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Numerical investigation on the air flow characteristics of a core house with the presence of kitchen house using computational fluid dynamics

S N C Deraman¹, T A Majid¹, S S Zaini¹, W N W Yahya¹, J Abdullah¹ and M A Ismail²

¹Disaster Research Nexus, School of Civil Engineering, Universiti Sains Malaysia, Engineering Campus 14300 Nibong Tebal, Penang, Malaysia

²Advance Packaging and SMT Group, School of Mechanical Engineering, Universiti Sains Malaysia, Engineering Campus 14300 Nibong Tebal, Penang, Malaysia

Email: ceshaharudin@usm.my

Abstract. Most of the rural houses in Malaysia are classified as non-engineered building. These rural houses are characterized by having overhang roof and kitchen house. There have been many cases of such houses being damaged during thunderstorm events. This study investigates the changes in the air flow characteristics due to the presence of a kitchen house. The roof pitch of core house, overhang and gap height were maintained at 27°, 0.5 m and 0.5 m, respectively. Computational Fluid Dynamics (CFD) simulations based on Reynolds-averaged Navier-Stokes equations (RANS) was used together with turbulence model, RNG k- ϵ . The results showed that the presence of a kitchen house slightly increased the suction on the roof ridge but significantly changed the flow pattern in the windward direction.

1. Introduction

In Malaysia, most of the low-rise buildings in the rural area were wood frame structure. This type of structure is subjected to severe damage during a thunderstorm event [1]. The rural houses in Malaysia are mostly considered as low-rise non-engineered buildings. The houses are constructed with a minimum or no structural engineering consideration Muhammad et al., [2]. The characteristic of rural house in Malaysia is reflected with the presence of a kitchen house, the extension unit that is typically lower than the core house. This structure is attached to the core house and the size depends on the free space within the vicinity of the core house. Figure 1 shows an example of a rural house that suffers from roof blown-off and severe damage to the truss system during a windstorm event in the northern region of Peninsula Malaysia. Majid et al. [3] investigated the failure of roof truss system in Malaysia and reported that the damages are normally associated to the high uplift pressure generated on the roof.





Figure 1. Example of roof uplift and damage timber trusses of a rural house in Penang, Malaysia

The study on the wind pressure distribution surrounding a structure can be carried out either experimentally using wind tunnel test or numerically using computer simulations. There are several CFD applications to building analysis related to airflow assessment, wind condition around buildings, ventilation of buildings and wind driven rain on building façade [4]. Besides that, CFD is also used to predict the effects of wind flow on building and the people in and around them [5] to predict wind flows around buildings and structures under conditions very close to the actual state Tamura et al. [6] and to evaluate the interaction between wind and structures [7]. This paper demonstrates the effect of kitchen house on the wind flow surrounding the rural house model using the CFD method.

2. Methodology

An isolated gable roof of core house with attached kitchen house was generated and the schematic view of the 3D building model used in the study is shown in Figure 2. The eave height (H_e), width and length were set at 4 m, 8 m and 12 m, respectively. These dimensions were obtained from the post windstorm disaster survey conducted by Zaini et al. [8]. In their study, they proposed a normalized ratio of a typical rural house dimensions to be in the ratio of 3:2:1 representing length, width and height of the house, respectively. Thus, the shape of the generated model was relatively similar to the typical rural house in the Northern region of Peninsular Malaysia. A few parameters were fixed such as 27° roof pitch (gable roof), 0.5 m of roof overhang and 0.5 m gap height. Two models were investigated. The first model was an isolated building model and served as the control model. The other model incorporated the kitchen house positioned at the edge of the core house. The mean streamwise velocity approaching flow was set at 26.4 m/s. The isometric view of the model with kitchen house and the cross sectional plan view are shown in Figure 2 (a) and Figure 2 (b), respectively.

