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Application of passive cooling techniques in vernacular houses to modern urban houses: A case study of Malaysia

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Abstract

The main purpose of this paper is to determine potential vernacular passive cooling strategies for improving thermal comfort of modern urban houses in hot-humid climate of Malaysia. Field measurements were carried out in two traditional timber Malay houses and two traditional masonry Chinese shophouses to investigate their indoor thermal environments and passive cooling techniques. The results of the former showed that the indoor air temperatures were higher than the outdoor air temperatures by 1 °C during daytime under open window conditions and 2 °C at night under closed window conditions on average. The results of the latter revealed that indoor air temperatures adjacent to small courtyards were lower than immediate outdoors by up to 5-6 °C during daytime; at night, the indoor air temperatures maintained values similar to the outdoors. The small courtyards were effective to enhance night ventilation and nocturnal radiant cooling in the high mass shophouses. When assessed using an adaptive thermal comfort equation for hot-humid climates, the periods of indoor operative temperatures exceeding the 80% comfort upper limit in the Malay houses, Chinese shophouses, daytime ventilated and night ventilated terraced houses were 47%, 7-8%, 91% and 42%, respectively on fair weather days. By comparing these evaluations and relationships between indoor and outdoor thermal conditions of all houses, potential passive cooling strategies for the existing terraced houses including night ventilation, roof/ceiling insulation, window/wall shading, courtyard/forced ventilation, and microclimate and urban heat island mitigation were discussed.

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1. Introduction

It is generally believed that vernacular buildings have withstood time and are subtly crafted over generations in response to experience of conditions and use including the local climate and human comfort needs using passive systems (Oliver, 2006). Therefore, recent researchers were devoted to analyze the performance of traditional techniques adopted in and around vernacular buildings in order to derive principles for the use in modern urban houses (Rapoport, 2006). Traditional cooling techniques are considered to be particularly important because energy consumption by air conditioning has been rapidly increasing over the last few decades in the hot-humid climates like Indonesia.

This study aims to determine potential vernacular passive cooling strategies for improving indoor thermal comfort of modern urban houses in Malaysia by learning the traditional wisdoms seen in and around their vernacular buildings. Two fine examples of Malaysian vernacular architecture include the traditional Malay house and the traditional Chinese shophouse. The traditional Malay house is known as a well-ventilated detached building of timber structure usually seen in rural villages while the traditional Chinese shophouse is a narrow, deep-plan brick building situated in rows in relatively dense urban areas.The primary objectives of this study are dual, which include:

1. To investigate indoor thermal environments of the above-mentioned vernacular houses (traditional Malay house and traditional Chinese shophouse) and their passive cooling techniques;
2. To discuss potential application of the vernacular passive cooling techniques to modern urban houses for improving indoor thermal comfort in naturally ventilated condition.

The target modern houses are brick terraced houses, which form majority of the existing urban housing stock in Malaysia; the percentage of terraced houses in 2010 was 42% (DSM, 2012). Due to year-round uniformity of climatic conditions of lowland cities in Malaysia, it is assumed that there was little seasonal variation among the different measurement months and the results on fair weather days are comparable.

2. Field measurement in traditional Malay houses

2.1. Case study houses and measurement methods

The first 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 1). Pontian is located about 40 km to the west of the city of Johor Bahru in Peninsular Malaysia. Both houses were considered typical traditional Malay houses and shared the typical Malaysian rural village setting with many trees in their surroundings. Thus, the average outdoor air temperature is basically a few degrees lower than that of urban areas.

