Numerical investigation on the effects of wind direction to the air flow characteristics surrounding an isolated rural house

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Abstract. Rural house classified as a low-rise non-engineered building and it is vulnerable to damages during a windstorm event. Many studies have proven that the roof of a low-rise house is especially susceptible to damage and this phenomenon worsens for the case of rural house. This paper aims to investigate the change in distribution of pressure coefficient and streamlines pattern surrounding an isolated rural house by varying the wind directions. The analysis was conducted using Computational Fluid Dynamics method embedded in ANSYS FLUENT software package. The results showed that in most cases, the roof ridge exhibited the highest suction. The maximum suction was observed for Model A2 (30° from the normal to the major face of the kitchen house).

1. Introduction
Rural houses in Malaysia are known as the Traditional Malay House. Mostly, this type of house is built based on the general knowledge and experience of local expertise. In the engineering point of view, the rural houses are classified as non-engineered building [1]. Recently, there are many reports on the failure of the rural houses located in the northern region of Peninsular Malaysia due to windstorm [2], [3]. Most of the damages occurred on the roofing system and the phenomenon is associated with the formation of high local suction and large pressure fluctuating around the roof structure [4]. Although the direction of a strong wind can be anticipated based on the monsoon seasons but the orientation of a rural house obviously cannot be controlled. As such, many cases pertaining to the wind angle attack on a rural house can be expected. This study aims to determine the distribution of pressure coefficient along the roof profile subjected to varying wind direction using Computational Fluid Dynamics (CFD) analysis.

2. Methodology
This section explains the numerical procedures to perform the CFD analysis in ANSYS Fluent 14. The model was generated using Gambit software.

2.1. Building data
Figure 1 show the details of the single storey rural model used in this study. The rural house consists of a core house with an extension (commonly known as kitchen house). This model represents the typical ratio of 3:2:1 for the dimension of the length, width and height for rural houses located in the
northern region of Peninsular Malaysia [5]. The gap between the core and the extension house, and the roof pitch were fixed at 0.25m and 27°, respectively.

This study consider 5 different directions of wind attack that are 30°, 60°, 90°, 120° and 150° as shown in Figure 2. The 90° wind attack is the direction of wind that normal to the roof ridge.

![Figure 1](image1.png)

**Figure 1.** Cross section showing the dimensions of the rural house model.

![Figure 2](image2.png)

**Figure 2.** Variation of wind direction applied to the model.
2.2. Computational method

The surrounding of the models was bounded by the rectangular computational domain that can to accommodate the building model perform the CFD simulation with reliable results. The vertical and horizontal domains, represented as the boundary condition are shown in Figure 3. Previous researchers suggested that the inlet, lateral and top domain should be at least 5H [6] whereas the outlet domain should be at least 15H [7] away from the target building. In this case, H is taken as the height of the target building with H = 4m. Blockage ratio for this domain was calculated to be 2.97% following the recommendation by Baetke et al. [8]. Symmetrical boundary conditions were applied to the top and lateral boundaries in order to create a parallel flow. In CFD simulations, the roughness length was expressed as equivalent to the sand-grain roughness. In this case, the roughness height, $k_s$ and roughness constant, $C_s$ were taken as 0.035 mm and 0.5, respectively [9].

![Figure 3](image1.png)

**Figure 3.** Computational domain and boundary condition for CFD analysis showing the a) side view and b) plan view [9].
A structured grid scheme was generated for the whole domain. In order to capture the details of the air flow the grid scheme was made finer within the vicinity of the wall and roof surfaces compared to the region away from the model. High smoothness and fine quality grid give more accurate result for CFD simulation but it will significantly extend the computational time [10]. In order to minimise the effect of grid distortion, the ratio between two consecutive cells was set at 1.075 complying with the recommendation by Abohela et al. [11] and Montazeri & Blocken[12]. Based on the grid sensitivity test conducted earlier [9], the total grid was maintained at 4528800 cells for the whole domain. The wind velocity was set to be 26.4 m/s representing the equivalent speed for a storm at 10 m above ground, as stated in the Beauford Scale. For a flow through a rectangular domain, the appropriate boundary condition was used at the inlet and it is governed by the equations (1), (2), (3) and (4) [13]:

$$U(z) = U_h \left( \frac{Z}{Z_h} \right)^\alpha$$  \hspace{1cm} (1)

where,

- $U(z)$ = wind speed
- $U_h$ = wind speed at height $z_{ref}$
- $z$ = height
- $Z_h$ = reference height
- $\alpha$ = wind shear exponent

$$k(z) = \frac{u_*^2}{\sqrt{C_\mu}}$$  \hspace{1cm} (2)

where,

- $k(z)$ = Turbulent kinetic energy
- $u_*$ = Friction velocity
- $C_\mu$ = Constant, 0.09

$$\varepsilon(z) = \frac{u_*^2}{K(z + z_o)}$$  \hspace{1cm} (3)

