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Effect of Venturi-Shaped Roof Angle on Air Change Rate of a Stairwell in Tropical Climate

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ABSTRACT

The objective of this study is to investigate the effect of venturi-shaped roof angle on air change rate (ACH) of a stairwell. Computational Fluid Dynamics (CFD) analysis was conducted to perform the analysis of ACH of a stairwell in a tropical educational institution. A geometrical representation of the experimental dimension was recreated in the CFD simulation. The experimental investigation was carried out using an open circuit low speed wind tunnel for validation purpose. Two k-ε turbulent models were evaluated namely RNG k-ε model and standard k-ε model. It was found that RNG k-ε model closely resembled the trend of those obtained from wind tunnel experiments. Good correlation between the numerical and experimental results was observed (less than 8% average difference). Furthermore, it was found that when the roof angle increased from 40° to 50°, the average ACH was increased by 72%. It was also observed that the indoor speed at level 4 dropped for roof angle below 23°. This certainly is an indicator to promote more studies to investigate the roof design configuration for better natural ventilation into buildings, which is in line with Malaysia's government vision of sustainable energy for all and a greener Malaysia.

Keywords: *Stairwell, Air Change Rate, Tropical Climate, CFD, Roof Angle*

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Introduction

Transitional spaces are defined as locations where physical environment bridges between the interior and exterior environment – a modified climate characterized by highly variable physical conditions [1]. Transitional spaces are generally further divided into two categories: opened to the environment (such as stairwell, balcony, and corridor) and fully enclosed (such as lift lobby). The stairwell is one of the building's transitional spaces which act as both buffer spaces and physical links. The wind is able to induce into the stairwell for ventilation through openings such as window and roof for the purpose of improving air quality and enhancing thermal comfort. All buildings with more than one floor will certainly have staircase either as a main access or act as an emergency exit. In this paper, the stairwell is of interest for investigation due to the relatively warmer weather condition in Malaysia which is located at the tropical climatic region, and it 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's condition. According to Feriadi and Wong [2], people in the hot and humid climate generally prefer cooler environment condition and higher wind speed. Hence, it is inevitable to study air ventilation system in stairwell in order to maintain the thermal comfort of the occupants.

From literature review, there has been consistent effort over the years to utilize natural ventilation especially the wind induced method for building ventilation [3-6]. However, passive cooling is one of the most difficult problems to solve in tropical climatic regions including Malaysia. In warm climates, especially where the humidity is high throughout the year, comfort depends not only on the rate of fresh air supply into the building, but even more on the speed at which the air moves across the occupants for promoting cooling evaporation. It is possible to gain natural ventilation in the building with proper design. Besides openings such as doors or windows, the roof is another element that has attracted the attention of many researchers in recent years who believe that it can also enhance natural ventilation due to its exposure to highest wind speed [3, 7, 8]. To date, to the best of authors' knowledge, there is not much attention to increase the air change rate at the stairwell, which is critically important for many buildings in Malaysia since staircase is the only means for occupants to go in and out of the building. Furthermore, from literatures [3, 8], it was found that the shallow ellipse roof, which was similar to Bronsema's design had the best performance in terms of higher airflow. Therefore, in this present study, the stairwell located at University Putra Malaysia (UPM) was selected for investigation due to its venturi-shaped flat roof, which had similar feature to encourage airflow into the building as shown in previous studies.

