Investigation of Roof Pitch and Wind Induced Ventilation by Computational Fluid Dynamics

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ABSTRACT: Previous studies have shown that the roof pitch may affect wind pressure distribution on the surface of buildings. However, little is known about the details of wind pressure distributions affected by roof pitches due to the time consuming and expensive traditional methods, such as full scale study, wind tunnel. With an understanding that wind pressure coefficient difference of inlets and outlets determines the efficiency of natural ventilation, this study attempts to investigate the effects of roof pitches on wind pressure coefficient distribution on a building envelope and estimate wind induced ventilation in a building with reference to variable roof pitches and wind direction in the urban environments by computational fluid dynamics. The results showed the tendency of wind pressure coefficient distribution and its maximal and minimal values on the surfaces under the different conditions. Eventually, it provided the guidelines for designers to decide the suitable roof pitch and the positions of inlet and outlet for wind induced ventilation.

Keywords: roof pitch, wind pressure coefficient, CFD, air change rate coefficient

1. INTRODUCTION

Natural ventilation is a desirable technique for designers due to its merits on health, comfort, and energy savings [1]. The previous studies have shown that the roof pitch may affect the wind pressure distributions on the building surfaces [2] [3], but little is known about its detail. As the roof is one of the main components of building forms, it is necessary to study how the roof pitch may have effects on natural ventilation.

The wind pressure coefficient which is independent of wind speed but dependent on building form, wind direction and surroundings [4] is a dimensionless coefficient used to calculate the natural ventilation rate of a building. Therefore, in order to investigate the influence of roof pitch on wind pressure coefficient, it is assumed that wind speed, building form except roof and surrounding are constant. The wind pressure coefficient can be usually measured through four approaches: full scale test, wind tunnel, empirical method and computational fluid dynamics. The former three methods are traditional, but they have more disadvantages, such as expensive, time consuming and inaccurate [5]. Nowadays, the advanced method Computational Fluid Dynamics (CFD) is more and more popular. Many researchers have explored this way and their results show good agreement with wind tunnel tests and full scale test [6].

In this study, the leading commercial CFD code FLUENT 6.2 was employed to test wind pressure coefficient distribution on the building surfaces with variable roof pitches and wind incidences. The free stream velocity at building height at inlet boundary was taken to normalize pressure coefficient *Cp* (equation 1).

$$Cp = \frac{2(P_s - P_r)}{\rho U_r^2} \qquad (1)$$

Where P_s is the surface static pressure, and P_r and U_r refer to static pressure and velocity of reference condition.

After that, the results of wind pressure difference between windward and leeward walls were applied to estimate the air change rate coefficient with the roof pitch change in the typical building.

2. METHODS

This study firstly chose the appropriate CFD turbulence model and computational domain, and then conducted a grid independent test. After that, a series of tests was performed to acquire the wind pressure coefficient on the building envelope under the different roof pitches and wind incidences. Finally, the basic equation was used to calculate air change rate coefficient with respect to roof pitches.

2.1 CFD method

2.1.1 The basic equation and turbulent model:

Navier-Stokes equations are the fundament of CFD technique [7]. As wind is a typical fully developed turbulent flow and it is also taken as incompressible flow, it is recommended that the improved k-ε turbulence model is feasible to study wind environment [8]. According to the characteristics of wind flow, realizable k-ε turbulence model and non-equilibrium wall function were more appropriate to study wind flow around bluff body than other RANS turbulence models [9].

2.1.2 Computational domain,

The computation domain follows the advice of COST action C14 [8]. It is decided by the maximum building height and the tested scope. The computational domain is shown in figure 1. Hm means the maximal height of the tested building with the larger roof pitch. In this study, the side and height of the tested building is 12.6m, and the maximal roof pitch is 35 degree, so the maximal Hm is 17m. The domain size is 318.6m × 216.6m ×119m.

