RESULTS AND DISCUSSION

Complete Natural Ventilation Strategy

Figure 4 presents the simulated indoor air temperatures in the master bedroom for the four natural ventilation conditions that represent night ventilation, daytime ventilation, no ventilation and full-day ventilation. It is noted that temporal variations of indoor temperatures in each simulation have similar patterns over the 10-day analysis period. Thus, results are shown in statistical summaries for the whole period. As expected, night ventilation provides the lowest indoor air temperatures among the tested open window conditions (Figure 4). This is due to the nocturnal ventilative cooling through open windows and thermal mass effect of the cooled building structures that lowers the night-time and peak indoor temperatures of the following day. Daily maximum (95th percentile) and minimum (5th percentile) indoor air temperatures in night ventilated condition are 1.7 °C and 1.3 °C lower than those of daytime ventilation, respectively. Nevertheless, the daily minimum air temperature in the night ventiled room is still 2.7 °C higher than the outdoors.

Further passive cooling techniques are applied consecutively as shown in Figure 5 in addition to night ventilation and daytime ventilation, respectively. The most effective technique in reducing the daily maximum air temperature in night ventilated condition is roof insulation; the said temperature is decreased by 0.9 °C compared to applying night ventilation only (Figure 5a). Most of the solar heat gain in the master bedroom, which is on the first floor, probably comes through the roof due to its relatively large surface area and high noon solar altitude at the location. With less heat gain during the day and a cooler adjacent attic space for the whole day, the building structures maintain cooler and serve to reduce the minimum air temperature as well. Techniques that reduce solar radiation through roof into the building would be important. In fact, high reflectivity roof coating reduces the mean indoor air temperature most among all of the techniques in Figure 5a, i.e. by 0.6 °C. The high reflectivity coating probably improves nocturnal cooling additionally by virtue of the less heated roof surface on exposure to the sun and absence of thermal insulation at night. Nevertheless, all of the solar control techniques are

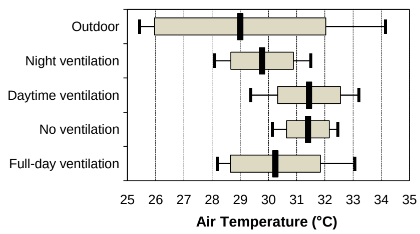

Figure 4 Statistical summary (5th and 95th percentiles, mean and ± one standard deviation) of simulated indoor air temperatures in different natural ventilation conditions for complete NV strategy.

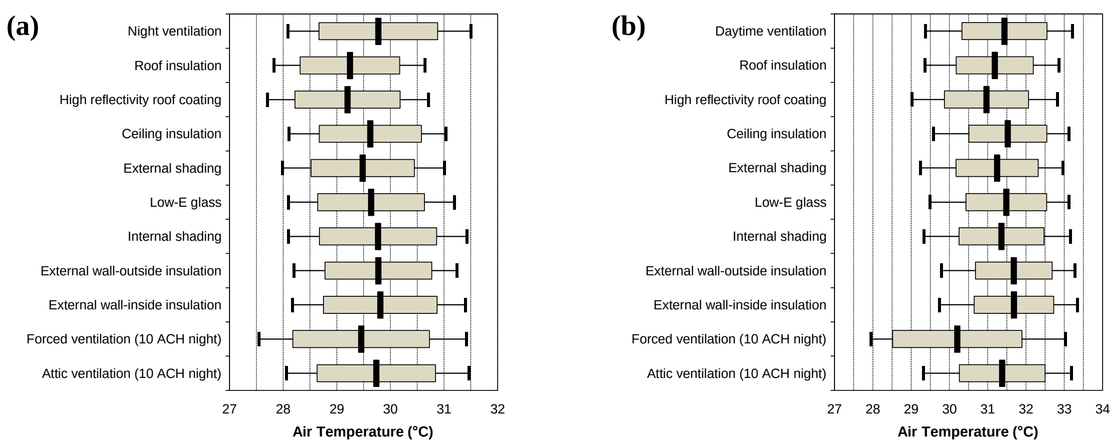

Figure 5 Statistical summary (5th and 95th percentiles, mean and ± one standard deviation) of simulated indoor air temperatures in (a) night ventilated and (b) daytime ventilated conditions with respective passive cooling techniques for complete NV strategy.

