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EFFECTS OF SINGLE-SIDED AND CROSS-VENTILATED SLIDING GLASS WINDOW OPENINGS ON THE INDOOR ENVIRONMENT OF A ROOM IN A HOT AND HUMID CLIMATE

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Graphical abstract

Abstract

There are two natural ventilation strategies, namely single-sided and cross ventilation. For a building with a deep layout plan and where cross ventilation is impossible, single-sided ventilation is used. This study aimed to compare the performance of both strategies using sliding glass windows. The method used was field measurement, which was executed in one room of a double-storey detached house. The predicted indoor thermal comfort was calculated using the Adaptive Thermal Comfort index. The main finding from the study agreed with those of previous studies, whereby cross ventilation was found to provide greater indoor airflow than single-sided ventilation. However, with each strategy, indoor thermal comfort could only be achieved only during the morning hours. The findings also show that the wind velocity decreased upon approaching the window opening and reduced further when the indoor space was reached. Another interesting finding is that cross ventilation had the capacity to enhance the indoor air velocity at one of the measurement times. This study is significant as it will stimulate future exploration and investigation of both natural ventilation strategies in hot and humid climates.

Keywords: Natural ventilation, field measurement, thermal comfort, wind-driven ventilation, hot and humid climate

Abstrak

Terdapat dua strategi pengudaraan semula jadi, iaitu pengudaraan satu sisi dan silang. Untuk bangunan dengan pelan susun atur yang mendalam dan di mana pengudaraan silang adalah mustahil, pengudaraan satu sisi digunakan. Kajian ini bertujuan membandingkan prestasi kedua-dua strategi menggunakan tingkap kaca gelongsor. Kaedah yang digunakan ialah pengukuran lapangan, yang dilaksanakan dalam satu bilik di sebuah rumah dua tingkat. Keselesaan terma dalaman dikira menggunakan indeks Keselesaan Terma Suai. Penemuan utama daripada kajian ini adalah selari dengan kajian terdahulu, di mana pengudaraan silang memberikan aliran udara yang lebih baik berbanding pengudaraan satu sisi. Walau bagaimanapun, keselesaan terma dalaman untuk kedua-dua strategi hanya dicapai pada waktu pagi sahaja. Penemuan juga menunjukkan bahawa halaju angin berkurangan apabila menghampiri bukaan tingkap, dan semakin berkurangan apabila sampai ke ruang dalaman. Antara penemuan lain yang menarik ialah pengudaraan silang mempunyai kapasiti untuk meningkatkan halaju udara dalaman pada salah satu masa pengukuran. Kajian ini penting dalam meningkatkan lebih banyak penerokaan dan penyiasatan masa hadapan bagi kedua-dua strategi pengudaraan semula jadi untuk iklim panas dan lembap.

Kata kunci: Pengudaraan semula jadi, kajian lapangan, keselesaan terma, pengudaraan terpacu angin, iklim panas dan lembap.

1.0 INTRODUCTION

Natural ventilation refers to the process of substituting stale indoor air with fresh outdoor air by natural means and without the aid of any mechanical device [1]. In natural ventilation, the two main driving forces that induce the flow of air are pressure differences, which create wind-driven ventilation, and thermal differences, which cause stack effect ventilation. Many factors influence natural ventilation in buildings, including the ventilation strategy, the configuration and orientation of the windows, and the window-to-wall ratio. Of these, the ventilation strategy has been found to have the greatest impact on the natural ventilation performance [2]. In addition, poor building design, specifically in terms of envelope design, creates greater demand for cooling appliances and manufactured lighting sources [3]. The indoor air temperature can also be reduced with a well-designed system of air circulation in which air enters the indoor space using a brilliant wall design [4].