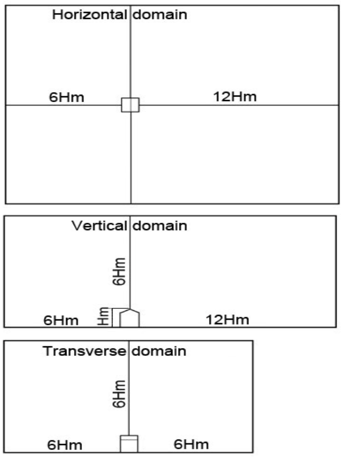

Figure 1: Schematic of computational domain

2.1.3 Boundary conditions

The boundary conditions in CFD are to represent the influence of the reduced surroundings on the models. The top boundary and lateral boundaries are set as symmetry, in which shear stress is zero. The outlet is set as outflow, which means the boundary has no impact on the upstream flow and flow velocity profile does not change in the flow direction. The ground was set as wall condition with roughness length zero. The inlet boundary employed the mean wind vertical profile. There are two kinds of methods to describe the mean wind profile: logarithmic law and power law. In this study, the mean velocity profile referenced the atmosphere boundary layer wind tunnel validated by Lee [10]. According to his suggestion, the gradient wind speed is 9.8m/s, and the value of urban power law exponent is 0.28.Table 1 summaries the boundary conditions.

Table 1 .Boundary Conditions

Boundary	Conditions	Comments
inlet	Velocity inlet	$U = U_G\left(\frac{z}{z_G}\right)^{\alpha}$, $\alpha = 0.28$ $k = \frac{3}{2}(UI)^2$, $\varepsilon = C_\mu^{3/4}\frac{k^{2/3}}{\ell}$ UG = 9.8m/s; $Z_G = 280m$ $C_\mu = 0.09$, $\ell = 0.07L$ I=0.24
outlet	outflow	zero diffusion flux
top	symmetry	zero normal velocity, zero normal gradient of variables
ground	wall	Smooth, Non-equilibrium wall function
sides	symmetry	zero normal velocity, zero normal gradient of variables

2.1.4 Computational grids and solution

Computational grid resolution, stretching factor, and mesh quality decide the accuracy of the solution [7]. In order to avoid truncation error, the stretching factor is less than 1.25, usually 1.2. Three size grid 1 (52x48x32), grid 2 (78x72x48) and grid 3 (117x108x72) were investigated to compare the solution of the velocity of specified point around building. Taken the fine grid 3 as standard, the results show that the solution of the grid 1 is 0.8% larger than that of grid 3, and the grid 2 is 0.5% less. It can be concluded that grid is independent. In order to save computational resource, the grid size 64x56x38 between grid 1 and grid 2 were applied into the continue study. The grid was structured, and cells are hexahedra. And the local grid near the ground and model were adapted grid refinement to meet the requirement of near wall function 30<y+<300 [9].

In addition, the segregated solver which can save computational resources was employed. The coupling between pressure and velocity distribution was used by SIMPLIC discretization scheme. The second order upwind scheme was used for the final solution. Eventually, the variables are constant. The standard of convergence was taken the averaged pressure coefficient and the velocity of the special point.

2.2 Building models

The prototype building model was a cube with the side 12.6m from Hussain and Lee [11] with no obstructions around. According to Liddament's[12] investigation of wind pressure coefficient on building facades, the roof pitch angles were classified as <10º, 11~30º, >30º. But these results did not show the effects of roof pitches on building walls. In this study, the three typical roof pitch angles: 10º, 20º and 35º were chosen and four wind incidence angle: 0º, 20º, 45º, 90º were investigated (figure 2).

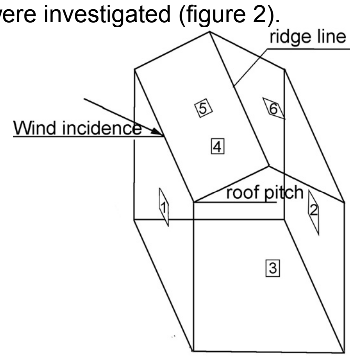

Figure 2: Schematic of building model and wind incidence

2.3 Air change rate coefficient

According to BS 5925 [13] formula of calculation air change rate due to wind only:

$$Q = C_d A_w V(\Delta C_p)^{1/2} \qquad (2)$$

Where C_d is discharge coefficient of opening, A_w is opening area, ΔCp is wind pressure coefficient difference between inlet and outlet, and V is the wind velocity at building height. If we investigate the roof pitch affects on natural ventilation, it is better to assume that the other parameters are constant. Therefore, the air change rate coefficient can be simplified as:

$$C_Q = (\Delta C_{pr} / \Delta C_{po})^{1/2} \quad (3)$$

Where C_Q = Air change rate coefficient

ΔC_{pr} = wind pressure coefficient difference between inlets and outlets on buildings with roof pitches

