Effectiveness of free running passive cooling strategies for indoor thermal environments: Example from a two-storey corner terrace house in Malaysia

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Effectiveness of free running passive cooling strategies for indoor thermal environments: Example from a two-storey corner terrace house in Malaysia

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Abstract

The widespread use of air-conditioning to achieve indoor cooling of residential buildings has caused increased electricity consumption. Effective passive cooling strategies, such as natural ventilation, are important for reducing energy consumption. Field measurements of thermal performance for a corner terrace house in Kuala Lumpur were conducted to clarify the effectiveness of free running (FR) ventilation as a passive cooling strategy with configurations: without ventilation, full ventilation, day ventilation, and night ventilation. Measurements were conducted for all bedrooms and a family area on the first floor. For comparison, a mixed mode (MM) consisting of FR, ventilation with a ceiling fan, and cooling with an air-conditioner, which represents the actual conditions of this house, was measured in the living and dining area on the ground floor. Operative temperature was compared with the predicted temperature using an adaptive thermal comfort equation (ACE) under relevant international standards. The mean indoor temperature under FR was approximately 27 ºC–37 °C, and 27 ºC–33 °C in MM. Full ventilation and day ventilation recorded better correlation between outdoor and indoor temperature compared with no ventilation and night ventilation. Furthermore, compared with the ACE for a hot-humid climate, MM ventilation resulted in an operative temperature 58% less than the acceptable comfort temperature; thus, it performed better and was closer to international standards than was FR ventilation, which resulted in an operative temperature of 27% less than the acceptable comfort temperature. FR was not adequate to provide comfortable conditions without assistance from MM.

Keywords: free running ventilation, mixed mode ventilation, passive cooling, thermal environment, corner terrace house, hot-humid climate

1. Introduction

Global warming has serious impacts on urban areas [1]. To reduce the impact of heat waves, urban dwellers use air-conditioning (AC) systems [2,3,4]; however, this considerably increases energy consumption [3] and indirect increase in CO_2 emissions through electrical power generation further exacerbates the global warming issue [1].

Passive cooling without energy consumption can also effectively resolve thermal discomfort during heat waves [2,5,6,7]. Passive cooling methods include free running (FR) mode ventilation to release heat from the building [2,5,8,9,10,11], installation of a shading device [5,6,11,12], installation of heat insulation on the envelope of the building [5,6,11,12], and the use of courtyards to avoid heat [11,13,14].

FR mode ventilation can be classified into two main categories: buoyancy-driven and wind driven ventilation. Buoyancy-driven ventilation uses the stack effect or chimney effect to allow hot air into the building in order to raise and flush out warm air through high-level windows or openings. Mathur et al. [15] found that a roof solar chimney enhanced FR ventilation in a residential building during summer in India. Krzaczek et al. [10] reported that in the absence of wind, stack ventilation was able to maintain and slightly exceed the standard required air change rate in a cold climate during the period between spring and summer in a residential building in Poland.

Wind-driven ventilation arises from the pressure difference created by wind around window openings and can be further classified as cross- and single-sided ventilation. Michael et al. [9] conducted field measurements on cross ventilation for cooling in a Mediterranean climate during the summer period; they found that wind-driven ventilation with a double window is more effective than with a single window. However, the effectiveness of FR ventilation is related to the outdoor temperature; for example, Suárez et al. [16] studied the impact of outdoor climate change on heating and cooling energy demand in a Mediterranean climate and concluded that FR ventilation is sensitive to the effects of outdoor temperature change. Yang and Clements [8] and Michael et al. [9] found that to obtain cooling and remove heat from internal spaces, incoming air must be cooler than the indoor temperature. To optimize the advantage of cross ventilation and minimize the impact of outdoor temperature change, several field studies [2,9,16] have been conducted on the use of windows to control ventilation and minimize the impact of outdoor temperature change. Controlling ventilation through windows can be performed using four different approaches: full day ventilation, no ventilation, day ventilation, and night ventilation [2,9,16]. Night ventilation was found to be effective in temperate climates, where it is possible to maintain indoor thermal comfort during summer [9] and reduce energy consumption for the cooling load [7]. However, according to Santamouris et al. [7], the contribution of night ventilation to cooling demand decreases when the air flow rate increases. In contrast, Kubota et al. [2] reported that night ventilation in a hot-humid climate is unable to achieve the required indoor thermal comfort level compared with full day ventilation, which benefits from high relative humidity during the daytime [2]. When windows are opened for ventilation at night, humid air can enter a building; with daybreak and the closing of windows, this humid air gets trapped inside the building. The subsequent high relative humidity in the building causes thermal discomfort during the daytime. However, opening the window during the daytime can reduce the relative humidity level, but at the same time, it also allows additional heat to enter the building [17].

The outdoor thermal environment is effected directly by different building forms [13]. Taleghani et al. [13] considered thermal comfort within five different building forms in the Netherlands and found that orientation and position of a house within the same building form impact climate conditions. For example, outdoor wind speed and air temperature vary between intermediate and corner units of a linear block [13]. However, no further research has considered whether these different outdoor thermal environments (intermediate and corner units) impact on indoor thermal comfort or whether it has the same effect in other climates, especially in tropical regions with a constantly high outdoor air temperature throughout the year. In hot-humid climates, such as that in Malaysia, which has an average outdoor air temperature of 28 °C [18], terrace houses in linear blocks are one of the common urban housing types [19] that face the urban heat island effect [20].

According to Zaki et al. [4], indoor air temperatures in low-cost apartments in Malaysia are approximately 22 °C–31 °C. In another study by Lee et al. [20] on a terrace house in Johor Bahru, Malaysia, and Zakaria et al. [21] on an urban house, the indoor temperature was 29 °C–30 °C. Both studies showed that indoor temperature is relatively high and related closely to outdoor air temperature. Further research is required to investigate how to reduce the indoor temperature of terrace that constitute 47.8% of new launches of residential property in 2018 in Malaysia [22], and especially that of corner unit terrace houses, which have the advantages of better outdoor wind speed and more windows, using passive cooling methods. Previous studies on FR ventilation were conducted mainly on detached buildings [5,6,9,20] and intermediate unit terrace houses [2,12] with different outdoor environments and cross ventilation capabilities.

The objective of this study was to clarify the effectiveness of different FR mode ventilation strategies for a corner unit terrace house in Kuala Lumpur. At the same time, the actual living environment of mixed mode (MM) ventilation consisting of a combination of FR, ceiling fan, and AC was also recorded for comparison. The results from FR and MM were compared with relevant international standards for predicting indoor comfort temperature based on outdoor temperature.

2. Materials and methods

2.1. Location and climate

Field measurements were conducted in a two-storey corner terrace house (Fig. 1) located in Taman Melati, Kuala Lumpur, Malaysia (3°13'10.3"N 101°43'33.9"E) from 15 February 2018 until 11 March 2018. Kuala Lumpur lies in an equatorial region and has a tropical rain forest climate year-round. Fig. 2 shows the monthly mean air temperature from January 2018 to December 2018, obtained from a weather station located at the Universiti Teknologi Malaysia, which is approximately 5 km away from the investigated house. The mean outdoor air temperature and relative humidity were 28±2 °C and 80±7%, respectively; these are similar to the findings of Khalid et al. [23], who reported on monthly mean outdoor temperatures and relative humidity throughout the year. The outdoor air temperature being constant throughout the year owing to the equatorial tropical climate, the measurement schedule was decided based on the arrangement with the owner of the investigated house, and the weather conditions during that period.

2.2. Investigated house

The total built up area of the house is approximately 178 m^2. The house consists of a living area, dining area, kitchen, and study room on the ground floor, together with three bedrooms and a family area on the first floor. The heights of the ground and first floors are 3.0 and 3.2 m, respectively. Fig. 3a shows the site of the investigated corner terrace house with three sides of the building facing open space. Fig. 3b,c show floor plans and Fig. 3d,e are the elevation views of the house showing the opening of windows at three sides of the building.

The construction of the house was completed in 2004 with brick walls on a reinforced concrete frame structure. The floor slabs on both floors are reinforced concrete slabs. The first floor was covered with cement board ceiling and concrete roof tiles on the roof level. No heat insulation was installed in the roof attic or walls. Table 1 shows detailed information on the investigated house, and Table 2 lists the building materials used on various components of the investigated house.

2.3. Ventilation strategies

FR was applied to the unoccupied first floor with four ventilation strategies: without ventilation (WV), full ventilation (FV), day ventilation (DV), and night ventilation (NV). A window was used to control ventilation by closing or opening from 8:00 to 20:00 in daytime and opening from 20:00 to 8:00 at night time according to the sun rise and sun set times in connection with the changes in outdoor temperature in Malaysia; same timings were adopted by Kubota et al. [17] in his research. Moreover, while the door was kept closed during the measurement. No ventilation fan or exhaust was installed in the house, and no cooling or ceiling fans were switched on during the measurement period. Each strategy was measured for 3 consecutive days. At the same time, MM was applied concurrently on the ground floor without any control of ventilation. Two persons lived on the ground floor during the measurement period. The MM consisted of FR ventilation, FR ventilation with ceiling fan, or cooling (CL) with ceiling fan. Measurements were conducted in the living and dining areas. Table 3 displays details of investigation strategies.

