International Journal of Applied Engineering Research ISSN 0973-4562 Volume 13, Number 5 (2018) pp. 2635-2647

Wind Tunnel Study of Different Roof Geometry Configurations for Wind Induced Natural Ventilation into Stairwell in Tropical Climate

Lip Kean Moey[1], Nor Mariah Adam[1,*], Kamarul Arifin Ahmad[2], Luqman Chuah Abdullah[3]

[1]*Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Putra Malaysia, Serdang, Selangor, Malaysia.*

[2]*Department of Aerospace Engineering, Faculty of Engineering, Universiti Putra Malaysia, Serdang, Selangor, Malaysia.*

[3]*Department of Chemical and Environmental Engineering, Faculty of Engineering, Universiti Putra Malaysia, Serdang, Selangor, Malaysia.*

Abstract

Demand on buildings is in increasing trend all over the world as human population increases. This subsequently increases the electricity consumption and result in more greenhouse gases release to the atmosphere causing global warming. Natural ventilation is an effective method to reduce building electricity consumption. In this study, two types of roof namely flat surface roof and ellipse surface roof were investigated through wind tunnel experiment to evaluate the ventilation performance of a stairwell in tropical climate. The incoming wind speed of range 1 m/s to 5 m/s is set in the wind tunnel to simulate the wind speed in Malaysia. The wind speed of all openings for the reduced stairwell model is of the main concern because higher wind speed will lead to higher air change rate (ACH), which is the criteria to assess the natural ventilation performance of a building. Results have indicated that the measured air speed at inlets and outlets are higher for ellipse surface roof as compared to those of the flat surface roof. The measured air speed difference is more than 22.8% on outlet openings for ellipse surface roof when the incoming wind speed is 2-5 m/s. The study indicates that roof design configuration has an impact on ventilation performance in tropical climate as the temperature difference between inside and outside is negligible.

Keywords: natural ventilation, stairwell, wind tunnel, roof geometry

INTRODUCTION

Malaysia is one of the fastest growing economy among developing counties in the world particularly during the 90s. Many initiatives related to country infrastructure have been introduced and implemented by the Malaysia government to realize the vision 2020. Furthermore, in order for the country to stay relevant, the government has set a goal through TN50 for Malaysia to become a top 20 country in the world by the year 2050. The increase in the number of construction projects in recent decades such as commercial buildings and residential areas has a positive impact to the national development in terms of economic growth and standard of living, but at the same time it also increases the energy demand in Malaysia [1]. In 2012, the electricity generated in the country is around 135 GWh and the consumption is around 117 GWh [2].

With an average annual growth rate of 1.8%, Malaysia population will increase to approximately 33.4 million in 2020. This will certainly accelerate the increase in electricity demand and it is predicted that per capita electricity demand is forecasted to reach 7571 kwh/person in year 2030 [3]. Furthermore, record by Malaysia Energy Statistics Handbook shows that for electricity generation mix, 88.4% of electricity generated in 2015 is by fossil fuels [4] and it is expected that the figure will remain over the next decade. The electricity capacity of Malaysia through RE is expected to increase to about 11% of overall electricity generation or 2080 MW by 2020 [3].

Hassan et al. [2] showed that buildings consume above 40% of total world energy particularly on electricity, and release around one-third of greenhouse gases (GHG) through fossil fuels burning in generating electricity. In Malaysia, over 40% of greenhouse gases emission to the atmosphere is contributed by existing buildings and its communities, which is the contributor to global warming [2]. Therefore, recognizing the importance of environmental sustainability, various policies such as the Malaysian Standard MS 1525: 2007 Code of Practice on Energy Efficiency and use of Renewable Energy for Non – Residential Buildings has been introduced to help preserve the environment [1]. One of the sources of alternative energy that the Government of Malaysia has always been on the lookout is wind. From literature, there has been consistent effort over the years to utilize the wind induced method for building ventilation [5-8].

* Corresponding author. E-mail address: mariah@upm.edu.my
Tel.: +603-89466345; Fax: +603-86567122

Ventilation is a process where the air in an enclosed space is changing with the external environment. During ventilation, air is changing continuously and is replaced by fresh air from a clean source. With the aid of ventilation, good indoor air quality and thermal comfort can be achieved by eliminating contaminated air that possibly has harmful concentration to human beings, as well as to increase wind speed inside the buildings. With the absence of ventilation, the consequences are excessive humidity, condensation, overheating and build-up of unpleasant odors, smokes and pollutants. Therefore, HVAC system (Heating, Ventilating and Air-Conditioning) is introduced in the commercial and industrial buildings to improve the air quality and thermal comfort inside the buildings. Feriadi and Wong [9] showed that people in the hot and humid climate generally prefer cooler environment condition and higher wind speed. However, with the presence of this HVAC system, the air quality and thermal comfort inside the buildings is improved, but the system is a very energy intensive system such that the HVAC system requires large fans, ductwork systems, air-conditioning and heating units [10]. This is due to HVAC systems account for up to 60% of domestic buildings energy consumption [11]. Alternative method to achieve good indoor air quality and thermal comfort in a domestic buildings is by using natural ventilation where the ventilation method is renewable and cost effective, in the form of air filtration and natural air ventilation through windows and openings of the buildings.

Natural ventilation is a natural phenomenon where the force of the natural wind creates a wind pressure and stack effect to aid and direct the movement of the air through the windows and openings of the buildings. Incident wind force on a building surface will create a positive pressure on the windward side of the building while a relative negative wind pressure on the leeward side of the building. This difference of pressure will create pressure difference inside the building through openings, causing the airflow inside the building flow from high pressure region to the low pressure region. However, this method of ventilation may be restricted to the limited range of climates, types of buildings and microclimates [10].

Stack effect normally recognized when the temperature inside the building is higher than the temperature outside of the building, warm air will rise and exit through windows and openings in the building, therefore cooler, dense air from below will replace the escaped warm air. The performance of the stack effect is the highest when the wind speed is relative low but the performance is reduced during the summer periods when the temperature differences are minimal [10].

Natural ventilation analysis of buildings can be studied by using different methods, for example (1) scaled down water tank experiments [12], (2) analytical or semi-empirical formulae [12], (3) full-scale measurements [13], (4) numerical simulation with Computational Fluid Dynamics (CFD) [14], and (5) scaled down atmospheric boundary layer wind tunnel experiments [15]. Water tank experiment and analytical formulae can be used for relatively less complex configuration to study the effect of natural ventilation such as the combined effect of wind and buoyancy as driving forces. But these methods are less practical for certain building configuration in certain environment condition. For the full scale measurements, the data gathered are very valuable but it is time consuming and expensive and the boundary conditions are uncontrollable. CFD allows full control over the boundary conditions. However, its accuracy is an important concern and solution validation are needed. As for the wind tunnel experiments, the boundary condition can be better controlled. It is important to note that experiments need to be performed in an atmospheric boundary layer wind tunnel [5].

