CFD Prediction on the Pressure Distribution and Streamlines around an Isolated Single-Storey House Considering the Effect of Topographic Characteristics

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Abstract. Single-storey houses are classified as low rise building and vulnerable to damages under windstorm event. This study was carried out with the aim to investigate the pressure distribution and streamlines around an isolated house by considering the effect of terrain characteristics. The topographic features such as flat, depression, ridge, and valley, are considered in this study. This simulation were analysed with Ansys FLUENT 14.0 software package. The result showed the topography characteristics influence the value of pressure coefficient and streamlines especially when the house was located at ridge terrain. The findings strongly suggested that wind analysis should include all topographic features in the analysis in order to establish the true wind force exerted on any structure.

1. Introduction

Natural disaster such as windstorm can cause significant impact and possess a threat to the surrounding. Thunderstorms are capable of producing hail, heavy rain, frequent lightning, and strong gusty winds. The strong winds can reach high speeds causing significant damage [1]. The failure of roofing system during wind storm event occurs due to the inadequate design consideration in wind analysis. Current code of Practice in Malaysia (MS 1553:2002) only consider flat, ridge and escarpment condition in the analysis although the terrain can be in many other forms such as valley, depression and cliff. Many studies have been conducted to study the wind effect using Computational Fluid Dynamics simulations [2-4]. However, most of the studies were performed in 3-D environment and only considered flat terrain. As such, very limited information pertaining to the pressure distribution along the wall and roof profile of a house can be found in the open literature. On the other hand, CFD simulations in 2-D environment can be found in many articles [5-7] but no attempt has been made to include a house model in the analysis. This study demonstrates the change in the pressure distribution due to the change in the topographic characteristics in 2-D environment.
2. Methodology

This section explains the numerical procedures to perform the CFD analysis in ANSYS Fluent 14. The model was generated using ANSYS Design Modeller.

2.1. Building Data

The model consisted of a core house with an extension as shown in Figure 1. A gap between the core and the extension house was measured to be 1.15 m. The roof pitch was set to be 22°. This model represents the average dimensions of the rural house located in the northern region of Peninsula Malaysia [8]. The section of the model was divided into five zones namely:

Zone A (wall of the extension house up to bottom of roof overhang)
Zone B (top of roof overhang for extension house until bottom of overhang of core house)
Zone C (top of overhang roof for core house until the roof apex)
Zone D (leeward roof)
Zone E (leeward wall)

Figure 1. Section showing the dimensions of the model

2.2. Topography characteristics

This study only considers 4 types of topographic characteristics namely flat, depression, ridge and valley as shown in Figure 2 [9]. A flat terrain is taken as an open ground and a depression is a situation when a flat terrain possesses a drop. Similarly a ridge is a ground with an elevated crest and a valley is taken as groove in the land. The difference between depression and valley is condition at the inlet of the computational domain. In all cases, the house was located at the centre of the domain.
2.3. Computational Domain
The boundary condition influence the size of the computational domain which encloses the built area in which the flow shall be calculated [10]. Mochida et al. [11] and Shirasawa et al. [12] stated that the lateral and top boundary should be set at 5H or more away from building. In this case, H is the height of target building. The outflow boundary should be set not more than 15H behind the building [13]. As such, the computational domain for all models was set in this manner and the example is shown in Figure 3. The overall dimension must be large to avoid obstruction of the flow development. It is worth mentioning that the boundary arrangement ensured that the blockage ratio was below 3% as recommended by Tominaga et al. [13].

2.4. Model Generation
The number of mesh was generated by controlling the maximum and minimum face size. The final mesh for the flat, depression, ridge and valley was set at 792 247, 558 818, 642 026 and 653 070, respectively. RNG K-ε model was used in this study based on the recommendation by Tominaga et al. [2] as the model produced the best performance in the prediction of the turbulent kinetic energy. The governing equations in obtaining turbulence kinetic energy, \( k \) are given as follow:

\[
\frac{\partial (\rho k)}{\partial t} + \nabla \cdot (\rho k \mathbf{u}) = \nabla \cdot (\mu_k \nabla k) + P_k - \rho \varepsilon
\]

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \nabla \cdot (\rho \varepsilon \mathbf{u}) = \nabla \cdot (\mu_k \nabla \varepsilon) + C_1 \frac{\varepsilon}{k} P_k - C_2 \rho \varepsilon
\]
\[ v_x = v_{x,\text{free}} \left( \frac{v}{\delta} \right)^\alpha \]  

(1)

