Numerical research on cross-ventilation flow of a generic building in unsheltered and sheltered conditions: impact of cross-section

Puxian Ding1,2,3*, Xiaoqing Zhou1,2,3, Weihao Chen1,2,3, and Wuduo Jin1,2,3

1Academy of Building Energy Efficiency of Guangzhou University, 510006 Guangzhou, China
2Guangdong Provincial Key Laboratory of Building Energy Efficiency and Application Technologies, 510006 Guangzhou, China
3School of Civil Engineering, Guangzhou University, 510006 Guangzhou, China

Abstract. The performances of ventilation in the buildings with quadrate and cylindrical cross-sections are compared numerically. The incoming jet in the cylindrical unsheltered-building is more horizontal in comparison to the quadrate unsheltered-building. The dimensionless volume flow rates in the quadrate and cylindrical unsheltered-buildings are respectively 0.503 and 0.553. The incoming jet in the sheltered-buildings flows to the floors immediately. The velocity near the floor in the cylindrical sheltered-building is greater than that in the quadrate sheltered-building. The dimensionless volume flow rates in the quadrate and cylindrical sheltered-buildings are respectively 0.130 and 0.210. Comparing with the quadrate buildings, the ventilation rates in the cylindrical unsheltered and sheltered buildings increased by 10% and 61%.

1 Introduction

Cross-ventilation driven by wind pressure difference is an important ventilation method since it can provide a fast and effective way to remove large amounts of pollutants and internal heat from a building [1-2]. This is good for air-quality improvement and building energy reduction. The rate of the ventilation is the key factor in designing the cross-ventilation [3-4]. The ventilation rate of a building depends on the size and the position of the windows, the building roof and the airflow conditions around the building and so on [5-7]. The cross-section of the buildings influences the airflow around buildings significantly. However, the effects of the cross-section of the buildings on the cross-ventilation are rarely studied. In this paper, numerical study on the cross-ventilation flow of a generic cylindrical building in unsheltered and sheltered conditions is conducted.

An efficient hybrid turbulence numerical method based on the production-limited eddy simulation (PLES) proposed by us in the previous paper [8] is applied. The buildings are located within the atmospheric boundary layer.

2 Description of study cases

For analysing the cross-ventilation flow of a generic cylindrical building in unsheltered and sheltered conditions shown in Figs. 1 and 2, the results of the wind tunnel experiments conducted by Tominaga and Blocken [9] and Shirzadi et al. [10] are chosen as the referred for validation. Two conditions including a generic building unsheltered and sheltered shown in Fig.

3 Simulation method
The air is incompressible and Newtonian fluid. The continuity and momentum governing equations can be written in the Cartesian tensor form as follows.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \otimes \mathbf{u}) = -\nabla p + \mu \nabla^2 \mathbf{u} + \mathbf{f}$$

where \(\mathbf{u}\) and \(p\) are the velocity components and the pressure respectively, \(\mu\) is the dynamic viscosity, and \(\sigma\) represents the Reynolds stresses. The overbar means ensemble-averaged.

The underlying RANS model of the PLES model is the SST \(k-\omega\) model [11], which works as the original \(k-\omega\) model within the inner boundary layer and the standard \(k-\omega\) model in the outer region. The modelled transport equations of the turbulence kinetic energy \(k\) and the specific dissipation rate \(\omega\) are as follows.

$$\frac{\partial (\rho k)}{\partial t} + \nabla \cdot (\rho \mathbf{u} k) = \nabla \cdot (\mu \nabla k) + \frac{\rho k}{\omega} \frac{\partial \omega}{\partial t}$$

$$\frac{\partial \omega}{\partial t} + \nabla \cdot (\mathbf{u} \omega) = \frac{C_{\mu}}{k} \frac{\partial}{\partial t} \frac{\partial k}{\partial t} + \frac{\partial}{\partial t} \frac{\partial \omega}{\partial t}$$

where \(u_i\) and \(u_j\) are the velocity components, \(\rho\) and \(p\) are the density and the pressure respectively, \(\mu\) is the dynamic viscosity, and \(\sigma\) represents the Reynolds stresses. The overbar means ensemble-averaged.