2.4. Measurement setup

The indoor air temperature (T_i), relative humidity (RH_i), globe temperature (T_g) and air velocity (V_i) were measured; Fig. 4 shows the location and type of climatic parameter measurements conducted in the investigated house. The T_i and RH_i were measured at three different heights (0.5, 1.5, and 2.5 m) in the investigated areas (Fig. 5a) to represent the thermal environment above the floor, in the middle of the room, and below the ceiling. The T_g and V_i were measured 1.5 m above the floor. In the roof attic, roof air temperature (T_{a_R}) was measured at 0.8 m (1/3 of attic height) and 1.6 m (2/3 of attic height) above the ceiling level at the centre of the roof attic (Fig. 5b) to obtain the vertical variation in air temperature between the roof tiles and ceiling. The surface temperature for roof tiles (T_{s_R}) was measured at the bottom surface of a roof tile facing east. At the same time, the top surface temperature (T_{s_CT}) and bottom surface temperature (T_{s_CB}) of the ceiling board (Fig. 5c and 5d) and external surface temperature (T_{s_WE}) and internal surface temperature (T_{s_WI}) of the external wall (Fig. 5e and 5f) were measured in the family area.

The weather station to observe the background condition was mounted in the front yard of the target house, and the outdoor air temperature T_o and relative humidity RH_o were measured at 1.5 m (human height at ground floor), 3.0 m (height of first floor), and 4.5 m (human height at first floor) from the ground level to capture the outdoor vertical temperature profile. The external sensor was housed in a fan aspirated solar shield to avoid any effects of solar radiation (Fig. 6a). Simultaneously, solar radiation (SR) was measured 5.0 m above the ground to avoid the influence of any shadows casted from the surroundings. In addition, the anemometer was set at 1.7 m to measure outdoor wind condition (Fig. 6b). The location of the weather station is shown in Fig. 7. The distance from the weather station to the south wall of the target building is 3.5 m, whilst that to the southern brick boundary wall with a height of 1.4 m is 1.5 m. Ideally, an anemometer to capture the background wind condition should have been placed at a much higher position compared to the roof height of surrounding buildings in order to avoid the influence of specific flow natures created by the sheltering of the buildings. However, the authors could not find a suitable location in the study area that satisfied this requirement. Nevertheless, considering the direction of the prevailing wind which is from southeast and southwest, we believe that the measured velocity data are of use in grasping the general background wind condition. Fig. 8a shows the hourly mean wind speed and direction of prevailing wind at the investigated house and its comparison with the data collected from weather station located at Malaysia-Japan International Institute of Technology (MJIIT) Universiti Teknologi Malaysia (UTM) [25] (Fig. 8b), which is approximately 5 km away from the investigated house. Both weather stations show a consistent prevailing wind from southeast (local 14%, MJIIT 24%) and southwest (local 16%, MJIIT 16%). Fig. 9 shows that the two weather stations are closely related in terms of daily mean air temperature during the period of measurement with a coefficient of determination (R^2) value of 0.63.

The air infiltration of each room was assessed by investigating the consistency of the air change rate per hour (ACH) with the window closed using the CO_2 gas trace method [26] (Fig. 7). This approach ensured that measurement of the indoor thermal environment was not affected by inconsistent air infiltration. The CO_2 sensors were placed in the four corners of the room. Before measurement, a fan was used to circulate CO_2 to ensure a uniform mixture with existing air in the room. The measurement was conducted twice per room to check the consistency of the ACH. The outdoor CO_2 level was measured for comparison. ACH was determined by the least-square method [26].

The instruments used in field measurements are listed in Table 4. All indoor and outdoor instruments recorded at 1-min intervals, except for CO_2, which was at 15-s intervals. All instruments were calibrated, and their consistency was verified prior to measurement.

3. Results

3.1. Indoor and outdoor thermal environments

Table 5 shows the average from two measurements of ACH for the three investigated bedrooms. The master bedroom had the highest ACH (0.58), followed by bedroom 3 (0.45), and bedroom 2 (0.36). In comparison, bedroom 2, which had a lower window to floor ratio, had lower ACH compared with bedroom 3 with the same floor area but a greater window to floor ratio. When compared with ASHRAE Standard 62.1–2010 [27] on the minimum ventilation rate for bedrooms (8.50 m^3/hour per person), bedrooms 2 and 3 had slightly higher ventilation rates (11–28 m^3/hour), even with all windows closed. However, the master bedroom had the highest infiltration of the bedrooms. In general, all three bedrooms had similar ACH with all windows closed.

The indoor climatic data for the different ventilation strategies, together with the outdoor climatic data, are plotted in Fig. 8. Missing lines between each approach indicate a break in the data collection and the setup of a new approach. The T_o was approximately 24 °C–38 °C (Fig. 8a), while the corresponding RH_o ranged from 34% to 97% (Fig. 8b). The mean T_o values for the four ventilation strategies were 35.0 °C (WV), 36.0 °C (FV), 35.6 °C (DV), and 36.6 °C (NV). The hourly peak for SR was 1043 W/m^2 (Fig. 8d), recorded during NV, and the mean V_o was 0.55 m/s (Fig. 8e). Fig. 8a–b show the temporal variations of mean T_i and RH_i for three different levels in the bedrooms. T_i was approximately 27 °C–37 °C in bedrooms with FR ventilation. Meanwhile, RH_i

was 46%–76% in the bedrooms. The overall T_g was approximately 27 °C–38 °C (Fig. 8c) and was generally similar to T_i.

Among four FR ventilation strategies, NV recorded the widest range of T_i (~27 °C–37 °C). However, the *SR* contributed to the high T_i during NV; the mean daytime *SR* during the NV period was 514 W/m^2, much higher than that of other FR ventilations (424 W/m^2; Fig. 8d). In general, the air velocity for all ventilation strategies was very low; such a condition might not be significant for indoor thermal comfort. On the other hand, on the ground floor, T_i was in the range of 27 °C–33 °C. The minimum T_i was the same as on the first floor, but the maximum T_i was much lower with a 4 °C difference. Fig. 8a shows the sharp drop of T_i when CL was switched on during hot days in the living area under MM ventilation. Meanwhile, RH_i was 51%–83% on the ground floor and approximately 6% higher than that on the first floor.

3.2. Vertical indoor air temperatures under FR and MM

Table 6 lists the mean T_i at the 0.5, 1.5, and 2.5 m levels in all investigated areas. In general, T_i was lower near the floor and higher towards the ceiling. The greatest difference in mean T_i between the floor and ceiling level was 1.9 °C, recorded in bedroom 2, followed by 1.8 °C in bedroom 3, both under FV with windows opened for the whole day, even though the mean T_o during FV was only the second highest among all scenarios. However, during NV (with highest T_o and SR), the difference was lower (1.7 °C) in bedroom 2 when windows were closed during the daytime. This shows that, besides outdoor temperature, opening the window plays a significant role in indoor temperature. In contrast, WV recorded the lowest vertical difference (0.5 °C) and maintained a more stable T_i when all windows were closed. However, in DV and NV, the differences were approximately 1 °C. Meanwhile, the mean T_i recorded at 1.5 m height for all three rooms was approximately 31 °C.

The vertical differences in air temperature on the ground floor (MM ventilation) were analysed for comparison. Fig. 9 shows the vertical variations in mean T_i over 3 days at three different heights for all investigated rooms and ventilation strategies; in addition, T_o is plotted together with solar radiation and prevailing winds. The vertical difference in mean T_i on the ground floor was much lower (less than 1 °C) than that of the first floor. With MM ventilation, a ceiling fan or AC was switched on to maintain thermal comfort. This approach contributed to a more evenly distributed temperature on the ground floor. Meanwhile, the mean T_i recorded at 1.5 m height under MM was approximately 30 °C. At the same time, the vertical variation in mean T_o outdoors between 1.5 and 4.5 m was minimal (0.2 °C). The temperature was slightly higher near the ground level. This is a reverse scenario when compared with the indoor environment, where higher temperatures occurred at higher levels within a room. In contrast, the mean T_i in the attic was high (32 °C, with an extreme maximum of 49 °C); this is directly related to T_o and SR. High temperature in the attic also contributed to the greater vertical difference in T_i on the first floor. However, the highest mean recorded during NV in the attic (33.7 °C) did not correspond to the highest vertical difference in the rooms.

3.3. Relationship between indoor and outdoor air temperature

The relationship between indoor and outdoor air temperature differed for different FR ventilation strategies. Table 7 and Fig. 10 show the regression analysis of the correlation between T_o and T_i across four ventilation strategies based on 69 samples of hourly mean air temperature collected from 3 days of measurements for each ventilation strategy. Fig. 10 shows that T_i in all bedrooms under all four FR ventilation strategies was affected directly by T_o. All correlations were found to be statistically significant with the probability $|p| < 0.001$. FV and DV recorded better correlation between T_o and T_i compared with WV and NV based on the higher coefficient of determination (R^2; Table 7). The higher gradients of the regression reflect a higher influence of T_i on T_o. In general, bedroom 3 had the highest gradient, with the T_i heavily impacted by T_o. However, NV and FV had the highest gradients and most significant influence from $T_{o.}$

When T_o was low during the night-time, FV and NV (Fig. 10b, d) corresponded well with low T_i. However, in WV and DV with windows closed at night-time (Fig. 10a, c), T_i remained relatively high at 30 °C, even though the T_o was low (24 °C). Meanwhile, during the daytime when T_o was high (36 °C), T_i was relatively similar for all FR ventilations in all bedrooms (approximately 34 °C). The results show that FV and NV are better passive cooling methods during the night compared with WV and DV. However, during daytime, there is no specific advantage from any FR ventilation strategy.

The data also show that different rooms respond differently to outdoor temperature (Fig. 10b), perhaps reflecting the different building characteristics of the rooms. For example, Fig. 10a shows that master bedroom and bedroom 2 responded well under daytime WV (i.e., lower T_i) as compared with bedroom 3.