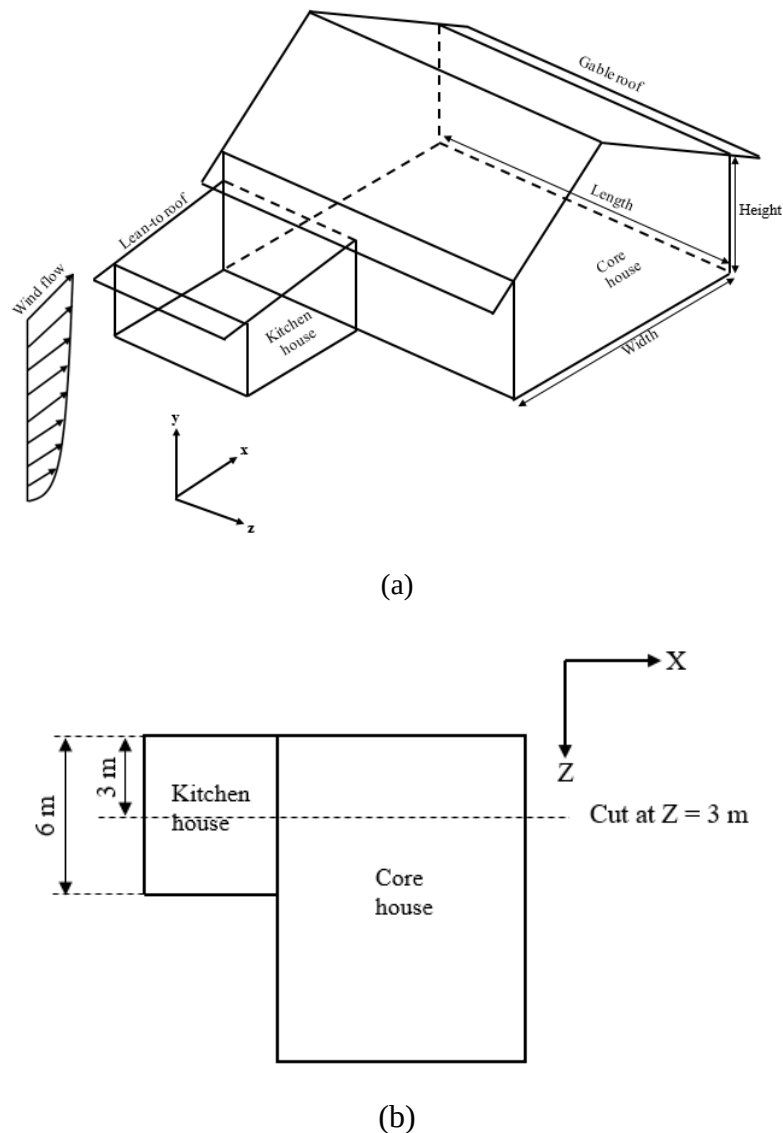


Figure 2. Schematic representation of the rural house model with kitchen house showing the (a) isometric view (b) sectional plan view

The boundary condition followed the recommendation by Tominaga et al. [9]. The inlet boundary condition was set as vertical wind profile of streamwise velocity and obeyed a power law relationship with an exponent of $1/7$, corresponding to an open terrain category. The vertical wind profile, turbulent kinetic energy and turbulent dissipation rate were incorporated into the algorithm via User Define Function (UDF). Likewise, the outlet boundary condition from the domain imposed zero static pressure and was placed far from the region where the influence of the target house was negligible. The upper and side of the domain was set as symmetry boundary conditions, implying zero normal velocity and zero gradients for all the variables at these boundaries [9]. The boundary condition corresponding to the actual ground surface was used with roughness height, $k_s = 0.035$ m and roughness constant, $C_s = 0.5$.

The computational grid consisted 4,968,000 cells for the domain of all models. The average y^+ value over the windward and the leeward roofs were in the range of 21 to 30. The equation of C_p was calculated using the following equation,

$$C_p = \frac{(P_s - P_{ref})}{0.5\rho V^2} \quad \text{Equation 1}$$

where,

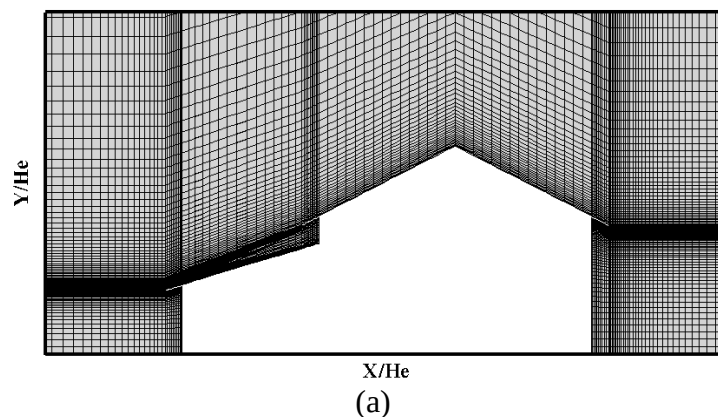
- C_p = pressure coefficient at the middle of wall surfaces
- P_s = static pressure at the middle of wall surfaces
- P_{ref} = reference pressure which is at the reference height (height of the building)
- ρ = density of the air
- V = velocity at reference height.

