Experimental Assessment of Cross-Ventilation Effectiveness in Idealized Models with Roof Openings

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Experimental Assessment of Cross-Ventilation Effectiveness in Idealized Models with Roof Openings

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Abstract: *Cross ventilation is a natural ventilation mechanism that can be utilized in the roof with the suitable placement of openings on the windward and leeward façades. Wind tunnel experiments were conducted to study the influence of different opening configurations in the roof on indoor ventilation for a cross ventilated dwelling model. Wind velocity was measured using a hot wire anemometer (HWA) placed near each of the openings. The dwelling model was set to have a windward opening located at the middle section of the pitched roof (M1). On the roof's leeward façade, three openings were tested: lower section (L2), middle section (M1) and upper section (U2). The findings have shown that the M1-L2 case had the highest outlet-to-inlet velocity ratio, suggesting that such opening placement is most suitable to enhance cross ventilation in the attic, demonstrating the feasibility of rooftop cross ventilation for real-world application.*

Keywords: natural ventilation; cross ventilation; wind tunnel experiment; roof opening; wind velocity

1. INTRODUCTION

With the growing concern for urban heat island (UHI), a phenomenon which occurs because of the higher temperature in an urban area than that in its surrounding area, necessity and demand for indoor space cooling are increasing. The UHI phenomenon occurs in urban areas worldwide, and Malaysia, a country with a hot and humid climate all year round, is no exception [1,2]. Qaid et al. [3] remarked that one of the major causes of UHI is urbanization wherein urban areas are continuously expanding with the increase of urban population and the decrease of vegetation cover.

The rising energy consumption in the building sector in Malaysia is largely contributed by the frequent use of the air conditioner (AC) for indoor space cooling [4,5]; residential and commercial buildings in urban areas are not typically designed to optimize natural ventilation. This is primarily due to the generally low wind speed in the urban area which is not effective for heat transport. One major source of heat in urban areas is anthropogenic heat which essentially refers to heat that is generated from human activities, such as from vehicles and AC systems [6]. During the daytime, in addition to heat from solar radiation, the ambient air temperature can increase because of anthropogenic heat, creating an unconducive environment without proper ventilation [7].

In modern urban settings, most residential sectors rely heavily on mechanical ventilation, particularly air conditioning, for cooling. HVAC systems account for approximately 39% of total residential energy use, making energy management a critical priority, according to Aridi et al. [8]. In fact, the peak consumption of AC was normally observed in summer in temperate climate [9]. Furthermore, the UHI effect increases urban residents' dependence on air conditioning, raising electricity demand from 22% to 36% [10]. To combat high electricity consumption, natural ventilation can be utilized since it is energy efficient as it does not consume electricity or mechanical systems to circulate the air subsequently making it a cost-saving method. Natural ventilation efficiency may be improved by installing features like size or position of window openings [11] where a bigger opening size and strategic placement of windows provide cooling demands as much as 84%. Cross ventilation is one of the natural ventilation mechanisms utilized to reduce dependency on mechanical ventilation. It is based on wind-driven principle where wind flow is driven by the pressure difference; wind travels from an opening (windward façade, high pressure area) to outlet (leeward façade, low pressure area).

The potential sustainable strategy is lowering the thermal load of the building, which is the amount of heat energy that needs to be removed, that can be implemented through natural ventilation or more effectively, through a combination of mechanical ventilation (e.g. AC and fan) and natural ventilation. Essentially, the envelope of a building, comprised of the outer walls and roof, is directly exposed to solar radiation during the daytime. The heating of these outer surfaces can increase the indoor temperature. The roof of a house is often not obstructed by surrounding structures to provide a sufficient level of shade from solar heating. Therefore, it has the highest temperature compared to other outer surfaces of a house, causing immediate heating of stagnant air in the attic; this can result in a higher indoor temperature [12, 13]. If proper ventilation in the attic can be designed, the thermal load of a house can be reduced; in other words, the rise of the attic temperature can be reduced or prevented. This will subsequently prevent the increase of indoor temperature in living spaces of a house. The investigation of passive cooling designs and ventilated roofs by Kain et al. [14] suggested that the roof element plays a significant role in creating different air pressures around the exterior and the interior of a building; the inflow of air into the building is increased when the air pressure difference between the building's exterior and interior is large. Modifications to the building's roof design can affect the cross-ventilation flow rate into the building; for instance, the building with a gable roof has better flow intake than the building with a flat roof [15]. This is potentially because the roof improves indoor natural ventilation due to its exposure to high wind speed.