There are two types of natural ventilation strategies, namely single-sided and cross ventilation. The single-sided strategy allows outdoor air to enter a space via an opening and flow out from that space through the same opening or another opening located in the same wall. Meanwhile, the cross ventilation strategy allows the incoming air to enter through one or more openings, while the outgoing air leaves via another opening located in the other wall or on another side of the room [5]. With single-sided ventilation, the exchange of outdoor and indoor air can occur via the means of the stack effect and wind pressure. Meanwhile, cross ventilation usually happens due to wind pressure [6].

Previous studies have suggested that cross ventilation offers an effectively substantial ventilation rate compared to single-sided ventilation [5,6,7]. The effectiveness of single-sided ventilation is merely about 2.5 H from the opening. Meanwhile, cross ventilation has been found to be effective up to 5 H from the opening. 'H' refers to the ceiling height of the room [5]. Previous research on the thermal performance of building ceilings has suggested that positioning the rear and front openings centrally and near the ceiling helps to reduce the costs of electricity for cooling purposes [10].

The performance of single-sided ventilation is somewhat difficult to predict as it is influenced by many factors, such as the building location and its surroundings, the configuration of the openings, the indoor and outdoor temperature differences, the indoor temperature gradients, the wind speed and direction, as well as the air turbulence [11]. It has been indicated that single-sided ventilation has difficulty in capturing wind, which consequently results in higher energy demands for cooling [12]. The urban density and the aspect ratio of street canyons also have considerable influence on wind-induced single-sided ventilation. The airflow, however, can be improved with an appropriate building envelope design. In addition, the presence of a horizontal element in the middle of an opening has also been found to potentially create greater pressure differences, which drive the ventilation [13]. Nevertheless, even with single-sided ventilation, the correct spatial orientation and height can result in high thermal acceptability for a mean air velocity of less than 1 m/s [14].

Large window openings are the normal options for buildings that use natural ventilation for cooling [15]. Higher airflow can be achieved by installing a larger window [16], which results in a greater window-to-wall ratio [17]. However, larger window openings may also cause an increase in the solar heat gained. In a hot and humid climate, it is ineffective to have large window openings as this allows excessive heat to enter the space at the same time. An effective window opening size can enhance indoor thermal comfort [18]. Effective airflow through an opening may increase the ventilation rate and eventually also result in improved indoor air quality [19]. Nevertheless, to achieve the indoor thermal comfort in a hot and humid climate via natural ventilation is still a great challenge [20].

The external shading device also affects the air that flows into the indoor space. The shading device can either enhance or reduce the indoor ventilation [21]. The building design and orientation also contribute by maintaining wind uniformity and lowering the indoor temperature, thus providing better indoor natural ventilation [22]. A building design that responds poorly to the climate may produce insufficient air velocity for natural ventilation and excessive sunlight, eventually causing the indoor space to overheat [16, 14]. Despite the many challenges in conducting natural ventilation research, this concept is worth investigating and exploring as natural ventilation has positive effects on human health and encourages zero-carbon ventilation systems [24].

2.0 THE INFLUENCE OF AIR VELOCITY ON THERMAL COMFORT IN HOT AND HUMID CLIMATES

In hot and humid climate conditions, it is very challenging to achieve human thermal comfort due to the constantly high air temperature and humidity throughout the year. The annual mean air temperature in Malaysia is normally around 27.5 °C, while the relative humidity is approximately 79.5% [25]. In such as climate, the heat exchange between the human body and the environment via evaporative heat transfer is less effective due to the high relative humidity in the air. Hence, to achieve thermal comfort, air must pass at a high velocity through the human body to increase the evaporative heat loss.