Fig. 11 shows the correlation between outdoor and indoor temperature for the three bedrooms under all FR conditions. Most of the time, T_o had a smaller effect on the master bedroom than on the other rooms, regardless of ventilation strategy (Fig. 11a). However, bedroom 2 and bedroom 3 responded well in terms of T_o (Fig. 11b, c), especially under FV and NV and during the night-time when T_o is low. The correlation was strongest for bedroom 3, possibly owing to the high ratio of external wall to floor area (Table 1), with the large external wall of bedroom 3 acting as a thermal mass to mitigate the temperature between the indoor and outdoor. The other reason for the master bedroom maintaining a higher indoor temperature during the night was the room being west-facing. The external wall of the master bedroom acted as a thermal mass and absorbed heat from the evening sun and released it to the room during the night. In contrast, when the outdoor temperature increased during the daytime, the master bedroom maintained a better indoor temperature compared with bedrooms 2 and 3.

3.4. Influence of surface temperature on indoor air temperature

Fig. 12 shows variations in the surface temperature of the roof tile, ceiling board, and brick wall across the four ventilation strategies applied in the family area. The roof tile surface, which experienced direct exposure to solar radiation, recorded a wide range of surface temperature (23 ºC–64 °C), with the most significant difference between night-time (low) and daytime (high). The mean maximum surface temperature across four measurement periods was approximately 61 °C and at 13:00 to 14:00 in the afternoon (Fig. 10a). Meanwhile, the attic recorded the high mean maximum air temperature (45 °C) as a result of heat radiated from roof tiles in the daytime. At the bottom part of the roof, the top surface of the ceiling was heated by radiant heat from the attic air with a mean maximum surface temperature of 42 °C, which is 3 °C lower than the air temperature in the attic. After the heat reached the bottom surface of the ceiling, the temperature was reduced to 40 °C, followed by an indoor air temperature of approximately 34 °C at 1.5 m height from the floor level of the family area. The maximum temperature in the family area was achieved at 16:00 to 17:00, approximately 3 hours after the maximum temperature recorded on the roof tiles.

In contrast, the variation of mean minimum temperature across four measurements on different components of the roof was much smaller. The mean minimum temperature on the roof tiles was 24 °C, followed by 26 °C for the attic air, and 27 °C for the top surface of the ceiling. The minimum temperature was recorded at 07:00 to 08:00 in the morning, as the sun rose.

Compared with the roof, the external wall surface recorded a mean maximum surface temperature of 38 °C and 34 °C on the internal surface of the wall. The maximum temperature for the external surface was recorded at 15:30 to 16:30, but for the internal surface it was recorded at 16:30 to 17:30. Fig. 10b shows the time lag of approximately 1 hour between the maximum temperatures of the external and internal wall surfaces. When compared with indoor air temperature, the time of maximum temperature recorded at the ceiling bottom surface and wall internal surface were very close at 16:00 to 17:00. The results reflect that the source of heat in the rooms (T_i = 35 °C) mainly comes from the roof through the ceiling (T_{s_CB} = 40 °C); in contrast, for the wall, T_{s_WI} = 34 °C during the peak hour when the maximum temperature was recorded. At the same time, the mean maximum outdoor temperature was 36 °C, which is only 1 °C higher than the indoor air temperature.

3.5. Difference between indoor and outdoor air temperatures

Outdoor air temperature (T_o) was measured concurrently with indoor air temperature (T_i) in order to clarify the influence of outdoor temperature on indoor air temperature (Fig. 13). The conditions of T_o were almost identical for WV, FV, and DV, with mean T_o of approximately 28 °C; however, T_o was higher for NV (30 °C). The mean difference between T_i and T_o was lowest during NV (2.5 °C).

Fig. 14 and Fig. 15 show the differences between the four ventilation strategies during the daytime and night-time, respectively. For FR whole day measurements, rooms on the first floor recorded a difference of 1.9 °C–3.7 °C, which is a wider range than that of the MM ground floor (2.6 °C–3.6 °C).

During the daytime (Fig. 14), the differences were lower for areas with FR ventilation (2.0 °C) compared with MM ventilation (2.9 °C). The results show that indoor temperatures under FR ventilation were influenced by outdoor temperatures during the daytime. The differences between the four FR ventilation strategies were not significant. This shows that opening or closing windows in the daytime did not affect the indoor temperature. Meanwhile, when different rooms were compared, all areas with FR ventilation had a similar difference between indoor and outdoor temperature. Thus, we conclude that differences in building characteristics of the bedrooms did not affect the thermal performance of the rooms during the daytime.

At night (Fig. 15), differences were more obvious among the four ventilations strategies. NV performed the best and had the smallest difference, followed by FV. When outdoor temperature was low, opening windows created a cooling effect that helped to reduce the indoor temperature. Closing windows during the night under WV and DV resulted in a considerable difference between indoor and outdoor temperatures. For the bedrooms with FR ventilation, bedrooms 2 and 3 performed slightly better during NV and FV. The poor performance of the master bedroom might be because of the west facing external wall, which functions as a thermal mass that absorbs heat in the afternoon and releases it during the night.

Overall, NV performed better than the other ventilation strategies. It allowed effective cooling at night and maintained a reasonable indoor temperature during daytime. MM performed slightly better than FR with a higher difference in the daytime and lower difference at night.

3.6. Indoor comfort temperature using adaptive comfort standards

According to various adaptive comfort standards, the acceptable indoor comfort temperature based on T_{op} for a natural ventilated space can be predicted using T_o. Different standards adopt slightly different equations for predicting the comfort temperature. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 55 [29] defines the acceptable thermal environment for occupant-controlled naturally conditioned spaces based on a neutral value between the 80% upper and lower acceptability limits of T_{op} in the space. The equation for the calculation of indoor T_{op} is

$$T_{comfop} = 0.31T_{outmm} + 17.8 \tag{1}$$

where T_{comfop} is indoor neutral T_{op} (°C) and T_{outmm} is daily mean outdoor air temperature (°C). The European Standard EN15251 [30] adopts a different equation for calculation of acceptable indoor temperatures for design of buildings without mechanical heating and cooling systems. This equation is

$$T_{comfop} = 0.33T_{outmm} + 18.8 \tag{2}$$

Toe et al. [31] also developed an adaptive thermal comfort equation for naturally ventilated buildings in hot-humid climates using the ASHRAE RP-884 database. Their equation is:

$$T_{comfop} = 0.57T_{outmm} + 13.8 \tag{3}$$

Table 8 summarises the average values for the calculated mean radian temperature (T_{mrt}), T_{op}, and absolute humidity (AH) in all rooms with different ventilation modes and approaches. T_{op} was consistently at approximately 31 °C on the first floor under FR and approximately 30 °C on the ground floor under MM.

In Fig. 16, the T_{op} for all rooms are plotted against the neutral operative temperatures of three comfortable temperatures predicted from the adaptive thermal comfort equation (ACE). The missing lines between each approach in this figure indicate breaks in data collection and the setup of a new approach. Neither the FR or MM ventilation strategies complied with T_{comfop} under ASHRAE Standard 55. However, for EN15251, only 2% of the T_{op} values were below T_{comfop}. When compared with ACE for hot-humid climate, FR performed better with 27% of the T_{op} values under FR and 58% under MM below T_{comfop}. Of the 27% of FR values, 21% occurred during the night. For FR ventilation, bedroom 3 recorded the highest percentage of compliance (34%). However, during the daytime, T_{op} values were generally higher than T_{comfop}, at only 4%–7% below T_{comfop}. During the night, the percentages were higher and ranged from 16% to 29%. Bedroom 3 maintained the highest percentage of compliance (29%).

4. Discussion

The present study was aimed at determining the indoor thermal comfort based on outdoor temperatures. The methodology involved clarifying the effectiveness of various FR mode ventilation strategies for a corner unit terrace house in Kuala Lumpur, Malaysia. Four FR ventilation strategies (without ventilation, full ventilation, day ventilation, and night ventilation) were applied in a two-storey corner terrace house to clarify the effectiveness of FR ventilation as a passive cooling method and to compare it with actual thermal conditions under MM ventilation. The collected data were compared with related international standards on adaptive thermal comfort to check the acceptability of measured indoor air temperature.

For the temporal variations in bedrooms, the range of recorded T_i 27 °C–37 °C was greater than that reported by Zaki et al. [4]; they reported indoor temperatures of 29 °C–31 °C in apartments in Kuala Lumpur. It was also higher than the requirement for normal comfortable room temperature in Malaysia (24 °C–26 °C) [28]. Moreover, the T_i of 34 °C during the daytime was much higher than that reported by Zakaria et al. [21] (29 °C–30 °C for an urban house in Malaysia); the difference might be due to the installation of roof insulation. However, the better performance of FV is consistent with the findings of Zakaria et al. [21] when using the full day ventilation strategy for urban houses in a hot-humid climate. The mean T_i was found to be lower near the floor level and gradually rose towards the ceiling level. This was in line with the finding by Toe and Kubota [11]. The primary source of heat for the first floor rooms was the roof through the ceiling. For the ground floor (under MM), the mean T_i values at three different levels were approximately 1.5 °C lower than on the first floor (under FR).

FV and DV recorded better correlation between T_o and T_i compared with WV and NV. This suggests that opening windows at night is a better passive cooling strategy than opening windows during the daytime, which in line with findings by Kubota et al. [2] and Michael et al. [9]. No significant differences were found between mean T_i for the master bedroom, bedroom 2, and bedroom 3 during daytime. As such, differences in mean T_i were not related to physical differences in orientation, window to wall ratio, or air flow rate of the bedrooms.