3. Results and discussion

The Computational Fluid Dynamics method in ANSYS 14.0 software package was used to predict the distribution of the pressure coefficients, streamlines and pressure contour along the designated roof profile.

3.1 Grid Sensitivity Analysis

A grid-sensitivity analysis was performed to ensure the accuracy of the results based on two additional grid schemes namely the coarse grid (2,837,900 cells) and the fine grid (8,154,800 cells). The average y^+ value for the coarse grid over the windward and the leeward roofs were between 50 and 100. Similarly, the y^+ values were recorded to be in the range 5 to 10 in the case of the fine grid scheme. Figure 3 shows that the sectional view of the three different grid schemes.



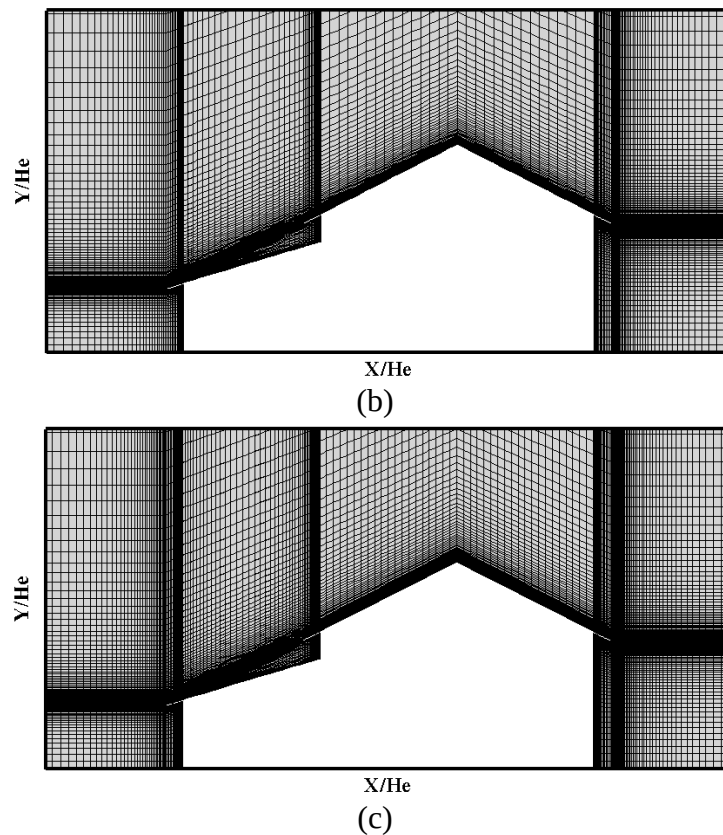


Figure 3. View of grids for grid-sensitivity test: (a) Coarse grid; (b) Medium grid; (c) Fine grid.

3.2 Comparison of pressure coefficient (C_p)

Pressure coefficient (C_p) is a non-dimensional parameter describing the loading effect on buildings and other structures [10]. Figure 4 shows the results of C_p for both models according to the designated zones namely:-

- Zone A (overhang roof on the windward direction),
- Zone B (upwind roof),
- Zone C (downwind roof) and
- Zone D (overhang)

The graph shows that the distribution pattern of C_p is similar for both models and particularly true for almost all zones. It can be seen that overhang roof (Zone A) experienced high pressure underneath the overhang surface. In this zone, a sudden drop changing the C_p values to become negative (suction) at the upper side of the overhang was observed for the model without kitchen house. Following that, the C_p slightly increased in Zone B and gradually drop as it approached the apex of the roof. The maximum suction was located at roof ridge, in between Zone B and Zone C. The suction effect slightly decreased and maintained throughout Zone C and Zone D.

By setting the model without kitchen house as a reference, it can also be seen that the results from the model with kitchen house experienced higher pressure at the windward side compared to the model without kitchen house (Zone A). The percentage difference at the upper side of the overhang roof near to the edge was calculated to be 202%. In Zone B, the percentage difference of C_p near to the roof overhang was found to be approximately 205%. On the contrary, the roof ridge showed approximately 16% difference suggesting that the presence of kitchen house mainly influence the distribution of the

pressure coefficient at the overhang roof on the windward direction. For the Zone C and Zone D, the values of C_p were almost similar for both models.