Natural ventilation plays a significant role in thermal comfort, particularly in indoor spaces, depending on the local climate [26]. In a hot and humid climate, the neutral temperature for indoor thermal comfort can be increased with the presence of higher air velocity [27]. In addition, greater air velocity can also reduce the number of people who feel thermal discomfort [28] because those who live in hot or warm environments are sensitive to air movements. Their sensation of thermal comfort can be changed with merely a slight variation in the air velocity [29]. For indoor air temperatures of 29 °C to 31 °C, indoor thermal comfort can be achieved with the presence of 0.81 m/s air velocity [30]. Meanwhile, an indoor comfort temperature of 30 °C can be increased to 34 °C with the presence of 0.6 m/s air velocity [27]. Nevertheless, people in hot and humid climates have a greater tolerance to higher indoor air temperatures than those who live in temperate and cold climates [19, 23, 24].

Therefore, this study was executed due to the important role air velocity plays in achieving human thermal comfort in hot and humid climates. It is essential to apply an appropriate natural ventilation strategy to achieve sufficient air velocity. In this study, field measurement was conducted for both single-sided and cross ventilation conditions. The purpose was to compare how effectively they achieved indoor thermal comfort in a hot and humid climate. Despite the many studies related to both natural ventilation strategies, their potential in hot and humid climates has remained unexplored. Although previous studies have recommended that cross ventilation provides greater airflow than single-sided, the potential of single-sided ventilation is still worth investigating because many spaces in buildings cannot afford to cross ventilation as they follow a deep layout plan. Hence, single-sided ventilation is still utilised in these spaces.

3.0 METHODOLOGY

The research methodology used in this study was field measurement. This was conducted using measuring tools that involved two multifunctional indoor environmental instruments: the Delta Ohm thermocouple infrared thermometer (two units) and the Testo 400 Universal IAQ (one unit), as well as one unit of a portable weather station, the HOBO U30 Station. The Delta Ohm and Testo instruments were able to measure the air temperature, air velocity, mean radiant temperature and relative humidity. All these parameters are necessary for determining indoor environmental conditions, especially indoor thermal comfort. All the instruments were calibrated prior to the measurement to ensure the reliability of the data measured. The field measurement was executed in a double-storey detached house (Figure 1) located on the campus of a higher institution in Malaysia, namely Universiti Kebangsaan Malaysia (UKM). The portable weather station was placed 6.7 metres from the house, as shown in Figure 1.

Figure 1 The double-storey detached house used in the study

A room 3.8 metres in length, 2.9 metres in width and 2.5 metres in height, which was located at level two of the house, was selected for the measurement. The reason for selecting only one room instead of the whole house was the limited number of instruments available. In addition, the room was chosen for its location, which was more free from surrounding obstructions compared to the other rooms. Moreover, the room also had openings on different facades, which fulfilled the requirement to explore both single-sided and cross ventilation conditions. Figures 2 and 3 depict the conditions of the room and all the measuring instruments when both single-sided and cross ventilation were assessed. Meanwhile, Figure 4 shows the distance of the indoor environmental instruments from the walls. The Delta Ohm instruments were located near the openings to measure the air velocity and temperature that passed through the openings when assessing single-sided and cross ventilation. Meanwhile, the Testo instrument was placed in the middle of the room to measure the air velocity and air temperature inside the room.

The openings to the room were sliding glass window openings. One opening, which was installed in the north-facing wall, had two glass panels, while the other opening, which faced east, had four glass panels. They had the standard industrial dimensions: 1.2 metres wide by 1.2 metres high for the two glass panel openings, and 2.4 metres wide by 1.2 metres high for the four glass panel openings. Therefore, each window panel had the dimensions of a 0.6-metre width times a 1.2-metre height.

The window frames were made of aluminium, while the glasses were categorised as clear glass panels. During the measurement, only one panel of each window was opened to allow the incoming and outgoing airflow. The heights of all the indoor environmental instruments were adjusted to be 1.5-metres from floor level. This height was considered appropriate, being within reach of most people when standing.

