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Toward Sustainable Building Design: Improving Thermal Performance by Applying Natural Ventilation in Hot–Humid Climate

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Abstract

This study primarily aims to investigate the improvement in indoor thermal conditions by passive cooling approaches without auxiliary cooling from air-conditioning equipment. A field study is carried out in The View apartments, Penang, Malaysia, to ascertain the environmental performance of these glazed residential buildings. This study explores the potential of using natural ventilation as a passive cooling system for residential buildings in Malaysia. The impact of natural ventilation strategy is investigated in selecting different rooms, days and orientations. The impact of daytime and night-time natural ventilation as a passive cooling strategy is also investigated and compared with that of unventilated situations. Results show significant improvements in indoor environmental performance by 80% and 50% at daytime and night-time, respectively, in cases where natural ventilation is applied and considered in the building.

Keywords: Hot–Humid Climate, Natural Ventilation, Residential Building, Sustainable Design, Thermal Performance

1. Introduction

With the threat of global warming and increasing energy cost, keeping residential buildings cool will become increasingly important. Hot and humid regions are one of the hardest climates to ameliorate through design because high humidity and daytime temperatures result in high indoor air temperatures exceeding the upper limit of the thermal comfort zone. Malaysia has maintained high economic growth; therefore, its energy consumption has increased dramatically. Commercial and residential buildings alone account for about 13.6% of total energy consumption and 48% of electricity consumption[1,2]. Therefore, Malaysia has a strong need and great potential to apply efficient strategies in lowering energy consumption in buildings. Thus, buildings, energy and the environment have become some of the key issues facing the building professions[3]. With the increasing population and living standards, energy is becoming more and more important because of a possible energy shortage in the future[4].

The availability of cheap energy resources has promoted the construction of houses with ineffective envelope designs without consideration of the utilization of natural resources. Such promotion has resulted in complete reliance on mechanical means to manipulate indoor temperature and finally achieve thermal comfort at high energy consumption. The South East Asian Average Building Energy Index (BEI) is 233 kWh/m^2/yr, whereby the Malaysian average is 269kWh/m^2/yr, whereby 64% is for air conditioning, 12% lighting and 24% general equipment[5]. However, the level for low energy buildings recommended by Green Building Index GBI is between 90-150 kWh/m^2/yr[6]. For example, an analysis of building energy consumption in Hong Kong, Singapore and Saudi Arabia shows that the building envelope design accounts for 37%, 25% and 43%, respectively, of the peak cooling load[7–9]. A study of household energy use[10] by the Center for Environment, Technology and Development, Malaysia, found that air conditioning takes up nearly 45% of the average household electricity consumption and that air conditioning is the largest consumer of electricity in the home (Figure 1). The results of a national census showed

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that the total number of households with air-conditioners in Malaysia dramatically increased from 229,000 in 1990 (6.5%) to 775,000 in 2000 (16.2%) and then to 1,414,591 in 2010 (22.3%)[11–13].

An alternative method to overcome this problem is by providing natural ventilation that is an efficient passive method for cooling and is energy-efficient. An indoor thermal environment is one of the main important characteristics of buildings. A comfortable thermal environment is a prerequisite for the performance of day-to-day activities. In traditional buildings, a comfortable environment is achieved solely by utilizing a proper combination of building materials and natural resources. Thus, this study aims to overcome the overheating problem in high-rise glazed residential buildings in Malaysia.

2. Previous Studies

In hot and humid climates, indoor air temperature is normally higher than outdoor air temperature, especially in glazed building envelopes, because of internal heat gains and solar radiation transmitted through the building enclosure. Thus, many studies have investigated the impact of natural ventilation in buildings in tropical regions, such as Malaysia[14–18]. Most of these studies have focused on the effect of natural ventilation on reducing indoor air temperature, reducing energy consumption and enhancing users' thermal comfort. However, few of these studies have dealt with the large glazed area as a main material for a new high-rise residential building façade. Thus, this study aims to evaluate the dynamic behavior of different room orientations under different ventilation strategies in highly glazed residential buildings to properly select the combination that minimizes dependence on mechanical means and enhances indoor thermal comfort.

