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Comparison of Different Hybrid Turbine Ventilator (HTV) Application Strategies to Improve the Indoor Thermal Comfort

Ismail, M.* and Abdul Rahman, A. M.

School of Housing, Building & Planning (HBP), Universiti Sains Malaysia (USM), 11800 Penang, Malaysia

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ABSTRACT: This paper discusses the results of the full-scale field measurement study to investigate the most efficient application strategy of the Hybrid Turbine Ventilator (HTV) in improving the indoor thermal comfort in hot-humid tropics. The effects of three different HTV application strategies performance on improving the levels of indoor air temperature, relative humidity (RH) and air velocity were evaluated for a three-clear day period. The results were analyzed and compared based on two thermal comfort indices i.e. Operative Temperature (OT) and Standard Effective Temperature (SET*). The study shows that the HTV for the occupied space with extractor fan at ceiling level is the most efficient strategy when it succeeded to reduce indoor air temperature and relative humidity of up to 0.7°C and 1.7%RH, respectively. It also succeeded to induce air velocity in the occupied level up to 0.38m/s in average and reduced the level of OT by 60% and SET* by 90% compared to the existing condition. The overall results also indicated that the performance of the HTV could be enhanced by applying the device for both occupied space and attic space at the same time and ensure that openings are kept opened.

Key words: Stack ventilation, Turbine ventilator, Solar energy, Thermal Comfort, Hot-humid climate

INTRODUCTION

Generally, building sector consumes about 30-40% of the world's energy demand and it is expected to increase rapidly in the near future (Santamouris, 2005). In South-East Asian countries, example of the hot and humid tropical region, the average energy consumption of building is 233kWh/m²/yr, of which about 60% is for air-conditioning. This scenario of high energy consumption due to the extensive use of air-conditioning system is quite frustrating since various studies indicated that people in hot-humid tropical climate are more tolerable to higher temperature due to the acclimatization factor (Givoni, 1992).

Concerning this issue, various studies have been done in order to find out possible alternatives to air-conditioning without compromising the environment and people's thermal comfort. One of the ventilation strategies that is considerable cheap and technologically simple to operate is the use of wind-driven turbine ventilator (Abdul Rahman, 2004). According to Dale and Ackerman (1993), the conventional Ø305mm turbine ventilator was helpful to increase attic ventilation rates by approximately 15% from 5.3 to 6.1 air changes per hour (ACH) on average as compared to the existing condition of the roof equipped with soffit vents in the test house under the windy condition of USA. On the other hand, Lai (2003) showed that the installation of the device in building or factory in Taiwan high-outdoor wind condition of between 10 m/s to 30 m/s is significantly capable to increase ventilation rate from 60m³/h (with no ventilator) to 140m³/h for a Ø500mm turbine ventilator.

However, since its function is totally depends on the outdoor wind condition, its applicability and effectiveness in erratic and low-wind velocity region is always questionable. These weaknesses have been revealed by Lai (2003) who found that

*Corresponding author E-mail: mazran79@hotmail.com

in the low wind-velocity condition, the fins of the turbine actually blocked the airflow in the connecting duct, resulting in much lower extraction rate of air compared to open stub. This limited use of the turbine ventilator has prompted some researchers worldwide to investigate the possible improvements of the device. West (2001) carried out an experimental study on the effect of turbine height on its ventilation performance and found that 13.5% improvement in flow rates can be achieved by increasing 50% of the blade height. Meanwhile, Khan et al. (2008) investigated the effect of different forms of turbine blades and showed that the curved vane ventilator could produce 25% larger flow rate compared to the straight vane ventilator of the same size.

On the other hand, several studies attempted to investigate the possibility of combining the turbine ventilator with electrical extractor fan in an effort to improve its ventilation performance, especially in the low-wind velocity condition. This includes the study by Kuo and Lai (2005) on the combination of the roof turbine ventilator with bathroom ventilation system equipped with extractor fan in subtropical climate of Taiwan. The study found that such combination is effective to achieve sufficient air change rate required for hygienic need with the ventilation increment created by the ventilator with outdoor airflow (ventilation increment induced by per-unit outer wind speed) was 53.26 CMH/(m/s). Following this study, Lai (2006) conducted a prototype development study of the hybrid turbine ventilator that integrated the wind-force turbine ventilator with PV-powered inner fan and found that the prototype is successful to increase ventilation rate, especially with a rate rotation speed of 1500 rpm and a battery. However, the result showed that its optimal operation could only be achieved in low outdoor wind speed up to 5 m/s. This illustrated the problems of having a turbine itself which could possibly be a major resistance for much higher rate of extraction air that could be produced by the inner fan below. In a more recent study, Zain-Ahmed et al. (2007) investigated the potential of the prototype hybrid ventilator that combined conventional turbine ventilator with lightpipe and found that such combination is significant to improve both indoor ventilation and daylighting conditions.

Following these studies, the authors intend to investigate the actual performance of the hybrid solar-wind turbine ventilator (HTV) in the real building and under real weather conditions by conducting full-scale field measurement study. For this purpose, a new configuration of the HTV with 20cm inner duct in the turbine and larger free outlet area on the upper part was developed in order to allow more extraction rate of air. To evaluate the significance effect of this HTV in improving thermal comfort condition in hot-humid tropical building, three different application strategies i.e. HTV for attic space and 2 HTVs for Indoor (occupied space) with different locations of the extractor fan were studied. This is to find out the most effective strategy in reducing internal air temperature along with relative humidity and at the same time increasing air velocity in the occupied zone. Using simplified comparisons of Operative Temperature (OT) and Standard Effective Temperature (SET*) indices, the results then will lead to reveal the best application strategy for improving indoor thermal environment in this region, and consequently suggests its possibility to be used in the low-wind velocity area worldwide.