One of the criteria to assess the natural ventilation performance of a building is by calculating its air change rate or also known as ACH (air changes per hour). ACH is essentially the ratio of the volume of air replace from the building to its own volume. Higher ACH means better ventilation system works in replacing indoor air with fresh outdoor air. ACH can be calculated using Equation 1.

$$ACH = \frac{3600 \times Q}{V} \tag{1}$$

Where Q = Volumetric flow rate into the enclosure (m^3/s)
V = Volume of the enclosure (m^3)

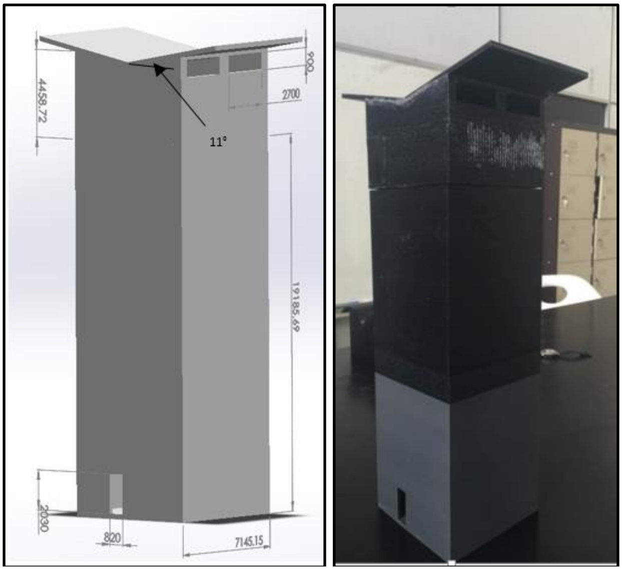
There are several methods that can be used to analyse the ventilation performance in buildings such as analytical models, empirical models, multizone network models, zonal models, small-scale experimental models, full-scale experimental models and Computational Fluid Dynamics (CFD) models. Each of them has its own advantages, disadvantages and suitability with the analysis that needs to be performed. Some methods are more practical while others might be more complicated but give results with better accuracy. Therefore, it is important to set the main focus of the analysis to select the most appropriate method or even a combination of several methods for validation purpose.

In recent researches e.g., [7, 9-11], full scale on-site measurements, reduced scale wind tunnel measurements, and Computational Fluid Dynamics (CFD) are the most widely used methods. The advantage of using full scale on-site measurements is that the real situation can be studied and full complexity of the problem is taken into account. However, this method can only be performed in a limited number of points in space and there is little to no control over the boundary conditions [12]. Reduced scale wind tunnel measurements allow control on the boundary conditions but at the expense of similarity requirements that is sometimes incompatible. Moreover, its performance is also limited to a set of points in space [13]. CFD has some advantages over wind tunnel measurements because simulations can be performed in full scale model; so it is not affected by scaling problems and similarity constraints. Moreover, CFD provides availability of whole flow field data in all points of the computational domain which is crucial when it comes to comparison of different wind criteria.

In this paper, the effect of venturi-shaped flat roof to the ventilation of the stairwell is under investigation by using CFD. Validation of CFD result is done through reduced-scale wind tunnel experiments.

Description of Building and Roof Geometry

The stairwell has five levels and the dimension of approximately 7 × 7 × 25 m (L × W × H), with the roof angle of 11˚. A reduced scale model (1:50) of the stairwell (Figure 1) was manufactured using FORTUS 250MC machine. FORTUS 250MC machine is a 3D printer with fine layer resolution on a bigger build space that allows to manufacture larger prototype and also a more effective product testing and development which is paired with office-friendly system. The accuracy of the printed part is ± 0.241mm. The material used for the printing is an ABSplus-P430 thermoplastic. The total printing time for this model is approximately 100 hours. Note that the door at the top floor is closed during both the wind tunnel experiments and CFD simulation. This is because the door is closed in actual practice.



(a) (b)

Figure 1: (a) Solidworks assembly drawing of the stairwell with venturi-shaped flat roof (door is facing the east direction) (b) Reduced scale model for wind tunnel experiments

Wind Tunnel Measurements

A reduced scale model (1:50) of the stairwell with venturi-shaped flat roof was constructed and placed in the open circuit low speed wind tunnel in the Aerodynamics Laboratory, UPM. The front view and rear view inside the test section of the wind tunnel is shown in Figure 2. The dimension of the test section was 1 × 1 × 2.5 m (W × H × L), resulting in a blockage ratio of less than 2%. The measurement positions on the building are shown in Figure 3. All measurement positions were in the middle of each opening and window. The air reference velocity and speed measurements were performed by using pitot-tube with a monitor Testo 510 and hot wire anemometer, respectively (Figure 4). Both devices had the accuracy of 0.01m/s. Speed measurements were made for 2 m/s, which was equivalent to fan speed of 3.6 Hz for wind directions from the south (window of the stairwell is facing west). Each reading was repeated five times.