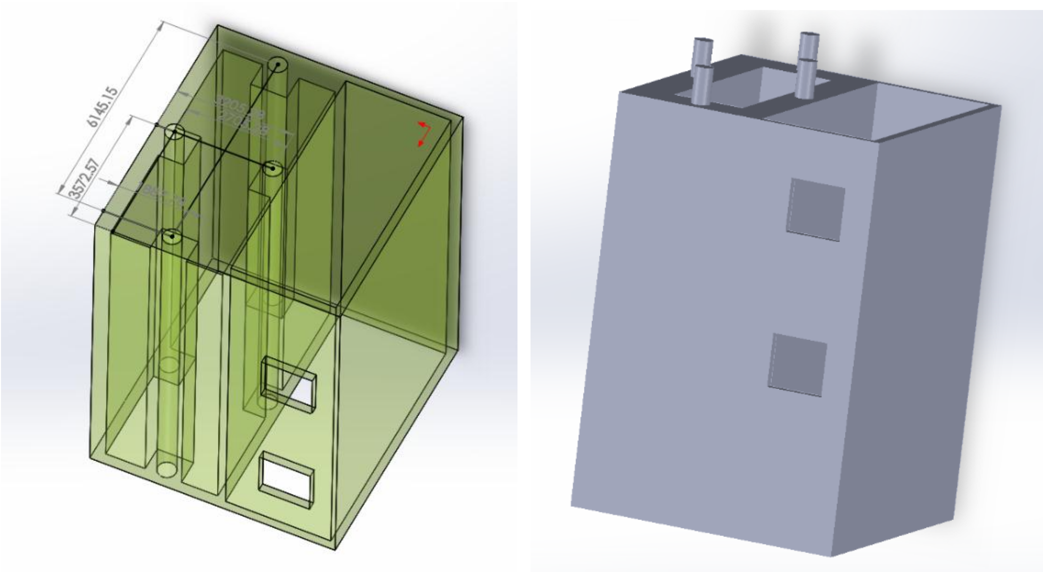
Motivation of Study

The stairwell is one of the building's transitional spaces which acts as both buffer spaces and physical links. The wind is able to induce into the stairwell for ventilation through openings for the purpose of improving air quality and enhancing thermal comfort. Besides openings such as doors or windows, the roof is another element that has attracted the attention of many researchers in recent years that believe can also enhance natural ventilation due to its exposure to highest wind speed [16]. All buildings with more than one floor will certainly have staircase either as a main access or act as an emergency exit. The stairwell is of interest for investigation due to the relatively warmer weather condition in Malaysia, which is located at the tropical climatic region, is unfavorable for staircase occupants. Furthermore, the current available air ventilation system failed to consider low wind speed weather that makes it impractical to use it in Malaysia condition. In this paper, the effect of venturi-shaped flat surface roof and ellipse surface roof to the ventilation of the stairwell is under investigation by using reduced-scale wind tunnel experiments.

METHODOLOGY

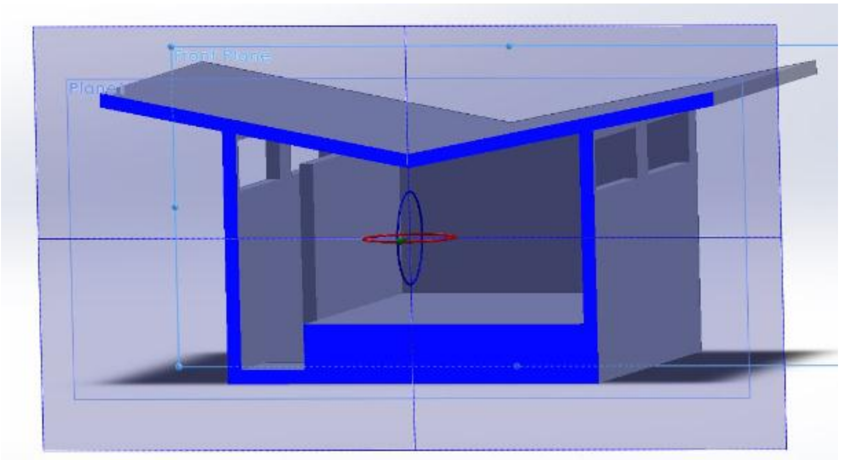
CAD Modeling

In this study, the model was first drawn using the Solidworks software (Dassault Systèmes SOLIDWORKS Corp, USA). Solidworks software is a powerful software that allow us to generate 3D model and its engineering drawing. Using the dimension measured previously [17], different parts of the stairwell were created namely the external wall of the building, the staircase inside the building and the roof. The external wall was separated into two parts (top and bottom) due to the maximum allowable size inside the 3D printing machine. Furthermore, female and male connection was introduced to allow the external wall (top and bottom parts) for easy connection without affecting the structure of the prototype (Fig. 1). This is because the structure with leakage will affect the accuracy of measuring results during wind tunnel experiments. Two types of roofs are identified for investigation in this study, namely flat surface roof and ellipse surface roof, both with inclined angle of 11˚, (Fig. 2). Previous study has shown that ellipse surface roof has higher ventilation rate [18].

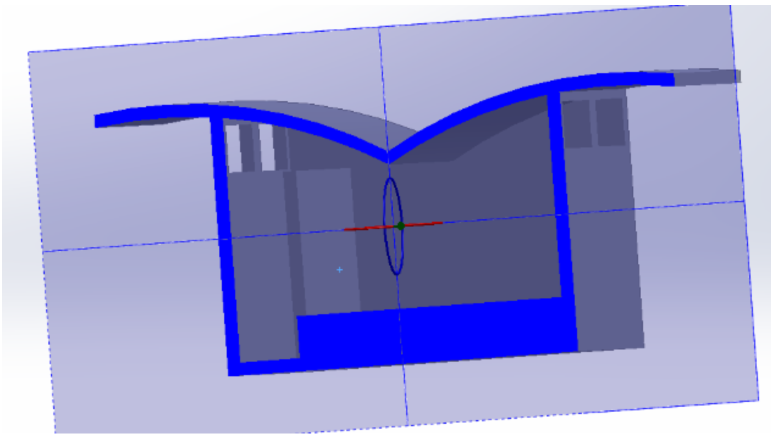


(a) Top part (b) Bottom part

Figure 1. Illustration of external wall



(a) Flat surface roof



(b) Ellipse surface roof

Figure 2. Illustration of roof for the stairwell

Rapid Prototyping

After completion of all parts for the whole building, the file was converted and transferred to rapid prototype station to be manufactured using FORTUS 250MC. FORTUS 250MC is a 3D printer with fine layer resolution with a bigger build space that allow to manufacture larger prototype and also a more effective product testing and development which paired with office-friendly system. The material used for the printing is an ABSplus-P430 thermoplastic. It has three variant colors, namely red, ivory and yellow. There are three type of layer thickness, 0.178mm, 0.254mm and 0.330mm, the smaller the number the finer the product will be and the accuracy of the printed part is claimed to be ± 0.241mm. The structure of the support element are soluble which allow the ease of cleaning or removing of the support element using the ultrasonic tank. The purpose of the support element was to support the studied part that requires support so that it will not collapse during printing. The maximum allowable build envelope (XYZ) is 254mm x 254mm x 305mm, therefore the building envelope was fully utilized for the parts needed to be printed out.

