rate. In this case, it is assumed that ventilation brings in humidity from the outdoor air (Kurnitski and Seppänen, 2009). Nevertheless, the daytime absolute humidity is 20-23 g/kg' indoors (Figures 5.3b and 5.4b).

On the other hand, indoor air speed as high as 0.56 m/s is observed in the front living hall of MH 2 through open windows during daytime (Figure 5.4c). The corresponding value in MH 1 is 0.28 m/s (Figure 5.3c). Cross ventilation in the front living hall of MH 2 is better than that of MH 1 probably due to having more windows on several different sides (see Figure 5.2). When ceiling fan was used in MH 1, indoor air speeds of 0.68 m/s on average were obtained at the measurement point (Figure 5.3c). It is noted that occupants of MH 2 also used another ceiling fan further from the air speed measurement point in the front living hall whose usage is shown in grey in Figure 5.4c.

Figure 5.5 confirms that the indoor absolute humidity is higher at high indoor operative temperature than at the lower end, as discussed above. The operative temperatures span widely between 24°C and 34°C. None of the data in both front living halls falls within the comfort zone recommended by ASHRAE (2010) for typical indoor environments at 0.5 clo level.

Temporal variations of the same indoor operative temperatures are plotted in Figure 5.6 for thermal comfort evaluation. This evaluation is based on the thermal comfort criteria that are developed in this study (see Chapter 3: Section 3.3.6). The calculation method of operative temperature is based on ISO 7726 (BSI, 2002) (see Eq. 4.6 in Chapter 4). In Figure 5.6, the 80% comfortable upper limit is drawn for each day based on the measured outdoor air temperatures. The 80% comfortable upper limits range between 28.2-28.7°C for MH 1

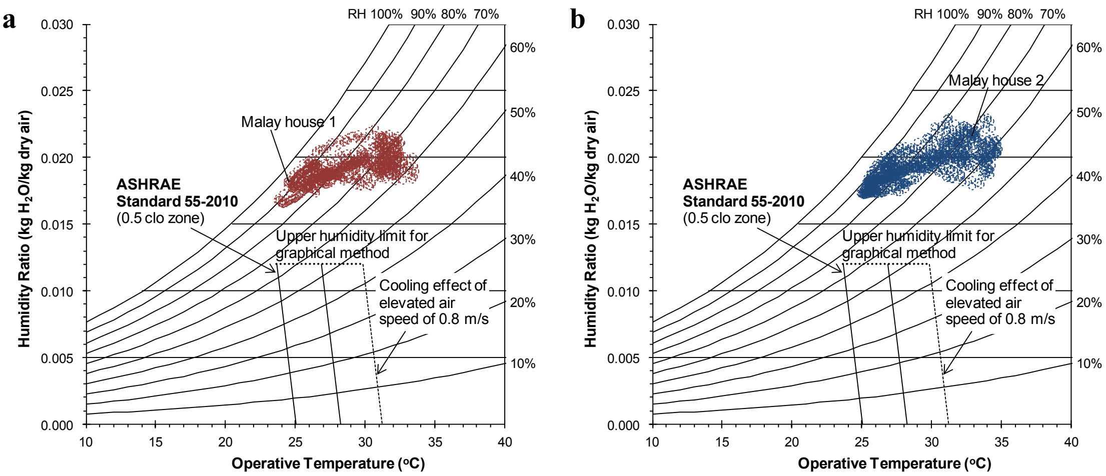


Figure 5.5. Scatter diagram of indoor operative temperatures and indoor humidity in the front living halls on a psychrometric chart. (a) MH 1; (b) MH 2. In figure (b), the measured globe temperatures are shown for MH 2.

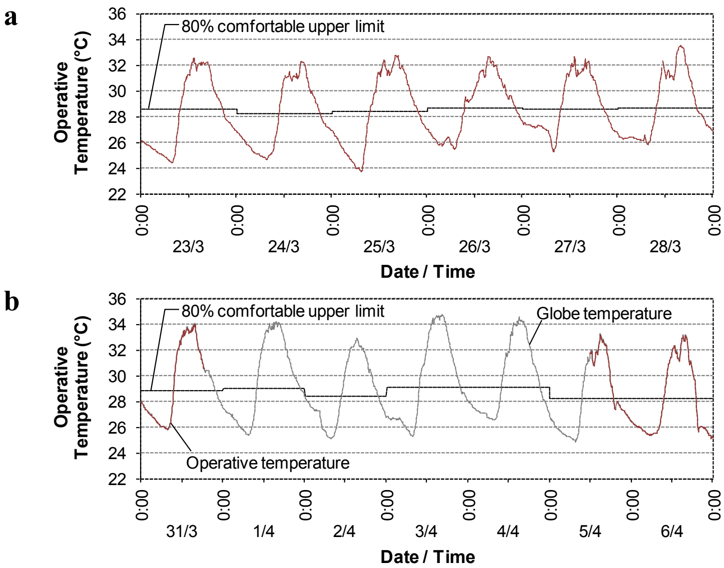


Figure 5.6. Temporal variations of indoor operative temperatures in the front living halls and the corresponding temperature limits for thermal comfort. (a) MH 1; (b) MH 2. In figure (b), the measured globe temperature is shown in grey line to substitute for the unavailable operative temperature.

and 28.2-29.1°C for MH 2. Table 5.2 summarizes the indoor operative temperature deviations from the 80% comfortable upper limits and the exceeding periods on these fair weather days.

The evaluation reveals that the indoor operative temperatures in both front living halls basically exceed the 80% comfortable upper limits for the whole afternoon period. At the peak period, the indoor operative temperatures are 4.0-4.8°C and 4.6-5.7°C above the proposed limits in MH 1 and MH 2, respectively (Figure 5.6 and Table 5.2). The exceeding periods are 47% in both MH 1 and MH 2 (Table 5.2). As observed, ceiling fan and/or cross ventilation was used by the occupants (see Figures 5.3c and 5.4c) most likely to adapt to these high temperatures and improve the indoor thermal comfort. It was found from interview that the households generally perceived their thermal sensation in the front living halls as "slightly warm" (+1) and "warm" (+2) on the ASHRAE scale on afternoons of fair weather days (see Table 5.3), though they perceived it to be from "neutral" (0) to "cool" (-2) from the evening until early morning. Our evaluation agrees with their subjective response.

5.3.4 Thermal Environment Variations in the Whole House (Indoors and Outdoors)

A statistical summary of the measured indoor air temperatures in each room of both houses is illustrated in Figure 5.7. All descriptive statistical values for all rooms including

Table 5.2. Summary of thermal comfort evaluation in the front living halls of Malay houses on fair weather days.

Malay house	Deviation of indoor operative temperature from the 80% comfortable upper limits (°C)[a]		Exceeding period (%)
	Daily maximum	Daily minimum	
MH 1	4.0 to 4.8	-2.9 to -4.7	47
MH 2	4.6 to 5.7	-2.5 to -3.8	47

[a] Positive values indicate indoor operative temperatures above the 80% comfortable upper limits and negative values indicate indoor operative temperatures below the 80% comfortable upper limits.

Table 5.3. General perception of thermal sensation on the ASHRAE scale by household during the hottest period of the day for respective rooms. See room legend in Figure 5.7.

Malay house 1								
Room	MB	FL	M	B2	K	RL		
Thermal sensation	No data	+1	+1	No data	+2	+3		
Malay house 2								
Room	MB	FL	RL	K	W	B2	D	B3
Thermal sensation	+2	+2	+3	+3	+2	+2.5	+3	+2.5

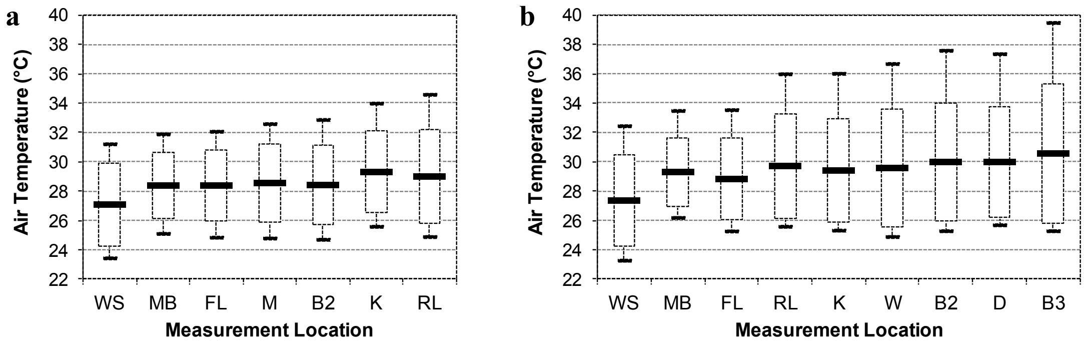


Figure 5.7. Statistical summary (5th and 95th percentiles, mean and ± one standard deviation) of measured air temperatures. (a) MH 1; (b) MH 2. WS: weather station; MB: master bedroom; FL: front living hall; M: middle hall; B2: bedroom 2; K: kitchen; RL: rear living hall; W: walkway; D: dining; B3: bedroom 3.

the front living halls are higher than those of the respective weather station measurements. This implies that the whole houses are generally warmer than the outdoor conditions during both daytime and night-time. Nevertheless, the indoor air temperatures vary largely among the different rooms particularly in terms of daily maxima, which are represented by 95th percentiles (Figure 5.7). Both front living halls are among the rooms with the lowest daily maximum (95th percentile), mean and minimum (5th percentile) air temperatures. It is considered that both front living halls also have better thermal comfort compared to other spaces in the whole house. As compared in Table 5.3, both households perceived their front living halls to be less hot than most other rooms during the hottest period of the day.

As discussed in Section 5.3.3, one of the possible major causes of indoor air temperature elevations above the outdoor is solar radiation heat gain through the building envelope. Due to the high noon solar altitude at the location, radiant heat through the roof is probably larger than from the walls and the windows. Heat flux was measured on the underside surface of the ceiling in the front living hall of MH 1 during the measurement period. The maximum heat flux ranges from 29-38 W/m^2 in the afternoons. Figure 5.7 shows that rooms that were installed with ceiling, i.e. the front living halls (FL), master bedrooms (MB) and middle hall (M) of both houses, have lower daily maximum air temperatures compared to the other rooms without ceiling. As explained before, traditional Malay houses used thatch roof without using ceiling in the past, and was reported to be cooler than zinc roof in a previous field measurement (Markus and Morris, 1980). The result implies that the zinc roof would require at least ceiling installation in order to reduce solar heat gain through the roof in the occupied rooms.

Figure 5.8 displays the hourly vertical sun path on a measurement day, i.e. 25 March for MH 1 and 3 April for MH 2, on fisheye photos taken at 1.5m height above floor on the window planes in the front living halls using equisolid-angle projection lens. To project the position of the sun into the hemispherical fisheye lens image, geometrical model equations based on an object coordinate system (X, Y, Z), the camera coordinate system and the image coordinate system (x', y'), as described in Schneider *et al.* (2009), are used. We assume the object (the sun) coordinates to be the same in the camera coordinate system. The position of the sun at a particular time in the camera coordinate system is thus represented by X and Y coordinates as follows:

$$X = Z \tan \delta \quad (5.1)$$

$$Y = Z \tan \varepsilon \quad (5.2)$$

$$\delta = \theta - \omega \quad (5.3)$$

$$\varepsilon = \frac{\tan \gamma}{\cos \delta} \quad (5.4)$$

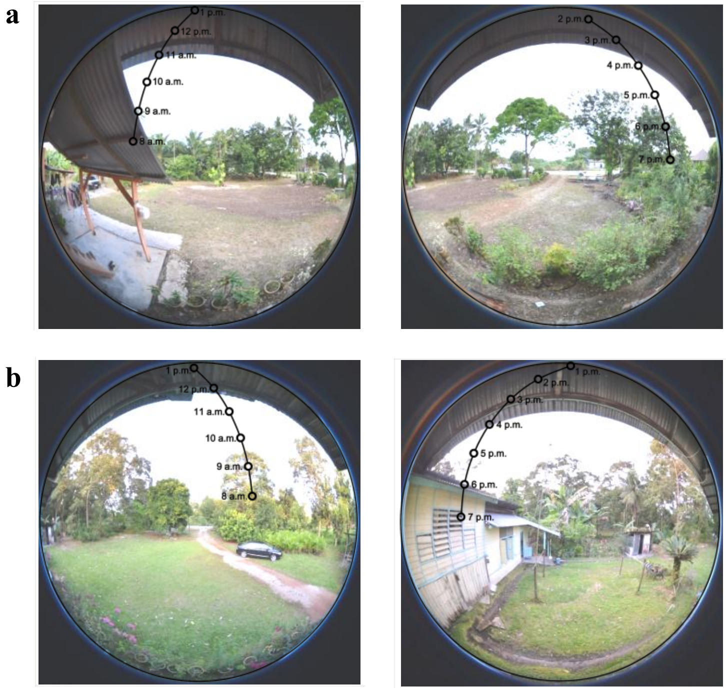


Figure 5.8. Vertical sun path diagrams of windows in the front living halls. (a) MH 1; (b) MH 2.

where δ is horizontal shadow angle (°) (Eq. 5.3), ε is vertical shadow angle (°) (Eq. 5.4), θ is solar azimuth angle (°), ω is azimuth angle of the window surface (°) and γ is solar altitude angle (°) (Szokolay, 1980). The *Z* coordinate is given an imaginary fixed value of 10 for ease of calculation. The *X* and *Y* coordinates are transformed into the image coordinates using the following equations for equisolid-angle projection:

$$x' = c \times \frac{\sin(0.5\beta)}{\sqrt{(\frac{Y}{X})^2+1}} + x_0' + \Delta x' \quad (5.5)$$

$$y' = c \times \frac{\sin(0.5\beta)}{\sqrt{(\frac{X}{Y})^2+1}} + y_0' + \Delta y' \quad (5.6)$$

and

$$\beta = \arctan\frac{\sqrt{X^2+Y^2}}{Z} \quad (5.7)$$

where c is the principal distance of the lens, x_0 and y_0 are coordinates of the principle point, and Δx and Δy are correction terms which contain additional parameters to compensate for

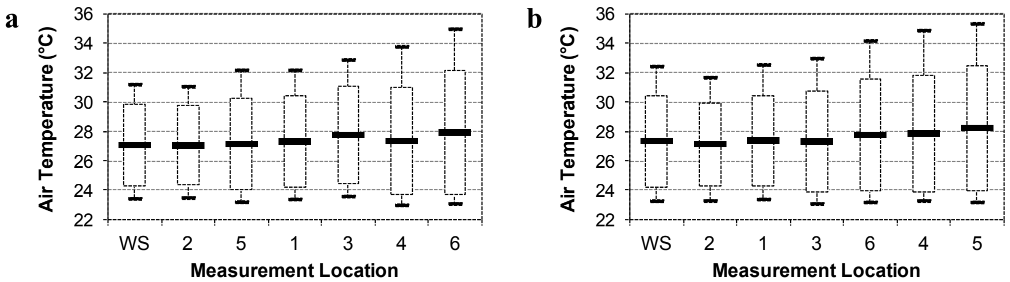


Figure 5.9. Statistical summary (5th and 95th percentiles, mean and ± one standard deviation) of measured air temperatures at outdoor locations. (a) MH 1; (b) MH 2. WS: weather station.

systematic effects (Schneider *et al.*, 2009). Since these values are unknown, *c* is assumed to be 1 and the latter terms are omitted.

As shown in Figure 5.8, shading from direct solar radiation is provided by the roof overhang from around noon until 4 p.m. It should be noted that the shading would also reduce the solar heat received on opaque walls. Further shading by trees could prevent direct solar radiation at lower solar altitude as well as shield the building structures and indoor spaces from diffuse solar radiation. In comparison, Bedroom 3 of MH 2 is likely to be heated the most by the afternoon solar radiation on its protruded western wall with shorter overhang (see Figures 5.2b and 5.7b). The room was also surrounded by unshaded, dry ground surface outdoors (see Figure 5.2b).

Figure 5.9 shows a statistical summary of the measured air temperatures at several outdoor locations of both houses. Similar to the indoor air temperature variations among rooms, the outdoor air temperatures vary especially in terms of daily maxima, which are represented by 95th percentiles. In both houses, outdoor air temperatures under shade trees (locations 2) have the lowest daily maxima compared to all other locations including the weather station (Figure 5.9). However, areas surrounded by low dense plants of about building height (locations 6) are hotter than open grass areas (weather station) during daytime, probably due to blocked wind for heat dissipation. As expected, relatively high maximum outdoor air temperatures are observed in open paved areas, i.e. locations 4 and 5 of MH 2 (Figure 5.9b).

The different outdoor microclimate likely influences the indoor thermal conditions of the adjacent rooms. For example, the master bedroom of MH 1 and the kitchen of MH 2 have relatively low indoor air temperatures despite their western locations in the respective houses (Figure 5.7). They likely receive shading and cooling effects from the immediate shade trees (see Figure 5.2). On the other hand, the hotter air and heated dry surface outside Bedroom 3 of MH 2 probably contribute to increase the indoor air temperature of the room during daytime, as mentioned above. The results imply that the microclimate afforded by shade trees is a cooling source for the lightweight timber houses. Low dense plants are less effective for cooling.

5.3.5 Cooling Potential of the Traditional Malay Houses in Relation to Outdoor Conditions

We analyse the relationship between indoor and outdoor thermal conditions on fair weather days in the traditional Malay houses based on the results presented in Section 5.3.3. The analysis method is similar to that applied to the terraced houses (see Chapter 4: Section 4.3.5).

Figure 5.10a reveals that the indoor operative temperatures in the Malay houses have linear relationships with the outdoor air temperatures, even though the households literally practiced daytime ventilation. A change in the slopes of the regression lines, i.e. segmented regression as found in the daytime ventilated terraced house (see Figure 4.34a in Chapter 4), is not seen. Two possible reasons are that the lightweight building structures afford little heat modulation and the houses are basically porous to air infiltration even in closed window states. The regression line for MH 1 falls slightly lower than that of MH 2 (Figure 5.10a). Both regression lines show that the indoor operative temperatures follow the outdoor air temperatures closely at gradients of about 0.9 and are always 1-2°C higher than the outdoors at outdoor air temperatures between 22-33°C. The possible reasons that indoor air temperature exceeds the outdoor air temperature are discussed in Section 5.3.3. It is expected that the regression lines for the Malay houses would be steeper and closer to the outdoor air temperature if their windows are open at night.

Further, Figure 5.10a shows that the scatter of the indoor operative temperatures is tightly centred around the regression lines at high outdoor air temperatures. The result implies that the solar heat control in the front living halls during daytime is probably effective. In comparison, the indoor operative temperatures in the terraced houses scatter further above the regression lines at the upper end of the outdoor air temperature, as discussed in Chapter 4: Section 4.3.5 (see Figures 4.34a, 4.35a, 4.36a, 4.37a and 4.38a). We infer that the solar heat control in the Malay houses is possibly better than that of the existing terraced houses.

Figure 5.10b shows that the linear regression lines for relative humidity show inverse patterns compared to the regression lines for temperature. Indoor relative humidity in both Malay houses is consistently lower than the outdoor relative humidity by around 10%. The gradients of the regression lines are about 0.9.

Strong linear indoor-outdoor relationships are also seen in terms of absolute humidity in the Malay houses (Figure 5.10c). The slopes of the regression lines are about 0.7-0.8. As discussed above, infiltration and thus mass transport likely occur in the porous timber houses with upper ventilation openings throughout the day, even though windows are closed at night. The regression lines show that indoor absolute humidity in the Malay houses is lower than the outdoors but outdoor absolute humidity is high at 16-24 g/kg'. These points are discussed in Section 5.3.3.

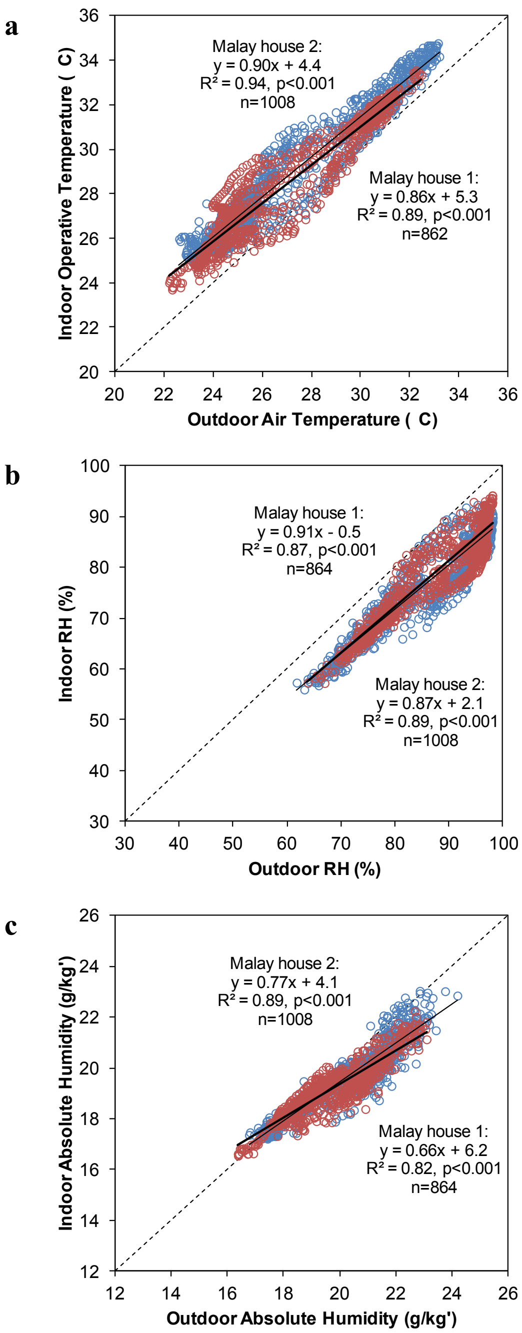


Figure 5.10. Relationships between outdoor conditions and indoor conditions in the front living halls of Malay houses. (a) Operative temperature; (b) Relative humidity; (c) Absolute humidity. Red points and thick regression lines represent MH 1 while blue points and thin regression lines represent MH 2. Dashed lines represent indoor conditions equaling outdoor conditions. In figure (a), the measured globe temperatures are shown for MH 2.

5.4 The Field Measurement in Traditional Chinese Shophouses

5.4.1 The Case Study Houses (TTCLC of NUS)

Our following field measurement was conducted in two adjacent traditional Chinese shophouses (CSH 1 and CSH 2) located in the core heritage zone of Melaka, Malaysia in October 2011 (Figure 5.11). The two selected buildings were originally constructed around the Dutch colonial era in the 19th century. Major restoration was made by the National University of Singapore (NUS) in 2004. These shophouses are currently used as an academic centre named Tun Tan Cheng Lock Centre for Asian Architectural and Urban Heritage (TTCLC). They were occupied only on alternate weekdays, i.e. Monday, Wednesday and Friday, from 10 a.m.-5 p.m. during the measurement period. Although architectural designs of traditional Chinese shophouses vary among different construction years, these selected shophouses were considered representative of their original construction era (Raja Shahminan, 2008; TTCLC, 2013).

CSH 1 had three courtyards while CSH 2 had two courtyards (Figure 5.12). The sizes of the courtyards increased from the front to the rear of the buildings. The front courtyards (CY1) and middle courtyards (CY2) of both shophouses were deep atrium-type courtyards encircled by two-storey structures while the rear large courtyard (CY3) of CSH 1 was surrounded by single-storey structures. The front courtyards (CY1) measured 3.4-3.6m by 3.8m in CSH 1 and 2.6m by 4.0m in CSH 2, respectively, at the first floor level. The middle courtyards (CY2) had larger dimensions, which is 3.9-4.1m by 4.9m in case of CSH 1. The middle courtyard of CSH 2 (2-CY2) was located at the end of the building lot and its configuration differed from the other courtyards (Figure 5.12). The corresponding roof openings of the courtyards were smaller than the sizes given above. This was due to the presence of roof overhangs for protection from the rain and solar radiation. For example, the roof opening size of the front courtyard in CSH 1 (1-CY1) measured 2.7-2.8m by 2.6m, which was about half the size of the courtyard below in area (see Figure 5.19).

Windows in the two shophouses comprised half-height timber and glass panel windows with upper ventilation openings (permanently open) above them. These ventilation openings were seen on almost all the internal partition walls as well. The external main door and windows were opened only on the ground floor in CSH 2 and on the first floor in CSH 1, respectively, when occupied, i.e. from 10 a.m.-5 p.m. on alternate weekdays. Air conditioner was not installed in both buildings. On the other hand, ceiling fans were installed in most of the rooms. Nevertheless, the ceiling fans were not used during the measurement period except for the ones in the courtyard-adjacent living halls, which were operated only briefly in CSH 1 and for a few hours in CSH 2 during daytime on three days (12, 14 and 17 October) (see Figure 5.13c). The building structures were of timber frame and masonry/concrete with lime-plastered brick walls, thus both buildings were considered to have high thermal mass.

The thickness of the walls is 350mm or more. As shown in Figure 5.11bc, the front courtyard of CSH 1 (1-CY1) had a planted tree and terra cotta brick floor while the corresponding courtyard of CSH 2 (2-CY1) had graveled floor surface without any plant.

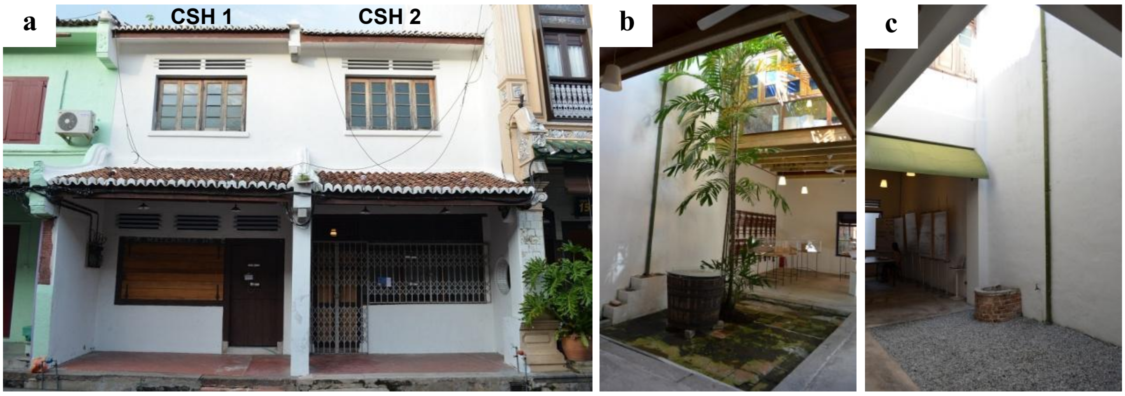


Figure 5.11. Views of the case study Chinese shophouses. (a) Front facade; (b) Courtyard of CSH 1 (1-CY1); (c) Courtyard of CSH 2 (2-CY1).

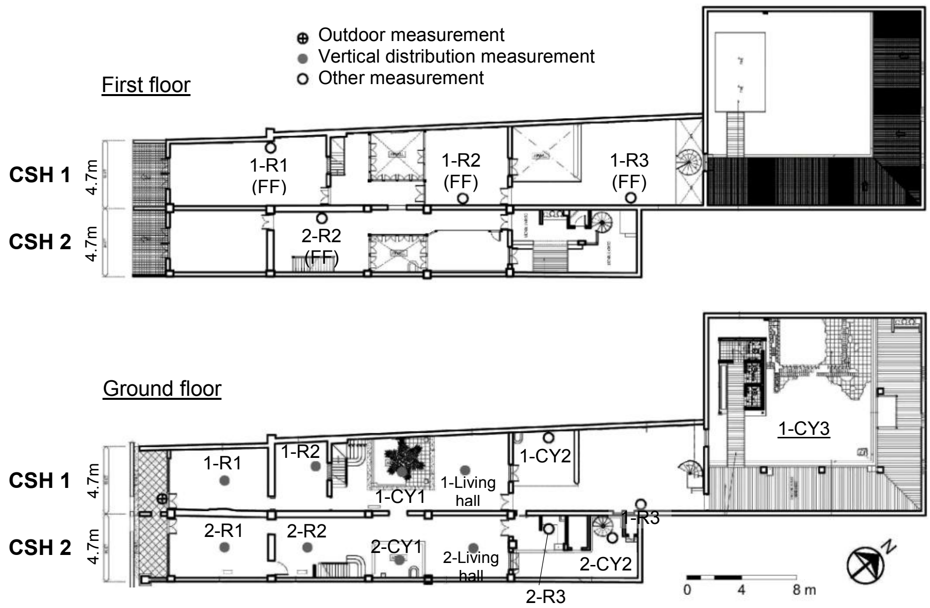


Figure 5.12. Floor plans of the case study Chinese shophouses. Note: Floor plan with permission of TTCLC (2011), National University of Singapore.

5.4.2 The Measurement Methods

Measurements of all physical thermal comfort variables were taken at 1.5m height above floor at the centre of the courtyard-adjacent living halls in both Chinese shophouses (Figure 5.12). As shown in Figure 5.11bc, there was no partition between the front courtyards and encircling spaces on the ground floor, including the said living halls, and therefore these living halls were considered semi-open spaces to the outdoors. The floor-to-ceiling heights are about 4m on the ground floor and about 3.5m on the first floor in both shophouses. As indicated in Figure 5.12, vertical distributions of temperatures were investigated at four points on the ground floor in each house including at the front courtyards (CY1). Air temperature and relative humidity were also measured in several rooms on both floors of the

Table 5.4. Description of measurement instruments used in the Chinese shophouses.

Measured variable	Instrument model	Accuracy
Living halls		
Air temperature and RH at 1.5m above floor	Vaisala HMP155 and T&D TR-72U	±0.10°C; ±1.0% RH at 0-75% RH and ±0.3°C; ±5% RH
Air speed	Kanomax 0965-03	±0.15m/s
Globe temperature	Type T thermocouple inside 75mm and 150mm diameter black globes	±0.1%+0.5°C plus ±0.5°C for cold junction compensation
Vertical thermal distributions		
Air temperature	Type T thermocouple, T&D TR-52 and HOBO U12-006	±0.1%+0.5°C plus ±0.5°C for cold junction compensation, ±0.3°C and ±0.25°C
Surface temperature (floor and ceiling)	Type T thermocouple and T&D TR-52	±0.1%+0.5°C plus ±0.5°C for cold junction compensation and ±0.3°C
Other rooms		
Air temperature and RH	T&D TR-72U and HOBO U12-011	±0.3°C; ±5% RH and ±0.35°C; ±2.5% RH
Outdoor (veranda)		
Air temperature, RH and barometric pressure	T&D TR-73U	±0.3°C; ±5% RH; ±1.5 hPa
Weather station		
Air temperature and RH	Vaisala HMP155	±0.13°C; ±1.0% RH at 0-90% RH
Wind speed and wind direction	Young 05103-47	±0.3m/s; ±3°
Global horizontal solar radiation	Hukseflux SR11	±5% for daily sums
Rainfall	Davis Rain Collector II	±3%, ±1 rainfall count at 0.2-50 mm/hr

shophouses. A weather station (Campbell Scientific C-CR800) was placed on a grass area located about 500m away from these shophouses. The measurement instruments used are outlined in Table 5.4. All measurements were logged automatically at 10-minute intervals.

5.4.3 Thermal Comfort in the Front Courtyard-Adjacent Living Halls

Figure 5.13 shows the temporal variations of the thermal variables measured in the front courtyard-adjacent living halls at 1.5m height above floor with the corresponding outdoor conditions on 12-17 October. The outdoor air temperature and humidity in this figure are those obtained at the veranda located in front of CSH 1 (see Figure 5.12). The outdoor wind speed, global horizontal solar radiation and rainfall are shown based on the measurement data of the weather station. The veranda space was surrounded by artificial surfaces including asphalt road and therefore gave relatively high air temperatures throughout the day compared to the weather station. Nevertheless, the measurements at the veranda space reflect the immediate ambient environment which is of interest for our data analysis in this case. As given in Figure 5.13a, the maximum outdoor air temperatures are about 34-36°C while the nocturnal outdoor air temperatures are about 26-28°C.

Figure 5.13a reveals that indoor air temperatures in both living halls are lower than the outdoors during daytime by up to 5-6°C. At night, the indoor air temperatures maintain similar values to the outdoors. The cooling effects caused by the planted tree in the front courtyard of CSH 1 (1-CY1) are not seen in this figure. On the other hand, relative humidity is above 60% throughout the day in the two living halls (Figure 5.13b). Absolute humidity in CSH 1 is slightly higher than that in CSH 2 by up to about 1 g/kg'. This is probably due to the transpiration of the tree in the front courtyard of CSH 1 (1-CY1). The increase in absolute humidity results in the higher relative humidity in CSH 1 compared with that of CSH 2 (Figure 5.13b). Daytime relative humidity in CSH 1 ranges from 65-70% while nocturnal relative humidity in the same room is about 75-85%.

Wind speeds measured by the weather station at an open location near the shophouses average about 0.9 m/s during daytime and about 0.5 m/s at night (Figure 5.13c). Despite the presence of the outdoor wind, the corresponding indoor air speeds in the living halls of both shophouses show calm conditions of less than 0.1 m/s almost throughout the day, except when the ceiling fan was used, as indicated at the bottom of the figure. The result implies that both living halls obtained little cross ventilation even when the external door or windows were opened. The indoor air speed increases to about 0.6 m/s when the ceiling fan was switched on in the living hall of CSH 2.

As described earlier, these Chinese shophouses were constructed of masonry, brick and concrete structures that have relatively high thermal capacities. Thus, basically the diurnal ranges of surface temperatures of the indoor building structures would be small due to the thermal mass effect. Accordingly, the mean radiant temperatures in both living halls recorded slightly higher values than the air temperatures during night-time while it is lower

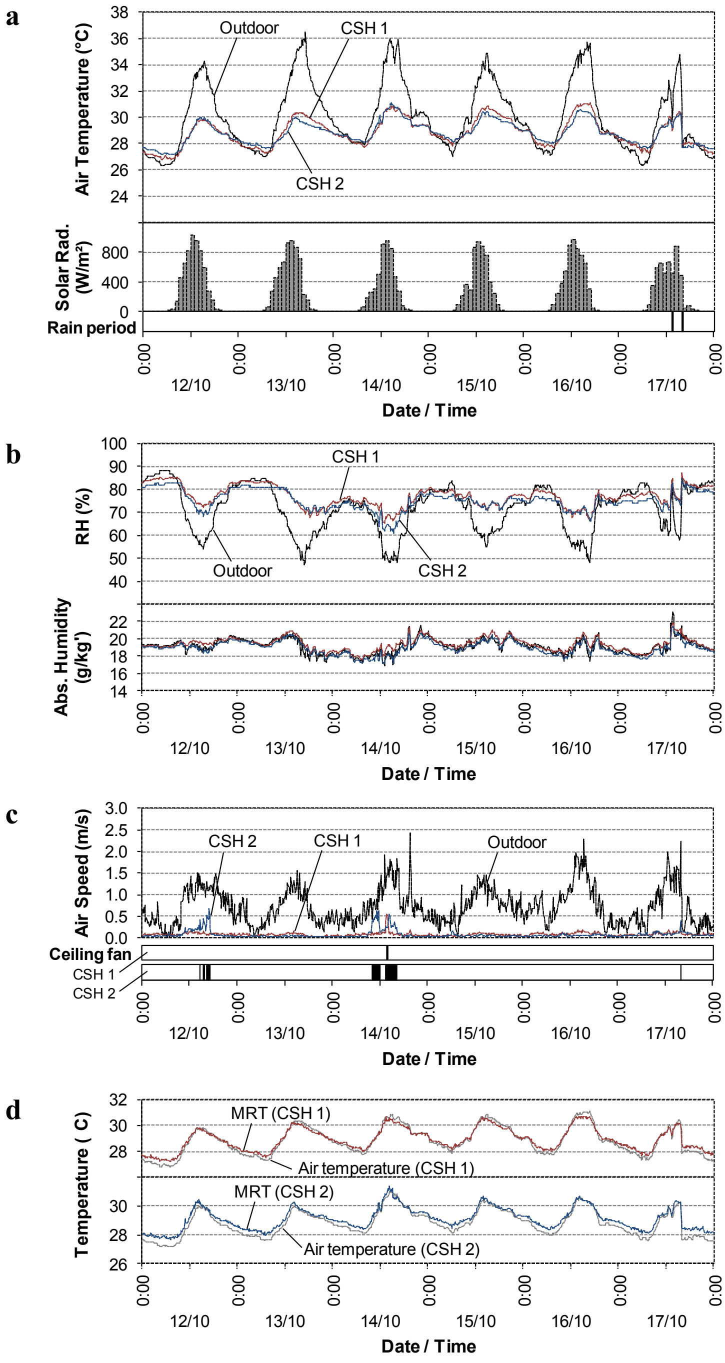


Figure 5.13. Temporal variations of the measured thermal variables at 1.5m above floor in the front courtyard-adjacent living halls of Chinese shophouses and the outdoors. (a) Air temperature and solar radiation; (b) Relative humidity and absolute humidity; (c) Air speed and ceiling fan usage; (d) Mean radiant temperature. In figure (c), black bars indicate used for "ceiling fan".

than the air temperature during daytime in CSH 1 (Figure 5.13d). The mean radiant temperature in CSH 2 is slightly higher compared to its air temperature as well as the mean radiant temperature of CSH 1 probably because there is less shading in its adjacent courtyards (2-CY1 and 2-CY2). The mean radiant temperature and operative temperature are calculated according to ISO 7726 (BSI, 2002) (see Eqs. 4.5 and 4.6 in Chapter 4).

We plot the indoor operative temperatures and humidity of the two living halls on a psychrometric chart in Figure 5.14. The data are concentrated between 27-31°C indoor operative temperature and absolute humidity of 17-22 g/kg'. None of the data in both living halls falls within the comfort zone recommended by ASHRAE (2010) for typical indoor environments at 0.5 clo level.

Temporal variations of the same indoor operative temperatures are presented in Figure 5.15 for thermal comfort evaluation. This evaluation is based on the thermal comfort criteria that are developed in this study (see Chapter 3: Section 3.3.6). The 80% comfortable upper limit is displayed for each day based on the measured outdoor air temperatures. The 80% comfortable upper limits range from 29.5-30.6°C for the measurement days. Table 5.5 summarizes the indoor operative temperature deviations from the 80% comfortable upper limits and the exceeding periods on fair weather days.

The evaluation shows that the indoor operative temperatures in both living halls are below the 80% comfortable upper limits almost throughout the day (Figure 5.15). The periods of exceeding the 80% comfortable upper limits on fair weather days are only 7% and 8% in CSH 1 and CSH 2, respectively (Table 5.5). Maximum deviations of the peak indoor operative temperatures above the 80% comfortable upper limits are only 0.5°C (Table 5.5). The small operative temperature offset from the said upper limit as seen briefly in the

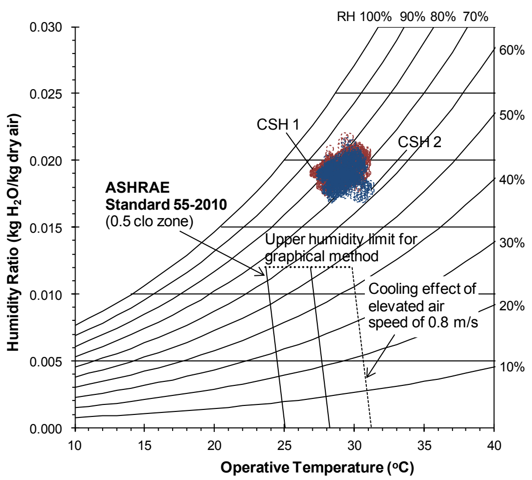


Figure 5.14. Scatter diagram of indoor operative temperatures and indoor humidity in the front courtyard-adjacent living halls of Chinese shophouses on a psychrometric chart.

Table 5.5. Summary of thermal comfort evaluation in the front courtyard-adjacent living halls of Chinese shophouses on fair weather days.

Chinese shophouse	Deviation of indoor operative temperature from the 80% comfortable upper limits (°C)[a]		Exceeding period (%)
	Daily maximum	Daily minimum	
CSH 1	-0.3 to 0.5	-2.4 to -3.1	7
CSH 2	-0.3 to 0.5	-2.1 to -2.6	8

[a] Positive values indicate indoor operative temperatures above the 80% comfortable upper limits and negative values indicate indoor operative temperatures below the 80% comfortable upper limits.

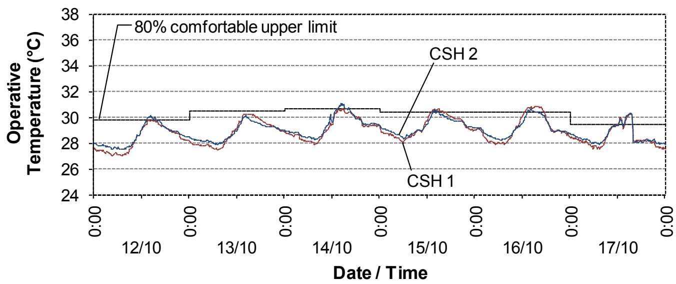


Figure 5.15. Temporal variations of indoor operative temperatures in the front courtyard-adjacent living halls of Chinese shophouses and the corresponding temperature limits for thermal comfort.

afternoons might be compensated with the use of ceiling fan by the occupants (Figure 5.13c). The result implies that the indoor thermal conditions in the front courtyard-adjacent living halls are comfortable when the adaptive model for hot-humid climate is taken into account.

5.4.4 Thermal Environment Variations in the Whole Shophouse

Indoor air temperatures measured at 1.5m above floor in several spaces in both Chinese shophouses are averaged over four periods of time for fair weather days (Figures 5.16 and 5.17). The average air temperatures on the ground floor are illustrated as line charts while the average air temperatures on the first floor are noted in figures. Figure 5.18 further indicates a statistical summary of the measured air temperature and humidity in selected spaces of CSH 1.