Therefore, this study aims at corroborating the potential of cross ventilation studies in the roof attic through wind tunnel experiment using a scaled dwelling model. The model has a rooftop that features fixed openings on the windward façade and varying opening positions (upper, middle, lower) on the leeward façade. In this study, the most effective roof opening configuration for enhancing cross ventilation using a scaled dwelling model tested in a wind tunnel is determined and analyzed.

2. METHODOLOGY

A series of experiments were carried out in an open-loop wind tunnel of Malaysia-Japan International Institute of Technology (MJIIT), Universiti Teknologi Malaysia (UTM), following the work of Wijaya et al. [16]. Fig. 1 shows the workflow of the study involving wind tunnel experiments based on a single dwelling model with a gable roof. The passive device was based on the work of Wijaya et al. [16] where a castellated wall barrier and roughness blocks were used to develop a fully turbulent flow along the test section of the wind tunnel. The 'models' refer to the different roof opening configurations tested. Additionally, wind velocity was measured at inlet and outlet openings of the model using a constant temperature hot-wire anemometer (HWA, model 55P11 Dantec). The schematic of the experimental set-up is shown in Fig. 2.

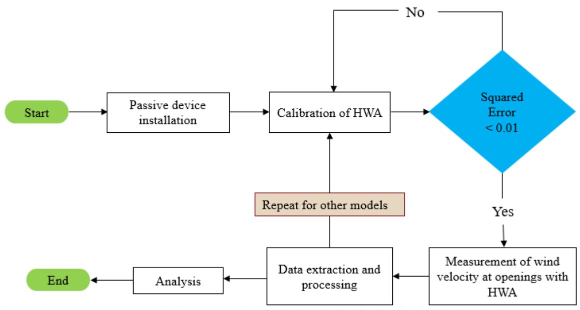

Fig. 1. Workflow of the study

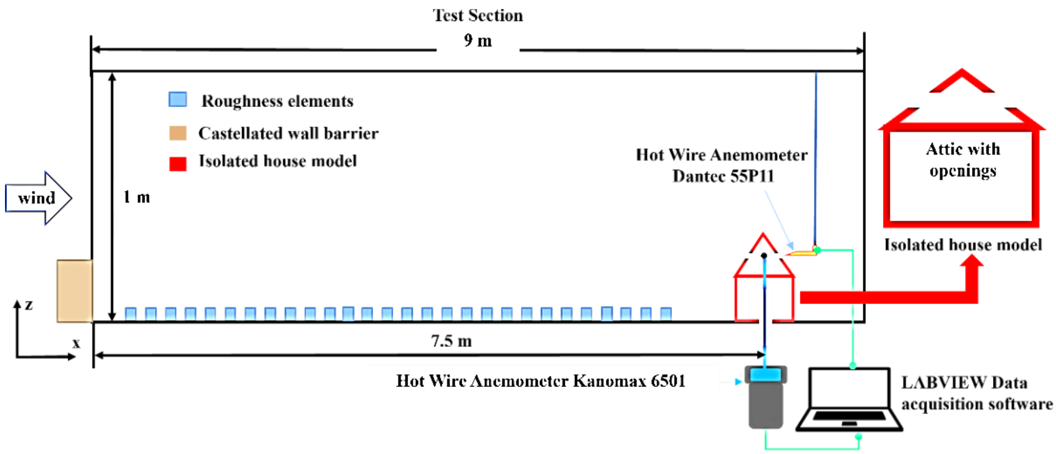

Fig. 2. Experimental set-up

2.1 Mean velocity profile

The incoming mean velocity profile is represented using the power law, as shown by Eq. (1),

$$\frac{U_{mean}}{U_{ref}} = \left(\frac{z}{z_{ref}}\right)^{\alpha} \qquad \text{Eq. (1)}$$

where, U_{mean} is mean wind velocity, U_{ref} is the reference mean wind velocity (i.e., 10 m/s) at the reference height, z_{ref} of 400 mm above the surface, and α is power law exponent. Based on the power law, Fig. 3 is obtained to show the relationship between the normalized mean velocity, u/u_{ref} and the normalized height, z/z_{ref} for which α was obtained to be 0.37.