Liping and Hien[19] studied the impacts of various ventilation strategies and building envelopes on indoor thermal environments for naturally ventilated residential buildings in Singapore by coupled simulations between building simulation ESP-r and CFD-Fluent. Four ventilation strategies, namely, night-time-only ventilation, daytime-only ventilation, full-day ventilation and no ventilation, were evaluated for hot–humid climate according to the number of thermal discomfort hours in the whole typical year. The full-day ventilation strategy is the best way to increase indoor thermal comfort. The optimum window-to-wall ratio (0.24) can improve indoor thermal comfort for full-day ventilation and 600 mm horizontal shading devices are needed for each orientation to improve thermal comfort. Another study by Haase and Amato[20] investigated the impact of natural ventilation as well as building location and climate on thermal comfort. Natural ventilation has good potential in tropical regions. In Kuala Lumpur the improvement of thermal comfort by natural ventilation ranged between 9% and 41%.

Tantasavasdi et al.[21] explored the potential of using natural ventilation as a passive cooling system to reduce the energy used for new house designs in Thailand. If natural ventilation is used in the winter months, the total energy savings are less than 20% in a year. However, indoor air quality would significantly improve. A study in 2011[14] used field measurement and computer simulation tools to investigate the thermal performance of ventilated and unventilated glazed rooms in Malaysia. Rooms with a large glazed window area are relatively cool during night-time only and a small glazed window area performs well during daytime as well as at night-time.

By contrast, the night ventilation concept has been developed further for buildings in hot–humid climates at the Florida Solar Energy Center FSEC. Chandra[22] used a ceiling fan to raise the indoor convective heat transfer coefficient and increase the night ventilation rate. Night ventilation seems to be the most promising concept to use for heat removal. Many studies have investigated night ventilation, but experimental and theoretical studies on the appropriateness of the technique in the tropics have not been documented properly. Another study[18] investigated through experimental study the effectiveness of night ventilation for residential buildings in the hot–humid climate of Malaysia. Most occupants use daytime ventilation instead of night ventilation in Malaysian residential areas. Field experiment results show that full-day ventilation provides better thermal comfort for occupants in Malaysian houses than other ventilation strategies.

3. Climatic Analysis

Penang is an island located north of Peninsular Malaysia on its west coast. The local latitude of Penang is 5.35°N and its longitude is 100.30° E. The local climate is hot and humid tropical characterized by uniform high temperatures, high humidities and abundant rainfall throughout the year. According to the Malaysian Meteorological Department[23], Malaysia has a diurnal temperature ranging from a minimum of 23 °C to 27 °C to a maximum of 30 °C to 34 °C. Thus, no particular hot or cold season is observed. Annual rainfall is evenly distributed throughout the year and relative humidity ranges from 74% to 86%, although the months of September to November are considered the wettest. The maximum (max), minimum (min) and average dry bulb temperatures, as well as the average relative humidity in Penang, where the case study is conducted, are shown in Figure 2.

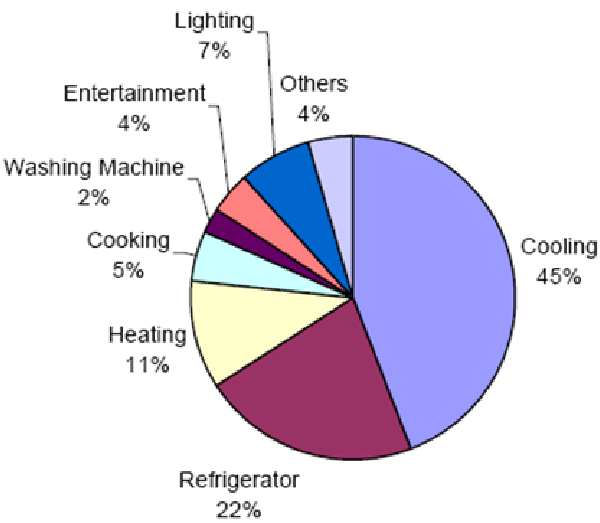


Figure 1. Average home electricity consumption (CETDAM 2006).

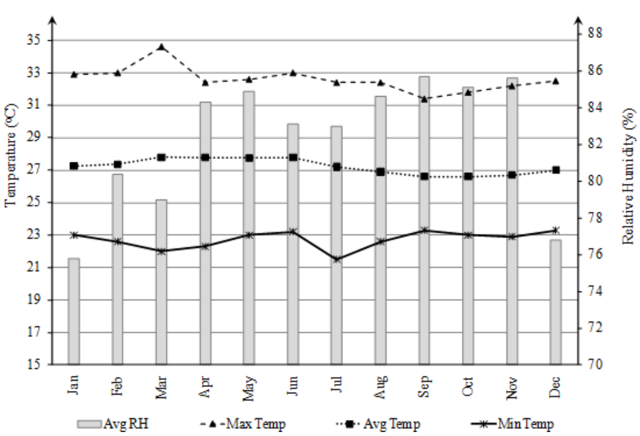


Figure 2. Maximum, minimum, and average dry bulb temperature and average relative humidity in Penang.