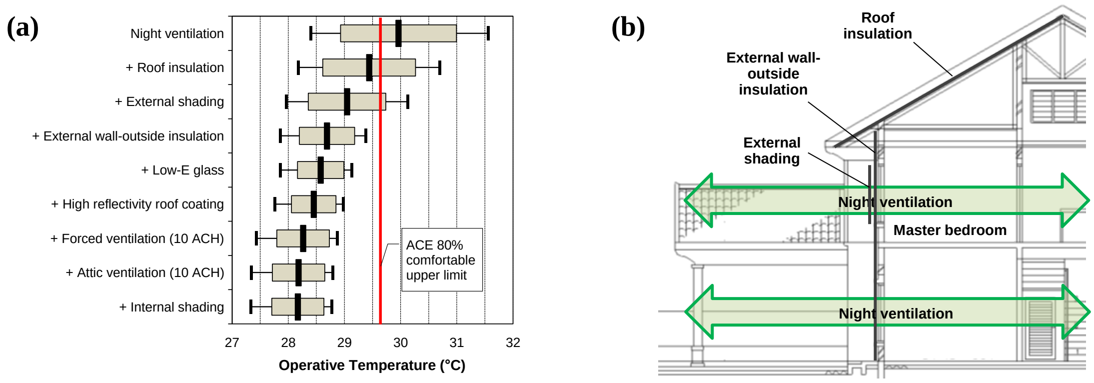

Figure 6 (a) Thermal comfort evaluation and (b) conceptual illustration of combined passive cooling techniques for complete NV strategy.

less effective in daytime ventilated condition compared to night ventilated condition (Figure 5b). The inflow of hot outdoor air through open windows during daytime increases the indoor air temperature and diminishes their cooling effects. On the other hand, forced ventilation with an air change rate of 10 ACH in the room at night lowers the daily minimum air temperatures most, i.e. by 0.6 °C and 1.4 °C in night ventilated and daytime ventilated conditions, respectively.

Figure 6a shows the simulated indoor operative temperatures for combinations of the most effective technique for each of the building elements. The techniques are applied accumulatively and step-by-step from more effective ones to less effective ones in night ventilated condition. The results are evaluated for thermal comfort using an adaptive comfort equation (ACE) for naturally ventilated buildings in hot-humid climates (Toe and Kubota, 2013). The 80% comfortable upper limits predicted using daily mean outdoor air temperatures of the analysis period average 29.6 °C. Figure 6a indicates that the daily maximum indoor operative temperature is reduced by 2.2 °C and meets the 80% comfortable upper limit when roof and external wall-outside surface insulation (R-value 4 m^2K/W), and external window shading (shading factor 0.75) are applied in addition to night ventilation under the heated urban climatic conditions. Alternatively, the comfort limit is also met by substituting the roof insulation with high reflectivity roof coating, though daily maximum temperature is higher in the latter. It is implied that introducing these four techniques to existing urban terraced houses may satisfy indoor thermal comfort in naturally ventilated condition on fair weather days (Figure 6b).

Partial Air Conditioning Strategy

Figure 7 shows the simulated sensible cooling loads in the air-conditioned master bedroom by considering different natural ventilation conditions for the master bedroom and other zones. The cooling load is 50.2 MJ/day when daytime ventilation is applied to the whole house (Case 1), which represents the current behaviour of most households. By applying night ventilation to the whole house except the master bedroom, the cooling load is reduced by about 5% even when the master bedroom is daytime ventilated (Case 5). Building structures that are cooled at night keep adjacent indoor temperature low and reduce the cooling load indirectly. The highest reduction in cooling load, i.e. 8%, is seen when the master bedroom receives no natural ventilation and other zones are night ventilated (Case 6).

Further passive cooling techniques are applied consecutively as shown in Figure 8 in addition to the ventilation conditions of Cases 1 and 6, respectively. For Case 1 the most effective technique in lowering

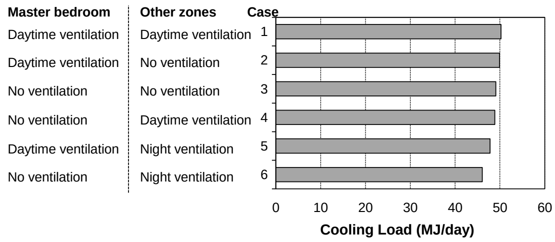

Figure 7 Simulated sensible cooling loads in different natural ventilation conditions for partial AC strategy.

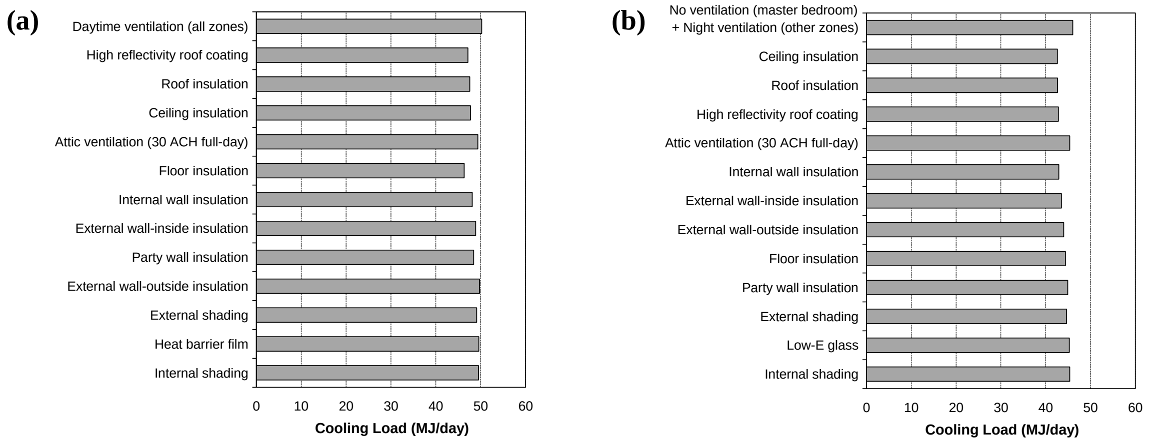

Figure 8 Simulated sensible cooling loads in ventilation conditions of (a) Case 1 and (b) Case 6 with respective passive cooling techniques for partial AC strategy.