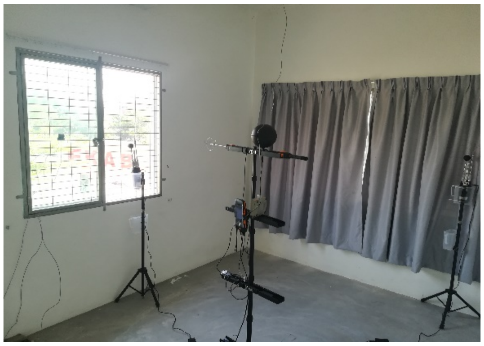

Figure 2 Room conditions for single-sided ventilation

Figure 3 Room conditions for cross ventilation

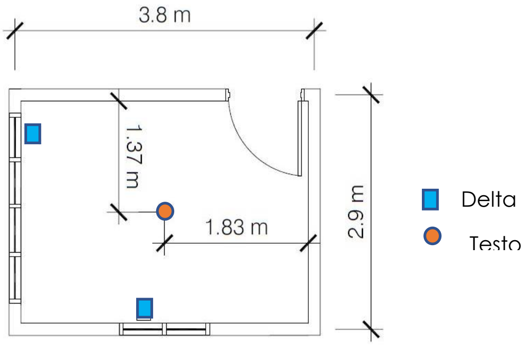

Figure 4 Locations of the indoor environmental instruments within the room.

The single-sided and cross ventilation measurements were executed on different days between February and April 2021. Although executed on different days, the data recorded for the outdoor environmental conditions was not substantially different, as illustrated in Table 1. The conditions were measured from 7 a.m. to 7 p.m. (13 hours) at five-minute intervals. The data was recorded only during the daytime as in a hot and humid climate, window openings are normally closed at night due to the presence of mosquitoes.

As the data in Table 1 shows, the average hourly air temperatures were almost identical for the single-sided and cross ventilation measurements. Meanwhile, although the relative humidity and wind velocity were slightly different, these differences were not hugely significant.

Table 1 The average outdoor air temperature (T_o), wind velocity (V_o) and outdoor relative humidity (RH_o) data for both single-sided and cross ventilation

Time	Single-sided ventilation			Cross ventilation		
	Hourly average T_o (deg C)	Hourly average V_o (m/s)	Hourly average RH_o (%)	Hourly average T_o (deg C)	Hourly average V_o (m/s)	Hourly average RH_o (%)
7 am	23.9	0.12	96	24.3	0.06	99
8 am	26.0	0.15	91	26.1	0.23	94
9 am	28.6	0.37	81	28.5	0.26	86
10 am	30.7	0.63	73	30.8	0.47	78
11 am	32.2	0.87	66	32.3	0.75	71
12 pm	33.1	0.83	61	33.3	0.85	66
1 pm	34.0	1.10	57	33.9	0.93	65
2 pm	34.9	1.24	54	34.4	1.10	62
3 pm	34.7	1.28	54	34.0	1.20	63
4 pm	34.2	1.19	58	31.8	1.15	70
5 pm	32.8	0.92	65	31.0	0.81	73
6 pm	30.5	0.62	72	30.2	0.61	75
7 pm	28.9	0.32	78	28.7	0.31	81

As Table 1 shows, similar trends are evident in the temperature and velocity readings. At 34.7 °C, single-sided ventilation showed an air velocity reading of 1.28 m/s, while at 34.2 °C, the air velocity recorded was 1.19 m/s. On the other hand, cross ventilation showed the opposite trend: at the highest temperature, the air velocity recorded was the second highest, 1.0 m/s. Meanwhile, at the second highest temperature, the air velocity recorded was the highest, 1.20 m/s. During the lowest air velocity reading for both single-sided and cross ventilation, the temperature also showed the lowest reading. In addition, cross ventilation recorded an extremely low air velocity of 0.06 m/s, while the equivalent for single-sided ventilation was 0.12 m/s.

4.0 RESULTS AND DISCUSSION

The extracted and analysed data is shown in Figures 5 and 6. Two sets of analyses are presented, namely the indoor air velocity and the indoor environmental conditions, which specifically determine indoor thermal comfort. These two sets of analyses were selected for the discussion of the findings as they demonstrate how implementing single-sided and cross ventilation affected the indoor air velocity and, eventually, the thermal comfort in the room.