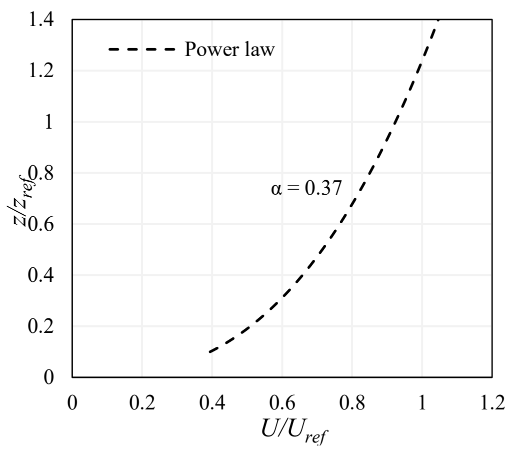

Fig. 3. Mean velocity profile based on the power law

2.2 Roof opening configuration

In this study, three different opening combinations were tested, as shown in Fig. 4. The vertical position of the inlet opening was at the middle of the windward façade. For clarification, the opening configurations are described as follows:

a) M1-U2: Middle opening on the windward slope and upper opening (centreline height of 200 mm) in leeward slope.

b) M1-M2: Middle opening on the windward slope and middle opening on leeward slope (centreline height of 185 mm).
c) M1-L2: Middle opening on windward slope and lower opening on leeward slope (centreline height of 170 mm).

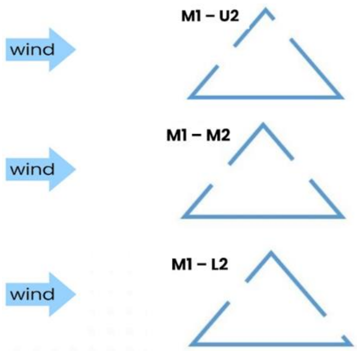

Fig. 4. Three tested configurations of cross ventilation

3. RESULT ANALYSIS

In this section, the experimental data are discussed in relation to the measured wind velocity. The purpose of this section is to deduce the optimum configuration for cross ventilation within the scope of this study.

3.1 Instantaneous velocity distribution

Instantaneous velocity was the measured velocity from the hot-wires anemometer. It was taken for a duration of 10 seconds at 10 kHz frequency. Figs. 5-7 show the time-series distribution of instantaneous velocity taken at the outlet opening for the three cases, M1-U2, M1-M2, and M1-L2, respectively. The mean velocity is also shown in each figure to illustrate the fluctuation of instantaneous velocity with respect to the mean velocity.

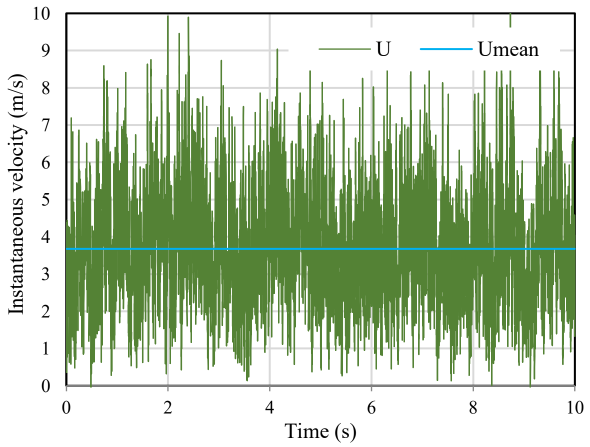

Fig. 5. Instantaneous velocity distribution taken at the outlet opening for M1-U2