ΔC_{po} = wind pressure coefficient difference between inlets and outlets on buildings with flat roof

3. RESULTS

3.1 Pressure coefficient distribution on the facades

3.1.1 The characteristics of pressure coefficient distribution at wind incidence 0º

Windward pressure coefficient generally rises with the increase of the building height. Its maximum value appears at appropriate 0.8 building height, then dramatically dropped (figure 3). Compared with

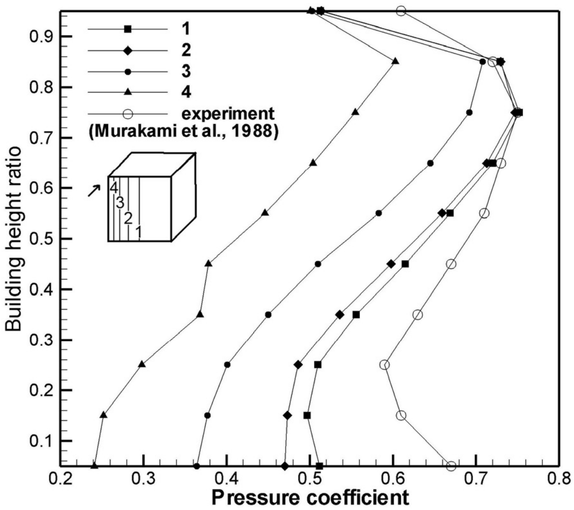

Figure 3: Pressure coefficient distribution on windward walls

the four vertical lines which distances 1/2, 1/3, 1/6, 1/12 building width respectively from the side edge of the windward face (as the wind pressure coefficient distribution is symmetric along the central line), the central line has the larger pressure coefficient, which may be because the edges of buildings separate wind flow and reduce wind pressure on the area and the upwind standing vortex increases pressure on the wall near the ground. The value on vertical central line shows the similar tendency as that of the wind tunnel experiment by Murakami et al. [14], but there is the larger difference between them near the ground.

Leeward is under suction condition, so the pressure on it is negative. The difference of pressure coefficient distribution on the leeward wall is about 0.12 (figure 4). It can be concluded that the position on leeward wall will not largely affect pressure coefficient distribution, which contrasts to that on the windward. The minimum value is appeared at about 0.75 building height near the vertical edges. The central line had the largest values among the four lines on the façade.

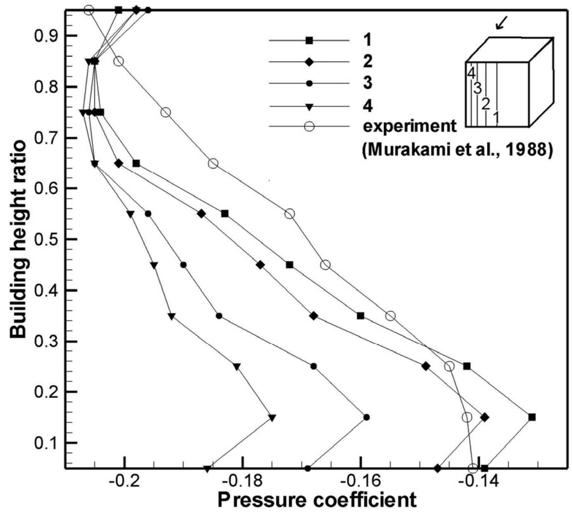

Figure 4: Pressure coefficient distribution on leeward walls

Pressure coefficient distribution on side walls are different form windward and leeward walls. In this study, five horizontal lines along upstream edge to downstream edge were carried out. From figure 5, it can be seen that the near upstream edge line has distinct negative values. Along the wind direction, the coefficient gradually increases, but all the data are negative. The least negative value is at the up corner near the upstream edge. The values near the downstream edge tend to constant in the vertical.