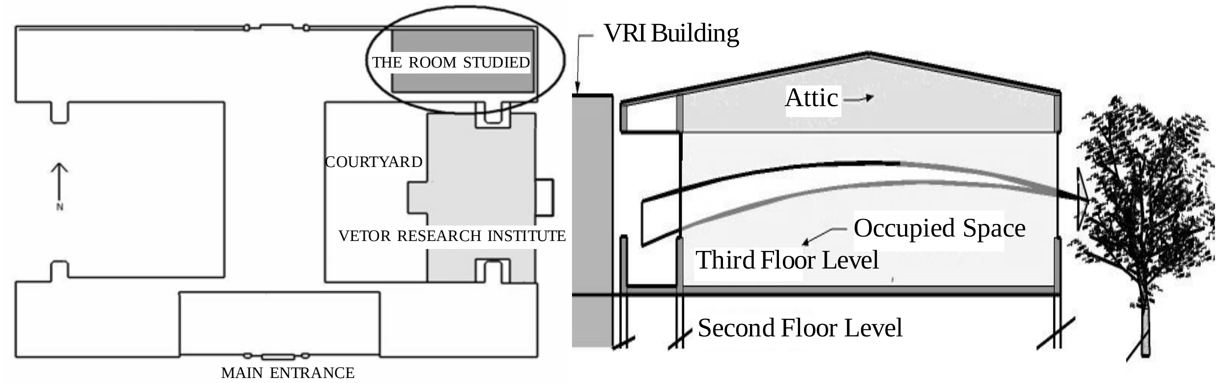
MATERIALS & METHODS

The field study was conducted in the rectangular room (in the top floor of an institutional building in Malaysia) with a dimension of 27.5m x 12m and 2.85 m height. The total floor area is approximately 330.0 m² and the volume of the occupied space and attic is 940.5 m³ and 330.0 m³, respectively. To ensure the conducive indoor environment, insulation barrier in the roof and large openings of 330.0 m² which is equivalent to 17% of the openings to floor area ratio was applied. However, from the observation, the room still suffered a hot indoor air problem which is mainly due to relatively wide area of its roof exposed to the sun. This problem is worsen by the presence of large vegetations and newly built buildings adjacent to it which limit the effectiveness of natural cross ventilation to ventilate the most area of the room (Fig. 1).

As a response to the findings from the previous studies which illustrated that the turbine itself could possibly be a major constraint to achieve higher rate of extraction air, a new configuration of the device with larger free outlet area on the upper part has been developed using conventional 18" turbine ventilator Fig.2(a). Integrated with solar-powered extractor fan with Ø30cm fan blade and Ø35cm aluminum ventilation duct, three complete sets of the HTVs were installed on the roof along with 6 panels of polycrystalline photovoltaic (20 watt each) Fig. 2(b).In order to investigate the most efficient use of the device in improving thermal environment, three different application strategies and the existing condition without it were studied. Table 1 below summarizes all the HTV application strategies studied.

Since the studies have been done on the different days which represent different outdoor climatic conditions, the measurements for both outdoor and indoor conditions were taken. The ambient temperature and relative humidity were measured at a height of 1 meter above the (third) floor level and were protected from the sun. The global solar radiation was measured by a pyranometer located on the parapet wall near the roof. At the same time, all sensors for indoor temperature, relative humidity and air velocity were located in the middle of the room with a distance of 1.0 m above the floor (occupied level) and 6 m from both side walls. Data from all sensors were recorded continuously at fifteen minute intervals for three clear days onto a BABUC data logger for each case. However, the data analyzed in this paper was based only on the period of 9.00am to 10.00pm as this period of time is considered to be among the most critical time to achieve indoor comfort condition under this hot-humid climate.

The main aim of the study is to investigate the effectiveness of each application strategy of HTV in improving indoor thermal environment. Although the results could demonstrate the pros and cons of each strategy, the comparison analysis between all the strategies should be made to reveal the most

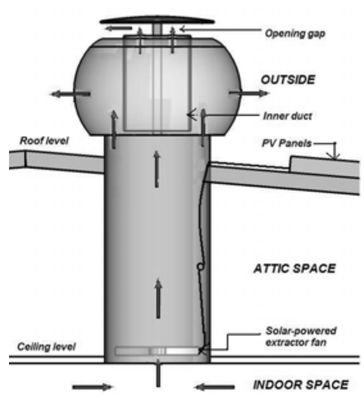
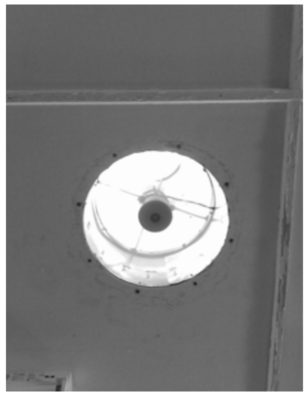
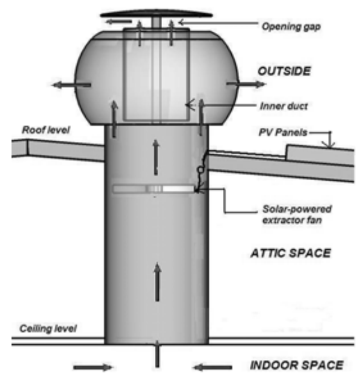
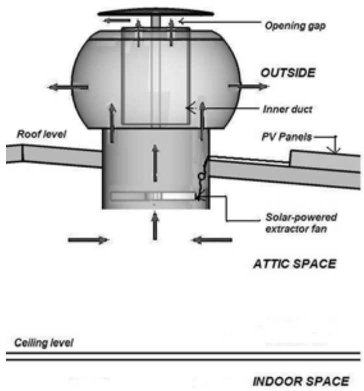