The wall-adapting local eddy-viscosity (WALE) model [12] is applied as the SGS eddy viscosity in the PLES model. The WALE turbulent viscosity is calculated by the equations (10-12).

$$\mu_{wale} = \rho L_{w} \left( \frac{S''}{S'_{e}} \right)^{3/2}$$

$$L_{w} = 0.32 \delta_{y}^{+0.3}$$

$$S'' = 0.5 (g_{u}^{2} + g_{v}^{2}) - (1/3) \delta_{y} g_{u} g_{v}$$

where \(V\) is the cell volume.

### 3.2 Boundary conditions

The velocity and turbulent kinetic energy of the inlet boundary condition are the same as the wind tunnel experiments. The turbulence dissipation rate \(\epsilon\) and the specific dissipation rate \(\omega\) are calculated by below equations.

$$\epsilon = C_{\mu}^{+} k \frac{d(\omega)}{dx}$$

$$\omega = \frac{\epsilon}{C_{\mu}^{+} k}$$

The symmetry boundary condition is set at the lateral and upper walls. The outflow boundary condition is used at the outlet. The building and ground surfaces are set to the wall boundary condition. The random 2D vortexes are generated on the plane above \(x/b=0.5\) (b is the length of the side wall) from the inlet where modelled turbulence kinetic energy is converted into resolved energy using the vortex method [13].

### 4 Model validation

The comparisons of mean streamwise velocity from the PLES model with the experimental result in the unsheltered condition.

The comparisons of mean streamwise velocity from the PLES model with the experimental results in the unsheltered and the sheltered conditions are shown in Figs. 3 and 4 respectively. These profiles prove that the PLES model can obtain satisfactory simulation results. Taken the experimental results from the reported papers as the basic data, the errors of the volume ventilation rates in the unsheltered and sheltered cases are
respectively 0.6% and 8.3%. The normalized mean square errors of the time-averaged streamwise velocity are respectively 0.002 and 0.005. The comparisons of the simulation results with the experimental data show that the utilized numerical method is capable of predicting the cross-ventilation flow of a generic building in unsheltered and sheltered conditions.

5 Results and discussion

Then, the performances of ventilation in the buildings with quadrate and cylindrical cross-sections are compared numerically. Figs. 5 and 6 give the profiles of the mean streamwise velocity for the quadrate and cylindrical unsheltered-buildings and sheltered-buildings respectively. The incoming jet in the centre of the cylindrical unsheltered-building is more horizontal in comparison to the quadrate unsheltered-building. And the mean streamwise velocity is greater in the center of the cylindrical unsheltered-building, but smaller over the floor. The dimensionless volume flow rates in the quadrate and cylindrical unsheltered-buildings are respectively 0.503 and 0.553.

The incoming jets in the sheltered-buildings flow to the floors immediately. The velocity near the floor in the cylindrical sheltered-building is greater than that in the quadrate sheltered-building. The dimensionless volume flow rates in the quadrate and cylindrical sheltered-buildings are respectively 0.130 and 0.210.

In summary, comparing with the quadrate buildings, the ventilation rates in the cylindrical unsheltered and sheltered buildings increased by 10% and 61%.

6 Conclusions
The performances of ventilation in the buildings with quadrate and cylindrical cross-sections are compared numerically. The incoming jet in the cylindrical unsheltered-building is more horizontal in comparison to the quadrate unsheltered-building. The mean streamwise velocity is greater in the center of the cylindrical unsheltered-building. The dimensionless volume flow rates in the quadrate and cylindrical unsheltered-buildings are respectively 0.503 and 0.553.

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This work is supported by the National Natural Science Foundation of China (Grant No. 52078146), the Postdoctoral Research Project of Guangzhou (Grant No. 62104340), and the Key Project of Basic Research and Applied Basic Research in Universities of Guangdong Province (Grant No. 2018KZDXM050). We also acknowledge the Network Center of Guangzhou University for providing HPC computing resources.

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