Figures 5.16a and 5.17a show that indoor air temperatures are about 1.5°C lower than the outdoors at 8 a.m.-12 p.m., except for the middle courtyards (CY2) which average 29.4°C in

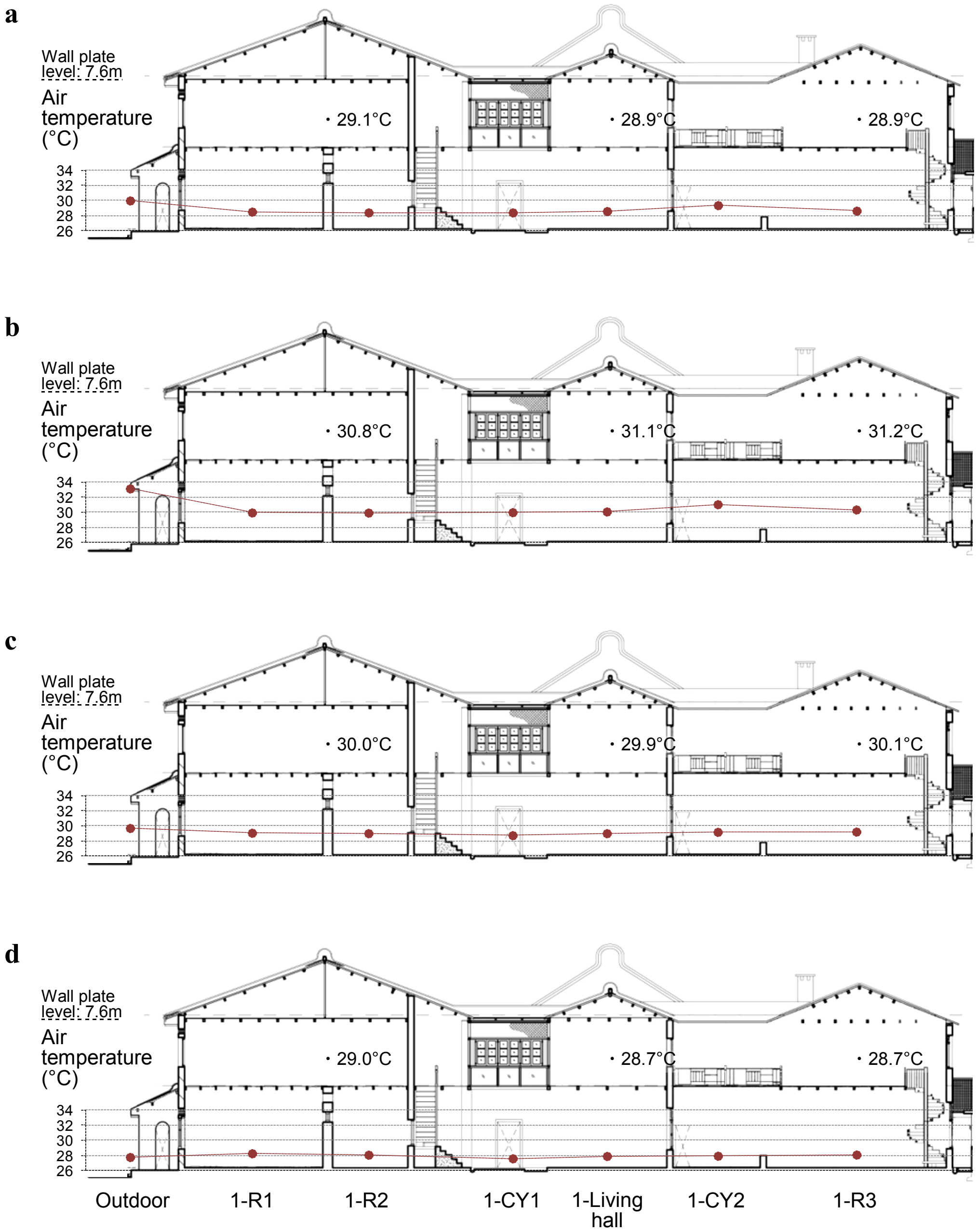


Figure 5.16. Average air temperatures at 1.5m above floor in different rooms and courtyards of CSH 1. (a) 8 a.m.-12 p.m.; (b) 12 p.m.-8 p.m.; (c) 8 p.m.-12 a.m.; (d) 12 a.m.-8 a.m. Note: Sectional drawing with permission of TTCLC (2011), National University of Singapore.

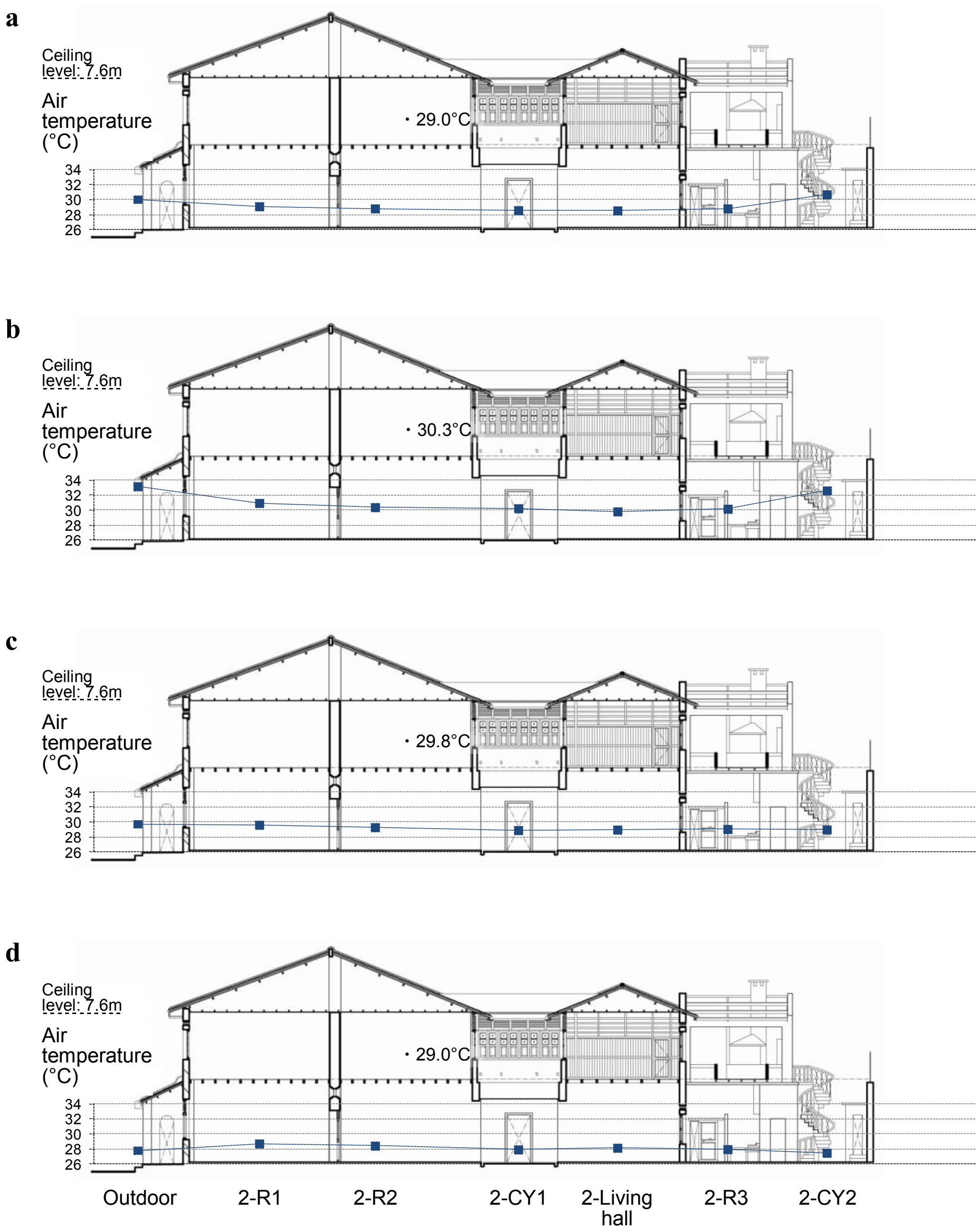


Figure 5.17. Average air temperatures at 1.5m above floor in different rooms and courtyards of CSH 2. (a) 8 a.m.-12 p.m.; (b) 12 p.m.-8 p.m.; (c) 8 p.m.-12 a.m.; (d) 12 a.m.-8 a.m. Note: Sectional drawing with permission of TTCLC (2011), National University of Singapore.

CSH 1 and 30.7°C in CSH 2. The outdoor air temperature averages 30.0°C during this period. In contrast, air temperatures in the two front courtyards (CY1) maintain almost the same air temperatures as their surrounding rooms.

The air temperature differences among the spaces increase at 12 p.m.-8 p.m. (Figures 5.16b and 5.17b). Indoor air temperatures on the ground floor in both shophouses are about 3°C lower than the outdoors on average. This is mainly because of the thermal mass effect. The heavyweight structures are cooled during the night-time and contribute to reduce the daytime indoor air temperatures. We have observed this phenomenon in the brick terraced houses when we apply night ventilation (Kubota *et al.*, 2009). Nonetheless, it is interesting to see the similar effect in the indoor spaces of the Chinese shophouses with adjacent open courtyards, such as the living halls. The average air temperatures in rooms R1 and R2 of CSH 2 are 1.0°C and 0.5°C higher than the corresponding rooms in CSH 1, respectively. This is mainly because only the front main door of CSH 2 was opened during this period.

Figures 5.16b and 5.17b further show that air temperatures in the front courtyards (CY1) of both shophouses have almost the same values as their surrounding rooms. On the other hand, the average air temperatures in the middle courtyards (CY2) of CSH 1 and CSH 2 are about 1°C and about 3°C higher than the surrounding rooms, respectively. We imply that the size of the courtyard affects its air temperature significantly.

We present horizontal sun path diagrams of respective courtyards on a measurement day (15 October) in Figure 5.19. The solar altitude is projected into the hemispherical fisheye lens image using the following equation for equisolid-angle projection:

$$r' = 2c \times sin\frac{\beta}{2} \tag{5.8}$$

where *r'* is the projected radius in the fisheye lens image, β is the incidence angle, i.e. 90° minus solar altitude angle (°), and *c* is the principal distance of the lens (Schneider *et al.*, 2009). As presented in Figure 5.19, the roof overhangs provide shading effectively to each courtyard except CY2 of CSH 2. The planted tree in the front courtyard (CY1) of CSH 1 also gives further shade to the courtyard. As indicated in the sun path diagrams, both front courtyards (CY1) received direct solar radiation briefly for only less than an hour around 1 p.m. on the measurement day. The middle courtyard (CY2) of CSH 1 received direct solar radiation for less than two hours between 12 p.m. and 2 p.m. The middle courtyard (CY2) of CSH 2 received direct solar radiation for 2 hours or more from 12 p.m. to 2 pm. It is implied that the said courtyard (2-CY2) was heated the most among the four courtyards.

Figure 5.20 shows the relationships between the sky view factors of the courtyards and their air temperatures measured at 1.5m above floor. Although the result may not be statistically significant due to the small sample size, the relationships between the two variables are strong with coefficients of determination (R^2) above 0.9, particularly in terms of the daily maxima (95^{th} percentile) and the mean values. It is seen that reduction in the sky view factor of a courtyard reduces its air temperature. As given in Figure 5.18a, CY1 has lower air temperatures than those of CY2 in terms of daily peak and mean values in CSH 1. In fact, the mean air temperature in the said front courtyard (1-CY1) is the lowest among all the indoor spaces of CSH 1 at 28.7°C (Figure 5.18a). This means that the small front courtyard functions as a cooling source, or heat sink, to the surrounding rooms.

Indoor air temperatures decline gradually from the periods 8 p.m.-12 a.m. and 12 a.m.-8 a.m. (Figures 5.16cd and 5.17cd). The reductions are up to about 2°C except for the middle

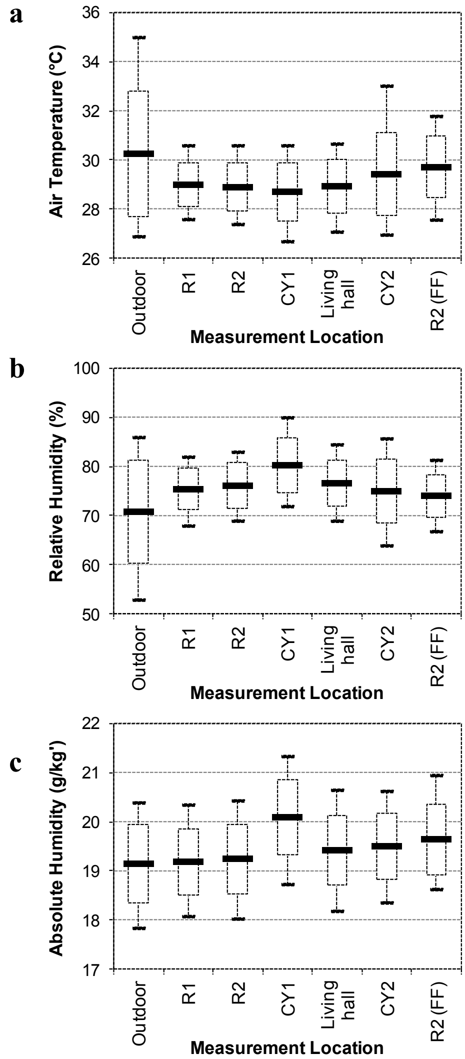


Figure 5.18. Statistical summary (5^{th} and 95^{th} percentiles, mean and ± one standard deviation) of measurements at 1.5m above floor in different rooms and courtyards of CSH 1. (a) Air temperature; (b) Relative humidity; (c) Absolute humidity.

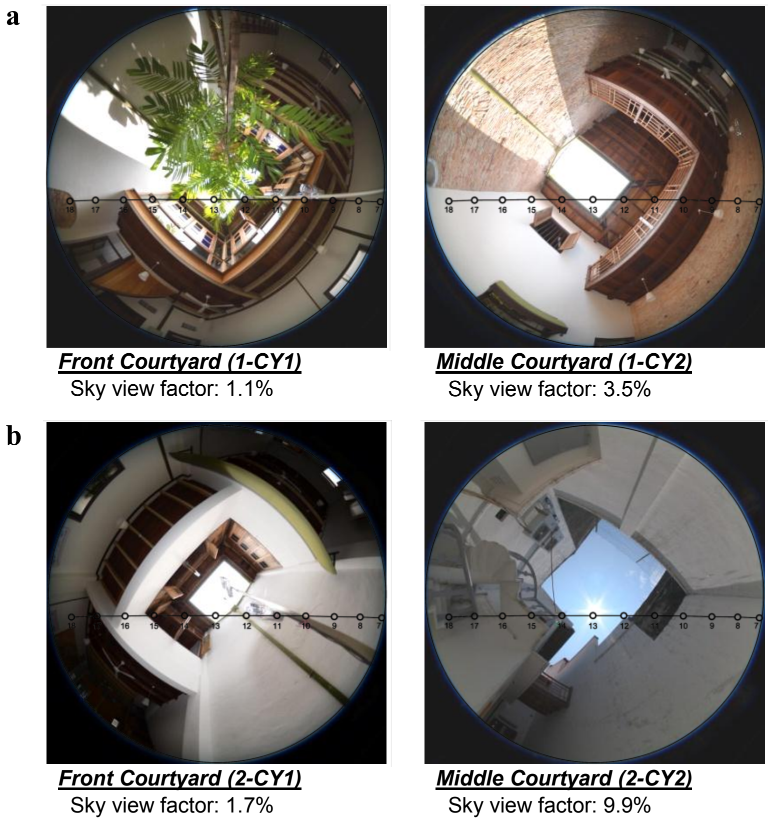


Figure 5.19. Horizontal sun path diagrams of courtyards on 15 October. (a) CSH 1; (b) CSH 2. Note: Fisheye photos were taken at 1.5m above floor at the approximate centre of the courtyards using equisolid-angle projection lens. The top of photos is directed to the north.

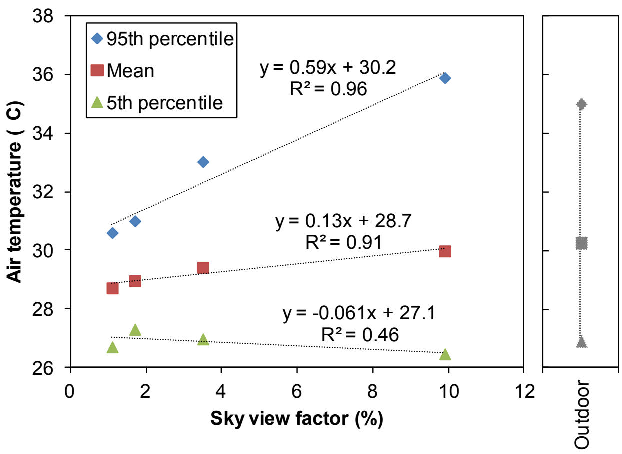


Figure 5.20. Relationships between sky view factors of courtyards and their air temperatures at 1.5m above floor.

courtyards (CY2), which are warmer during daytime. The indoor air temperatures in the different rooms and courtyards of both shophouses show a flat distribution around 28°C, which are similar to the outdoor air temperature, during 12 a.m.-8 a.m. (Figures 5.16d and 5.17d).

5.4.5 Vertical Thermal Distributions in the Front Courtyards

Vertical thermal distributions in the front courtyards and rooms on the ground floor are analysed based on air temperature measurements at various heights and the floor and ceiling surface temperatures. The temperatures are averaged to represent daytime (12 p.m.-8 p.m.) and night-time (12 a.m.-8 a.m.) conditions for fair weather days.

Figures 5.21a and 5.22a show that the surface temperatures of building structures, i.e. the ceilings and the floors, of the two Chinese shophouses are about 1°C lower than the air temperatures during daytime (12 p.m.-8 p.m.) due to the structural cooling effect with night ventilation. In the front courtyards (CY1), air temperatures at 1.5m height are 1-2°C lower than those at higher levels and about 3°C lower than the outdoors on average during this period. It is clear that the air temperature in the front courtyards increases with height. Especially in CSH 1, the surface temperature and air temperature at lower levels are well cooled by the planted tree and wetted ground surface and therefore emphasize the temperature gradient (Figure 5.21a). The temperature gradient causes thermal stratification in the front courtyards, thus prevents vertical air exchanges within the air volume in the courtyards and the outdoors. This is likely one of the main causes of maintaining relatively low air temperatures during daytime in the front courtyards and their adjacent rooms despite the hot outdoor conditions.

In contrast, the above temperature gradient is not observed at night (12 a.m.-8 a.m.) except for the floor surface temperature in the front courtyard of CSH 1 (Figures 5.21b and 5.22b). The result implies that the vertical air exchanges occur in this case and therefore indoor air temperatures are lowered sufficiently to reach the outdoor level. In fact, Figures 5.21b and 5.22b show that the surface temperatures of the building structures in both shophouses are about 1°C higher than the air temperatures at 1.5m height during this period. Relatively cool air from the immediate outdoor, which averages 27.8°C, enters the buildings probably not only from the ventilation openings on the external walls but also from the roof openings of the courtyards, and cools the warmed building structures effectively during night-time. This contributes to lower the daytime indoor air temperatures on the following day. Thus, it can be implied that the front courtyards (CY1) play an important function to prevent the hot outdoor air from entering the indoor spaces during daytime while accelerating nocturnal ventilative cooling on the other hand.

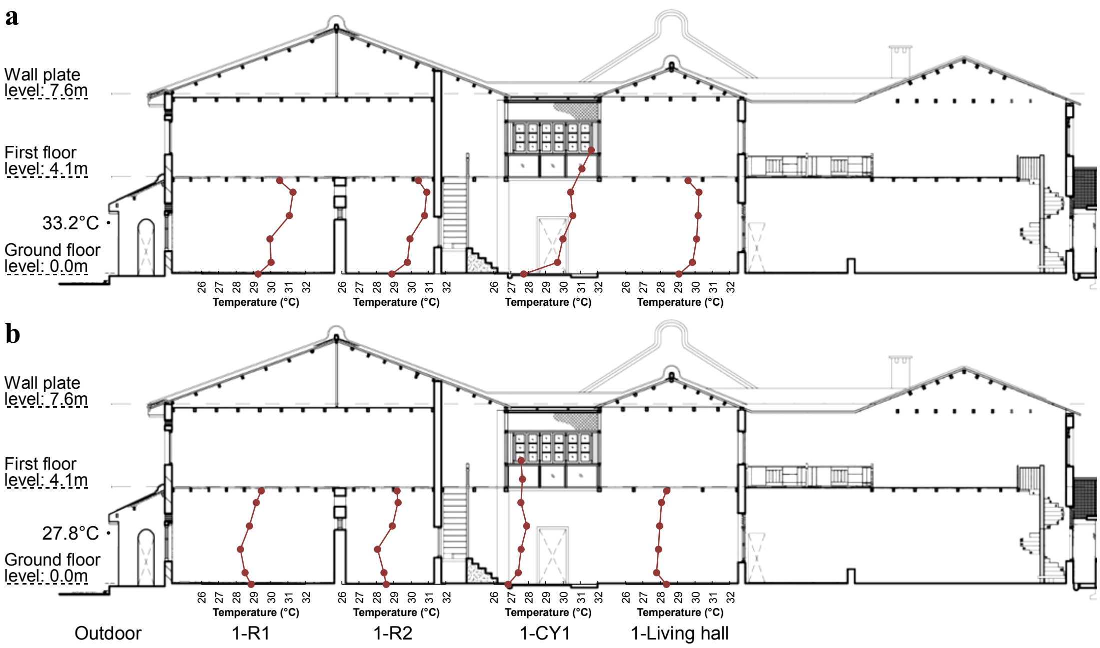


Figure 5.21. Vertical temperature distributions in the front courtyard and rooms on the ground floor of CSH 1. (a) 12 p.m.-8 p.m.; (b) 12 a.m.-8 a.m. Note: Sectional drawing with permission of TTCLC (2011), National University of Singapore.

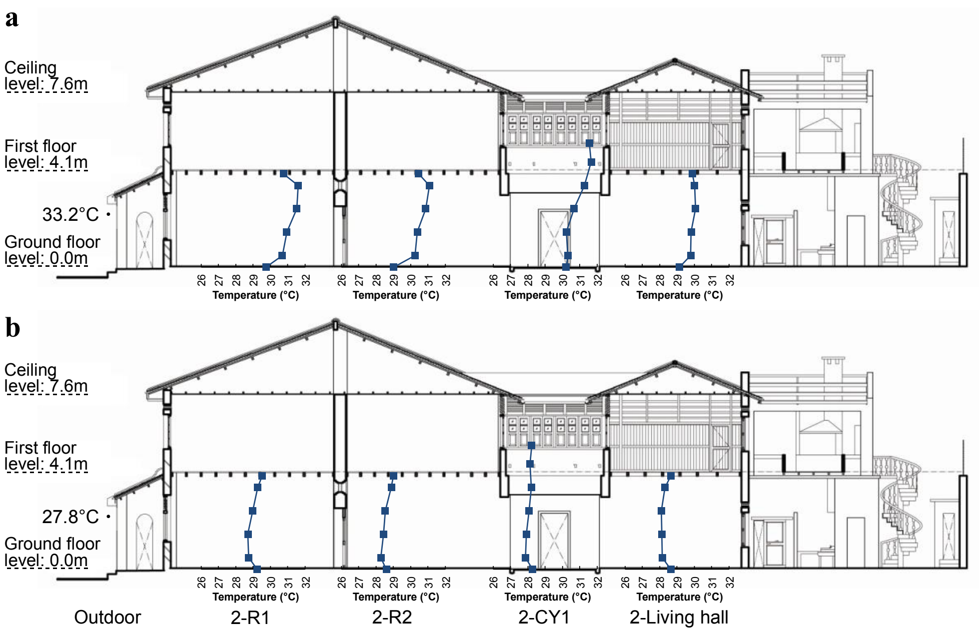


Figure 5.22. Vertical temperature distributions in the front courtyard and rooms on the ground floor of CSH 2. (a) 12 p.m.-8 p.m.; (b) 12 a.m.-8 a.m. Note: Sectional drawing with permission of TTCLC (2011), National University of Singapore.

5.4.6 Cooling Potential of the Traditional Chinese Shophouses in Relation to Outdoor Conditions

We analyse the relationship between indoor and outdoor thermal conditions on fair weather days in the traditional Chinese shophouses based on the results presented in Section 5.4.3. The analysis method is similar to that applied to the terraced houses (see Chapter 4: Section 4.3.5).

Figure 5.23a shows the result of the temperature relationship. Interestingly, the indoor operative temperatures are related to the outdoor air temperatures by segmented regression lines that almost resemble those in the night ventilated terraced house but not daytime ventilated terraced house (see Figure 4.34a in Chapter 4). It was noted that windows on external facades of the Chinese shophouses were not open at night; the indoor spaces were basically open to courtyards. The result emphasizes a key finding of this thesis that the small front courtyards function as a night ventilation cooling source to their adjacent indoor spaces.

In detail, the break-points are 28.7°C and 28.2°C for CSH 1 and CSH 2, respectively (Figure 5.23a). At the break-points, the indoor operative temperatures are about equal to the outdoor air temperatures so that the regression lines before the break-points predict indoor operative temperatures that are close to the outdoor air temperatures. The slopes of the regression lines before the break-points are about 0.6. Meanwhile, the slopes of the regression lines after the break-points are about 0.3.

Figure 5.23a also shows that the indoor operative temperatures in the Chinese shophouses do not scatter widely above the regression lines after the break-points. Possible reasons include: (1) the evaluated spaces in the Chinese shophouses are located on the ground floor and are less affected by solar radiation on the roof; (2) the solar control inside the courtyards and adjacent spaces is good (see the sun path analysis in Figure 5.19); and additionally, (3) ventilation with hot outdoor air is prevented by the stable thermal stratification in the front courtyards during daytime (see Section 5.4.5).

The regression lines for relative humidity show inverse patterns compared to each temperature relationship (Figure 5.23b). The regression models for the Chinese shophouses resemble that of the night ventilated terraced house (for example see Figure 4.38b in Chapter 4). The lines are segmented and the break-points occur at 75% RH and 80% RH for CSH 1 and CSH 2, respectively.

On the other hand, indoor absolute humidity in the Chinese shophouses has strong linear relationships that are almost equal to the outdoor absolute humidity (Figure 5.23c). This pattern resembles the regression lines for the daytime ventilated terraced house and also the Malay houses (see Figure 4.34c in Chapter 4 and Figure 5.10c). The result suggests that mass transfer of water vapour might occur throughout the day although vertical air exchange of heat is minimized during daytime in the courtyards and indoor spaces of the Chinese shophouses.

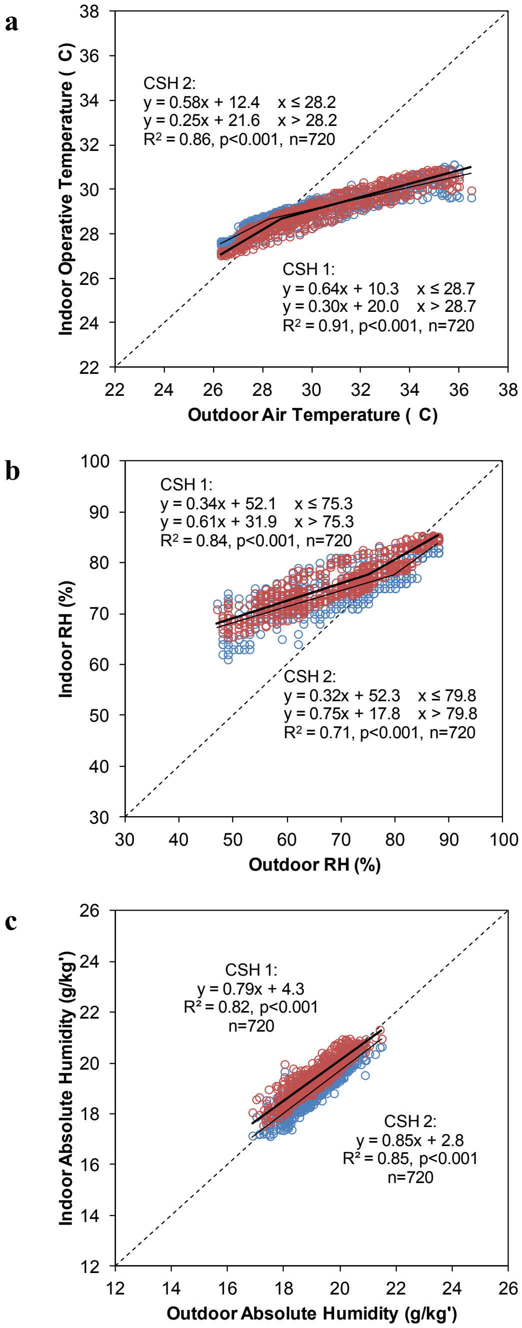


Figure 5.23. Relationships between outdoor conditions and indoor conditions at 1.5m above floor in the front courtyard-adjacent living halls of Chinese shophouses. (a) Operative temperature; (b) Relative humidity; (c) Absolute humidity. Red points and thick regression lines represent CSH 1 while blue points and thin regression lines represent CSH 2. Dashed lines represent indoor conditions equaling outdoor conditions.

6

Numerical Modelling and Simulation of Passive Cooling Techniques

In parallel with the previous chapter, we investigate other passive cooling techniques that we were unable to test in the full-scale field experiment in the terraced houses using computer simulation in this chapter. The objectives of the numerical modelling and simulation are explained firstly in Section 6.1. Section 6.2 describes the simulation programs used, i.e. TRNSYS and COMIS, and their relevant mathematical models. Details of the base model of the terraced house and its validity are given in Section 6.3. Several simulation test cases and weather conditions are considered; they are rationalized in Section 6.4. Finally, the simulation results are discussed in Section 6.5. They include the effects of respective passive cooling techniques, i.e. respective simulation cases, as well as a combination of the most effective techniques.

It shall be clarified here that modelling refers to the task of making a logic machine which represents the material properties of the building and physics processes in it, whereas simulation refers to numerical experimentation with the model in order to investigate its response to changing conditions inside and outside the building (Jankovic, 2012). In this thesis, we deal with dynamic simulation models, i.e. the dynamic heat transfer responses of the model were simulated at time steps of one hour or less.

6.1 Objectives of the Numerical Modelling and Simulation

As introduced, this computer simulation task is basically to extend what we could not do or have not done yet in our various field works in Chapters 4 and 5. Two major directions that we work on within this thesis are: (1) to increase the cooling effects of night ventilation in the existing terraced house; and (2) to examine the different abilities of the terraced house to provide indoor thermal comfort under the influence of urban and rural climatic conditions. The first objective is formulated based on our results so far which show that night ventilation is the most effective natural ventilation condition for cooling in the brick terraced house. Nevertheless, solar radiation heat gains should be reduced and the night ventilation rate increased (see Chapter 4: Sections 4.3.3, 4.3.4 and 4.3.5). The second objective is set in consideration of the likely huge influence of urban climates on the performance of passive cooling; urban heat islands might hinder the actual use of the passive cooling techniques. It is interesting to also see from another viewpoint; rural climates that give relatively cool environments might enhance the actual use of the same techniques.

This thesis is part of a larger project and is implemented as the initial part of that project (see Chapter 1: Section 1.2). A third objective of this numerical modelling exercise is to initiate a base model that will be used for further simulation studies in the project. Few numerical modelling exercises have been done with regard to Malaysian terraced houses and even fewer were made using comprehensive and flexible programs such as TRNSYS (see for example Mohd Isa *et al.*, 2010 and Sadafi *et al.*, 2011). The flexibility of TRNSYS software means that the model can be efficiently coupled with even computational fluid dynamics (CFD) models in the future. This will be very useful, for example to simulate the detailed air flow in the courtyard for understanding stratified heat and mass transfer phenomena clearly. As a whole project, the simulation studies are intended to be followed by real measurement in full-scale experimental houses. Thus, a reasonably good but not highly precise model is required. In fact, the validity of our base model is comparable to other simulation works published in international journals (see Section 6.3.3).

6.2 The Simulation Programs Used

6.2.1 Overview of Building Simulation Programs

Literally hundreds, if not thousands, of building simulation programs are available today. A comprehensive reference that continuously reviews the available programs is the Building Energy Software Tools Directory coordinated by the US Department of Energy. At the time of this writing 397 tools were listed (US Department of Energy, 2013). Nevertheless, not all of them are capable of performing whole building dynamic thermal analysis. Another recent publication that reviewed the capabilities of twenty major building energy simulation programs, including TRNSYS, was Crawley *et al.* (2008). A more detailed version was the report by Crawley *et al.* (2005). Further comparison was not necessary; we did not attempt it.

It is agreeable that TRNSYS is one of the most comprehensive and flexible dynamic simulation programs that could serve our simulation objectives not only within this thesis but also for the whole project (see Section 6.1). Since we were to simulate the terraced house in natural ventilation conditions, we used TRNSYS and COMIS, which is a multi-zone airflow network program, in coupled simulations; indoor temperatures and air flow rates are interdependent in naturally ventilated buildings. Further details of the two programs are given in Section 6.2.2.

6.2.2 The TRNSYS-COMIS Coupled Simulation Programs

TRNSYS is a complete yet extensible simulation environment for the transient simulation of thermal systems, including multi-zone buildings (Klein *et al.*, 2012). Its application is wide – ranging from small systems such as domestic hot water systems to whole building simulations that may include passive cooling strategies, HVAC equipments, occupants and renewable energy systems. The software was developed by Solar Energy Laboratory (SEL) at University of Wisconsin-Madison and made available since 1975. A current release, i.e. TRNSYS Version 17.01.0025, was used in this work.

TRNSYS has a modular structure. In our work, as in most typical TRNSYS works, each TRNSYS project comprised selected components called Type that 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. During the simulation, the components were called by the TRNSYS engine and their mathematical models iterated until convergence was reached within the specified tolerances. Output files were generated and post-processed in Excel spreadsheets after the simulation.

COMIS is a multi-zone airflow network model that can simulate infiltration and ventilation through crack flow and flow through large openings in multi-zone buildings (Dorer *et al.*, 2005; Feustel, 1999). Although not used in this study, COMIS is also capable of simulating HVAC systems and contaminant transport. It was first developed through an international workshop hosted by Lawrence Berkeley National Laboratory (LBNL) in 1988-1989. A current release, i.e. COMIS Version 4.2.0.28, was used in this study. The COMIS model works in a modular structure that is similar to TRNSYS in the Simulation Studio.

Since we used TRNSYS Type 56 'Multi-zone Building' to model the thermal zones of the terraced house, it was relevant to implement coupling between TRNSYS and COMIS via Type 157 in TRNSYS based on the concept developed by Dorer and Weber (2001). In this coupling method, Type 157 was treated like any other TRNSYS components and COMIS was thus called together in each iteration step until the mass and energy balance per zone reached convergence. Data that were transferred from Type 157 to Type 56 were the air flow rates per zone while data that were transferred from Type 56 to Type 157 were the zone air temperatures. The air flow included flow from outside air and flow between zones. The weather data, simulation time and schedules were defined in TRNSYS and used

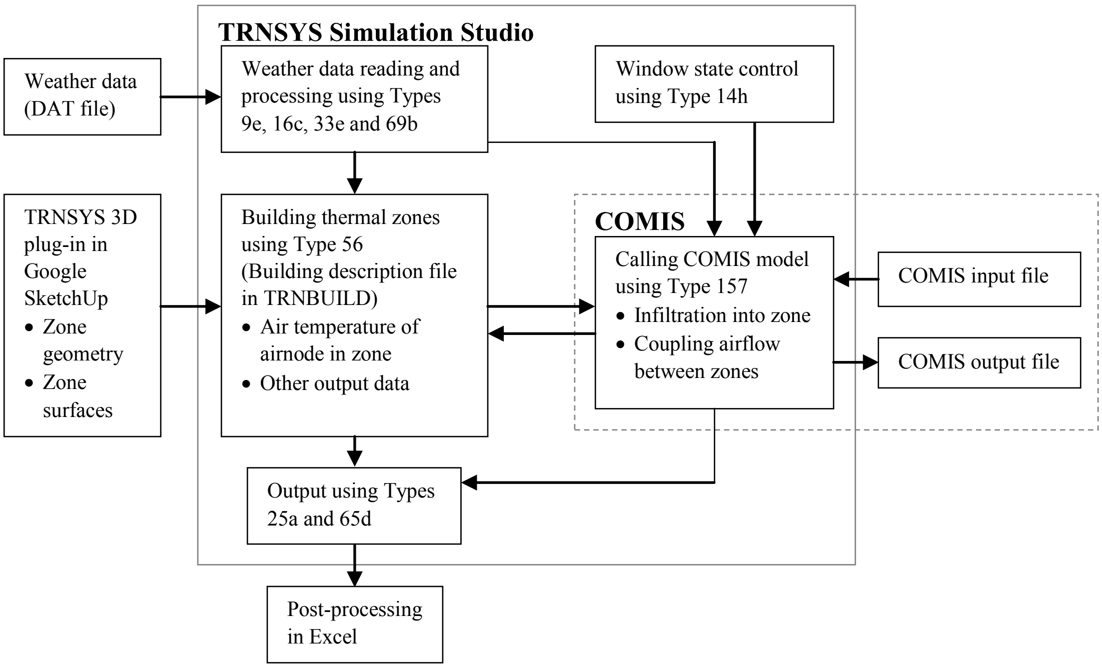


Figure 6.1. Components and data transfer in the TRNSYS-COMIS simulation model of this study.

simultaneously by both TRNSYS and COMIS models. The coupling relationship between the two programs in our whole simulation model is depicted in Figure 6.1.

6.2.3 The Numerical Solver and Components Used

The components that we modelled for simulating the base model and simulation test cases were similar (see Figure 6.1). The source code of the TRNSYS and COMIS simulation engines and their component models, i.e. the equations governing each TRNSYS type and COMIS air flow component, was documented in detail in their respective user manuals (Dorer *et al.*, 2005; Klein *et al.*, 2012) and the references listed in them. Here we provide the key points.

The TRNSYS Solver

The TRNSYS simulation engine simultaneously solves a set of algebraic and differential equations in the system model at each simulation time step based on the parameter and input values at the beginning of the time step. Results are returned as average values over the time step. In this simulation, the Modified-Euler method was selected for being the most consistent analytical method of solving differential equations used in many components (Klein *et al.*, 2012). The successive solution method that should be used for buildings and systems with a thermal capacity, as in our case, was applied. All of the simulations attained convergence within a tolerance of 0.01, i.e. changing by less than 1% of the iteration value.

The COMIS Solver

In COMIS, the building was modelled in a typical manner as a network of pressure nodes linked by air-mass flow paths. 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, i.e. the room or zone, represented by each internal pressure node is assumed to be well mixed and has a fixed uniform pressure and temperature at each time step. Meanwhile, the wind pressure field around the building is attributed to external pressure nodes. Based on the principle of air mass conservation, a system of non-linear equations was linearized initially and then solved in iterations using a modified Newton-Raphson method known as Solver 6 'trust region line search' (Feustel and Raynor-Hoosen, 1990). The resulting flow rates are functions of pressure differences between nodes that consider the wind distribution and thermal buoyancy.

Components Related to the Weather File

We employed exact weather data that were measured on site or obtained directly from the local meteorological station in the simulation. These weather data were first read by Type 9e, i.e. a data reader in free format, in TRNSYS as average values over the data time interval without interpolation. The raw weather data covered dry bulb temperature, relative humidity, wind speed, wind direction, barometric pressure and global horizontal solar radiation.

Several other weather variables were derived to provide the necessary input for the simulation. The total horizontal radiation was divided into its beam and sky diffuse components on the horizontal surface by Type 16c, i.e. a solar radiation processor that estimates the diffuse fraction as a function of the clearness index, solar altitude angle, dry bulb temperature and relative humidity using the correlations developed by Reindl *et al.* (1990). The clearness index is the ratio of hourly global horizontal solar radiation to hourly extraterrestrial radiation. The incident radiation components received on respective building surfaces including vertical and tilted surfaces were then estimated internally as defined in Type 56. Another important thermal load considered in the simulation was the long-wave radiation exchange from external surfaces of the building to the atmosphere; effective sky temperature was a required input. The effective sky temperature was estimated by Type 69b as a function of the dry bulb temperature, dew point temperature, atmospheric pressure and cloudiness factor of the sky assuming the sky as an ideal black body emitter (Martin and Berdahl, 1984). Since the cloudiness factor of the sky was unknown, it was determined as a ratio of global horizontal radiation to sky diffuse horizontal radiation according to Kasten and Czeplak (1980). Moist air properties were estimated from the known dry bulb temperature and relative humidity using a psychrometric processor, i.e. Type 33e. The derived variables were humidity ratio, dew point temperature, densities of air with and without water vapour, and enthalpy.

The Thermal Model of Type 56 Multi-zone Building

This component describes the thermal behaviour of the building, divided into different thermal zones and airnodes, through the TRNBUILD user interface. In this simulation, all thermal zones contained one airnode each except for the staircase zone which was modelled with an upper airnode and a lower airnode (see Section 6.3.1). The heat balance model of the whole building basically considers: (1) convective heat fluxes to the airnodes; (2) short-wave and long-wave radiation, conduction and convection heat fluxes to the walls and windows; and (3) the thermal history of high thermal mass walls, i.e. walls that are defined as massive in the type, using a transfer function (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 since the terraced house had ordinary constructions comprising opaque facades and punched windows. An exception was the staircase zone which employed the detailed model for internal long-wave radiation exchange due to having two airnodes. The standard models distribute the radiation based on absorptance weighted area ratios of all inside surfaces in a zone and model the radiation exchange using an artificial temperature node. The detailed model uses a three dimensional matrix method that considers view factors among the inside surfaces and the airnodes.

External shading of windows was modelled in three dimensions using the auxiliary program TRNSHD that was developed by Hiller *et al.* (2000). The program automatically considers all external walls and obstructions as potential shadow casting surfaces, thus roof overhangs, self-associated façade obstructions and adjacent buildings were included. The shading matrix generated by TRNSHD estimates both beam and diffuse radiation fractions according to the solar position and solar geometry in patches; the diffuse fraction assumes an isotropic sky. The effect of shading from beam radiation on opaque walls is not taken into account. 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 windows were modelled using data from the WINDOW 4.1 program developed at LBNL (Mitchell *et al.*, 2011). The window model calculates the transmission, reflection and absorption of solar radiation for the window glazing and frames. External and internal shading devices and edge correction for glazing spacers are considered.