(a) (b)

Fig. 1. The test-bed (a) third floor plan of the building (b) graphic cross sectional view

Fig. 2. Configuration of the HTV (a) before installation (b) three complete sets of the HTV installed on the roof

Table 1. Conceptual designs of the different types of HTV strategies

	Strategies	Configuration	Extractor fan location
1.	**Hybrid Turbine Ventilator (HTV) for Indoor** (fan at ceiling level)		
2.	**Hybrid Turbine Ventilator (HTV) for Indoor** (fan near roof level)		
3.	**Hybrid Turbine Ventilator (HTV) for Attic**		

efficient application strategy under the hot humid climate of this region. Therefore, two simplified comparisons were made;In comparing the ventilation performance of each strategy that was done in different days which represents various climatic conditions, the authors realized that it is not easy and almost impossible to produce the accurate and objective answer. However, a simplified comparison using Relativeness Index (RI) was used as an indicator to formulate general and subjective conclusions (Khedari *et al*., 2000). This index count on the value of difference between average indoor temperature and outdoor temperature, dT (°C) as a comparison tool. In addition to the air temperature, evaluation of the ventilation performance also involved the reduction level of relative humidity in both attic and occupied spaces and air velocity at the occupied level.

From the literature review, it was found that generally neutral temperature for people’s thermal comfort in the hot-humid tropics ranges from 24°C to 29°C for natural ventilated building. However for this study which is done in Malaysia, the neutral temperature was chosen as 26.5°C, which is 0.2°C higher than Zain-Ahmed *et al.* (1997) and 0.2°C lower than neutral temperature proposed by Abdul Rahman (1999) based on Model Year Climate Data. To validate this value, it was tested by the two main thermal comfort theories i.e. the Predicted Mean Vote (PMV) and the Adaptive Model. The PMV theory represents the 'predicted mean vote' (on the thermal sensation scale) of a large population of people exposed to a certain controlled environment (Fanger, 1970). On the other hand, the adaptive approach is based on empirical observation of the results from field surveys which include the variations in outdoor climate for determining thermal preferences indoor (De Dear and Brager, 1998, Nicol and Humphreys, 2002).

To validate the thermal neutrality using the PMV theory, the Software ASHRAE Thermal Comfort Program V1.0 was used to make the calculations with several assumptions:

- The Mean Radiant Temperature (MRT) was assumed to be the same as the air temperature (26.5°C),
- The relative humidity is 80% (the mean value for this climate),
- The metabolic rate is 1.0 met to indicate seating and writing activity and
- The clothes were assumed to be 0.5 Clo

Moreover, the air movement was taken as 0.1m/s to represent the condition with still air. From the analysis, it was found that the value for the PMV and Predicted Percent Dissatisfied (PPD) were 0.4 and 9%, respectively. Based on ISO7730, these values were obviously within the comfort zone when that standard stated that an acceptable PPD should be <10% which corresponds to a PMV between -0.5 and 0.5.On the other hand, the expression by de Dear and Brager (2002) based on Auliciems (1981) correlation was used to validate the thermal neutrality of 26.5°C using the Adaptive Model.

$$T_{comf} = 0.31T_{a,out} + 17.8$$

Where T_{comf} = optimum comfort temperature and $T_{a,out}$ = mean outdoor dry bulb temperature of the month.

However, since the study was done during the two months period of May and June 2008, where the mean temperatures were recorded as 27.8°C and 28.2°C respectively by Bayan Lepas (Penang, Malaysia) Meteorological Station, the average value of 28.0°C was chosen for the calculation. Based on the equation, the thermal neutrality was found to be equal to 26.5°C. However, according to this theory, the comfort zone can be taken as ±2.0°C about the neutrality temperature. Thus, the value of 28.5°C was used as the upper limit of comfort in this study, considering also the acclimatization of people to hot humid conditions and living in naturally ventilated building.

RESULTS & DISCUSSION

The analyzed data of indoor thermal condition without the use of HTV indicated that usually the indoor air temperature was lower than ambient during 11.00am to 4.00pm. However, with the use of HTV, the lower indoor air temperature relative to ambient could be earlier by one hour and extended by one hour compared the existing condition. This is due to the HTV installed on the roof begun to effectively operate from 9.00am to 5.00pm. This observed condition illustrated the period of time when adequate incident solar radiation is received by the crystalline photovoltaic to generate solar electricity to run the device.

As a simplified comparison of the effectiveness of different extractor fan locations along with existing condition without the use of HTV, Fig. 3 below shows the air temperature difference between indoor and outdoor of the hottest days of each strategy.The lower temperature difference means the higher air change rate (ach) and consequently the lower temperature of the indoor air. From the graph, it can be said that the reduction of air temperature is not very much influenced by the location of the extractor fan since the lower values of air temperature achieved by both HTV compared to existing condition are almost the same, which the up and down differences that occurred sometimes were mainly because of the different level of solar radiation it received. However, it can be seen that the effect of HTV for both strategies in reducing internal peak temperature is not significant after 5.00pm due to the end of solar radiation.