(a) (b)

Figure 2: (a) Front view and (b) rear view inside the test section of the wind tunnel

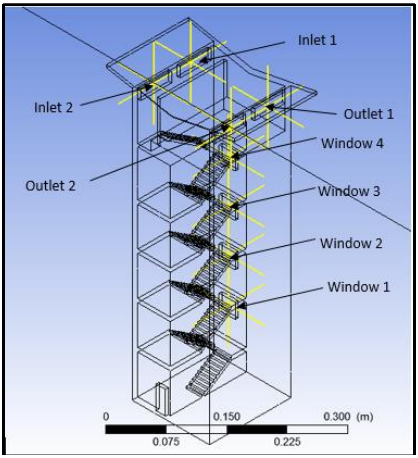


Figure 3: Measurement positions for both the wind tunnel experiments and CFD simulation

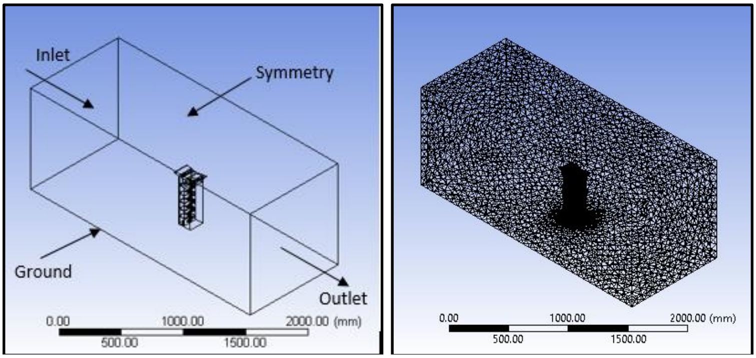
Figure 4: Hot wire anemometer and Testo 510 for the pitot-tube

CFD Setup

The stairwell geometry was modelled in ANSYS DesignModeler before generation of a computational model. A computational model (0.14 × 0.14 × 0.5 m) was made according to the reduced scale building model used for the wind tunnel measurements. The same scale was used for validation purpose. The computational domain had dimensions of L × W × H = 2.5 × 1 × 1 m with velocity inlet and atmospheric pressure outlet as shown in Figure 5a.

One plane was set as a velocity inlet with the opposite boundary wall set as pressure outlet to simulate a velocity flow field [14]. Figure 5b shows the scale model of the stairwell and its generated computational mesh. The second-order upwind scheme was adopted for the convection term, and a semi-implicit method for pressure-linked equation (SIMPLE) algorithm was used for steady state analysis. Convergence was monitored carefully and all scaled residuals showed no further reduction with the increasing number of iterations.

Most of the locations in Malaysia are classsified as class I, which indicates the average annual wind speed of 1 – 5 m/s [15]. Therefore, at the inlet of the domain, the speed of 2 m/s was set in this study to investigate the effect of roof angle on building ventilation.



