Numerical analysis of surface pressure coefficients for a building with balconies

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Abstract

Knowledge of the pressure distribution on building walls is essential to evaluate wind-induced natural ventilation and to assess wind loads on building walls and building components. Computational Fluid Dynamics (CFD) can be a valuable tool for determining mean wind pressure coefficients on building facades. However, while many CFD studies of mean wind pressure on buildings have been performed in the past, the vast majority of these studies focused on simple building geometries without facade details. This paper presents a systematic evaluation of 3D steady RANS CFD for predicting mean wind pressure distributions on windward and leeward surfaces of a medium-rise building with and without balconies. The evaluation is based on a grid-sensitivity analysis and on validation with wind-tunnel measurements. The impact of several computational parameters is also investigated, including the resolution of the computational grid, the turbulence model and building balconies. The results show that steady RANS can accurately reproduce the mean wind pressure distribution across the windward facade. 3D steady RANS CFD has also been shown to provide accurate predictions of the mean wind pressure at the leeward wall in case of a perpendicular approach flow wind direction. This however is not the case for oblique flow.

1 Introduction

Knowledge of the pressure distribution on building walls is essential to evaluate wind-induced natural ventilation and to assess wind loads on building walls and building components (e.g. Chen, 2009; Cóstola et al., 2009). The pressure distribution on building walls is influenced by a wide range of factors including approach-flow conditions (Stathopoulos, 1997), urban surroundings (Kim et al., 2012) and building geometry (Uematsu & Isyumov, 1999). In particular, building facade details such as balconies and other protrusions can affect the peak and mean surface pressure distributions on buildings walls and roofs (Stathopoulos & Zhu, 1988). Computational Fluid Dynamics (CFD) can be a valuable tool for determining mean wind pressure coefficients on building facades. CFD has been used on many occasions in the past to determine mean wind-induced pressure distributions on building facades. However, the vast majority of these studies focused on relatively simple building shapes and plane with smooth facades. To the best of our knowledge, a detailed evaluation of steady Reynolds-averaged Navier-Stokes (RANS) CFD has not yet been performed for mean wind pressure distributions on building facades with protrusions or recessions. This paper therefore presents a systematic and detailed evaluation of 3D steady RANS CFD for predicting mean wind pressure distributions on building facades with and without balconies for both normal and obliquely approach-flow conditions. The evaluation is based on a grid-sensitivity analysis and on validation with wind-tunnel measurements by Chand et al. (1998). The impact of several computational parameters is also investigated, including the resolution of the computational grid, the turbulence model and building balconies.

2 Description of wind-tunnel experiments

Atmospheric boundary layer wind-tunnel measurements of wind-induced surface pressure on the facades of a medium-rise building were conducted by Chand et al. (1998). The open-circuit wind
tunnel was 14 m long and had a test section of $2.5 \times 1.8 \text{ m}^2$. The atmospheric boundary layer was generated by a combination of three devices: vortex generators, a grid of horizontal rods and a set of roughness elements on the floor of the test section. The resulting vertical profile of mean wind speed at the location of the building (but without building model present) is represented by a log law with aerodynamic roughness length $z_0 = 0.008 \text{ m}$ (model scale, corresponding to $0.24 \text{ m}$ in full scale) and a friction velocity $u'_{\text{ABL}} = 0.73 \text{ m/s}$. The measured incident longitudinal turbulence intensity ranges from $13\%$ near ground level to about $3\%$ at gradient height. Because these profiles were measured at the (virtual) location of the building, they represent the incident, rather than the approach-flow conditions. The building at scale 1:30 had dimensions width $\times$ depth $\times$ height $= 0.60 \times 0.25 \times 0.50 \text{ m}^3$ (reduced scale, see Fig. 1a) corresponding to full-scale dimensions $18 \times 7.5 \times 15 \text{ m}^3$, resulting in a blockage ratio of about $6.6\%$. To evaluate the effect of building balconies on the mean pressure coefficient, measurements were carried out for a building with and without balconies.

Mean surface pressures were measured along three vertical lines on the windward and leeward facade. Each measurement line was positioned in the middle of the balconies and 45 holes were drilled at equidistant points along it (Fig. 1a). In the remainder of this paper, we will refer to these vertical lines as “edge lines” and “centre line”.

![Figure 1: (a) Geometry of building model and balconies by Chand et al. (1998). (b) Close view of the grid on the building and ground surfaces (total number of cells: 2,102,250).](image)

### 3 CFD simulations: reference case

A reference case is defined as a starting point for the sensitivity analysis. It includes a fixed choice for the computational geometry and grid, solver settings and turbulence model, as outlined below.