According to the 10-Day Agromet Bulletin[23], some places in Penang exhibit the highest daily solar radiation of more than 6.1 kWh/m^2 per day. This energy cannot be utilized efficiently, thus creating discomfort and causing heat gain problems that should be eliminated from building space.

4. Baseline and Methodology

4.1 Baseline Configuration

The View (Twin Towers) condominium (Figure 3.) is located at Gelugor district, Penang, Malaysia. The residential scheme consists of two towers (A and B), each 29-storey high with three units on each floor. The two towers are connected by a sky-bridge at the 14th floor and both towers have a total of 164 units. The View was developed and constructed by Ivory Properties Group, which completed project construction in 2007. Given site considerations such as the Penang Bridge and the sea view, the buildings are oriented to the southeast (tower A) and the northeast (tower B). The floor area of each unit is approximately 184 m^2. The View's residential design is selected because it exemplifies the trend of modern residential design, which has mostly glass façade that can contradict energy-efficient building design in the tropics.

4.2 Description of Rooms

The potential of using natural ventilation as a passive cooling system is investigated in three rooms at The View, namely, A9, B3 and A10. A and B indicate the tower's name and the associated numbers indicate the room's level. The room's location, orientation and geometrical shape are illustrated in Figures 4 to 6. The natural ventilation impact on indoor thermal performance was investigated through these three rooms for the following reasons:

- The three spaces have the same geometric form and volume, with an overall floor area of 19.4 m^2 and a volume of about 62.1 m^3.
- The rooms have the same WWR and WFR of about 40% and 80%, respectively.
- The rooms are designed to allow cross-ventilation through two operable windows in different orientations.
- The rooms have high thermal mass. The external wall material is reinforced concrete (45 cm thick), making the windows the main source of overheating the indoor environment.

- The rooms also have the same inlet area, which accounted for about 14.5% of the total glazed area.
- However, the only difference between the rooms is their orientation.

Figure 3. The View's main elevation, Penang.

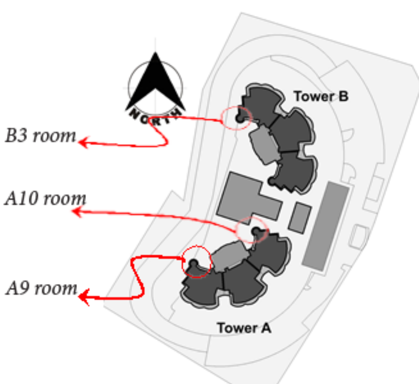


Figure 4. The View's top view indicating selected rooms.

4.3 Methodology

The dynamic behavior of different room orientations under different ventilation strategies should be evaluated to properly select the option that minimizes dependence on mechanical means and reduces energy consumption. This study explores the potential of using natural ventilation as a passive cooling system for residential buildings in Malaysia. The impact of natural ventilation strategy is investigated in selecting different rooms, days and orientations. For analyzing the effect of natural ventilation, the performance of each room in both towers has been measured in terms of MRT, air velocity and in/outdoor air temperature T_i and T_o. For this purpose continuous environmental monitoring was carried out using several data logging equipment BABUC/A and BABUC/M. A continuous measurement was undertaken in each room during the period of April to July. The data logger station was placed at the central part of each room at 1 m above floor level. The parameters were measured at 10 minute intervals and recorded continuously. Ventilated condition was depicted with all operable windows open, while un-ventilated condition with windows tightly closed. For more comprehensive analysis and to investigate the effect of solar radiation in day time as compared to no solar radiation at night-time, in/outdoor environmental data has been separated to two parts, that is (7:00 AM – 7:00 PM depicting day-time) and (7:00 PM – 7:00 AM depicting night-time). At the end of the measurement period the data was exported to Microsoft Excel 2007 spreadsheet for analysis.

4.4 Observation

The rooms' description above indicates that the room geometry is a compact shape that increases heat gains

Figure 5. Geometry of typical room.

