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(Attached Form 6)

学位論文の要旨（論文の内容の要旨）
Summary of the Dissertation (Summary of Dissertation Contents)

論　文　題　目
Dissertation title
Application of Passive Cooling Techniques to Improve Indoor Thermal Comfort of Modern Urban Houses in Hot-Humid Climate of Malaysia

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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.