#### 3.1 Computational geometry and grid

In this study a computational model was made of the reduced-scale building model used in the wind-tunnel measurements. The dimensions of the computational domain were chosen based on best practice guidelines (Franke et al., 2007, Tominaga et al., 2008). The upstream domain length is $5H = 2.5 \text{ m}$. The resulting dimensions of the domain were $W \times D \times H = 10.6 \times 10.25 \times 3 \text{ m}^3$, which corresponds to $318 \times 307.5 \times 90 \text{ m}^3$ in full scale. The computational grid was created using the surface-grid extrusion technique presented by van Hooff and Blocken (2010), resulting in a hybrid grid with 2,102,250 prismatic and hexahedral cells (Fig. 1b).

#### 3.2 Boundary conditions

In the simulations the inlet boundary conditions (mean velocity $U$, turbulent kinetic energy $k$ and turbulence dissipation rate $\varepsilon$) were based on the measured incident vertical profiles of mean wind
speed $U$ and longitudinal turbulence intensity $I_u$ (Fig. 2) The turbulent kinetic energy $k$ was calculated from $U$ and $I_u$ using $k(z)=\alpha(I_u(z)u(z))^2$, where $\alpha=1$ is chosen, as recommended by Tominaga et al. (Tominaga et al., 2008). The turbulence dissipation rate $\varepsilon$ is given by $\varepsilon(z)=u^3/\kappa(z+z_0)$, with $\kappa$ the von Karman constant ($=0.42$). For the ground surface, the standard wall functions by Launder and Spalding (Launder & Spalding, 1974) with roughness modification by Cebeci and Bradshaw (Cebeci & Bradshaw, 1977) are used. The values of the roughness parameters, i.e. the sandgrain roughness height $k_s$ (m) and the roughness constant $C_n$, were determined using their consistency relationship with the aerodynamic roughness length $z_0$ derived by Blocken et al (Blocken et al., 2007). Zero static pressure is applied at the outlet plane. Symmetry conditions, i.e. zero normal velocity and zero normal gradients of all variables, are applied at the top and lateral sides of the domain.

Figure 2: (a) Measured profile (dotted line) and fitted log law profile (solid line) of ratio of mean wind speed $U$ to mean wind speed $U_H$ at building height. Inlet vertical profile of (b) turbulent kinetic energy $k$ and (c) turbulence dissipation rate $\varepsilon$.

3.3 Solver settings

The commercial CFD code Fluent 6.3.26 was used to perform the simulations. The 3D steady RANS equations were solved in combination with the realizable $k-\varepsilon$ turbulence model (Shih et al., 1995). The SIMPLE algorithm was used for pressure velocity coupling, pressure interpolation was second order and second order discretization schemes were used for both the convection terms and the viscous terms of the governing equations.

3.4 Results and comparison with wind tunnel experiments

The simulation results are compared with the wind-tunnel measurements. The pressure coefficients are computed as $C_p = (P-P_0)/(0.5 \times \rho \times U_{ref}^2)$ where $P$ is the pressure at the surface, $P_0$ the reference static pressure, $\rho = 1.225$ kg/m$^3$ and $U_{ref}$ is the reference wind speed at building height ($U_{ref} = 7.1$ m/s at $z = 0.5$ m). Fig. 3 compares the CFD results and the wind-tunnel results of $C_p$ along the vertical measurement lines at the facade (shown in Fig. 1a) for the case with balconies. The general agreement is quite good. For the lines at the windward facade (Fig. 3a and 3b), the average absolute deviation between CFD results and measurements is 0.052 and 0.072 for the edge lines and centre line, respectively. Also at the leeward facade, the agreement is quite good (Figs. 3c and d). The average absolute deviation between CFD results and measurements is 0.069 and 0.070 for the edge lines and centre line, respectively. Note that there is a systematic underestimation of the absolute value of $C_p$ by CFD at the leeward facade.
Figure 3: Comparison of pressure coefficient ($C_p$) by CFD simulation results and wind-tunnel experiments along (a) edge lines on windward facade; (b) centre line on windward facade; (c) edge lines on leeward facade; (d) centre line on leeward facade.

4 CFD simulations: sensitivity analysis

To analyse the sensitivity of the results to various geometrical and computational parameters, systematic changes are made to the reference case that was outlined in the previous section. In every section, one of the geometrical or computational parameters is varied, while all others are kept identical to those in the reference case.

4.1 Impact of computational grid resolution

Performing a grid-sensitivity analysis is important to reduce the discretization errors and the computational time. In this study, a grid-sensitivity analysis was performed based on two additional grids: a coarser grid and a finer grid. Coarsening and refining was performed with an overall linear factor $\sqrt{2}$. As mentioned before, the basic mesh had 2,102,250 cells. The coarse grid had 720,937 cells, while the fine grid had 6,755,370 cells. The three grids are shown in Fig. 4.

