Wind-induced pressure coefficients on buildings dedicated to air change rate assessment with CFD tool in complex urban areas

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ABSTRACT

The paper presents a numerical methodology to assess the natural ventilation. UrbaWind is an automatic computational fluid dynamics code. It was developed to model the wind in urban environments. The turbulence modelling, namely the dependence of turbulence length on the distance from wall, and the model constants were calibrated in order to reproduce with good agreements flow separation around buildings walls and pressure coefficient field on façades. Numerical results match well with the experiments: separation patterns and pressure field on walls in dense urban areas. Examples are presented at the end of the paper in order to show the advantages of the methodology for urban designers as they need pressure coefficients to assess the air change rate of buildings.

KEYWORDS

Natural ventilation, Wind, Air change rate, Pressure coefficient, Numerical simulations

1 INTRODUCTION

From an urban designer point of view the knowledge of the urban climatology, especially the wind flow around buildings, is crucial in many applications such as air quality and thermal behaviour inside buildings since the air and heat exchanges depend on the wind pressure on façades). CFD tools dedicated to computing the wind flow inside a built environment give advantages to understand and interpret the wind in any urban area. Wind mappings become useful to urban designers to optimize the master plan: position and orientation of buildings to improve natural ventilation, small energy production and pedestrians wind comfort. In the initial sketch designers should give a technical answer to improve the master plan as quickly as possible. As simulations are carried out with a high level of accuracy, CFD may be time consuming for large and complex urban master plans. A short time response is expected during the sketch process whereas computational time can be very long. In that context, methodology should be defined to increase the efficiency of the numerical approaches.
Three improvements axes were highlighted:

- Time of computation reduced by improving the mesher and the solver, using a turbulence model that speeds up the convergence
- For natural ventilation assessment, a macroscopic approach remains the best way to reduce the time to compute Air Change Rate (ACH). Compute the flow through windows and inside any building in an urban area is not common for consulting services

- Information delivered by the CFD tool is not always understandable by designers and may not be used without statistical treatment including the local climatology.

It is well known that the natural ventilation of a building is driven by the combined forces of wind and thermal buoyancy. The pressure field on the building's envelope generates flows through openings allowing the indoor environment refreshment. When opening areas are large enough, and except for high volumes, natural ventilation is mainly driven by wind forces.

Commonly cross-ventilation efficiency is assessed considering flow-rates through openings depending on the external wind pressure at openings. The cross-wind flow rate depends on the size of the openings A, on their aerodynamic efficiency, namely their aerodynamic discharge coefficients C, on the pressure coefficients on the building envelope Cp and on the reference wind velocity upstream the building U_{WIND}. For a simple volume with two openings, the cross wind flow rate was written by Aynsley et al. (1977):

$$Q = \sqrt{\frac{Cp_1 - Cp_2}{\frac{1}{A_1^2 C_1^2} + \frac{1}{A_2^2 C_2^2}}}\, U_{WIND} = A_a \sqrt{\Delta Cp}\, U_{WIND} \quad (1)$$

Hence, mass flow rate depends on three variables: the wind velocity far upstream the buildings U_{WIND}, the aerodynamic area A_a and the pressure differential ΔCp. If the number of openings is greater or if the internal volume is divided into sub volumes, a resolution for non-linear system has to be used. These methods called macroscopic approaches give air change rate from the pressure field characteristics.

The pressure on the envelope of the buildings can be given with tables (among others Clarke et al. 1990, Liddament, 1986) or with parametric models based on wind tunnel data (among others Grosso 1992, Muehleisen and Patrizi 2013, Costola et al. 2009). Numbers of numerical thermal software use macroscopic ACH assessment such as among others Energy+ to design natural ventilated buildings. Pressure coefficient data are given by AIVC or ASHRAE databases. Unfortunately for designers, these tables or correlations are potentially inapplicable when buildings are irregular and different from the simple shape or when they are at the side of other buildings in a complex urban area. Costola et al. (2009) give analytical relationship for sheltered buildings for homogeneous urban master plan. Unfortunately, although useful, such analytical approach suffers from an obvious lack of universality.

