The Effect of Building Shape Modification on Wind Pressure Differences for Cross-ventilation of a Low-Rise Building

Cheng See Yuan

Department of Thermal-Fluid, Faculty of Mechanical Engineering, Kolej Universiti Teknikal Kebangsaan Malaysia, PO Box 1200, 75450 Ayer Keroh, Melaka, Malaysia.

Abstract

The present study investigates the effect of alteration in the building shape due to some common remodelling practice on the wind pressure differences \( \Delta p \) for cross-ventilation of a semi-detached low-rise building using Computational Fluid Dynamics (CFD). A commercial code ANSYS CFX was employed to solve the flow governing equations. The standard \( k - \varepsilon \), renormalisation group (RNG) \( k - \varepsilon \) and Shear Stress Transport (SST) turbulent models were adopted for comparison and the computed velocity was validated against full-scale measurement data. Results computed with these three turbulent models were able to capture the trend of the measured wind speed at the chosen locations with appreciable discrepancy level. Maximum wind pressure differences \( \Delta p \) for cross-ventilation under the effect of building remodelling was calculated based on the CFD results. At the windward side, highest \( \Delta p \) was provided when expansion is made on the kitchen zone of the back neighbouring house. The house with fencing provided the lowest \( \Delta p \) value. In general, for all types of building remodelling, \( \Delta p \) value for houses on the windward side was higher by 447\% (on the average \( \Delta p \) value) compared to the houses on the leeward side.

Keywords: cross-ventilation, wind pressure differences, building remodelling, wind-induced pressure, pressure coefficient, CFD.

1. Introduction

Ventilation in a building is important in providing good indoor air quality and thermal comfort for occupants, as well as to reduce sick building syndrome (Yang et al 2006). There are two ways to achieve desired ventilation rate in a building, namely the natural and the mechanical ventilations. Although mechanical ventilation systems are in advantage over natural ventilation systems such as capable of providing a controlled rate of air change and respond to the varying needs of occupants, however, it required running cost. In addition, mechanical ventilation systems also producing carbon dioxide which is the major greenhouse gas causes global warming.

On the other hand, natural ventilation system has the potential to reduce the energy cost required for mechanical ventilation and cooling of buildings while maintaining adequate thermal comfort and ventilation rates (Emmerich et al 2003). Most importantly, natural ventilation strategies improve indoor air quality (IAQ) and improve occupant comfort, which translates directly to healthier, more productive building occupants (Cascadia Chapter U.S. Green Building Council 2006). Some studies had also indicated that occupants reported fewer symptoms in buildings with natural ventilation compared to buildings with mechanical ventilation (Mendell, 1996). Because of these potential benefits, natural ventilation is being increasingly proposed as a means of saving energy and improving indoor air quality within commercial buildings, particularly in the "green” and “sustainable buildings” communities (Emmerich et al 2003).
Natural ventilation can result from wind pressure and from temperature difference (Burnett et al 2005). In the cases when temperature difference is small between the indoor and outdoor climate, natural ventilation approach would have to rely fully on wind pressure differences around building envelopes, and this type of ventilation is known as the cross-ventilation. To fully utilize the potential of cross-ventilation, the design of building shape and orientation in relative to the wind direction is important. This is because they affect the way wind flow around the building, and thus influence the distribution of wind-induced pressure on it.

For some reasons, house owners would renovate or remodel their house to meet certain needs, such as to expend the existing room space, to build a porch at the front or side of the house for leisure purposes, or to build fencing for privacy or safety reasons. These renovations or remodelling practice may change the pattern of wind flow around the house, and result in changes of the overall pressure coefficient distribution on the building envelopes. Hence, performance of cross-ventilation inside the house is affected.