The turbulence kinetic energy are given as follow:

\[ k = \frac{u^*}{\sqrt{c\mu}} \]  

(2)

whereas:

\[ u^* = \frac{k\nu}{\ln\left[ \frac{H+z_0}{z_0} \right]} \]  

(3)

The dissipation rate is given by:

\[ \epsilon = \frac{u^{*2}}{k(x+z_0)} \]  

(4)

where,

- \( \kappa \) = Karman constant (0.4)
- \( v_x \) = mean velocity
- \( z_0 \) = Roughness length (0.035)
- \( H \) = Height of building
- \( c\mu \) = 0.085

### 2.5. Input parameter

Table 1 shows the input parameter required in Ansys Fluent 14.

| Parameter               | Input data                                                   |
|-------------------------|--------------------------------------------------------------|
| Turbulence model RNG K-\( \epsilon \) | \( C_\mu = 0.0845 \), \( C_1-\epsilon = 1.42 \), \( C_2-\epsilon = 1.68 \) Near wall treatment = Standard wall function |
| Materials               | Solid (steel) Density = 2719 kg/m\(^3\), Fluid (air) Density = 1.172 kg/m\(^3\), Viscosity = 1.8628 \times 10^{-5} \text{ kg/m.s} |
| Boundary condition      | Ground Roughness height, \( K_s \) (m) = 0.035 Roughness constant, \( C_s = 1 \), Inlet User defined function |
| Solution method         | Pressure velocity coupling SIMPLE Spatial discretization Gradient= Least Square Cell Based Pressure= Second Order Momentum= Second Order Upwind |
| Number of iteration     | 5000                                                         |
3. Result and Discussion

3.1. Pressure Coefficient

The pressure coefficient was calculated using Tominaga et al. [2],

\[ C_p = \frac{P_s - P_{ref}}{0.5 \rho U_{He}^2} \]  

where:

- \( C_p \) = Pressure coefficient
- \( P_s \) = Static pressure at the wall surfaces
- \( P_{ref} \) = Reference pressure
- \( \rho \) = Air density (kg/m\(^3\))
- \( U_{He} \) = Velocity (m/s)

Figure 4 shows the distribution of the pressure coefficient for all models. In the case of the flat terrain, the maximum pressure was located in Zone A followed by a drop as it approaches Zone B. Zone C showed that almost pressures were in the form of suction, including the maximum suction. The suction continued in Zone D and over the leeward wall in Zone E. The house located in depression and valley exhibited relatively the same profile but the suction was only seen with the end of Zone C and starting of Zone D. However, in the case of a house located on flat terrain, the maximum pressure coefficient was higher (0.59) than all models, including the flat depression (0.2). Similarly, the highest suction was exhibited by the model with ridge terrain. The maximum suction for valley, depression, flat, and ridge was recorded to be -1.37, -1.64, -2.38 and -2.41, respectively. High suction can cause more damage to the roof of a building.

Figure 4. Pressure coefficient for all terrain
Figure 5 displays the mean velocity contour for all types of topography. It can be seen that the ridge gives the higher magnitude of velocity in the x direction. Depression and valley exhibited low or negative wind speed before impinging the house. This finding suggests that the presence of downslope reduces the energy of the wind flow and as a result lower pressure and suction are developed compared to flat terrain and ridge.

![Mean velocity contour](image)

**Figure 5.** Mean velocity contour for (a) Flat (b) Depression (c) Valley (d) Ridge

### 3.2. Streamlines

Figure 6 shows the streamlines flow pattern for different terrain characteristics. The same streamline pattern was observed for flat terrain and ridge at upstream region where small eddy was formed at the extension house. On the hand, depression and valley exhibited almost the same pattern prior striking the wall of the extension. In this case, the region of the recirculation was enlarged. Wake region was formed behind the model after flow passing the roof pitch of the core house. An obvious recirculation region was formed behind the house for ridge terrain.

![Streamlines](image)

**Figure 6:** Streamlines flow for (a) Flat (b) Depression (c) Valley (d) Ridge
4. Conclusion
The research was carried out to investigate pressure distribution along the wall and the roof of single-storey house situated in different terrain topography. As the building is located on higher ground with upwind slope in parallel to the wind direction, the magnitude of the pressure coefficient increased significantly both in pressure and suction. As such, in real design work, the detail topographic must be considered in the analysis in order to produce a safe and economical design. In order to appreciate the fully appreciate the effect of terrain characteristic on low rise building, other types of terrain and combinations of terrain characteristic are recommended.

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