In parallel with the sensible energy balance calculation, Type 56 calculates a moisture balance that considers the free floating humidity ratios in the naturally ventilated zones so that latent load is also modelled. We employed the effective capacitance humidity model, which defines sorption effects of adsorptive/desorptive materials with an enlarged moisture capacity of the air (Klein *et al.*, 2012).

The Air Flow Components

Crack flow represents the air leakage characteristics of the building constructional joints and surfaces for the whole building envelope as well as internal surfaces. In COMIS, the crack flow simulation rests on the power law equation:

$$Q = C_Q(\Delta P)^n \quad (6.1)$$

where Q is volume flow (m^3/s), C_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 flow coefficient is related to the form and size of the crack while the flow exponent characterises the flow regime as laminar, transitional or turbulent. Modifications to the basic power law equation that account for the influence of the air properties (density and viscosity, or simplified as temperature) and flow rate were described in Feustel and Raynor-Hoosen (1990). In this study, temperature correction in the crack was not applied because measurement data to determine the actual air leakage temperature were unavailable; standard reference data were used for the flow coefficients. Nevertheless, 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 gradient over the height of the air flow component is assumed.

Natural ventilation through open windows is a main interest of this simulation. 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, assuming that density stratification on both sides of the opening is linear and turbulence effects are represented by an equivalent pressure difference profile (Feustel and Raynor-Hoosen, 1990). When 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 open, bi-directional flow is calculated by incorporating 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.

Ventilation Control via Forcing Functions

In this transient simulation, natural ventilation was achieved by controlling the opening and closing of windows in a daily (24-hour) pattern. Type 14h, which is a time-dependent forcing function, was used to define the window states at respective hours in a stepwise manner.

6.3 Modelling of the Base Model

6.3.1 The Base Model Terraced House

One of the case study terraced houses that we used to perform the field experiment, i.e. TH 2 (see Chapter 4: Section 4.3.1), was modelled for the purpose of this simulation study. The reasons were obvious: (1) the terraced house represents common terraced houses in terms of spatial design and building structures (see Chapter 4: Sections 4.1.2 and 4.1.3); (2) sufficient building data were available to enable making a complete model; and (3) we could validate the model based on the field experiment data. Thus, the selected house fitted our study objectives and was convenient to model.

Description of the real house and the floor plans are given in Chapter 4: Section 4.3.1. The base model followed these data as well as the experimental setup outlined in Chapter 4: Section 4.3.2. The specifications of the house in the computer model are further given in Section 6.3.2.

The whole house was modelled in three dimensions using the TRNSYS 3D plug-in in Google SketchUp interface so that the three dimensional data were read in TRNBUILD. The building model comprised 17 thermal zones to represent each partitioned room or functional space as follows: Living, Dining, Multipurpose room, Dry kitchen, Wet kitchen, Bath 3, Stairs, Family, Master bedroom, Bath 1, Bedroom 2, Bedroom 3, Bath 2 and four attic spaces (see floor plans and sectional drawing in Figures 4.22 and 4.30 in Chapter 4). The staircase zone had two airnodes to represent the upper floor and the lower floor connections. All protruding elements on the building facades and immediate surrounding objects, i.e. neighbouring houses, that might shade the studied house were also modelled in three dimensions. Figure 6.2 illustrates exterior views of the model.

6.3.2 The Model Specifications

The geographical location of the base model followed that of the actual house, i.e. 1°31’20”N and 103°38’23”E at an elevation of 21.3m above sea level. Weather data that was

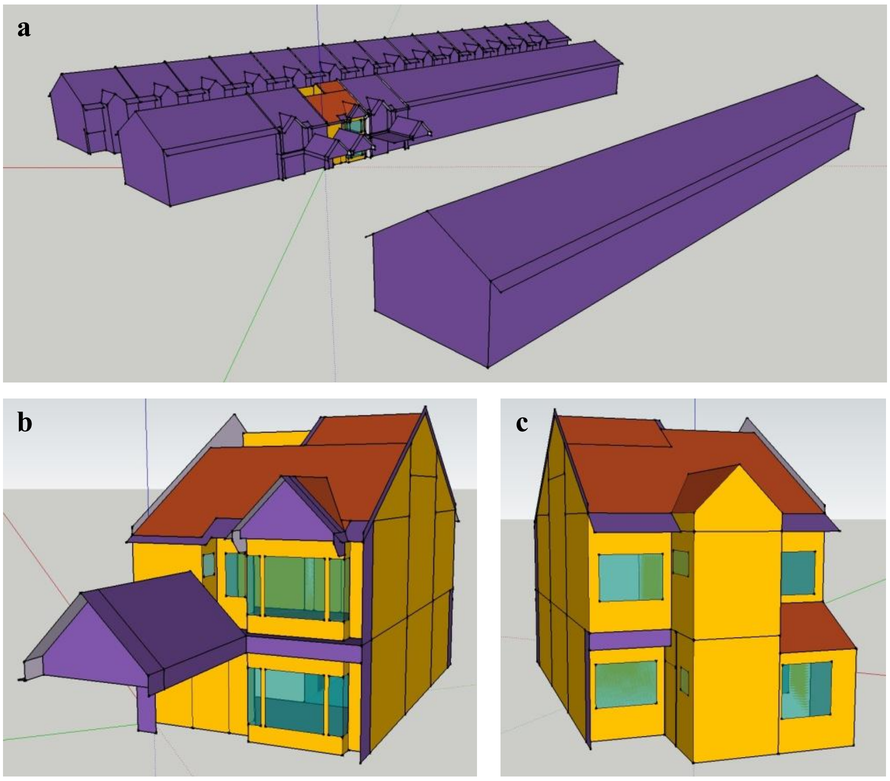


Figure 6.2. Exterior views of the base model terraced house in Google SketchUp program. (a) Location of the terraced house in the whole model; (b) Front view of the terraced house; (c) Rear view of the terraced house. The green axis points towards the north. Surfaces in purple are shading objects and their heat transfers are not simulated.

measured on site throughout the field experiment period, i.e. 20 June-29 August, was used. The simulation time step was set to coincide with the weather data at 15-minute intervals. The building was oriented towards northwest, which means that the external façade of the master bedroom faces northwest.

Table 6.1 lists the thermal properties of the building materials that were assigned to the base model. The density and specific heat capacity of each material was the average value from reference books or the collected Malaysian data where available (see Figures 4.7 and 4.8 in Chapter 4). Thermal conductivity was derived from the density using Eq. 4.1 (see Chapter 4: Section 4.1.3). Exceptions were data for the concrete roof tile, fibre-cement ceiling board and aluminium foil, which were obtained from the manufacturers. The thermal properties of the windows (glazing and frame) and soil were standard data in the WINDOW (Mitchell *et al.*, 2011) and TRNSYS libraries, respectively. The constructional layers and reference U-values of respective building elements are summarized in Table 6.2. It should be noted that during the simulation, variable U-values depending on the zone and ambient

Table 6.1. 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 (batten, door, floor)	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

n/a: not applicable.

Table 6.2. Constructional layers and reference U-values of the base model.

Building element	Constructional layers	Reference U-value[a] (W/m^2K)
External and internal walls	20mm thick cement plaster + 100mm thick clay brick + 20mm thick cement plaster	2.75
Party wall	20mm thick cement plaster + 200mm thick clay brick + 20mm thick cement plaster	2.07
Ground floor	8mm think ceramic tile + 22mm thick cement screed + 100mm thick concrete slab + soil layer	3.75[b]
First floor (timber flooring)	15mm thick timber flooring + 15mm thick cement screed + 100mm thick concrete slab + 20mm thick cement plaster	2.81
First floor (ceramic tile flooring)	8mm thick ceramic tile + 22mm thick cement screed + 100mm thick concrete slab + 20mm thick cement plaster	3.29
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 + 25mm thick timber batten + aluminium foil	2.67
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

[a] Includes convective and radiative heat transfer coefficients of 7.7 W/m^2K for inside surface and 25 W/m^2K for outside surface.

[b] Excludes soil layer.

Table 6.3. Wind pressure coefficients of the base model.

Building facade	Wind direction relative to building axis[a]							
	0°	45°	90°	135°	180°	225°	270°	315°
Ground floor level								
Front façade	0.197	0.099	-0.204	-0.073	-0.072	-0.081	-0.121	0.030
Front façade (NE side)	-0.294	0.099	0.081	-0.039	-0.188	-0.152	-0.124	-0.100
Front façade (SW side)	-0.299	-0.101	-0.124	-0.152	-0.187	-0.036	0.086	0.099
Rear façade	-0.072	-0.081	-0.121	0.030	0.197	0.099	-0.204	-0.073
Rear façade (SW side)	-0.184	-0.150	-0.124	-0.106	-0.316	0.100	0.104	-0.027
First floor level								
Front façade	0.426	0.209	-0.330	-0.106	-0.113	-0.121	-0.173	0.065
Front façade (NE side)	-0.496	0.247	0.246	-0.079	-0.331	-0.286	-0.219	-0.177
Front façade (SW side)	-0.506	-0.178	-0.219	-0.283	-0.327	-0.073	0.256	0.248
Rear façade	-0.113	-0.121	-0.173	0.065	0.426	0.209	-0.330	-0.106
Rear façade (NE side)	-0.312	-0.052	0.293	0.249	-0.540	-0.183	-0.218	-0.274
Rear façade (SW side)	-0.312	-0.274	-0.218	-0.183	-0.540	0.249	0.293	-0.052
Roof level								
Front façade	0.436	0.205	-0.334	-0.089	-0.107	-0.109	-0.135	0.072
Rear façade	-0.107	-0.109	-0.135	0.072	0.436	0.205	-0.334	-0.089
NE side façade	-0.472	0.180	0.489	0.136	-0.329	-0.151	-0.173	-0.142
30° Pitched roof: front	0.138	0.067	0.283	0.217	0.165	0.268	0.185	0.112
30° Pitched roof: rear	0.220	0.301	0.389	0.094	0.194	0.157	0.254	0.372
45° Pitched roof: front	-0.508	-0.264	0.546	0.420	0.352	0.442	0.282	-0.114
45° Pitched roof: rear	0.381	0.456	0.624	-0.273	-0.527	-0.105	0.319	0.476
Flat roof	0.093	0.081	0.153	0.059	0.063	0.040	0.039	0.048

[a] The building axis points towards the building orientation, i.e. NW.

temperatures at each time step were used to calculate the dynamic heat transfers. A time base of 1h was set for the transfer function to represent the thermal mass behaviour of the brick walls. Due to their small thermal mass, the thin fibre-cement ceiling boards were modelled as thermal resistant layers, i.e. their thermal mass was not considered; otherwise, they would

Table 6.4. Flow coefficients and flow exponents of the base model. Note: Selected data from Orme and Leksmono, 2002.

Building element	Flow coefficient	Flow exponent (-)
Crack component[a]	Unit: kg/sm^2Pa^n	
Plastered brick wall	2.18×10^{-5}	0.85
Concrete slab	2.54×10^{-5}	0.84
Tiled roofing[b]	9.68×10^{-3}	0.55
Fibre ceiling board	1.14×10^{-4}	0.76
Large opening component[c]	Unit: $kg/smPa^n$	
Window (hinged, with rubber seal)	1.57×10^{-4}	0.60
Window (hinged, without rubber seal)	8.95×10^{-4}	0.60
Window (sliding)	2.78×10^{-4}	0.60
Window (louvred)[d]	2.88×10^{-3}	0.60
External door (hinged)	1.45×10^{-3}	0.60
Internal door	1.57×10^{-3}	0.60

[a] The flow coefficient is given per surface area.

[b] Less airtight construction was assumed by applying a multiplication factor of 2 to the original value.

[c] The flow coefficient is given per length of joint.

[d] The given flow coefficient per louvre is 4.114×10^{-4} $kg/smPa^n$.

have required a smaller time base. The party walls on both sides of the house were modelled as boundary walls with identical zone temperatures assumed on both sides of the walls. On the other hand, the boundary condition for the ground floor was the constant soil temperature assumed to be the average air temperature at the site over the whole simulation period.

The total nett air volume of the whole house is 538 m^3; that of the master bedroom is 65 m^3. The total thermal capacitance of an airnode is the thermal capacitance of the air volume plus that of any mass not modelled as building elements. Since the house was modelled unfurnished, only the thermal capacitance of the air was considered. The multiplication factor for the humidity capacitance of the air was 5, which was assumed to account for the humidity capacitance of the air volume plus wall surfaces. Initial zone air temperatures and relative humidity for the simulation were based on the field experiment data.

Parameter and input values for wind and air flows are typically difficult to find due to lack of empirical data for all specific cases or if without wind tunnel facility. In this study, wind pressure coefficients were estimated using a parametrical model developed by Grosso (1992, 1995) known as CPCALC$^+$. The calculation considers terrain roughness (wind velocity profile exponent), surrounding buildings (building height and density), aspect ratios and wind direction. Strictly speaking, the tool applies to rectangular block buildings without overhangs (Grosso, 1992). The wind pressure coefficients on the ground floor facades were reduced by a multiplication factor of 0.5 to assume the presence of obstructions. Table 6.3

summarizes the derived data that we applied to the base model. Flow coefficients and flow exponents of cracks and openings were selected from references compiled in Orme and Leksmono (2002) (Table 6.4). The selected data were assumed to correspond with the local construction workmanship in terms of airtightness. Meanwhile, discharge coefficients were calculated internally in COMIS or estimated using a function given in the manual (Dorer *et al.*, 2005). A wind velocity profile exponent of 0.20 was used to represent the suburban terraced housing area (Counihan, 1975).

6.3.3 Validity of the Base Model

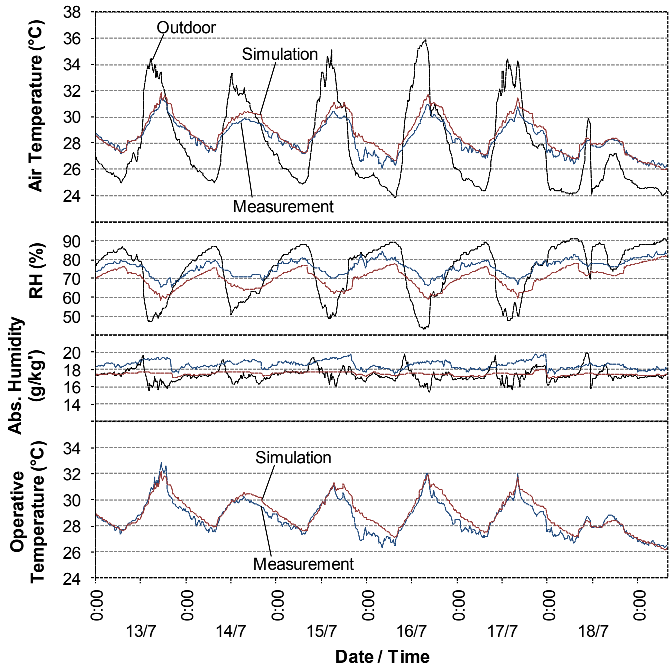
We employed empirical validation of the base model by comparing the simulation results with the field experiment data of Chapter 4: Section 4.3.3. This validation focuses on the master bedroom, as does our further simulation. The reason is based on the survey findings that existing households used air conditioners mainly in master bedrooms (see Chapter 4: Section 4.2.3); it is implied that the cooling energy can be reduced if the thermal comfort of the room is improved through passive cooling.

Figure 6.3 shows the temporal variations of the simulation results of the base model compared to the measurement data. Four ventilation conditions, i.e. night ventilation, daytime ventilation, no ventilation and full-day ventilation, are included. The validation period spans about three weeks in total. It begins at least nine days after the simulation start time for all conditions, thus allowing the model to acquire sufficient thermal history. Overall, Figure 6.3 illustrates good agreement between the simulation and measurement data in terms of air and operative temperatures. It should be noted that the relatively large difference between the simulated and measured temperatures seen on the first night for daytime ventilation and no ventilation is due to the open window condition during the field experiment (Figure 6.3bc). The difference continues in the daytime on the first day for no ventilation condition due to the thermal mass effect (Figure 6.3c).

On the other hand, the simulated relative humidity and absolute humidity are constantly lower than the measurement data by about 5-10% RH and about 1-2 g/kg', respectively, for all ventilation conditions (Figure 6.3). Humidity transport simulation could be a limitation of this model because both TRNSYS and COMIS are not specialized humidity simulation programs. Nevertheless, their daily patterns approximate those of the field measurement. The result implies that the sorption effects of the building surfaces are accounted for properly in the model by the humidity capacitance ratio.

Two statistical error tests that are commonly found in existing literature to check the deviations of simulation results from actual data are the mean bias error (MBE) and the root mean square error (RMSE). We apply them to measure the validity of this model. They are calculated as follows:

a



b

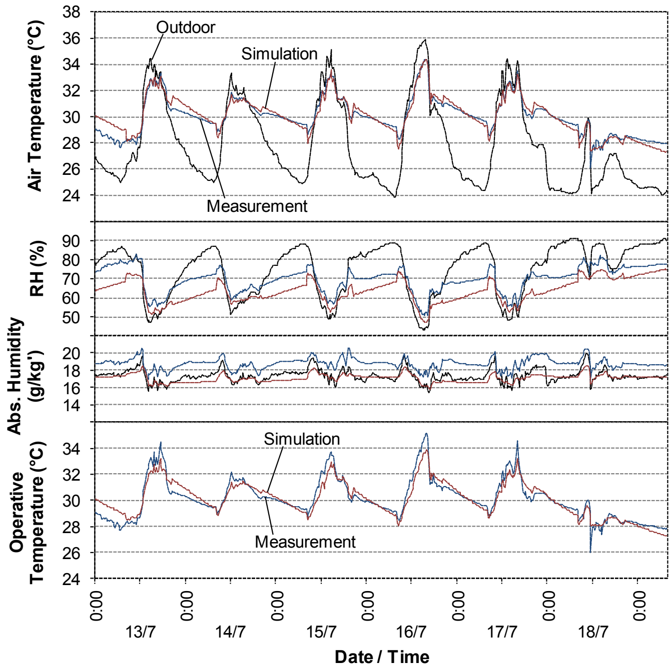
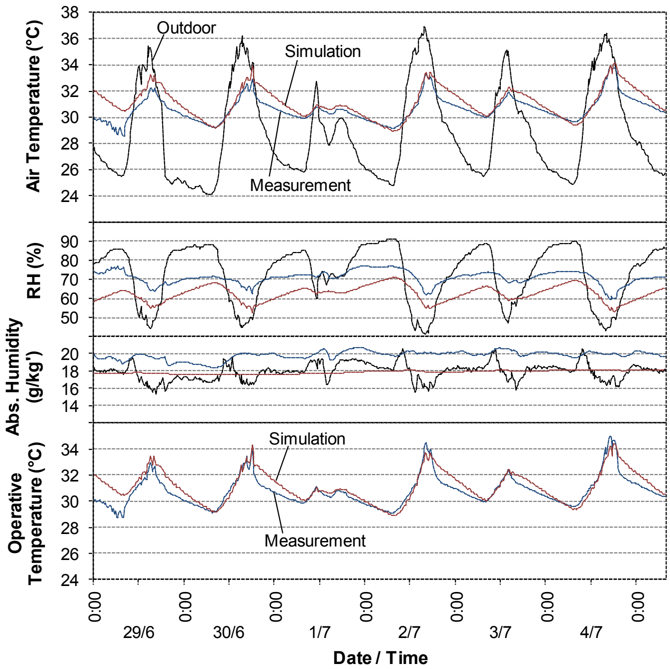


Figure 6.3. Temporal variations of the simulated data in the master bedroom of the base model compared to the field experiment data of the same room in the terraced houses for respective ventilation conditions. (a) Night ventilation (measurement data from Case 1-TH 2); (b) Daytime ventilation (measurement data from Case 1-TH 1); (c) No ventilation (measurement data from Case 2-TH 1); (d) Full-day ventilation (measurement data from Case 3-TH 1).

c



d

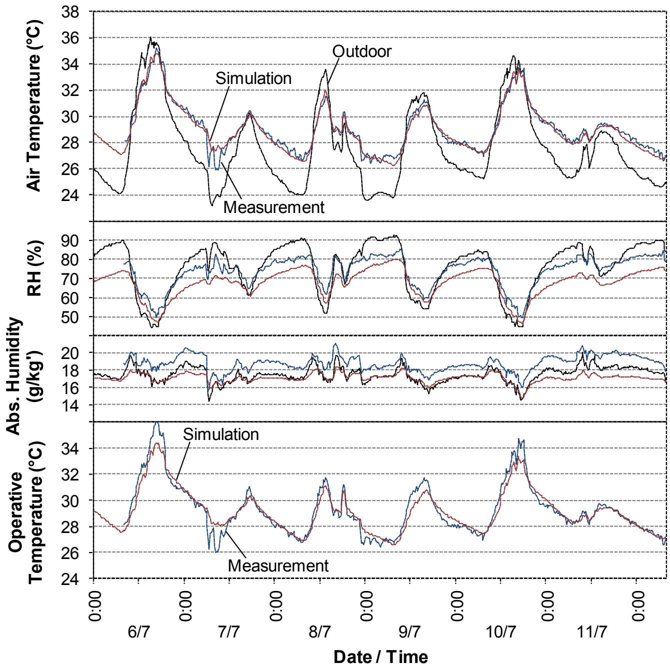


Figure 6.3. Temporal variations of the simulated data in the master bedroom of the base model compared to the field experiment data of the same room in the terraced houses for respective ventilation conditions. (a) Night ventilation (measurement data from Case 1-TH 2); (b) Daytime ventilation (measurement data from Case 1-TH 1); (c) No ventilation (measurement data from Case 2-TH 1); (d) Full-day ventilation (measurement data from Case 3-TH 1) (*continued*).

$$\text{MBE} = \sum_{i=1}^{N}(L_{is} - L_{i\text{m}})\,/N \tag{6.2}$$

$$\text{RMSE} = \sqrt{\sum_{i=1}^{N}(L_{is} - L_{i\text{m}})^2/N} \tag{6.3}$$

where L_{is} is the *i*th simulated value, L_{im} 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. Table 6.5 shows that the MBE for air temperature, operative temperature and absolute humidity range between -0.09°C and 0.35°C, -0.09°C and 0.32°C, and -1.04 g/kg' and -2.00 g/kg', respectively. Meanwhile, the RMSE for the same variables are 0.31-0.51°C, 0.46-0.58°C and 1.10-2.04 g/kg', respectively. Coefficients of determination (R^2) further test the linear relationships between the simulated and measured values. The R^2 values for air temperature are above 0.90 while the R^2 values for operative temperature are above 0.85 (Table 6.5).

The temperature errors and corresponding R^2 values of this model are similar to or smaller than errors reported in other validation work that simulated ventilative cooling techniques. For example, Finn *et al.* (2007) reported MBE and RMSE of 0.46°C and 0.88°C for air temperature, and MBE and RMSE of 1.14°C and 1.35°C for mean radiant temperature in a night ventilated building model. In another work that simulated a terraced house in Malaysia, the average air temperature difference between simulation and field measurement was 0.4°C (Sadafi *et al.*, 2011). In a simulation performed using TRNSYS, Geros *et al.* (1999) employed a building model which had a mean difference between measured and simulated temperatures of about 0.3°C with an R^2 value of about 0.90. It is concluded that the base model of this study is satisfactorily accurate in describing the thermal behaviour of the terraced house despite the acknowledged model limitation on humidity.

Table 6.5. Summary of statistical error tests of the base model.

Ventilation condition	Air temperature			Operative temperature			Absolute humidity		
	MBE (°C)	RMSE (°C)	R^2	MBE (°C)	RMSE (°C)	R^2	MBE (g/kg')	RMSE (g/kg')	R^2
Night ventilation	0.35	0.50	0.94	0.32	0.55	0.89	-1.04	1.10	0.60
Daytime ventilation	-0.05	0.31	0.96	-0.09	0.46	0.90	-1.70	1.76	0.39
No ventilation	0.35	0.51	0.92	0.24	0.51	0.86	-2.00	2.04	0.28
Full-day ventilation	-0.09	0.36	0.97	-0.06	0.58	0.93	-1.69	1.80	0.55

6.4 Simulation of Passive Cooling Techniques

6.4.1 The Simulation Test Cases

The simulation test cases focus on four aspects of passive cooling techniques, i.e. natural ventilation condition, thermal insulation, window shading and forced ventilation. Their functions are to reduce solar radiation heat gain through the building envelope and increase natural ventilation rate especially to enhance night ventilation in consideration of its potential to cool the brick terraced houses. In particular, the cases were designed to examine the cooling effects of:

- Night ventilation in urban climate
- Night ventilation with thermal insulation
- Night ventilation with window shading
- Increased night ventilation rate using forced ventilation
- Combinations of the effective techniques from above

Table 6.6 summarizes the simulation test cases in detail. These techniques were selected by considering their practicality to be applied to the existing terraced houses through relatively simple building modification and/or behavioural adjustment. The cases related to natural ventilation condition replicated the window opening patterns of the field experiment to represent night ventilation, daytime ventilation, no ventilation and full-day ventilation conditions. The change of window states for night ventilation and daytime ventilation occurred at 8 a.m. and 8 p.m. as before.

The primary elements of the building envelope that affect its thermal performance are the wall, roof and glazing. Thermal insulation was applied to the roof, ceiling and external wall at the outside and inside surfaces in respective simulation cases (Tables 6.6 and 6.7; Figure 6.4). Thermal insulation are materials that retard conductive, convective and radiative heat flux, when properly applied, by virtue of high thermal resistance or low apparent thermal conductivity of the material (ASHRAE, 2009). Several traditional and advanced materials have been developed to function as thermal insulation for buildings to date (see for example Jelle, 2011). Nevertheless, thermal insulation in buildings is not a common practice in Malaysia at present. The available building thermal insulation products are mainly rock wool and glass wool (fibre glass), which can be categorized as mineral wool, in blanket and board forms (Department of Standards Malaysia, 2010; MIMG, 2009). The products' thermal resistances or R-values range from 0.5-4.4 m^2K/W (Poly Glass Fibre Insulation, 2012; Rockwool Asia, 2012; Roofseal, 2012). The simulation test cases evaluated five levels of insulation thermal resistances in this range and assuming thermal properties typical of mineral wool (AIJ, 2011; Al-Homoud, 2005; ASHRAE, 2009) (Table 6.8). Table 6.9 further provides the reference U-values of respective building elements with thermal insulation.

Table 6.6. The simulation test cases and their test conditions.

Passive cooling technique	Test conditions 1	2	3	4
Open windows (all external windows)	*Night ventilation* • Closed 8 a.m.-8 p.m. Open 8 p.m.-8 a.m.	*Daytime ventilation* • Open 8 a.m.-8 p.m. Closed 8 p.m.-8 a.m.	*No ventilation* • Closed 24h	*Full-day ventilation* • Open 24h
Thermal insulation	*Roof* • R 0.5 • R 1 • R 2 • R 3 • R 4	*Ceiling* • R 0.5 • R 1 • R 2 • R 3 • R 4	*External wall – outside surface* • R 0.5 • R 1 • R 2 • R 3 • R 4	*External wall – inside surface* • R 0.5 • R 1 • R 2 • R 3 • R 4
Window shading (all external windows)	*External shading device* • SF 0.25 from 8 a.m.-8 p.m. • SF 0.50 from 8 a.m.-8 p.m. • SF 0.75 from 8 a.m.-8 p.m.	*Internal shading device* • SF 0.25 from 8 a.m.-8 p.m. • SF 0.50 from 8 a.m.-8 p.m. • SF 0.75 from 8 a.m.-8 p.m.		
Forced ventilation	*In attic* • 10 ACH 24h • 10 ACH night	*In master bedroom* • 30 ACH 24h • 30 ACH night • 40 ACH night • 50 ACH night	*In family area (whole house)* • 30 ACH 24h • 30 ACH night • 40 ACH night • 50 ACH night	

Shading of external window glazing was modeled as external shading device and internal shading device (Table 6.6 and Figure 6.4). It is generally known that external shading device is more effective in reducing solar heat gain than internal shading device because the solar transmission is removed before entering the space (Brown and DeKay, 2000). Nevertheless, internal shading device can be relatively easy to maintain and install in retrofit buildings. In TRNSYS, the specification of shading devices is given as shading factor (SF), i.e. the ratio of the opaque area of the shading device to the whole window area (no shading equals to 0) (Klein *et al.*, 2012). Three levels of shading factor, i.e. 0.25, 0.50 and 0.75, were simulated for each shading device. The values represented 75%, 50% and 25% solar transmission,

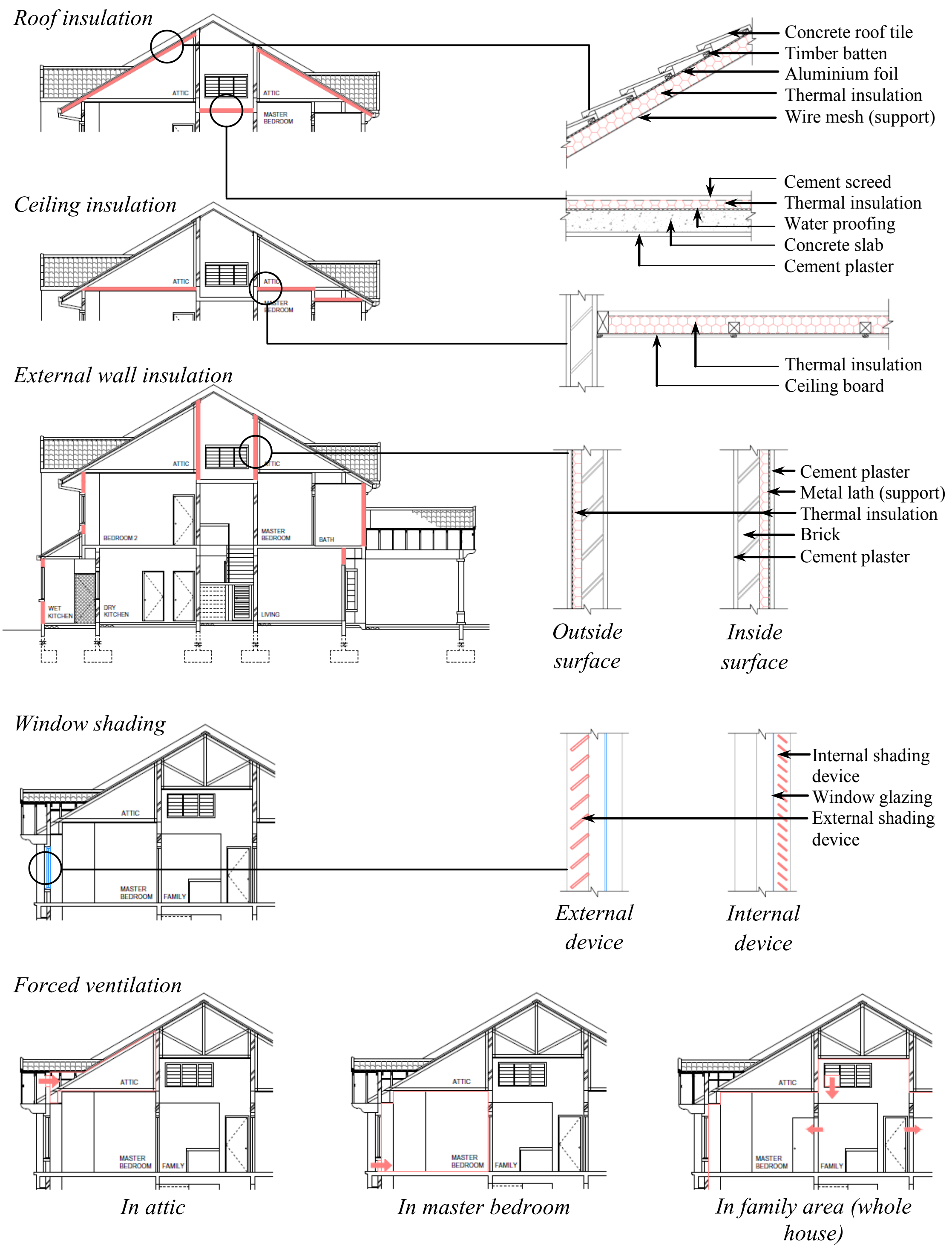


Figure 6.4. Conceptual illustrations of the simulation test cases. Note: Modified from architectural drawings with permission of Arkitek MAA (2010).

Table 6.7. Placement of thermal insulation in the constructional layers of respective building elements.

Insulated element	Constructional layers
Pitched roof	20mm thick concrete roof tile + 25mm thick timber batten + aluminium foil + thermal insulation
Flat roof	22mm thick cement screed + thermal insulation + 100mm thick concrete slab + 20mm thick cement plaster
Ceiling	Ceiling board + thermal insulation
External wall – outside surface	20mm thick cement plaster (inside) + 100mm thick clay brick + thermal insulation + 20mm thick cement plaster (outside)
External wall – inside surface	20mm thick cement plaster (inside) + thermal insulation + 100mm thick clay brick + 20mm thick cement plaster (outside)

Table 6.8. Thermal properties of the thermal insulation (mineral wool) used in the simulation.

Test condition	Density (kg/m^3)	Specific heat capacity (kJ/kgK)	Thermal conductivity (kJ/hmK)	Thickness (mm)	Thermal resistance	
					(hm^2K/kJ)	(m^2K/W)
R 0.5	80	0.84	0.144	20	0.139	0.5
R 1	80	0.84	0.144	40	0.278	1.0
R 2	80	0.84	0.144	80	0.556	2.0
R 3	80	0.84	0.144	120	0.833	3.0
R 4	80	0.84	0.108	120	1.111	4.0

Table 6.9. Reference U-values of building elements with thermal insulation.

Thermal insulation level	Reference U-value[a] (W/m^2K)				
	Pitched roof	Flat roof	Ceiling (master bedroom)	Ceiling (other zones)	External wall[b]
R 0.5	1.14	1.26	1.39	1.47	1.16
R 1	0.73	0.77	0.82	0.85	0.73
R 2	0.42	0.44	0.45	0.46	0.42
R 3	0.30	0.30	0.31	0.31	0.30
R 4	0.23	0.23	0.24	0.24	0.23

[a] Includes convective and radiative heat transfer coefficients of 7.7 W/m^2K for inside surface and 25 W/m^2K for outside surface.

[b] The reference U-value is the same for thermal insulation placed on the outside and inside surfaces.

respectively. The shading devices were used during daytime between 8 a.m. and 8 p.m. in all related cases.

Forced ventilation was applied to three spaces, i.e. the attic space above the master bedroom, the master bedroom itself and the family area on the first floor, respectively (Table 6.6 and Figure 6.4). Besides thermal insulation on the roof or ceiling, attic ventilation might be useful to remove heat that enters through the roof in the terraced house. On the other hand, night ventilation rate in the master bedroom could be increased in order to amplify the structural cooling effect at night. Alternatively, ventilation above the family area represented whole house ventilation by assuming that internal doors were open. It is found from the validated base model that the infiltration rates in the attic space average 1.7 ACH for all ventilation conditions since the attic space was equally not ventilated. Meanwhile, the natural ventilation rate in the master bedroom averages 13 ACH during the night ventilation period. In the simulation test cases, forced ventilation was applied to increase the ventilation rates to 10 ACH in the attic and 30-50 ACH in the master bedroom and family area, respectively, for the whole day (24-hour) or at night (8 p.m.-8 a.m.). In the simulation model, forced ventilation was applied as infiltration of outdoor air, i.e. at outdoor air temperature and humidity. Based on the principle of mass balance, it is expected that the effects also emulate the use of exhaust fan.

The test cases related to thermal insulation, window shading and forced ventilation were simulated in night ventilation and daytime ventilation (open window) conditions. In this thesis, our interest of natural ventilation conditions is placed most in them – the former being the most effective cooling technique that we find at this point for the terraced houses and the latter being the actual behaviour of the majority of households surveyed but creating warmer indoor conditions. The simulation test cases outlined above were repeated for two weather conditions that represented an urban climate and a rural climate (see Section 6.4.3). A total of 152 simulation cases were thus performed in this study.

6.4.2 Climatic Conditions of Major Cities in Malaysia

Before determining the weather conditions for the simulation in Section 6.4.3, we consider the climatic conditions of major cities in Malaysia in this section.

The land masses of Malaysia lie between latitudes 1-7°N and longitudes 100-119°E (Sani, 1998). Most of the economic and urban development has taken place at lowland areas along the west coast of Peninsular Malaysia. It follows that most of the terraced houses are built in these urban areas (see Figure 4.4 in Chapter 4). In general, the lowland areas are uniformly hot and humid year-round with slightly cooler and warmer seasons being largely determined by rainfall incidences which, in turn, are influenced by the monsoons (Lim and Abu Samah, 2004; Sani, 1990/91). The seasons in Malaysia are thus recognized as the northeast monsoon (November – February), the southwest monsoon (May – September) and two transitional or intermonsoon seasons (March – April, October) (Lim and Abu Samah, 2004).

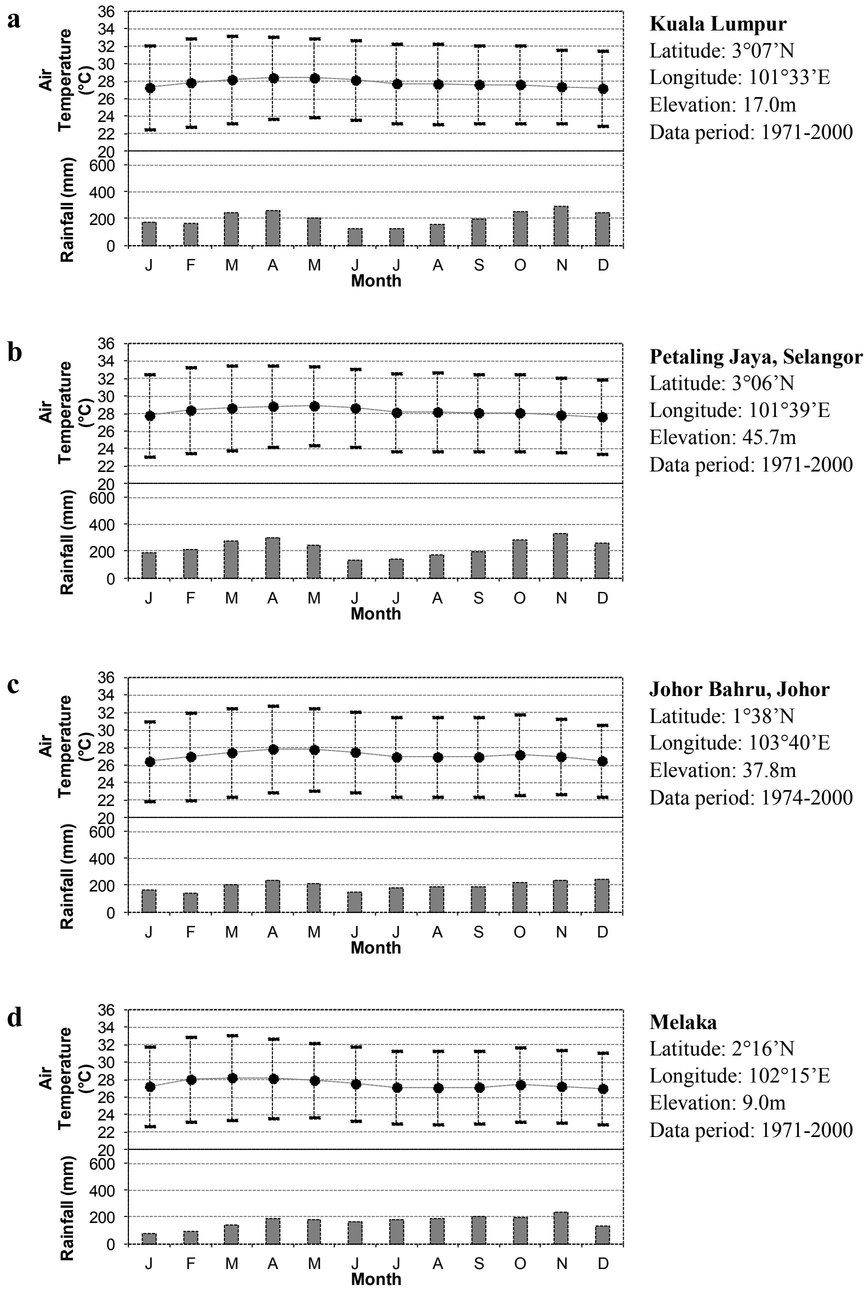
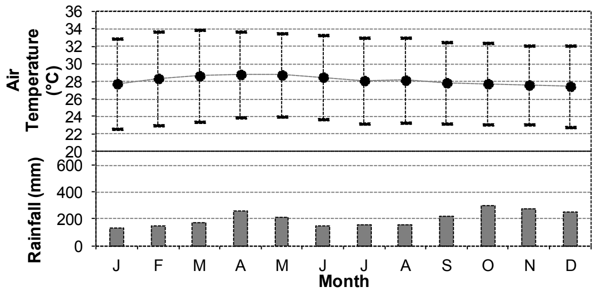


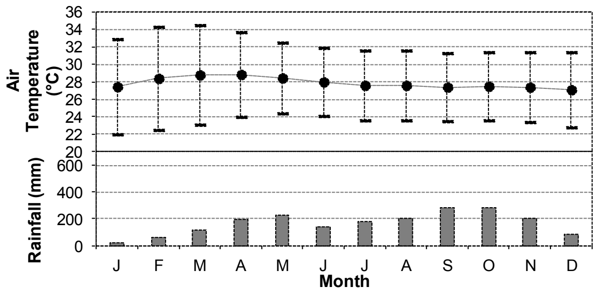
Figure 6.5. Historical monthly air temperatures (daily maximum, daily minimum and their mean) and rainfalls of major cities in Malaysia. (a) Kuala Lumpur; (b) Petaling Jaya; (c) Johor Bahru; (d) Melaka; (e) Ipoh; (f) Alor Setar; (g) Kuantan; (h) Kuching. Note: The name of the meteorological station in Johor Bahru is Senai station. Source: MMD, 2013; WMO, 2013.

e



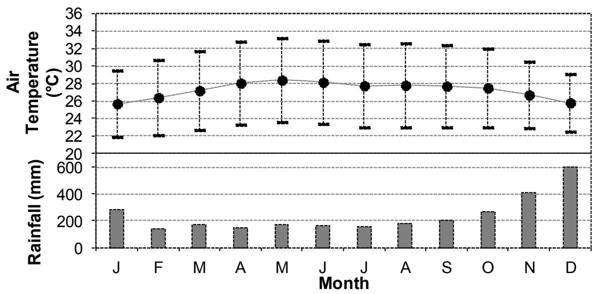
Ipoh, Perak
Latitude: 4°35'N
Longitude: 101°06'E
Elevation: 39.0m
Data period: 1971-2000

f



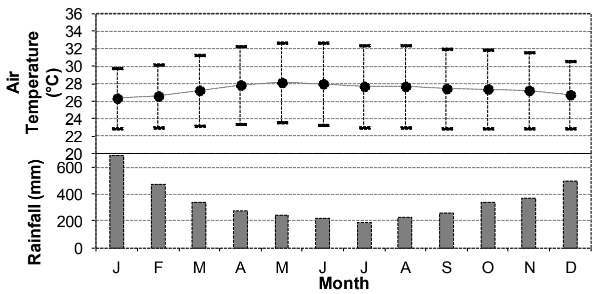
Alor Setar, Kedah
Latitude: 6°12'N
Longitude: 100°44'E
Elevation: 4.0m
Data period: 1971-2000

g



Kuantan, Pahang
Latitude: 3°47'N
Longitude: 103°13'E
Elevation: 15.0m
Data period: 1971-2000

h



Kuching, Sarawak
Latitude: 1°29'N
Longitude: 110°20'E
Elevation: 26.0m
Data period: 1971-2000

Figure 6.5. Historical monthly air temperatures (daily maximum, daily minimum and their mean) and rainfalls of major cities in Malaysia. (a) Kuala Lumpur; (b) Petaling Jaya; (c) Johor Bahru; (d) Melaka; (e) Ipoh; (f) Alor Setar; (g) Kuantan; (h) Kuching. Note: The name of the meteorological station in Johor Bahru is Senai station. Source: MMD, 2013; WMO, 2013 (*continued*).