In summary, the pressure coefficient on outside walls of buildings could not be known with this method in complex urban places for two reasons:

- They depend strongly on the buildings shape and the pressure field is very inhomogeneous on the building envelope
- They depend strongly on the influence of neighboring buildings

The pressure on the building walls depends on the flow patterns. CFD software used to compute wind in large urban area solve the Reynolds Averaged Navier- Stokes Equations where turbulent fluxes are known through the turbulence energy balance equation. Separation or reattachment of the flow on walls, length of a recirculation area in a building wake depend on the ability of the turbulence model to well consider the diffusion of momentum in the flow.
The first purpose of this work is to present a CFD methodology with a one-equation turbulence model allowing to catch the mean flow separation and to extract pressure field on building walls. Validation will be shown with a detached cube (Costola et al. 2009) and a high rise building of the Architectural Institute of Japan (Tominaga et al., 2008).

The second aim of the paper is to present through examples the limitation of analytical approaches giving Cp values especially in complex urban areas. Order of magnitude of discrepancies will be given in order to suggest to any building designers to assess the pressure coefficient values to use complex method rather than analytical approach or databases.

2 NUMERICAL APPROACH: METHODOLOGY AND VALIDATION

2.1 Wind computation in any complex urban area

The CFD method of UrbaWind consists of solving the Reynolds-Averaged Navier-Stokes equations on an unstructured rectangular grid with automatic refinement of the mesh near obstacles. The CFD tool delivers the tri-dimensional mean velocity field, the turbulence energy field and the mean pressure for each point in the domain.

When the airflow is steady and the fluid incompressible, the mean equations for the mean velocity components $\overline{u_i}$ contains unknown quantities, the turbulent fluxes that can be solved by one-equation or two-equation models.

The equations resolution is based on a finite volume method with a rectangular multi-bloc refined mesh. A very efficient coupled multi-grid solver is used for a fast convergence for every kind of geometry. (Ferry, 2002). Boundary conditions are automatically generated. The mean velocity profile at the computation domain inlet is determined by the logarithmic law in the surface layer, and by the Ekman function (Garratt, 1992). A 'Blasius'-type ground law is implemented to model frictions (velocity components and turbulent kinetic energy) at the surfaces (ground and buildings). The effect of porous obstacles is modelled by introducing a volume drag force in the cells lying inside the obstacle.

The transport equation for the turbulent kinetic energy *k* contains a dissipation term ε deduced from the mixing-length theory.

$$\frac{\partial}{\partial x_i}\left[\rho\overline{u}_i k-\left(\frac{\mu_T}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right]=P_k-\varepsilon=\mu_T\left(\frac{\partial\overline{u}_i}{\partial x_j}+\frac{\partial\overline{u}_j}{\partial x_i}\right)\frac{\partial\overline{u}_j}{\partial x_j}-\varepsilon \qquad (2)$$

The turbulence viscosity μ_t is considered as the product of a length scale with a speed scale, which are both characteristic scales of the turbulent fluctuations.

$$\mu_t=\rho k^{1/2}L_T \text{ and } \varepsilon=C_\mu\frac{k^{3/2}}{L_T} \qquad (3)$$

The turbulent length scale L_T varies linearly with the distance at the nearest wall *d*. The dependence of L_T on the distance via a coefficient C_L was defined in order to well reproduce the flows separation around typical building façades and roofs. C_μ is usually fixed at 0.09 for grid turbulence (standard k-ε model). In a boundary layer, the C_μ constant depends on the stability. The model defining the turbulence length scale by Yamada and Arritt (Hurley, 1997) suggest a dependence of C_μ on the stability criteria in the range 0.01-0.09. Comparisons with experimental results were made in order to calibrate the C_L and C_μ. for such urban flows.

X_R is the length of the recirculation area in the wake of a tall building sized as 20x20x40 m (figure 1). Velocity magnitude on the wake axis was plot versus the distance from the backward wall (figure 2). Flow separation above the building roof is also highlighted (figure 2) and the flow separation length X_{R_TOP} extracted. All the results were summarized in the table 1. These results were compared with many numerical simulations and experiments of Meng and Hibi (1998) described by Tominaga *et al.*(2008).