(a) (b)

Figure 5: (a) Computational domain generated for reduced-scale model, (b) generated computational mesh

Since the computational domain was relatively larger than the stairwell, applying uniform meshing size caused the mesh size of the stairwell itself to be too large to provide an accurate measurement. Therefore, face sizing was inserted only for the stairwell in order to ensure the stairwell, which was the interest of this study, had a finer mesh. On the other hand, sizing for the rest of the computational domain was set to be fine. The 3D steady RANS equations were solved with the stamdard k-ε turbulence model using ANSYS Fluent 16. Besides iterative convergence, grid convergence should also be assessed to reduce numerical errors. In this study, grid sensitivity analysis was performed in two stages. First, face sizing of 20mm, 10mm, 8mm, and 7mm for the stairwell and fine mesh for the rest of the computational domain were compared (Figure 6). It clearly showed that the face sizing of 8mm and 7mm had similar trend in terms of speed. It showed that a small deviation of less than 5% was found between the faze sizing of

8mm and 7mm in terms of speed for various positions of the stairwell. Therefore, the faze sizing of 8mm was retained for further analysis.

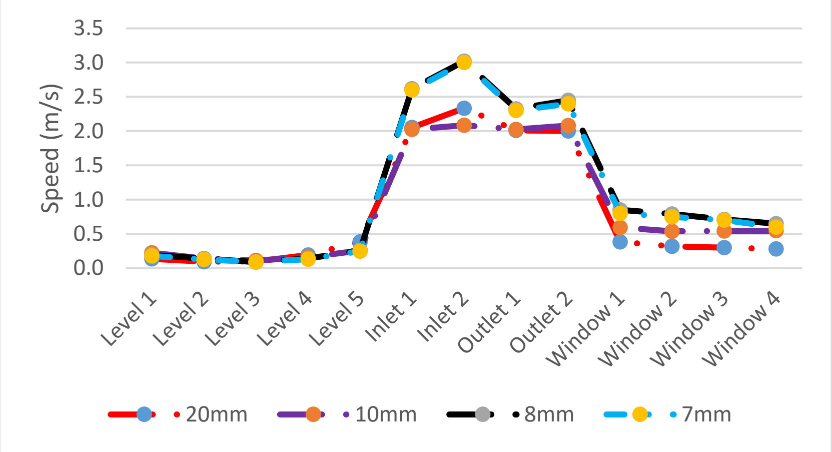


Figure 6: Speed predicted by RNG *k*-*ε* model with different face sizing (20mm, 10mm, 8mm, and 7mm) for various positions of the stairwell

Second, three grids namely coarse, medium, and fine were compared for the grid sensitivity analysis (Figure 8). The model with face sizing of 8mm had 253401 elements for the coarse grid, 274421 elements for the medium grid, and 357635 elements for the fine grid. The results on the three grids were compared in terms of the speed for various positions of the stairwell, indicating only a limited dependence of the results on the grid resolution. A deviation of less than 8% was found between the coarse grid and the middle grid. On the other hand, a smaller deviation of less than 3% was found between the middle grid and the fine grid. Therefore, the middle grid (with face sizing of 8mm) was retained for further analysis. The average element quality for this setting was 0.83186 which was considered satisfactory in a 0 – 1 scale.

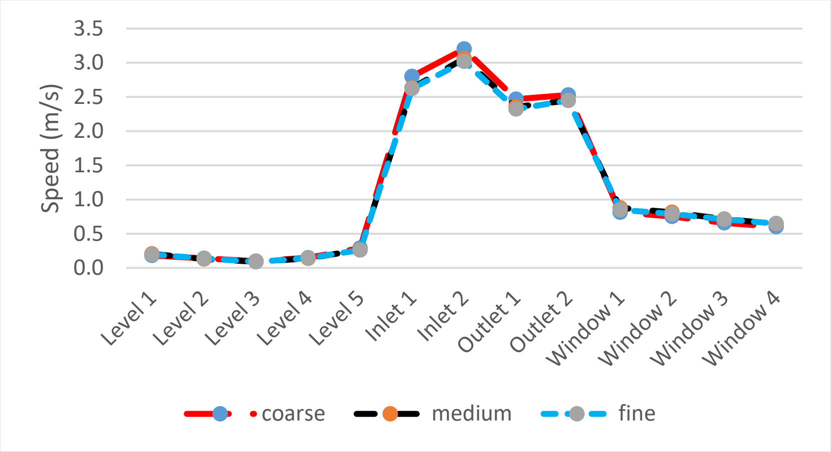


Figure 7: Speed predicted by RNG *k*-*ε* model for various positions of the stairwell for the coarse, medium, and fine grids