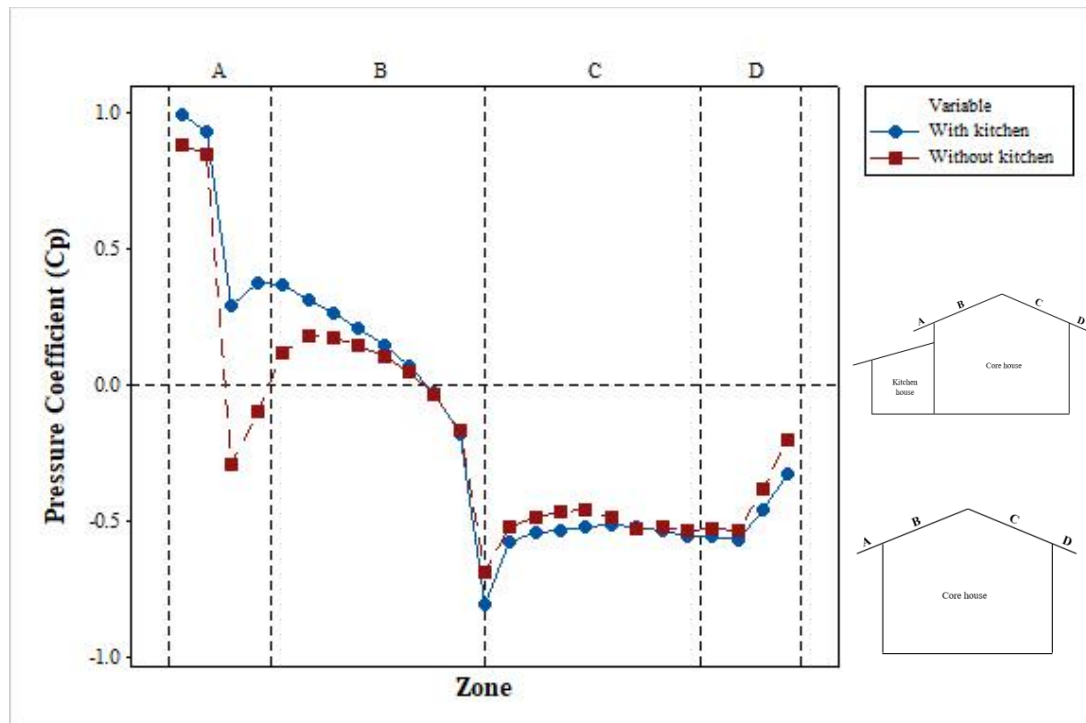


Figure 4. Distribution of C_p for the model with and without kitchen house

3.3 Spatial distribution of pressure coefficient

Furthermore, the effect of the kitchen house was investigated using the C_p distribution contour. Figure 5 (a) and (b) show the 2D C_p contour along the transverse profile for both models. The positive pressure was developed as the air flow impinged the model and formed high pressure coefficient in front of the wall. On the other hand, the negative pressure (suction) was generated in front of the windward wall for the model with kitchen house only. The C_p contour pattern was almost similar for all models and a large upward lift force on the underside of the overhang was observed. In the case of the model with kitchen house, the positive pressure was formed underneath the overhang roof of the kitchen and the core house. As such, the findings suggested that the presence of kitchen house caused high C_p values (pressure) at the windward side. As the wind flow along the leading roof surface, suction was progressively developed and became maximum at the ridge. This phenomenon is true for both models.