Estimate time of 22 hours was needed to print out the flat surface roof for the 1:50 scaled model, followed by staircase top and bottom of total 18 hours and 38 minutes, external wall top part of 31 hours and 44 minutes and bottom part of 29 hours and 36 minutes. For the ellipse surface roof, the estimated printing time was 23 hours. The total time needed to print out all the parts was about 125 hours. After all the part were printed, the parts were then submerged into the ultrasonic tank to remove the supporting element that may cause blocking the opening of the parts. The ultrasonic cleaning tank used the ultrasound range from 20 KHz to 400 KHz and with addition of cleaning agent to act as a solvent to dissolve the support element in the printed parts. The parts were submerged inside the ultrasonic tank for overnight to remove all the support element.

After the support element was removed using the ultrasonic tank, the parts were rinsed with clean water to remove excess clean agent inside the parts. With all the cleaning agent and water removed, the staircase part was joined into the wall part (Fig. 3). The roof part and the wall parts were taped using a tape to seal off the leakage between both parts.

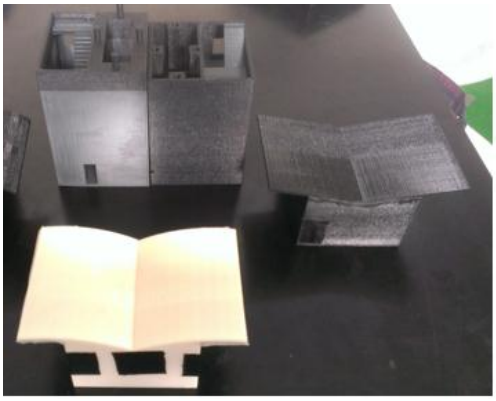


Figure 3. Model of 1:50 scaled flat and ellipse roof and the joined stair and wall part

Wind Tunnel Experiments

The wind tunnel experiment was conducted in an open loop wind tunnel located in aeronautical laboratory at University Putra Malaysia (UPM). The wind tunnel (Fig. 4) is designed with a rectangular box shape with transparent wall to allow better visualization on the ongoing experiment and test section with height, width and length of 1m, 1m and 2.5m respectively, as the movement of air is generated by a 10 bladed fan connected by 3 parallel belt to the 75 HP or 55 KW motor which is able to generate up to maximum wind speed of 50 m/s. The total length of this wind tunnel is 14.5 meters with an overall height of 4 meters. Due to this massive amount of wind speed, layers of filter and protective layer were used to protect the blades and also the testing object used inside the test section from damaging the 10 pieces of blades.

The incoming wind speed of range 1 m/s to 5 m/s is set in the wind tunnel to simulate the wind speed in Malaysia (Fig. 5). This is due to most of the locations in Malaysia are classified as class I, which indicates the average annual wind speed of 1 – 5 m/s [19]. The incoming wind speed was controlled by using pitot-tube with a monitor Testo 510. The speed of various opening positions of the model is measured by the hot wire anemometer (Fig. 6). It is a 13mm (0.5”) large display LCD with dual function meter display. The sensor structure consist of measurement for air velocity using a tiny glass bead thermistor and also measurement of temperature using a precision thermistor with operating temperature range from 0˚C to 50˚C. The measurement positions on both models are shown in Fig. 7. The door at ground floor, opening 1 and 2, window, opening 3 and 4 faces east, south, west, and north direction, respectively.

In this study, the wind speed of all openings for the model is of the main concern. This is because higher wind speed will lead to higher air change rate (ACH), which is the criteria to assess the natural ventilation performance of a building. Table 1 shows the Design of Experiments (DOE) for the wind tunnel experiments. The distribution of air flow rate at the openings and windows with incoming wind speed of range 1 m/s to 5 m/s was studied with the approaching air from the south direction. All the measurement for wind speed were repeated for both flat surface roof and ellipse surface roof.

During the experiment, the wind speed was controlled by a switch which vary from 0 Hz to 50 Hz. For example, to get a 2, 3, 4, and 5 m/s wind speed, the frequency for the motor is 3.6, 4.8, 6.2, and 7.2 Hz, respectively. Note that the frequency will fluctuate after a long period of load, therefore, the motor will be halt and to be cooled down for some time after approximately one hour of usage. When the motor is cooled down, the experiments will be continued. Verification of experiment settings can be checked through pitot-tube readings.

Figure 4. Test section view of the wind tunnel

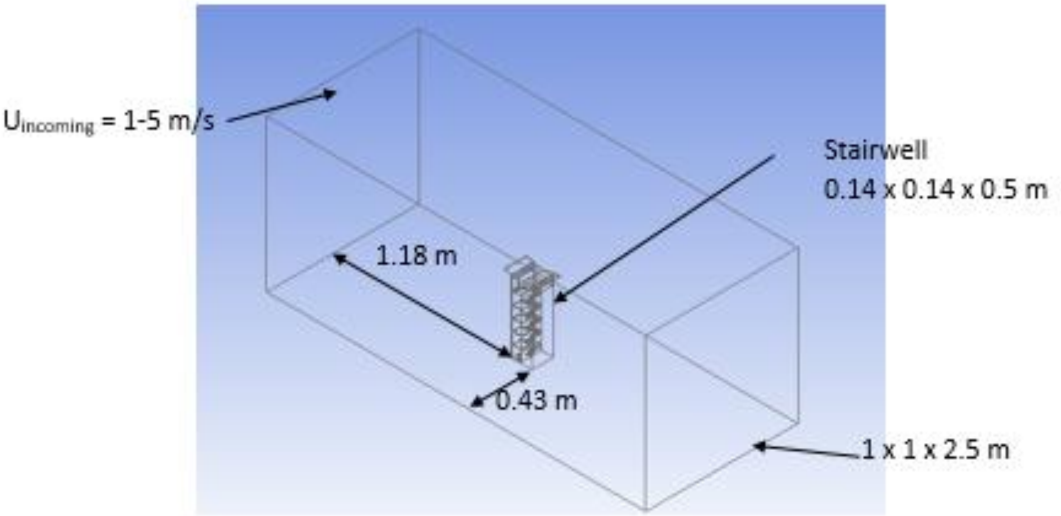
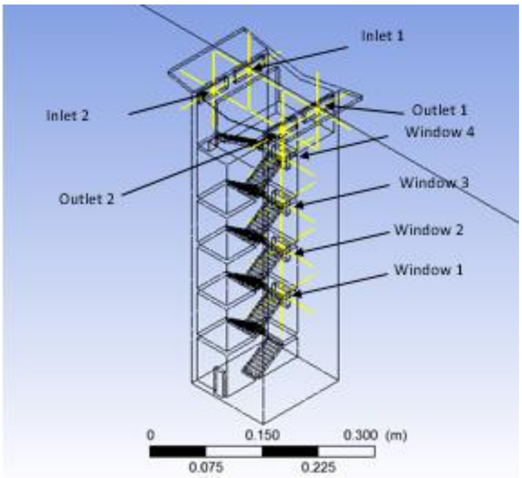