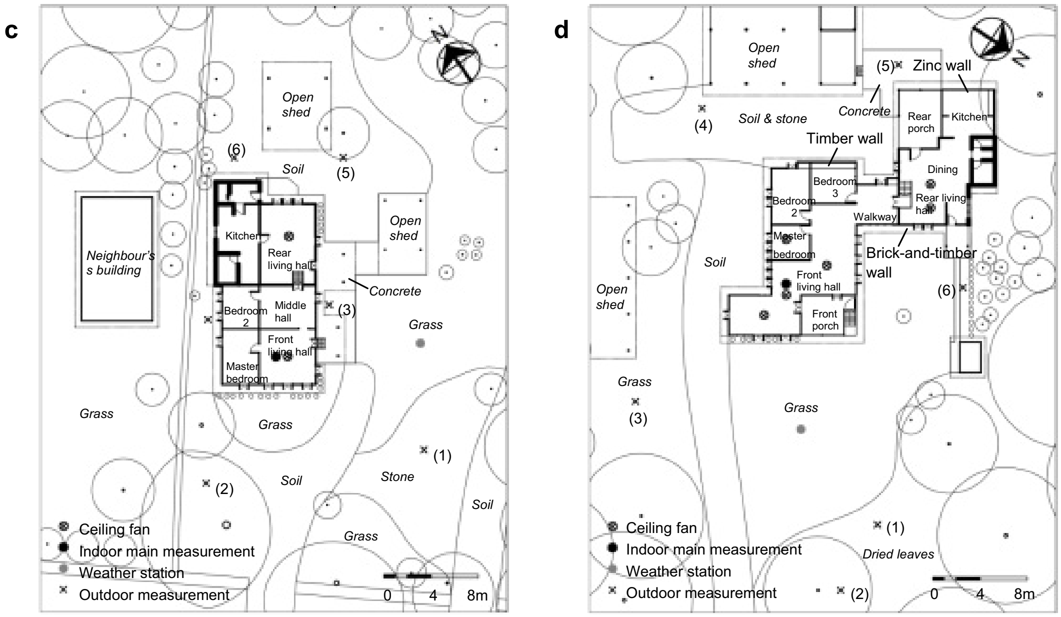

Fig. 1.The case study Malay houses.(a) Exterior view of MH 1; (b) Exterior view of MH 2; (c) Plan of MH 1; (d) Plan of MH 2.

They had timber structures elevated more than 1 m above the ground for the front parts of the houses (front living hall and all bedrooms). The rear parts of both houses were of brick-and-timber structures on the ground (rear living hall, dining, kitchen and bathroom) (Figure 1c-d). The roofing material was zinc; traditional thatch roof was not used. Both MH 1 and MH 2 were installed with ceiling in the front living halls and master bedrooms.

Measurements of all physical thermal comfort variables were taken at 1.5 m height above floor in the front living halls of the two houses (Figure 1c-d). The floor-to-ceiling heights of the halls are 2.7 m in MH 1 and 2.9 m in MH 2. Air temperature was also measured in all other rooms and at various outdoor locations of both houses. 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. A detailed description of the instruments used including the accuracy of sensors is presented in Toe and Kubota (2013a). All measurements were logged automatically at 10-minute intervals. The household sizes were seven persons for MH 1 and five persons for MH 2. Both houses were occupied throughout the measurement period.

2.2. Results and Discussion

Figure 2 presents the measured air temperatures and humidity in the front living halls of MH 1 and MH 2 on fair weather days. As shown, maximum outdoor air temperatures are 31-33 °C while outdoor relative humidity is always above 60%. Daily global horizontal solar radiation ranges from about 4000-5900 Wh/m2 on these days. In general, the indoor air temperatures in both halls follow the pattern of the outdoor air temperatures without time lag, as expected of the lightweight timber structures with low airtightness. The 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. It was noted that both households regularly opened windows during daytime when they were in and closed windows at night. 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 (Figure 2a).

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 2b). The higher mean radiant temperature seen in the front living hall of MH 2 implied that the radiant heat likely caused its slightly higher indoor air temperature compared to MH 1 (Toe and Kubota, 2013a).

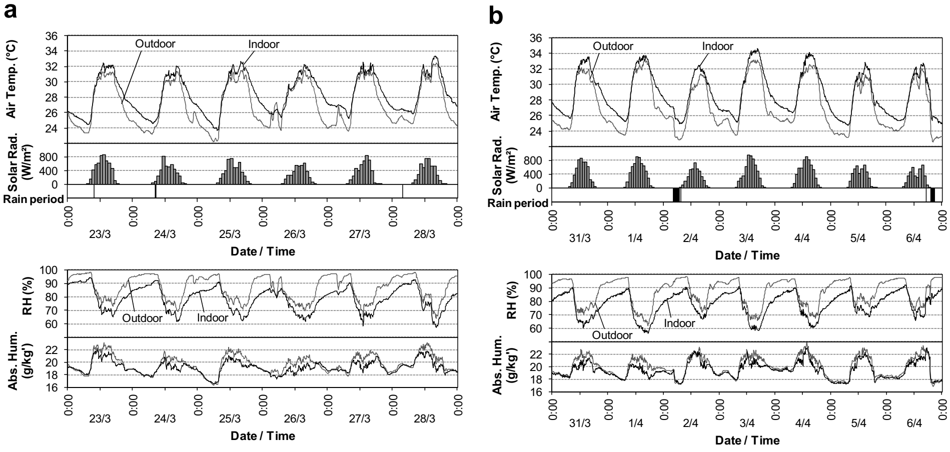

Fig. 2.Temporal variations of the measured air temperature and humidity in the front living halls and the corresponding outdoor conditions.(a) MH 1; (b) MH 2.