The key objective of the work presented here was to investigate the extent to which changes in building shapes due to remodelling can affect the wind pressure differences \( \Delta p \) required for cross-ventilation for a particular low-rise building design. The problems were tackled with numerical approach using computational fluid dynamics (CFD) simulations. RNG \( k - \varepsilon \) turbulent model was adopted to calculate the pressure coefficient distribution over the building envelopes. Maximum wind pressure differences \( \Delta p \) for cross-ventilation were then estimated for each house. Note that the scopes of this work are focus on how \( \Delta p \) may be affected by building shape modifications, the influence of adjacent buildings and climate conditions are omitted. Thus the results presented in this study should not be generalized for the assessment of overall ventilation performance of any particular real building.

In Section 2, the numerical methodology of CFD is explained with regard to issues related to the computational domain, boundary conditions and grid sensitivity studies. The validation approach is presented in Section 3. Next in Section 4, the CFD results and the estimated maximum \( \Delta p \) for cross-ventilation are discussed. Finally, conclusions are given in Section 5.

2. CFD Simulation

2.1 Geometry of the Building Models

Four double-storey low-rise buildings were investigated; one with the original shape and the other three the remodelled houses with extra front pouch cover, fencing and expended zone, respectively (see Figure 1). For convenient in discussions on the simulation results, they are designated as cases I, II, III and IV.

These houses were designed in a way that they are attached at the side and back to the neighbouring houses, so it’s termed quarter-detached building, with symmetric plane at the side and back. Height of the ground floor and first floor were 3.2 m and 3.0 m, respectively. Perimeter of each house was 31.5 m, so the perimeter of the whole building was 63.0 m. For the houses with expended zone, 12.3 m of perimeter is added, thus the perimeter of the whole building become 75.3 m. The dimensions of the extra front pouch cover are 2.8 m high, 3.35 m long and 10.6 m wide. Whilst the fencing was 1.35 m high and surrounded the buildings at the distance of 7.114 m. Details geometry of the original and remodelled houses and designations of each walls and area are as shown in Figure 2.

In the simulation, wind direction is normal to the façade of the building. Thus two houses were at the windward side and the other two at the leeward side. These houses were further defined as left and right houses (see Figure 2).
2.2 CFD Tool

The problem was studied using ANSYS CFX, which is a general-purpose, unstructured-grid commercial computational fluid dynamic (CFD) code. In ANSYS CFX, a hybrid finite-element/finite-volume approach was used to discretizing the Navier-Stokes equations (ANSYS CFX 2005). As a finite volume method, it satisfies strict global conservation by enforcing local conservation over control volumes which are constructed around each mesh node. The finite element methodology is used to describe the solution variation within each element. The resulting equation system is solved with a fully coupled Algebraic Multi-grid (AMG) solver (Raw 1996).

2.3 Turbulent Models
In the literature, some deficiency of the standard $\kappa-\varepsilon$ model to predict the turbulent flow around full-scale buildings had been addressed (e.g. Oliveira and Younis 2000; Hoxey and Richards 1993; Hoxey et al 1993). Oliveira and Younis (2000) summarized that the standard $\kappa-\varepsilon$ model which was applied to simulate the turbulent flow around a full-scale building, failed to predict the flow separation at the windward side of the roof, which is in contrast to the experimental observation. Similar result has been observed by Hoxey and Richards (1993) and by Hoxey et al (1993). Murakami et al (1990) show that the assumption of isotropic turbulence used in the $\kappa-\varepsilon$ model is strictly not applicable to flows in and around buildings. Burnett et al (2005) studied the wind pressure at external surfaces of high-rise residential flats concluded that the $\kappa-\varepsilon$ model predictions for the tail flats do not agreed with the LES results. They also stated that the two-dimensional results may not prove valid for the backside flats, as the two-dimensional results do not agree with the three-dimensional results for those flats.

In spite of these deficiency of the standard $\kappa-\varepsilon$ model in full-scale building predictions, some literature on the other hand, stated that $\kappa-\varepsilon$ model was able to predict the main characteristics of the mean flow around a building. Yang et al (2006) studied the flow around a cubical building, reported that results produced by standard $\kappa-\varepsilon$ model are similar to the prediction of RNG $\kappa-\varepsilon$ for pressure distribution on the windward wall, while at the maximum difference of only 0.2 on the leeward wall. Moreover, the difference for the mean speed was below 7%. In the present study, the standard $\kappa-\varepsilon$, RNG $\kappa-\varepsilon$ and SST turbulence models are applied. This allowed comparison be made between the models.