Figure 5. Illustration of experimental setup in wind tunnel test section

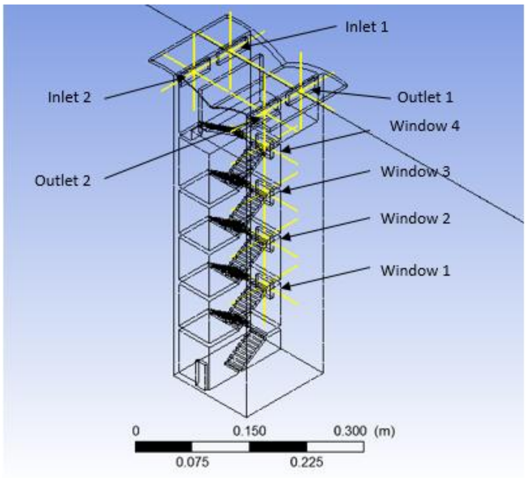
(a) Sensor of hot wire anemometer inside the test section

(b) Display of anemometer (air temperature in ˚C and air velocity in m/s) and display of Testo 510 for the pitot-tube

Figure 6. Hot wire anemometer and pitot-tube used for airflow measurements



(a) Scaled stairwell with flat surface roof



(b) Scaled stairwell with ellipse surface roof

Figure 7. Measurement positions on the scaled stairwell for wind tunnel experiments

Table 1. Design of experiments (DOE) for wind tunnel experiment

Experiment #	Roof angle (degree)	Incoming wind speed (m/s)				
Experiment 1 (FSR[1])	11	1	2	3	4	5
Experiment 2 (ESR[2])	11	1	2	3	4	5

[1]Flat surface roof, [2]Ellipse surface roof

RESULTS

Table 2 shows the measured air speed at inlets and outlets near the roof top for flat and ellipse surface roof. It is observed that the measured air speed at inlet 1 is consistently smaller than those of inlet 2 for both flat and ellipse surface roof. For flat surface roof, the difference between speed at inlet 1 and inlet 2 is gradually reduce from 8.2% when incoming wind speed is 1 m/s to 1.9% when incoming wind speed is 5 m/s (Fig. 8). This indicates that the effect of inlets is noticeable when the incoming wind speed is small, e.g., 1 m/s and 2 m/s. This is due to the orientation of staircase inside the stairwell which affects the air coming into the stairwell through the inlets. On the other hand, the difference between speed at outlet 1 and outlet 2 is also gradually reduce, from 3.8% when incoming wind speed is 1 m/s to 1.3% when incoming wind speed is 5 m/s. It is observed that the difference between speeds at both outlets is less than 2% when incoming wind speed is 3 m/s and above. Besides incoming wind speed of 1 m/s, the speeds at inlets are consistently between 14 – 19% more than those of the outlets as the incoming wind speed increases.

Similar to flat surface roof, as the incoming wind speed increases, the speed at all inlets and outlets increases for ellipse surface roof (Fig. 9). It is observed that for ellipse surface roof, the difference between speed at inlet 1 and 2 is gradually reduce from 5.1% when incoming wind speed is 1 m/s to 0.5% when incoming wind speed is 5 m/s. The difference between speeds at both inlets is less than 2% when incoming wind speed is 3 m/s and above. This indicates that there is no effect on the orientation of staircase inside the stairwell when air coming into the stairwell through the inlets for ellipse surface roof. On the other hand, the difference between speed at outlet 1 and outlet 2 is in the range of 0.3 – 2.8%. Besides, as the incoming speed increases, the trend of speed at outlets is closely resemble those of the inlets.

Table 2. Measured air speed at inlets and outlets near the roof top for flat and ellipse surface roof with incoming wind speeds of 1-5 m/s from south direction

Incoming wind speed (m/s)	Inlet 1 (m/s)[1]	Inlet 1 (m/s)[2]	% Difference
1	1.59 ± 0.01	1.77 ± 0.01	11.3
2	2.65 ± 0.03	2.73 ± 0.04	3.0
3	3.64 ± 0.09	3.92 ± 0.04	7.7
4	4.74 ± 0.05	4.92 ± 0.04	3.8
5	5.79 ± 0.03	6.12 ± 0.03	5.7

Incoming wind speed (m/s)	Inlet 2 (m/s)[1]	Inlet 2 (m/s)[2]	% Difference
1	1.72 ± 0.01	1.86 ± 0.01	8.1
2	2.85 ± 0.07	2.86 ± 0.06	0.4
3	3.83 ± 0.09	3.99 ± 0.04	4.2
4	4.93 ± 0.03	4.98 ± 0.03	1.0
5	5.90 ± 0.07	6.15 ± 0.04	4.2

Incoming wind speed (m/s)	Outlet 1 (m/s)[1]	Outlet 1 (m/s)[2]	% Difference
1	1.59 ± 0.02	1.83 ± 0.01	15.1
2	2.21 ± 0.04	2.82 ± 0.05	27.6
3	3.13 ± 0.07	3.90 ± 0.06	24.6
4	3.85 ± 0.07	4.80 ± 0.05	24.7
5	4.69 ± 0.02	5.94 ± 0.01	26.7

Incoming wind speed (m/s)	Outlet 2 (m/s)[1]	Outlet 2 (m/s)[2]	% Difference
1	1.65 ± 0.01	1.78 ± 0.01	7.9
2	2.28 ± 0.03	2.80 ± 0.06	22.8
3	3.19 ± 0.05	3.98 ± 0.06	24.8
4	3.79 ± 0.07	4.77 ± 0.05	25.9
5	4.63 ± 0.01	5.92 ± 0.01	27.9