where,

- $\varepsilon(z)$ = turbulent dissipation
- $u_*$ = Friction velocity
- $K$ = Von Karman constant, 0.4
- $z$ = Height
- $z_o$ = Roughness length

$$u_* = \frac{K U_h}{\ln \left( \frac{h + z_o}{z_o} \right)}$$  \hspace{1cm} (4)

where,

- $u_*$ = Friction velocity
- $K$ = Von Karman constant, 0.4
- $U_h$ = Reference height
- $h$ = Height
- $z_o$ = Roughness length
The mean streamwise velocity of the approaching flow obeyed a power law with an exponent of 0.25, corresponding to an open terrain condition. Turbulence model RNG $k-\varepsilon$ was used following the recommendation by Tominaga et al. [14] and Quan et al [15] due to its enhanced performance. In the case of the transport equations (pressure, momentum and turbulence), a second-order differencing was used together with a “SIMPLE” pressure-velocity coupling approach [11], [16]. The computational results were considered to be converged when all the scaled residuals levelled off and reached a value ranging from $1\times10^{-4}$ until $1\times10^{-7}$.

3. Results and discussions

3.1. Pressure coefficient
In the present study, the effect of wind direction on the pressure coefficient, $C_p$ along the roof was analyzed. For this purpose, the $C_p$ was calculated from equation (5)[14]:

$$C_p = \frac{P_S - P_{ref}}{0.5 \times \rho \times U_h^2} \quad (5)$$

where,

- $C_p$ = pressure coefficient
- $P_S$ = static pressure
- $P$ = reference pressure
- $\rho$ = air density (kg/m$^3$)
- $U_h$ = reference height (m/s)

All measurements were observed at a cut section through the center of the kitchen house. The section of the model as shown in Figure 4 was divided into nine zones namely:
- Zone A (wall of the kitchen house)
- Zone B (overhang on windward roof of kitchen house)
- Zone C (windward roof of kitchen house)
- Zone D (gap height between ridge of kitchen house and edge of core house)
- Zone E (overhang on windward roof of core house)
- Zone F (windward roof of core house)
- Zone G (leeward roof of core house)
- Zone H (overhang on leeward roof of core house)
- Zone I (leeward wall of core house)
Figure 4. Divided section of the model.

Figure 5 shows the pressure distribution profile along the mid-axis of the kitchen house for five different wind directions ranging from 30° to 150°. Generally, the graph shows that the magnitude of $C_p$ differs from one another. However, the profile still exhibits the similar trend. Most of the windward part of the kitchen house (Zone A until Zone E) experienced a positive pressure while the roof and windward part of core house (Zone E until Zone I) experienced a suction effect. The highest suction occurred on the ridge of core house. In most area, except for the roof ridge, Model A3 with the wind direction of 90° encountered the highest pressure among all models followed by Model A2, Model A4, Model A1, and Model A5. The maximum $C_p$ (-3.18) on the roof ridge was recorded for Model A2 (wind direction of 60°) and the minimum $C_p$ (-1.92) for model A3 (wind direction of 90°). In most cases, the maximum suction was located at the ridge of the core house. However, Model A5 exhibited the maximum suction at leeward wall of the core house. This finding suggested that oblique wind angle attack significantly affects the pattern of the pressure distribution especially when angle moves further away from the normal direction.
Figure 5. Pressure distribution profile along the mid-axis of kitchen house for five different wind direction.

3.2. Streamlines

**Figure 6** shows the streamlines of the flow pattern for five different wind directions. Generally, the pattern of the streamlines showed some similarities. At the windward direction of the kitchen house, a vortex was formed due to the formation of a separating region. A slight change in the pattern was observed at the windward overhang of the core house and at the gap (Zone D). In the case of the model subjected to oblique wind direction (30°, 60°, 120° and 150°), a vortex was formed at the upper side of the overhang (refer Figure 6 (a), (b), (d) and (e)). As the wind progressed to the leeward side of the core house, a mixing layer was formed and created a wake region behind the model. Moreover, the size of vortex at the gap height region for Model A1 and Model A2 showed a larger vortex than Model A4 and Model A5. The formation of vortex region for Model A4 and Model A5 was found to be relatively nearer to the leeward wall compared to Model A2 and Model A3 causing slight higher magnitude of suction. It is worth mentioning that the vortex for Model A5 concentrates underneath the overhang of the leeward roof and part of the leeward wall. This finding explains the maximum suction occurred at this region.
Figure 6. Streamlines of flow pattern for (a) 30° (b) 60° (c) 90° (d) 120° and (e) 150° wind direction.

4. Conclusion
From the study that has been conducted, it can be concluded that the overall graph pattern showed some similarities however the magnitude of $C_p$ varies significantly when there are changes in angle of wind attack. This finding is particularly true for the region at the overhang roof and leeward wall of the rural house model. Moreover, the maximum negative $C_p$ on the roof ridge increased when the rural house model was subjected to oblique wind direction. The maximum suction was observed for Model A2 (30° from the normal to the major face of the kitchen house).

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