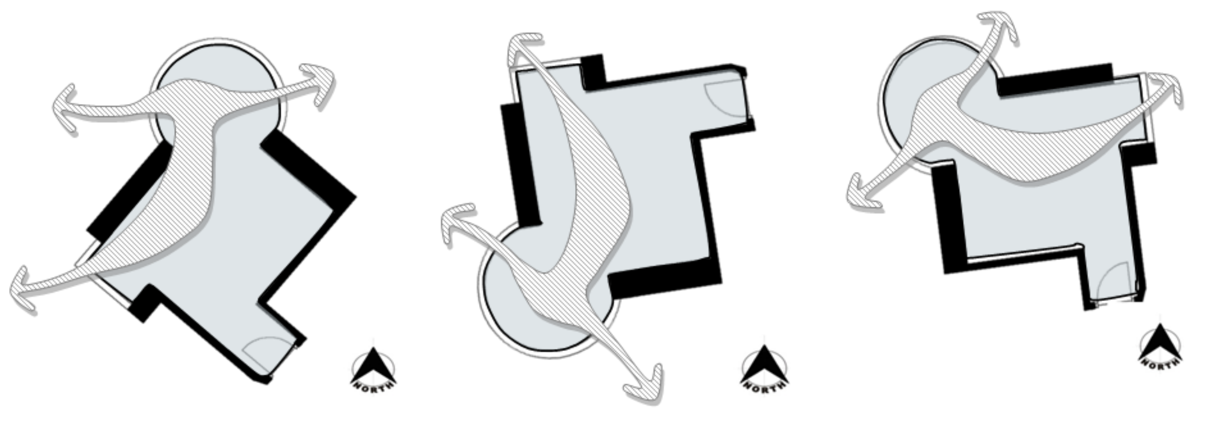


Figure 6. Estimated indoor air behavior caused by operable windows.

because of the large glazed area. Moreover, there is no particular orientation could be seen in any investigated rooms due to that each room has an opening glazed windows in varied external walls. Therefore, the long axes of the rooms are faced (NE and SW), (N and SW) and (E and W) respectively. The impact of natural ventilation on improving indoor thermal comfort is also discussed. Figure 6 shows that the opening aperture area (i.e., 14.5% of the total glazed area) is too small to achieve adequate natural ventilation for an acceptable comfort level. By contrast, the room is designed to have two windows in opposite directions; this design increases air flow even under closed-door conditions. Thus, the cross-ventilation effect in this particular room can remove significant internal heat gain caused by the large glazed area and create a comfortable indoor environment depending on outdoor climate conditions.

5. Results and Discussion

5.1 Data Analysis

The figures below show that when spaces are naturally ventilated through open windows and even when wind reaches lower speeds, especially at daytime, indoor air temperature in the three rooms approaches the outdoor air temperature level. Therefore, a maximum difference in indoor/outdoor air temperature occurs mainly during night-time because of high wind hourly speeds during the day and mostly calm periods at night. However, in unventilated spaces, indoor air temperature does not follow outdoor temperature, with maximum differences between them particularly during night-time.

5.2 Room Thermal Behavior during Daytime

The interior air temperature rises considerably above the outdoor air temperature in the three rooms when they were unventilated during daytime as depicted in Figures 7, 9 and 11. The differences between in/outdoor air temperature during daytime reached 3.55 , 2.34 and 3.80 °C in unventilated rooms A9, B3 and A10, respectively. It is worth mentioning that all opening were air tight, thus, the infiltration rates was zero. Moreover, those rooms are unprotected from intensive solar radiation during daytime, especially A10, which is oriented to the east–west axis. According to thermal comfort requirements for tropical climate, in these conditions, the rooms can be uncomfortable even when outside temperature is pleasant.