On the other hand, Fig. 4 below shows the impact of both HTVs for Indoor strategies in reducing the level of temperature for the average three-day period. The lower value achieved by each strategy means that more indoor air temperature is reduced and more significant the

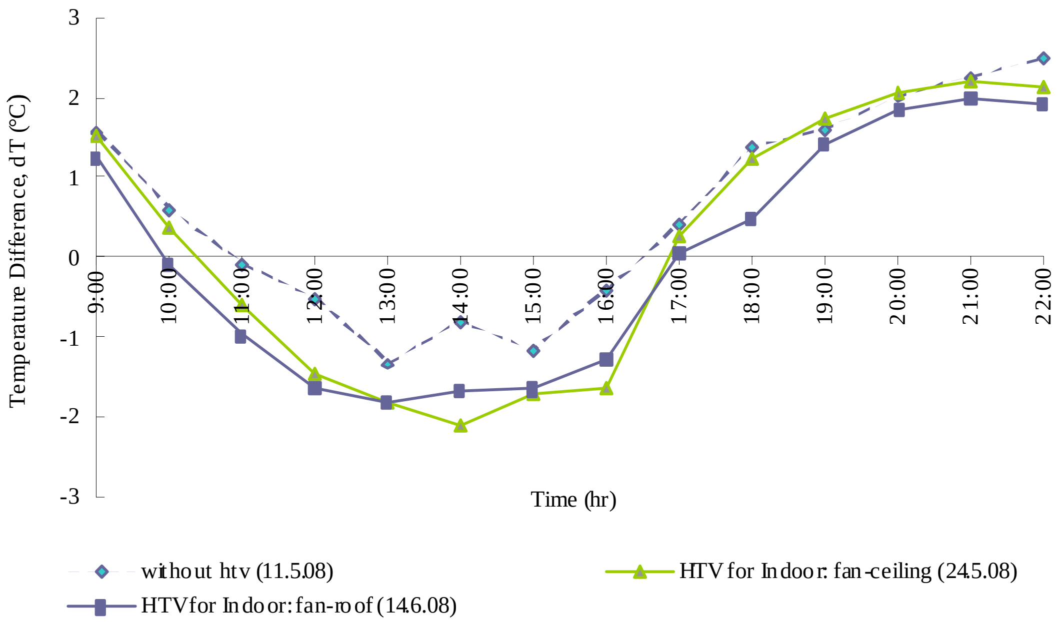


Fig. 3. Comparison of the difference between indoor and outdoor temperature for different ventilation strategies (windows and doors closed)

strategy would be. By the graphs, it can be seen that both HTV strategies show almost the same reduction of 0.7°C lower than existing condition(without HTV). However, it still can be observed that the mean minimum air temperature of HTV for Indoor (fan near roof level) is slightly lower than HTV for Indoor (fan at ceiling level). This is mainly due to the higher solar radiation and solar intensity it received at that time which means the higher rate of the extractor fan it has and consequently, the lower temperature it produced.

On the other hand, the results regarding mean maximum temperature shows a contradiction when the HTV with fan at ceiling level shows a better result which is mainly because of the same solar radiation factor. Thus, it can be concluded that the reduction level of indoor air temperature is not verymuch influenced by the extractor fan location since the ACH and ventilation rate that matters most, which are hugely determined by the the rotation rate of the solar-powered extractor fan.