The findings of this study confirm that FR passive cooling strategies are effective for indoor thermal environments in a two-storey corner terrace house. This is in line with other research studies [2,5,8,9,10,11] that used FR ventilation to release heat from the buildings. Moreover, the study shows the effectiveness of NV in cooling indoor thermal environment is in line with findings of Kubota et al. [2] and Michael et al. [9]. It demonstrates the significant role of outdoor thermal environment in the effectiveness of FR ventilation, this is consistent with findings of Yang and Clements [8] and Michael et al. [9] that the incoming air must be cooler than the indoor temperature to attain the cooling of and remove heat from internal spaces.

However, when compared with relevant international standards, the performance of FR was not adequate to provide a comfortable condition for this modern urban house without assistance from MM ventilation. The calculated T_{op} on the first floor was 31 °C, a proximately 3.3 °C higher than the acceptable comfort temperature defined by ASHRAE Standard 55, 1.8 °C higher than that defined by EN15251, and 0.9 °C higher than that defined by ACE hot-humid. FR ventilation could not achieve the indoor comfort temperature under ASHRAE 55 or EN15251. Meanwhile, FR performed better under ACE hot-humid with 27% of the calculated T_{op} below the acceptable comfort temperature. However, MM ventilation on the ground floor performed better and was 1 °C lower than FR with 58% of T_{op} values below the acceptable comfort temperature under ACE hot-humid.

5. Conclusions

The results of the present study led to the following conclusions:

- Full ventilation and day ventilation configurations showed better correlations between outdoor and indoor temperatures when compared with no ventilation and night ventilation configurations.
- MM ventilation strategy was found to be better than FR strategy for providing thermal comfort in hot and humid climates; the former also performed closer to the international standards.
- Outdoor thermal environment significantly influences the effectiveness of FR ventilation.
- FR strategy alone was found to be inadequate in providing the required thermal comfort.

However, this study was conducted on a single house and each ventilation strategy was measured for only 3 days. In future studies, we plan to allocate a longer period of measurement to capture a wider variation of outdoor conditions. The findings of this study can be applied to a terraced house design, and particularly to window design, to control FR ventilation in residential buildings. Furthermore, the floor heights of residential buildings should be increased to more than 3 m to avoid heat accumulation at high levels during the daytime, as this affects thermal comfort in the room. Further study is also required to avoid dependence on energy-intensive MM ventilation.

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Our special thanks to Dr. Waqas Khalid, Farah Nurhanis, Shahab Bazri, Nurnida Elmira Othman, and Husna Aini from Malaysia-Japan International Institute of Technology, Universiti of Teknologi Malaysia, for their contributions to this research.

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Table 1 Detailed information on the investigated house

Variable	Room					
	Master Bedroom	Bedroom 2	Bedroom 3	Family Area	Living Area	Dining Area
Level	First	First	First	Ground	Ground	Ground
Orientation	West	East	East/South	South	West	South
Floor area (m^2)	15.2	9.6	9.6	16.3	15.2	15.7
External wall area (m^2)	8.1	6.2	16.6			
Window area (m^2)	2.9	2.2	3.6			
Window to wall ratio	0.36	0.35	0.22			
External wall to floor ratio	0.53	0.65	1.73			

Table 2 Building materials used in investigated house

Component	Material	U-value W/(m^2K)]
Window	Aluminium frame fixed single clear glass casement window	5.7
Door	Solid hard wood panel door	0.64
Ceiling (ground floor)	150-mm thick reinforced concrete slab	0.30
Ceiling (first floor)	4-mm thick cement board	1.40
Wall material	114-mm think brick wall with 18-mm thick cement plaster on both sides	2.15
Floor material (ground floor)	150-mm thick reinforced concrete slab with 15-mm thick broken marble finish	0.20
Floor material (first floor)	150-mm thick reinforced concrete slab with 6-mm thick hard wood parquet finish	0.20
Roof covering material	Concrete roof tile	0.70
Shading device to window	Canopy roof with concrete roof tile	0.70

Note: U-value based on common building materials in Malaysia [13].

Table 3 Details of ventilation modes and strategies

Floor	Room	Ventilation Mode	Ventilation Strategy	Date	Window Operation Day (8:00–20:00)	Window Operation Night (20:00–8:00)
First	Master Bedroom, Bedroom 2, Bedroom 3, Family Area	FR	WV	15–18/2/2018	Closed	Closed
			FV	18–21/2/2018	Open	Open
			DV	21–24/2/2018	Open	Closed
			NV	8–11/3/2018	Closed	Open
Ground	Living Area, Dining Area	MM	FR or FR with ceiling fan or CL with ceiling fan	15–24/2/2018, 8–11/3/2018	Open (closed when CL switched on)	

Note: FR: free running, MM: mixed mode, WV: without ventilation, FV: full ventilation, DV: day ventilation, and NV: night ventilation, CL: cooling mode.

Table 4 List of instruments used

Space	Instrument	Parameter	Manufacturer, Country	Sensor Type	Resolution	Accuracy and Range
Indoor	Thermo recorder U12-013	T_i	Onset, USA	External sensor tmc1-hd	0.03 °C	±0.35 °C [0 °C to 50 °C]
		T_g		External sensor tmc1-hd + 40 mm black sphere		
		RH_i		Internal sensor	0.05% *RH*	±2.5% *RH* (10% to 90%)
	Hot-wire anemometer	V_i	Kanomax, Japan	Needle probe 6542-2G	0.01 m/s	±2% of reading or ±0.015 m/s whichever is greater
	TR-76Ui	CO_2 concentration	T&D, Japan	Internal sensor		±50 ppm ±5% reading [0 to 9999 ppm]
	Data logger GL820	T_i T_s	Graphtec, Japan	Thermocouple type K		±(0.05% of reading +1.0 °C)
Outdoor	Thermo recorder U12-013	T_o	Onset, USA	External sensor tmc1-hd	0.03 °C	±0.35 °C [0 to 50 °C]
		RH_o		Internal sensor	0.05% *RH*	±2.5% *RH* (10% to 90%)
	Ultrasonic anemometer HD52.3D	V_o	Deltaohm, Italy	Ultrasonic	0.01 m/s	±0.2 m/s or ±2% [0 to 35 m/s], ±2% [>35 m/s]
	Pyranometer CM11	*SR*	Kipp & Zonen, Netherlands			sensitivity 7 to 14 μV/W/m²
	Multifunction data logger HD31	CO_2 concentration	Deltaohm, Italy	HD31.B3 CO_2 probe	1 ppm	±(50 ppm + 3% of measure) [0…5,000 ppm]

Table 5 Average ACH of investigated rooms

Room	Volume (m^3)	Average ACH	Standard Deviation	Air flow rate (m^3/h)
Master bedroom	48.6	0.58	0.01	28.0
Bedroom 2	30.7	0.36	0.02	11.0
Bedroom 3	30.7	0.45	0.01	13.7

Note: ACH: air change rate per hour.

Table 6 Indoor air temperature at various height across four FR and MM ventilation strategies.

		Indoor air temperature, T_i (°C)							
Room and Mode	Height	Mean	SD	Mean	SD	Mean	SD	Mean	SD
FR at first floor		WV		FV		DV		NV	
Master bedroom	0.5 m	31.0	1.1	30.1	1.4	30.3	1.0	31.1	1.5
	1.5 m	31.4	1.6	30.9	1.7	30.8	1.5	32.1	2.0
	2.5 m	31.5	1.9	31.2	2.1	30.9	1.7	32.5	2.4
Bedroom 2	0.5 m	31.1	0.8	29.6	1.6	30.6	1.1	30.6	1.4
	1.5 m	31.7	1.3	30.9	2.2	31.2	1.6	31.6	1.6
	2.5 m	31.8	1.6	31.5	2.3	31.5	1.9	32.1	1.9
Bedroom 3	0.5 m	31.7	1.6	29.7	2.4	30.6	1.6	30.9	2.2
	1.5 m	31.7	1.8	30.3	2.6	30.7	1.8	31.3	2.4
	2.5 m	32.2	2.3	31.5	2.8	31.3	2.3	32.4	2.6
Family area	0.5 m	30.9	1.0	30.4	1.2	30.3	1.1	30.8	1.9
	1.5 m	31.4	1.3	31.1	1.6	30.8	1.4	31.4	1.4
	2.5 m	31.7	1.6	31.6	2.0	31.1	1.7	32.0	1.2
MM at ground floor									
Living area	0.5 m	29.6	0.8	29.4	0.7	29.3	0.7	29.9	0.7
	1.5 m	29.8	0.8	29.6	0.6	29.5	0.6	30.0	0.7
	2.5 m	30.4	0.7	29.7	0.5	29.7	0.5	30.3	0.6
Dining area	0.5 m	29.3	0.9	28.9	0.9	29.0	0.9	29.6	0.8
	1.5 m	29.8	0.8	29.4	0.8	29.4	0.8	30.1	0.8
	2.5 m	30.3	0.9	29.9	0.9	29.9	0.9	30.7	1.0

Note: WV: without ventilation, FV: full ventilation, DV: day ventilation, NV: night ventilation, MM: mixed-mode, SD: standard deviation

Table 7 Mean indoor climatic parameters for bedrooms across four FR ventilation strategies.

