Numerical Simulation of Passive Cooling Strategies for Urban Terraced Houses in Hot-Humid Climate of Malaysia

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ABSTRACT

The objective of this study was to determine energy-saving modifications through passive cooling to urban terraced houses in Malaysia. Effects of two strategies, i.e. complete natural ventilation (NV) strategy and partial air conditioning (AC) strategy, were simulated using TRNSYS and COMIS. The complete NV strategy relied fully on naturally ventilated condition in the whole house for achieving thermal comfort in the master bedroom while the partial AC strategy was aimed at reducing the cooling load in the air-conditioned master bedroom by applying passive cooling techniques to the whole house. The results revealed that indoor thermal comfort was achieved in complete NV strategy by applying multiple passive cooling techniques that prevent external heat on the outer building envelope and night ventilation, even under heated urban climatic conditions. In partial AC strategy reductions of about 39% to 56% in the sensible cooling load compared to the current scenario were obtained by using several techniques including night ventilating other spaces and insulating inner surfaces of the master bedroom.

INTRODUCTION

Energy savings are important in the global building sector due to concerns about energy security and effects of global warming. In hot developing regions such as Southeast Asia, cooling demand in residential buildings is a major concern since it is predicted to rise sharply in the coming decades in line with rapid urbanization and population and economic growth (Liu et al., 2010; Sivak, 2009). It can be seen widely in the region that brick-walled buildings are becoming a common construction for urban houses in recent years. In Malaysia, a nationwide census in 2010 showed that 85% of the existing urban houses used brick and another 5% used brick and plank for their outer walls (Department of Statistics Malaysia, 2012). Unlike traditional lightweight constructions, the high thermal mass building envelope of brick houses might be difficult to be cooled in the hot-humid climate. It has been reported in 2009 that space cooling in brick houses accounted for 29% of the annual household energy consumption on average in the city of Johor Bahru, Malaysia (Kubota et al., 2011). It is thus crucial to apply passive cooling strategies wherever possible to these urban houses for energy-saving.

Passive cooling encompasses techniques for solar and heat control, heat modulation and heat...
dissipation using naturally driven phenomena such as natural ventilation, radiative cooling, evaporative cooling and ground cooling (Santamouris and Kolokotsa, 2013). Passive cooling techniques have been studied in various climatic regions. However, few comprehensive studies were made outside moderate and hot-dry climates, including field monitoring and numerical modeling exercises with regard to existing Malaysian houses (Kubota et al., 2009; Mohd Isa et al., 2010; Sadafi et al., 2011). Some of the main climatic factors negatively 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. Due to dependency on climatic conditions, further local studies are required to predict effects of a passive cooling system before implementation.

The objective of this study is to determine energy-saving modifications through passive cooling to Malaysian urban houses. The target houses are terraced houses, which formed majority (42% as of 2010) of the existing urban housing stock (Department of Statistics Malaysia, 2012). This study analyses the effects of two passive cooling strategies, i.e. complete natural ventilation (NV) strategy and partial air conditioning (AC) strategy, on thermal comfort and cooling load, respectively, through numerical simulation using TRNSYS and COMIS programs.

METHODS

Description and Modeling of the Case Study Terraced House

One of the case study terraced houses from a previous field experiment (Kubota et al., 2009) was modeled in this simulation study. The selected terraced house represents typical modern terraced houses in terms of spatial design and building structures (Toe, 2013). The house measures 6.7 m by 13.1 m with a total floor area of 155 m$^2$, which is an average sized double-storey terraced house (Figure 1). Floor-to-ceiling height of rooms is 3.05 m. The total nett air volume of the whole house is 538 m$^3$; that of the master bedroom is 65 m$^3$. The building was oriented towards northwest, which means that the external façade of the master bedroom faces northwest. It was constructed of brick and concrete and had single glazing windows. The entire house was not insulated. Description of the constructional layers of the terraced house and their reference U-values in the computer model is given in Table 1.