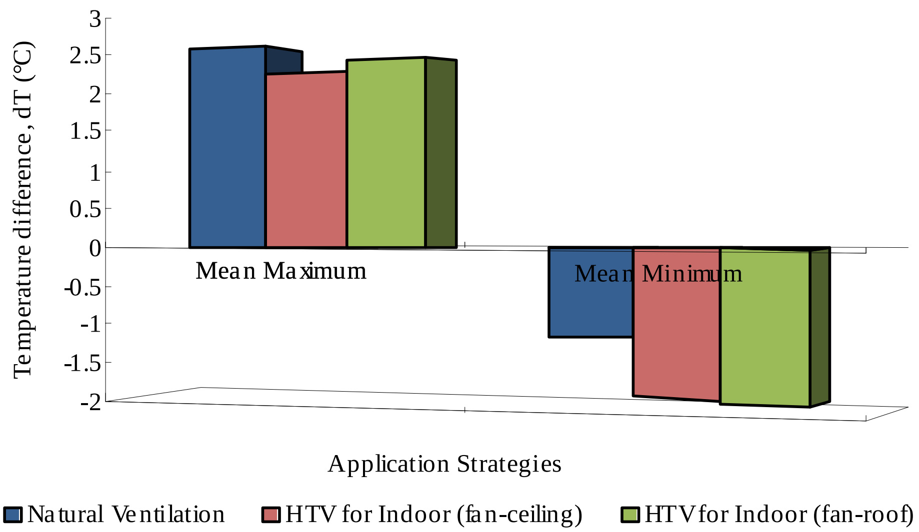
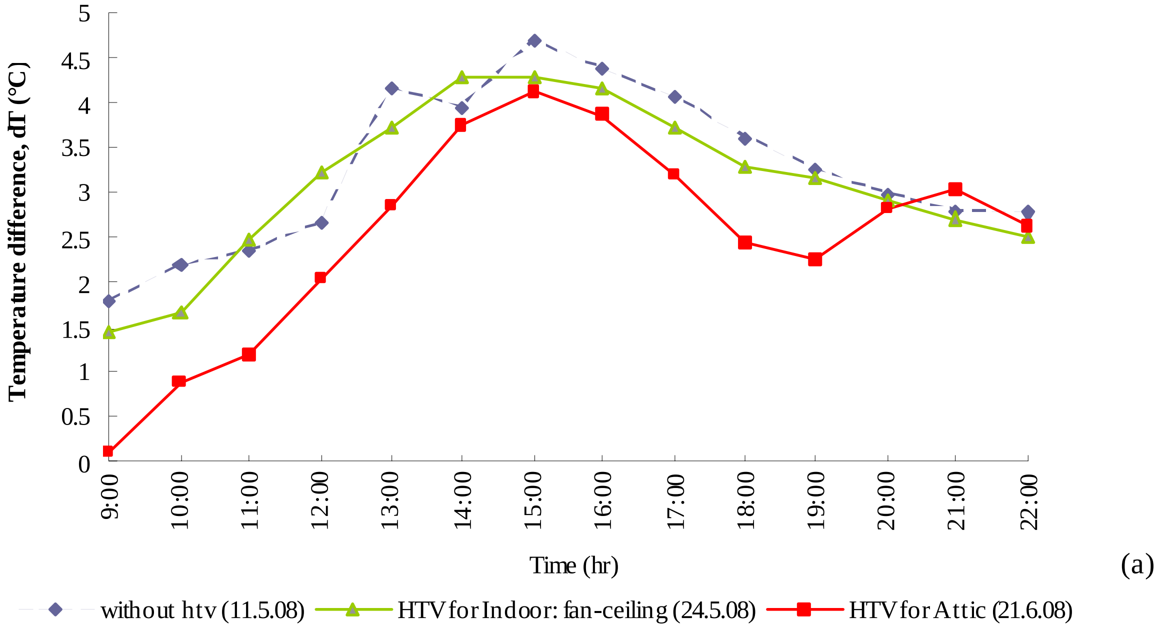


Fig. 4. Comparison of the mean maximum and mean minimum indoor-outdoor air temperature differences for different ventilation strategies when windows and doors closed

Regarding the profile of air velocity in the closed case, as expected, the application of HTV with fan at ceiling level shows the best result in highest air velocity produced, where the mean maximum air velocity for three days study achieved is 0.10m/s, the value of 0.04m/s higher than when the fan was near roof level. However, the advantage of having extractor fan placed at the ceiling level which means nearer to the occupied zone is not very helpful to create ample air movement of 0.25 - 1.0m/s needed to improve thermal condition. To investigate the effect of applying HTV for attic ventilation, the measurements of air temperature and relative humidity were also taken in the attic space. From the results, it was found that HTV for Attic strategy succeeded to reduce attic air temperature by approximately 0.9°C and 1.0°C compared to HTV for Indoor (fan at ceiling level) and the case without HTV, respectively. Fig. 5(a) below shows the example of the temperature reduction which represents the attic-outdoor temperature difference for the hottest day of each strategy.



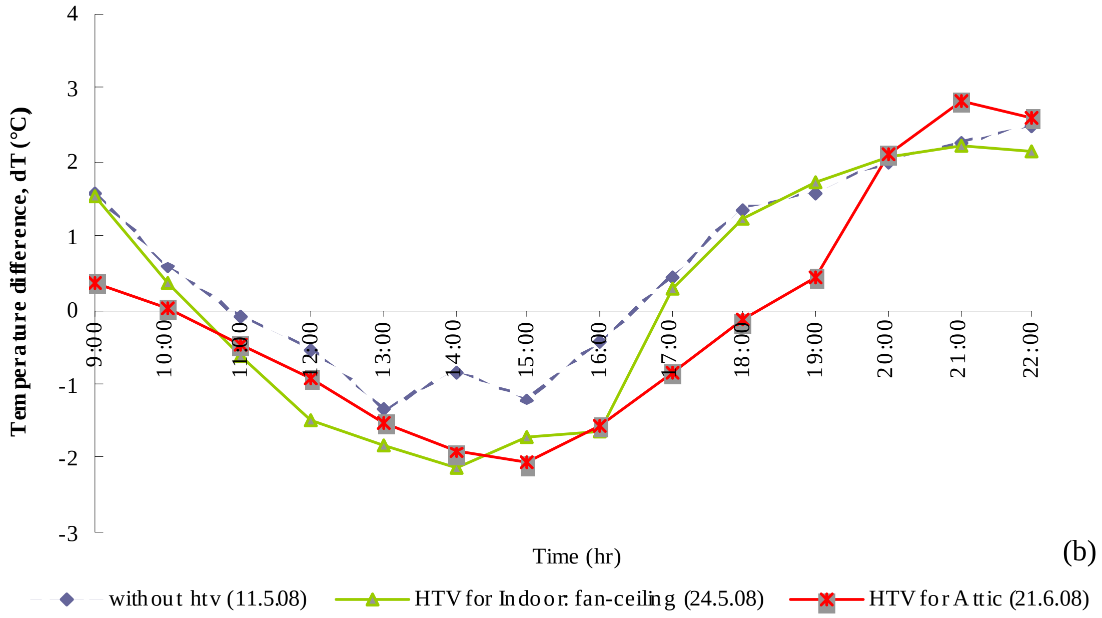


Fig. 5. Comparison of the temperature differences in the closed case for different ventilation strategies (a) attic-outdoor difference (b) indoor-outdoor difference

However, although its effect in reducing indoor (occupied space) air temperature is slightly better than existing condition in the afternoon, the more significant effect of this strategy is quite obvious from 4.00pm to 7.00pm when solar radiation gets weak Fig. 5(b). The positive results during this period compared to HTV for Indoor strategy clearly shows the importance of this strategy to lower down the level of heat radiated from the ceiling to indoor spaces, which at these times cannot be forced out effectively with HTV for Indoor due to weak solar radiation. In addition, the study also shows that this HTV for Attic strategy is quite significant to reduce relative humidity level in the occupied space, as shown in the Fig. 6.