In terms of humidity, Figure 2 shows 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). Nevertheless, the daytime absolute humidity is 20-23 g/kg' indoors. Under the high indoor air temperature and indoor humidity ratio (>16 g/kg'), cross ventilation and/or ceiling fan were used by the occupants in both houses most likely to improve the indoor thermal comfort by evaporative heat loss.

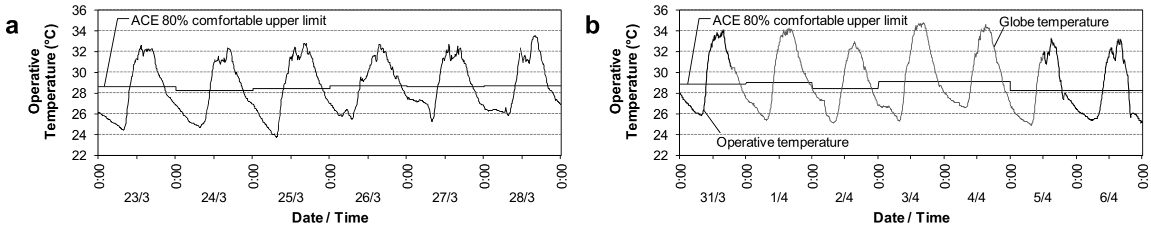

Fig. 3. Temporal variations of indoor operative temperature in the front living halls and the corresponding temperature limit for thermal comfort. (a) MH 1; (b) MH 2. In figure (b), the measured globe temperature is shown in grey line to substitute for the unavailable operative temperature.

Figure 3 evaluates the indoor operative temperatures in the front living halls of MH 1 and MH 2 for thermal comfort on the basis of an adaptive comfort equation (ACE) developed by the authors for naturally ventilated buildings in hot-humid climates (Toe and Kubota, 2013b). The 80% comfortable upper limit in Figure 3 is drawn on the basis of the daily mean outdoor air temperature that was measured by the weather station. The resulting limit ranges between 28.2-28.7 °C on the fair weather days for MH 1 and 28.2-29.1 °C for MH 2. The indoor operative (or globe) temperatures in both halls basically exceed the 80% upper limit for the whole afternoon period (Figure 3). At the peak period, the indoor operative (or globe) temperatures are 4.0-4.8 °C and 4.6-5.7 °C above the limit in MH 1 and MH 2, respectively. The exceeding periods are 47% in both houses on these fair weather days.

3. Field measurement in traditional Chinese shophouses

3.1. Case study shophouses and measurement methods

The second field measurement was conducted in two adjacent traditional Chinese shophouses (CSH 1 and CSH 2) located in the core heritage zone of Malacca, Malaysia in October 2011 (Figure 4). The buildings were originally constructed around the Dutch colonial era in the 19th century and restored in 2004 by the National University of Singapore (NUS) to function as an academic centre. They were occupied by two staff members on alternate weekdays from 10 a.m.-5 p.m. during the measurement period. CSH 1 had three courtyards while CSH 2 had two courtyards (Figure 4d). 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. Roof overhangs were present above the courtyards for rain and solar radiation protection. 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 gravelled floor surface without any plant (Figure 4b-c). 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. Ceiling fans were installed in most rooms but were rarely used. Air conditioner was not installed in both buildings. 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.