It is worth to highlight here that there were literatures found using the RNG *k*-*ε* turbulence model to investigate the effect of roof design configuration on the underpressure in the narrowest roof section for partly or completely drive of natural ventilation of the building [3]. On the other hand, the standard *k*-*ε* turbulence model was proven acceptable in the simulation of wind tower ventilation in terms of accuracy of prediction [4, 5]. Therefore, in this present study, both RNG and standard *k*-*ε* turbulence models were evaluated against the wind tunnel experiments in terms of accuracy for this application.

CFD Model Validation

Table 1 compares the CFD predicted by standard *k*-*ε* model and measured results of the wind speed at the inlets and outlets near the roof top. The average difference across the points was 8.2%. On the other hand, Table 2 compares the CFD predicted by RNG *k*-*ε* model and measured results of the wind speed at the inlets and outlets near the roof top. Average difference across the points was 5.6% with the highest at 7.46% at position outlet 2 (Figure 8).

Table 1: Comparison between predicted by standard *k*-*ε* model and measured air speed at inlets and outlets near the roof top with outdoor wind speed set at 2 m/s from the south direction

	Speed predicted by Standard *k*-*ε* model (m/s)	Measurements through wind tunnel experiments (m/s)	Difference (%)
Inlet 1	2.87	2.65	8.30
Inlet 2	3.09	2.85	8.42
Outlet 1	2.37	2.21	7.24
Outlet 2	2.48	2.28	8.77

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

Table 2: Comparison between predicted by RNG *k*-*ε* model and measured air speed at inlets and outlets near the roof top with outdoor wind speed set at 2 m/s from the south direction

	Speed predicted by RNG *k*-*ε* model (m/s)	Measurements through wind tunnel experiments (m/s)	Difference (%)
Inlet 1	2.63	2.65	0.75
Inlet 2	3.06	2.85	7.37
Outlet 1	2.36	2.21	6.79
Outlet 2	2.45	2.28	7.46

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

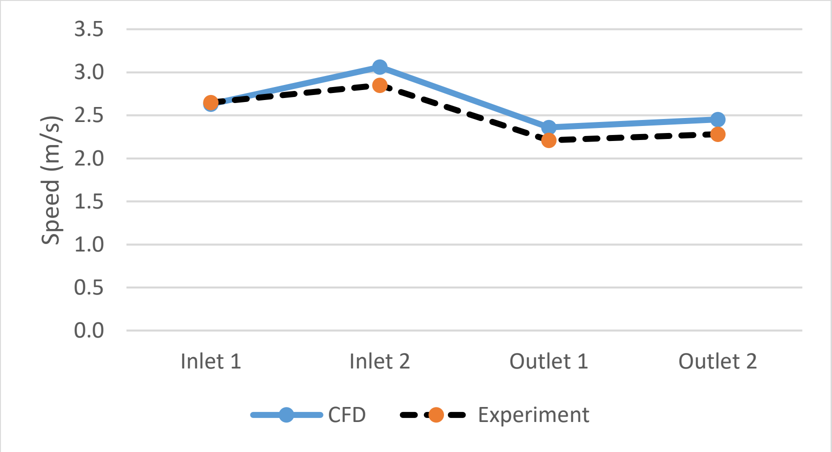


Figure 8: Comparison between results obtained from CFD simulations (RNG *k*-*ε* model) with the reduced scale model for inlets and outlets near the roof top

Table 3 compares the CFD predicted by standard k-ε model and measured results of the wind speed at the window of each floor. Average difference across the points was 9% with the highest at 11.29% (window 4). On the other hand, Table 4 compares the CFD predicted by RNG k-ε model and measured results of the wind speed at the window of each floor. Average difference across the points was 2.1% with the highest at 3.23% at window 4 (Figure 8).