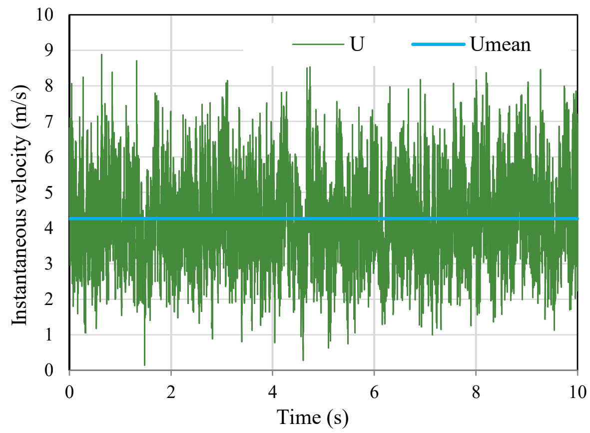

Fig. 6. Instantaneous velocity distribution taken at the outlet opening for M1-M2

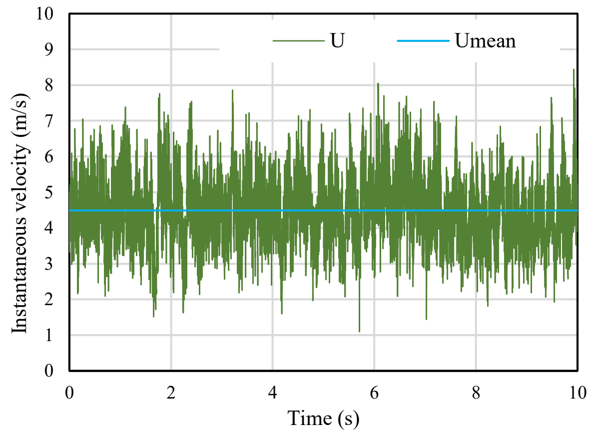

Fig. 7. Instantaneous velocity distribution taken at the outlet opening for M1-L2

Furthermore, Table 1 shows the summary of statistical data related to the instantaneous velocity, namely maximum, minimum, and average (or mean). Despite the higher maximum values obtained form M1-U2 and M1-M2 cases, the highest mean velocity was obtained for M1-L2. It can be deduced from these data that the opening placement, particularly on the leeward façade of the roof, can have a considerable effect on the cross ventilation in the roof.

Table 1. Statistical data of instantaneous velocity

Case	U_{max} (m/s)	U_{min} (m/s)	U_{ave} (m/s)
M1-U2	10.10	-0.12	3.67
M1-M2	8.89	0.14	4.27
M1-L2	8.84	1.10	4.49

3.2 Turbulence velocity

The turbulence velocity component, u' was calculated to indicate the turbulence intensity at the outlet opening for each case, using Eq. (2),

$$u' = U - U_{mean} \qquad \text{Eq. (2)}$$

where, U is instantaneous velocity and U_{mean} is mean wind velocity. To visualize the turbulence velocity distribution, the frequency distributions for the three cases are shown in Figs. 8-10. All figures show a nearly symmetrical distribution where the skewness value (skew) was less than 0.5. The values of maximum u' were varied by cases.