By contrast, when the rooms are ventilated during daytime (Figures. 8, 10 and 12), the temperature of the indoor air and surfaces closely follows the ambient temperature. Figures 13 and 15 show that the differences in indoor/outdoor air temperature reach 0.72, 0.59 and 0.80°C in A9, B3 and A10, respectively. Therefore, the reduction in indoor air temperature in the three rooms exceeds about 79.72%, 74.79% and 78.95% compared with that in the previous unventilated condition. The average indoor air temperatures recorded during daytime are 30.07, 29.76 and 28.75°C in the three rooms. Thus, despite the significant reduction by applying natural ventilation

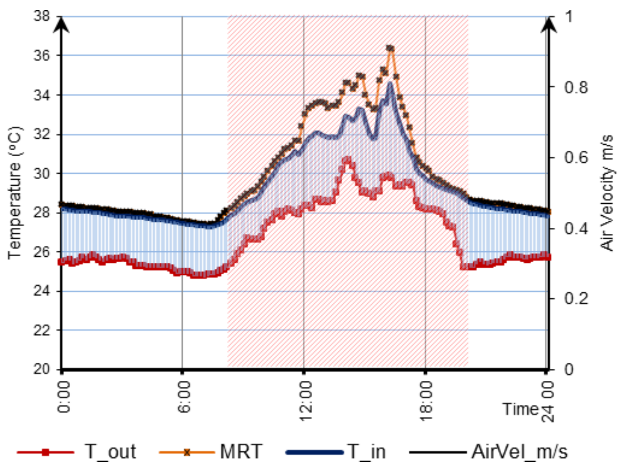


Figure 7. Room (A9)unventilated on 13 April 09..

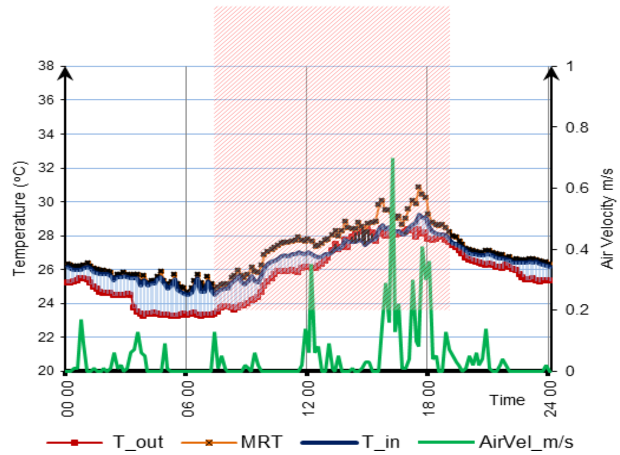


Figure 8. Room (A9) ventilated on 21 April 09.

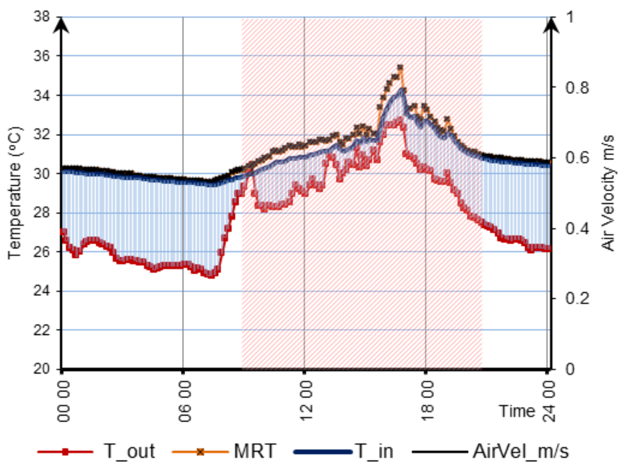


Figure 9. Room (B3) unventilated on 7 June 09.

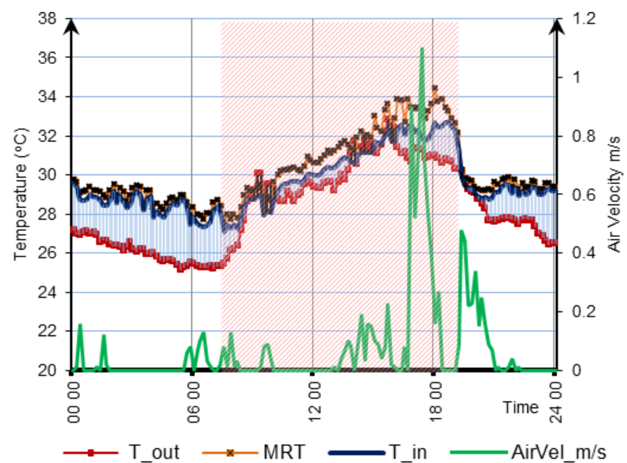


Figure 10. Room (B3) ventilated on 9 June 09.