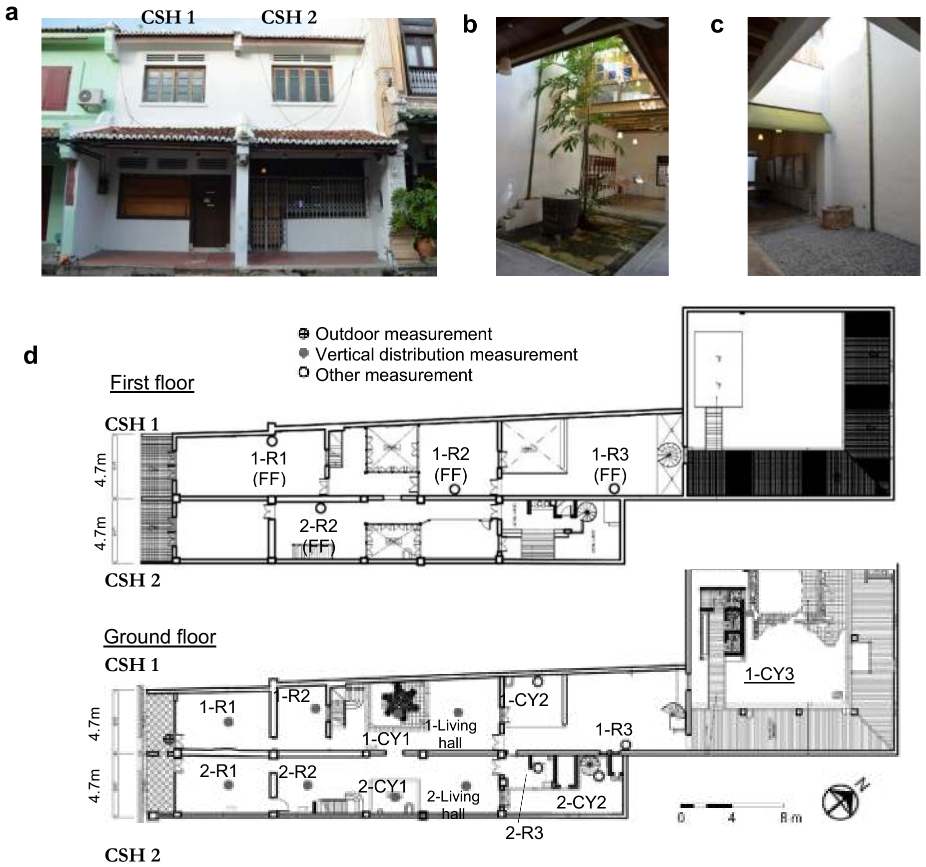

Fig. 4.The case study Chinese shophouses. (a) Exterior view; (b) Front courtyard of CSH 1 (1-CY1); (c) Front courtyard of CSH 2 (2-CY1); (d) Floor plans (with permission of TTCLC, National University of Singapore).

Measurements of all physical thermal comfort variables were taken at 1.5 m height above floor at the centre of the courtyard-adjacent living halls in both Chinese shophouses (Figure 4d). As shown in Figure 4b-d, there was no partition between the front courtyards and encircling spaces on the ground floor, including the said living halls. The floor-to-ceiling heights are about 4 m on the ground floor and about 3.5 m on the first floor. Further, vertical distributions of temperatures were investigated at four points on the ground floor in each shophouse including at the front courtyards (CY1) (Figure 4d). Air temperature and relative humidity were also measured in several rooms on both floors. A weather station (Campbell Scientific C-CR800) was placed on a grass area located about 0.5 km away from these shophouses. A detailed description of the instruments used is presented in Kubota et al. (2014). All measurements were logged automatically at 10-minute intervals.

3.2. Results and Discussion

Figure 5 shows the measured air temperatures and humidity in the front courtyard-adjacent halls at 1.5 m height above floor. The outdoor air temperature in this figure is that obtained at the veranda located in front of CSH 1 (Figure 4d). 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 (Figure 5). As shown, the maximum outdoor air temperatures are about 34-36 °C while the nocturnal outdoor air temperatures are about 26-28 °C. Daily global horizontal solar radiation at the weather station ranges from about 4900-6000 Wh/m2 on these days.

Indoor air temperatures in both living halls are lower than the outdoors during daytime by up to 5-6 °C mainly due to thermal mass effect (Figure 5). At night, the indoor air temperatures maintain similar values to the outdoors. On the other hand, relative humidity is above 60% throughout the day in the two living halls. 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. Daytime relative humidity in CSH 1 ranges from 65-70% while nocturnal relative humidity in the same room is about 75-85%.

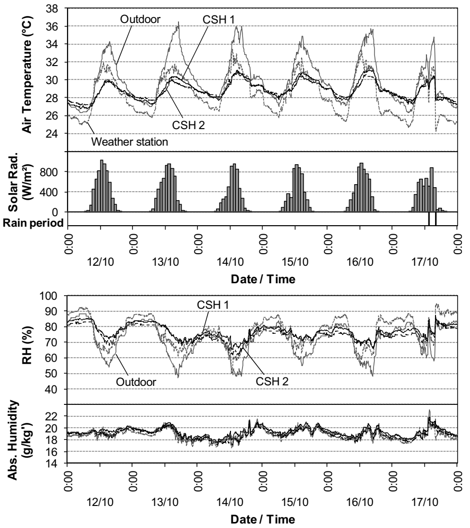

Fig. 5. Temporal variations of the measured air temperature and humidity in the front courtyard-adjacent living halls of CSH 1 and CSH 2 and the corresponding outdoor conditions.