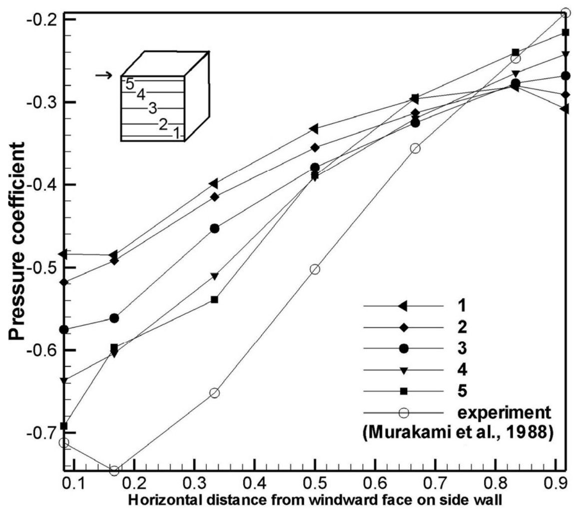

Figure 5: Pressure coefficient distribution on side walls

In general, the average result of CFD is lower about 10 percentage than that of wind tunnel experiment. From the above analysis, it can be seen that the openings on windward walls near the centre and the openings on leeward walls near the edges may be possible to get the larger pressure coefficient difference for natural ventilation. In addition, openings at about 0.8 building height may acquire larger pressure coefficient difference between inlets and outlets. The position of sharp edges of buildings can determine the wind pressure coefficient distribution.

3.1.2 The effects of Wind incidence

Wind incidence affects the wind pressure distribution. Wind direction perpendicular to the windward wall, the pressure coefficient distribution on the walls is symmetric, and the larger range is at 0.8 building height of the wall center. With the increase of incidence, the pressure coefficient generally decreases, and the larger ranges at the up corner near the upstream edge. the effect of wind incidence between 0º to 20º is negligible, but the incidence from 20º to 45º can largely reduce pressure coefficient. After 45º, pressure coefficient drops dramatically.

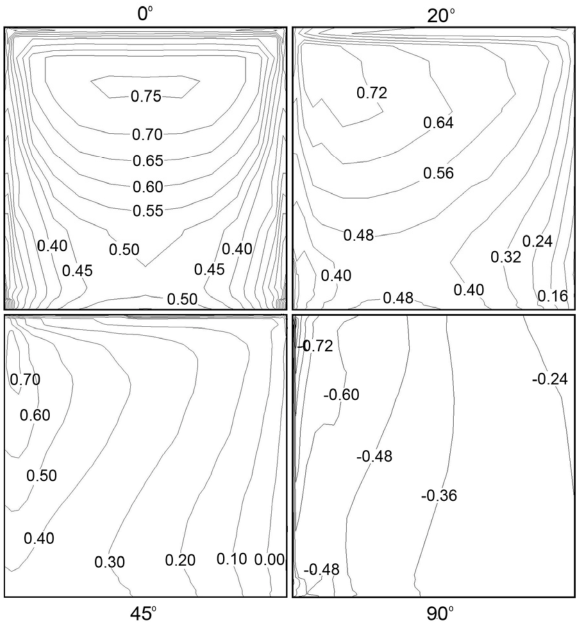

Figure 6: Effects of wind incidence on pressure coefficient distribution on windward walls

3.2 The effects of roof pitches on pressure coefficient distribution

3.2.1 Wind incidence at the angel 0º

Figure 7 and 8 use the contours of pressure coefficient to describe the effect of roof pitches on pressure coefficient distribution on windward and leeward walls. The characteristic of pressure coefficient distribution on the windward wall is similar, although the roof pitch varies (figure 7). However, with the increase of roof pith, the stagnation point will slightly move up along the building central vertical line, as the separation edge rises with the ridge line. The average pressure coefficient increases slightly. Especially the roof pitch between 0º and 20º, the pressure coefficient change can be neglected.

Pressure coefficient distribution on leeward wall has the similar tendency as that on windward wall. The range of larger negative pressure coefficient moves up near to the roof edge (figure 8). The largest negative value appears near the top corners.