2.4 Computational Domain and Mesh

To prevent blockage effects which can cause distortions of the inlet velocity profile and the full development of turbulent flow, domain dimensions should cover sufficient regions around the building (Versteeg and Malalasekera 1995). Hence, the computational domain was set as $5L$ ($L$ = building length) upstream and $10L$ downstream, $5L$ away from each side, and about $5L$ from the roof. It has been checked that extending further the domain do not produced appreciable change on the results but would substantially increase the computing time and memory requirement.

The literature revealed that 2-D simulation encountered inaccurate prediction of wind pressure on the roof and leeward wall (Oliveira and Younis 2000), thus only 3-D models were use for all cases in the present study. Each domain was discretized into around one million tetrahedral elements, with two hundred thousand nodes. Finer elements were applied nearby the building to give more details of the flow and pressure distribution on the building envelopes, as shown in Figure 3. Whilst larger elements were applied to the domain far from the building to save computational time required for the simulation.
2.5 Setting of Simulation and Boundary Conditions

The wind in the computational domain was defined to be air at 25 °C with density of 1.185 kg/m³ and dynamic viscosity of 1.831 x 10⁻⁵ kg/ms. Simulation was run at the reference pressure equalled to one standard atmospheric pressure (101.325 kPa) for steady state solution. Boundary condition for incoming wind was set as inlet with subsonic flow regime at the velocity of 2 m/s at the plane perpendicular to the front façades of the windward houses. This velocity was chosen based on the average value of the measured wind speed (for seven days) on the site of the real building using MK III Weather Station. The plane opposite to the inlet was set as the outlet boundary with subsonic flow regime and average static pressure of one atmospheric. The three planes facing the roof and sides of the building were set as symmetry. Finally the whole building and ground surfaces are set as non-slip wall with smooth surface.

2.6 Grid Independence Test

Grid sensitivity had been studied by employing four different grid sizes to capture the flow behaviours around the original building, as summarized in Table I. The higher the numbers of element means a relatively finer grid was employed. The convergence study shows that the residual for all cases level off at the order of 10⁻³ in 100 iterations. Convergence at a higher order was not possible due to the computing capacity and the complexity of the present problem. Even though a little improvement was observed at a finer grid, but the time spent for the simulation was significantly increased especially in the case of Grid4. In fact, running a simulation of more than 3 million elements grid scheme using 1.60GHz processor and 1 GB of RAM, the computer has almost been pushed to its limit. Moreover, with the dropped of about 40% residual and the increased of about 533% time spent in simulation, the use of Grid4 may not justified in practical application. In Table I, it was observed that Grid3 was adequate to produce consistence result at one significant digit for the velocity calculated at three different locations as indicated in Figure 4. Hence, a compromise of numerical accuracy and computational time led to the choice of the Grid3 scheme for the investigation of more scenarios under various turbulent models and building remodelling designs.

Table I. Grid schemes used for grid independent test.

<table>
<thead>
<tr>
<th>Mesh Name</th>
<th>Numbers of Elements</th>
<th>Final residual</th>
<th>Time (Hour)</th>
<th>Wind velocity (m/s)</th>
</tr>
</thead>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>P1</td>
</tr>
<tr>
<td>Grid1</td>
<td>917,726</td>
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<td>2.29</td>
<td>0.90</td>
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<tr>
<td>Grid2</td>
<td>1,156,469</td>
<td>3.32E-03</td>
<td>2.85</td>
<td>0.79</td>
</tr>
<tr>
<td>Grid3</td>
<td>1,781,095</td>
<td>2.85E-03</td>
<td>4.26</td>
<td>0.87</td>
</tr>
<tr>
<td>Grid4</td>
<td>3,113,190</td>
<td>2.04E-03</td>
<td>26.95</td>
<td>0.83</td>
</tr>
</tbody>
</table>