Investigating the effect of openings is important since some studies on the ventilation strategies in this climate found that the opened windows and doors could bring in hot and humid outdoor air to interior spaces, thus worsen the indoor thermal condition (Ahmed *et al.*, 2005). The adverse impact of having the openings opened seems to be true when Fig. 7(a) illustrates that the Indoor-outdoor relative humidity difference is lower when the windows and doors are opened compared to when it are closed. This means that the closed windows are helpful to ensure the indoor relative humidity remained lower although the humidity ambient is getting higher. From the graphs, it can also be observed that in this openings closed case, the HTV for indoor with fan at ceiling level shows the best performance in terms of humidity reduction when it succeeded to reduce relative humidity level by 1.7%RH as compared to the existing condition without any HTV installed.

However, the results of the studies regarding the profiles of air temperature (Fig. 7 (b) and air velocity (Fig. 7(c) show some contradictions when all the HTV application strategies were found to perform better when the windows and doors were opened. Moreover, the effect of openings is more obvious in the reduction of temperature using HTV for Attic strategy when its application in the opened case shows much more promising results compared to when openings were closed.This result demonstrates that if the application of the HTV for Attic strategy is simultaneously accompanied by the HTV for Indoor strategy to extract the hot indoor air out, the best indoor thermal condition could possibly be achieved (Fig. 7(a). This will indicate the most efficient application strategy of the HTV under this hot and humid climate region.

In this study, the mean value of the Operative Temperature, (OT) and Standard Effective Temperature (SET*) achieved by the different HTV application strategies were compared to evaluate the thermal comfort improvement. The

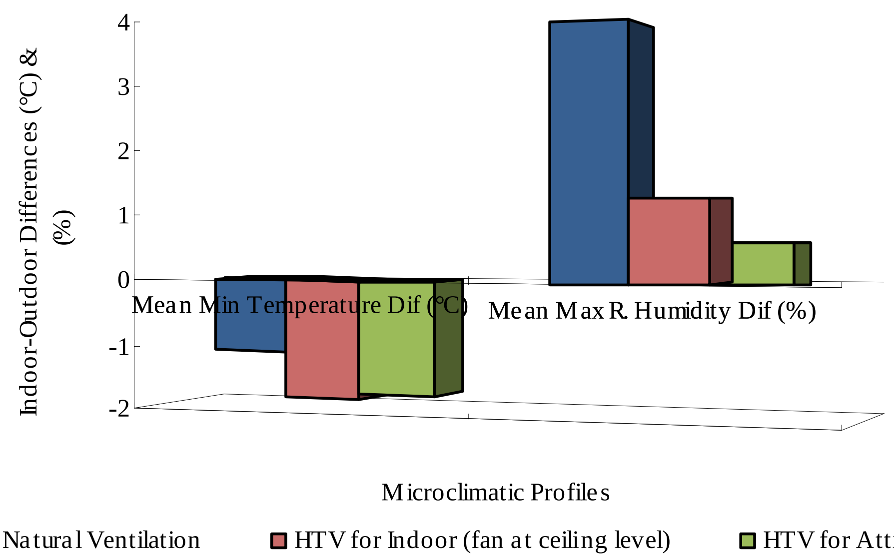


Fig. 6. Comparison of the mean minimum value of indoor-outdoor temperature difference and mean maximum value of indoor-outdoor relative humidity difference for different ventilation strategies (windows and doors closed)