4.1 Air Velocity

Figure 5 shows that the air velocity values dropped considerably between the outdoor and indoor spaces. The values decreased upon reaching the sliding glass window opening and, eventually, the indoor space, in both single-sided and cross ventilation conditions. However, of the two ventilation conditions, single-sided ventilation was found to have led to a greater reduction in air velocity compared to cross ventilation.

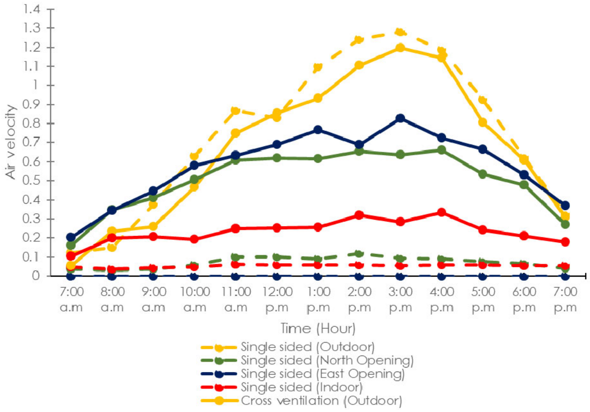

Figure 5 Air velocity for single-sided and cross ventilation

With single-sided ventilation, the outdoor wind velocity data indicates that the highest average value of 1.28 m/s was recorded at 3 p.m., while the lowest was 0.12 m/s at 7 a.m. The data trend for indoor air velocity shows that the values recorded ranged from 0.03 m/s to 0.06 m/s, considerably lower than the outdoor wind velocity. The wind velocity at 3 p.m. showed a decrement of 95.62% from outdoor to indoor, while the indoor reading resulted in an air velocity of only 0.05 m/s. Meanwhile, when the lowest outdoor wind velocity was recorded, 0.12 m/s at 7 a.m., the indoor air velocity was only 0.04 m/s, indicating a 61.78% decrease. In addition, from 10 a.m. to 6 p.m., the percentage was found to have fallen by more than 90%. Therefore, the results indicate that single-sided ventilation could not have enhanced the indoor air velocity in any way.

In cross-ventilation conditions, the indoor air velocity produced higher values than with single-sided ventilation, although for 85% (11 hours) of the overall measurement duration, the wind velocity during the single-sided measurement was higher than during the cross-ventilation measurement. The lowest indoor air velocity recorded in cross-ventilation conditions was 0.10 m/s, with an outdoor wind velocity of 0.05 m/s at 7 a.m. Meanwhile, in single-sided conditions, the indoor air velocity recorded was only 0.04 m/s, with an outdoor wind velocity of 0.15 m/s at that time. The measurement results show that the indoor air velocity did not depend entirely on the outdoor wind velocity since the ventilation conditions, whether single-sided or cross ventilation, were also influential.

The obvious increments and decrements recorded for the outdoor wind velocity from 7 a.m. to 7 p.m. resulted in slight differences in indoor air velocity over the measurement period. The highest decrement in air velocity from outdoor to indoor conditions was 76.22%, which occurred at 3 p.m. Meanwhile, the lowest decrement was recorded at 8 a.m., 14.35%. Hence, the results show that the air velocity in cross ventilation conditions fell at a lower rate compared to in single-sided ventilation conditions. Another interesting finding is that cross ventilation was observed to enhance the indoor air velocity, as shown in the result recorded at 7 a.m. During this period, the indoor air velocity was recorded as 0.1 m/s, 85% higher than the outdoor wind velocity, which was only 0.06 m/s. At other times, the trend indicated a decrement in air velocity from outdoor to indoor conditions, although it was still possible to enhance the indoor air in cross-ventilation conditions. The trend demonstrates that even when higher air velocity readings were obtained, both ventilation conditions recorded high temperature readings, as shown in Table 1. Meanwhile, the lowest temperature was found to correspond to the probability that the lowest air velocity would be recorded.