*Inlet 1 is at the left side of the windward wall

[1]Flat surface roof

[2]Ellipse surface roof

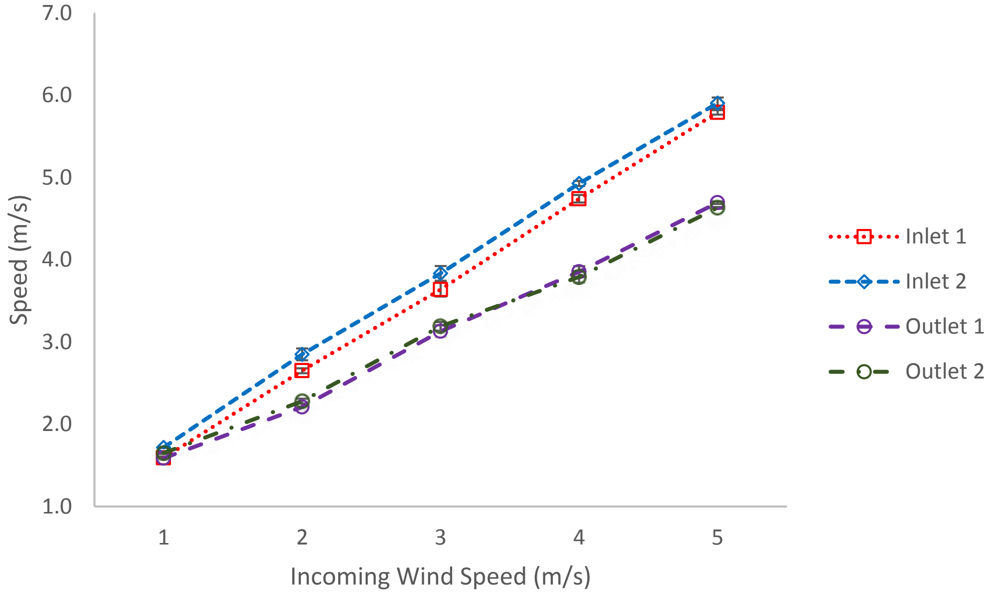


Figure 8. Comparison of speed at various openings near the flat surface roof with incoming wind speeds of 1-5 m/s from south direction

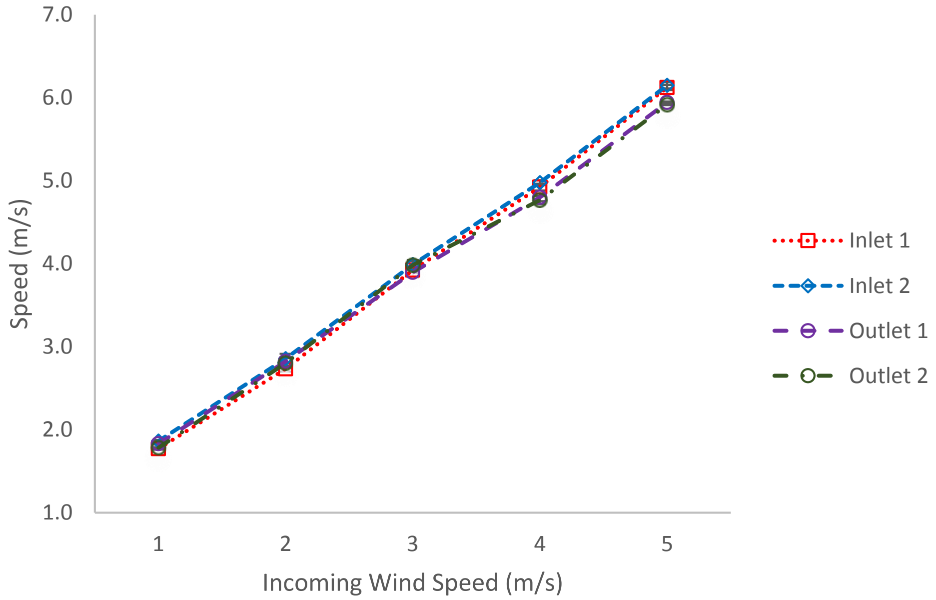


Figure 9. Comparison of speed at various openings near the ellipse surface roof with incoming wind speeds of 1-5 m/s from south direction

Fig. 10 shows the speed at inlets near both the flat surface roof and ellipse surface roof with incoming wind speeds of 1-5 m/s from south direction. As the incoming wind speed increases, the speed at the inlets increases irrespective of roof type. It is observed that the speed at inlet 1 for ellipse surface roof is 3.0 – 11.3% more than those of the flat surface roof. On the other hand, except for incoming wind speed of 1 m/s, the speed at inlet 2 for ellipse roof is only 0.4 – 4.2% more than those of the flat surface roof. This indicates that the ellipse surface roof able to induce more wind into the stairwell through inlet 1 as compared to inlet 2.

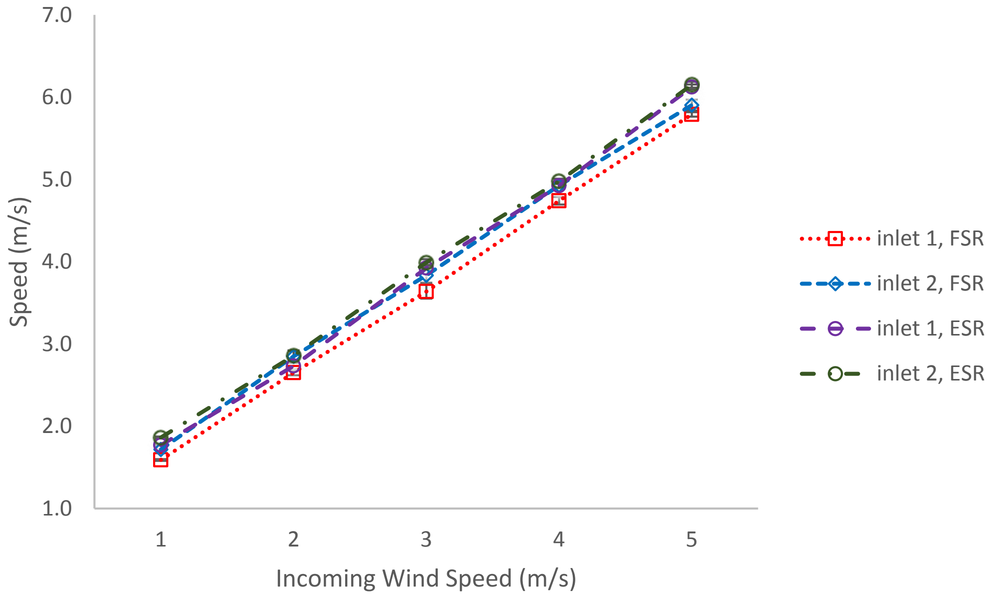


Figure 10. Comparison of speed at inlets near the flat surface roof (FSR) and ellipse surface roof (ESR) with incoming wind speeds of 1-5 m/s from south direction

Fig. 11 shows the speed at outlets near both the flat surface roof and ellipse surface roof with incoming wind speeds of 1-5 m/s from south direction. Similar to the inlets, as the incoming wind speed increases, the speed at the outlets increases irrespective of roof type. It is observed that the speed at outlets1 and 2 for ellipse surface roof is 7.9 – 27.9% more than those of the flat surface roof. This indicates that the ellipse surface roof is able to promote better ventilation inside the stairwell than flat surface roof.