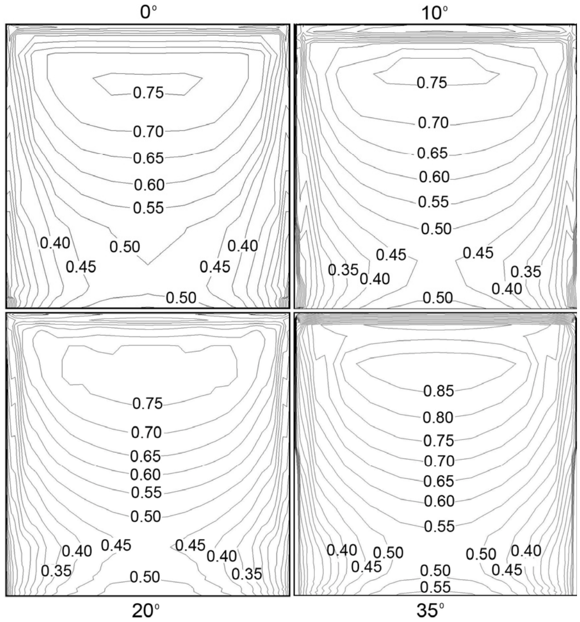

Figure 7: Effects of roof pitches on pressure coefficient windward walls

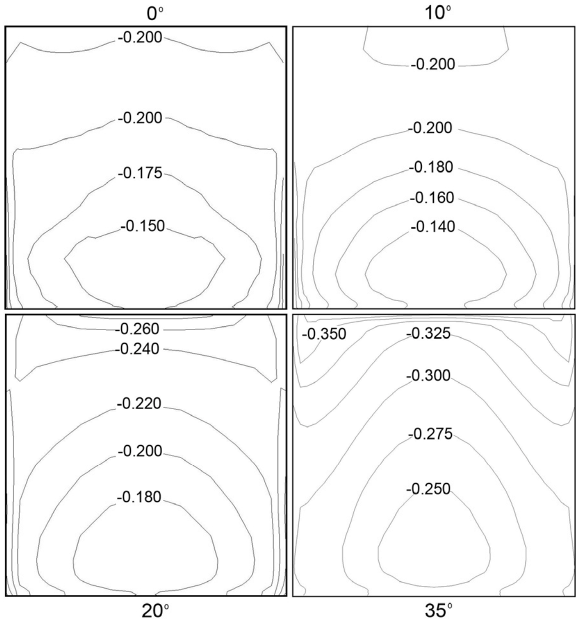

Figure 8: Effects of roof pitches on pressure coefficient distribution on leeward walls

3.2.2 Wind incidence at other angles

In this study, other incidence such as 20º and 45º and 90º at variable roof pitch were studied. As the above study showed the basic rules of pressure coefficient distribution on the walls, the following will show the area-weighted average pressure coefficient on the faces (Table 2). It will provide supplement for Liddmenent's study [12].

It can be seen that wind direction between 0º and 20º, the pressure coefficient change slightly and can be neglected. However, when the wind incidence rotates to 45º, pressure coefficient on windward decrease significantly. It can be concluded that wind incidence between 0º and 20º building orientation change will not affect natural ventilation.

Furthermore, care should be taken that the average pressure coefficient on the face is not taken as the maximum for determining the natural ventilation rate. It is therefore possible for architects to look at the pressure coefficients over the facades and position openings in such a way as to maximize the potential for natural ventilation.

Table 2: The area-weighted average pressure coefficient on the faces (figure 2)

Location		Wind incidence			
Roof Pitch	face	0º	20º	45º	90º
0º	1	0.55	0.49	0.30	-0.41
	2	-0.18	-0.22	-0.29	-0.41
	3	-0.41	-0.16	0.30	0.55
	4	-0.41	-0.39	-0.29	-0.18
	5	-0.50	-0.50	-0.50	-0.50
10º	1	0.52	0.50	0.29	-0.42
	2	-0.18	-0.24	-0.33	-0.42
	3	-0.41	-0.16	0.28	0.54
	4	-0.41	-0.43	-0.24	-0.20
	5	-0.74	-0.68	-0.58	-0.51
	6	-0.39	-0.49	-0.56	-0.51
20º	1	0.53	0.50	0.29	-0.44
	2	-0.21	-0.27	-0.34	-0.44
	3	-0.44	-0.21	0.29	0.58
	4	-0.44	-0.32	-0.25	-0.21
	5	-0.42	-0.43	-0.44	-0.46
	6	-0.61	-0.62	-0.65	-0.46
35º	1	0.56	0.52	0.34	-0.46
	2	-0.30	-0.28	-0.31	-0.46
	3	-0.61	-0.16	0.34	0.61
	4	-0.61	-0.44	-0.25	-0.22
	5	0.14	0.16	0.03	-0.55
	6	-0.48	-0.45	-0.48	-0.55