We summarize the historical monthly air temperatures and rainfalls of selected major cities in Malaysia in Figure 6.5. These data were provided by the Malaysian Meteorological Department and retrieved from WMO's website (WMO, 2013). Information about the meteorological stations of these data was obtained from MMD (2013) and listed in the figure. The mean temperatures are the average of the mean daily minimum and mean daily maximum air temperatures of each month. Figure 6.5a-e show that most cities along the west coast of Peninsular Malaysia have monthly mean air temperatures between 26.5-28.9°C and deviations of only 1.2-1.4°C among the months in a year. The rainfall patterns and thus the air temperatures show little annual variation in these cities. Johor Bahru, which is our main study location for the terraced houses, has slightly lower monthly mean air temperatures among the cities compared. The other cities shown in Figure 6.5f-h have monthly mean air temperatures between 25.7-28.9°C and slightly larger deviations among the months in a year. The deviations in Alor Setar, Kuantan and Kuching are 1.8°C, 2.7°C and 1.8°C, respectively. The deviations are increased mainly due to the higher rainfalls that occur in Kuantan and Kuching and less rainfall in Alor Setar during the northeast monsoon months. Nevertheless, the annual climatic variations of each city and among cities were considered small to justify our limited yet varied study periods which did not cover a full year and single study location of the terraced houses.

Urban climates are known to be modified by their physical built environment (urban geometries, materials and surfaces), lack of vegetation and huge presence of energy-based activities and thus usually differ from the climates observed at rural areas and remote meteorological stations. A major alteration is the urban heat island phenomenon, i.e. an artificial excess of heat that causes the air and surface temperatures in the urban canopy to be higher than in the rural surroundings (Gartland, 2008; Oke, 1987). In this matter, urban and suburban areas are included (Gartland, 2008). In the national statistics presented in Section 4.1.1, urban areas were defined as gazetted areas with their adjoining built-up areas having a combined population of 10,000 or more in which at least 60% of the persons aged 15 years and over were engaged in non-agricultural activities (Department of Statistics Malaysia, 2011a). In both definitions, what is clear is that rural areas are distinguished from urban and suburban areas.

Past studies in Malaysia showed that the maximum intensity of the heat island in urban centres, including Johor Bahru, ranged from 2-7°C (Kubota and Ossen, 2009; Sani, 1990/91). Both daytime and night-time heat islands were recorded with changing spatial and temporal patterns. The actual phenomena of heat islands and other climatic elements in urban and suburban areas are complex (see for example Oke, 1987 and Sani, 1990/91). They would not be described in-depth in this thesis. Nevertheless, a relevant point is that the passive cooling ability of the existing terraced houses would likely differ much under the influence of urban-rural climatic differences, more than seasonal differences. On the other hand, most of our analyses focus on fair weather days. Further considerations of the urban climate are given in the next section.

6.4.3 The Weather Conditions for the Simulation

Two sets of weather data were used in all simulation cases. The main idea is to have a set that represents an urban climate where many terraced houses exist and another set that represents a corresponding rural reference climate for comparison.

Three types of weather data files that are commonly used for building simulation purposes are: (1) historical years, for example test reference year (TRY); (2) typical years, for example typical meteorological year (TMY); and (3) synthetic years. Oxizidis *et al.* (2007) provided a review of them. It should be acknowledged that the TRNSYS program supplies typical weather data that are generated using Meteonorm V5 in TMY2 format and includes locations in Malaysia (Klein *et al.*, 2012). However, these typical weather years are still climatological descriptions of mainly rural locations near cities, not the cities themselves or building sites (Orme and Leksmono, 2002; Oxizidis *et al.*, 2007); the same applies to Malaysian data – one of the reasons being the lack of weather monitoring stations in urban centres. These choices could not fit our study objective.

An alternative was to employ actual weather data measured at the sites of interest, though a limitation would be that they provide only one realization of the time series for evaluating the passive cooling effects. Kubota and Ossen (2011) monitored several weather variables at the centre of a heat island in Johor Bahru city from August 2009 to May 2010. It was a study concerning the temporal characteristics of urban heat island intensity. The exact measurement location (latitude 1°29’19”N, longitude 103°45’41”E, elevation 26m above sea level) was a school surrounded by terraced housing neighbourhoods. The measurement interval was 10 minutes. Their rural reference site was UTM campus, which is a vast green area, but fewer variables were measured.

In this thesis, we employed the weather data measured at the centre of the heat island in Johor Bahru, as mentioned above, to represent the urban climate. For the reference rural site, we used hourly weather data at Senai station for the same measurement period (MMD, 2011) so that each data set contained all the weather variables of the location for the simulation. One exception was the absence of barometric pressure data in the city centre measurement which was substituted using the data of Senai station.

The simulation was run using the weather data for two whole months, i.e. January-February 2010. In this period, typical fair weather days occurred more consistently at both locations and the air temperature in Johor Bahru was relatively high compared to Senai during both daytime and night-time. Subsequently, the simulation results for a 10-day period of continuous typical fair weather days are analysed and presented in this thesis. It should be noted that the night-time heat island intensity was larger in the city centre compared to the suburban area (Kubota and Ossen, 2009), though daytime conditions in suburban areas could be similar to or hotter than urban centres (Sani, 1990/91). Thus, this simulation might yield results that differ from the field experiment.

A wind velocity profile exponent of 0.25 was used to represent the urban location (Counihan, 1975). Wind pressure coefficients for the urban location were estimated based on

Table 6.10. Wind pressure coefficients for the urban location.

Building facade	Wind direction relative to building axis[a]							
	0°	45°	90°	135°	180°	225°	270°	315°
Ground floor level								
Front façade	0.020	0.010	-0.025	-0.009	-0.009	-0.010	-0.015	0.003
Front façade (NE side)	-0.287	0.025	0.020	-0.010	-0.184	-0.149	-0.121	-0.097
Front façade (SW side)	-0.292	-0.099	-0.121	-0.148	-0.183	-0.009	0.022	0.025
Rear façade	-0.009	-0.010	-0.015	0.003	0.020	0.010	-0.025	-0.009
Rear façade (SW side)	-0.180	-0.146	-0.121	-0.103	-0.308	0.025	0.026	-0.007
First floor level								
Front façade	0.025	0.011	-0.048	-0.017	-0.017	-0.019	-0.028	0.004
Front façade (NE side)	-0.599	0.047	0.052	-0.017	-0.400	-0.345	-0.264	-0.213
Front façade (SW side)	-0.610	-0.215	-0.264	-0.342	-0.395	-0.016	0.054	0.048
Rear façade	-0.017	-0.019	-0.028	0.004	0.025	0.011	-0.048	-0.017
Rear façade (NE side)	-0.377	-0.011	0.063	0.048	-0.652	-0.221	-0.263	-0.331
Rear façade (SW side)	-0.377	-0.331	-0.263	-0.221	-0.652	0.048	0.063	-0.011
Roof level								
Front façade	0.217	0.102	0.045	0.012	0.015	0.015	0.018	0.036
Rear façade	0.015	0.015	0.018	0.036	0.217	0.102	0.045	0.012
NE side façade	-0.537	0.218	0.594	0.165	-0.374	-0.172	-0.197	-0.162
30° Pitched roof: front	0.011	0.004	0.013	0.016	0.014	0.019	0.009	0.008
30° Pitched roof: rear	0.152	0.171	0.148	0.050	0.137	0.089	0.097	0.210
45° Pitched roof: front	-0.050	-0.020	0.027	0.033	0.033	0.035	0.014	-0.009
45° Pitched roof: rear	0.299	0.288	0.252	-0.168	-0.168	-0.065	0.129	0.302
Flat roof	0.007	0.008	0.011	0.006	0.005	0.004	0.003	0.005

[a] The building axis points towards the building orientation, i.e. NW.

this exponent and a higher density using the same method given in Section 6.3.2. Table 6.10 summarizes the urban wind pressure coefficients. Most of the wind pressure coefficients for the urban location have smaller magnitude from zero than those of the base model.

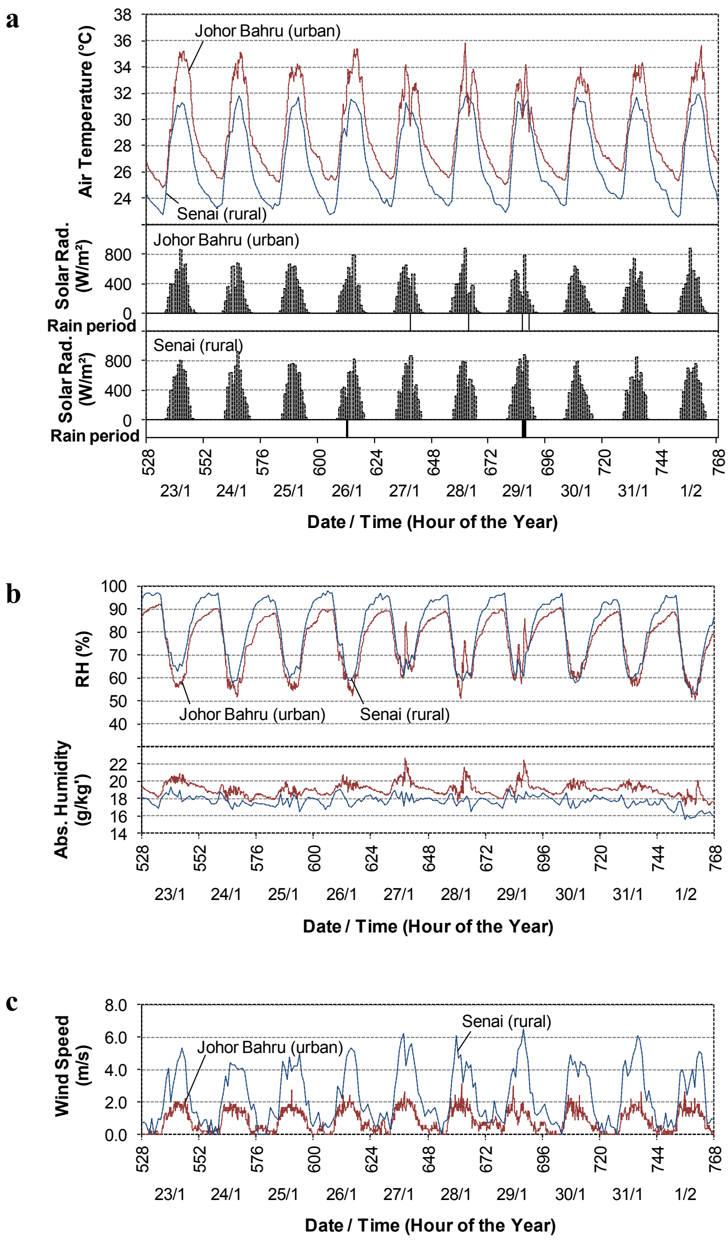


Figure 6.6. Temporal variations of measured weather variables at Johor Bahru city centre (urban location) and Senai station (rural reference site) for the simulation analysis period. (a) Air temperature, global horizontal solar radiation and rain period; (b) Relative humidity and absolute humidity; (c) Wind speed. Reference heights of wind speed measurements at Johor Bahru and Senai are 4.0m and 10.0m, respectively.

Meanwhile, the rural reference site assumed the same wind velocity profile and pressure distributions as the base model. The wind speed at Senai station, $v(z_{ref})$, which was measured at 10.0m height above ground, is converted to wind speed at the building height, $v(z)$, using the logarithmic equation:

$$\frac{v(z)}{v(z_{ref})} = \frac{\log(z-d)-\log z_0}{\log(z_{ref}-d_{ref})-\log z_{0ref}} \tag{6.4}$$

where z is building height above ground (m), z_{ref} is reference height for the wind speed measurement at Senai station (m), d is zero flow plane displacement height for the assumed building location (m), d_{ref} is zero flow plane displacement height at Senai station (m), z_0 is roughness length for the assumed building location (m) and z_{0ref} is roughness length at Senai station (m) (Grosso, 1992). The zero flow plane displacement heights and roughness lengths were obtained from Allard (1998) and Counihan (1975), respectively, to correspond with the terrain roughness of the location.

Figure 6.6 illustrates the weather conditions of Johor Bahru and Senai for the selected fair weather period. The two most important weather variables in building thermal simulation is solar radiation and air temperature. The air temperature is higher while the incoming solar radiation, i.e. daily global horizontal solar radiation, is lower in Johor Bahru compared to Senai on the fair weather days (Figure 6.6a), as usually seen due to climatic and atmospheric modifications by urban areas (Oke, 1987).

6.5 Assessments of the Simulated Techniques

6.5.1 Effects of Natural Ventilation in the Urban and Rural Climates

Temporal variations of the simulated indoor air temperatures in the master bedroom of the terraced house are presented in Figures 6.7-6.10 for the four open window conditions that represent night ventilation, daytime ventilation, no ventilation and full-day ventilation, respectively. The indoor temperatures in each natural ventilation conditions at each location have consistently similar patterns over the 10-day period. A statistical summary for the period is provided in Figure 6.11.

Overall, night ventilation provides the lowest indoor air temperatures among the tested open window conditions in both urban and rural climates (Figure 6.11). The pattern of this simulation result resembles the measurement result of the field experiment. The reasons for the different effects of the natural ventilation conditions are already discussed in Chapter 4: Section 4.3.3; here we describe the magnitude of the cooling effects under the influence of different locations.

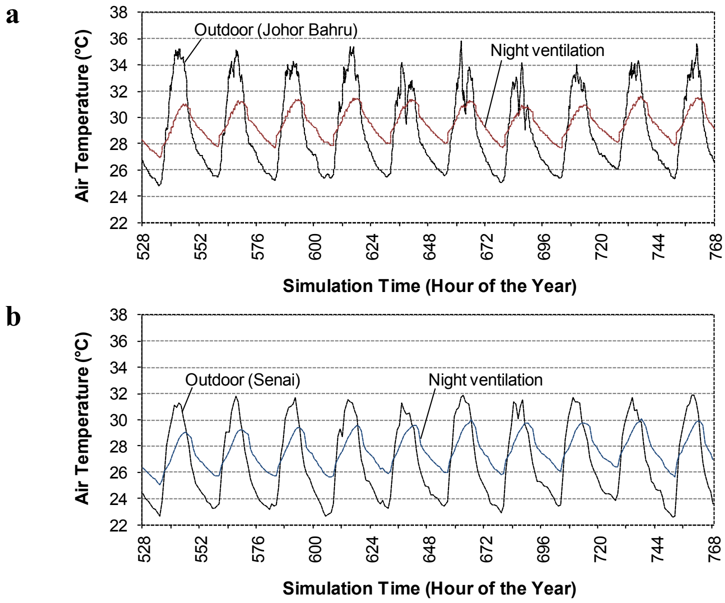


Figure 6.7. Temporal variations of simulated indoor air temperatures in the master bedroom of the terraced house in night ventilation condition. (a) Urban climate (Johor Bahru); (b) Rural climate (Senai).

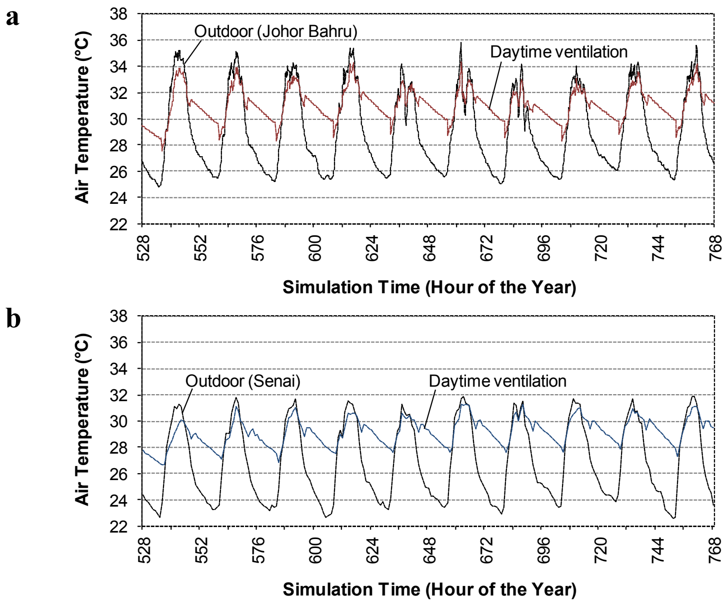


Figure 6.8. Temporal variations of simulated indoor air temperatures in the master bedroom of the terraced house in daytime ventilation condition. (a) Urban climate (Johor Bahru); (b) Rural climate (Senai).

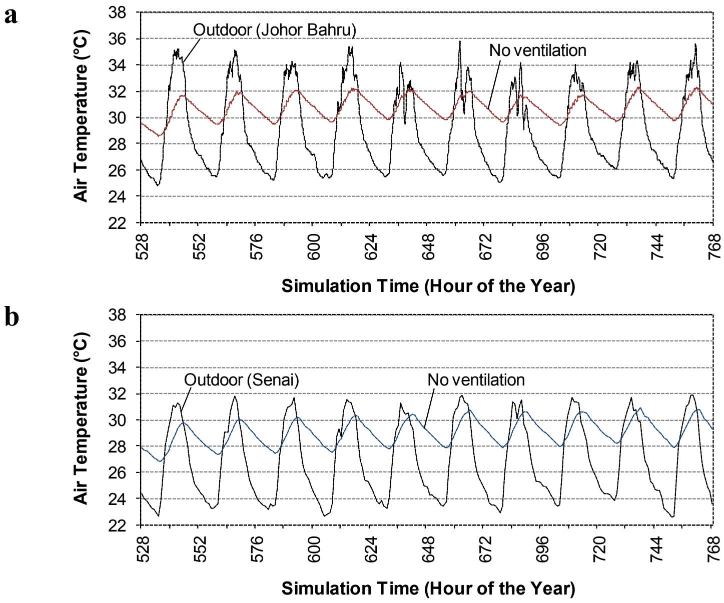


Figure 6.9. Temporal variations of simulated indoor air temperatures in the master bedroom of the terraced house in no ventilation condition. (a) Urban climate (Johor Bahru); (b) Rural climate (Senai).

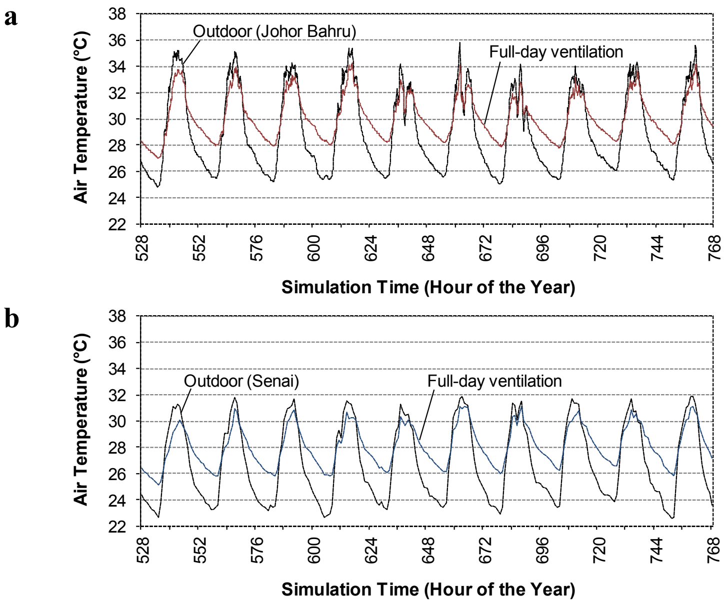


Figure 6.10. Temporal variations of simulated indoor air temperatures in the master bedroom of the terraced house in full-day ventilation condition. (a) Urban climate (Johor Bahru); (b) Rural climate (Senai).

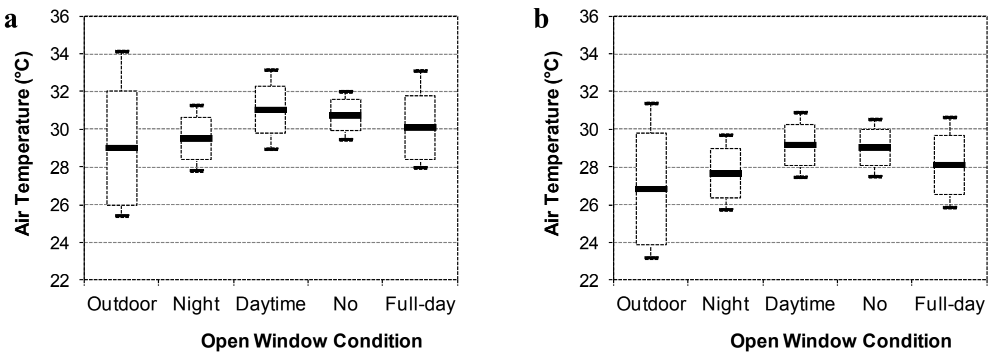


Figure 6.11. Statistical summary (5th and 95th percentiles, mean and ± one standard deviation) of simulated indoor air temperatures in the master bedroom of the terraced house in different open window conditions. (a) Urban climate (Johor Bahru); (b) Rural climate (Senai).

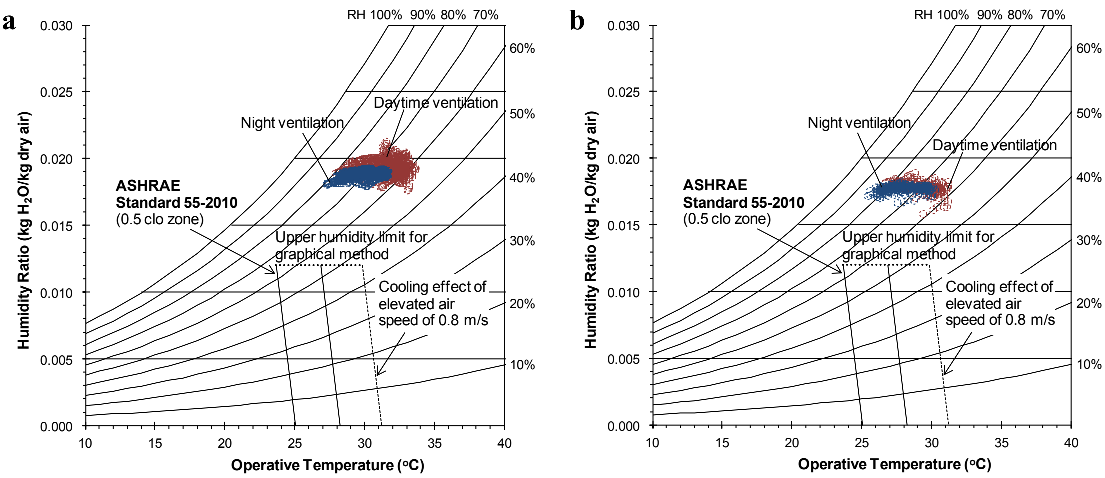


Figure 6.12. Scatter diagram of simulated indoor operative temperatures and indoor humidity in the master bedroom of the terraced house on a psychrometric chart. (a) Urban climate (Johor Bahru); (b) Rural climate (Senai).

In the urban climate (Johor Bahru), maximum air temperature (95th percentile) in the night ventilated master bedroom is 2.9°C lower than the outdoors (Figure 6.11a). The corresponding minimum air temperature (5th percentile) is 2.4°C higher than the outdoors. On the other hand, maximum and minimum air temperatures in the daytime ventilated master bedroom are 1.9°C and 1.2°C higher than those of the night ventilated room, respectively. The indoor air temperatures in night ventilation and daytime ventilation conditions average 29.5°C and 31.0°C, respectively, while the outdoor air temperature averages 29.0°C on these fair weather days.

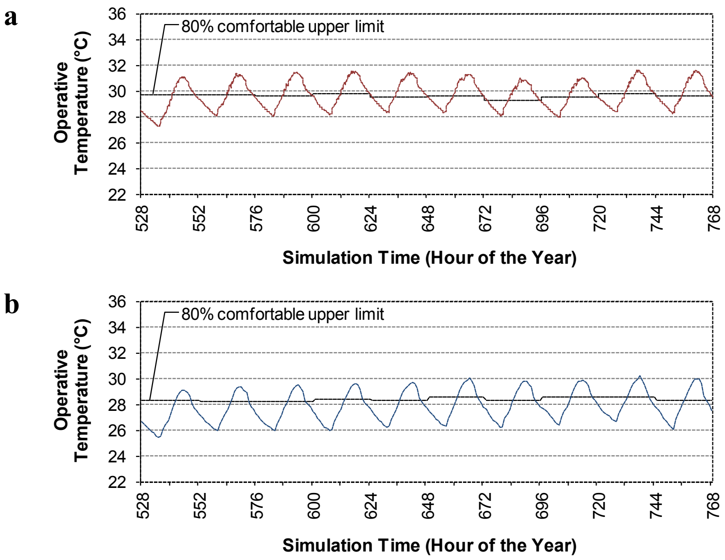


Figure 6.13. Temporal variations of simulated indoor operative temperatures in the master bedroom of the terraced house in night ventilation condition and the corresponding temperature limits for thermal comfort. (a) Urban climate (Johor Bahru); (b) Rural climate (Senai).

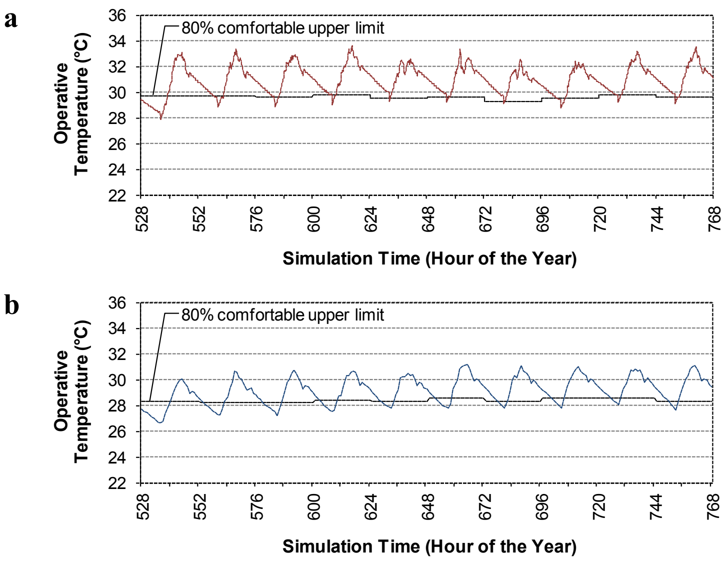


Figure 6.14. Temporal variations of simulated indoor operative temperatures in the master bedroom of the terraced house in daytime ventilation condition and the corresponding temperature limits for thermal comfort. (a) Urban climate (Johor Bahru); (b) Rural climate (Senai).

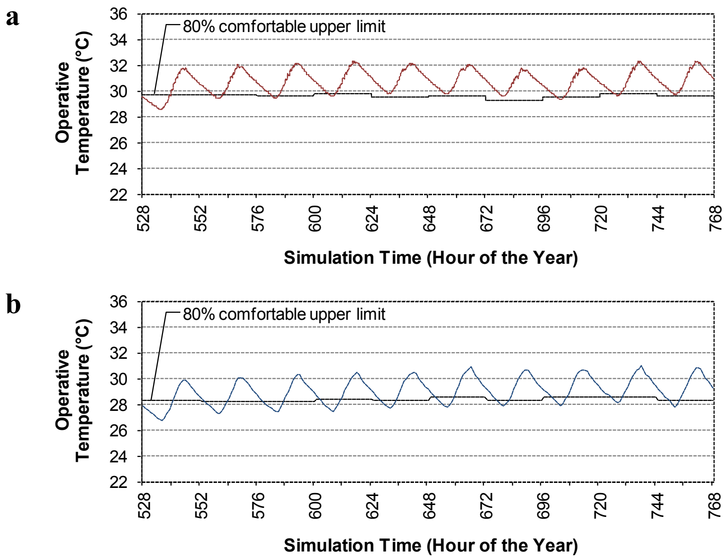


Figure 6.15. Temporal variations of simulated indoor operative temperatures in the master bedroom of the terraced house in no ventilation condition and the corresponding temperature limits for thermal comfort. (a) Urban climate (Johor Bahru); (b) Rural climate (Senai).

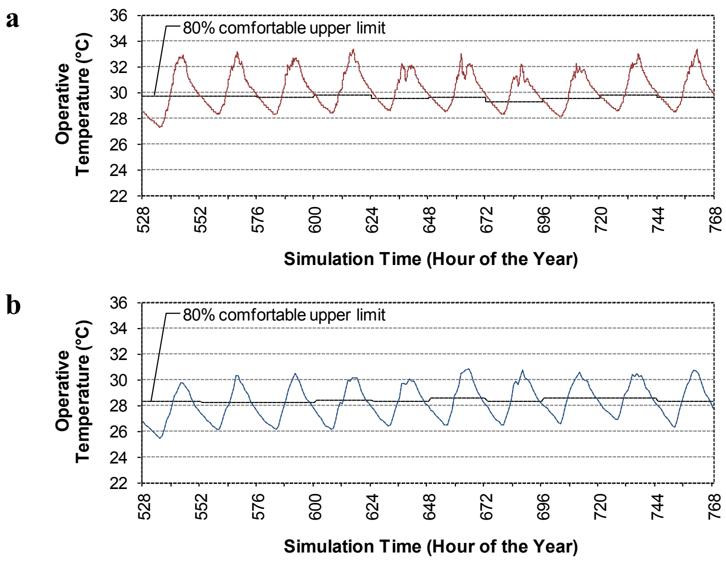


Figure 6.16. Temporal variations of simulated indoor operative temperatures in the master bedroom of the terraced house in full-day ventilation condition and the corresponding temperature limits for thermal comfort. (a) Urban climate (Johor Bahru); (b) Rural climate (Senai).

In the rural reference climate (Senai), maximum air temperature (95^{th} percentile) in the night ventilated master bedroom is 1.7°C lower than the outdoors (Figure 6.11b). The corresponding minimum air temperature (5^{th} percentile) is 2.6°C higher than the outdoors. In comparison, maximum and minimum air temperatures in the daytime ventilated master bedroom are 1.2°C and 1.7°C higher than those of the night ventilated room, respectively. The indoor air temperatures in night ventilation and daytime ventilation conditions average 27.6°C and 29.2°C, respectively, while the outdoor air temperature averages 26.8°C. Needless to say, these values are lower than those in the urban climate.

We plot the simulated indoor operative temperatures and humidity of the master bedroom on a psychrometric chart in Figure 6.12 for two open window conditions, i.e. night ventilation and daytime ventilation. None of the data falls within the illustrated comfort zone by ASHRAE (2010) for typical indoor environments at 0.5 clo level, even in the rural reference climate (Senai).

Temporal variations of the indoor operative temperatures are plotted in Figures 6.13-6.16 for thermal comfort evaluation of the tested open window conditions. As before, this evaluation is made based on the thermal comfort criteria that are developed in this study (see Chapter 3: Section 3.3.6). In Figures 6.13-6.16, the 80% comfortable upper limit is drawn for each day based on the outdoor air temperatures at respective locations. The 80% comfortable upper limits range between 29.3-29.8°C in the urban climate (Johor Bahru) and 28.3-28.6°C in the rural reference climate (Senai). This means that even by considering thermal adaptation to the urban climate, the comfort temperature upper limit could be raised by about 1°C only compared to the rural reference climate. Table 6.11 summarizes the indoor operative temperature deviations from the 80% comfortable upper limits and the exceeding periods.

The evaluation reveals that night ventilation provides more comfortable indoor operative temperature than the other open window conditions at both locations by reducing the period as well as magnitude of the temperature above the limit (Figures 6.13-6.16 and Table 6.11). In the urban climate (Johor Bahru), indoor operative temperatures in the daytime ventilated room are higher than the 80% comfortable upper limits for 88% of the time; the maxima are 2.9-3.9°C above the same limits (Figure 6.14a and Table 6.11). The exceeding period is reduced to 52% while the daily maximum indoor operative temperatures are 1.4-1.9°C above the same limits in the night ventilated room (Figure 6.13a and Table 6.11).

Meanwhile, in the rural climate (Senai), indoor operative temperatures in the night ventilated room are deemed more comfortable than in the urban climate under the same open window condition. The daily maximum operative temperatures are 0.8-1.7°C higher than the 80% comfortable upper limits and the exceeding period is 35% (Figure 6.13b and Table 6.11). Daily maximum indoor operative temperature reductions by night ventilation compared to daytime ventilation (and full-day ventilation) are more pronounced in the urban climate (Johor Bahru) than in the rural climate (Senai) (Table 6.11). This is likely due to the relatively high peak outdoor air temperatures at the urban location which influence the indoor thermal conditions much when windows are open during daytime. Conversely, daily

Table 6.11. Summary of thermal comfort evaluation in the master bedroom of the terraced house in different open window conditions (simulation results).

Open window condition	Deviation of indoor operative temperature from the 80% comfortable upper limits (°C)[a]		Exceeding period (%)
	Daily maximum	Daily minimum	
Urban climate (Johor Bahru)			
Night ventilation	1.4 to 1.9	-1.2 to -2.5	52
Daytime ventilation	2.9 to 3.9	-0.2 to -1.8	88
No ventilation	2.1 to 2.7	0.3 to -1.2	89
Full-day ventilation	2.7 to 3.7	-0.9 to -2.4	60
Rural climate (Senai)			
Night ventilation	0.8 to 1.7	-1.8 to -2.9	35
Daytime ventilation	1.7 to 2.8	-0.5 to -1.6	72
No ventilation	1.6 to 2.5	-0.4 to -1.5	68
Full-day ventilation	1.5 to 2.4	-1.6 to -2.9	45

[a] Positive values indicate indoor operative temperatures above the 80% comfortable upper limits and negative values indicate indoor operative temperatures below the 80% comfortable upper limits.

minimum indoor operative temperature reductions by night ventilation compared to daytime ventilation are larger in the rural climate (Senai) (Table 6.11).

Figure 6.17 shows a comparison of the relationships between outdoor air temperatures and indoor operative temperatures in the master bedroom in night ventilation condition at the urban and rural locations. Segmented regression is used (see the method in Chapter 4: Section 4.3.5). The break-point for the urban climate is 27.5°C while the break-point for the rural climate is 25.3°C, which is 2.2°C lower than that of the urban climate (Figure 6.17). The regression line for the urban climate is parallel to but 1.4°C higher than the regression line for the rural climate after the break-point (Figure 6.17). It signifies the influence of the urban-rural climatic differences for the same building, i.e. assuming the same heat modulation by the same thermal mass in closed window conditions.

The regression lines before the break-points represent the night ventilation period. The gradients are also almost similar at about 0.8 for the two locations (Figure 6.17). Despite assuming different wind fields around the building, the simulation reveals that the night ventilation rates in the urban and rural climates are similar at about 14 ACH, thus explaining the similar gradients. This is likely because outdoor wind speed is basically low at night even at the rural location (see Figure 6.6c). The result implies that higher night-time indoor operative temperatures are encountered in the night ventilated room in the urban climate likely due to relatively high outdoor air temperature, i.e. heat island occurrence, but not reduction in ventilation rate in comparison with the rural climate.

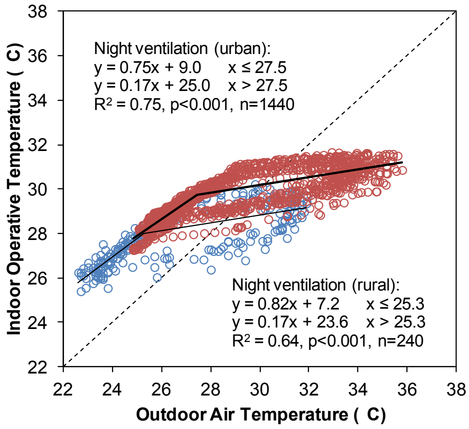


Figure 6.17. Relationships between outdoor air temperatures and indoor operative temperatures in the night ventilated master bedroom of the terraced house in the urban and rural climates. Red points and thick regression line represent urban climate while blue points and thin regression line represent rural climate. Dashed line represents indoor conditions equaling outdoor conditions.

6.5.2 Effects of Roof Insulation

The simulated indoor air temperatures in the master bedroom of the terraced house with roof insulation in the urban climate are summarized in Figure 6.18. Two open window conditions, i.e. night ventilation and daytime ventilation, were simulated. Figure 6.18a reveals that when thermal insulation with R-value of 0.5 m^2K/W, noted as R 0.5, was applied to the whole roof, the maximum (95th percentile), mean and minimum (5th percentile) indoor air temperatures in the night ventilated room are 0.5°C, 0.3°C and 0.1°C lower than those without roof insulation. Raising the R-value of the roof insulation to R 4 further reduces the corresponding indoor air temperatures to 0.9°C, 0.6°C and 0.3°C lower than those without the insulation. As expected, reduction in the maximum air temperature is higher since it is a direct effect of the reduction in solar heat gain through the roof during daytime. Air temperature in the adjacent unventilated attic space is also reduced by insulation at the roof level. With less heat gain during the day and a cooler adjacent attic space for the whole day, the building structures maintain cooler and likely serve to reduce the night-time indoor air temperature as well. On the other hand, the indoor air temperatures in the daytime ventilated master bedroom are almost similar whether the roof insulation was applied or not (Figure 6.18b). The inflow of hot outdoor air through open windows during daytime increases the indoor air temperature and diminishes the effect of the insulation.

Temporal variations of the indoor operative temperatures for the above simulation cases are given in Figure 6.19 to evaluate any thermal comfort improvement afforded by the roof insulation in the urban climate. Table 6.12 summarizes the result for all simulated roof insulation conditions. With night ventilation, the roof insulation of R 4 lowers the indoor

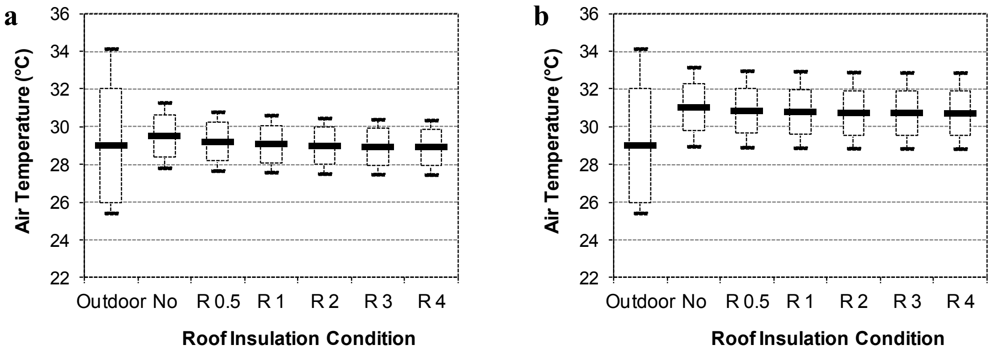


Figure 6.18. Statistical summary (5th and 95th percentiles, mean and ± one standard deviation) of simulated indoor air temperatures in the master bedroom of the terraced house in different roof insulation conditions in the urban climate (Johor Bahru). (a) Night ventilation; (b) Daytime ventilation.