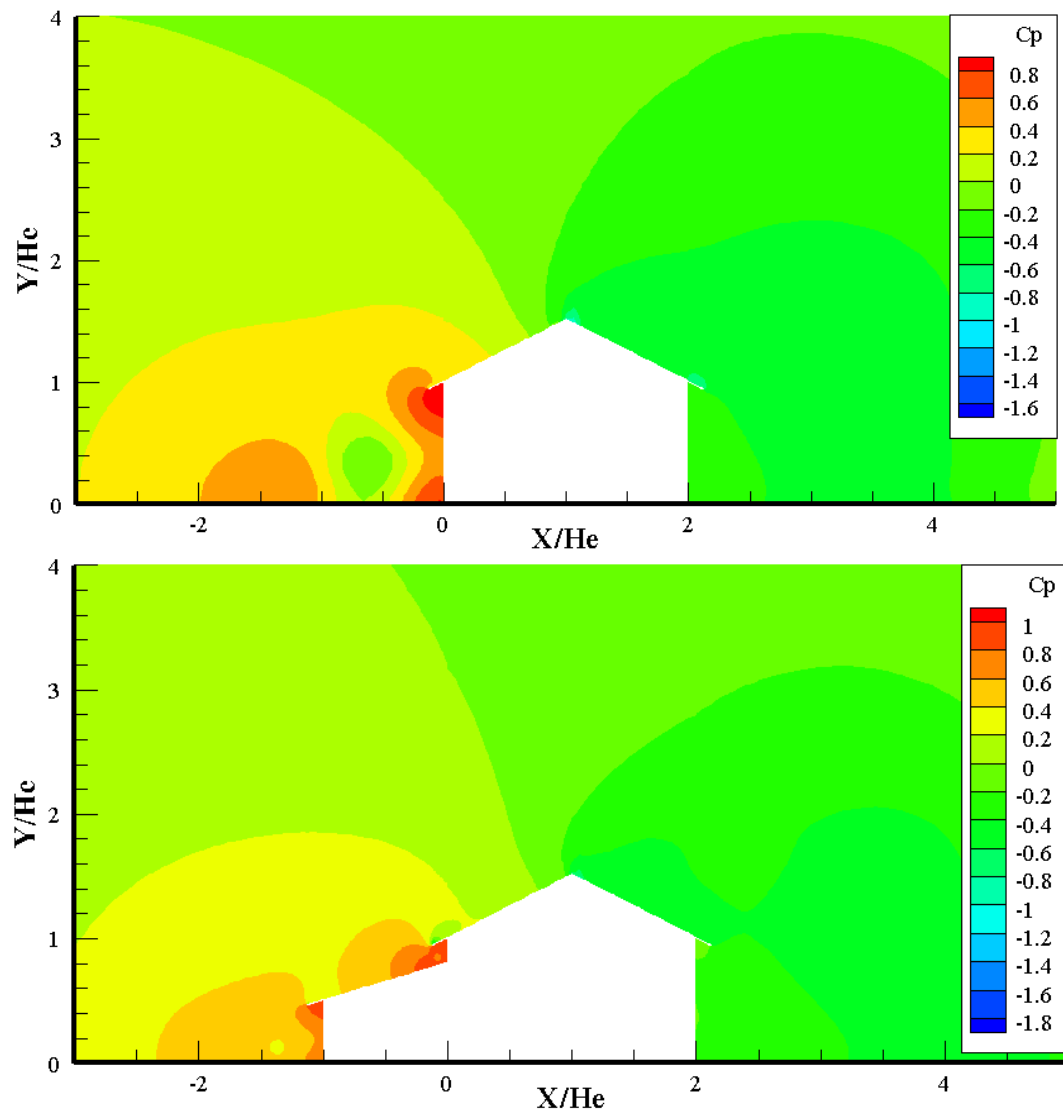


Figure 5. Pressure coefficient distribution for the model (a) without and (b) with kitchen house

3.4 Streamlines

Figure 6 shows the streamlines for both models. The model without kitchen house showed larger eddies being formed in front of the core house compared to the model with kitchen house. This effect is due to the large surface area of the wall exposed to the wind flow. It is expected that direct impingement of the flow onto the windward wall develops the stagnation point somewhere slightly above the center of the windward surface as mentioned by Liu [11]. This phenomenon is identified by the presence of streamlines that turn to either side and eventually move sideways to the wall. However, at the windward surface, the diversion of the streamlines can only be found beneath the overhang roof of the kitchen house and core house. The stagnation point is expected to be developed at these areas. As such, two stagnation points were developed for the model with kitchen house compared to only one for the model without kitchen house. Moreover, for the model with kitchen house, large eddies recirculated on the downwind slope of the roof near the overhang compared to the model without the kitchen house. The presence of kitchen house blocked the wind flow at the windward side and caused the succession of lower and higher pressure zones. Furthermore, the presence of kitchen house induced multiple areas of flow separation and recirculation areas. As such,

the presence of the kitchen house was found to drastically changed the flow pattern in the windward side. The wake region in the leeward side for both models was shown to be relatively similar.