Mode	Description	Master bedroom	Bedroom 2	Bedroom 3
WV	Equation	$T_i = 0.317T_o + 22.4$	$T_i = 0.298T_o + 23.1$	$T_i = 0.452T_o + 19.1$
	R^2	0.62	0.82	0.77
	Standard Error of slope	0.03	0.02	0.03
FV	Equation	$T_i = 0.355T_o + 20.7$	$T_i = 0.491T_o + 16.8$	$T_i = 0.622T_o + 12.9$
	R^2	0.63	0.89	0.85
	Standard Error of slope	0.03	0.02	0.03
DV	Equation	$T_i = 0.348T_o + 21.0$	$T_i = 0.417T_o + 19.5$	$T_i = 0.508T_o + 16.8$
	R^2	0.67	0.89	0.81
	Standard Error of slope	0.03	0.02	0.03
NV	Equation	$T_i = 0.404T_o + 19.8$	$T_i = 0.435T_o + 18.4$	$T_i = 0.642T_o + 12.2$
	R^2	0.49	0.84	0.80
	Standard Error of slope	0.05	0.02	0.04

Note: WV: without ventilation, FV: full ventilation, DV: Day ventilation, NV: night ventilation, T_i: indoor air temperature, T_o: outdoor air temperature, R^2: coefficient of determination. All the equations are statistically significant ($p<0.001$). Number of sample is 69.

Table 8 Average climatic parameter values in all rooms and ventilation modes

Room	Mode	T_{mrt} (°C)	SD (°C)	T_{op} (°C)	SD (°C)	AH (g/kg_{DA})	SD (g/kg_{DA})
Master bedroom	FR	31.3	1.8	31.3	1.8	18.2	1.0
Bedroom 2	FR	31.1	1.6	31.2	1.6	18.0	1.0
Bedroom 3	FR	31.3	2.4	31.2	2.3	17.6	1.0
Family area	FR	31.1	1.4	31.1	1.4	18.2	1.0
Living area	MM	30.3	0.7	30.0	0.7	18.0	1.2
Dining area	MM	29.6	0.9	29.7	0.9	18.2	1.1

Figure

Fig. 1 Location map of the investigated house (Google Maps, 2019).

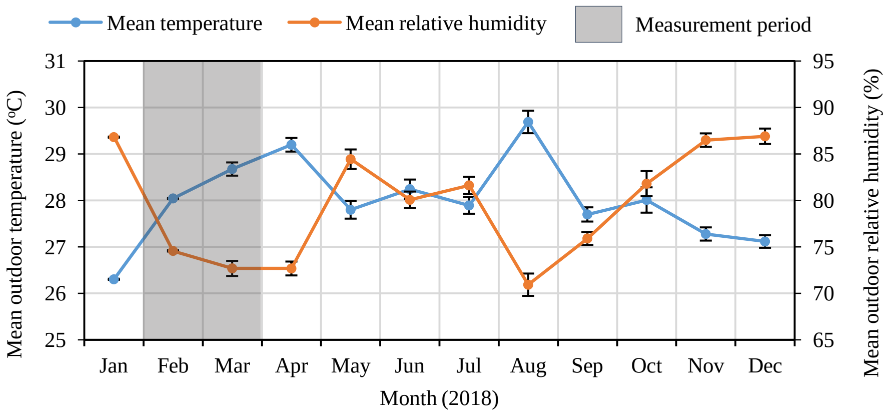
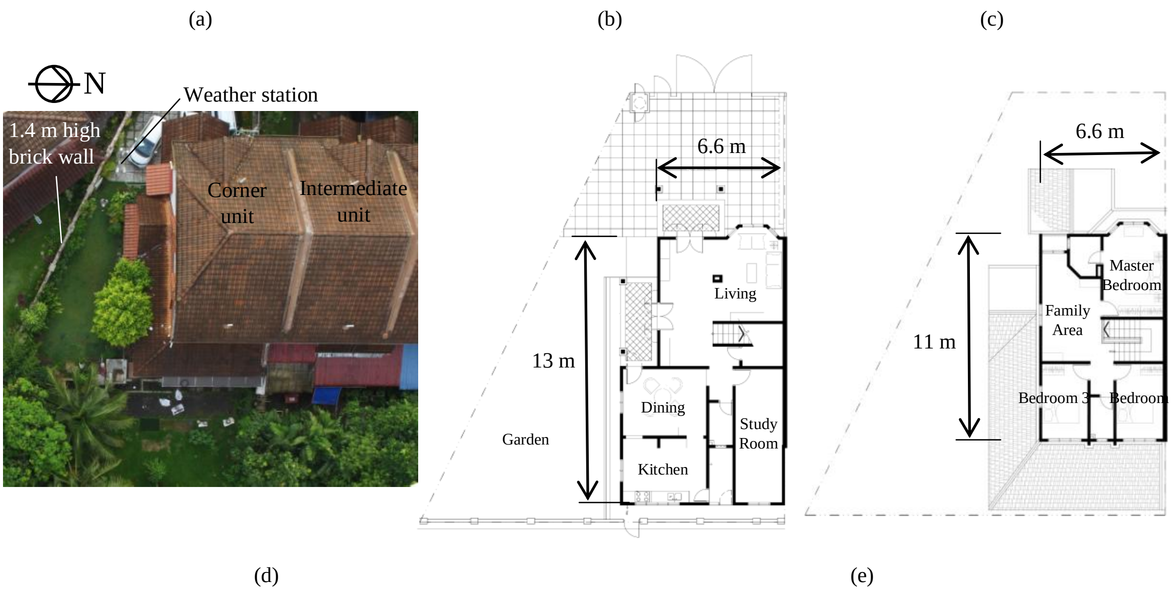


Fig. **2** Monthly mean outdoor air temperature and relative humidity obtained from a weather station located at Universiti Teknologi Malaysia, Kuala Lumpur. Error bars indicate standard errors.



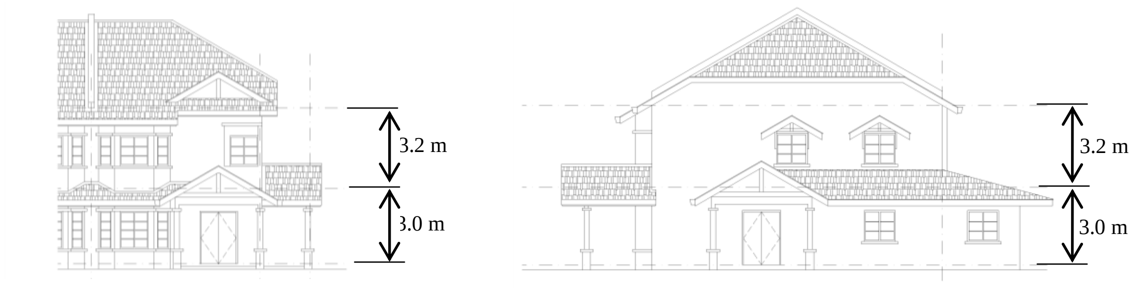


Fig. 3 Images of the investigated house. a) Site plan, b) ground floor plan, c) first floor plan, d) front view from west, and e) side view from south.

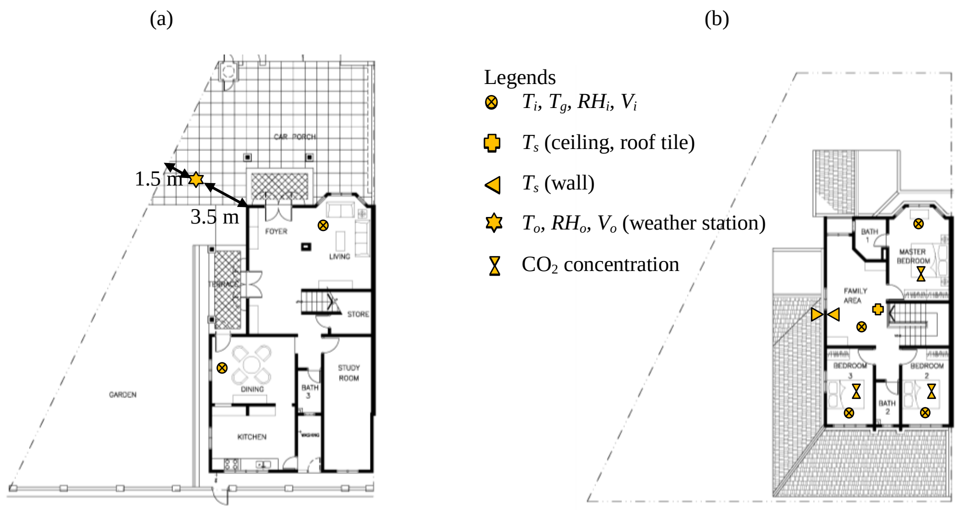


Fig. 4 Measurement locations in the investigated house: a) ground floor and b) first floor.

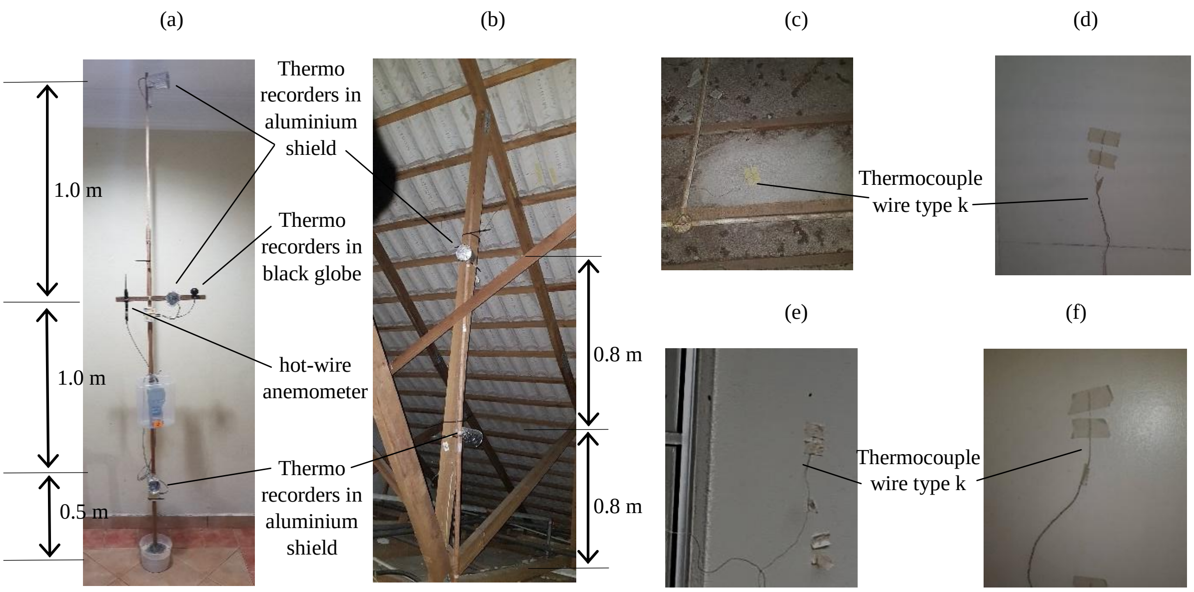


Fig. 5 Indoor measurement setup. a) Thermo recorders, hot-wire anemometer, and thermocouple wire type k at the b) roof attic, c) top of ceiling, d) bottom of ceiling, e) external surface of wall, and f) internal surface of wall.