Table 3: Comparison between predicted by standard k-ε model and measured air speed at windows with outdoor wind speed set at 2 m/s from the south direction

	Speed predicted by Standard k-ε model (m/s)	Measurements through wind tunnel experiments (m/s)	Difference (%)
Window 1	0.95	0.86	10.47
Window 2	0.88	0.81	8.64
Window 3	0.78	0.73	6.85
Window 4	0.69	0.62	11.29

Table 4: Comparison between predicted by RNG k-ε model and measured air speed at windows with outdoor wind speed set at 2 m/s from the south direction

	Speed predicted by RNG k-ε model (m/s)	Measurements through wind tunnel experiments (m/s)	Difference (%)
Window 1	0.88	0.86	2.33
Window 2	0.81	0.81	0.00
Window 3	0.71	0.73	2.74
Window 4	0.64	0.62	3.23

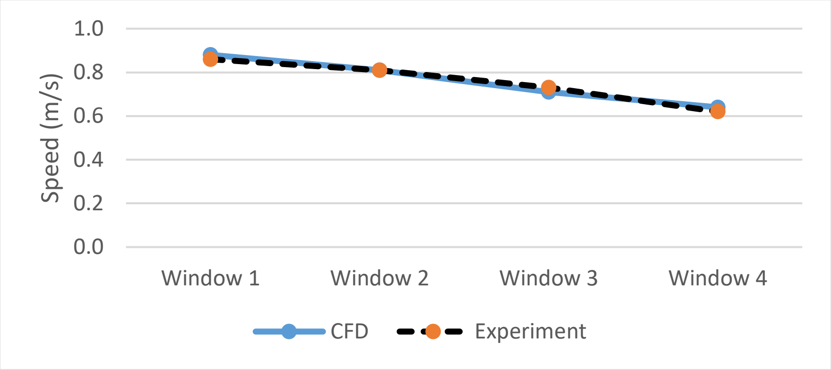


Figure 9: Comparison between results obtained from CFD simulations (RNG *k*-*ε* model) with the reduced scale model for the windows

Based on the comparison above, it clearly showed that results obtained from RNG *k*-*ε* model closely resembled the trend of those obtained from wind tunnel experiments. Therefore, the RNG *k*-*ε* model was retained to further investigate the effect of roof angle on ACH of the stairwell. Also, considering the average difference was less than 4%, it can be claimed that the validation of the CFD modelling study was acceptable.

Results and Discussion

Measurement positions of each level for CFD simulation are shown in Figure 10. Table 5 shows the effect of various roof angles (5˚ to 60˚) on average ACH of the stairwell. For roof angle of 11˚ which is the current roof condition, it gave the average ACH value of 3.1. As the roof angle increased from 11˚ to 20˚, there was a decrease in average ACH values by 35%. As the roof angle increased from 20˚ to 60˚, there seemed to be systematic increase in average ACH values. For example, when the roof angle increased from 30˚ to 40˚, the average ACH was increased by 31%. However, when the roof angle increased from 40˚ to 50˚, the average ACH was increased by 72%. Furthermore, for roof angle of 5˚, it was found that the average ACH increased by 53% compared to existing roof angle (11˚). This indicates that the current roof design is not at its optimum condition in terms of ACH of the stairwell.

Figure 11 shows the effect of varying roof angle on the indoor speed at level 4 of the stairwell. It was observed that the indoor speed at level 4 dropped for roof angle below 23˚, and increased for roof angle above 40˚. This observation is important in helping the building designers to consider the effect of roof angle for better building's natural ventilation.

It is important to mention the limitation of the present study. The outdoor wind was set only from the south direction. It is interesting to explore the effect of outdoor wind from a different direction, e.g., west direction (facing the windows) and subsequently its effect on roof angle for enhancing ACH. Furthermore, the author would like to recommend to explore non-flat roof for future investigation to enhance the wind induced into the stairwell.