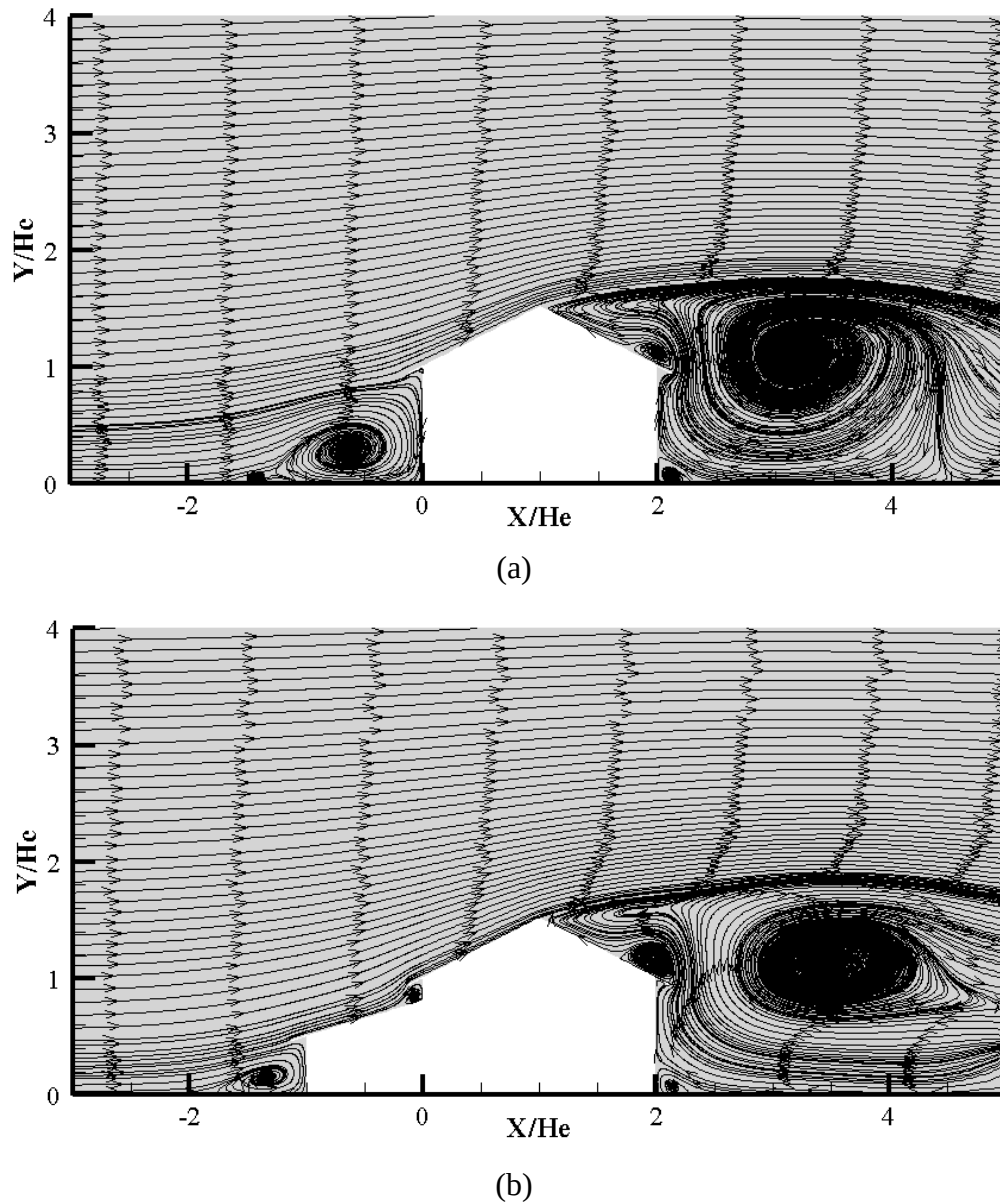


Figure 6. The streamlines along a rural house (a) without and (b) with kitchen house

4. Conclusion

In this study, the air flow around an isolated gable roof of a rural house with and without kitchen house were investigated using CFD simulation based on steady-RANS. It can be concluded that the presence of kitchen house influences the pressure coefficient at the windward side especially at the overhang roof of the core house. Besides that, the highest suction occurred at the roof ridge and the difference between the two models was approximately 16%. The C_p , contour and streamline pattern on the rest of the roof surface were found to be relatively similar.

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