The whole house was modeled as TRNSYS Type 56 ‘Multi-zone Building’ in three dimensions using the TRNSYS 3D plug-in in Google SketchUp interface (Klein et al., 2012). The building model comprised 17 thermal zones with corresponding air flow zones in COMIS to represent each partitioned room or functional space including attic spaces. All protruding elements on the building facades and immediate surrounding objects, i.e. neighbouring houses, that might shade the studied house were also modeled in three dimensions. A time base of 1 h was set for the transfer function to represent the thermal

Figure 1 (a) Exterior view and (b) floor plans of the case study terraced house.
mass behavior of the brick walls. The party walls on both sides of the house were modeled as boundary walls with identical zone temperatures assumed on both sides of the walls. Meanwhile, the boundary condition for the ground floor was the constant soil temperature assumed to be the average air temperature at the site over the whole simulation period. Thermal properties of building materials and parameter/input values for air flows were obtained from Malaysian manufacturers or reference data to correspond with the local construction (Toe, 2013). Wind pressure coefficients were estimated using a parametrical model developed by Grosso (1992) known as CPCALC+.

Coupling between the TRNSYS and COMIS models were implemented via Type 157 in TRNSYS so that air flow rates per zone and zone air temperatures were iterated in each time step until the mass and energy balance per zone reached convergence.

Model Validation

Empirical validation of the terraced house model was performed using the above-mentioned field experiment data from June-August 2007 (Kubota et al., 2009). This study focuses on the results in the master bedroom because existing households used air conditioners mainly in master bedrooms (Kubota et al., 2009); the study interest is to reduce this cooling energy. Figure 2 shows temporal variations of the simulation results compared to the measurement data at 1.5 m height above floor in the master bedroom. Two ventilation conditions, i.e. night ventilation and daytime ventilation, are shown. Overall, the

<table>
<thead>
<tr>
<th>Building Element</th>
<th>Constructional Layers</th>
<th>Reference U-value(^a) (W/m(^2)K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>External and internal walls</td>
<td>20 mm thick cement plaster + 100 mm thick clay brick + 20 mm thick cement plaster</td>
<td>2.75</td>
</tr>
<tr>
<td>Party wall</td>
<td>20 mm thick cement plaster + 200 mm thick clay brick + 20 mm thick cement plaster</td>
<td>2.07</td>
</tr>
<tr>
<td>Ground floor</td>
<td>8 mm thick ceramic tile + 22 mm thick cement screed + 100 mm thick concrete slab + soil layer</td>
<td>3.75(^b)</td>
</tr>
<tr>
<td>First floor (family and bedroom zones)</td>
<td>15 mm thick timber flooring + 15 mm thick cement screed + 100 mm thick concrete slab + 20 mm thick cement plaster</td>
<td>2.81</td>
</tr>
<tr>
<td>First floor (bath zones)</td>
<td>8 mm thick ceramic tile + 22 mm thick cement screed + 100 mm thick concrete slab + 20 mm thick cement plaster</td>
<td>3.29</td>
</tr>
<tr>
<td>Ceiling (master bedroom)</td>
<td>6 mm thick ceiling board</td>
<td>4.55</td>
</tr>
<tr>
<td>Ceiling (other zones)</td>
<td>3.2 mm thick ceiling board</td>
<td>5.54</td>
</tr>
<tr>
<td>Pitched roof</td>
<td>20 mm thick concrete roof tile + 25 mm thick timber batten + aluminium foil</td>
<td>2.67</td>
</tr>
<tr>
<td>Flat roof</td>
<td>22 mm thick cement screed + 100 mm thick concrete slab + 20 mm thick cement plaster</td>
<td>3.37</td>
</tr>
<tr>
<td>Window</td>
<td>6 mm thick single layer float glass</td>
<td>5.61</td>
</tr>
</tbody>
</table>

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

\(^b\) Excludes soil layer.