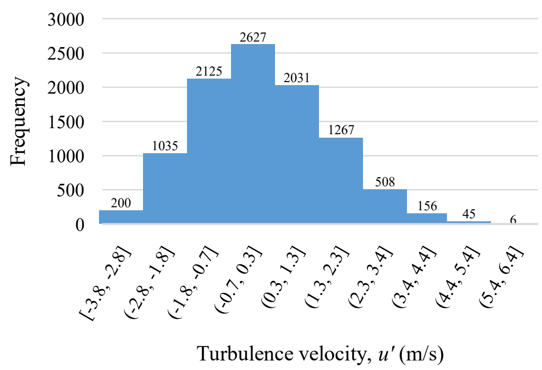

Fig. 8. Frequency distribution of turbulence velocity for M1-U2

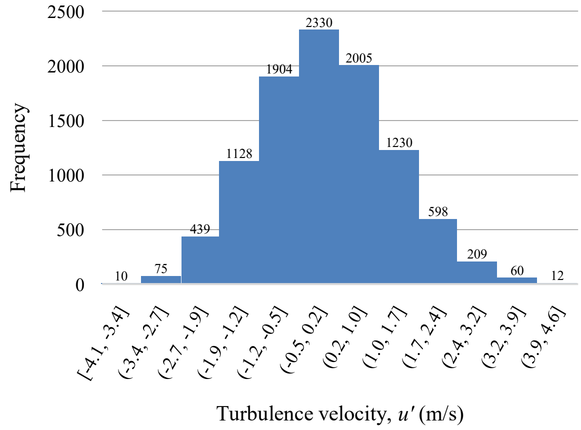

Fig. 9. Frequency distribution of turbulence velocity for M1-M2

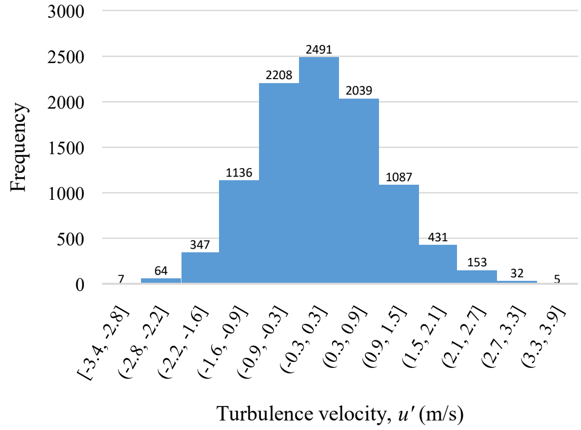

Fig. 10. Frequency distribution of turbulence velocity for M1-L2

For a clear comparison of turbulence velocity for the three cases, Table 2 shows the list of statistical data such as maximum, minimum, relative standard deviation, and skewness. The table shows that M1-M2 has the most symmetrical distribution with the lowest skewness value. In addition, M1-L2 has the lowest relative standard deviation, indicating that the overall data is more closely distributed approaching the mean value.

Table 2. Statistical data of turbulence velocity

Case	u'_{max} (m/s)	u'_{min} (m/s)	σ/U_{ref}	Skew
M1-U2	6.42	-3.80	0.153	0.37
M1-M2	4.62	-4.13	0.123	0.18
M1-L2	3.95	-3.39	0.095	0.21

3.3 Outlet-inlet velocity ratio

The effectiveness of cross ventilation in the rooftop was evaluated using the ratio of the outlet mean velocity, U_{out} to the inlet mean velocity, U_{in}. The value of U_{in} is the same for all three cases as the inlet opening is at the same centreline height (185 mm). Table 2 shows the ratio, U_{out}/U_{in} for each case. It was found that the M1-L2 case showed the highest ratio since U_{out} was the highest compared to two other cases. Hence, this suggests that cross ventilation effectiveness could be increased when the outlet opening was positioned lower than the position of the inlet opening.

Table 3. Outlet-inlet velocity ratio

Case	U_{in} (m/s)	U_{out} (m/s)	Ratio, U_{out}/U_{in}
M1-U2	7.151	3.673	0.51
M1-M2	7.151	4.265	0.60
M1-L2	7.151	4.487	0.63

4. CONCLUSION

Wind tunnel experiments were conducted in this study for three different opening configurations of the scaled model with a rooftop where the location of opening on windward façade is fixed in the middle while it varies on leeward façade. Firstly, the wind velocity at the openings of the dwelling model analysed indicated that M1-L2 was more efficient as the average instantaneous velocity was the highest.

Next, the overall statistical distribution of wind velocity analysed showed that M1-U2 recorded the highest frequency of instantaneous velocity, U at its outlet opening on leeward façade while M1-L2 was the only configuration which had a positive kurtosis indicating that it has the highest and sharpest peak. Lastly, for the effectiveness of cross ventilation in the roof of the model, case M1-L2 showed the highest value, indicating it was more efficient.

Finally, for future studies, other areas of the dwelling model such as the body and various location of inlet opening on windward façade with different combinations of opening position on leeward façade should be tested and the rate of cross ventilation should be determined as this will help further prove which configuration ultimately has the better indoor cross ventilation.

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