2.7 Simulation Assumptions

To made analysis possible on a complex flow situation, four assumptions were adopted: First, the envelopes were smooth. It means that the existence of any wiring, plumbing and drainage pipes were ignored, so were any unevenness of building surfaces due to existence of windows, kitchen and toilet exhausting. Second, the ground was smooth. Since the main objective of this study is to investigate the effect of building shapes modification on pressure distribution, thus the possible effects due to ground roughness were ignored for simplicity. Third, the envelopes are completely sealed. In a real building, it will not be sealed completely in spike of all windows and doors are closed. These openings or cracks present such like gaps of the door, window, or opening for various exhausting. Fourth, the envelope was adiabatic, i.e. at the same temperature as that of the wind and unaffected by solar radiation.
2.8 Presentation Variables

The pressure coefficient $C_p$ is defined as

$$C_p = \frac{p - p_{\infty}}{0.5 \rho U_w^2}$$  

Where,

- $p$ = Pressure at the building surface (Pa)
- $p_{\infty}$ = Static pressure of the free wind (Pa)
- $\rho$ = Air density (kg/m$^3$)
- $U_w$ = Velocity of the free wind (m/s)

The maximum wind pressure differences for cross-ventilation is defined as

$$\Delta p = p_{\text{max}} - p_{\text{min}}$$

Where,

- $p_{\text{max}}$ = Maximum surface pressure for a house under consideration (Pa)
- $p_{\text{min}}$ = Minimum surface pressure for a house under consideration (Pa)

Noted that at the first floor, the doors of the bedrooms are normally close for privacy reason, thus cross-ventilation potential was only estimated for the ground floor.

3. Full-scale Measurement

Validation is a process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model (AIAA 1998). In majority of cases, the CFD results were usually validated against wind-tunnel test results instead of the field test findings. This is because, extensive full-scale measurement in a real building is not always feasible due to the immense cost which may involve. However, results from the wind-tunnel test might alter from the field test results attributed to the Reynolds number or other scaling factor effects (Yang et al, 2006).

Under the constrain of resources available, a marginal level of validation was performed between the CFD and the field test results in the present study; wind data at three different locations at the real building (as illustrated in Figure 4) were measured for comparison. At point 1, a weather station was used to measure the wind magnitude and direction. Whilst, wind velocity at point 2 and 3 were recorded using hot-wire anemometers. Data were logged in the interval of 2 minutes. These three locations were chosen with the expectation that they will provide a general trend of the wind speed at these locations. Since the upstream wind was defined in the direction normal to the windward façade of the building in CFD simulation, thus the average of measured wind speed at 0° incident angle was compared to the calculated results.

4. Results and Discussion

4.1 Validation

Figure 4 shows the plots of normalized wind speed (wind speed at each location divided by wind speed at P1) at the three locations for measured and calculated results with three
different turbulent models. Even though discrepancy level is appreciable, especially at the side of the building, i.e. P3, but the calculated results successfully captured the general trend of the measured wind speeds. These errors are expected because in the full-scale measurement, the nature of the problem involved was transient, while in the CFD, steady state solution was adopted attributed to the constrain of the computer resources.

Figure 4. Plots of normalized wind speed at the three locations.

4.2 Comparison between the Standard $k - \varepsilon$, RNG and SST Models

Figure 5 (a) shows that all the three turbulent models adopted were having the same trend; positive $C_p$ for all the windward walls and negative $C_p$ for all the side and leeward walls. The $C_p$ predicted with the RNG and SST models were in a close agreement (maximum difference of 3%). Whilst appreciable divergence occurred between the results predicted with the standard $k - \varepsilon$ model and these two models, especially at the side and leeward walls. This might due to the limitation of $k - \varepsilon$ model to predict the flow at regions where reparation might occur, such as near side walls (Huang et al 2006).