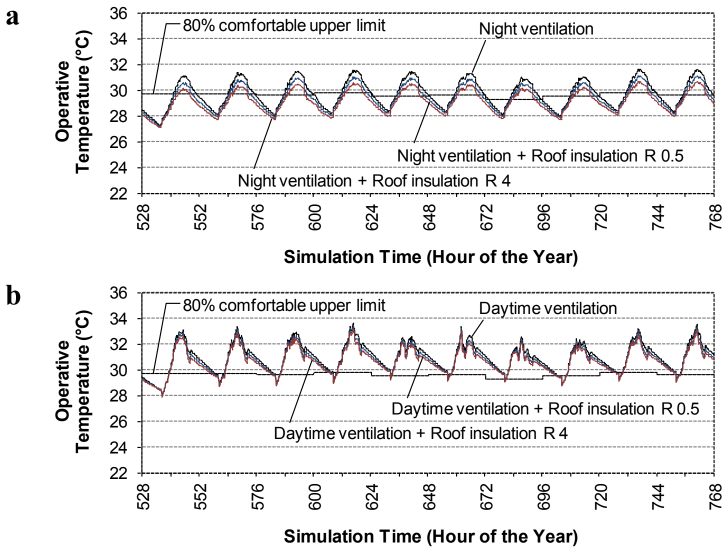


Figure 6.19. Temporal variations of simulated indoor operative temperatures in the master bedroom of the terraced house with roof insulation and the corresponding temperature limits for thermal comfort in the urban climate (Johor Bahru). (a) Night ventilation; (b) Daytime ventilation.

operative temperature throughout the day compared to using only night ventilation so that the maximum operative temperatures are 0.4-1.0°C above the 80% comfortable upper limits and the exceeding period is 32% (Figure 6.19a and Table 6.12). With daytime ventilation, the roof insulation of R 4 lowers the maximum operative temperatures to 2.6-3.4°C above the 80% comfortable upper limits but the exceeding period is reduced only slightly to 84%

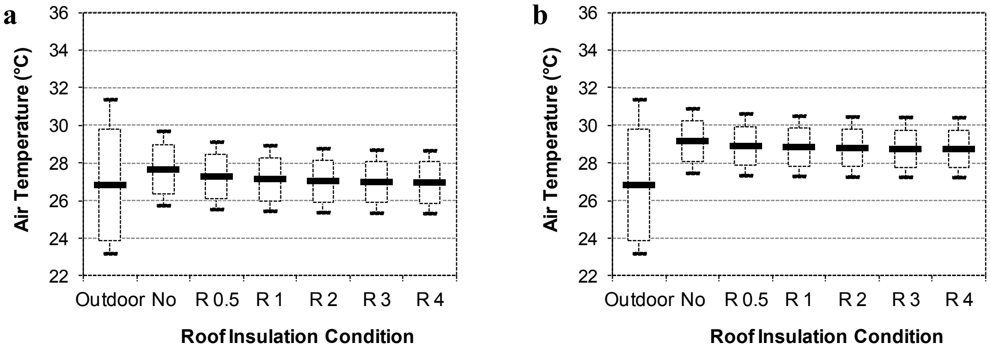


Figure 6.20. Statistical summary (5th and 95th percentiles, mean and ± one standard deviation) of simulated indoor air temperatures in the master bedroom of the terraced house in different roof insulation conditions in the rural climate (Senai). (a) Night ventilation; (b) Daytime ventilation.

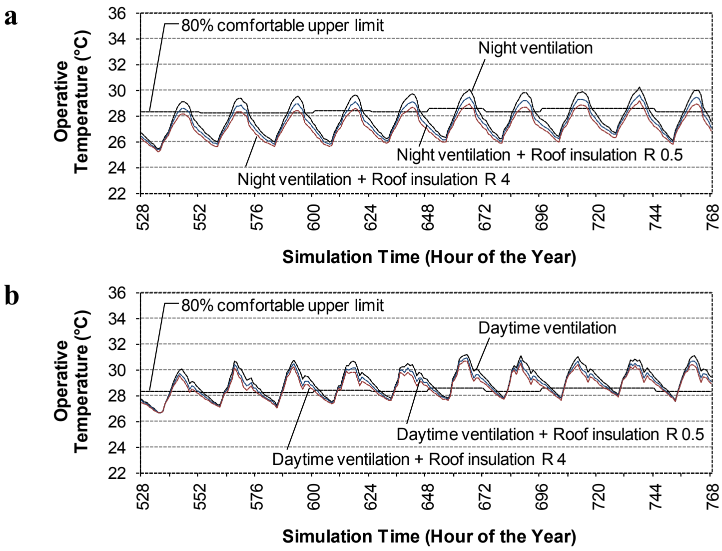


Figure 6.21. Temporal variations of simulated indoor operative temperatures in the master bedroom of the terraced house with roof insulation and the corresponding temperature limits for thermal comfort in the rural climate (Senai). (a) Night ventilation; (b) Daytime ventilation.

(Figure 6.19b and Table 6.12). The operative temperature reduction in the daytime ventilated room is likely due to the reduced radiant heat from the ceiling surface but not cooler air.

In the rural climate, using roof insulation with R-value of 0.5 m^2K/W reduces the maximum (95th percentile), mean and minimum (5th percentile) indoor air temperatures in the night ventilated master bedroom by 0.6°C, 0.3°C and 0.2°C compared to those without roof

Table 6.12. Summary of thermal comfort evaluation in the master bedroom of the terraced house with roof insulation in the urban climate (Johor Bahru).

Roof insulation condition	Deviation of indoor operative temperature from the 80% comfortable upper limits (°C)[a]		Exceeding period (%)
	Daily maximum	Daily minimum	
Night ventilation	*1.4 to 1.9*	*-1.2 to -2.5*	*52*
R 0.5	0.9 to 1.5	-1.3 to -2.5	41
R 1	0.7 to 1.3	-1.4 to -2.6	38
R 2	0.5 to 1.1	-1.5 to -2.6	35
R 3	0.5 to 1.0	-1.5 to -2.6	33
R 4	0.4 to 1.0	-1.5 to -2.6	32
Daytime ventilation	*2.9 to 3.9*	*-0.2 to -1.8*	*88*
R 0.5	2.7 to 3.7	-0.2 to -1.8	87
R 1	2.7 to 3.6	-0.3 to -1.8	86
R 2	2.6 to 3.5	-0.3 to -1.8	85
R 3	2.6 to 3.5	-0.3 to -1.8	85
R 4	2.6 to 3.4	-0.3 to -1.8	84

[a] Positive values indicate indoor operative temperatures above the 80% comfortable upper limits and negative values indicate indoor operative temperatures below the 80% comfortable upper limits.

Table 6.13. Summary of thermal comfort evaluation in the master bedroom of the terraced house with roof insulation in the rural climate (Senai).

Roof insulation condition	Deviation of indoor operative temperature from the 80% comfortable upper limits (°C)[a]		Exceeding period (%)
	Daily maximum	Daily minimum	
Night ventilation	*0.8 to 1.7*	*-1.8 to -2.9*	*35*
R 0.5	0.3 to 1.1	-2.0 to -3.0	27
R 1	0.1 to 0.9	-2.1 to -3.0	25
R 2	-0.0 to 0.7	-2.2 to -3.1	20
R 3	-0.1 to 0.6	-2.2 to -3.1	17
R 4	-0.2 to 0.6	-2.2 to -3.1	16
Daytime ventilation	*1.7 to 2.8*	*-0.5 to -1.6*	*72*
R 0.5	1.4 to 2.4	-0.6 to -1.6	67
R 1	1.4 to 2.3	-0.6 to -1.6	64
R 2	1.3 to 2.2	-0.6 to -1.7	62
R 3	1.2 to 2.2	-0.7 to -1.7	62
R 4	1.2 to 2.2	-0.7 to -1.7	61

[a] Positive values indicate indoor operative temperatures above the 80% comfortable upper limits and negative values indicate indoor operative temperatures below the 80% comfortable upper limits.

insulation (Figure 6.20a). Applying roof insulation of R 4 further reduces the corresponding indoor air temperatures to 1.0°C, 0.6°C and 0.5°C lower than those without roof insulation. Using roof insulation of R 0.5 and R 4 lowers the maximum (95th percentile) indoor air temperatures in the daytime ventilated master bedroom by 0.3°C and 0.5°C, respectively, compared to that without roof insulation (Figure 6.20b).

Figure 6.21a shows that indoor thermal comfort is improved by applying roof insulation to the night ventilated room. Roof insulation of R 4 reduces the indoor operative temperature throughout the day compared to using only night ventilation so that the maximum operative temperatures are at most 0.6°C above the 80% comfortable upper limits and the exceeding period is 16% (Figure 6.21a and Table 6.13). Figure 6.21b and Table 6.13 show that the roof insulation also lowers the indoor operative temperature in the daytime ventilated room. However, it would be difficult to meet the 80% comfortable upper limits because temperature in daytime ventilation condition is basically high.

The results imply that applying roof insulation improves the thermal comfort in all the tested conditions, though the temperature reductions are less in the daytime ventilated room. Applying roof insulation of higher thermal resistance increases the cooling effects.

6.5.3 Effects of Ceiling Insulation

In the urban climate, applying ceiling insulation with R-value of 0.5 m^2K/W (R 0.5) decreases the maximum (95th percentile) and mean indoor air temperatures in the night ventilated room by only 0.3°C and 0.1°C compared to those without ceiling insulation (Figure 6.22a). Using ceiling insulation of R 4 further reduces the corresponding indoor air temperatures to 0.6°C and 0.2°C lower than those without ceiling insulation. The cooling effects provided by ceiling insulation are thus smaller than those by roof insulation in the night ventilated room. The result is likely because the attic air temperature is not reduced by ceiling insulation while similar air leakage between the master bedroom and the attic through the ceiling boards was assumed. The indoor air temperatures in the daytime ventilated master bedroom are almost similar whether the ceiling insulation was used or not (Figure 6.22b).

Temporal variations of the indoor operative temperatures for the above simulation cases are shown in Figure 6.23 to evaluate any thermal comfort improvement afforded by the ceiling insulation. Table 6.14 summarizes the result for all simulated ceiling insulation conditions. With night ventilation, the ceiling insulation of R 4 improves the thermal comfort more than that of R 0.5 (Figure 6.23a). The former lowers the maximum indoor operative temperatures compared to using only night ventilation to 0.7-1.3°C above the 80% comfortable upper limits and the exceeding period is 45% (Table 6.14). With daytime ventilation, the ceiling insulation does not improve the indoor thermal comfort (Figure 6.23b and Table 6.14). In fact, the ceiling insulation increases the indoor operative temperature slightly during night-time probably due to its thermal resistance that blocks heat loss of the ceiling boards.

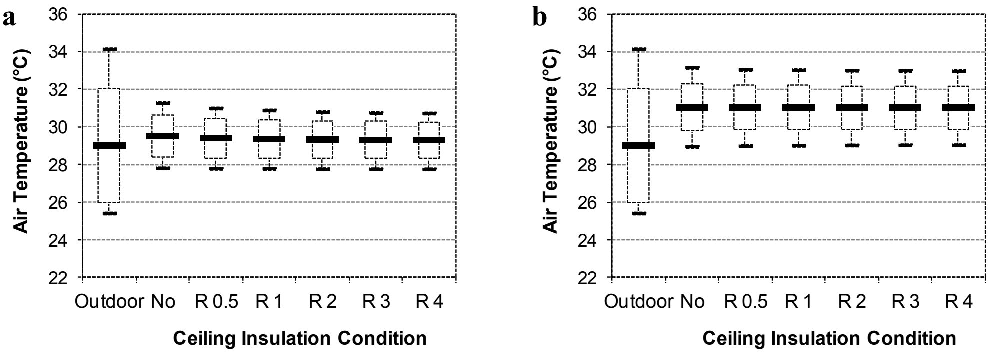


Figure 6.22. Statistical summary (5th and 95th percentiles, mean and ± one standard deviation) of simulated indoor air temperatures in the master bedroom of the terraced house in different ceiling insulation conditions in the urban climate (Johor Bahru). (a) Night ventilation; (b) Daytime ventilation.

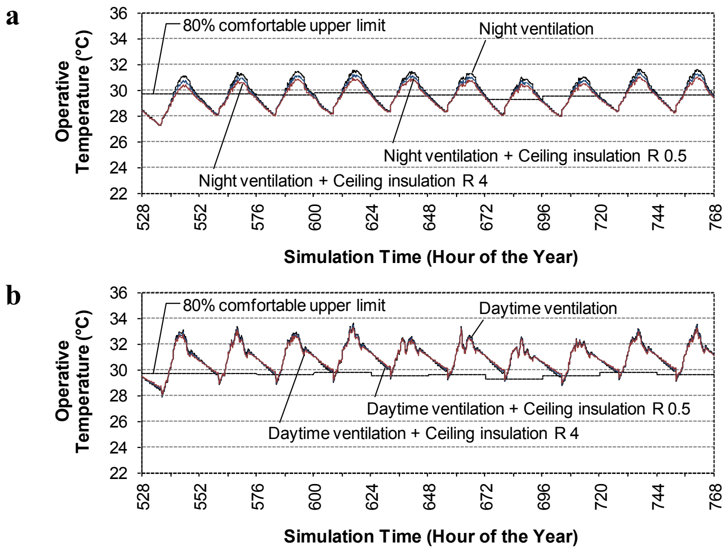


Figure 6.23. Temporal variations of simulated indoor operative temperatures in the master bedroom of the terraced house with ceiling insulation and the corresponding temperature limits for thermal comfort in the urban climate (Johor Bahru). (a) Night ventilation; (b) Daytime ventilation.

The effects of using ceiling insulation on the indoor air temperature for both open window conditions in the rural climate are similar to those in the urban climate (Figure 6.24).

Similarly, Figure 6.25 shows that in the rural climate indoor thermal comfort is improved by ceiling insulation in the night ventilated room but not daytime ventilated room. Ceiling insulation of R 4 lowers the maximum indoor operative temperatures compared to using only

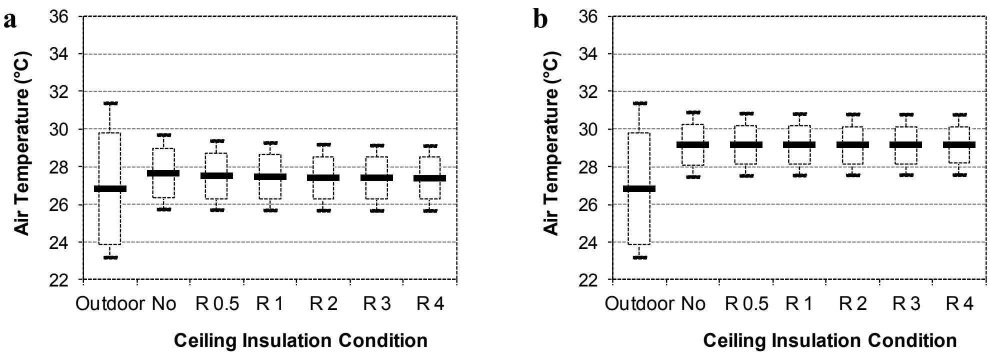


Figure 6.24. Statistical summary (5th and 95th percentiles, mean and ± one standard deviation) of simulated indoor air temperatures in the master bedroom of the terraced house in different ceiling insulation conditions in the rural climate (Senai). (a) Night ventilation; (b) Daytime ventilation.

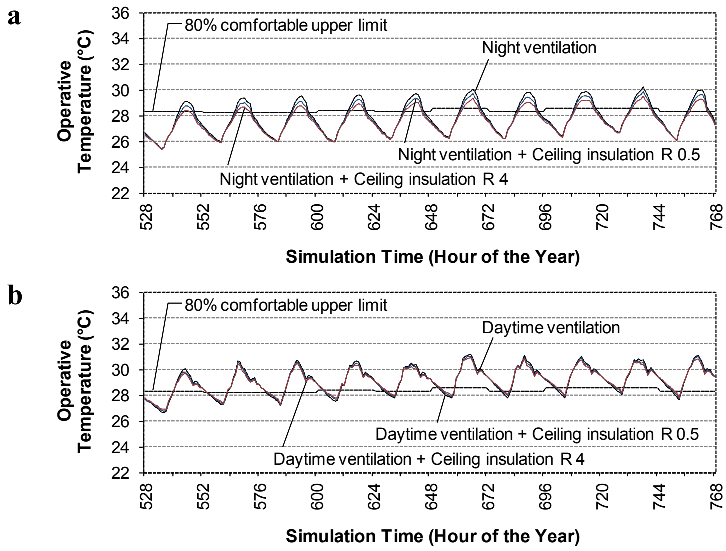


Figure 6.25. Temporal variations of simulated indoor operative temperatures in the master bedroom of the terraced house with ceiling insulation and the corresponding temperature limits for thermal comfort in the rural climate (Senai). (a) Night ventilation; (b) Daytime ventilation.

night ventilation to 0.1-1.0°C above the 80% comfortable upper limits and the exceeding period is 26% (Figure 6.25a and Table 6.15).

Altogether, the results imply that in both urban and rural climates, ceiling insulation is secondary to roof insulation and improves thermal comfort only in the night ventilated room

Table 6.14. Summary of thermal comfort evaluation in the master bedroom of the terraced house with ceiling insulation in the urban climate (Johor Bahru).

Ceiling insulation condition	Deviation of indoor operative temperature from the 80% comfortable upper limits (°C)[a]		Exceeding period (%)
	Daily maximum	Daily minimum	
Night ventilation	*1.4 to 1.9*	*-1.2 to -2.5*	*52*
R 0.5	1.0 to 1.6	-1.2 to -2.5	49
R 1	0.9 to 1.5	-1.2 to -2.5	47
R 2	0.8 to 1.4	-1.2 to -2.5	46
R 3	0.7 to 1.4	-1.2 to -2.5	46
R 4	0.7 to 1.3	-1.2 to -2.5	45
Daytime ventilation	*2.9 to 3.9*	*-0.2 to -1.8*	*88*
R 0.5	2.9 to 3.7	-0.2 to -1.8	91
R 1	2.8 to 3.7	-0.1 to -1.7	91
R 2	2.8 to 3.7	-0.1 to -1.7	91
R 3	2.8 to 3.6	-0.1 to -1.7	91
R 4	2.8 to 3.6	-0.1 to -1.7	91

[a] Positive values indicate indoor operative temperatures above the 80% comfortable upper limits and negative values indicate indoor operative temperatures below the 80% comfortable upper limits.

Table 6.15. Summary of thermal comfort evaluation in the master bedroom of the terraced house with ceiling insulation in the rural climate (Senai).

Ceiling insulation condition	Deviation of indoor operative temperature from the 80% comfortable upper limits (°C)[a]		Exceeding period (%)
	Daily maximum	Daily minimum	
Night ventilation	*0.8 to 1.7*	*-1.8 to -2.9*	*35*
R 0.5	0.5 to 1.3	-1.9 to -2.9	32
R 1	0.3 to 1.2	-1.9 to -2.9	30
R 2	0.2 to 1.1	-1.9 to -2.9	28
R 3	0.1 to 1.1	-1.9 to -2.9	27
R 4	0.1 to 1.0	-1.9 to -2.9	26
Daytime ventilation	*1.7 to 2.8*	*-0.5 to -1.6*	*72*
R 0.5	1.5 to 2.6	-0.4 to -1.5	75
R 1	1.5 to 2.6	-0.4 to -1.5	77
R 2	1.4 to 2.5	-0.4 to -1.4	77
R 3	1.4 to 2.5	-0.4 to -1.4	77
R 4	1.4 to 2.5	-0.3 to -1.4	78

[a] Positive values indicate indoor operative temperatures above the 80% comfortable upper limits and negative values indicate indoor operative temperatures below the 80% comfortable upper limits.

during daytime. Applying ceiling insulation of higher thermal resistance increases the said cooling effects for both climates.

6.5.4 Effects of External Wall (Outside Surface) Insulation

In the urban climate, applying thermal insulation with R-value of 0.5 m^2K/W (R 0.5) to the outside surface of external walls reduces only the maximum (95^{th} percentile) indoor air temperature in the night ventilated master bedroom by 0.3°C compared to that without the insulation (Figure 6.26a). Raising the R-value of the insulation shows negligible further effects. The relatively small cooling effects given by the external wall insulation compared to the roof insulation are likely because the building envelope of the terraced house is dominated by the roof in terms of surface area and the solar heat received. For the master bedroom, the incident daily total solar radiation on its external walls averages 19.2 kWh on these fair weather days, which is less than 20% of the incident daily total solar radiation on the roof of the attic space above the master bedroom. On the other hand, the mean and minimum (5^{th} percentile) indoor air temperatures in the daytime ventilated master bedroom are increased slightly with the use of the external wall insulation (Figure 6.26b).

Figure 6.27 evaluates any thermal comfort improvement obtained by using the insulation at the outside surface of external walls in the urban climate. Table 6.16 summarizes the evaluation result. With night ventilation, the external wall insulation of R 0.5 reduces the maximum indoor operative temperatures slightly compared to using only night ventilation to 1.0-1.6°C above the 80% comfortable upper limits; the exceeding period is still 50% (Table 6.16). With daytime ventilation, the indoor operative temperature is increased during night-time by the use of external wall insulation (Figure 6.27b). As a result, the exceeding period is increased (Table 6.16). The insulation likely reduces heat loss from the massive brick to the sky and atmosphere at night and the effect is obvious in closed window condition.

The effects of using external wall insulation at the outside surface on the indoor air temperature for both open window conditions in the rural climate are similar to those in the urban climate (Figure 6.28).

Similarly, Figure 6.29a shows that in the rural climate, external wall insulation of R 0.5 lowers the maximum indoor operative temperatures slightly compared to using only night ventilation to 0.5-1.3°C above the 80% comfortable upper limits (Table 6.17). The same insulation deteriorates the indoor thermal comfort during night-time in the daytime ventilated room (Figure 6.29b). It increases the exceeding period above the 80% comfortable upper limits by 10% or more compared to using only daytime ventilation (Table 6.17).

It is concluded that external wall insulation is less effective as a passive cooling technique compared to roof and ceiling insulation in the terraced house. It improves the indoor thermal comfort slightly during the peak temperature hour in the night ventilated room. Using insulation of higher thermal resistance provides negligible further cooling effects. Meanwhile, external walls should not be insulated in daytime ventilated room.

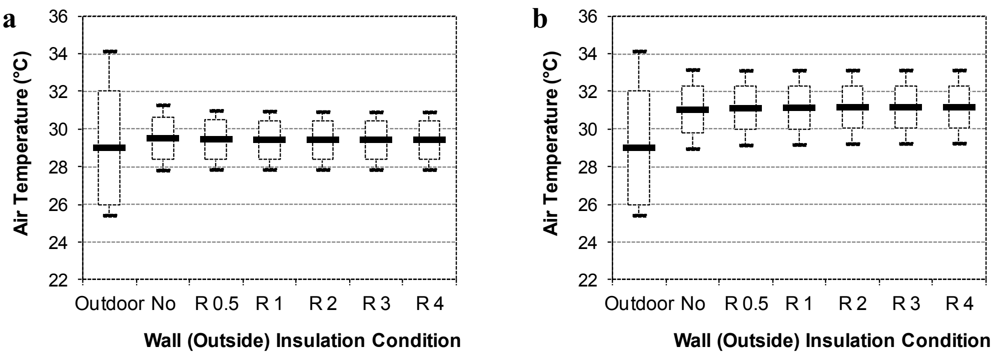


Figure 6.26. Statistical summary (5th and 95th percentiles, mean and ± one standard deviation) of simulated indoor air temperatures in the master bedroom of the terraced house in different external wall (outside surface) insulation conditions in the urban climate (Johor Bahru). (a) Night ventilation; (b) Daytime ventilation.

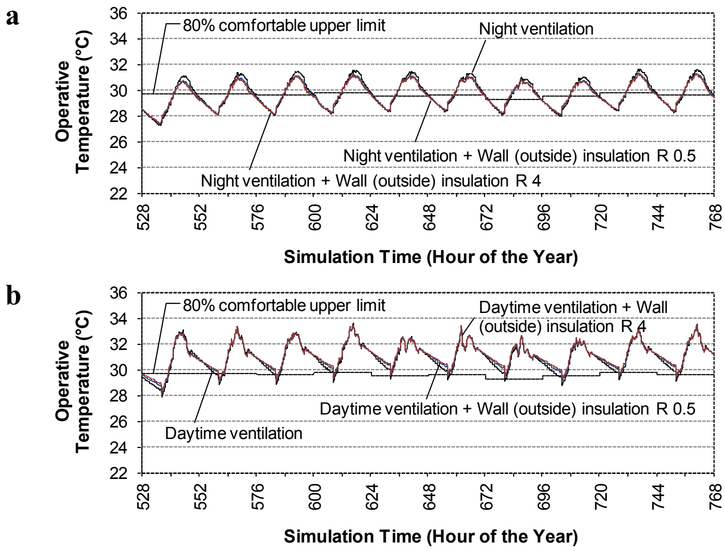


Figure 6.27. Temporal variations of simulated indoor operative temperatures in the master bedroom of the terraced house with external wall (outside surface) insulation and the corresponding temperature limits for thermal comfort in the urban climate (Johor Bahru). (a) Night ventilation; (b) Daytime ventilation.

6.5.5 Effects of External Wall (Inside Surface) Insulation

Figure 6.30a reveals that in the urban climate, insulating the inside surface of external walls gives negligible effects on the indoor air temperature in the night ventilated master

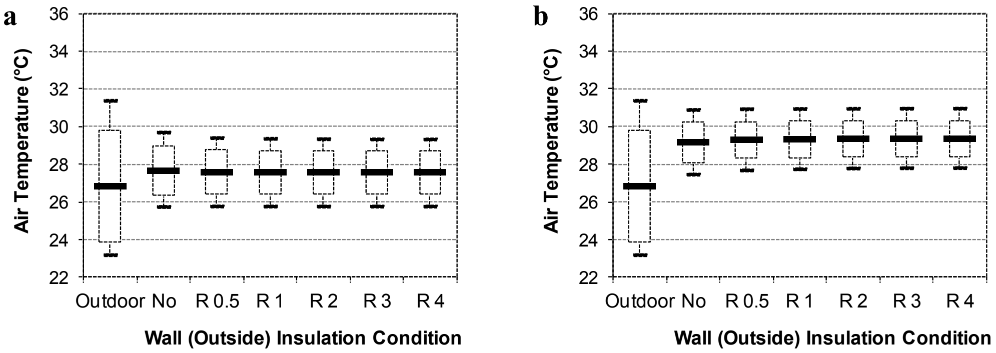


Figure 6.28. Statistical summary (5th and 95th percentiles, mean and ± one standard deviation) of simulated indoor air temperatures in the master bedroom of the terraced house in different external wall (outside surface) insulation conditions in the rural climate (Senai). (a) Night ventilation; (b) Daytime ventilation.

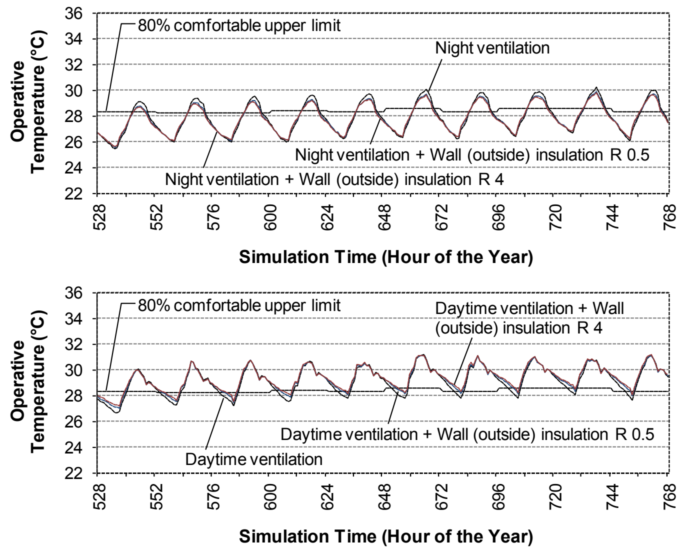


Figure 6.29. Temporal variations of simulated indoor operative temperatures in the master bedroom of the terraced house with external wall (outside surface) insulation and the corresponding temperature limits for thermal comfort in the rural climate (Senai). (a) Night ventilation; (b) Daytime ventilation.

bedroom. In the daytime ventilated room, the insulation causes slight increases in the mean and minimum (5th percentile) indoor air temperatures (Figure 6.30b). The insulation at the inside surface likely retards the conduction of heat from inside to the outer layers of the wall for heat loss to the atmosphere and sky. As before, the effect is obvious in closed window condition at night.

Table 6.16. Summary of thermal comfort evaluation in the master bedroom of the terraced house with external wall (outside surface) insulation in the urban climate (Johor Bahru).

External wall (outside surface) insulation condition	Deviation of indoor operative temperature from the 80% comfortable upper limits (°C)[a]		Exceeding period (%)
	Daily maximum	Daily minimum	
Night ventilation	*1.4 to 1.9*	*-1.2 to -2.5*	*52*
R 0.5	1.0 to 1.6	-1.1 to -2.3	50
R 1	1.0 to 1.6	-1.1 to -2.3	50
R 2	1.0 to 1.6	-1.1 to -2.3	50
R 3	1.0 to 1.6	-1.1 to -2.3	50
R 4	1.0 to 1.6	-1.1 to -2.3	49
Daytime ventilation	*2.9 to 3.9*	*-0.2 to -1.8*	*88*
R 0.5	3.0 to 3.8	0.0 to -1.6	92
R 1	3.0 to 3.8	0.1 to -1.5	93
R 2	3.0 to 3.8	0.1 to -1.5	93
R 3	3.0 to 3.8	0.1 to -1.5	93
R 4	3.0 to 3.8	0.1 to -1.5	93

[a] Positive values indicate indoor operative temperatures above the 80% comfortable upper limits and negative values indicate indoor operative temperatures below the 80% comfortable upper limits.

Table 6.17. Summary of thermal comfort evaluation in the master bedroom of the terraced house with external wall (outside surface) insulation in the rural climate (Senai).

External wall (outside surface) insulation condition	Deviation of indoor operative temperature from the 80% comfortable upper limits (°C)[a]		Exceeding period (%)
	Daily maximum	Daily minimum	
Night ventilation	*0.8 to 1.7*	*-1.8 to -2.9*	*35*
R 0.5	0.5 to 1.3	-1.7 to -2.8	33
R 1	0.4 to 1.3	-1.7 to -2.7	32
R 2	0.4 to 1.3	-1.7 to -2.7	32
R 3	0.4 to 1.3	-1.7 to -2.7	32
R 4	0.4 to 1.3	-1.7 to -2.7	32
Daytime ventilation	*1.7 to 2.8*	*-0.5 to -1.6*	*72*
R 0.5	1.6 to 2.8	-0.2 to -1.2	82
R 1	1.7 to 2.8	-0.1 to -1.2	83
R 2	1.7 to 2.8	-0.1 to -1.1	85
R 3	1.7 to 2.8	-0.1 to -1.1	85
R 4	1.7 to 2.8	-0.1 to -1.1	85

[a] Positive values indicate indoor operative temperatures above the 80% comfortable upper limits and negative values indicate indoor operative temperatures below the 80% comfortable upper limits.

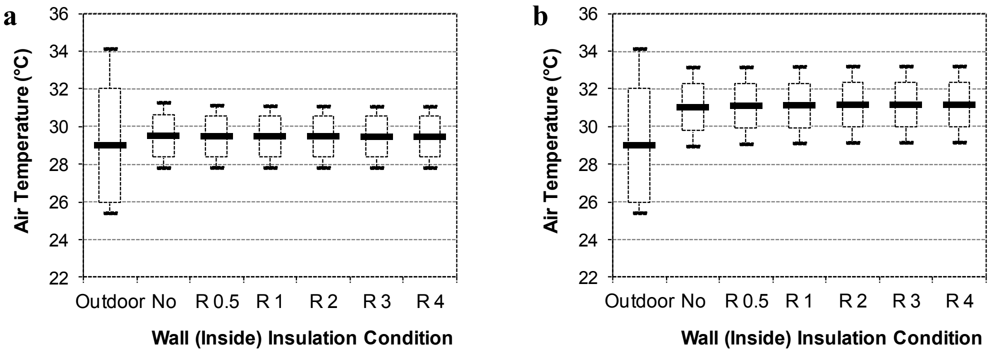


Figure 6.30. Statistical summary (5th and 95th percentiles, mean and ± one standard deviation) of simulated indoor air temperatures in the master bedroom of the terraced house in different external wall (inside surface) insulation conditions in the urban climate (Johor Bahru). (a) Night ventilation; (b) Daytime ventilation.

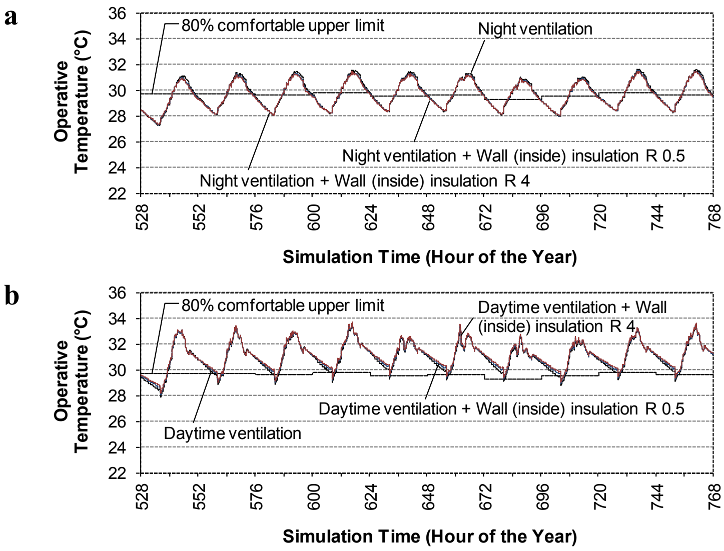


Figure 6.31. Temporal variations of simulated indoor operative temperatures in the master bedroom of the terraced house with external wall (inside surface) insulation and the corresponding temperature limits for thermal comfort in the urban climate (Johor Bahru). (a) Night ventilation; (b) Daytime ventilation.

Figure 6.31a and Table 6.18 show that in the urban climate, the thermal comfort improvement afforded by the external wall insulation is negligible in the night ventilated master bedroom. With daytime ventilation, the indoor operative temperature is increased during night-time by the use of the insulation at the inside surface, which is similar to the

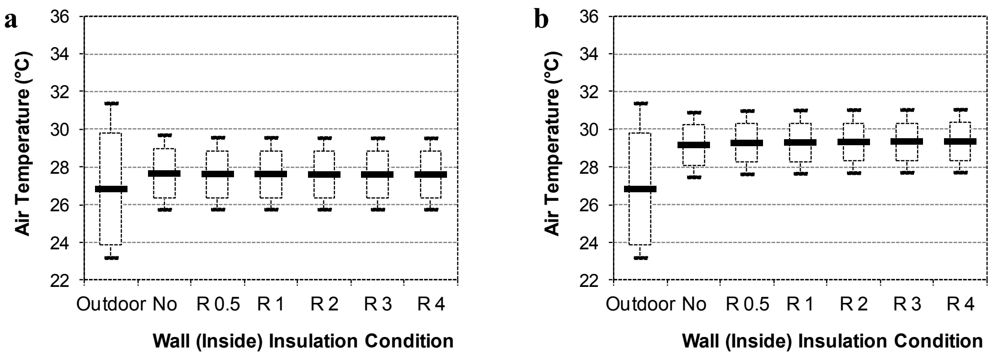


Figure 6.32. Statistical summary (5th and 95th percentiles, mean and ± one standard deviation) of simulated indoor air temperatures in the master bedroom of the terraced house in different external wall (inside surface) insulation conditions in the rural climate (Senai). (a) Night ventilation; (b) Daytime ventilation.

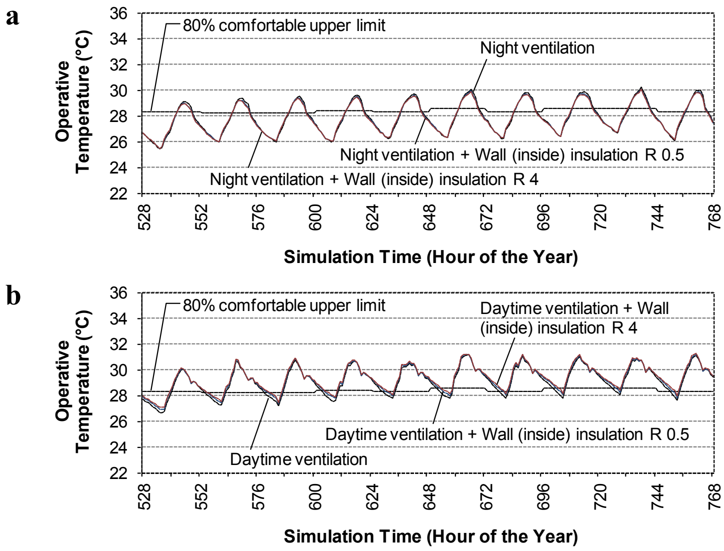


Figure 6.33. Temporal variations of simulated indoor operative temperatures in the master bedroom of the terraced house with external wall (inside surface) insulation and the corresponding temperature limits for thermal comfort in the rural climate (Senai). (a) Night ventilation; (b) Daytime ventilation.

case of insulating the outside surface (Figure 6.31b). Similarly, it increases the exceeding period (Table 6.18).

The effects of using external wall insulation at the inside surface on the indoor air temperature for both open window conditions in the rural climate are similar to those in the urban climate (Figure 6.32).

Table 6.18. Summary of thermal comfort evaluation in the master bedroom of the terraced house with external wall (inside surface) insulation in the urban climate (Johor Bahru).

External wall (inside surface) insulation condition	Deviation of indoor operative temperature from the 80% comfortable upper limits (°C)[a]		Exceeding period (%)
	Daily maximum	Daily minimum	
Night ventilation	*1.4 to 1.9*	*-1.2 to -2.5*	*52*
R 0.5	1.3 to 1.8	-1.2 to -2.4	51
R 1	1.2 to 1.8	-1.2 to -2.4	51
R 2	1.2 to 1.8	-1.2 to -2.4	50
R 3	1.2 to 1.8	-1.2 to -2.4	50
R 4	1.2 to 1.8	-1.2 to -2.4	50
Daytime ventilation	*2.9 to 3.9*	*-0.2 to -1.8*	*88*
R 0.5	3.0 to 3.9	-0.1 to -1.7	92
R 1	3.1 to 3.9	-0.0 to -1.6	92
R 2	3.1 to 3.9	0.0 to -1.6	92
R 3	3.1 to 3.9	0.0 to -1.6	93
R 4	3.1 to 3.9	0.0 to -1.6	93

[a] Positive values indicate indoor operative temperatures above the 80% comfortable upper limits and negative values indicate indoor operative temperatures below the 80% comfortable upper limits.

Table 6.19. Summary of thermal comfort evaluation in the master bedroom of the terraced house with external wall (inside surface) insulation in the rural climate (Senai).

External wall (inside surface) insulation condition	Deviation of indoor operative temperature from the 80% comfortable upper limits (°C)[a]		Exceeding period (%)
	Daily maximum	Daily minimum	
Night ventilation	*0.8 to 1.7*	*-1.8 to -2.9*	*35*
R 0.5	0.7 to 1.5	-1.8 to -2.8	34
R 1	0.7 to 1.5	-1.8 to -2.8	34
R 2	0.7 to 1.5	-1.8 to -2.8	34
R 3	0.6 to 1.5	-1.8 to -2.8	34
R 4	0.6 to 1.5	-1.8 to -2.8	33
Daytime ventilation	*1.7 to 2.8*	*-0.5 to -1.6*	*72*
R 0.5	1.8 to 2.9	-0.3 to -1.4	80
R 1	1.8 to 2.9	-0.2 to -1.3	81
R 2	1.8 to 2.9	-0.2 to -1.2	81
R 3	1.8 to 2.9	-0.2 to -1.2	82
R 4	1.8 to 2.9	-0.2 to -1.2	83

[a] Positive values indicate indoor operative temperatures above the 80% comfortable upper limits and negative values indicate indoor operative temperatures below the 80% comfortable upper limits.

Similarly, Figure 6.33a and Table 6.19 show that in the rural climate, the thermal comfort improvement afforded by the external wall insulation is negligible in the night ventilated room. Meanwhile, the same insulation deteriorates the indoor thermal comfort during night-time in the daytime ventilated room (Figure 6.33b and Table 6.19).

It is concluded that external wall insulation at the inside surface is not an effective passive cooling technique for the terraced house in all the tested conditions.

6.5.6 Effects of Window External Shading

In the urban climate, adding external shading device with a shading factor of 0.25, noted as SF 0.25, to external windows reduces the maximum (95th percentile) and mean indoor air temperatures in the night ventilated master bedroom by 0.2°C and 0.1°C compared to those without the shading device (Figure 6.34a). Each 0.25 increment in the shading factor gives additional air temperature reductions of the same magnitude. Shading at the outside reduces solar transmission through the glazing before the solar heat enters the room and the higher the shading factor the less solar heat is transmitted. The external shading device of SF 0.75, for example, reduces the incident daily total solar radiation on all windows of the master bedroom from 5.9 kWh (without shading device) to 1.5 kWh on average on these fair weather days. Despite the same solar heat transmission reductions, the indoor air temperature reductions in the daytime ventilated room are less pronounced (Figure 6.34b). This is because the cooling effect is diminished by the inflow of hot outdoor air through open windows during daytime.

Temporal variations of the indoor operative temperatures for the above simulation cases are shown in Figure 6.35 to evaluate any thermal comfort improvement afforded by the external shading device. Table 6.20 summarizes the result for all shading factors. With night ventilation, the external shading of SF 0.75 improves the thermal comfort more than that of SF 0.25 (Figure 6.35a and Table 6.20). The former lowers the maximum indoor operative temperatures compared to using only night ventilation to 0.8-1.4°C above the 80% comfortable upper limits and the exceeding period is 40% (Table 6.20). With daytime ventilation, the improvement is slight even with the external shading device of SF 0.75 (Figure 6.35b and Table 6.20).

In the rural climate, the indoor air temperature reductions provided by the external shading device are slightly more than those in the urban climate (Figure 6.36). Using external shading of SF 0.75 reduces the maximum (95th percentile), mean and minimum (5th percentile) indoor air temperatures in the night ventilated room to 0.7°C, 0.4°C and 0.2°C lower than those without the external shading (Figure 6.36a). Even in the daytime ventilated room, slight indoor air temperature reductions are seen in the rural climate (Figure 6.36b). This is likely because the incident daily total solar radiation on the windows is higher while the outdoor air temperature is lower in the rural climate than in the urban climate, thus shading from solar radiation is more effective in the rural climate.