(a) (b)

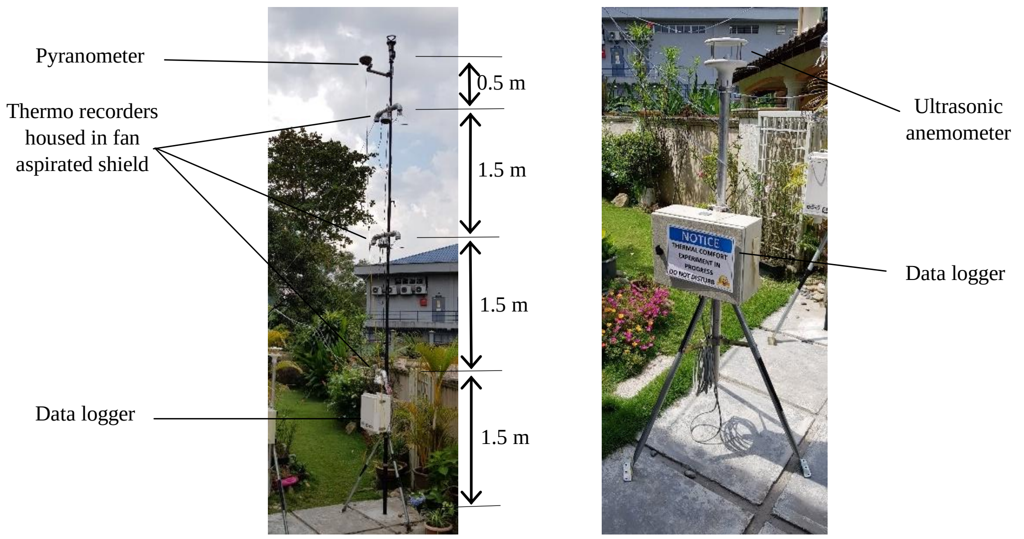


Fig. 6 Equipment setup for outdoor measurement. a) Thermo recorders and pyranometer; b) ultrasonic anemometer

Fig. 7: Layout of target house with surrounding building. Solid red circle refers to the location of the weather station (Microsoft Maps, 2019).

(a) (b)

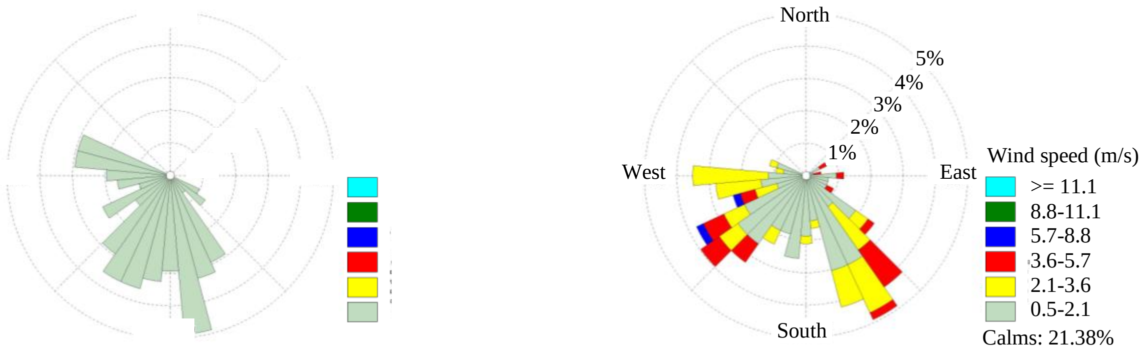


Fig. 8 Hourly mean wind speed and direction from 15 February 2018 to 11 March 2018 measured at (a) local weather station and (b) Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia weather station.

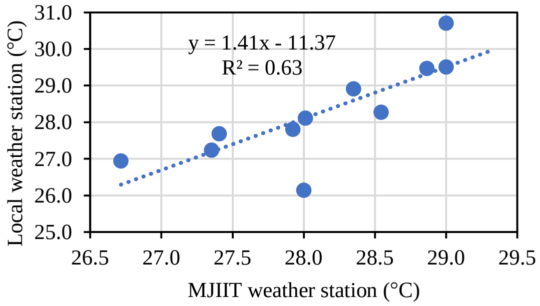


Fig. 9 Comparison of daily mean air temperature from 15 February 2018 to 11 March 2018 between local weather station and weather station at Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia.

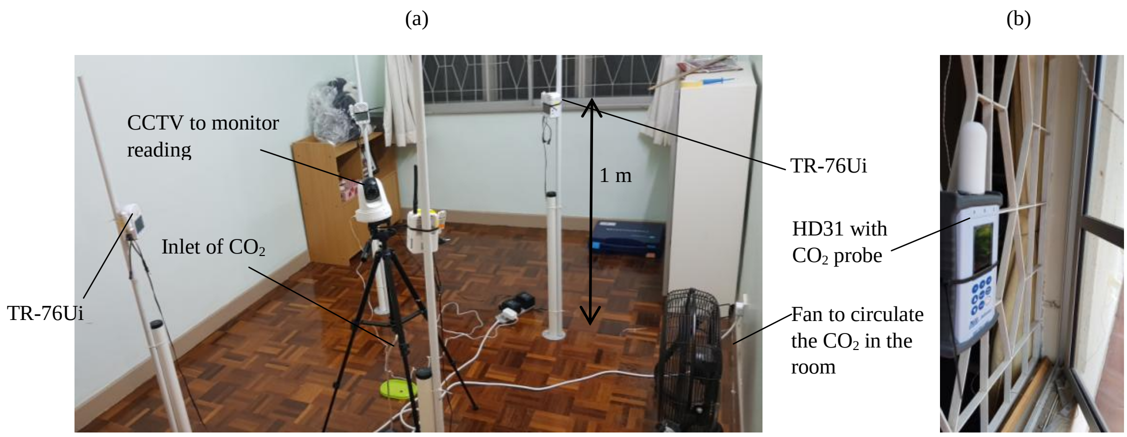


Fig. 7 Equipment setup for CO_2 concentration measurements. a) Indoor and b) outdoor.