Figure 6 evaluates the indoor operative temperatures in the front courtyard-adjacent living halls of CSH 1 and CSH 2 using the aforementioned ACE (Toe and Kubota, 2013b) and immediate outdoor air temperature. The 80% comfortable upper limit ranges from 29.8-30.6 °C on fair weather days. As shown, the overall period of indoor operative temperatures exceeding the 80% comfortable upper limit on the fair weather days are only 7% and 8% in

CSH 1 and CSH 2, respectively. Maximum deviations of the peak indoor operative temperatures above the 80% upper limit are only 0.5 °C. The result implies that the indoor thermal conditions in the said spaces are comfortable when thermal adaptation in hot-humid climate is considered.

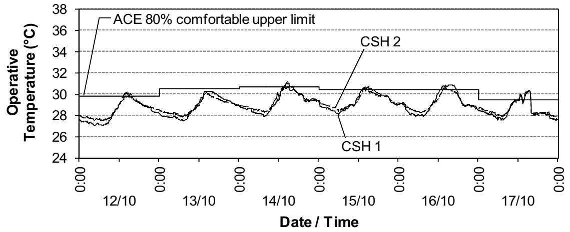

Fig. 6. Temporal variations of indoor operative temperature in the front courtyard-adjacent living halls of CSH 1 and CSH 2 and the corresponding temperature limit for thermal comfort.

4. Comparative assessment with modern terraced houses

4.1. Previous Field Experiment in Terraced Houses

A previous field experiment was conducted by the authors in two adjacent terraced houses in Johor Bahru, Malaysia from June to August 2007 to examine the effects of various ventilation strategies including daytime ventilation and night ventilation (Kubota et al., 2009). The houses were constructed of brick and concrete, and had elongated floor plans that measured 6.7 m by 13.1 m each (Figure 7). The entire houses were not insulated. Daytime ventilation refers to opening of all windows from 8 a.m.-8 p.m. while night ventilation refers to opening of all windows from 8 p.m.-8 a.m. In particular, daytime ventilation emulates the window opening behaviour of existing households that were observed in the previous survey, while night ventilation was found to provide the lowest indoor air temperatures (Kubota et al., 2009).

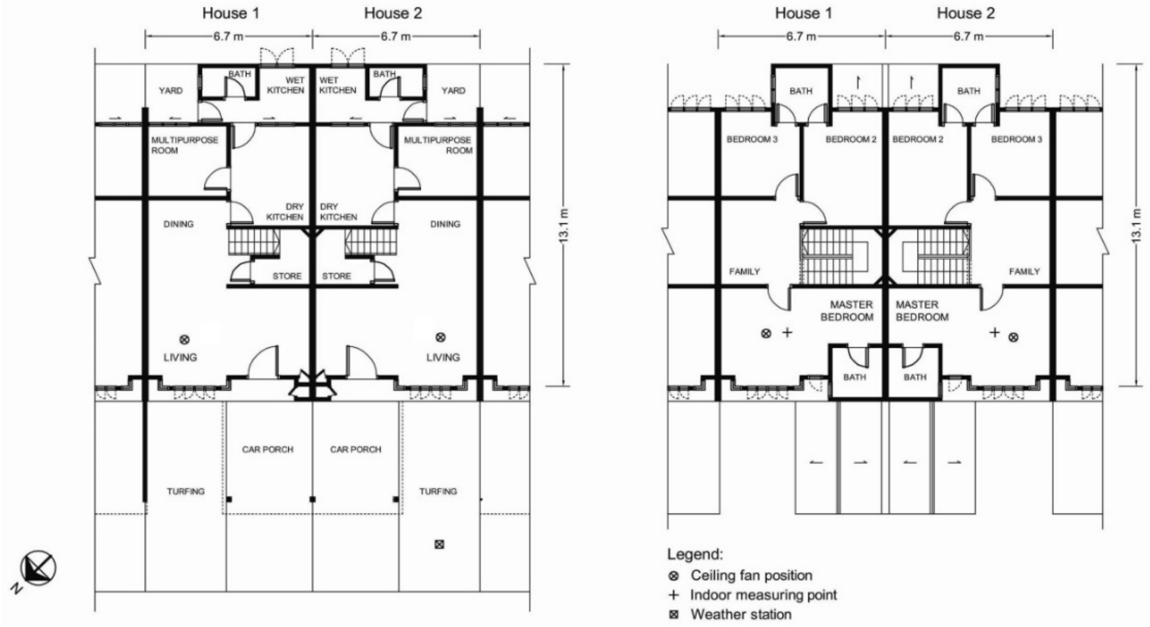

Fig. 7. Floor plans of the case study terraced houses. Source: Kubota et al., 2009