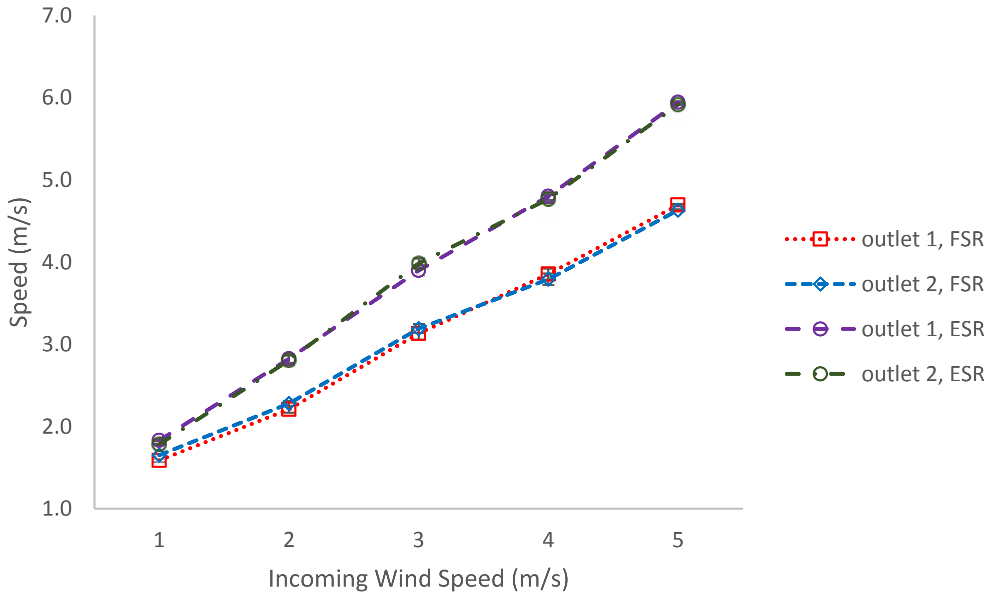


Figure 11. Comparison of speed at outlets near the flat surface roof (FSR) and ellipse surface roof (ESR) with incoming wind speeds of 1-5 m/s from south direction

Table 3 shows the measured air speed at window openings for flat and ellipse surface roof. As the incoming wind speed increases, the speed at all window openings except window 4 increases for flat surface roof. From Fig. 12, similar upward trend is observed for all window openings except window 4. This is evidenced by the speed at window 4 is approximately 28% lower than those of other window openings when the incoming wind speed is 5 m/s. On the other hand, for ellipse surface roof, window 1 has the highest speed regardless of incoming wind speed, follow by window 2, window 3, and window 4 (Fig. 13). This is due to there is a door (facing east direction) at ground floor, which is also play an important role in ventilating the stairwell.

Table 3: Measured air speed at window openings for flat and ellipse surface roof with incoming wind speeds of 1-5 m/s from south direction

Incoming wind speed (m/s)	Window 1 (m/s)[1]	Window 1 (m/s)[2]	% Difference
1	0.85 ± 0.01	0.81 ± 0.01	4.7
2	0.86 ± 0.04	0.85 ± 0.03	1.2
3	1.25 ± 0.02	1.04 ± 0.03	16.8
4	1.82 ± 0.03	1.30 ± 0.03	28.6
5	2.26 ± 0.04	1.67 ± 0.01	26.1

Incoming wind speed (m/s)	Window 2 (m/s)[1]	Window 2 (m/s)[2]	% Difference
1	0.80 ± 0.02	0.80 ± 0.01	0
2	0.81 ± 0.03	0.82 ± 0.01	1.2
3	1.02 ± 0.02	0.99 ± 0.02	2.9
4	1.52 ± 0.02	1.09 ± 0.02	28.3
5	2.12 ± 0.03	1.36 ± 0.02	35.8

Incoming wind speed (m/s)	Window 3 (m/s)[1]	Window 3 (m/s)[2]	% Difference
1	0.72 ± 0.01	0.76 ± 0.01	5.6
2	0.73 ± 0.04	0.67 ± 0.02	8.2
3	1.15 ± 0.03	0.74 ± 0.01	35.7
4	1.62 ± 0.02	0.97 ± 0.02	40.1
5	2.20 ± 0.02	1.28 ± 0.02	41.8

Incoming wind speed (m/s)	Window 4 (m/s)[1]	Window 4 (m/s)[2]	% Difference
1	0.69 ± 0.01	0.74 ± 0.01	7.2
2	0.62 ± 0.03	0.54 ± 0.02	12.9
3	0.90 ± 0.04	0.53 ± 0.02	41.1
4	1.21 ± 0.05	0.66 ± 0.03	45.5
5	1.53 ± 0.04	0.89 ± 0.03	41.8