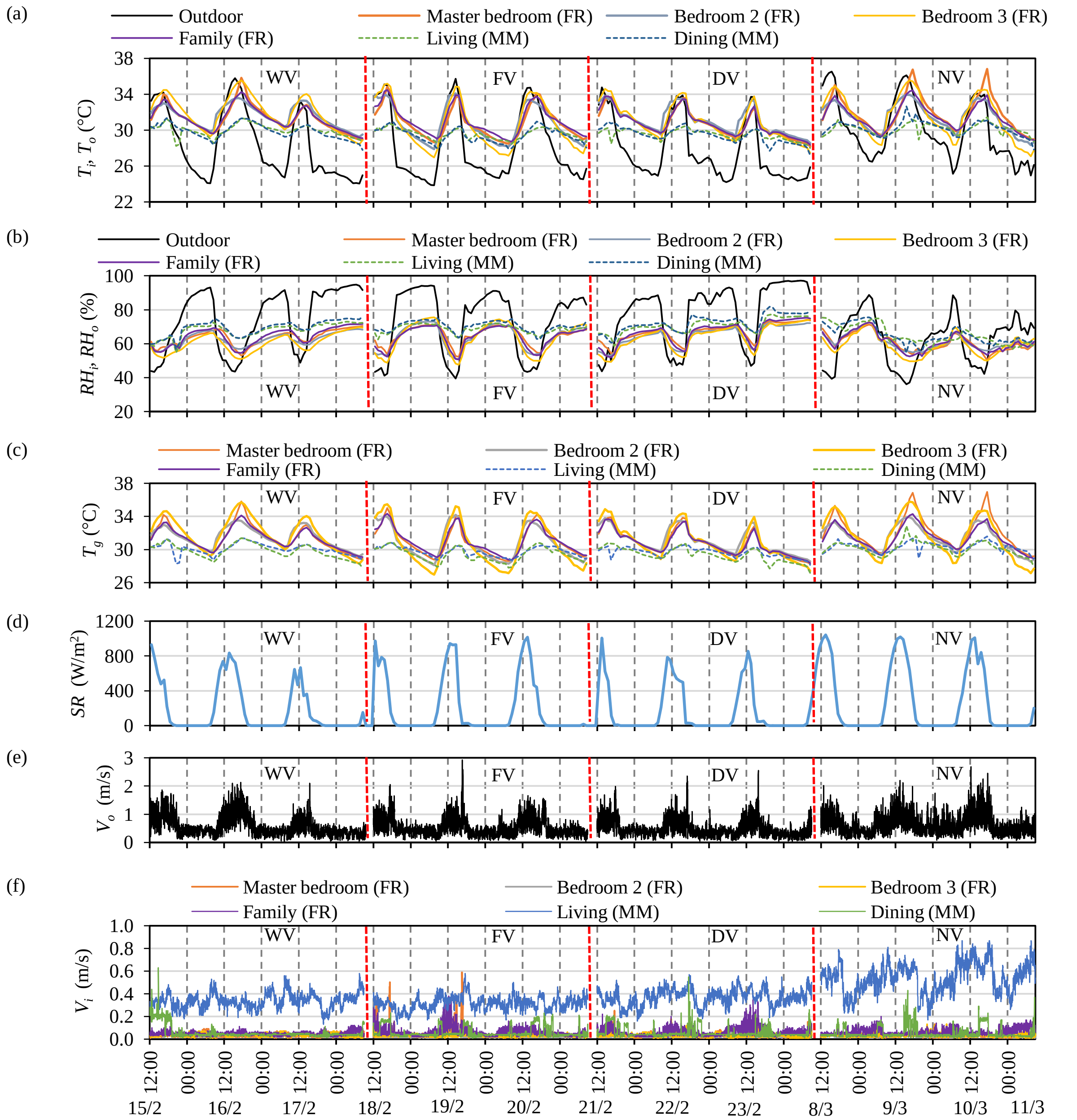


Fig. 8: Temporal variations of indoor and outdoor climatic parameters during measurement period: a) air temperature, b) relative humidity, c) globe temperature, d) solar radiation, e) wind speed, and f) air velocity. Note: WV: without ventilation, FV: full ventilation, DV: day ventilation, NV: night ventilation.

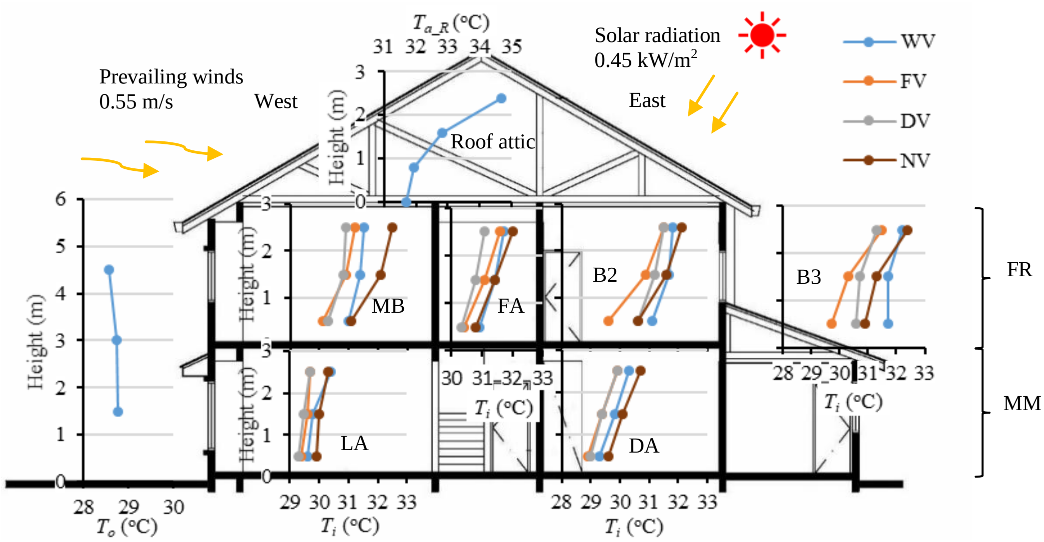


Fig. 9 Vertical profile of average indoor T_i and outdoor T_o at three different heights across four ventilation strategies. Note: MB: master bedroom, FA: family area, B2: bedroom 2, B3: bedroom 3, LA: living area, DA: dining area, FR: free running, MM: mixed mode, WV: without ventilation, FV: full ventilation, DV: day ventilation, NV: night ventilation.

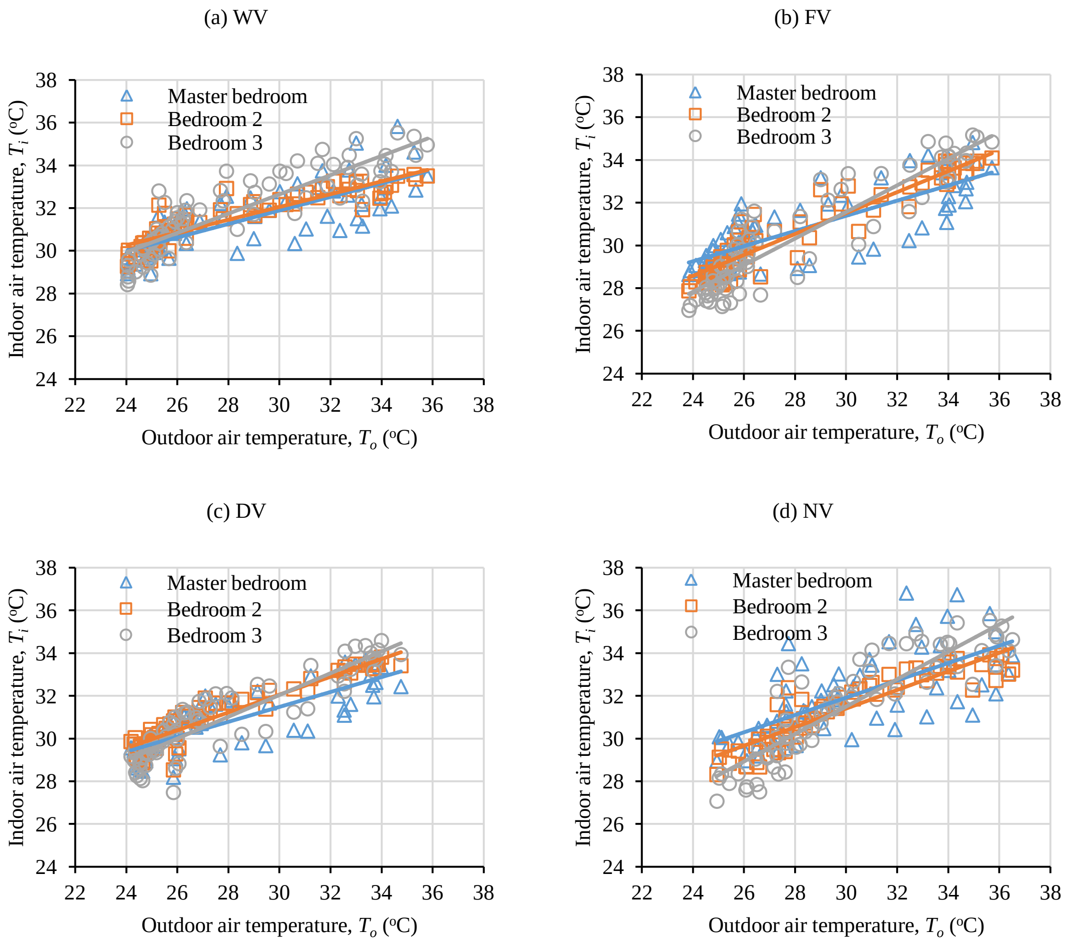


Fig. 10 Correlation between T_o and T_i across four ventilation approaches: a) WV, b) FV, c) DV, and d) NV. Lines show regression equations: blue, master bedroom; orange, bedroom 2; grey, bedroom 3. Note: Number of samples is 69, WV: without ventilation, FV: full ventilation, DV: day ventilation, NV: night ventilation.

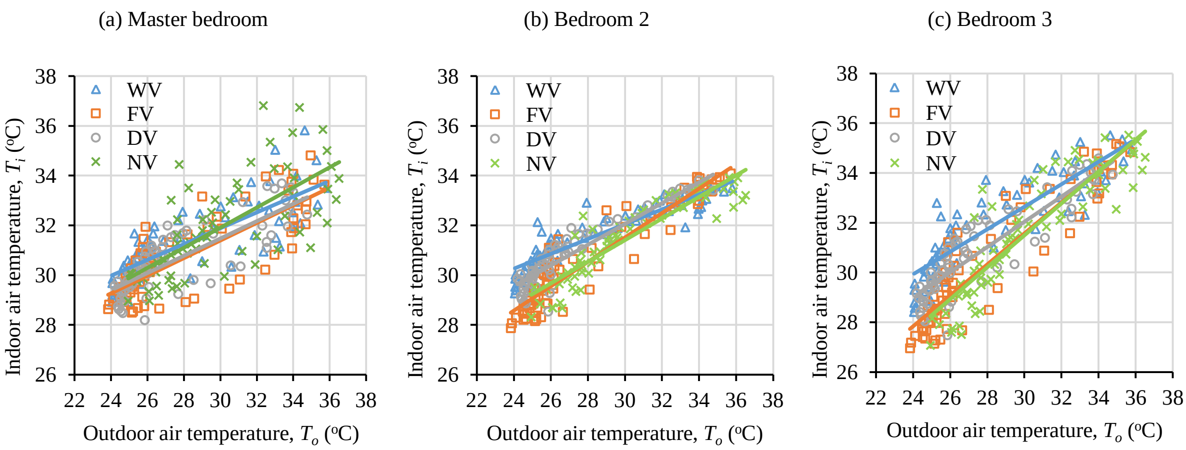


Fig. 11 Correlation between T_o and T_i across three bedrooms: a) master bedroom, b) bedroom 2, and c) bedroom 3. The lines show the regression equations: blue, WV; orange, F;, grey, DV; green, NV. Note: Number of samples is 69, WV: without ventilation, FV: full ventilation, DV: day ventilation, NV: night ventilation.