4.2. Comparison Results and Discussion

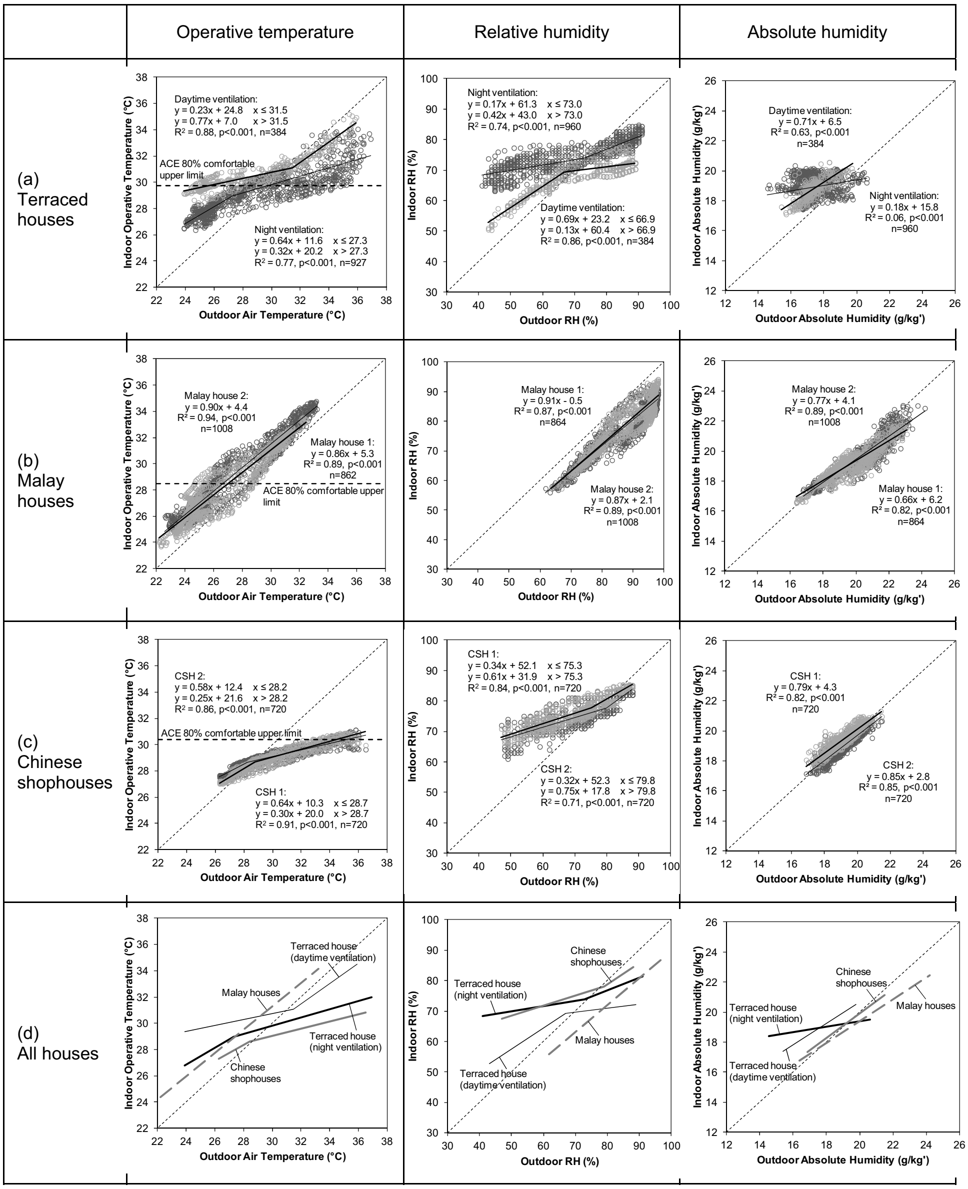

Figure 8. Relationships between indoor and outdoor temperatures, relative humidity and absolute humidity. (a) Terraced houses; (b) Malay houses; (c) Chinese shophouses; (d) All houses.