*Inlet 1 is at the left side of the windward wall

[1]Flat surface roof

[2]Ellipse surface roof

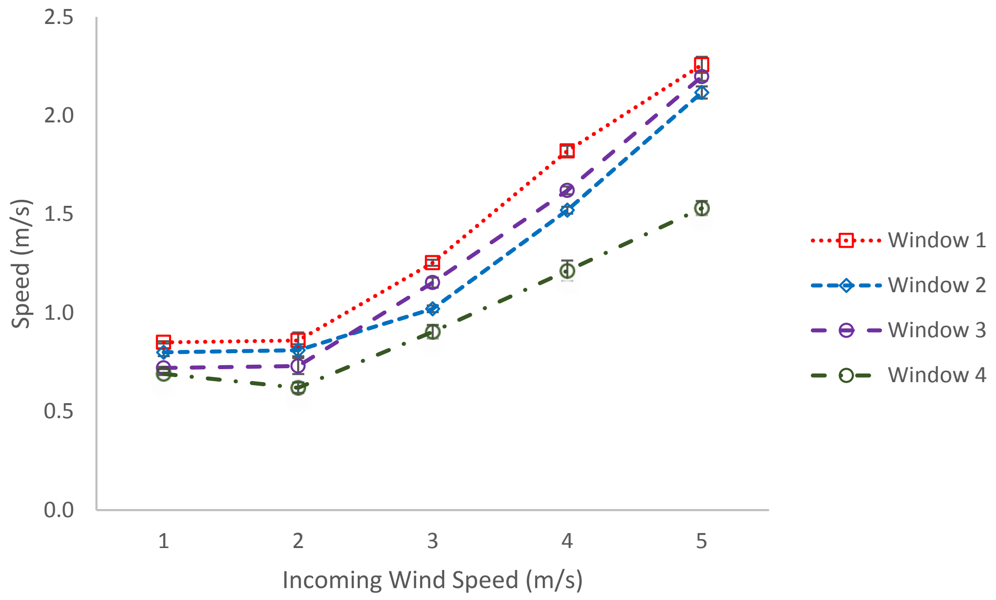


Figure 12. Comparison of speed at window openings for flat surface roof with incoming wind speeds of 1-5 m/s from south direction

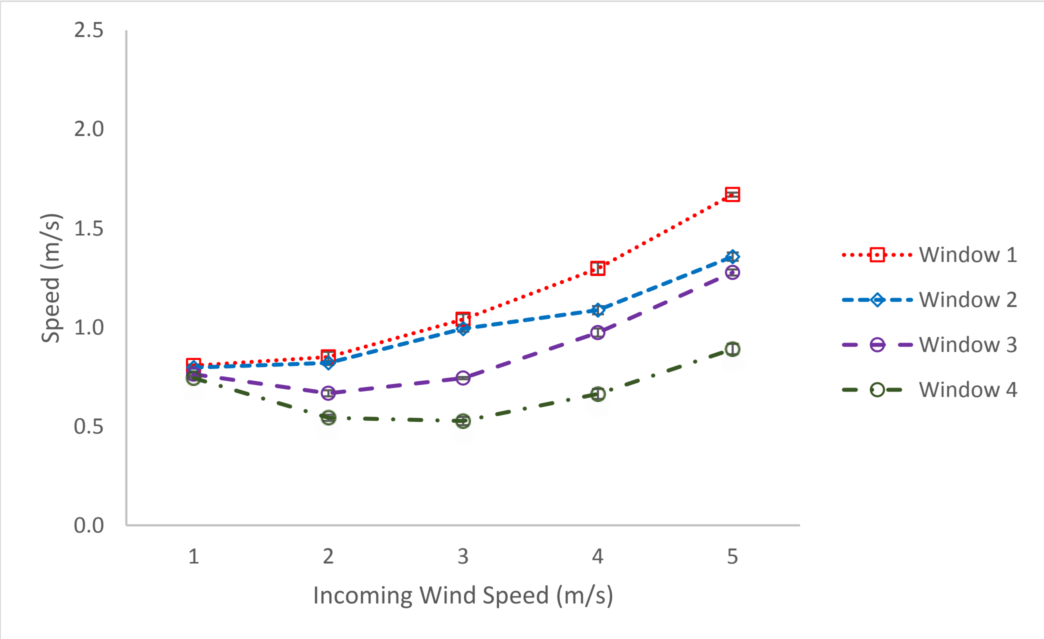


Figure 13. Comparison of speed at window openings for ellipse surface roof with incoming wind speeds of 1-5 m/s from south direction

Fig. 14 shows the speed at window openings 1 and 2 for both the flat surface roof and ellipse surface roof with incoming wind speeds of 1-5 m/s from south direction. It is observed that the difference for the speed at window 1 for flat surface roof is 4.7%, 1.2%, 16.8%, 28.6%, and 26.1% higher as compared to those of ellipse surface roof for incoming wind speed of 1,2,3,4, and 5 m/s, respectively. On the other hand, the difference for the speed at window 2 is small – less than 2.9% - between flat surface roof and ellipse surface roof when the incoming wind speed is 2 m/s and 3 m/s. However, the different is significant when the incoming wind speed is 4 m/s and 5 m/s – more than 28% difference between these two roofs.

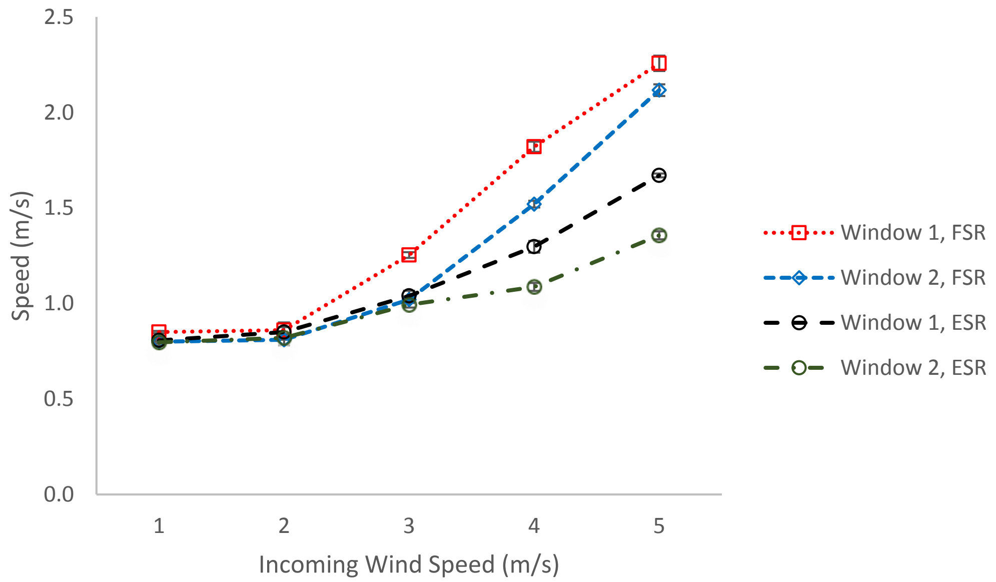


Figure 14. Comparison of speed at window openings 1 and 2 for flat surface roof (FSR) and ellipse surface roof (ESR) with incoming wind speeds of 1-5 m/s from south direction