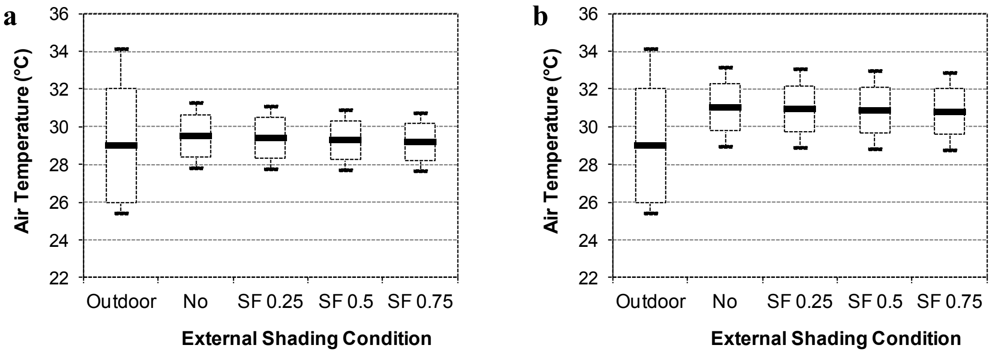


Figure 6.34. Statistical summary (5th and 95th percentiles, mean and ± one standard deviation) of simulated indoor air temperatures in the master bedroom of the terraced house in different window external shading conditions in the urban climate (Johor Bahru). (a) Night ventilation; (b) Daytime ventilation.

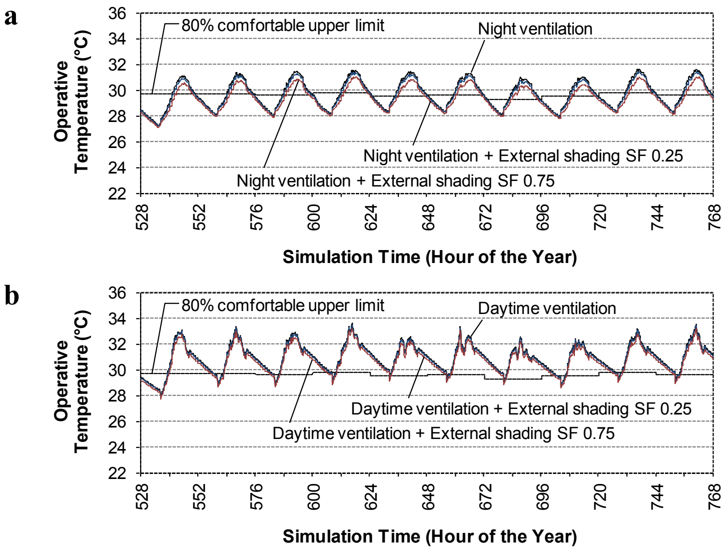


Figure 6.35. Temporal variations of simulated indoor operative temperatures in the master bedroom of the terraced house with window external shading and the corresponding temperature limits for thermal comfort in the urban climate (Johor Bahru). (a) Night ventilation; (b) Daytime ventilation.

Figure 6.37a shows that indoor thermal comfort is improved by applying external shading device in the night ventilated room. External shading of SF 0.75 reduces the maximum indoor operative temperatures compared to using only night ventilation to 0.2-0.9°C above the 80% comfortable upper limits and the exceeding period is 23% (Table 6.21). Figure 6.37b and Table 6.21 show that the external shading also lowers the indoor operative

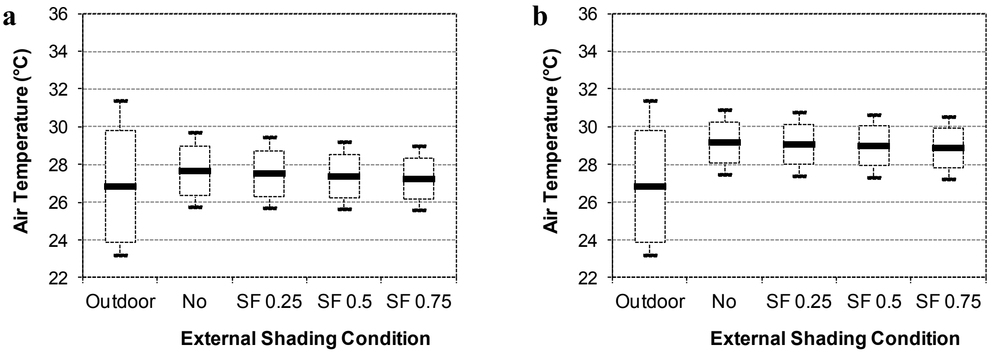


Figure 6.36. Statistical summary (5th and 95th percentiles, mean and ± one standard deviation) of simulated indoor air temperatures in the master bedroom of the terraced house in different window external shading conditions in the rural climate (Senai). (a) Night ventilation; (b) Daytime ventilation.

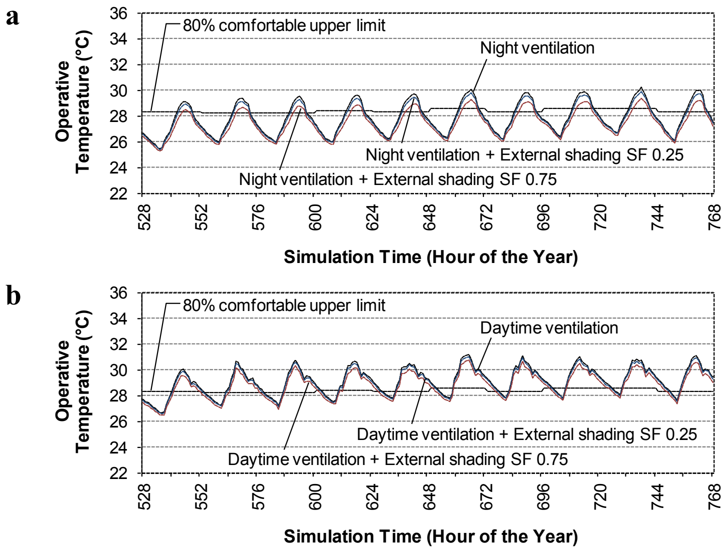


Figure 6.37. Temporal variations of simulated indoor operative temperatures in the master bedroom of the terraced house with window external shading and the corresponding temperature limits for thermal comfort in the rural climate (Senai). (a) Night ventilation; (b) Daytime ventilation.

temperature in the daytime ventilated room but would be difficult to meet the 80% comfortable upper limits because temperature in daytime ventilation condition is basically high.

The results imply that external shading of windows is effective to improve the thermal comfort of the night ventilated room in both urban and rural climates. A higher shading

Table 6.20. Summary of thermal comfort evaluation in the master bedroom of the terraced house with window external shading in the urban climate (Johor Bahru).

Window external shading condition	Deviation of indoor operative temperature from the 80% comfortable upper limits (°C)[a]		Exceeding period (%)
	Daily maximum	Daily minimum	
Night ventilation	*1.4 to 1.9*	*-1.2 to -2.5*	*52*
SF 0.25	1.2 to 1.8	-1.2 to -2.5	48
SF 0.50	1.0 to 1.6	-1.3 to -2.6	45
SF 0.75	0.8 to 1.4	-1.3 to -2.6	40
Daytime ventilation	*2.9 to 3.9*	*-0.2 to -1.8*	*88*
SF 0.25	2.8 to 3.8	-0.3 to -1.9	86
SF 0.50	2.7 to 3.7	-0.4 to -1.9	84
SF 0.75	2.6 to 3.5	-0.4 to -2.0	82

[a] Positive values indicate indoor operative temperatures above the 80% comfortable upper limits and negative values indicate indoor operative temperatures below the 80% comfortable upper limits.

Table 6.21. Summary of thermal comfort evaluation in the master bedroom of the terraced house with window external shading in the rural climate (Senai).

Window external shading condition	Deviation of indoor operative temperature from the 80% comfortable upper limits (°C)[a]		Exceeding period (%)
	Daily maximum	Daily minimum	
Night ventilation	*0.8 to 1.7*	*-1.8 to -2.9*	*35*
SF 0.25	0.6 to 1.4	-1.9 to -2.9	33
SF 0.50	0.4 to 1.1	-2.0 to -3.0	28
SF 0.75	0.2 to 0.9	-2.1 to -3.1	23
Daytime ventilation	*1.7 to 2.8*	*-0.5 to -1.6*	*72*
SF 0.25	1.6 to 2.6	-0.6 to -1.7	70
SF 0.50	1.4 to 2.5	-0.7 to -1.8	66
SF 0.75	1.3 to 2.3	-0.8 to -1.8	63

[a] Positive values indicate indoor operative temperatures above the 80% comfortable upper limits and negative values indicate indoor operative temperatures below the 80% comfortable upper limits.

factor would be desired though reduction in the natural lighting in the room should be considered. In the daytime ventilated room, the thermal comfort improvements are less than in the night ventilated room, especially in the urban climate.

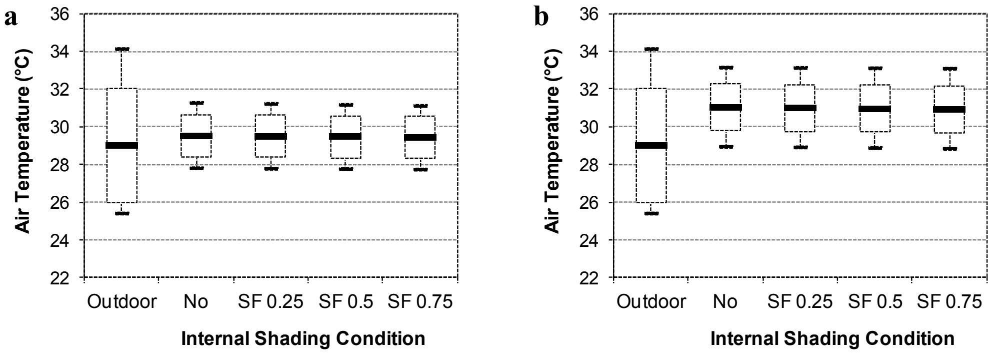


Figure 6.38. Statistical summary (5th and 95th percentiles, mean and ± one standard deviation) of simulated indoor air temperatures in the master bedroom of the terraced house in different window internal shading conditions in the urban climate (Johor Bahru). (a) Night ventilation; (b) Daytime ventilation.

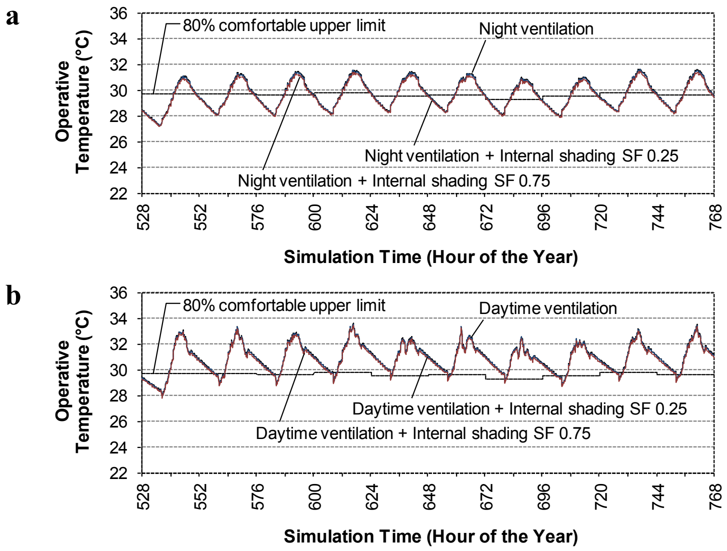


Figure 6.39. Temporal variations of simulated indoor operative temperatures in the master bedroom of the terraced house with window internal shading and the corresponding temperature limits for thermal comfort in the urban climate (Johor Bahru). (a) Night ventilation; (b) Daytime ventilation.

6.5.7 Effects of Window Internal Shading

Figure 6.38a shows that in the urban climate, adding internal shading device to external windows gives negligible reductions in the indoor air temperatures in the night ventilated

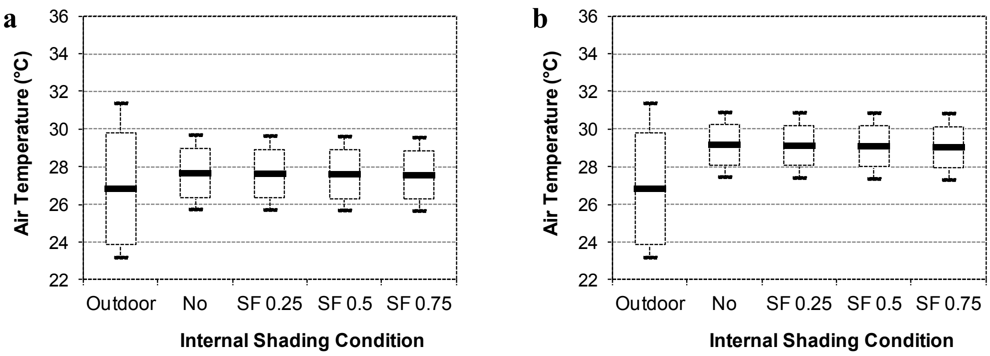


Figure 6.40. Statistical summary (5th and 95th percentiles, mean and ± one standard deviation) of simulated indoor air temperatures in the master bedroom of the terraced house in different window internal shading conditions in the rural climate (Senai). (a) Night ventilation; (b) Daytime ventilation.

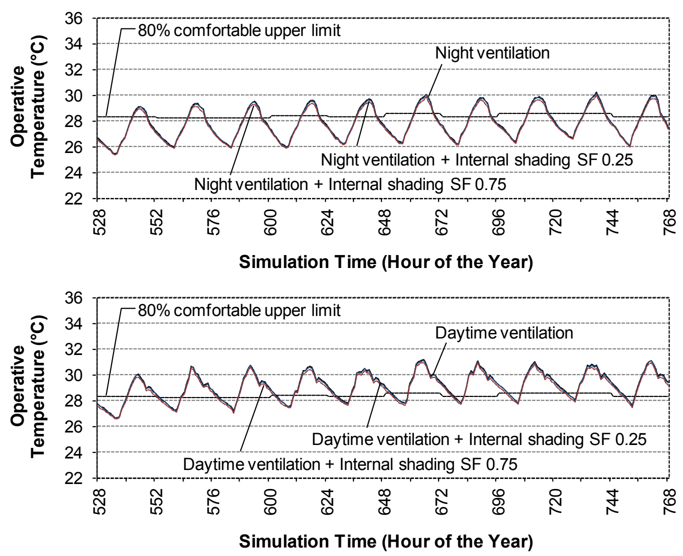


Figure 6.41. Temporal variations of simulated indoor operative temperatures in the master bedroom of the terraced house with window internal shading and the corresponding temperature limits for thermal comfort in the rural climate (Senai). (a) Night ventilation; (b) Daytime ventilation.

room, unlike the cooling effects of external shading. This is because the amount of incident solar radiation that is transmitted through the window glazing is the same with or without the internal shading. The solar radiation heat that enters between the glazing and the shading device would then warm the room air. The indoor air temperature reductions are also negligible in the daytime ventilated room (Figure 6.38b).

Table 6.22. Summary of thermal comfort evaluation in the master bedroom of the terraced house with window internal shading in the urban climate (Johor Bahru).

Window internal shading condition	Deviation of indoor operative temperature from the 80% comfortable upper limits (°C)[a]		Exceeding period (%)
	Daily maximum	Daily minimum	
Night ventilation	*1.4 to 1.9*	*-1.2 to -2.5*	*52*
SF 0.25	1.4 to 1.9	-1.2 to -2.5	51
SF 0.50	1.3 to 1.8	-1.2 to -2.5	50
SF 0.75	1.2 to 1.7	-1.2 to -2.5	48
Daytime ventilation	*2.9 to 3.9*	*-0.2 to -1.8*	*88*
SF 0.25	2.9 to 3.8	-0.3 to -1.9	87
SF 0.50	2.8 to 3.8	-0.3 to -1.9	86
SF 0.75	2.8 to 3.7	-0.3 to -1.9	85

[a] Positive values indicate indoor operative temperatures above the 80% comfortable upper limits and negative values indicate indoor operative temperatures below the 80% comfortable upper limits.

Table 6.23. Summary of thermal comfort evaluation in the master bedroom of the terraced house with window internal shading in the rural climate (Senai).

Window internal shading condition	Deviation of indoor operative temperature from the 80% comfortable upper limits (°C)[a]		Exceeding period (%)
	Daily maximum	Daily minimum	
Night ventilation	*0.8 to 1.7*	*-1.8 to -2.9*	*35*
SF 0.25	0.8 to 1.6	-1.9 to -2.9	34
SF 0.50	0.7 to 1.5	-1.9 to -2.9	34
SF 0.75	0.6 to 1.4	-1.9 to -3.0	32
Daytime ventilation	*1.7 to 2.8*	*-0.5 to -1.6*	*72*
SF 0.25	1.7 to 2.7	-0.6 to -1.7	71
SF 0.50	1.6 to 2.6	-0.6 to -1.7	69
SF 0.75	1.5 to 2.6	-0.6 to -1.8	67

[a] Positive values indicate indoor operative temperatures above the 80% comfortable upper limits and negative values indicate indoor operative temperatures below the 80% comfortable upper limits.

Consequently, the thermal comfort improvements afforded by the internal shading of windows are small and almost similar in both open window conditions (Figure 6.39 and Table 6.22). Reductions in the indoor operative temperatures are likely due to some blocked radiation and not cooler air.

The effects of using internal shading device on the indoor air temperature for both open window conditions in the rural climate are similar to those in the urban climate (Figure 6.40). The thermal comfort improvements are also almost similar (Figure 6.41 and Table 6.23).

The results confirm that the cooling effects of the internal shading are rather small and the indoor thermal comfort improvements are slight in all the tested conditions. It is less effective than the external shading device of similar shading factors.

6.5.8 Effects of Attic Forced Ventilation

In the urban climate, using forced ventilation in the attic space above the master bedroom gives almost no effect on the indoor air temperatures in the night ventilated master bedroom compared to the case without the forced ventilation (Figure 6.42a). In fact, the minimum (5^{th} percentile) air temperature in the attic space is reduced by 1.0°C when the forced ventilation at a rate of 10 ACH was used; it is lower than the room air temperature. Nevertheless, it does not contribute to cool the building structures and air in the master bedroom. The maximum (95^{th} percentile) air temperature in the attic is reduced to the outdoor level when the forced ventilation rate of 10 ACH was used for the whole day (noted as F 10 in the figure). The indoor air temperatures in the daytime ventilated master bedroom are also similar whether the attic forced ventilation was used or not (Figure 6.42b).

Consequently, the thermal comfort improvements afforded by the attic forced ventilation are negligible in both open window conditions (Figure 6.43 and Table 6.24).

The effects of using attic forced ventilation on the indoor air temperature of the master bedroom for both open window conditions in the rural climate are similar to those in the urban climate (Figure 6.44). The changing patterns of the air temperature in the attic are also similar to those in the urban climate, except that the maximum (95^{th} percentile) air temperature is higher than the outdoors when the forced ventilation rate of 10 ACH was used for the whole day. This is likely due to the higher solar radiation in the rural climate which increases solar heat gain in the attic.

Similarly, Figure 6.45 and Table 6.25 show that in the rural climate the thermal comfort improvements given by the attic forced ventilation are negligible in both open window conditions.

The results imply that the cooling effects of attic forced ventilation are seen only in the attic but does not contribute much to improve the thermal comfort in the master bedroom.

6.5.9 Effects of Room Forced Ventilation

Using forced ventilation in the master bedroom during night-time only and for the whole day provide different cooling effects in the room. Figure 6.46a shows that in the urban climate, using the forced ventilation at night, noted as N 30, N 40 and N 50 according to the

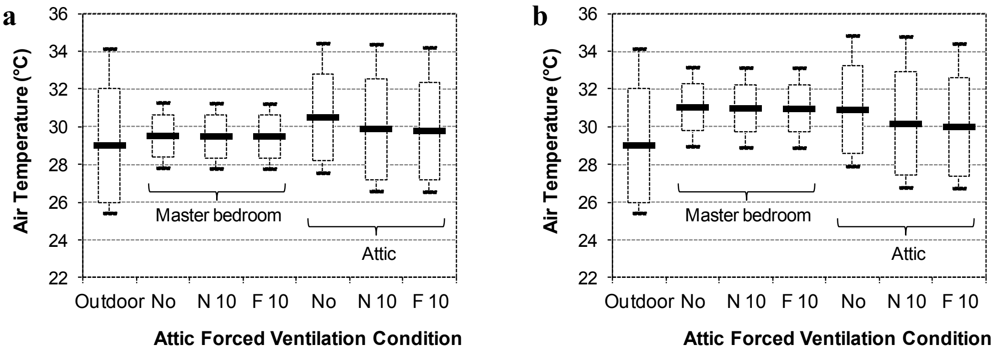


Figure 6.42. Statistical summary (5th and 95th percentiles, mean and ± one standard deviation) of simulated indoor air temperatures in the master bedroom and attic of the terraced house in different attic forced ventilation conditions in the urban climate (Johor Bahru). (a) Night ventilation; (b) Daytime ventilation. N: night; F: full-day; Numbers indicate ventilation rates (ACH).

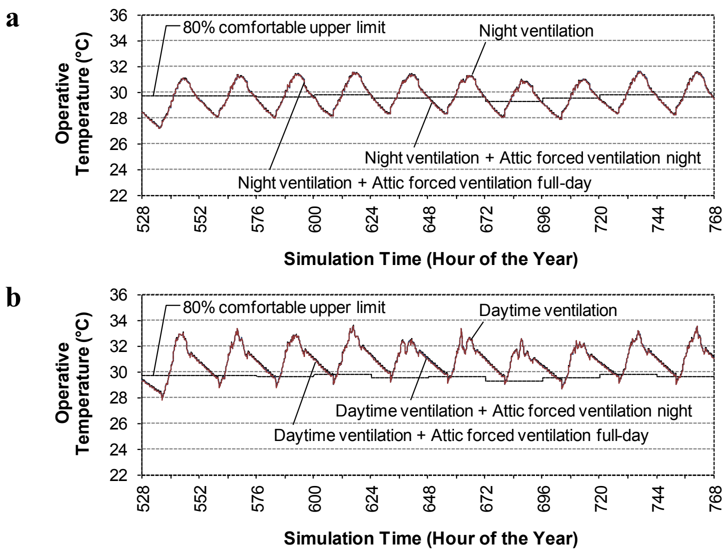


Figure 6.43. Temporal variations of simulated indoor operative temperatures in the master bedroom of the terraced house with attic forced ventilation and the corresponding temperature limits for thermal comfort in the urban climate (Johor Bahru). (a) Night ventilation; (b) Daytime ventilation.

air change rates, reduces the minimum (5th percentile) indoor air temperatures by 1.1-1.4°C compared to that without forced ventilation. Higher ventilation rates increase the cooling effect. The maximum (95th percentile) air temperatures are reduced slightly probably due to the structural cooling effect. On the other hand, using the forced ventilation for the whole day increases the maximum air temperature to only 1.0°C below the outdoors. It resembles

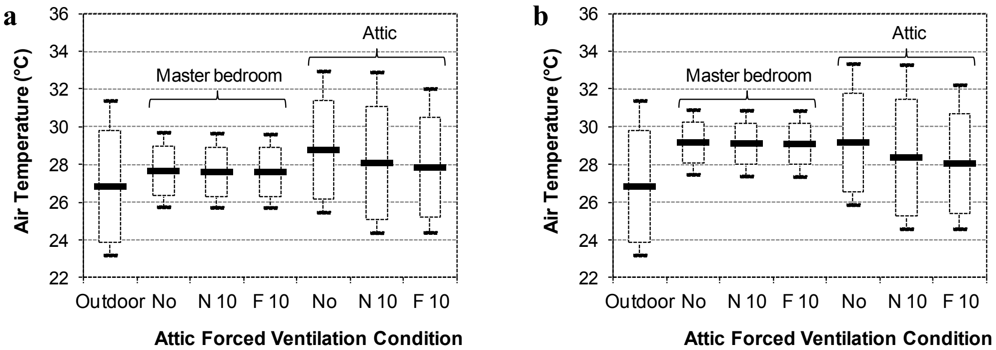


Figure 6.44. Statistical summary (5th and 95th percentiles, mean and ± one standard deviation) of simulated indoor air temperatures in the master bedroom and attic of the terraced house in different attic forced ventilation conditions in the rural climate (Senai). (a) Night ventilation; (b) Daytime ventilation. N: night; F: full-day; Numbers indicate ventilation rates (ACH).

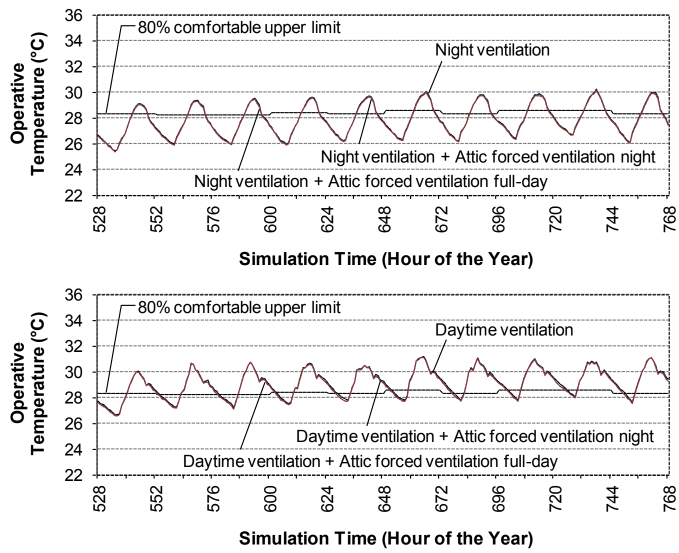


Figure 6.45. Temporal variations of simulated indoor operative temperatures in the master bedroom of the terraced house with attic forced ventilation and the corresponding temperature limits for thermal comfort in the rural climate (Senai). (a) Night ventilation; (b) Daytime ventilation.

daytime or full-day open window conditions (see Figure 6.11a). Similar effects are seen for respective forced ventilation conditions in the daytime ventilated master bedroom (Figure 6.46b).

Temporal variations of the indoor operative temperatures in the master bedroom are shown in Figure 6.47 to evaluate any thermal comfort improvement afforded by the room

Table 6.24. Summary of thermal comfort evaluation in the master bedroom of the terraced house with attic forced ventilation in the urban climate (Johor Bahru).

Attic forced ventilation condition	Deviation of indoor operative temperature from the 80% comfortable upper limits (°C)[a]		Exceeding period (%)
	Daily maximum	Daily minimum	
Night ventilation	*1.4 to 1.9*	*-1.2 to -2.5*	*52*
10 ACH night	1.4 to 1.9	-1.2 to -2.5	51
10 ACH 24h	1.4 to 1.9	-1.2 to -2.5	51
Daytime ventilation	*2.9 to 3.9*	*-0.2 to -1.8*	*88*
10 ACH night	2.9 to 3.9	-0.3 to -1.9	86
10 ACH 24h	2.9 to 3.8	-0.3 to -1.9	86

[a] Positive values indicate indoor operative temperatures above the 80% comfortable upper limits and negative values indicate indoor operative temperatures below the 80% comfortable upper limits.

Table 6.25. Summary of thermal comfort evaluation in the master bedroom of the terraced house with attic forced ventilation in the rural climate (Senai).

Attic forced ventilation condition	Deviation of indoor operative temperature from the 80% comfortable upper limits (°C)[a]		Exceeding period (%)
	Daily maximum	Daily minimum	
Night ventilation	*0.8 to 1.7*	*-1.8 to -2.9*	*35*
10 ACH night	0.8 to 1.6	-1.9 to -2.9	34
10 ACH 24h	0.8 to 1.6	-1.9 to -3.0	34
Daytime ventilation	*1.7 to 2.8*	*-0.5 to -1.6*	*72*
10 ACH night	1.7 to 2.8	-0.6 to -1.7	69
10 ACH 24h	1.7 to 2.7	-0.6 to -1.7	68

[a] Positive values indicate indoor operative temperatures above the 80% comfortable upper limits and negative values indicate indoor operative temperatures below the 80% comfortable upper limits.

forced ventilation. Table 6.26 summarizes the evaluation result. The night-time forced ventilation at a rate of 50 ACH improves the thermal comfort slightly more than that of 30 ACH. With night ventilation, the former reduces the night-time indoor operative temperature by 0.9°C on average compared to getting night ventilation only through open windows (Figure 6.47a). It decreases the maximum indoor operative temperatures to 1.2-1.7°C above the 80% comfortable upper limits and the exceeding period is 37% (Table 6.26). With daytime ventilation, the night-time forced ventilation improves the thermal comfort tremendously (Figure 6.47b). The night-time indoor operative temperature is reduced to the

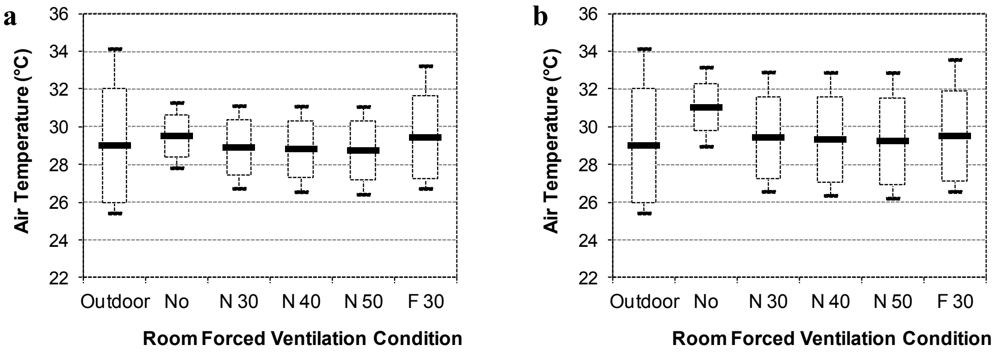


Figure 6.46. Statistical summary (5th and 95th percentiles, mean and ± one standard deviation) of simulated indoor air temperatures in the master bedroom of the terraced house in different room forced ventilation conditions in the urban climate (Johor Bahru). (a) Night ventilation; (b) Daytime ventilation. N: night; F: full-day; Numbers indicate ventilation rates (ACH).

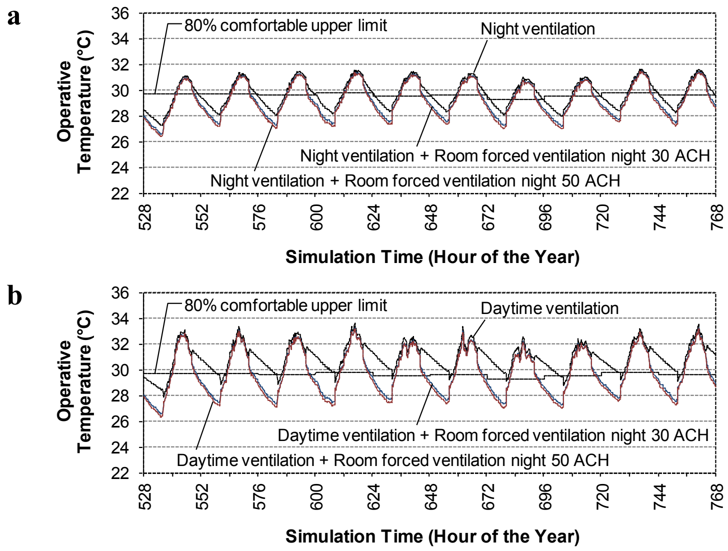


Figure 6.47. Temporal variations of simulated indoor operative temperatures in the master bedroom of the terraced house with room forced ventilation and the corresponding temperature limits for thermal comfort in the urban climate (Johor Bahru). (a) Night ventilation; (b) Daytime ventilation.

same level as that with night ventilation since the air change rates given by the forced ventilation are the same. By using the room forced ventilation of 50 ACH in the daytime ventilated room, the maximum indoor operative temperatures are lowered but still 2.5-3.5°C above the 80% comfortable upper limits (Table 6.26). However, the exceeding period is much less at 45% of the time (Table 6.26).

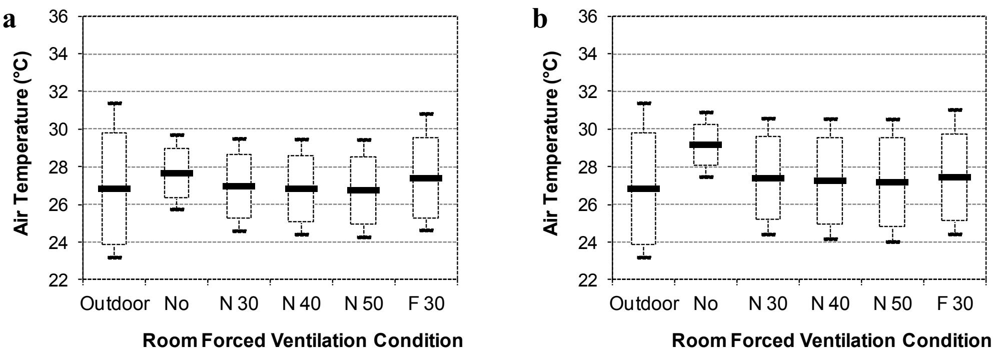


Figure 6.48. Statistical summary (5th and 95th percentiles, mean and ± one standard deviation) of simulated indoor air temperatures in the master bedroom of the terraced house in different room forced ventilation conditions in the rural climate (Senai). (a) Night ventilation; (b) Daytime ventilation. N: night; F: full-day; Numbers indicate ventilation rates (ACH).

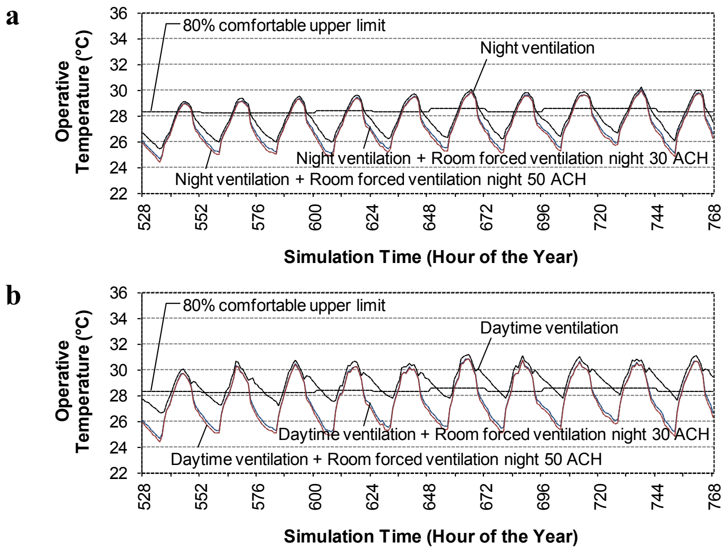


Figure 6.49. Temporal variations of simulated indoor operative temperatures in the master bedroom of the terraced house with room forced ventilation and the corresponding temperature limits for thermal comfort in the rural climate (Senai). (a) Night ventilation; (b) Daytime ventilation.

In the rural climate, the effects of the room forced ventilation on the indoor air temperature of the master bedroom are similar to those in the urban climate (Figure 6.48).

Similarly, Figure 6.49 and Table 6.27 show that in the rural climate, the night-time forced ventilation improves the indoor thermal comfort of the master bedroom for both open window conditions. With night ventilation, the room forced ventilation of 50 ACH reduces

Table 6.26. Summary of thermal comfort evaluation in the master bedroom of the terraced house with room forced ventilation in the urban climate (Johor Bahru).

Room forced ventilation condition	Deviation of indoor operative temperature from the 80% comfortable upper limits (°C)[a]		Exceeding period (%)
	Daily maximum	Daily minimum	
Night ventilation	*1.4 to 1.9*	*-1.2 to -2.5*	*52*
30 ACH night	1.3 to 1.8	-2.0 to -3.2	39
40 ACH night	1.2 to 1.7	-2.1 to -3.3	37
50 ACH night	1.2 to 1.7	-2.2 to -3.4	37
30 ACH 24h	2.5 to 3.6	-1.9 to -3.1	46
Daytime ventilation	*2.9 to 3.9*	*-0.2 to -1.8*	*88*
30 ACH night	2.6 to 3.6	-1.8 to -3.2	48
40 ACH night	2.5 to 3.6	-2.0 to -3.3	46
50 ACH night	2.5 to 3.5	-2.1 to -3.4	45
30 ACH 24h	2.9 to 4.1	-1.8 to -3.2	49

[a] Positive values indicate indoor operative temperatures above the 80% comfortable upper limits and negative values indicate indoor operative temperatures below the 80% comfortable upper limits.

Table 6.27. Summary of thermal comfort evaluation in the master bedroom of the terraced house with room forced ventilation in the rural climate (Senai).

Room forced ventilation condition	Deviation of indoor operative temperature from the 80% comfortable upper limits (°C)[a]		Exceeding period (%)
	Daily maximum	Daily minimum	
Night ventilation	*0.8 to 1.7*	*-1.8 to -2.9*	*35*
30 ACH night	0.7 to 1.5	-2.6 to -3.6	29
40 ACH night	0.7 to 1.5	-2.8 to -3.8	29
50 ACH night	0.6 to 1.4	-2.9 to -3.9	29
30 ACH 24h	1.7 to 2.4	-2.6 to -3.7	35
Daytime ventilation	*1.7 to 2.8*	*-0.5 to -1.6*	*72*
30 ACH night	1.4 to 2.4	-2.5 to -3.7	38
40 ACH night	1.4 to 2.4	-2.7 to -3.8	38
50 ACH night	1.4 to 2.4	-2.8 to -3.9	38
30 ACH 24h	1.9 to 2.7	-2.5 to -3.7	40

[a] Positive values indicate indoor operative temperatures above the 80% comfortable upper limits and negative values indicate indoor operative temperatures below the 80% comfortable upper limits.

the night-time indoor operative temperature by 1.0°C on average compared to using night ventilation only through open windows (Figure 6.49a). It decreases the maximum indoor operative temperatures to 0.6-1.4°C above the 80% comfortable upper limits and the exceeding period is 29% (Table 6.27). With daytime ventilation, the night-time indoor operative temperature is also reduced to the same level as that with night ventilation (Figure 6.49b). This decreases the exceeding period above the 80% comfortable upper limits from 72% to 38% (Table 6.27).

The results imply that applying forced ventilation to the room of interest directly is a better passive cooling technique than to apply it to the attic. Forced ventilation at night improves the indoor thermal comfort for both open window conditions in the urban and rural climates. Nevertheless, assuming the same thermal mass, the structural cooling effects on the next day are increased only slightly by increasing the night ventilation rate through forced ventilation up to 50 ACH.

6.5.10 Effects of Whole House Forced Ventilation

As mentioned earlier, whole house forced ventilation was assumed by applying forced ventilation to the family area on the first floor and keeping internal doors open. The applied air change rates were for the air volume of the family area, i.e. 47 m^3.

Figure 6.50a shows that in the urban climate, using the forced ventilation at night, noted as N30, N40 and N50 according to the air change rates, reduces the minimum (5^{th} percentile) indoor air temperatures in the master bedroom by 0.7-0.9°C compared to that without forced ventilation. Higher ventilation rates increase the cooling effect. The maximum (95^{th} percentile) air temperatures are reduced slightly probably due to the structural cooling effect. The pattern of the cooling effects is similar to that of using forced ventilation directly in the master bedroom (see Figure 6.46a). However, the minimum air temperature reductions are smaller in this case. The simulation result implies that this reduction is likely due to air flow with the reduced air temperature in the family area but not increase in air change rate in the master bedroom; the ventilation rates between the master bedroom and the outdoors and between the master bedroom and the family area are changed little (due to the temperature changes). On the other hand, using the forced ventilation for the whole day increases the maximum air temperature in the master bedroom only slightly compared to that without forced ventilation (Figure 6.50a). This result is different from that of using forced ventilation in the master bedroom (see Figure 6.46a). Relatively small effects in the minimum and maximum indoor air temperatures are also seen for respective forced ventilation conditions in the daytime ventilated master bedroom (Figure 6.50b). As before, the ventilation rate in the master bedroom is changed little and it is low in closed window condition.

Temporal variations of the indoor operative temperatures in the master bedroom are shown in Figure 6.51 to evaluate any thermal comfort improvement afforded by the whole house forced ventilation. Table 6.28 summarizes the result for the various forced ventilation

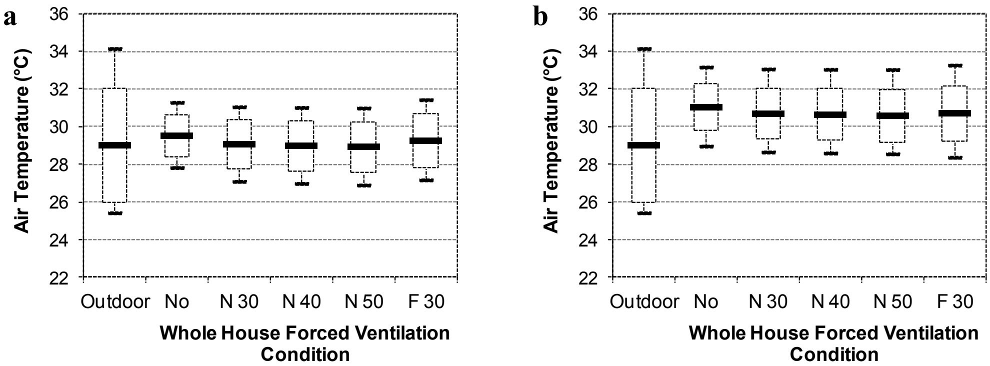


Figure 6.50. Statistical summary (5th and 95th percentiles, mean and ± one standard deviation) of simulated indoor air temperatures in the master bedroom of the terraced house in different whole house forced ventilation conditions in the urban climate (Johor Bahru). (a) Night ventilation; (b) Daytime ventilation. N: night; F: full-day; Numbers indicate ventilation rates (ACH).