4.2 Indoor Thermal Comfort

The indoor environmental conditions in this study are presented and analysed in relation to indoor thermal comfort. The measured indoor environmental data of the room during single-sided and cross ventilation is tabulated in Table 2. In this table, the indoor air velocity data utilised the values recorded by the Testo instrument, which was in the middle of the room.

Table 2 The hourly average indoor air temperature (T_a), indoor air velocity (V_a), indoor mean radiant temperature (T_{mrt}) and indoor relative humidity (RH_i) data for single-sided and cross ventilation

Time	Single-sided ventilation				Cross ventilation			
	Hourly average T_a (deg C)	Hourly average V_a (m/s)	Hourly average T_{mrt} (deg C)	Hourly average RH_i (%)	Hourly average T_a (deg C)	Hourly average V_a (m/s)	Hourly average T_{mrt} (deg C)	Hourly average RH_i (%)
7 am	29.1	0.05	28.9	70	28.2	0.10	28.3	77
8 am	29.8	0.04	29.6	68	28.8	0.20	29.0	76
9 am	30.9	0.04	30.8	64	29.8	0.21	30.1	72
10 am	31.5	0.05	31.5	62	30.8	0.19	31.2	68
11 am	31.7	0.06	31.8	59	31.5	0.25	31.9	64
12pm	32.3	0.06	32.4	56	32.3	0.25	32.8	60
1 pm	32.9	0.06	33.1	53	32.9	0.26	33.4	59
2 pm	33.5	0.06	33.7	51	33.4	0.32	33.9	57
3 pm	33.7	0.06	33.9	50	33.4	0.28	33.9	57
4 pm	33.7	0.06	33.9	52	32.4	0.33	32.8	60
5 pm	33.5	0.06	33.6	56	32.1	0.24	32.4	62
6 pm	33.0	0.05	32.9	58	31.6	0.21	31.8	64
7 pm	32.4	0.05	32.4	60	31.1	0.18	31.1	67

In this study, the operative temperature (T_{op}) was calculated to identify the room's thermal indoor environment. The T_{op} was utilised as this takes into account the parameters required for thermal comfort, which are the indoor air temperature, mean radiant temperature and air velocity. The equation used to calculate the T_{op} was as follows [33]:

$$T_{op} = A\,T_a + (1 - A)\,T_{mrt} \qquad (1)$$

A denotes the value as a function of the average air velocity, which refers to the value suggested in ANSI/ASHRAE Standard 55 [33]. Meanwhile, T_a represents the indoor air temperature and T_{mrt} indicates the mean radiant temperature. The results of the T_{op} of the room are presented in Table 3.

Table 3 The hourly average T_{op} (deg C) of the room

	Hourly average T_{op} (deg C)	
Time	Single-sided Ventilation	Cross Ventilation
7 am	29.0	28.3
8 am	29.7	28.9
9 am	30.9	29.9
10 am	31.5	31.0
11 am	31.8	31.7
12 pm	32.4	32.5
1 pm	33.0	33.1
2 pm	33.6	33.6
3 pm	33.8	33.6

The derived T_{op} was then compared with the predicted indoor comfort temperature, which had been obtained using the equation in the Adaptive Thermal Comfort (ATC) model. The comparison was undertaken to identify whether the application of single-sided or cross ventilation in the room would achieve the predicted level of indoor thermal comfort. For a naturally ventilated building, the ATC model has been found to be more appropriate than the Predicted Mean Vote (PMV) model because the indoor environment in a naturally ventilated building is constantly changing in relation to the outdoor conditions [34]. The ATC model has been widely used in previous studies that have investigated thermal comfort in a tropical climate [35]. The ATC model used in this study employed the equation developed by Toe and Kubota [36]:

$$T_c = 13.8 + 0.57\,T_o \qquad (2)$$

T_c denotes the predicted indoor comfort temperature, while T_o represents the outdoor air temperature. The value of 13.8 is the value of the y-intercept, while the value of 0.57 is the slope of the function, which is proportionate to the adaptation degree of tropical climatic conditions. Toe and Kubota [36] derived the values of 13.8 and 0.57 from the ASHRAE RP-884 tropical climate database. The comparative analyses of the T_{op} and T_c are presented in Figure 6.