3.3 Air change rate coefficient

After acquired the average pressure coefficient on the faces, the dimensionless air change rates coefficient (equation 3) applies the ratio of wind pressure coefficient differences of tested model and prototype to compare the building forms with respect to the potential of natural ventilation. It may be helpful for designer to decide appropriate form and orientation for natural ventilation.

In this study, the average pressure coefficient difference between windward and leeward facades was studied. If the air change rate of flat building model with wind incidence 0º was taken as the prototype, the cases of roof pitch (0º, 10º, 20º, and 35º) and wind direction (0º, 45º, and 90º) were investigated. From figure 9, it can be seen that wind direction affects the air change rate coefficient larger than roof pitches. In general, wind direction rotates from 0º to 20º, air change rate decreases by 1%. However, when wind direction changes from 0º into 45º, air change rate reduces by 10%. Next, roof pitches affect air change rate slightly. For instance, the building with 35 roof pitch have 5% larger air change rate than the flat. In addition, roof ridge line

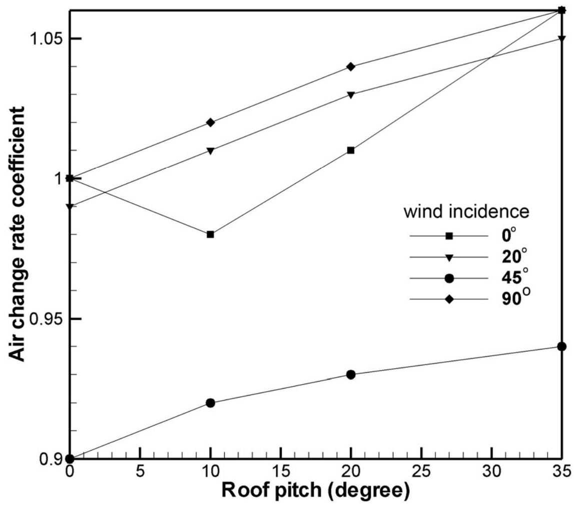

Figure 9: Air change rate coefficient with variable roof pitch

which is perpendicular to wind direction avails natural ventilation.

4. CONCLUSION

The investigation of effects of roof pitch on wind induced ventilation was carried out by computation fluid dynamics. Comparing the CFD results with those obtained from wind tunnel analysis showed good agreement. Compared with wind tunnel testing the CFD analysis gives more detail of wind pressure coefficient distribution on building facades.

It may be possible to obtain larger pressure coefficient difference for natural ventilation when the position of openings on windward walls are near the face centre and those on leeward walls are near the edges. In addition, openings at about 0.8 building height may acquire larger pressure coefficient difference between inlets and outlets.

The effect of wind incidence between 0º and 20ºon pressure coefficient and air change rate can be negligible. When wind incidence is up to 45º, air change rate can reduce by 10% of air change rate.

The position of upwind sharp edges of buildings can determine wind pressure coefficient distribution. From wind induced ventilation of view, roof ridge line which is perpendicular to wind direction is better than that is parallel to wind direction.

Compared with wind incidence, roof pitch can slightly increase wind induced ventilation rate. It further confirms that using regular boxes as models to study a group of building is acceptable and feasible.

Air change rate coefficient can be useful to compare the building forms with respect to the potential of wind induced natural ventilation.

CFD provides more details on wind pressure coefficient distribution on building facades than wind tunnel. Pressure coefficient can be taken as one parameter to study the effects of building forms on natural ventilation.

Further work will involve studying the effect of surrounding on the wind induced ventilation and building the method to predict wind induced ventilation potential.

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