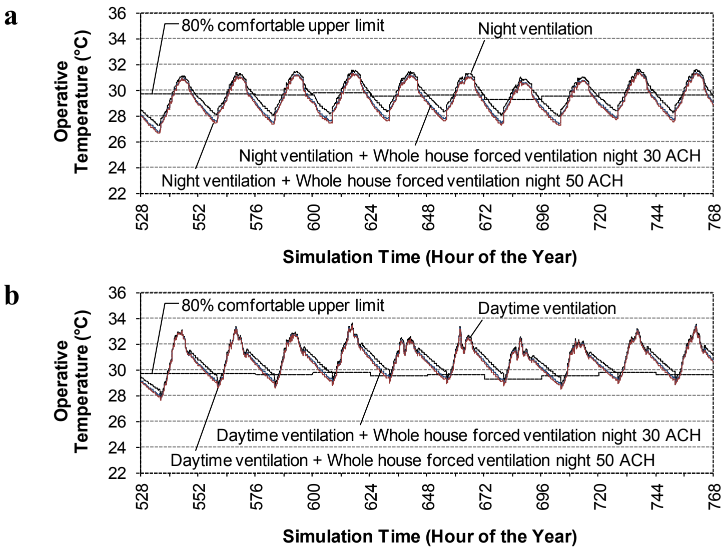


Figure 6.51. Temporal variations of simulated indoor operative temperatures in the master bedroom of the terraced house with whole house forced ventilation and the corresponding temperature limits for thermal comfort in the urban climate (Johor Bahru). (a) Night ventilation; (b) Daytime ventilation.

conditions. Similar to the case of room forced ventilation, the night-time forced ventilation at a rate of 50 ACH in the family area improves the thermal comfort slightly more than that of 30 ACH. With night ventilation, the former reduces the night-time indoor operative temperature by 0.6°C on average compared to not using forced ventilation (Figure 6.51a). It decreases the maximum indoor operative temperatures to 1.2-1.7°C above the 80%

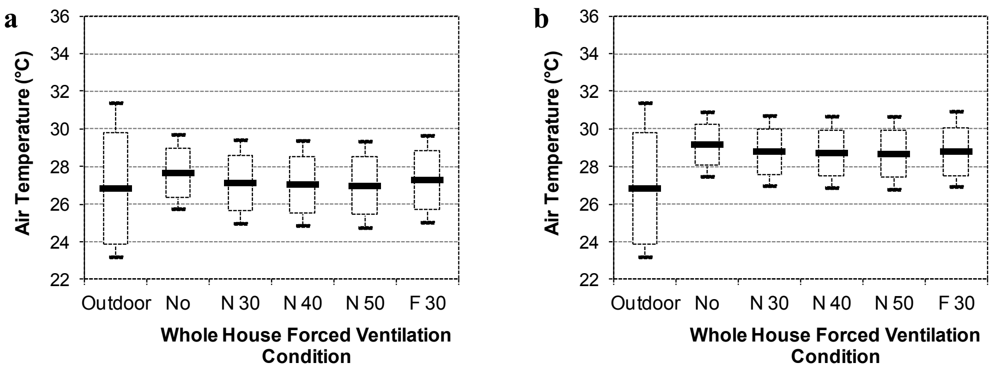


Figure 6.52. Statistical summary (5th and 95th percentiles, mean and ± one standard deviation) of simulated indoor air temperatures in the master bedroom of the terraced house in different whole house forced ventilation conditions in the rural climate (Senai). (a) Night ventilation; (b) Daytime ventilation. N: night; F: full-day; Numbers indicate ventilation rates (ACH).

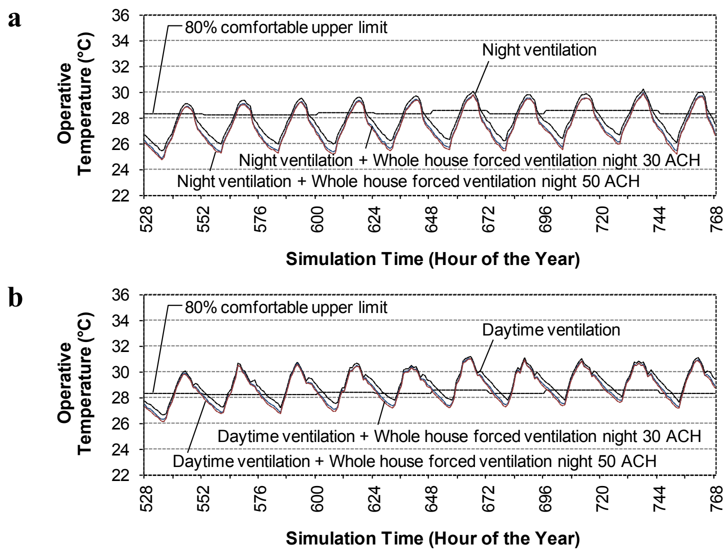


Figure 6.53. Temporal variations of simulated indoor operative temperatures in the master bedroom of the terraced house with whole house forced ventilation and the corresponding temperature limits for thermal comfort in the rural climate (Senai). (a) Night ventilation; (b) Daytime ventilation.

comfortable upper limits and the exceeding period is 39% (Table 6.28). With daytime ventilation, the night-time forced ventilation of 50 ACH lowers the night-time indoor operative temperature by 0.5°C on average compared to the case without forced ventilation (Figure 6.51b). Unlike using forced ventilation in the master bedroom, the temperature is not reduced to the same level as that with night ventilation. It reduces the maximum indoor

Table 6.28. Summary of thermal comfort evaluation in the master bedroom of the terraced house with whole house forced ventilation in the urban climate (Johor Bahru).

Whole house forced ventilation condition	Deviation of indoor operative temperature from the 80% comfortable upper limits (°C)[a]		Exceeding period (%)
	Daily maximum	Daily minimum	
Night ventilation	*1.4 to 1.9*	*-1.2 to -2.5*	*52*
30 ACH night	1.2 to 1.7	-1.8 to -3.0	41
40 ACH night	1.2 to 1.7	-1.8 to -3.0	40
50 ACH night	1.2 to 1.7	-1.9 to -3.1	39
30 ACH 24h	1.6 to 2.1	-1.7 to -2.9	44
Daytime ventilation	*2.9 to 3.9*	*-0.2 to -1.8*	*88*
30 ACH night	2.8 to 3.8	-0.5 to -2.0	78
40 ACH night	2.7 to 3.7	-0.5 to -2.0	75
50 ACH night	2.7 to 3.7	-0.6 to -2.1	74
30 ACH 24h	2.9 to 3.9	-0.8 to -2.3	78

[a] Positive values indicate indoor operative temperatures above the 80% comfortable upper limits and negative values indicate indoor operative temperatures below the 80% comfortable upper limits.

Table 6.29. Summary of thermal comfort evaluation in the master bedroom of the terraced house with whole house forced ventilation in the rural climate (Senai).

Whole house forced ventilation condition	Deviation of indoor operative temperature from the 80% comfortable upper limits (°C)[a]		Exceeding period (%)
	Daily maximum	Daily minimum	
Night ventilation	*0.8 to 1.7*	*-1.8 to -2.9*	*35*
30 ACH night	0.6 to 1.4	-2.4 to -3.4	29
40 ACH night	0.6 to 1.4	-2.5 to -3.5	28
50 ACH night	0.6 to 1.3	-2.6 to -3.6	28
30 ACH 24h	0.8 to 1.6	-2.4 to -3.4	31
Daytime ventilation	*1.7 to 2.8*	*-0.5 to -1.6*	*72*
30 ACH night	1.6 to 2.6	-0.8 to -2.0	61
40 ACH night	1.6 to 2.6	-0.9 to -2.1	60
50 ACH night	1.5 to 2.6	-0.9 to -2.2	59
30 ACH 24h	1.9 to 2.7	-1.0 to -2.1	62

[a] Positive values indicate indoor operative temperatures above the 80% comfortable upper limits and negative values indicate indoor operative temperatures below the 80% comfortable upper limits.

operative temperatures to 2.7-3.7°C above the 80% comfortable upper limits (Table 6.28). The exceeding period is also reduced but still high at 74%.

In the rural climate, the effects of the whole house forced ventilation on the indoor air temperature of the master bedroom are similar to those in the urban climate (Figure 6.52).

Similarly, Figure 6.53 shows that in the rural climate, the night-time forced ventilation lowers the indoor operative temperature of the master bedroom for both open window conditions. With night ventilation, the whole house forced ventilation of 50ACH reduces the night-time indoor operative temperature by 0.7°C on average compared to not using forced ventilation (Figure 6.53a). It decreases the maximum indoor operative temperatures to 0.6-1.3°C above the 80% comfortable upper limits and the exceeding period is 28% (Table 6.29). With daytime ventilation, the night-time indoor operative temperature is reduced by 0.6°C on average compared to the case without forced ventilation (Figure 6.53b). The maximum indoor operative temperatures and the exceeding period are also reduced (Table 6.29). As before, it would be difficult to meet the 80% comfortable upper limits because temperature in daytime ventilation condition is basically high.

The results imply that using forced ventilation at night in the family area, i.e. the central zone of the house, provides cooling effects to adjacent rooms with openings to it by virtue of interzonal air flow with the cooled air from the family area. It may be useful as a passive cooling technique for the whole house and can be energy-efficient if cooling more than one room is desired since the air volume that requires the forced ventilation is likely to be less. The temperature reductions and thermal comfort improvement are slightly less than by using forced ventilation in the room of interest directly for night ventilation condition. However, they are much less for daytime ventilation condition.

6.5.11 Effects of Combined Techniques

Based on the results of the simulation test cases, the passive cooling techniques that are effective to improve the indoor thermal comfort of the night ventilated master bedroom are roof insulation, ceiling insulation, external wall (outside surface) insulation, window external shading, room forced ventilation at night and whole house forced ventilation at night. Two combinations of the more effective techniques were further simulated as follows:

- Night ventilation + 3 techniques, i.e. roof insulation of R 4, window external shading of SF 0.75 and room forced ventilation of 50 ACH at night
- Night ventilation + 4 techniques, i.e. roof insulation of R 4, external wall (outside surface) insulation of R 0.5, window external shading of SF 0.75 and room forced ventilation of 50 ACH at night

The combination of the four techniques means that the whole building envelope is either insulated or shaded. Both combinations were also simulated in the daytime ventilation (open window) condition and were repeated for the urban and rural climates. Ceiling insulation was excluded since roof insulation is more effective and it would be redundant to use both simultaneously. Also, it is noted earlier that room forced ventilation is more effective than whole house forced ventilation. Nevertheless, the latter may be useful for cooling more than one room.

Figures 6.54-6.55 present the temporal variations of the simulated indoor air temperatures in the master bedroom of the terraced house in the urban and rural climates, respectively, for the combined passive cooling techniques. Statistical summaries for the 10-day period are given in Figure 6.56.

In the urban climate, using the three techniques for the night ventilated master bedroom, noted as NV+3, decreases the maximum (95th percentile), mean and minimum (5th percentile) indoor air temperatures by 1.7°C, 1.5°C and 1.6°C compared to those using only night ventilation (Figure 6.56a). Adding the combination to four techniques (NV+4) further reduces the maximum (95th percentile) and mean indoor air temperatures to 2.3°C and 1.7°C lower than those using only night ventilation. Meanwhile, using the three techniques for the daytime ventilated master bedroom, noted as DV+3, reduces the maximum (95th percentile), mean and minimum (5th percentile) indoor air temperatures by 0.8°C, 2.1°C and 2.9°C compared to those using only daytime ventilation (Figure 6.56a). Adding the combination to four techniques further reduces only the maximum (95th percentile) indoor air temperature slightly. The result thus agrees that external wall insulation is unnecessary in the daytime ventilated room.

Similar changes are seen in the rural climate. Figure 6.56b shows that using the three techniques for the night ventilated master bedroom, noted as NV+3, decreases the maximum (95th percentile), mean and minimum (5th percentile) indoor air temperatures by 2.0°C, 1.7°C and 1.8°C compared to those using only night ventilation. Adding the combination to four techniques (NV+4) further reduces the corresponding indoor air temperatures to 2.6°C, 1.9°C and 1.9°C lower than those using only night ventilation. Meanwhile, using the three techniques for the daytime ventilated master bedroom, noted as DV+3, reduces the maximum (95th percentile), mean and minimum (5th percentile) indoor air temperatures by 1.0°C, 2.5°C and 3.6°C compared to those using only daytime ventilation (Figure 6.56b). All of these reductions are more than those seen in the urban climate. Adding the combination to four techniques further reduces only the maximum (95th percentile) indoor air temperature slightly in the daytime ventilated room.

We plot the simulated indoor operative temperatures and humidity of the master bedroom on a psychrometric chart in Figure 6.57 for the combination of four techniques. A considerable shift to the left, i.e. lower indoor operative temperatures, is observed for each plot compared to using only open windows (see the corresponding plots in Figure 6.12). However, none of the data falls within the illustrated comfort zone by ASHRAE (2010) for typical indoor environments at 0.5 clo level in both climates. This is mainly because the indoor humidity is higher than the upper absolute humidity limit of 12 g/kg' that is used for the graphical method in the standard.

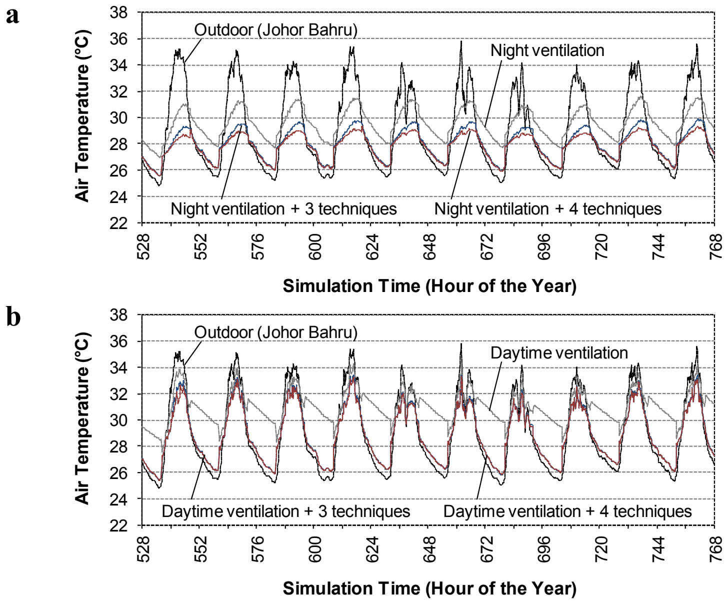


Figure 6.54. Temporal variations of simulated indoor air temperatures in the master bedroom of the terraced house with combined passive cooling techniques in the urban climate (Johor Bahru). (a) Night ventilation; (b) Daytime ventilation.

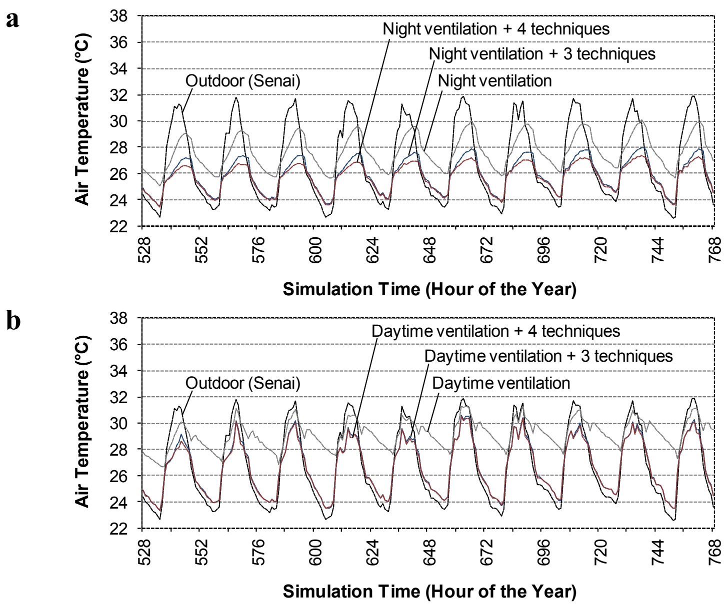


Figure 6.55. Temporal variations of simulated indoor air temperatures in the master bedroom of the terraced house with combined passive cooling techniques in the rural climate (Senai). (a) Night ventilation; (b) Daytime ventilation.

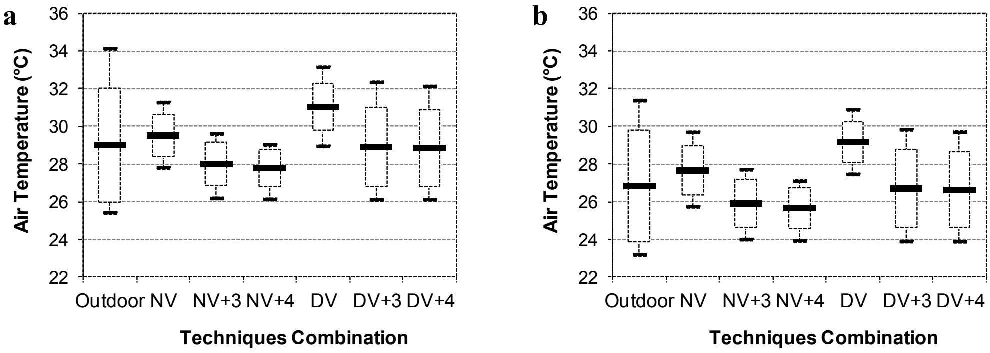


Figure 6.56. Statistical summary (5th and 95th percentiles, mean and ± one standard deviation) of simulated indoor air temperatures in the master bedroom of the terraced house using different combinations of passive cooling techniques. (a) Urban climate (Johor Bahru); (b) Rural climate (Senai). NV: night ventilation; DV: daytime ventilation.

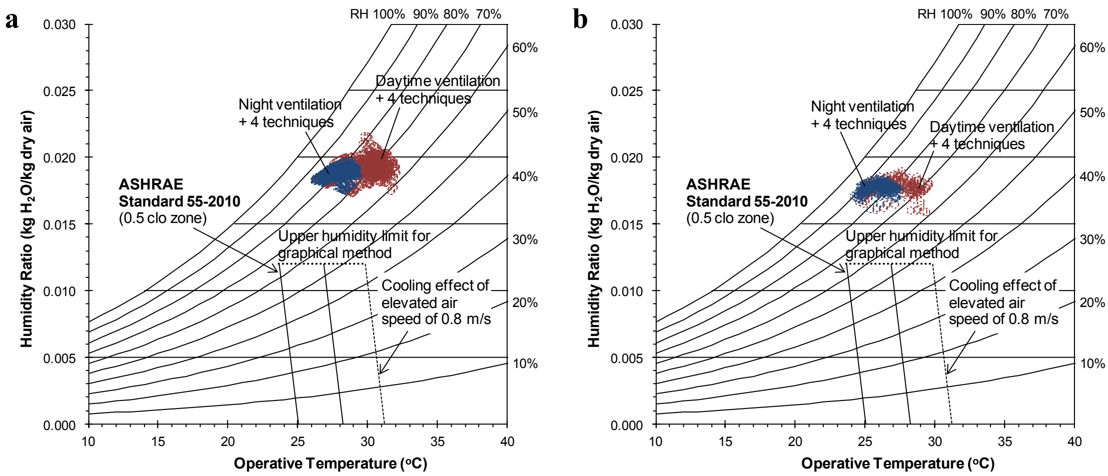


Figure 6.57. Scatter diagram of simulated indoor operative temperatures and indoor humidity in the master bedroom of the terraced house with combined passive cooling techniques on a psychrometric chart. (a) Urban climate (Johor Bahru); (b) Rural climate (Senai).

Temporal variations of the indoor operative temperatures are drawn in Figures 6.58-6.59 for thermal comfort evaluation of the combined passive cooling techniques. Tables 6.30-6.31 summarize the indoor operative temperature deviations from the 80% comfortable upper limits and the exceeding periods in the urban and rural climates, respectively.

In the urban climate, both combinations lower the indoor operative temperature in the night ventilated room to meet the 80% comfortable upper limits for the whole day (Figure 6.58a). The maximum indoor operative temperatures obtained by using three techniques are close to the upper limits and 0.2°C higher at most (Table 6.30). The exceeding period is reduced to 4% compared to using only night ventilation. Meanwhile, the maximum indoor operative temperatures obtained by using four techniques are 0.4-0.9°C below the upper limits; there is no exceeding period (Table 6.30). With daytime ventilation, both combinations of passive cooling techniques give almost similar indoor operative temperature profiles, which imply that the external wall insulation improves the indoor thermal comfort little (Figure 6.58b). The maximum indoor operative temperatures obtained by using three techniques are reduced to 1.7-2.7°C above the 80% comfortable upper limits and the exceeding period is 38% (Table 6.30).

In the rural climate, both combinations lower the indoor operative temperature in the night ventilated room to well below the 80% comfortable upper limits for the whole day (Figure 6.59a). The maximum indoor operative temperatures obtained by using three techniques and four techniques are 0.5-1.1°C and 1.1-1.7°C below the said limits, respectively (Table 6.31). There is no exceeding period for both combinations. With daytime ventilation, both combinations give almost similar indoor operative temperature profiles (Figure 6.59b). The maximum indoor operative temperatures obtained by using three techniques are reduced to 0.3-1.3°C above the 80% comfortable upper limits and the exceeding period is 25% (Table 6.31).

It is concluded that the tested combinations of passive cooling techniques provide thermal comfort in the night ventilated room in the urban and rural climates if occupants' thermal adaptation to the outdoor climate is considered. Thermal comfort in the rural reference climate is deemed more comfortable than in the urban climate when the same techniques are used.

In the final analysis, Figure 6.60 shows a comparison of the relationships between outdoor air temperatures and indoor operative temperatures in the night ventilated master bedroom with the combination of four passive cooling techniques at the urban and rural locations. Segmented regression is used (see the method in Chapter 4: Section 4.3.5). The break-point for the urban climate is 27.8°C while the break-point for the rural climate is 25.6°C, which is 2.2°C lower than that of the urban climate (Figure 6.60). The corresponding break-points when simulating only night ventilation (open window) condition are almost similar (see Figure 6.17). Nevertheless, adding the four techniques shifts the break-points closer to the indoor-equals-outdoor line.

In both climates, the slopes of the regression lines after the break-points are reduced from 0.17 to less than 0.1 (see Figures 6.17 and 6.60). The slope reductions are mainly due to the solar heat prevention techniques, i.e. window external shading, roof insulation and external wall (outside surface) insulation, and some additional structural mass cooling by the increased night ventilation rate. The gap between the two regression lines after the break-points are increased from 1.4°C to about 2.4°C (see Figures 6.17 and 6.60). This observation implies that the same passive cooling techniques are more effective in the rural climate than in the urban climate. The hotter outdoor air and lower incident solar radiation (likely due to atmospheric pollution) at the urban location mean that there is less room to benefit from a b

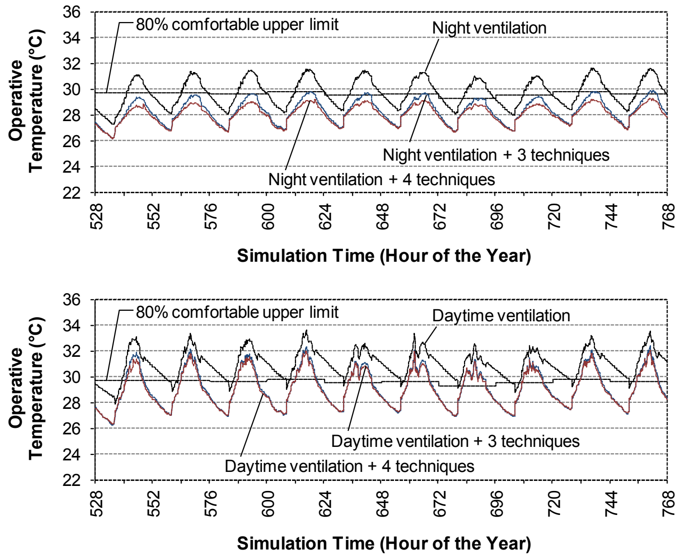


Figure 6.58. Temporal variations of simulated indoor operative temperatures in the master bedroom of the terraced house with combined passive cooling techniques and the corresponding temperature limits for thermal comfort in the urban climate (Johor Bahru). (a) Night ventilation; (b) Daytime ventilation.

a b

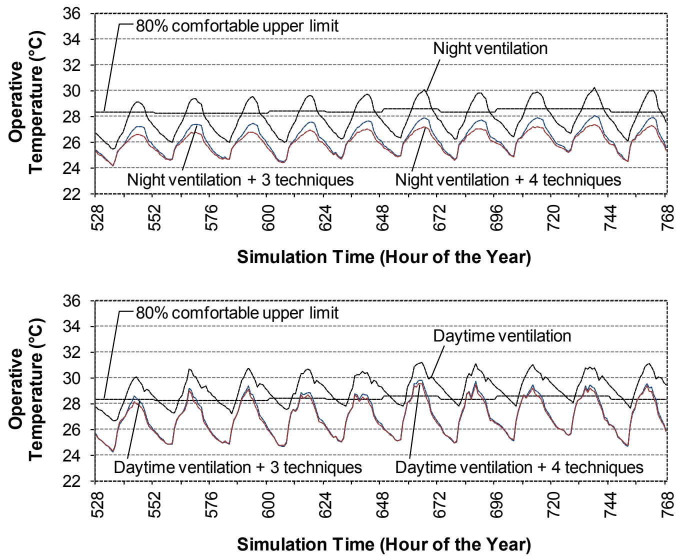


Figure 6.59. Temporal variations of simulated indoor operative temperatures in the master bedroom of the terraced house with combined passive cooling techniques and the corresponding temperature limits for thermal comfort in the rural climate (Senai). (a) Night ventilation; (b) Daytime ventilation.

Table 6.30. Summary of thermal comfort evaluation in the master bedroom of the terraced house with combined passive cooling techniques in the urban climate (Johor Bahru).

Combination of passive cooling techniques	Deviation of indoor operative temperature from the 80% comfortable upper limits (°C)[a]		Exceeding period (%)
	Daily maximum	Daily minimum	
Night ventilation	*1.4 to 1.9*	*-1.2 to -2.5*	*52*
Night ventilation + 3	-0.3 to 0.2	-2.5 to -3.6	4
Night ventilation + 4	-0.9 to -0.4	-2.6 to -3.6	0
Daytime ventilation	*2.9 to 3.9*	*-0.2 to -1.8*	*88*
Daytime ventilation + 3	1.7 to 2.7	-2.3 to -3.5	38
Daytime ventilation + 4	1.6 to 2.4	-2.2 to -3.4	36

[a] Positive values indicate indoor operative temperatures above the 80% comfortable upper limits and negative values indicate indoor operative temperatures below the 80% comfortable upper limits.

Table 6.31. Summary of thermal comfort evaluation in the master bedroom of the terraced house with combined passive cooling techniques in the rural climate (Senai).

Combination of passive cooling techniques	Deviation of indoor operative temperature from the 80% comfortable upper limits (°C)[a]		Exceeding period (%)
	Daily maximum	Daily minimum	
Night ventilation	*0.8 to 1.7*	*-1.8 to -2.9*	*35*
Night ventilation + 3	-1.1 to -0.5	-3.3 to -4.1	0
Night ventilation + 4	-1.7 to -1.1	-3.3 to -4.1	0
Daytime ventilation	*1.7 to 2.8*	*-0.5 to -1.6*	*72*
Daytime ventilation + 3	0.3 to 1.3	-3.0 to -4.1	25
Daytime ventilation + 4	-0.2 to 1.1	-3.0 to -4.0	20

[a] Positive values indicate indoor operative temperatures above the 80% comfortable upper limits and negative values indicate indoor operative temperatures below the 80% comfortable upper limits.

ventilative cooling and solar heat prevention techniques. It will be essential to mitigate urban heat islands and improve urban climatic and atmospheric conditions to increase the effectiveness of passive cooling techniques in urban houses.

The regression lines before the break-points represent the night ventilation period. Although the same forced ventilation rates were used, i.e. 50 ACH, the regression line for the rural climate is positioned at lower indoor and outdoor temperatures and its gradient is slightly higher than the regression line for the urban climate. The same conclusion that nocturnal ventilative cooling will be more effective at cooler outdoor conditions is drawn.

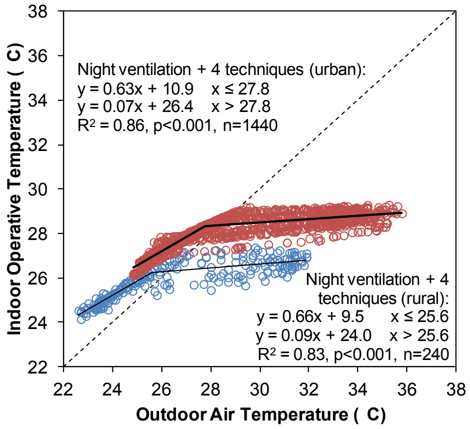


Figure 6.60. Relationships between outdoor air temperatures and indoor operative temperatures in the night ventilated master bedroom of the terraced house with combined passive cooling techniques in the urban and rural climates. Red points and thick regression line represent urban climate while blue points and thin regression line represent rural climate. Dashed line represents indoor conditions equaling outdoor conditions.

7

Proposed Application of Passive Cooling Techniques

In this chapter, we integrate the findings of the whole study and propose some application of the passive cooling techniques to the terraced house. Section 7.1 compares the results of the field experiment in the terraced houses (Chapter 4), the field measurement in the vernacular houses (Chapter 5) and the simulation of the terraced house in the urban and rural climates (Chapter 6). The comparison focuses on two aspects: (1) cooling potential of the different houses and cooling techniques in relation to outdoor conditions; and (2) improvements on the indoor thermal comfort according to the adaptive thermal comfort criteria developed in Chapter 3. In Section 7.2, we propose several options of modifications to the existing terraced house to increase its adaptive capacity for passive cooling. The expected indoor thermal comfort and cooling energy saving benefits are estimated.

7.1 Comparison of the Different Passive Cooling Techniques

7.1.1 Cooling Potential in Relation to Outdoor Conditions

The main purpose of this comparison study is to determine the potential passive cooling techniques for the existing terraced houses. Figure 7.1 compares the relationships between the indoor and outdoor conditions of the terraced houses and the traditional Malay houses. The regression line that represents daytime ventilation in the terraced house is obtained from Figure 4.34 while the regression line that represents night ventilation in the terraced house is obtained from Figure 4.38 (see Chapter 4: Section 4.3.5). They are derived from the field experiment data in the master bedrooms. The regression line for the Malay houses is derived

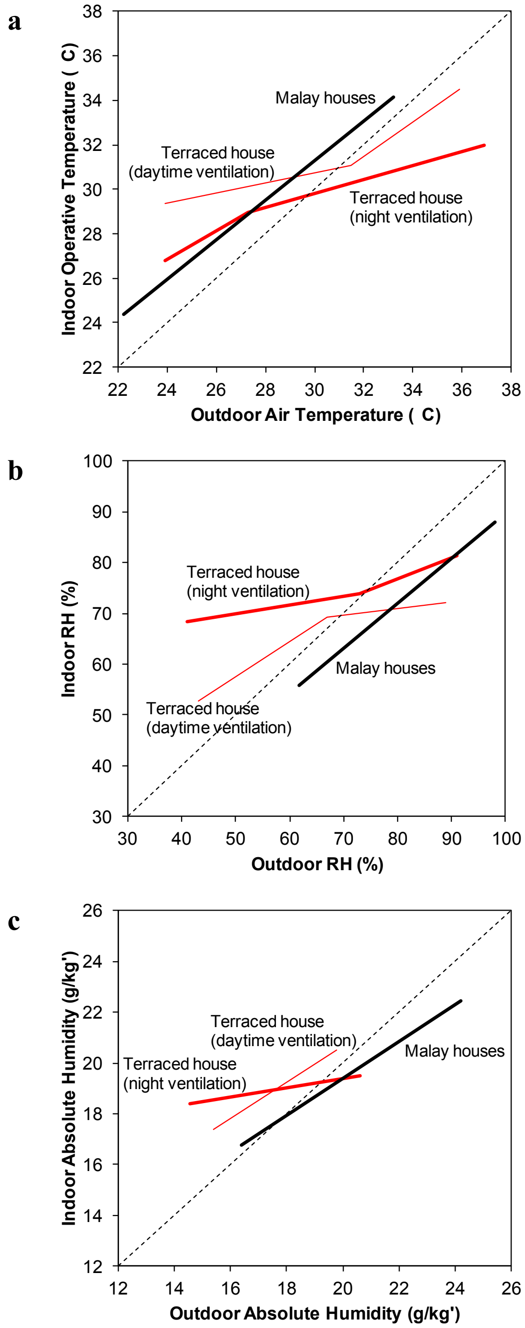


Figure 7.1. Comparison of the relationships between outdoor conditions and indoor conditions in terraced houses (field experiment) and Malay houses. (a) Operative temperature; (b) Relative humidity; (c) Absolute humidity. Dashed lines represent indoor conditions equaling outdoor conditions.

from the data in Figure 5.10 (see Chapter 5: Section 5.3.5). Data from the front living halls of both traditional Malay houses are combined.

Figure 7.1a shows that the regression line for the Malay houses predicts higher indoor operative temperature than those predicted by the regression lines for the terraced houses after the break-points. The high thermal mass structures of the terraced house might not necessarily be worse than the lightweight structures, i.e. the traditional Malay houses, in terms of keeping the daytime indoor operative temperatures low relative to the outdoor temperature even in daytime ventilation condition. It is clear that the terraced house is even cooler in night ventilation condition. Nevertheless, as discussed in Chapter 5: Section 5.3.5, the solar heat control in the Malay houses is possibly better than that of the existing terraced houses. The solar heat controls that are present in the front living halls of the Malay houses include shading by roof overhang and shade trees. Based on the result of the simulation study (see Chapter 6: Section 6.5.6), external shading of windows is one of the effective passive cooling techniques for the terraced house.

On the other hand, for the same thermal mass effect, the regression line for the night ventilated terraced house has a smaller gradient and predicts higher indoor operative temperature than that of the Malay houses (Figure 7.1a). It was noted that windows of the Malay houses were kept closed in this case; the indoor operative temperature would be lower and closer to the outdoor air temperature if their windows were open at night. It is expected that the lightweight structures would be superior to the existing terraced houses at night in both open window conditions.

The other important point is the outdoor air temperature. It is observed in Figure 7.1a that the outdoor air temperature at the site of the terraced houses falls in a higher range than that at the site of the Malay houses. It could be argued that the field measurement was carried out in different months and might cause their difference, although the seasonal variation in Malaysia is small (see Chapter 6: Section 6.4.2). We compare the outdoor air temperatures as measured on site to standard meteorological data at Senai station (MMD, 2011) for the respective measurement periods in Figure 7.2. Senai station is the nearest governmental

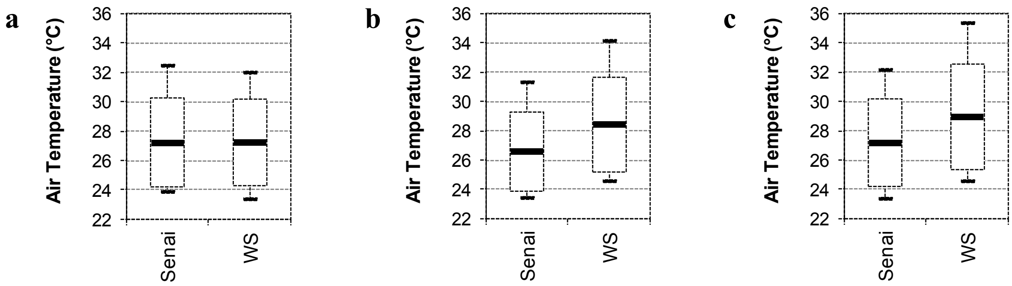


Figure 7.2. Statistical summary (5th and 95th percentiles, mean and ± one standard deviation) of outdoor air temperatures at Senai station (Senai) and measured on site (WS) on fair weather days. (a) Malay houses; (b) Terraced houses (Case 1); (c) Terraced houses (Cases 1-3).

meteorological station to both sites; it is located at an airport about 20km northwest from the city centre, about 10km northeast from the case study terraced houses and about 40km northeast from the case study Malay houses. In the analysis, we assume that both Pontian and Johor Bahru share the similar climatic conditions of Senai station.

Figure 7.2ab reveal that the maximum (95th percentile), mean and minimum (5th percentile) outdoor air temperatures at Senai station are 1.2°C, 0.6°C and 0.5°C lower during the measurement period for Case 1 in the terraced houses than during the measurement periods in the Malay houses. Figure 7.2c additionally shows that the corresponding values are 0.3°C, 0.0°C and 0.5°C lower during the measurement period for Cases 1-3 in the terraced houses than those in the Malay houses. The results suggest that the terraced house site, i.e. suburban area, is hotter probably due to various microclimatic and urban heat island effects rather than seasonal difference. We infer that buildings of lightweight structures would perform worse in urban areas than in rural areas especially in their peak indoor temperatures due to the relatively hot outdoor air in urbanized locations. On the other hand, it would be fundamental to lower the outdoor air temperature in urban sites such as by adopting the rural microclimatic controls and mitigating urban heat islands to increase the cooling effects in the terraced houses. This point is also implied through the simulation study that compares results using urban and rural weather data (see Chapter 6: Sections 6.5.1 and 6.5.11).

In Figure 7.1b, the regression line for the Malay houses predicts lower indoor relative humidity than that predicted by the regression line for the night ventilated terraced house. It is also lower than the daytime ventilated terraced house at outdoor relative humidity below 80%. While the outdoor relative humidity ranges much higher in case of the Malay houses, the ranges of indoor relative humidity in the terraced houses for both ventilation conditions are only slightly lower than that of the Malay houses.

Figure 7.1c also shows that the regression line for the Malay houses predicts lower indoor absolute humidity than those predicted by the regression lines for the terraced houses in both ventilation conditions. The regression line for the daytime ventilated terraced house is parallel to that of the Malay houses, albeit higher. Similarly, the outdoor absolute humidity ranges much higher and wider in case of the Malay houses than for the terraced houses. This is likely an effect of the high evapotranspiration in the rural area due to vast vegetation, moist soil and dew, as noted in Chapter 5: Section 5.3.3. We deduced earlier that in the rural area, ventilation with outdoor air might bring in humidity during daytime. Nevertheless, the lower half of the regression line for the Malay houses, which represents night-time condition, shows that the indoor humidity control is better than that of the terraced houses. The humidity control likely occurs through the permanent ventilation openings and porous timber structures.

Figure 7.3 compares the relationships between the indoor and outdoor conditions of the terraced houses and the traditional Chinese shophouses. The regression lines that represent the terraced houses are the same as Figure 7.1. The regression line that represents the Chinese shophouses is derived from the data in Figure 5.23 (see Chapter 5: Section 5.4.6).

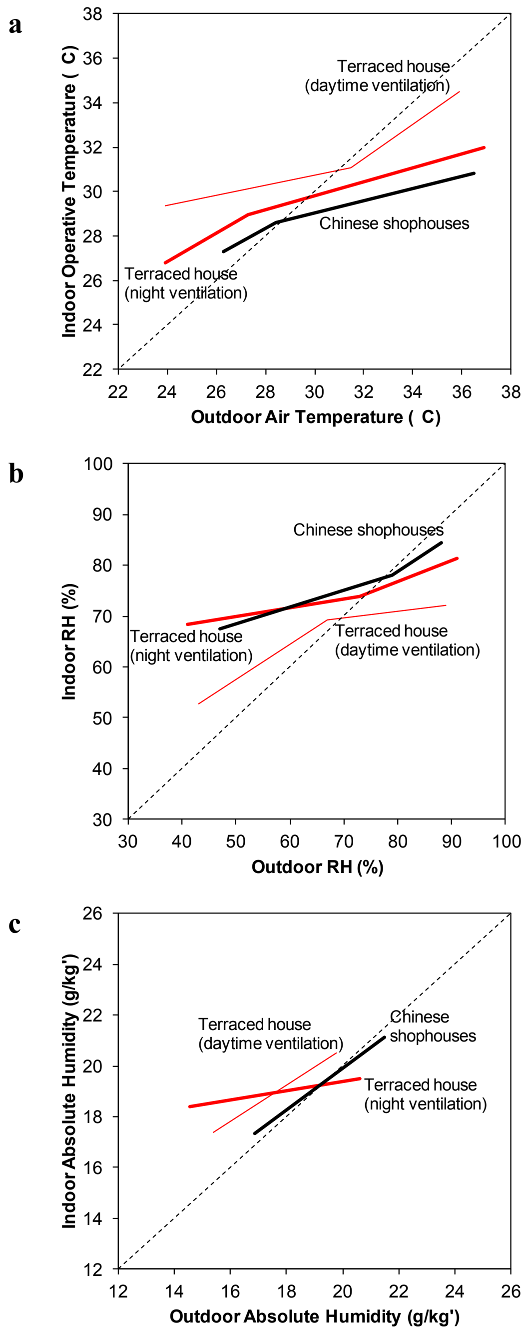


Figure 7.3. Comparison of the relationships between outdoor conditions and indoor conditions in terraced houses (field experiment) and Chinese shophouses. (a) Operative temperature; (b) Relative humidity; (c) Absolute humidity. Dashed lines represent indoor conditions equaling outdoor conditions.

Data from the front courtyard-adjacent living halls of both traditional Chinese shophouses are combined.

Figure 7.3a confirms that the regression line for the Chinese shophouses resembles that of the night ventilated terraced house. The two regression lines are parallel before and after the break-points. Moreover, the regression line for the Chinese shophouses constantly predicts lower indoor operative temperature than that predicted for the night ventilated terraced house. The regression line before the break-point for the Chinese shophouses is closer to the indoor-equals-outdoor line compared to the line for the terraced house. The result implies that the nocturnal ventilative cooling afforded by the small courtyards in the Chinese shophouses is better than the night ventilation through open windows in the terraced house at similar outdoor air temperature. Besides providing good ventilation rate at night by the courtyards, the cooling effects during daytime could be enhanced by the higher thermal mass and better solar control in the living halls of the Chinese shophouses (see Chapter 5: Section 5.4.6).

In terms of relative humidity, Figure 7.3b shows that the regression lines for the Chinese shophouses and night ventilated terraced house are almost similar. The regression line for the Chinese shophouses predicts slightly higher indoor relative humidity than in the night ventilated terraced house at outdoor relative humidity above 60%.