Figure 4: Computational grids for grid-sensitivity analysis. (a) Coarse grid; (b) basic grid; (c) fine grid.
The results for $C_P$ on the three grids are compared in Fig. 5 indicating only a very limited dependence of the results on the grid resolution. A small deviation is between the coarse grid and basic grid for the upper part of the building, and between fine grid and basic grid for the space between the third and fourth floors. Negligible grid sensitivity is found for the other parts. Therefore, the basic grid is retained for further analysis.

Figure 5: Results for grid-sensitivity analysis: pressure coefficient ($C_P$) values along (a) edge line and (b) centre line for the three grids.

4.2 Impact of turbulence model

3D steady RANS simulations were made in combination with five turbulence models: (1) the standard $k-\epsilon$ model ($Sk-\epsilon$) (Jones & Launder, 1972); (2) the realizable $k-\epsilon$ model ($Rk-\epsilon$) (Shih et al., 1995); (3) the renormalization Group $k-\epsilon$ model ($RNG k-\epsilon$) (Yakhot et al., 1992); (4) the standard $k-\omega$ model ($Sk-\omega$) (Wilox, 1998) and (5) the Reynolds Stress Model (RSM) (Launder et al., 1975). The results are shown in Fig. 6. The differences between the models are most pronounced near ground level, where the RNG $k-\epsilon$ model tends to overestimate the pressure variations. The standard $k-\omega$ model generally provides a slight overestimate of the pressure, while the results of the RSM are very close to those of the standard and realizable $k-\epsilon$ model (reference case).

4.3 Impact of building balconies

The impact of building balconies on $C_P$ is investigated by comparing simulations for buildings with and without balconies. The results are displayed in Figs. 3 and 7. Fig. 7 compares the simulated and measured $C_P$ along the edge lines and centre line for the facade without balconies. For both the windward and the leeward facade, a good to very good agreement with the measurements is obtained. The main deviations are again found at the lower half of the facade. The average absolute deviations in Fig. 7a-d are 0.045, 0.046, 0.039 and 0.055, respectively.

4.4 Impact of building balconies for oblique approach flow

Simulations and measurements were also made for oblique flow (wind direction 45°). Figs. 8a-c show the results for the windward facade with balconies. The average absolute deviations in Fig. 8a-c are 0.035, 0.058 and 0.039, respectively. Figs. 8d-f show the results for the leeward facade with balconies, with averaged absolute deviations of 0.095, 0.156 and 0.068, respectively. Overall, a good agreement is obtained, although locally some significant discrepancies are noted.
Figure 6: Impact of turbulence model on CFD simulation results of pressure coefficient ($C_p$) along (a and b) edge lines and (c and d) centre line.

Figure 7: Comparison of pressure coefficient ($C_p$) by CFD simulation results and wind-tunnel experiments for building without balconies along (a) edge lines on windward facade; (b) centre line on windward facade; (c) edge lines on leeward facade; (d) centre line on leeward facade.
Discussion

It is important to mention the two main limitations of this study. First, only an isolated medium-rise building was considered. Further work should assess the accuracy of steady RANS to reproduce the effect of balconies on pressure distributions on high-rise buildings, and on buildings surrounded by other buildings. Second, the study only considered steady RANS CFD simulations and a good agreement was obtained between CFD simulations and wind-tunnel measurements. However, larger deviations were obtained for wind pressures on the leeward facade for oblique wind. Obtaining a better agreement here would necessitate the use of Large Eddy Simulation (LES).

In spite of these limitations, the present study has analysed the possibilities and limitations of steady RANS for assessing the effect of balconies on wind-induced pressure coefficients. It has also investigated the effect of the balconies on these coefficients by comparing buildings with and without balconies. Finally, a detailed sensitivity study has been performed, including the most important computational parameters such as computational grid, turbulence model, and wind direction.

Conclusions

This paper has presented a systematic evaluation of 3D steady RANS CFD for the prediction of the mean wind pressure distribution on windward and leeward surfaces of a medium-rise building with and without balconies. The evaluation is based on a grid sensitivity analysis and on validation with wind-tunnel measurements. The study was motivated by the lack of knowledge on the accuracy and reliability of CFD for determining mean wind pressure coefficients on building facades with balconies. It has also been shown that the presence of building balconies can indeed lead to very strong changes in wind pressure distribution on these windward facades, because the balconies introduce multiple
areas of flow separation, recirculation and reattachment. 3D steady RANS CFD has also been shown to provide accurate predictions of the mean wind pressure at the leeward wall in case of a perpendicular approach flow wind direction. This however is not the case for oblique flow, where large discrepancies with the wind-tunnel measurements have been found.

References