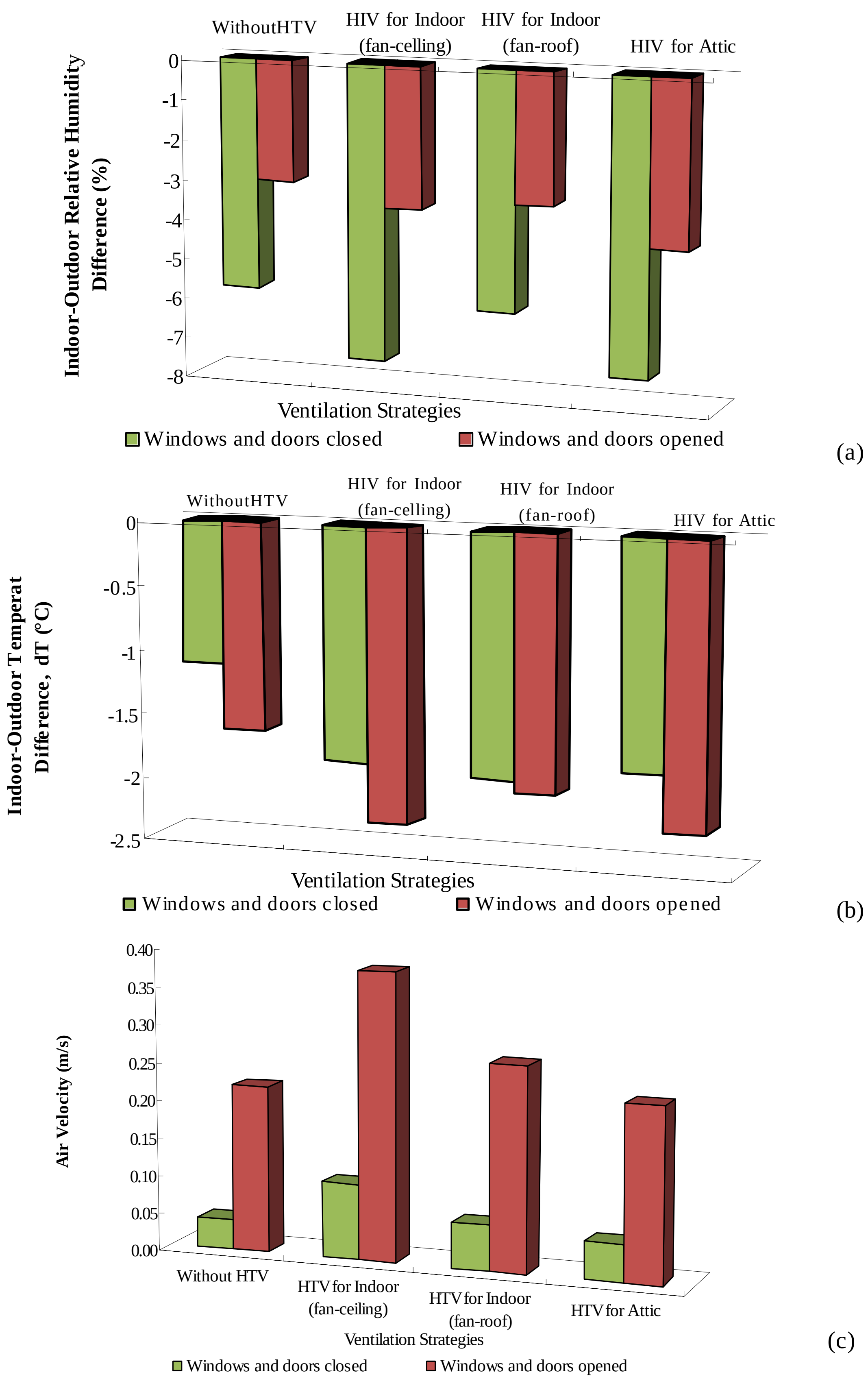


Fig. 7. Comparison of the indoor climatic conditions for different ventilation strategies when the openings are closed and opened a) mean indoor-outdoor relative humidity difference b) mean minimum indoor-outdoor temperature difference c) mean maximum indoor air velocity

value of OT was taken as the average temperature of Indoor Temperature and Mean Radiant Temperature (MRT), since air velocity is found to be <0.2m/s and MRT is within 4°C at all the time for the closed case. As for the opened case, the expression below was used since there were sometimes air velocities exceeded 0.2m/s.

$$t_o = At_a + (1\text{-}A)\ t_r$$

where t_o = operative temperature (°C), A = 0.6 for air velocity between 0.2 and 0.6m/s, t_a = air temperature (°C) and t_r = MRT (°C).

On the other hand, the Software ASHRAE Thermal Comfort Program V1.0 was used to calculate the SET* with metabolic rate was assumed to be 1.0 met and clothes to be 0.5 clo.For the purpose of comparison, the value of differences between the mean OT and mean SET* of the room compared to mean outdoor temperature were used as comparison tools. In this case, the values achieved by the existing condition were acted as base cases and the percentage of reduction achieved by each strategy were evaluated to find out the most efficient strategy. In addition, the number of hours of OT and SET* achieved by each strategy which were above the upper comfort limit of 28.5°C were also counted in order to make a subjective conclusion of the effectiveness of the HTV in satisfying people's thermal comfort in this region.

From the findings that are summarized in Table 2, it can be concluded that the comparison results of thermal comfort improvement is almost in line with the finding from ventilation performance comparison. For the closed case, the higher reduction of OT and SET* when the fan was at roof level strategy compared to when the fan at ceiling level strategy is the same like in previous comparison. A detailed analysis then revealed that the lower OT and SET* achieved is mainly due to the higher 3 days average of solar radiation received by the first strategy, which is 378.5w/m² compared to only 324w/m² for the later strategy. This condition illustrates that the higher average of solar radiation received means that the higher rate of the extractor fan produced and more constant its operation would be.

However, in general both HTV for Indoor strategies showed better performances compared to HTV for Attic strategy, especially in the closed case when it succeed to reduce OT by 28.6% to 57.1% and SET* by 16.7% to 33.3%. But, the

Table 2. Comparison of the difference between mean OT and mean SET* compared to mean outdoor temperature and reductions achieved by different ventilation strategies (a) Closed Case (b) Opened Case

(Closed Case)	Operative Temperature (OT) (°C)		Standard Effective Temperature (SET*) (°C)	
	Mean OT–Mean Outdoor, d*T* (°C)	Reduction (%)	Mean SET*–Mean Outdoor, d*T* (°C)	Reduction (%)
Without HTV	0.7	-	1.2	-
HTV for Indoor (fan at ceiling level)	0.5	28.6	1.0	16.7
HTV for Indoor (fan near roof level)	0.3	57.1	0.8	33.3
HTV for Attic	0.6	14.3	1.1	8.3