The best choice to reproduce the flow separation both in the wake and the upper vortices gives a couple of reference values for C_L and C_μ.

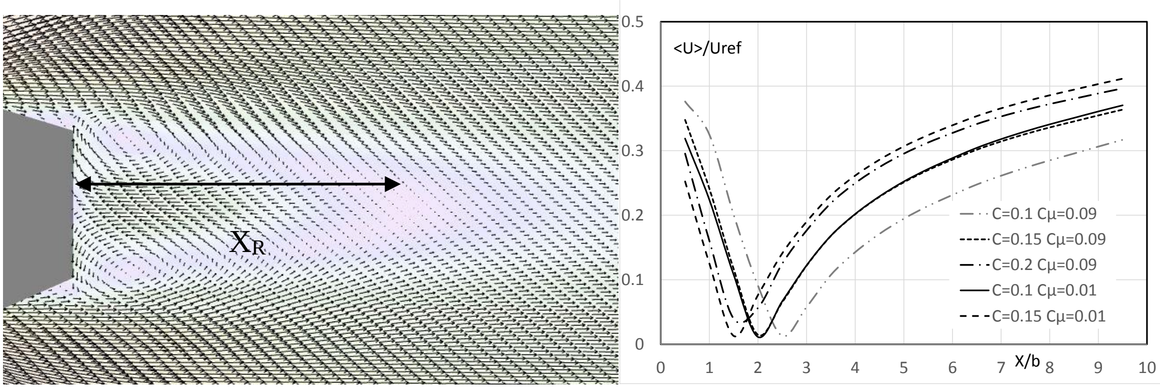

Figure 1 Recirculation in the wake of a square high-rise building

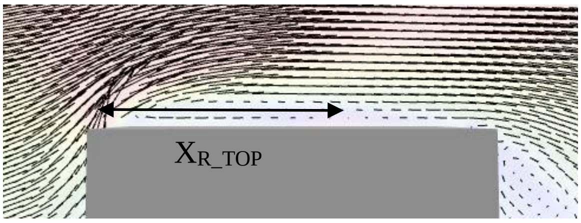

Figure 2 Flow separation above the roof of a square high-rise building

Table 1 : Comparison of Reattachment length of Numerical models and Experimental value (b is edge)

Turbulence model	**Reference**	**X_R/b**	**X_{R_TOP}/b**
k-ε (Standard)	Tominaga el al.	2.7	No separation
k-ε (Modified)	Tominaga el al.	3 to 3.2	0.52 to 0.58
Differential stress model	Mochida et al.	4.2	>1
LES	Tominaga el al.	1 to 2.1	0.50 to 0.62
k-l (C_L=0.2, Cμ=0.09)	UrbaWind	1.7	0.25
k-l (C_L=0.15, Cμ=0.09)	UrbaWind	2.5	0.60
k-l (C_L=0.1, Cμ=0.09)	UrbaWind	2.5	0.70
k-l (C_L=0.15, Cμ=0.01)	UrbaWind	1.5	0.60
k-l (C_L=0.1, Cμ=0.01)	UrbaWind	2	0.70
Experiment	Meng and Hibi	1.42	0.52

2.2 Wind-induced pressure coefficients on buildings

For a simple volume with two openings, the cross wind flow rate can be deduced from the analytical Aynsley formula (1). When more than two openings are connected with an indoor volume, the ACH computation needs to use the iterative process. The internal pressure is not known and the flow rate through openings are solved with a Newton-Raphson iterative method (Fhassis *et al.* 2010). In the case of a flat with several rooms, the free aerodynamic area of the opening *k* is replaced by an equivalent aerodynamic surface, taking into account the door aerodynamic surface A_{door} of the secondary room (Sanquer *et al.*, 2011).

$$A_k^{eq} = 1/\sqrt{\frac{1}{A_k^2}+\frac{1}{A_{door}^2}} \tag{4}$$

All the macrospcopic methods use as an input the external pressure fields on the walls where the openings are fitted. It becomes crucial to evaluate with precision the pressure field even in a complex urban area.