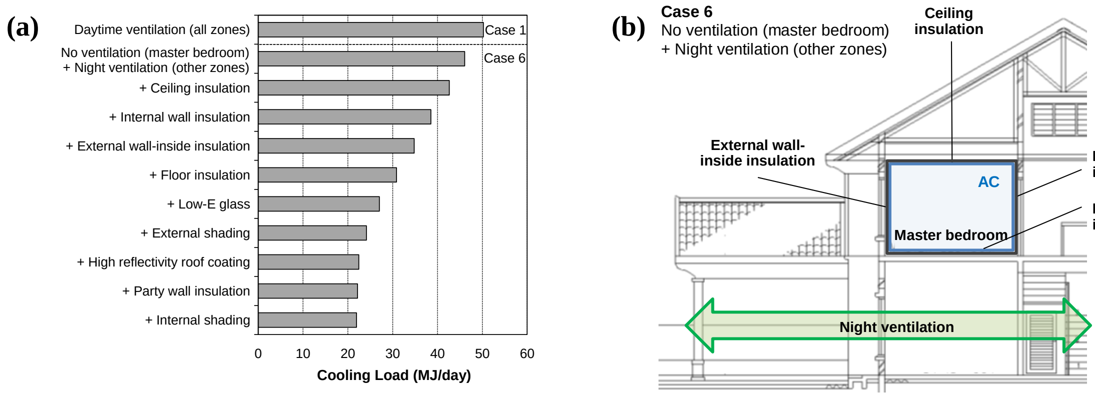

Figure 9 (a) Simulated sensible cooling loads and (b) conceptual illustration of combined passive cooling techniques for partial AC strategy.

the cooling load is floor insulation; the reduction is about 8% compared to the current condition (Figure 8a). Applying high reflectivity roof coating and roof or ceiling insulation give reductions of 6% and 5% each, respectively. For Case 6 ceiling insulation decreases the cooling load most by about 7%, followed by roof insulation and high reflectivity roof coating (Figure 8b). Besides, wall insulation is more effective on internal wall, followed by external wall-inside surface. Overall, all of the passive cooling techniques except floor insulation, party wall insulation and attic ventilation give greater reductions in the cooling load in Case 6 compared to Case 1, likely due to exclusion of hot outdoor air in closed window conditions during daytime.

Figure 9a presents the simulated sensible cooling loads for combinations of the most effective techniques in the ventilation condition of Case 6. As before, the techniques are applied accumulatively in step-by-step basis. Compared to the current condition (Case 1), the cooling load of the master bedroom is reduced by about 39% to 30.9 MJ/day when the ceiling, internal wall, external wall-inside surface and floor are insulated (R-value 4 m^2K/W) for Case 6 (Figure 9). The cooling load is lowered by 56% to 21.9 MJ/day when all of the techniques are used simultaneously, although the further reductions by high reflectivity roof coating, party wall insulation and internal shading are only about 3% or less each.

It is implied from the above simulation results that changing from daytime ventilation to night ventilation is fundamental to gain better effectiveness of other passive cooling techniques for both complete NV and partial AC strategies. Due to the intense solar heat gain through the roof, roof insulation for complete NV strategy and ceiling insulation for partial AC strategy provide the greatest cooling effects. In particular, for complete NV strategy techniques that prevent external heat on the outer building envelope are relatively effective to keep the indoors cool (Figure 6b). On the other hand, for partial AC strategy insulating the inner surfaces is relatively effective to reduce the cooling load (Figure 9b). Since the master bedroom is air-conditioned in this strategy, these techniques aid to prevent the mechanically cooled indoor air from being transferred outward.

CONCLUSIONS

The simulation results of a typical Malaysian terraced house reveal that indoor thermal comfort may be achieved in naturally ventilated condition by applying multiple passive cooling techniques that prevent external heat on the outer building envelope and night ventilation, even under heated urban climatic conditions. When air conditioning is used in the master bedroom, reductions of about 39% to 56% in the sensible cooling load compared to the current scenario can be reached by using several techniques including night ventilating other spaces and insulating inner surfaces of the master bedroom.

Further consideration of different building orientations, annual performance, cost-and-benefit effectiveness, and effects on indoor humidity as well as latent cooling load would be useful to realize their practical implementation in the urban terraced houses. Such modifications are expected to contribute largely to energy savings and carbon emission mitigation.

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