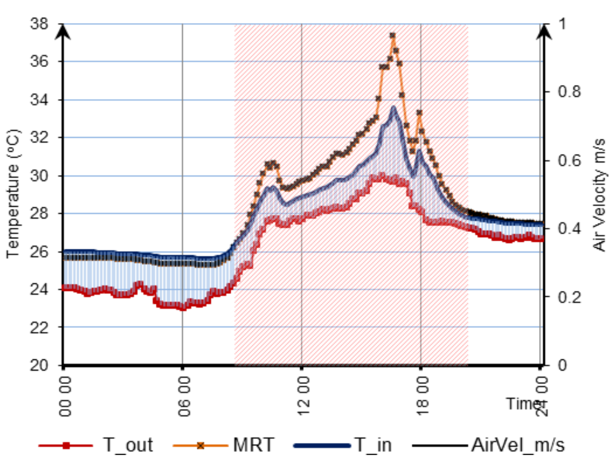


Figure 11. Room (A10) unventilated on 13 July 09.

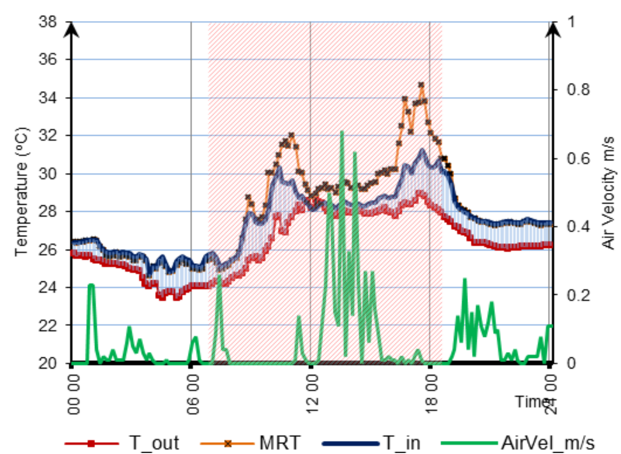


Figure 12. Room (A10) ventilated on 14 July 09.

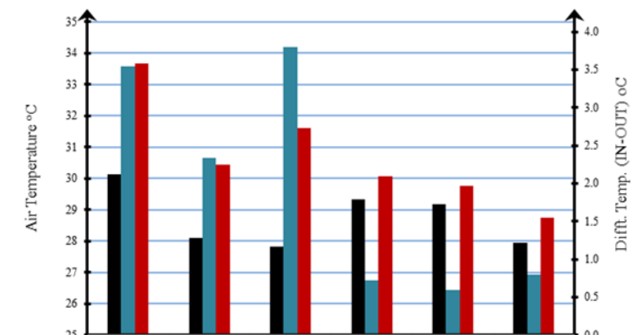
during daytime, the indoor air temperature is still higher than the comfortable level.

5.3 Rooms' Thermal Behavior during Night-Time

Without ventilation during night-time, the indoor air temperature was kept higher than the outdoor air temperature. Figures 14 and 16 show that the differences in indoor/outdoor air temperature increase during a heat wave period up to 1.9, 3.0 and 1.3°C in A9, B3 and A10, respectively. This increase was achieved by the high thermal mass of the external walls and also because of the high tied windows with minimum infiltration range and intensive solar gain during daytime. Because of these conditions, the rooms can be quite uncomfortable even when outside temperature is pleasant.

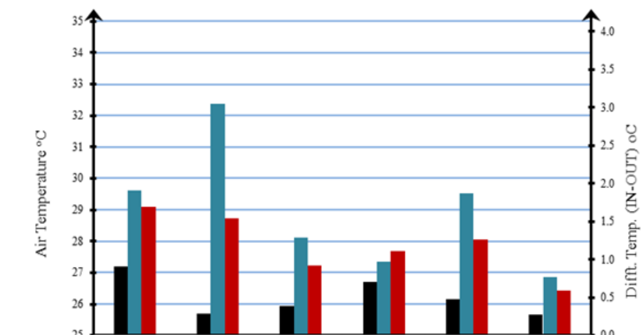
By contrast, when the rooms are ventilated at night, indoor temperature during night hours drops drastically, in turn lowering the indoor daily average temperature. Consequently, the indoor air speed, even when windows are open, is significantly low at night and the indoor/outdoor temperature differences are greater than those during daytime. Figure 16 indicates that calm periods occur mostly at night. The average indoor/outdoor differences are 0.96, 1.87 and 0.76°C in A9, B3 and A10, respectively. Therefore, the reduction in indoor air temperature during night-time in the three rooms exceeds 50%, 38.7% and 41% compared with that in previous unventilated conditions.