Figure 2 Temporal variations of the simulation and measurement data in the master bedroom in (a) night ventilation and (b) daytime ventilation conditions.
validation results are satisfactory in terms of air and operative temperatures with root mean square errors (RMSE) of 0.31-0.55 °C and coefficients of determination (R²) of 0.89-0.96.

**Simulation Test Cases and Weather Conditions**

Table 2 summarizes the simulation test cases of this study. The techniques were selected by considering their practicality to be applied to existing terraced houses through relatively simple building modification and/or behavioural adjustment. In particular, night ventilation is considered a potential passive cooling technique for brick houses while daytime ventilation emulates the window opening behavior of the majority of existing households (Kubota et al., 2009). The complete NV strategy relies fully on naturally ventilated condition in the whole house for achieving thermal comfort in the master bedroom. Meanwhile, the partial AC strategy attempts to reduce the cooling load in the master bedroom by applying passive cooling techniques to the whole house. It was assumed that air conditioning was used only in the master bedroom for nine hours per day (21:00-6:00) with a set temperature of 23 °C.

This study deals with the sensible cooling load only. Internal heat gains from occupants (4 persons; seated at rest), lighting (5 W/m²) and common household appliances were considered in all simulations. It is noted that infiltration rates in the master bedroom average 0.1 ACH when no ventilation was applied for both complete NV and partial AC strategies.

Weather conditions for the simulation were taken from an actual weather data set measured at the centre of a heat island in Johor Bahru, Malaysia to represent urban climate of typical terraced housing neighbourhoods (Kubota and Ossen, 2011). The geographical location is 1°29′19″ N and 103°45′41″ E at an elevation of 26 m above sea level. A wind velocity profile exponent of 0.25 was used to represent the urban location (Counihan, 1975). The simulation time step was set to coincide with the weather data at 10-minute intervals. The simulation was run using the above weather file for two whole months, i.e. January-February 2010. Subsequently, simulation results for a 10-day period of continuous typical fair weather days are analysed in this study. As shown in Figure 3, outdoor air temperature ranges from 25-36 °C while outdoor relative humidity ranges from 50-90% over the period. The analysis period begins several days after the simulation start time, thus allowing the model to acquire sufficient thermal history. Output files were generated and post-processed in Excel spreadsheets after the simulation.

**Table 2. Simulation Test Cases.**

<table>
<thead>
<tr>
<th>Technique</th>
<th>Test Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural ventilation (open window period)</td>
<td>Night ventilation (20:00-8:00); daytime ventilation (8:00-20:00); no ventilation (0 h); full-day ventilation (24 h)</td>
</tr>
<tr>
<td>Forced ventilation</td>
<td>10 ACH or 30 ACH night (20:00-8:00) in master bedroom</td>
</tr>
<tr>
<td>Attic ventilation</td>
<td>10 ACH night (20:00-8:00) or 30 ACH full-day (24 h) in attic</td>
</tr>
<tr>
<td>Thermal insulation</td>
<td>Roof; ceiling; external wall – outside surface; external wall – inside surface; internal wall; party wall; floor (R-value: 4 m²K/W)</td>
</tr>
<tr>
<td>Window shading</td>
<td>External shading; internal shading (Shading factor, SF: 0.75)</td>
</tr>
<tr>
<td>High reflectivity roof coating</td>
<td>Solar reflectance: 0.8, longwave emissivity: 0.9</td>
</tr>
<tr>
<td>Window glazing</td>
<td>Low-E glass (U-value: 2.54 W/m²K, G-value: 0.44) or heat barrier film (U-value: 5.73 W/m²K, G-value: 0.48)</td>
</tr>
</tbody>
</table>

![Figure 3 Temporal variations of weather data for the simulation analysis period.](image-url)
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 ventilated 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.
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 m²K/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...
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 m²K/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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