Figure 6 depicts the comparative analyses of the operative indoor temperature (T_{op}) and predicted indoor comfort temperature (T_c) for both single-sided and cross ventilation. The T_{op} for both conditions indicated lower temperatures compared to the T_c during the morning hours, which were from 7 a.m. to 11 a.m. Starting from 12 p.m., the T_{op} was higher than the T_c, a pattern that continued until 5 p.m. for cross ventilation and 7.00 p.m. for single-sided ventilation. Therefore, from the results shown in Figure 5, it can be summarised that the thermal comfort inside the room could only be achieved during the morning hours. Meanwhile, from noon until late evening, the room's thermal condition remained uncomfortable. Nevertheless, during the late evening hours, the thermal condition of the room with cross ventilation was found to be slightly better, than that of the room with single-sided ventilation.

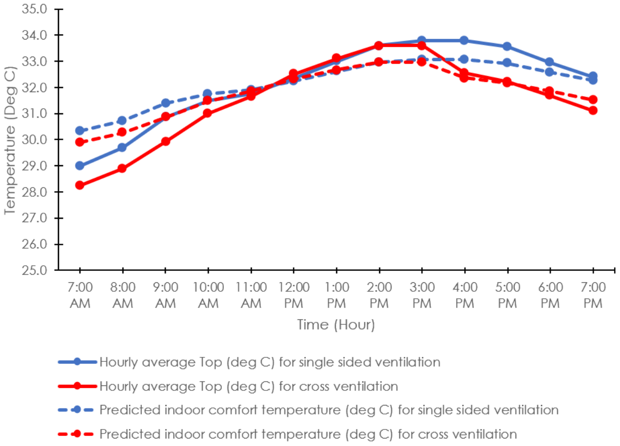

Figure 6 The comparative analyses of T_{op} against T_c for single-sided and cross ventilation

5.0 CONCLUSION

The field measurement in this study compared the indoor environmental conditions of a room in single-sided and cross ventilation conditions. The findings agree with those of other previous studies, which have emphasized that greater indoor air velocity occurs in a cross-ventilated space or room compared to one with single-sided ventilation. However, besides the similar findings, this study shows that the indoor air velocity does not merely depend on the outdoor air velocity; it is also highly influenced by the ventilation types applied to the room. This study demonstrates that although the outdoor wind velocity measured during the single-sided ventilation was higher than the wind velocity recorded during cross ventilation, the indoor air velocity was not substantially greater. The study also presents the usual pattern of outdoor air velocity, which decreased when approaching the window opening and, eventually, entering the indoor space. However, this study also shows that this usual pattern may be otherwise in cross-ventilation conditions. For instance, the results at 7 a.m. showed that the indoor air velocity was higher than the outdoor wind velocity. Hence, this study offers various recommendations that are worth investigating in future research. Among the potential future studies are the performance of the other types of windows using the single-sided and cross ventilation strategies, the effective methods of enhancing the indoor air velocity using cross ventilation strategy, as well as the possibility of increasing the indoor air velocity for a room or space using single-sided ventilation. Overall, the findings of this study are useful and significant, and they should stimulate future investigations of single-sided and cross ventilation strategies, especially in terms of achieving thermal comfort in a hot and humid climate. In addition, the method of investigation could be expanded to include the use of numerical simulation, for instance, with computational fluid dynamics software.

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