As a result of the combination of low air speed and warm temperature, the indoor environment is often



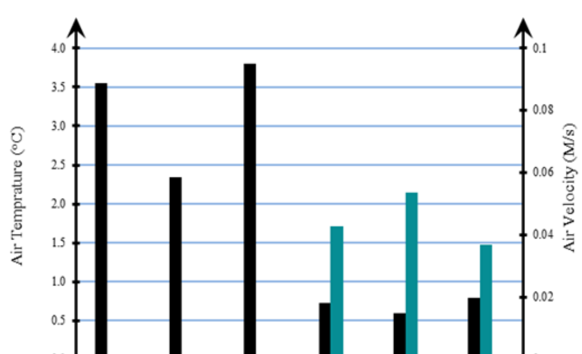
	R3-A9-UnVent	R3-B3-UnVent	R3-A10-UnVent	R3-A9-Vent	R3-B3-Vent	R3-A10-Vent
OUTDOOR	30.12	28.09	27.81	29.34	29.17	27.95
INDOOR	33.67	30.43	31.61	30.07	29.76	28.75
Diff In-Out	3.55	2.34	3.80	0.72	0.59	0.80

Figure 13. Summary of average air temperature in ventilated and unventilated R3 rooms (daytime).



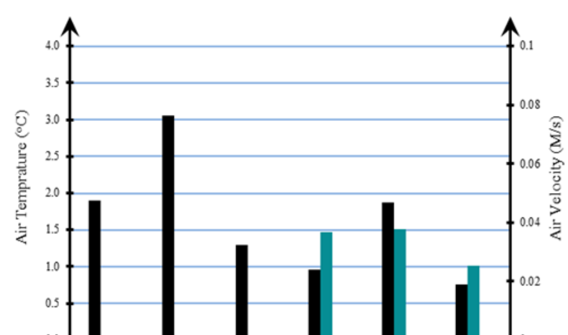
	R3-A9-UnVent	R3-B3-UnVent	R3-A10-UnVent	R3-A9-Vent	R3-B3-Vent	R3-A10-Vent
OUTDOOR	27.18824074	25.68	25.94	26.71	26.17	25.67
INDOOR	29.0912963	28.73	27.23	27.67	28.04	26.43
Diff In-Out	1.90	3.05	1.29	0.96	1.87	0.76

Figure 14. Summary of average air temperature in ventilated and unventilated R3 rooms (night-time)..



	R3-A9-UnVent	R3-B3-UnVent	R3-A10-UnVent	R3-A9-Vent	R3-B3-Vent	R3-A10-Vent
Diff In-Out	3.55	2.34	3.80	0.72	0.59	0.80
% of Diff's Reduction	0.00	0.00	0.00	79.6%	74.7%	79.0%
Air Velocity	0	0	0	0.04	0.05	0.04

Figure 15. Air temperature reduction with reference to air velocity in ventilated and unventilated R3 rooms (daytime).



	R3-A9-UnVent	R3-B3-UnVent	R3-A10-UnVent	R3-A9-Vent	R3-B3-Vent	R3-A10-Vent
Diff In-Out	1.90	3.05	1.29	0.96	1.87	0.76
% of Diff's Reduction	0.00	0.00	0.00	49.3%	38.6%	40.9%
Air Velocity	0	0	0	0.04	0.04	0.03

Figure 16. Air temperature reduction with reference to air velocity in ventilated and unventilated R3 rooms (night-time).

most uncomfortable during evening hours. In general, naturally ventilated spaces are more comfortable than unventilated rooms regardless of the thermal comfortable level consideration.

6. Conclusion

This study, conducted in several series over many weeks, demonstrates the following:

- Daytime ventilation with a maximum air velocity cannot bring the indoor average temperature below the outdoor level regardless of the fenestration's orientation. However, the effect of night time ventilation on indoor daytime conditions may not always be significant.
- The natural ventilation reduces the difference in T_i-T_o by 80% and 50% during daytime and night-time, respectively.
- It is noticed that the glazed area in all investigated rooms are quite large compared to aperture area. It would be suggested that if the aperture area is increased at the expenses of the glazed area, a positive results could be achieved.
- The field experiment results show that full-day ventilation provides better thermal condition for occupants in Malaysian apartments compared with other only day/night ventilation strategies.

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