RNG and SST models predicted the almost symmetrical $C_p$ results for the left and right houses. However asymmetrical results were obtained in the case of standard $k - \varepsilon$ model. Moreover, the standard $k - \varepsilon$ model predicted a higher $C_p$ at the side walls for the leeward left building (Figure 5 (b)). Contrary, in the cases of RNG and SST, higher $C_p$ was at the front wall. Based on these differences in the results predicted, and the fact that RNG is found to be more accurate in the literature (e.g. Evola and Popov 2006) compared to the standard $k - \varepsilon$ model, RNG model was used for the follow-up investigations of wind-induced pressure for various cases of remodelling.
Figure 5. $C_p$ at each particular wall at the ground floor for the left and right houses predicted with different turbulent models (a) Windward houses and (b) Leeward houses.

4.3 Distribution of $C_p$

For the ground floor envelopes of windward houses, Figure 6 (a) shows no significant change on $C_p$ value between the case I and case II buildings. For the case IV building, alteration of $C_p$ was obtained at the sides and back façade. The most obvious indication was the increased of negative $C_p$ at façade G5 by about 58% compared to the case I building. In these three cases, maximum $C_p$ was at the front façade G1, while minimum $C_p$ was at the side façade G5. Hence, openings at these two façades are to be opened if maximum cross-ventilation potential is desired. For the building with fencing, significant dropped of $C_p$ was obtained as expected, by 50% and 4% for the maximum and minimum $C_p$, respectively. The location for maximum $C_p$ was at the front façade G1 while minimum $C_p$ was at façade G2.
All the $C_p$ values on the ground floor façades of leeward houses were negative (see Figure 6 (b)). In all cases, differential of $C_p$ value was smaller compared to the windward houses (reduced by 83% of the differential between the average maximum and minimum $C_p$ of all cases).

![Figure 6. The pressure coefficient $C_p$ on ground floor envelopes for different building remodelling (a) Windward houses and (b) Leeward houses.](image)

4.4 Maximum Wind Pressure Differences $\Delta p$ for Cross-ventilation

Based on the simulation predictions, maximum $\Delta p$ for cross-ventilation under the effect of remodelling of building was calculated for each house at the ground floor, as shown in Figure 7. On the windward side, the highest $\Delta p$ value pertains to the houses in case IV. This follows by the case II houses and then the original houses, case I. Whilst, as expected the houses with fencing (case III) provided the lowest $\Delta p$ value due to the obstruction of the approaching wind. These results imply that, when compared to the original building, the remodelled building provided about 22% and 3% higher ventilation rate for the cases IV and II, respectively. While case III provided about 93% lower ventilation rate.
For the leeward houses however, the highest $\Delta p$ value was found on the original houses, case I. This follow by the case IV and II houses, while case III houses was the lowest. In general, $\Delta p$ value for houses on the windward side was higher by 447% (on the average $\Delta p$ value) compared to the houses on the leeward side.

\[\text{Figure 7: The maximum wind pressure differences for cross-ventilation under the effect of building modifications. The results were computed for ground floor houses where cross-ventilation is important.}\]

4.5 Transport of Odour inside Houses

By analyzing the distributions of $C_p$ on the building walls, one can answer the design question concerning transport of odour inside the building: which openings are to be used so that the flow of air due to cross-ventilation would not carry unpleasant odours (such that from the kitchen or toilet) to the living area? For this analysis, reference is once again made to Figure 6 (a) and (b) for the windward and leeward houses, respectively.

For the windward houses, Figure 6 (a) shows that $C_p$ is higher for opening on G1, the front sliding door than that at the side and back openings (i.e. side sliding door, kitchen window, back door, toilet window and bedroom window) in cases I, II and IV. This may enable air to flow from L (living room) toward K (kitchen), T (toilet) and B (bedroom), i.e. the living area may not be contaminated by airflow from the kitchen and toilet.