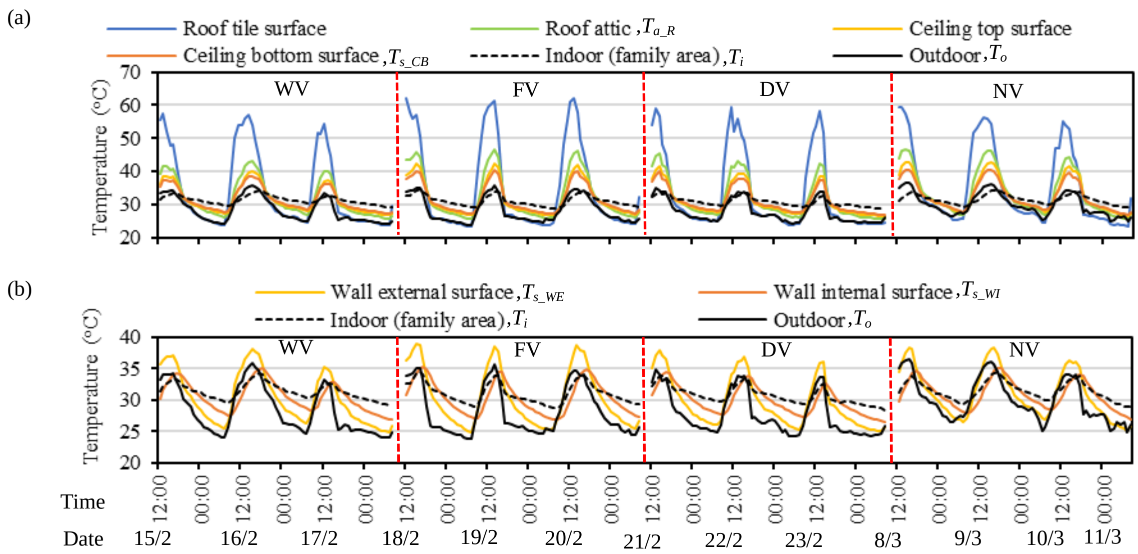


Fig. 12 Comparison between T_s and T_i across four ventilation strategies. a) T_s for top and bottom surface of ceiling board and roof tile, and T_i for roof attic; b) T_s for external and internal surface of external wall, and T_i for indoor and T_o for outdoor. Note: WV: without ventilation, FV: full ventilation, DV: day ventilation, NV: night ventilation.

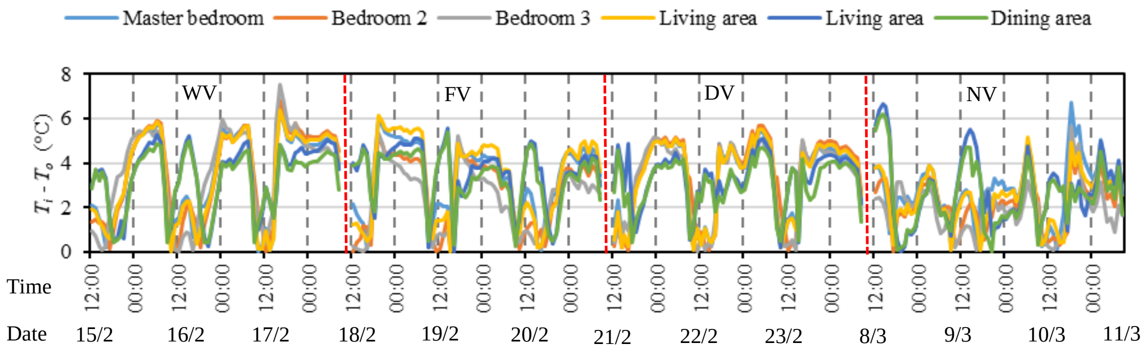


Fig. 13 Variations in difference between indoor and outdoor air temperature across four ventilation strategies. Note: T_i: indoor air temperature, T_o: outdoor air temperature, WV: without ventilation, FV: full ventilation, DV: day ventilation, NV: night ventilation.

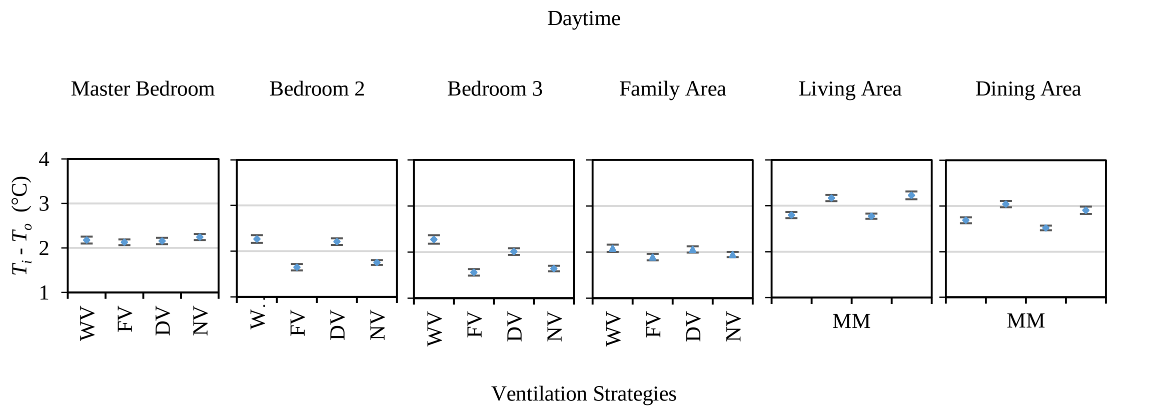


Fig. 14 Variations in mean difference between indoor and outdoor air temperature across four ventilation strategies for daytime. Note: T_i: indoor air temperature, T_o: outdoor air temperature, WV: without ventilation, FV: full ventilation, DV: day ventilation, NV: night ventilation, MM: mixed mode.

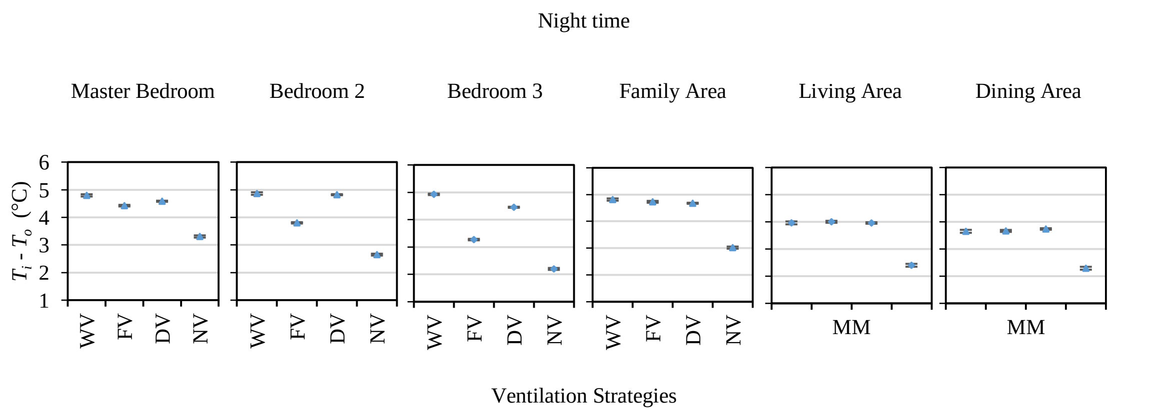
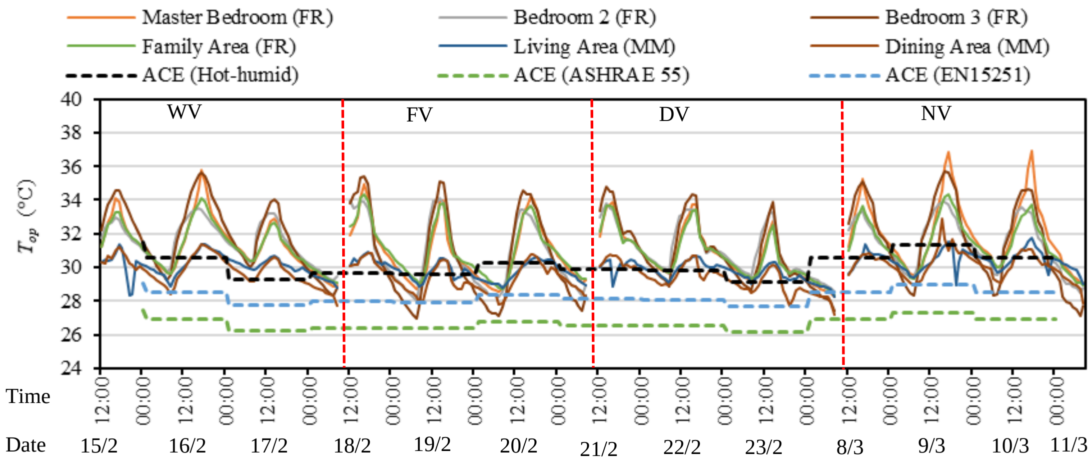


Fig. 15 Variation of mean difference between indoor and outdoor air temperature across four ventilation strategies for night time. Note: T_i: indoor air temperature, T_o: outdoor air temperature, WV: without ventilation, FV: full ventilation, DV: day ventilation, NV: night ventilation, MM: mixed mode.



Note: FR: free running, MM: mixed mode, SD: standard deviation, T_{mrt}: mean radiant temperature, T_{op}: operative temperature, *AH*: absolute humidity.

Fig. 16 Operative temperatures for all rooms across four ventilation approaches compared with related international standards.