Figure 8a-c presents scatter plots of the said three variables against outdoor conditions on fair weather days. The measured data in the living halls represent the indoor conditions in case of the Malay houses and Chinese shophouses while the measured data in the master bedrooms represent those of the terraced houses. Figure 8a reveals that the indoor-outdoor temperature relationships are segmented for daytime ventilation and night ventilation in the terraced houses, most likely due to the change in open window conditions and thermal mass effect. The regression line for night ventilation predicts lower indoor operative temperature compared to daytime ventilation. Nevertheless, it predicts indoor temperature that is about 2-3 °C higher than the outdoors before the break-point, which is night-time condition. Figure 8a further shows the 80% comfortable upper limit of 29.7 °C that is obtained from the ACE using the mean outdoor air temperature of the measurement period. As shown, even when night ventilation is applied, the measured operative temperatures exceed the upper limit, especially after the break-point, which is daytime closed window condition.

The indoor operative temperatures in the Malay houses have linear relationships with the outdoor air temperatures, likely due to the lightweight structures and being porous to air infiltration even in closed window states (Figure 8b). The regression lines show that the indoor temperatures follow the outdoors closely and are always 1-2 °C higher than the outdoors. Meanwhile, the regression lines for the Chinese shophouses are segmented and similar to that of the night ventilated terraced house, although external windows were closed at night in case of the Chinese shophouses (Figure 8c). Further, indoor operative temperatures at high outdoor temperatures in the Malay houses and Chinese shophouses do not scatter as wide as those of the terraced houses (Figure 8a-c). The results imply that solar controls in the traditional houses are likely more effective.

Figure 8d summarizes the regression lines that are obtained from Figure 8a-c. Overall, 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, which are mainly daytime conditions. The high thermal mass structure of the terraced houses might not necessarily be worse than the lightweight structure, i.e. the traditional Malay houses, in keeping the daytime indoor temperatures low relative to the outdoor temperature. It is clear that the terraced house is even cooler in night ventilation condition. Nevertheless, it is expected that the lightweight structure would be cooler at night. Moreover, the solar heat control in the Malay houses is possibly better than that of the existing terraced houses. The solar control techniques that are found in the Malay houses include shading by roof overhang and shade trees. It is also noteworthy that the outdoor air temperature at the terraced house site falls in a higher range than that at the Malay house sites, probably due to various microclimatic and urban heat island effects (Toe and Kubota, 2013a). The latter is lower than the former by 1.7 °C on average. The regression line for the Chinese shophouses constantly predicts lower indoor operative temperature than that for the night ventilated terraced house (Figure 8d). 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 structural 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.

5. Conclusions and proposed application of vernacular passive cooling techniques

The main purpose of this study is to determine potential vernacular passive cooling strategies for the existing terraced houses. For the terraced houses, night ventilation would reduce the thermal discomfort experienced by existing households who used daytime ventilation but it is insufficient to provide indoor thermal comfort throughout the day. Key findings from the field measurements are summarized in the following points:

1. The indoor air temperatures in the traditional Malay houses are higher than the outdoor air temperatures by 1 °C during daytime under open window conditions and 2 °C at night under closed window conditions on average. The indoor operative temperatures in both houses exceed the ACE 80% comfortable upper limit during most of the daytime; the exceeding periods are 47%. Nevertheless, the solar heat control in the Malay houses is better than that of the existing terraced houses. The solar control techniques include shading by roof overhang and shade trees. It was also found that the outdoor air temperature at the Malay house sites is generally lower by 1.7 °C on average than that at the terraced house site, probably due to various microclimatic factors and less urban heat island effects.
2. For the traditional Chinese shophouses, indoor air temperatures adjacent to small courtyards are lower than the immediate outdoors during daytime by up to 5-6 °C. At night, the indoor air temperatures maintain values similar to the outdoors. The indoor thermal conditions are considered comfortable for most of the measurement period (92-93%) based on the evaluation using the ACE. The small courtyards are effective to enhance night ventilation and nocturnal radiant cooling in the high mass shophouses.

3. In terms of indoor and outdoor temperature relationships, the regression line for the Malay houses predicts higher indoor operative temperature than those predicted by the regression lines for the terraced houses in daytime conditions. Meanwhile, the regression line for the Chinese shophouses constantly predicts lower indoor operative temperature than that for the night ventilated terraced house.