In case III, $C_p$ is maximum for the opening on G1 and minimum for the opening on G2 (which are the front sliding door and front side door at the living room). Thus three flow situations may exist. First, when all openings are left wide, outdoor air may enter the house through opening on G1 at the living area and exit though opening on G2 and other openings at K, T and B. Second, when opening on G1 is close, undesirable flow pattern may exist that outdoor air may enter the house through openings at K and T and flows toward L in order to exit the house through openings on G2 and G4. Thus the flow of air may carry unpleasant odours from the kitchen and toilet to the living area. Hence, when opening on G1 is closed, openings on G2 and G4 should also be shut so that air would enter through opening on G8, the back door and exit through opening on G5, the kitchen window. This third flow situation thus avoids contamination at the living area.

For the leeward houses, Figure 6 (b) shows that $C_p$ was lower on openings at K (i.e. kitchen window and back door) for cases I, II and III. Hence, risk of contamination at the living area
may be avoided when these openings are left wide. For case IV, the openings of highest and lowest \( C_p \) were on G1 and G4, respectively. Whilst \( C_p \) on the openings at the kitchen were quite even. Thus two flow situations may exist. First, when opening on G1 is open, outdoor air may enter the house through opening on G1 at the living area and exit though opening on G4 and other openings at K, T and B. Hence, risk of contamination may be avoided. Second, when opening on G1 is closed, air from the kitchen and toilet would flow toward the living room in order to exit the house through opening on G4. Hence, risk of contamination at the living area occurs. This may be avoided by not using opening on G4 when the opening on G1 is closed, however air circulation at the kitchen may not occur due to the evenness of \( C_p \) value. As an alternative, mechanical ventilation should be employed.

5. Conclusions

The objective of this study was to investigate the effect of alteration in the building shapes on wind pressure differences for cross-ventilation of a semi-detached low-rise building using CFD. The simulation results show that remodelling may have positive or negative impact on the wind pressure differences depending on types of building shape modification. For the cases investigated in this study, case IV remodelling provided about 22% higher wind pressure differences (compared to the original building, i.e. case I) for houses at the windward side, while case III provided about 31% lower wind pressure differences. In case II, less significant impact is estimated, with about 5% higher wind pressure differences.

For the leeward houses however, all remodelling buildings, i.e. cases II, III and IV, imparted negative impact on the wind pressure differences, each of which provided about 41, 68 and 35% lower wind pressure differences, respectively. Overall, wind pressure differences for houses on the windward side were higher by 447% (on the average wind pressure differences value) compared to the leeward houses. Hence, higher cross-ventilation rate should be expected for windward houses, in particular, the case IV remodelled building. These results provide a better understanding of how some common remodelling practice can influence the wind pressure differences required for cross-ventilation.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tr>
<td>( C_p )</td>
<td>Pressure coefficient</td>
<td>-</td>
</tr>
<tr>
<td>( L )</td>
<td>Building length</td>
<td>m</td>
</tr>
<tr>
<td>( k )</td>
<td>Turbulent kinetic energy</td>
<td>( m^2/s^2 )</td>
</tr>
<tr>
<td>( \Delta p )</td>
<td>maximum wind pressure differences for cross-ventilation</td>
<td>Pa</td>
</tr>
<tr>
<td>( p )</td>
<td>Pressure at the building surface</td>
<td>Pa</td>
</tr>
<tr>
<td>( p_s )</td>
<td>Static pressure of the free wind</td>
<td>Pa</td>
</tr>
<tr>
<td>( p_{\text{max}} )</td>
<td>Maximum surface pressure for a house under consideration</td>
<td>Pa</td>
</tr>
<tr>
<td>( p_{\text{min}} )</td>
<td>Minimum surface pressure for a house under consideration</td>
<td>Pa</td>
</tr>
<tr>
<td>( U_i )</td>
<td>wind speed at respective location</td>
<td>m/s</td>
</tr>
<tr>
<td>( U_c )</td>
<td>Velocity of the free wind</td>
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<tr>
<td>( \rho )</td>
<td>Air density</td>
<td>kg/m(^3)</td>
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<td>( \varepsilon )</td>
<td>Turbulent dissipation rate</td>
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References