Before using a CFD tool to provide pressure value, comparisons were made with experimental data on Silsoe cube (Richards et al., 2007) resumed by Costola et al. (2009). This is valuable round robin test to check the ability of CFD to capture the flow separation around a cube. The pressure field obtained along the trajectory 0-1-2-3 with UrbaWind matches well the experimental results obtained for a detached low-rise building (figure 3). The wind speed reference level is the building height.

These value are in accordance to those given in the AIVC database for pressure coefficient on low-rise buildings up to 3 storeys (Liddament, 1986).

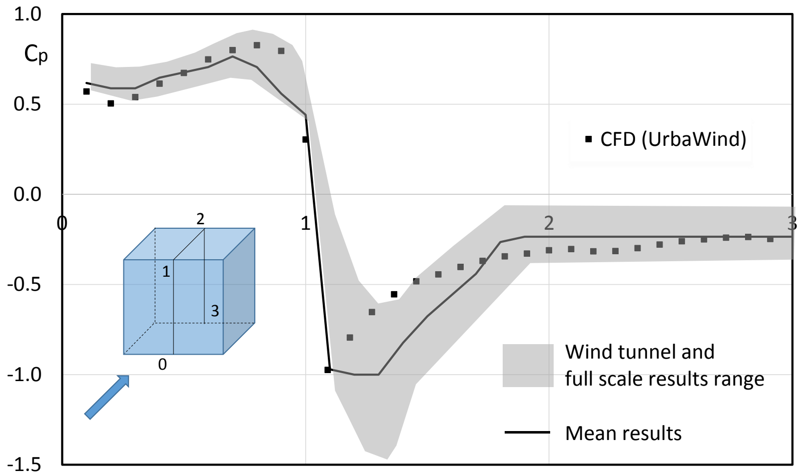

Figure 3 Pressure on the walls of a low-rise detached building: comparison of different wind tunnel experiments and numerical results (UrbaWind)

3 PRESSURE FIELD ON A BUILDINGS WALLS IN A COMPLEX URBAN AREA

Further computations were carried out for the same low-rise building located in a more complex urban environment (figure 4). Various wind incidences were computed.

The potential of natural ventilation defined as the maximum differential of pressure coefficient, is deduced from the curves on figure 4. For example ΔCp decreases from unity (detached, 0°) to less than 0.1 (urban, 0°). For oblique wind incidence (45°), ΔCp vanishes from 0.7 to less than 0.2. AIVC table gives ΔCp=0.45 at 0° and 0.35 at 45° for urban configuration where surrounding buildings height is equal to the reference building height. By using (1), it may be easily shown that the gap on air change rate reach 100% because ΔCp is overestimated by twice by using ΔCp from tables rather than data from more complex assessment method. Influence of surrounded buildings should not be considered only as a modification of the roughness that changes the wind profile instead of considering the local influence of buildings on the wind.

Figure 4 shows also that the potential of natural ventilation depends on the position of the buildings in the urban layout. Buildings H, M and L have respectively high, medium and low level for Natural Ventilation. Although analytical formulae exist for this urban layout, it may be difficult to introduce the position of the buildings and the buildings's geometries as inputs of the formulae to reflect the sheltering effects.

This analysis shows the difficulties to extract Cp from numerical tables or analytic relations in order to describe the influence of urban environment since the signature is the wind aerodynamic interactions with all neighbour buildings.