Based on the above observations and comparative assessment, the potential passive cooling strategies (modifications) for the existing terraced houses are illustrated in Figure 9. The detailed descriptions are summarized as follows:

a. Night ventilation: As described above, application of night ventilation is one of the most promising passive cooling strategies for the terraced houses of high thermal mass structures. It has been reported that night ventilation alone can reduce the peak indoor air temperature by 2.5 °C and nocturnal air temperature by 2.0 °C on average compared to the current daytime ventilation (Kubota et al., 2009).
b. Roof/ceiling insulation: The existing terraced houses are not insulated. Hence, it is apparent that installation of thermal insulation would reduce the indoor operative temperature significantly. In particular, as seen from the case study of the Malay houses, insulation for roof or ceiling would be important since the solar altitude during daytime is always high in Malaysia.

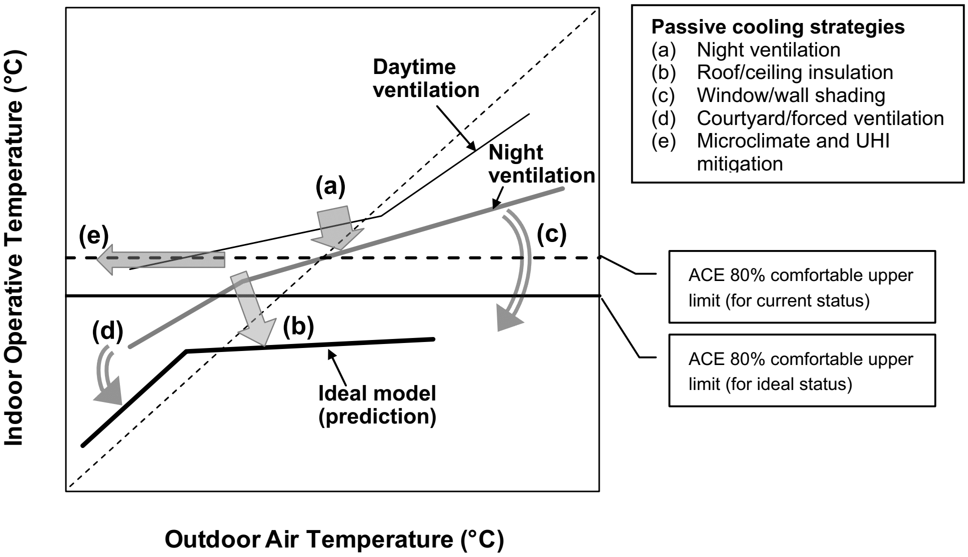

Fig. 9. Potential passive cooling strategies for existing terraced houses in Malaysia.

c. Window/wall shading: As shown in Figure 8a for instance, the indoor operative temperature at higher values, i.e., at the upper end of the outdoor air temperature, in the terraced houses is more widely scattered compared to those in the Malay houses and Chinese shophouses. This is likely caused by the increase in indoor heat from solar radiation through unshaded parts of the windows/walls as well as ceiling/roof. Therefore, it would be possible to reduce the peak air temperatures by applying proper shading such as roof overhang and strategic shade trees to the windows and walls as observed in the Malay houses.
d. Courtyard/forced ventilation: The nocturnal indoor operative temperatures in the terraced houses are still 2-3 °C higher than the outdoor air temperature even under open window condition. One way to reduce the nocturnal indoor air temperature to the outdoor level is to apply courtyard to the building as seen in the Chinese shophouses, though major modification may be required. An alternative way is to install exhaust fan in the target room or at a higher place such as the atrium above the staircase to ventilate the whole house during night-time. These strategies would enhance nocturnal structural cooling and therefore reduce the indoor air temperature not only at night but also during daytime on the following day.

e. Microclimate and urban heat island mitigation: As seen in the case studies of the Malay houses, outdoor air temperature in a rural setting can be a few degrees lower than that of an urban area. Further, the cooling effects of surrounding shade trees were observed at the Malay house sites. These strategies may be beyond building design controls, i.e., passive cooling techniques, but it is worthwhile to note the effects of these mitigation measures on indoor thermal conditions.

The thick line (in black) in Figure 9 indicates the predicted indoor-outdoor temperature relationship of an ideal model that reflects the above-proposed passive cooling strategies. The model assumes lower outdoor air temperature and therefore the ACE comfortable upper limit is decreased accordingly. Nevertheless, it is anticipated that if the above-mentioned modifications are applied to the existing terraced houses, then it is possible to meet the required comfort limit throughout the day.

Acknowledgements

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