(a)

(Opened Case)	Operative Temperature (OT) (°C)		Standard Effective Temperature (SET*) (°C)	
	Mean OT–Mean Outdoor, d*T* (°C)	Reduction (%)	Mean SET*–Mean Outdoor, d*T* (°C)	Reduction (%)
Without HTV	-0.2	-	-0.1	-
HTV for Indoor (fan at ceiling level)	-0.5	60.0	-1.0	90.0
HTV for Indoor (fan near roof level)	-0.4	50.0	-0.3	66.7
HTV for Attic	-0.6	66.7	-0.5	80.0

(b)

relatively higher reduction of OT and SET* achieved by the HTV for Attic strategy in the opened case, which is 66.7% for OT and 80% for SET* show that this strategy is also significant if there is an avenue for the heat radiated from the ceiling to be expelled out.

The results from the study regarding the frequencies of temperatures above the comfort limits confirmed the potential of this attic ventilation strategy when the percentage of OT and SET* achieved in the range of comfort level is almost as efficient as with HTV for indoor strategies, if outdoor condition is taken into account. By the graph of this opened case Fig. 8. it can be concluded that although all the HTV application strategies show better performances than the existing condition, the fact that 75% to 90% of the OT and 75% to 95% of the SET* were above the upper comfort limits of 28.5°C revealed that significant enhancement should be made to the device and its application strategy. One possible solution derived from the results is by applying the HTV for both occupied space and attic space at the same time and ensure that openings are kept opened.

CONCLUSION

A study to investigate the most efficient HTV application strategy in improving thermal comfort condition was carried out in a medium size room within an institutional building. Using simplified comparisons of thermal comfort indices, the pros and cons of each strategy were identified. The results show that:

1)The strategy of the HTV for Indoor (fan at ceiling level) with windows and doors are kept opened is the most effective HTV application strategy, especially in terms of inducing higher air velocity in the occupied level. The ability to induce air velocity of up to 0.38m/s and to decrease the air temperature and relative humidity by up to 0.7°C and 1.7%RH in average have resulted in reducing the levels of OT by 60% and SET* by 90% compared to the existing condition.

2)However, although the mean indoor air temperature and relative humidity produced by two HTV for Indoor Strategies i.e. fan at ceiling level and fan near roof level are lower than existing condition and HTV for Attic strategy, the performance between both strategies is not very much different in terms of those profiles. This indicates that the reduction of air temperature and relative humidity levels are more influenced by Air Change Rate (ACH) and ventilation rate which in this context is mainly determined by the correlation between the rotation rate of the solar-powered extractor fan and the level of solar radiation it received.

3)From the results, it was also found that common application of the turbine ventilator which is for attic space alone is not very efficient strategy since the air temperature and relative humidity produced in the occupied space was higher compared to both HTV for Indoor strategies, except during the evening when it showed better performance.

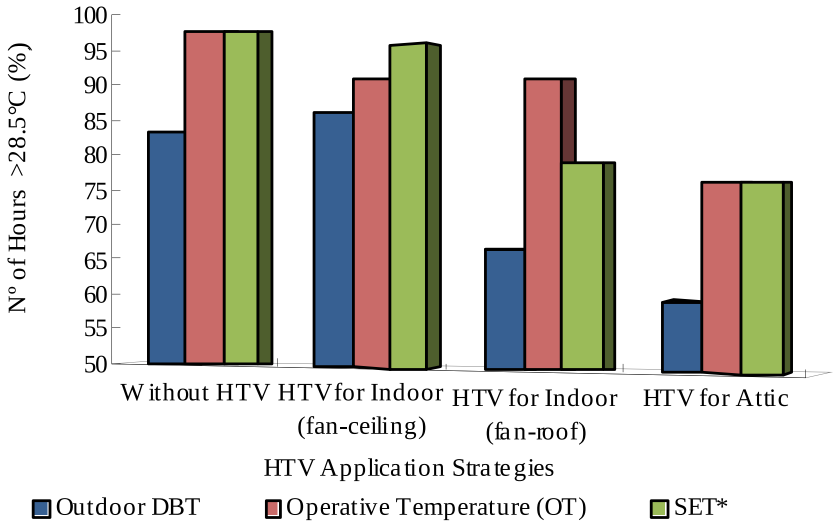


Fig. 8. Frequencies of number of hours above the upper comfort limits for different ventilation strategies when windows and doors are opened

However, it was observed that the HTV for attic strategy was able to reduce the attic air temperature by approximately 1.0°C in average compared to the existing condition of the attic space, and was also helpful to improve the occupied space conditions by reducing the SET* level by 80% in the opened case. These results show that this strategy is also significant if it is simultaneously accompanied by another strategy to extract hot occupied space air which is radiated from the ceiling out to the outside.

4)Generally, it can be concluded that although all the HTV application strategies achieved to produce relatively lower air temperature and humidity compared to existing condition of the room, its effectiveness in satisfying people's thermal comfort condition in this hot and humid tropical region is far from acceptable. The mean Operative Temperature (OT) and Standard Effective Temperature (SET*) of around 29.0°C to 30.0°C which were equivalent to 70% -90% of the time i.e. from 9.00am to 10.00pm were out from acceptable upper limit of comfort condition shows that a significant enhancement should be made to improve the device. Thus, since the study clearly shows that reducing an air temperature and humidity in the attic is equally important as in the occupied space, so the applications of the HTV for attic and occupied space at the same time could be a possible answer.

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