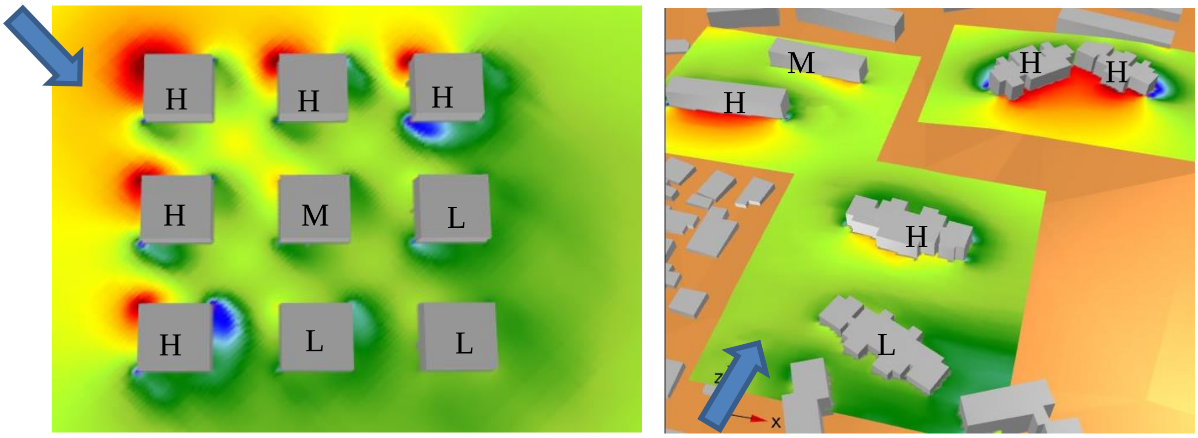

Figure 4 Example of CFD computation in complex urban area: mappings of pressure field

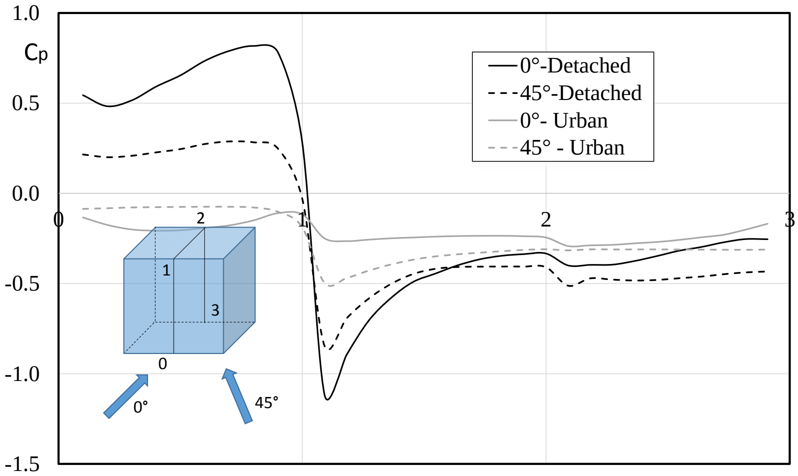

Figure 5 Pressure on the walls of a low-rise building Influence of the urban environment

On figure 5, the pressure field depends clearly on the shape of the buildings. Strong inhomogeneity of pressure field along the side wall should be considered in order to assess the scenario of the indoor ventilation. Figure 6 represents 4 screenshots for 2 similar shapes of a squared low rise building. We can observe that a slight change of building shape close to the corner can lead to a pressure field change because of a modification of the position of the flow separation. For instance for a wind incidence in front of the façade, the pressure coefficient close to the corner (in the red circle) becomes close to zero by changing the corner shape compared to a value close to +0.5. For a wind incidence of 45°, the influence of the shape is not too strong. Pressure field does not depend on the corner shape in this wind direction.