On the other hand, Figure 7.3c reveals that the regression line for the Chinese shophouses is parallel to that of the daytime ventilated terraced house but not night ventilated terraced house in terms of absolute humidity. In fact, the regression line for the Chinese shophouses predicts indoor absolute humidity that is almost equal to the outdoors and lower than that predicted by the regression line for the daytime ventilated terraced house. It should be noted that in this figure, the regression line for the Chinese shophouses includes the data of both living halls that were adjacent to the courtyards without plant and with plant. The result signifies that the indoor humidity control in the Chinese shophouses is relatively good and might be assisted by the courtyards throughout the day.

One of our previous survey results shows that the majority of the households living in terraced houses did not open windows at night for fears of security, among other reasons (see Chapter 4: Section 4.2.3). We infer from the above result that the application of courtyards could be a possible means to boost night ventilation in the terraced houses without literally opening windows on external facades during night-time. Control of indoor absolute humidity might also be better through courtyards.

Figure 7.4 compares the relationships between the outdoor air temperature and indoor operative temperature in the night ventilated terraced house that were obtained through the field experiment and numerical simulation. The regression line for the field experiment case is the same as Figures 7.1a and 7.3a. It represents the suburban outdoor conditions. The other two regression lines are obtained from Figure 6.17 (see Chapter 6: Section 6.5.1). They represent the urban and rural outdoor conditions. While the field experiment and numerical simulation might yield slightly different results due to their methodological differences, Figure 7.4 generally shows that the maximum outdoor air temperature from the field experiment (suburban) is higher while the minimum outdoor air temperature is lower

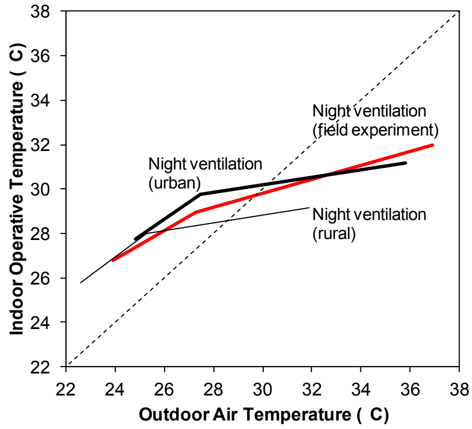


Figure 7.4. Comparison of the relationships between outdoor air temperature and indoor operative temperature in the night ventilated terraced house from the field experiment and numerical simulation. Dashed line represents indoor conditions equaling outdoor conditions.

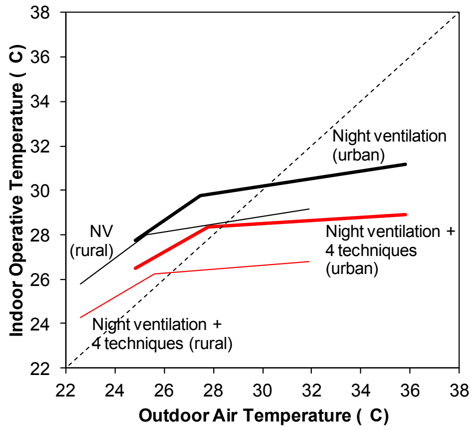


Figure 7.5. Comparison of the relationships between outdoor air temperature and indoor operative temperature in the night ventilated terraced house without and with combined passive cooling techniques in the urban and rural climates (numerical simulation). Dashed line represents indoor conditions equaling outdoor conditions. NV: night ventilation.

compared to those of the urban location. The conditions agree with those stated in the literature on urban heat island (Kubota and Ossen, 2009; Sani, 1990/91) (see Chapter 6: Section 6.4.3). Consequently, the regression line for the urban climate predicts slightly higher indoor operative temperature at lower outdoor air temperature while it predicts slightly lower indoor operative temperature at higher outdoor air temperature compared to the regression line from the field experiment (Figure 7.4). Comparison between the urban and rural climates is discussed in Chapter 6: Section 6.5.1. Overall, Figure 7.4 signifies that the indoor operative temperature would be lowest in the rural climate due to its cooler outdoor air compared to the urban and suburban locations for the same terraced house and open window conditions.

Figure 7.5 further compares the relationships between the outdoor air temperature and indoor operative temperature in the night ventilated terraced house without and with additional passive cooling techniques from the numerical simulation results. As before, the regression line that represents night ventilation is obtained from Figure 6.17 (see Chapter 6: Section 6.5.1). Night ventilation was applied through open windows only. The other two regression lines are obtained from Figure 6.60 (see Chapter 6: Section 6.5.11). They represent night-time open window conditions with four other passive cooling techniques, i.e. roof insulation of R 4, external wall (outside surface) insulation of R 0.5, window external shading of SF 0.75 and room forced ventilation of 50 ACH at night.

Figure 7.5 shows that the regression lines for night ventilation with combined passive cooling techniques in both urban and rural climates predict lower indoor operative temperatures compared to those predicted by the regression lines for night ventilation only in the respective climates. Before the break-points, the former lines are closer to the indoor-equals-outdoor line than the latter lines. This is due to the increased night ventilation rates using forced ventilation. After the break-points, the slopes of the former lines are reduced compared to the latter lines. As discussed in Chapter 6: Section 6.5.11, the lower lines and lower slopes are mainly due to the solar heat prevention techniques, i.e. window external shading, roof insulation and external wall (outside surface) insulation, and some additional structural mass cooling by the increased night ventilation rate.

Further, Figure 7.5 shows that the highest indoor operative temperature is predicted by the regression line for night ventilation only in the urban climate while the lowest indoor operative temperature is predicted by the regression line for night ventilation with multiple passive cooling techniques in the rural climate. The other two regression lines predict almost similar ranges of indoor operative temperature but the outdoor air temperatures range differently. The result implies that a combination of multiple passive cooling techniques (including night ventilation) plus reduction in its outdoor air temperature by adopting the rural microclimate and mitigating urban heat islands would provide the highest cooling potential for the existing terraced houses. It is expected that for the terraced houses in suburban locations, the indoor operative temperature would be slightly higher during daytime and slightly lower at night compared to that of the urban terraced houses.

Figure 7.6 compares all of the regression lines from the previous figures. The regression lines are segmented except for the regression line for the Malay houses, which is linear. They represent the night ventilated terraced house and the Chinese shophouses. Compared to the regression lines before the break-points for the night ventilated terraced house (field experiment, urban and rural), the lower half of the regression line for the Malay houses predicts lower indoor operative temperature at similar outdoor air temperature by virtue of its lightweight structures. Using night ventilation through open windows and forced ventilation

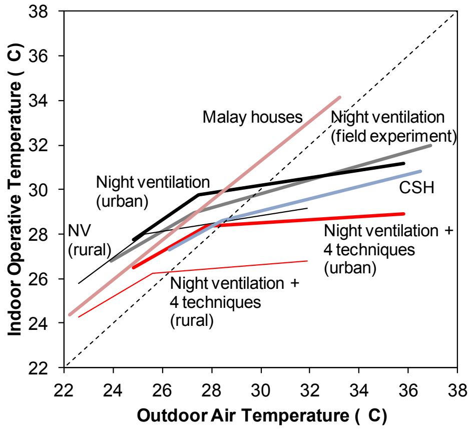


Figure 7.6. Comparison of the relationships between outdoor air temperature and indoor operative temperature in the night ventilated terraced house from the field experiment and numerical simulation, Malay houses and Chinese shophouses. Dashed line represents indoor conditions equaling outdoor conditions. NV: night ventilation; CSH: Chinese shophouse.

in the terraced houses, noted as night ventilation + 4 techniques (urban and rural) in the figure, could lower the indoor operative temperature further. Interestingly, the regression line before the break-point for the Chinese shophouses predicts similar indoor operative temperature compared to that predicted by the corresponding line for the night ventilated terraced house combined with four techniques in the urban climate. The result emphasizes that the nocturnal ventilative cooling potential of the courtyards in the Chinese shophouses is as good as that of forced night ventilation at a rate of 50 ACH in the terraced houses. As before, the lowest indoor operative temperature throughout the day is predicted by the regression line for night ventilation with four other passive cooling techniques in the rural climate.

7.1.2 Improvements on the Indoor Thermal Comfort

Table 7.1 compares the thermal comfort evaluation of the terraced houses from the field experiment and numerical simulation, the Malay houses and the Chinese shophouses. Data for the terraced houses are selected from Table 4.5 (see Chapter 4: Section 4.3.3), Table 6.11 (see Chapter 6: Section 6.5.1) and Tables 6.30-6.31 (see Chapter 6: Section 6.5.11). Data for the Malay houses and the Chinese shophouses are derived from Table 5.2 (see Chapter 5: Section 5.3.3) and Table 5.5 (see Chapter 5: Section 5.4.3), respectively. All data represent conditions on fair weather days.

Table 7.1 shows that in the terraced house, the exceeding periods, i.e. thermal discomfort periods, for daytime ventilation condition are 91% based on the field experiment and 88% in

Table 7.1. Comparison of thermal comfort evaluation in terraced houses from the field experiment and numerical simulation, Malay houses and Chinese shophouses.

House/Passive cooling condition	Deviation of indoor operative temperature from the 80% comfortable upper limits (°C)[a]		Exceeding period (%)
	Daily maximum	Daily minimum	
Terraced houses (field experiment)			
Daytime ventilation	2.9 to 5.8	-0.4 to -1.0	91
Night ventilation	0.9 to 4.0	-1.7 to -3.1	42
Terraced house (urban)			
Daytime ventilation	2.9 to 3.9	-0.2 to -1.8	88
Daytime ventilation + 4	1.6 to 2.4	-2.2 to -3.4	36
Night ventilation	1.4 to 1.9	-1.2 to -2.5	52
Night ventilation + 4	-0.9 to -0.4	-2.6 to -3.6	0
Terraced house (rural)			
Daytime ventilation	1.7 to 2.8	-0.5 to -1.6	72
Daytime ventilation + 4	-0.2 to 1.1	-3.0 to -4.0	20
Night ventilation	0.8 to 1.7	-1.8 to -2.9	35
Night ventilation + 4	-1.7 to -1.1	-3.3 to -4.1	0
Malay houses			
MH 1 and MH 2	4.0 to 5.7	-2.5 to -4.7	47
Chinese shophouses			
CSH 1 and CSH 2	-0.3 to 0.5	-2.1 to -3.1	8

[a] Positive values indicate indoor operative temperatures above the 80% comfortable upper limits and negative values indicate indoor operative temperatures below the 80% comfortable upper limits.

the urban climate. The results are slightly higher from the field experiment, which was carried out in the suburban location. Deviations of the daily maximum indoor operative temperatures above the 80% comfortable upper limits reach 2.9-5.8°C and 2.9-3.9°C in the two locations, respectively. It is expected that the occupants of existing terraced houses, who mostly used daytime ventilation through open windows, experience these thermal discomfort conditions. Even in the rural climate, the exceeding period is 72% and the deviations are 1.7-2.8°C above the upper limits. In comparison, the exceeding periods in the night ventilated terraced house are 52% and 42% in the urban and suburban locations, respectively. In the rural climate, the exceeding period is further reduced to 35% for the night ventilated terraced house. The results imply that the basic passive cooling technique for the brick terraced houses would be night ventilation but it is insufficient to provide indoor thermal comfort in all locations.

Table 7.2 further compares the thermal comfort evaluation for respective passive cooling techniques in the night ventilated terraced house based on the numerical simulation result.

Table 7.2. Comparison of thermal comfort evaluation for respective passive cooling techniques in the night ventilated terraced house (numerical simulation).

Passive cooling technique	Deviation of indoor operative temperature from the 80% comfortable upper limits (°C)[a]		Exceeding period (%)
	Daily maximum	Daily minimum	
Night ventilation (urban)	*1.4 to 1.9*	*-1.2 to -2.5*	*52*
Roof insulation R 4	0.4 to 1.0	-1.5 to -2.6	32
Ceiling insulation R 4	0.7 to 1.3	-1.2 to -2.5	45
External wall (outside surface) insulation R 0.5	1.0 to 1.6	-1.1 to -2.3	50
External wall (inside surface) insulation R 0.5	1.3 to 1.8	-1.2 to -2.4	51
Window external shading SF 0.75	0.8 to 1.4	-1.3 to -2.6	40
Window internal shading SF 0.75	1.2 to 1.7	-1.2 to -2.5	48
Attic forced ventilation 10 ACH night	1.4 to 1.9	-1.2 to -2.5	51
Room forced ventilation 50 ACH night	1.2 to 1.7	-2.2 to -3.4	37
Whole house forced ventilation 50 ACH night	1.2 to 1.7	-1.9 to -3.1	39
Night ventilation (rural)	*0.8 to 1.7*	*-1.8 to -2.9*	*35*
Roof insulation R 4	-0.2 to 0.6	-2.2 to -3.1	16
Ceiling insulation R 4	0.1 to 1.0	-1.9 to -2.9	26
External wall (outside surface) insulation R 0.5	0.5 to 1.3	-1.7 to -2.8	33
External wall (inside surface) insulation R 0.5	0.7 to 1.5	-1.8 to -2.8	34
Window external shading SF 0.75	0.2 to 0.9	-2.1 to -3.1	23
Window internal shading SF 0.75	0.6 to 1.4	-1.9 to -3.0	32
Attic forced ventilation 10 ACH night	0.8 to 1.6	-1.9 to -2.9	34
Room forced ventilation 50 ACH night	0.6 to 1.4	-2.9 to -3.9	29
Whole house forced ventilation 50 ACH night	0.6 to 1.3	-2.6 to -3.6	28

[a] Positive values indicate indoor operative temperatures above the 80% comfortable upper limits and negative values indicate indoor operative temperatures below the 80% comfortable upper limits.

The data are selected from Tables 6.12-6.29 (see Chapter 6: Sections 6.5.2-6.5.10). The comparison shows that roof insulation of R 4 gives the highest reductions in the daily maximum indoor operative temperatures and exceeding periods among the simulated techniques in both urban and rural climates. This technique has the highest cooling potential for the terraced house and should be prioritized. Reductions in the daily maximum indoor operative temperatures for the urban terraced house by the other techniques are in the following decreasing order: ceiling insulation of R 4, window external shading of SF 0.75, external wall (outside surface) insulation of R 0.5, window internal shading of SF 0.75, and external wall (inside surface) insulation of R 0.5. It should be noted that insulating the external walls increases the daily minimum indoor operative temperatures slightly. On the other hand, room forced ventilation at night gives the highest reductions in the daily minimum indoor operative temperatures, which contributes also to reduce the exceeding period by 15% in the urban climate. Whole house forced ventilation at the same air change rate reduces the daily minimum indoor operative temperatures less but would be efficient to cool more than one room, as discussed in Chapter 6: Section 6.5.10.

Table 7.2 implies that adding a single passive cooling technique to the night ventilated terraced house also does not improve the indoor thermal comfort sufficiently. Using multiple techniques will be required to do so. This is exemplified in two combinations of selected passive cooling techniques that were simulated in this study (Table 7.1 and see Chapter 6: Section 6.5.11). Combinations of other passive cooling techniques and considerations other than the thermal comfort improvement, for example costs and energy implications, should be addressed further in future studies.

7.2 Proposed Modifications to the Terraced House for Passive Cooling

7.2.1 The Proposals at Different Adaptation Levels

Based on the study findings, modifications to the existing terraced house to incorporate passive cooling techniques are proposed at three adaptation levels as follows:

Adaptation Level 1: Basic Adaptive Capacity and Low Modification Costs

The first adaptation level is considered to provide basic adaptive capacity to the terraced house occupants for thermal comfort and will require few modifications to the building at low costs. As before, the recommended basic technique is night ventilation. This may be realized through occupants' behavioural changes alone, i.e. to open windows at night, or it may require minor installations of insect screens and security grilles in order to solve some of the problems of night-time open windows. The expected air change rate with the outdoor air will be about 13-14 ACH at night.

Another option is to apply forced ventilation at night. Suggested methods are to install ventilation fans in the room of interest or at the central zone of the house if cooling more than one room is desired. For the former method, windows may be kept open or closed at night. However, for the latter method, it is expected that the cooling will be effective only if external windows of the room are open and air flow between the room and the central zone occurs. Internal walls with upper ventilation openings or louvered internal doors may assist the interzonal air flow. The suggested ventilation rate is about 30-50 ACH at night.

Most of the existing terraced houses are equipped with ceiling fans. It is thus assumed that increased indoor air speed to elevate indoor comfort temperatures during daytime can be obtained by using ceiling fans at no additional cost.

Adaptation Level 2: Multiple Adaptive Capacity and Moderate Modification Costs

The second adaptation level considers using multiple passive cooling techniques so that the adaptive capacity of the night ventilated house can be enhanced from the first level. This means that more than one technique, including night ventilation, will be used. It is expected to require moderate modification costs. If sufficient techniques are used, thermal discomfort is possibly eliminated throughout the day.

The recommended passive cooling techniques for the night ventilated terraced house are:

- Roof insulation or ceiling insulation
  Roof insulation is more effective than ceiling insulation. A higher thermal resistance improves the cooling effects for both types of insulation placement. The suggested insulation level is R 4, 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.

- Shading of external windows
  External shading is more effective than 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. However, outdoor absolute humidity may increase.

- External wall (outside surface) insulation
  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 low thermal resistance, i.e. R 0.5 or 0.5 m^2K/W, is suggested. The expected thickness of the insulation, which will add to the wall thickness, is small.

- Forced ventilation at night
  Forced ventilation may be applied by installing ventilation fans in the room or at the central zone of the house, as explained earlier.

- Shade trees
  Tall shade trees are more effective than low dense plants in lowering the ambient air temperature and providing a cooler microclimate. Shade trees may also shade the adjacent windows and building structures.

- Upper ventilation openings on external walls
  Upper ventilation openings on external walls are expected to assist heat and humidity dissipation even when windows are closed. Examples are to install ventilation holes on the walls, louvered windows and lattice windows just below the ceiling level.

- 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 vapour 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.

In particular, one of the key findings from the Chinese shophouse study is that reduction in the sky view factor of a courtyard reduces its air temperature. The sky view factor depends on the area and height of the courtyard while its solar control depends also on the courtyard width-to-depth ratio and orientation. We analyse the terraced house floor plans that are first introduced in Chapter 4: Section 4.1.2 in order to see the possibility of courtyard application

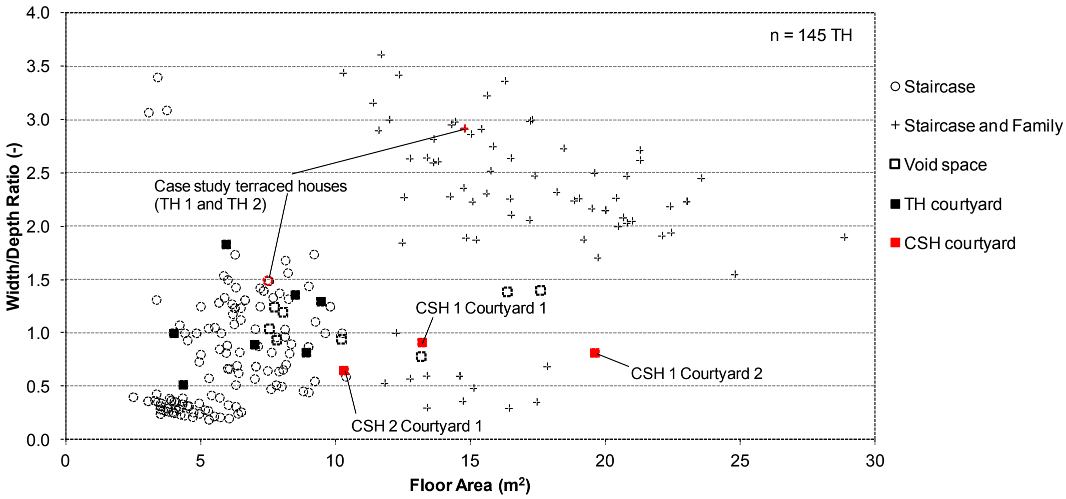


Figure 7.7. Classification of Malaysian terraced houses by floor area and width-to-depth ratio of the potential courtyard space.

in terraced houses. Double-storey terraced houses from the sample are analysed. Assuming a similar height and orientation for the terraced houses, the classification thus focuses on the area and width-to-depth ratio of the potential courtyard space.

Figure 7.7 shows that potential spaces in the terraced houses that could be modified to have courtyards of similar or smaller sizes and similar width-to-depth configurations as the front courtyards of the Chinese shophouses are mainly the staircase and void space. The existing courtyards in the terraced houses are also similar in size or smaller. The result implies that these existing two-storey voids, i.e. the staircase, void space and courtyard, is a practical choice for use as a nocturnal ventilative cooling source in the terraced houses in terms of their physical sizes. Further understanding of other factors that may govern the heat and mass transport phenomena inside the courtyard, for example thermal mass, surface properties and roof form is suggested.

Adaptation Level 3: Comprehensive Adaptive Capacity and High Modification Costs

The third adaptation level considers using most or all of the passive cooling techniques that are suggested above in order to provide comprehensive adaptive capacity to the terraced house occupants. Some overlapping techniques mean that the occupants have choices to employ different cooling techniques in different prevailing or desired circumstances to ensure thermal comfort at all times. For example, night ventilation may be obtained through open external windows, open windows to courtyards, room forced ventilation or whole house forced ventilation, as explained earlier. Since major alterations to the existing house will be required, it is expected that the modification costs will be high. Nevertheless, it is worth to note that in case of new houses, high additional costs may not be necessary to implement these passive cooling techniques. This is because some of the techniques, for example the courtyard, can be realized through design.

Further, at the neighbourhood and urban scales, modifications to provide cooler outdoor microclimates and mitigate urban heat islands will be beneficial to increase the cooling effects of the above techniques. If the urban microclimate resembles the rural climate, it is expected that the indoor operative temperature will be lowered by about 2°C or more. The cooling energy saving benefits will be huge since many urban houses will be influenced.

7.2.2 Estimation of the Cooling Energy Saving Benefits

One of the survey results determines that the household energy consumption for air conditioning is 6.71 GJ/year on average (see Chapter 4: Section 4.2.2). It is predicted that air conditioning will not be necessary to obtain thermal comfort and this amount of end-use energy can be saved if modifications to the existing terraced house at adaptation levels 2 and 3 (Section 7.2.1) are made. This amount of electricity is equivalent to 1864 kWh/year or approximately 155 kWh/month for one household. The nationwide energy saving will total about 9.3 million GJ/year or about 2.6 billion kWh/year assuming that 65%, i.e. the air conditioner ownership level found in the survey, of the existing brick terraced houses (2,134,609 units as of 2010 according to Department of Statistics Malaysia, 2012) will adopt the passive cooling techniques. It should be noted that the primary energy use required to generate this amount of electricity will be larger depending on the efficiency of the energy generation, and transmission and distribution losses.

Table 7.3 further estimates the annual financial savings that can be accrued due to the above cooling energy savings based on the current electricity tariff for domestic use in Malaysia (TNB, 2012). Two scenarios of electricity tariff are listed, i.e. (1) the current tariff with subsidized fuel for power generation; and (2) an increased tariff assuming that no subsidy is provided. The current subsidy of fuel for power generation in Malaysia is 38% (Ahmad *et al.*, 2011). The second scenario thus assumes the subsidized portion in addition to the current tariff.

Table 7.3 demonstrates that the potential financial savings for one household on the basis of the current tariff range from RM405.48/year to RM843.78/year depending on the category of monthly total electricity consumption for each household. The range translates into RM0.56 billion/year to RM1.17 billion/year for households nationwide. The ranges of financial savings increase to RM654.00/year to RM1360.94/year and RM0.91 billion/year to RM1.89 billion/year, respectively, if an increased tariff without fuel subsidy is assumed. The potential financial savings are also expected to be greater as the household air conditioner ownership level rises. It is predicted that the average savings will not likely fall into the categories of 400 kWh or less and below; the average total household electricity

Table 7.3. Estimation of the financial savings on electricity for air conditioning.

Category of household according to monthly total electricity use	Potential financial savings for the category per household[a] (RM/year)		Potential financial savings for the category nationwide[a, b] (RM billion/year)	
	Current tariff (with subsidy)	Increased tariff (without subsidy)	Current tariff (with subsidy)	Increased tariff (without subsidy)
200 kWh or less	405.48	654.00	0.56	0.91
300 kWh or less	544.68	878.52	0.76	1.22
400 kWh or less	700.44	1129.74	0.97	1.57
500 kWh or less	746.40	1203.87	1.04	1.67
600 kWh or less	764.52	1233.10	1.06	1.71
700 kWh or less	785.76	1267.36	1.09	1.76
800 kWh or less	805.56	1299.29	1.12	1.80
900 kWh or less	832.02	1341.97	1.15	1.86
901 kWh onwards	843.78	1360.94	1.17	1.89

[a] Electricity for air conditioning is assumed to be 155 kWh/month for one household.

[b] The number of households nationwide is assumed to be 1,387,496, i.e. 65% of the existing brick terraced houses as of 2010.

consumption found in the survey is more than 400 kWh. This means that the likely financial savings for households nationwide will exceed RM0.97 billion/year at the current electricity tariff for domestic use. At an increased tariff without subsidy, the corresponding savings may exceed RM1.57 billion/year.

Further studies to determine the modification costs to increase the adaptive capacity of the terraced houses for passive cooling will enable other economic evaluations, for example to estimate the net savings, rate of return and payback period of respective passive cooling techniques. From the government point of view, assessments of the fuel subsidy savings will be useful for other financial planning that may support the implementation of passive cooling techniques.

8

Conclusions

The aim of this doctoral thesis is to evaluate and propose application of passive cooling techniques to existing terraced houses in Malaysian urban areas for improving the indoor thermal comfort in naturally ventilated condition towards reducing cooling energy use. To achieve this goal, we implement the study to understand four key aspects, i.e. adaptive thermal comfort in hot-humid climate, existing households' behaviour and energy consumption for cooling, passive cooling techniques of vernacular houses and the effects of ventilative cooling in the terraced 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; combinations of some techniques are able to meet the indoor thermal comfort requirements. Modifications to the existing terraced house are proposed to increase its adaptive capacity for passive cooling and the cooling energy saving benefits are estimated. Section 8.1 summarizes these key findings. Further studies that will continue in this project and beyond are recommended in Section 8.2.

8.1 Key Findings of This Study

Review of Passive Cooling Studies

The review focuses on ventilative cooling, which is a well-accepted passive cooling technique used in hot-humid climate. In particular, night ventilation is effective for buildings of high thermal mass. The review shows that while a number of studies are available in the developing hot-humid regions, there is still lack of basic field data in many cases so that progress to develop passive cooling techniques is difficult to be made. Since the climatic condition typical of hot-humid regions differ greatly from other locations where many studies have been conducted, both basic and comprehensive studies are seen to be necessary in these regions. One of the recent interests is to evaluate the thermal performances of vernacular buildings using scientific methods since these buildings are rooted to the local context including the climate yet they are usually without proper documentation. It is derived that the suitable methods for this study would be to conduct field measurement in existing houses, including selected traditional vernacular houses and the terraced houses, followed by numerical simulation for further tests.

Building Occupants' Thermal Adaptation in Hot-Humid Climate

It is well recognized that in the adaptive comfort model, indoor comfort temperatures are climate-dependent but climate classification has not yet been attempted properly in studies that developed adaptive thermal comfort standards. In this sense, our review firstly shows that it might not be appropriate to adopt the existing adaptive comfort standards that were not developed specifically for hot-humid climate. Subsequently, this thesis clarifies the different adaptive comfort equations for three major climates, i.e. hot-humid, hot-dry and moderate, through a meta-analysis of the ASHRAE RP-884 database.

In particular, the thermal adaptation of occupants in the naturally ventilated buildings in hot-humid climate is different from the requirements given in the existing standards and also of the other climates in terms of:

- the relationship between indoor comfort temperature and outdoor air temperature
- the better temporal characterization of the outdoor air temperature in the equation
- the acceptable comfort temperature limits
- the effects of indoor air speed and humidity on comfort temperature

A new set of adaptive thermal comfort criteria is proposed for naturally ventilated buildings in tropical climates and hot-humid summer seasons of temperate climates. These criteria are used throughout this thesis to assess the passive cooling techniques. They may form a part of an energy-saving building standard that will be further developed for Malaysia.

Existing Households' Behaviour and Energy Consumption for Cooling

The national census in 2010 showed that 93% or more than 2.1 million units of the urban terraced houses were constructed using bricks for their outer walls. They are high thermal mass buildings that might benefit from nocturnal ventilative cooling. It is revealing to find in the surveys that few occupants applied night ventilation in the terraced houses. The key survey results are:

- Nearly 80% of the respondents usually opened windows from 10 a.m. to 6 p.m. but only 10% did so at night. Both air conditioner owners and non-owners practiced daytime ventilation similarly. The main reasons for not opening windows at night are insects and security, among others.
- The ownership levels of air conditioner in the terraced houses are 62% in 2004 (Survey 1) and 65% in 2009 (Survey 2). About 94% of the respondents installed air conditioner in the master bedroom. More than 50% of the owners used the air conditioner throughout the night. The average usage time is 7.6 hours per day in Survey 1 and 6 hours per day in Survey 2. The average temperature setting is 20.8°C. It is implied that most of them used air conditioner during sleep, though the reason for the low temperature setting was not investigated.
- The average yearly household energy consumption including electricity and gas among the respondents is 24.5 GJ/year. The total consumption by the respondents with air conditioner is 1.4 times that by non-owners. About a quarter, i.e. 24% or 6.71 GJ/year, of the total yearly energy consumption is attributed to air conditioning alone for the households with air conditioner. The high energy consumption for air conditioning is likely due to the long usage time and low temperature setting.

It is clear from the survey results that reducing air conditioner usage would be one of the most effective means to achieve energy-saving objectives in the urban terraced houses.

Effects of Nocturnal Ventilative Cooling in Existing Terraced Houses

From the review, we hypothesized that night ventilation, termed as nocturnal ventilative cooling, would be an effective passive cooling technique to improve the indoor thermal comfort in the master bedroom of the brick terraced houses. A full-scale field experiment was carried out in two typical terraced houses to examine the cooling effects of night-time open window conditions compared to other ventilation conditions. The main findings are:

- In all experimental cases, the indoor air temperatures in the night ventilated master bedroom are lower than those of the other ventilation conditions, i.e. daytime ventilation, no ventilation and full-day ventilation, throughout the day especially on fair weather days. Night ventilation lowers the maximum indoor air temperatures by 3.4-5.0°C and also delays the occurrence of the peak air temperatures by 1-3 hours compared to the outdoors. At night, indoor air temperatures in the night ventilated room are 1.7-2.0°C higher than the outdoors on average, likely due to the low ventilation rate at night. Using ceiling fans does not affect the room air exchange with the outdoor air much, though it is effective to increase the indoor air speed.

- With regard to the comfort temperatures, the 80% comfortable upper limits range between 27.6-30.1°C throughout the experimental period. Night ventilation provides more comfortable indoor operative temperature than the other ventilation conditions. Nevertheless, maximum indoor operative temperatures in the night ventilated room exceed the upper limits by 0.9-4.0°C on the afternoons of fair weather days. The high operative temperatures are likely caused by the incoming solar radiation through the windows and ceiling that was not insulated.
- In contrast, indoor operative temperature in the daytime ventilated room is above the 80% comfortable upper limits for 91% of the time. The low occurrence of comfortable operative temperature in the daytime ventilated room for the whole day might thus lead the actual households, who mostly practiced daytime ventilation, to use air conditioners at night.

The findings imply that night ventilation is a potential passive cooling technique for the terraced houses but the indoor thermal comfort is not acceptable yet. Other techniques would be required.

Passive Cooling Techniques of Vernacular Houses

The traditional Malay house is a well-ventilated detached building of timber structure usually seen in rural villages. The traditional Chinese shophouse is a narrow and deep-plan brick building situated in rows in relatively dense urban areas. Field measurement was carried out in these two types of vernacular houses. The main findings are:

The Traditional Malay Houses

- The front living halls of the two case study Malay houses are relatively cool when compared to other indoor spaces in the whole house. Their indoor air temperatures are 1°C or less higher than the corresponding outdoor air temperatures on average during daytime under open window conditions and 2°C or less at night under closed window conditions. No time lag between indoors and outdoors in terms of daily maximum and minimum air temperatures is seen.
- With regard to the comfort temperatures, the 80% comfortable upper limits range between 28.2-29.1°C (operative temperature) throughout the measurement period on fair weather days. The indoor operative temperatures exceed these comfort limits for the whole afternoon period by up to 4.0-5.7°C at the peak period. The evaluation agrees with the occupants' perception of thermal sensation.

- Large variations in the maximum indoor air temperatures are seen among the rooms in the whole house. One of the main factors that cause the variations is the presence or absence of ceiling boards under the zinc roof. The result implies that the zinc roof would require at least ceiling installation in order to reduce solar heat gain through the roof.
- Although outdoor absolute humidity is increased by high evapotranspiration of plants, moist soil and dew after sunrise, indoor absolute humidity is lower than the outdoors. The indoor humidity control is likely provided by permanent ventilation openings.
- It is concluded that the lightweight timber structures afford little heat modulation and the houses are basically porous to air infiltration even in closed window states. Under these circumstances, cooling of the indoor spaces for thermal comfort likely depends on cross ventilation, solar heat controls including shading of windows and walls by overhang and shade trees and the ceiling, and a cool microclimate. In particular, the relatively low outdoor air temperature at rural locations could be the essential cooling source for the lightweight houses.

The Traditional Chinese Shophouses

- Indoor air temperatures in the living halls that were adjacent to the front courtyards are lower than the immediate outdoors during daytime by up to 5-6°C. At night, the indoor air temperatures maintain similar values to the outdoors, even though external doors and windows were closed at night. The former is likely due to the cool storage effects of the high thermal mass structures. It is most interesting to see the effects in the living halls that were completely open to the courtyards.
- Despite the presence of outdoor wind, the corresponding indoor air speeds in the front courtyard-adjacent living halls are less than 0.1 m/s almost throughout the day. The result implies that both living halls obtained little cross ventilation even when the external door or windows were opened during daytime.
- With regard to the comfort temperatures, the 80% comfortable upper limits range between 29.5-30.6°C throughout the measurement period. The indoor operative temperatures are below these limits almost throughout the day; the exceeding periods are only 7-8%. The results imply that the thermal comfort conditions in the front courtyard-adjacent living halls are acceptable when the thermal adaptation for hot-humid climate is considered.
- The daily mean and minimum air temperatures in the front courtyards are the lowest compared to those of other indoor spaces in the Chinese shophouses. It is found that there are strong linear relationships between the sky view factors of the courtyards

and their daily maximum and mean air temperatures. Reduction in the sky view factor of a courtyard reduces its air temperature.
- The vertical thermal distributions in the front courtyards show that the air temperature increases with height in the afternoon. This temperature gradient causes a stable thermal stratification that likely prevents the hot outdoor air from entering the courtyards and indoor spaces during daytime. At night, the temperature gradient is not seen in the front courtyards; nocturnal ventilative cooling could be accelerated through the openings of the courtyards. The small front courtyards thus function as a night ventilation cooling source, or heat sink, to the surrounding living halls by virtue of their relatively small sky view factors that also provides good solar control.
- Another interesting finding is that indoor absolute humidity values in the front courtyard-adjacent living halls are almost equal to the outdoor absolute humidity. The result suggests that mass transfer of water vapour might occur throughout the day although vertical air exchanges of heat are minimized during daytime in the courtyards and indoor spaces. Further study is required to clarify this phenomenon.

Numerical Simulation of the Terraced House

One of the field experiment terraced houses was modelled using the TRNSYS and COMIS programs. Several passive cooling techniques including natural ventilation condition, thermal insulation, window shading and forced ventilation were simulated using weather data that represented an urban climate and a rural climate. The main findings are:

- Empirical validation of the base model terraced house shows that the mean bias errors for air temperature, operative temperature and absolute humidity range between -0.09°C and 0.35°C, -0.09°C and 0.32°C, and -1.04 g/kg' and -2.00 g/kg', respectively. The root mean square errors for the same variables are 0.31-0.51°C, 0.46-0.58°C and 1.10-2.04 g/kg', respectively. The model is satisfactorily accurate in describing the thermal behaviour of the terraced house. However, humidity modelling is a limitation of this study.
- With regard to the comfort temperatures, the 80% comfortable upper limits range between 29.3-29.8°C in the urban climate (Johor Bahru) and 28.3-28.6°C in the rural reference climate (Senai). This means that even by considering thermal adaptation to the urban climate, the comfort temperature upper limit could be raised by only about 1°C compared to the rural reference climate.
- In the urban climate, indoor operative temperatures in the daytime ventilated room are higher than the 80% comfortable upper limits for 88% of the time and the maxima are 2.9-3.9°C above the same limits. The exceeding period is reduced to 52% while the daily maximum indoor operative temperatures are 1.4-1.9°C above

the limits in the night ventilated room. Thermal comfort in the rural reference climate is deemed more acceptable than in the urban climate when the same techniques are used.

- It is predicted that indoor operative temperatures in the night ventilated room in the urban climate are 1.4°C higher than those in the rural climate at the same outdoor air temperature during daytime. It signifies the influence of the urban-rural climatic differences on the nocturnal ventilative cooling effects. Further, higher night-time indoor operative temperatures are encountered in the night ventilated room in the urban climate likely due to the relatively high outdoor air temperature, i.e. heat island occurrence, but not reduction in ventilation rate in comparison with the rural climate.
- The results of the simulation test cases show that the passive cooling techniques that are effective to improve the indoor thermal comfort of the night ventilated master bedroom are roof insulation, ceiling insulation, external wall (outside surface) insulation, window external shading, room forced ventilation at night and whole house forced ventilation at night. The tested combinations of these passive cooling techniques provide thermal comfort in the night ventilated room in the urban and rural climates if occupants' thermal adaptation for hot-humid climate is considered. Indoor operative temperatures in the daytime ventilated room do not meet the comfort limits in all of the test cases including the cases of combined techniques.
- With the combined techniques, indoor operative temperatures in the night ventilated room in the urban climate are 2.4°C higher than those in the rural climate at the same outdoor air temperature during daytime. The larger urban-rural differences imply that the same passive cooling techniques are more effective in the rural climate than in the urban climate. It will be essential to mitigate urban heat islands and improve urban climatic and atmospheric conditions to increase the effectiveness of passive cooling techniques in urban houses.

Proposed Application of Passive Cooling Techniques

The above results are compared with the existing thermal conditions of the terraced house. Potential passive cooling techniques that are identified from the vernacular houses and results of the numerical simulation are proposed to be implemented in the terraced house through building modifications. The key points are:

- The comparison results confirm that the basic passive cooling technique for the brick terraced houses would be night ventilation.
- Buildings of lightweight structures would perform worse in urban areas than in rural areas especially in their peak indoor temperatures due to the relatively hot outdoor

air in urbanized locations. It would be fundamental to lower the outdoor air temperature in urban sites such as by adopting the rural microclimatic controls and mitigating urban heat islands to increase the cooling effects in the terraced houses.

- The nocturnal ventilative cooling effect in the Chinese shophouses achieved through small courtyards is better than in the terraced houses with night-time open windows. Thus, courtyards may replace the need to open windows at night for night ventilation in the terraced houses. Potential spaces to be modified to accommodate similar small courtyards in the terraced houses are the existing two-storey voids, i.e. the staircase, void space or existing courtyard. Other methods of realizing night ventilation are forced ventilation in the room of interest or in the central zone of the house if cooling more than one room is desired.
- Modifications to the existing typical terraced house are proposed to increase its adaptive capacity for passive cooling at three adaptation levels. It is expected that indoor thermal comfort requirements can be met through the utilization of multiple passive cooling techniques.
- The potential cooling energy saving through eliminating the use of air conditioners is expected to be 6.71 GJ/year or 1864 kWh/year on average for one household. The nationwide energy saving will total about 9.3 million GJ/year or about 2.6 billion kWh/year by assuming the current air conditioner ownership level for the existing brick terraced houses. Consequently, it is estimated that the likely financial savings for households nationwide will exceed RM0.97 billion/year at the current electricity tariff for domestic use. At an increased tariff without subsidy, the corresponding savings may exceed RM1.57 billion/year.

8.2 Further Studies

In this thesis, we do not deal with thermal comfort for night-time sleep environments. We also did not investigate the thermal sensation of occupants in the terraced houses when they used low temperature setting for air conditioners in bedrooms and the reason that they used it. It will be useful to understand the thermal adaptation of occupants in naturally ventilated bedrooms compared to air-conditioned bedrooms. It is also relevant to study the thermal comfort requirements prior to sleep time since thermal discomfort during the initial segment of sleep is said to be more disruptive to sleep quality than the same thermal exposure during later sleep segments.

Moreover, in terms of the proposed adaptive thermal comfort criteria for naturally ventilated buildings in hot-humid climate, further studies are recommended, particularly to determine suitable percentages of occupants in comfort, to develop an increased air speed allowance and to verify the applicability of the criteria to the driest month in the tropical savannah climate.

Two interesting phenomena in the courtyards that need further study are the stratified heat and mass (water vapour) transport mechanisms. For interzonal flow study, CFD simulation is recommended. The base model of this study can be readily coupled with CFD models in the future. Further understanding of factors that may govern the thermal stratification and cooling effects inside the courtyard other than the sky view factor of the courtyard is also useful. Subsequently, these factors can be tested for courtyards in the terraced houses through simulation to determine the effective courtyard configuration and properties.

The passive cooling techniques included in this study are by no means exhaustive. Internal heat gain is also not included. Further techniques, internal heat gains and different building orientations are some of the aspects that can be studied efficiently through simulation of the same base model. It may be worth to also model other typical groups of the terraced houses, for example the single-storey terraced house. Other areas of study that will be beneficial to increase the thermal performance of the passive cooling techniques are urban heat island mitigation and outdoor microclimatic control.

Further, humidity control techniques are not dealt with in-depth in this study. It is also found that comprehensive building thermal and energy simulation programs may not be able to model the indoor humidity levels accurately in naturally ventilated conditions. These could be critical areas of study for indoor high-humidity conditions in the tropics.

Economic studies are encouraged to evaluate the cost and benefit effectiveness in modifying existing terraced houses for passive cooling. Such financial estimations may attract the actual implementation of the techniques and help decision-making on modification in stages by households. At the governmental level, assessments of the energy savings and fuel subsidy savings will aid national planning towards overall carbon mitigation measures.

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