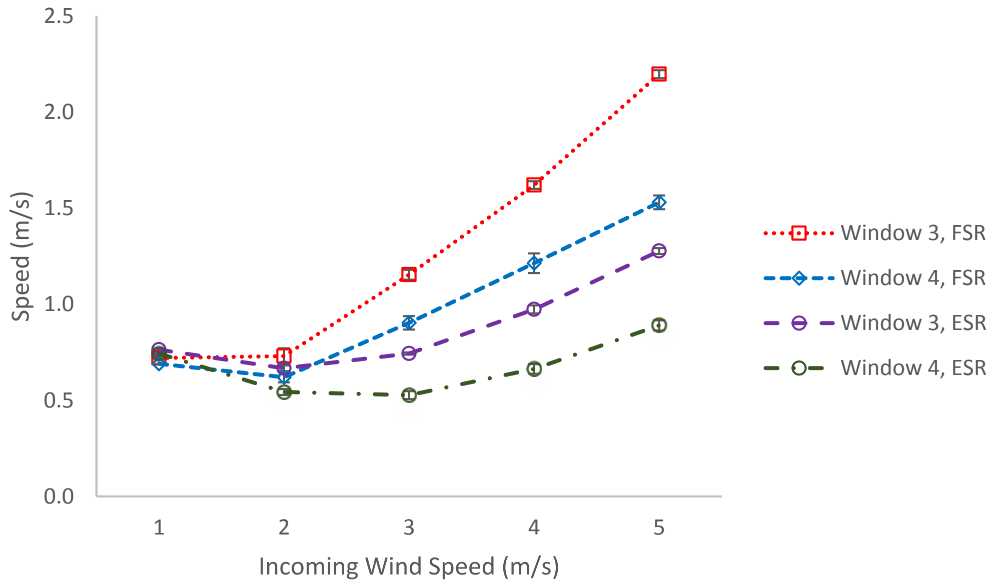


Figure 15. Comparison of speed at window openings 3 and 4 for flat surface roof (FSR) and ellipse surface roof (ESR) with incoming wind speeds of 1-5 m/s from south direction

Fig. 15 shows the speed at window openings 3 and 4 for both the flat surface roof and ellipse surface roof with incoming wind speeds of 1-5 m/s from south direction It is observed that the difference for the speed at window 3 for flat surface roof is 8.2%, 35.7%, 40.1%, and 41.8% highter as compared to those of ellipse surface roof for incoming wind speed of 2,3,4, and 5 m/s, respectively. Similarly, the speed at window 4 for flat surface roof is 12.9%, 41.1%, 45.5%, and 41.8% highter as compared to those of ellipse surface roof for incoming wind speed of 2,3,4, and 5 m/s, respectively.

CONCLUSIONS

In this study, wind tunnel experiment was conducted to evaluate the ventilation performance of a stairwell in tropical climate. Two roofs are of interest namely flat surface roof and ellipse surface roof. The speed at inlets and outlets for the ellipse surface roof is higher as compared to those of the flat surface roof. The results obtained are in line with previous study by Bronsema that the roof is carried out as windcatcher to increase the ventilation performance. The result has indicated that roof design configuration has an impact on ventilation performance in tropical climate as the temperature difference between inside and outside is almost similar. Future research will focus on the use of CFD to increase the insights in stairwell aerodynamics and flow patterns so that the air change rate can be improved for better ventilation.

REFERENCES

[1] A. S. Ahmad, M. Y. Hassan, H. Abdullah, H. A. Rahman, M. S. Majid, and M. Bandi, "Energy efficiency measurements in a Malaysian public university." pp. 582-587.

[2] J. Hassan, R. Zin, M. A. Majid, S. Balubaid, and M. Hainin, "Building energy consumption in Malaysia: an overview," Jurnal Teknologi, vol. 70, no. 7, 2014.

[3] R. Ali, I. Daut, and S. Taib, "A review on existing and future energy sources for electrical power generation in Malaysia," Renewable and Sustainable Energy Reviews, vol. 16, no. 6, pp. 4047-4055, 2012.

[4] E. Commission, "Malaysia energy statistics handbook 2016," Putrajaya, 2016.

[5] T. van Hooff, B. Blocken, L. Aanen, and B. Bronsema, "A venturi-shaped roof for wind-induced natural ventilation of buildings: wind tunnel and CFD evaluation of different design configurations," Building and Environment, vol. 46, no. 9, pp. 1797-1807, 2011.

[6] B. R. Hughes, J. K. Calautit, and S. A. Ghani, "The development of commercial wind towers for natural ventilation: A review," Applied Energy, vol. 92, pp. 606-627, 2012.

[7] J. K. Calautit, and B. R. Hughes, "Measurement and prediction of the indoor airflow in a room ventilated with a commercial wind tower," Energy and Buildings, vol. 84, pp. 367-377, 2014.

[8] J. K. Calautit, and B. R. Hughes, "Wind tunnel and CFD study of the natural ventilation performance of a commercial multi-directional wind tower," Building and Environment, vol. 80, pp. 71-83, 2014.

[9] H. Feriadi, and N. H. Wong, "Thermal comfort for naturally ventilated houses in Indonesia," Energy and Buildings, vol. 36, no. 7, pp. 614-626, 2004.

[10] N. Khan, Y. Su, and S. B. Riffat, "A review on wind driven ventilation techniques," Energy and Buildings, vol. 40, no. 8, pp. 1586-1604, 2008.

[11] B. R. Hughes, and M. Cheuk-Ming, "A study of wind and buoyancy driven flows through commercial wind towers," Energy and Buildings, vol. 43, no. 7, pp. 1784-1791, 2011.

[12] P. F. Linden, "The fluid mechanics of natural ventilation," Annual review of fluid mechanics, vol. 31, no. 1, pp. 201-238, 1999.

[13] T. Van Hooff, and B. Blocken, "Coupled urban wind flow and indoor natural ventilation modelling on a high-resolution grid: A case study for the Amsterdam ArenA stadium," Environmental Modelling & Software, vol. 25, no. 1, pp. 51-65, 2010.

[14] T. Van Hooff, and B. Blocken, "On the effect of wind direction and urban surroundings on natural ventilation of a large semi-enclosed stadium," Computers & Fluids, vol. 39, no. 7, pp. 1146-1155, 2010.

[15] P. Karava, T. Stathopoulos, and A. Athienitis, "Airflow assessment in cross-ventilated buildings with operable façade elements," Building and Environment, vol. 46, no. 1, pp. 266-279, 2011.

[16] B. Bronsema, "Earth, Wind & Fire–Air-conditioning powered by nature."

[17] L. K. Moey, N. M. Adam, and K. A. Ahmad, "Effect of venturi-shaped roof angle on air change rate of a stairwell in tropical climate," Journal of Mechanical Engineering, vol. 4, no. 4, pp. 135-150, 2017.

[18] M. Boroojerdian, N. M. Adam, and A. S. M. Rafie, "Wind tunnel study on the pressure coefficient performance of different venturi shaped roof configurations for wind induced natural ventilation." pp. 287-291.

[19] S. Lawan, W. Abidin, W. Chai, A. Baharun, and T. Masri, "Reviewing wind speed and energy distribution in Malaysia," European Academic Research, vol. 1, no. 8, 2013.