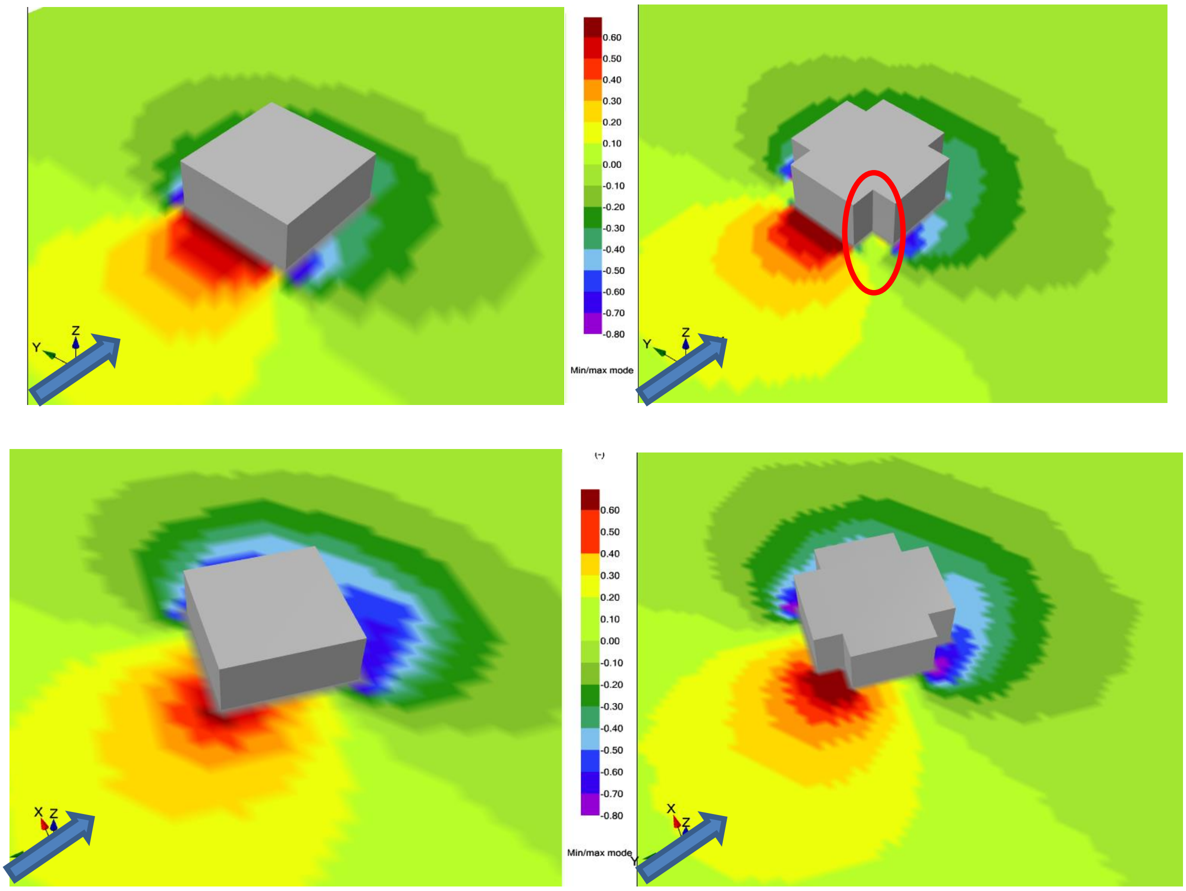

Figure 6 mappings of pressure coefficients at half height above the ground
Left : Silsoe Cube; Right : Cube with modified corners
Top : wind direction 0°; Bottom : wind direction 45°

This analysis shows the difficulties to extract Cp from numerical tables or analytic relations in order to describe the influence of every kind of buildings shape for various wind directions. Pressure field is strongly dependent on the flow separation patterns that cannot be summarized with precision with simple analytical formula.

4 CONCLUSIONS

The paper presents a numerical methodology to compute the wind-induced pressure coefficients on buildings in order to assess the natural ventilation in any urban area. UrbaWind, an automatic computational fluid dynamics code, was developed to model the wind in urban environments by optimizing the meshing and solving processes. Accurate results computed as quickly as possible will be useful for urban designers.

The turbulence modelling, namely the dependance of turbulence length on the distance from wall and the $C\mu$ value of the k-l model were calibrated in order to well reproduce the flow separation around builings walls. Numerical results were compared with well documented experiments: Siloe cube as a low-rise building and a 1:1:2 tower as high-rise buildings. Comparisons were made on separation patterns and on pressure field on walls.

Some real examples are presented to show the advantages of the numerical methodology versus the analytical approach in order to extract pressure coefficients in buildings from numerical simulation CFD as inputs for thermal approach.

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