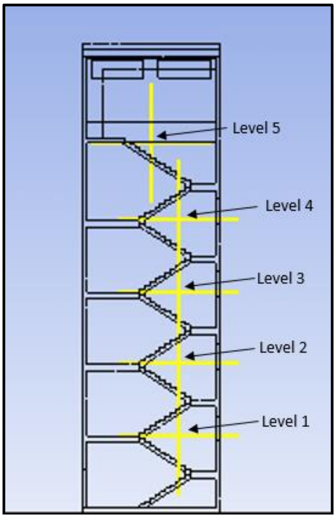


Figure 10: Measurement positions of each levels for CFD simulation

Table 5: Comparison of the effect of roof angle on average ACH with outdoor wind speed set at 2 m/s from the south direction

Roof angle	Indoor speed (m/s)					Average	ACH
	Level 1	Level 2	Level 3	Level 4	Level 5		
5°	0.18	0.09	0.14	0.35	0.53	0.26	4.74
*11°	0.17	0.12	0.15	0.19	0.24	0.17	3.10
20°	0.18	0.15	0.16	0.02	0.04	0.11	2.00
30°	0.22	0.17	0.14	0.11	0.15	0.16	2.91
40°	0.27	0.20	0.18	0.11	0.31	0.21	3.82
50°	0.34	0.22	0.19	0.35	0.68	0.36	6.56
60°	0.43	0.22	0.21	0.68	1.40	0.59	10.74

*Existing roof angle

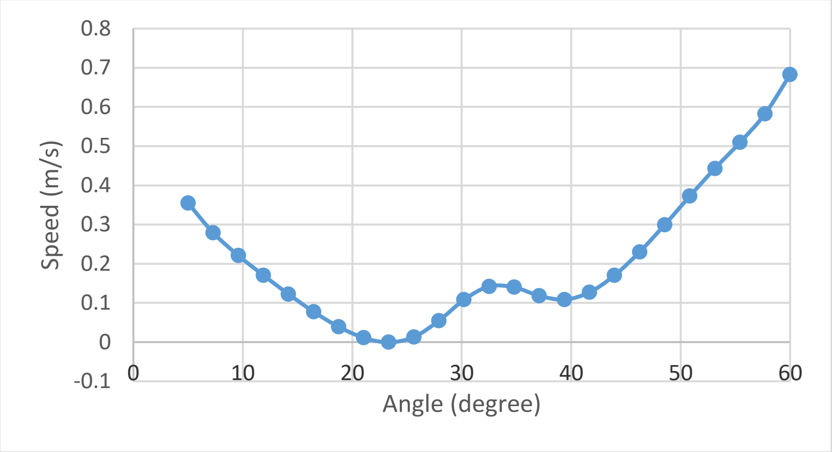


Figure 11: Effect of varying roof angle on the indoor speed at level 4 of the stairwell

Conclusion

In this study, CFD analysis was conducted to perform the analysis of ACH of a stairwell in tropical climate. Two k-ε turbulent models were evaluated namely RNG k-ε model and standard k-ε model. It was found that RNG k-ε model closely resembled the trend of those obtained from wind tunnel experiments. The CFD simulations were generally in good agreement (0-7.46%) with the wind tunnel measurements. It was found that when the roof angle increased from 40˚ to 50˚, the average ACH was increased by 72%. It was also observed that the indoor speed at level 4 dropped for roof angle below 23˚. This certainly is an indicator to promote more studies to investigate the roof design configuration for better natural ventilation into buildings.

All buildings with more than one floor will certainly have staircase either as the main access or act as an emergency exit. With the improved ACH at stairwell, this may encourage occupants to choose and use staircase more often, which leads to energy saving. This will certainly promote green living in our daily life, which has a positive influence on our next generation and in line with Malaysia’s government vision of sustainable energy for all and a greener Malaysia.

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