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CFD simulation of forced convective heat transfer in street canyon: effect of wind direction and tree planting

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SUMMARY:
The convective heat transfer coefficient (CHTC), which represents the convective heat transfer ability between building outside facades and external environment, plays an important role in simulations of building energy and outdoor thermal environment. The CHTC of building facades is affected by many factors such as inflow wind patterns, surface-to-air temperature difference, and surrounding buildings. By the computational fluid dynamic (CFD) method, many kinds of CHTC correlations as a function of different key factors have been proposed by previous researchers. However, most of them are focused on a single building. As one of the most typical components in cities, the street canyon usually has different local flow structures from that of a single building, therefore, it is necessary to establish special CHTC correlations for it. In this study, high-resolution CFD simulations are conducted to investigate the forced CHTC of building outside facades in the street canyon. Wind direction effects are considered at different reference wind velocities, and new CHTC correlations will be generalized. In addition, the influence of a typical layout of tree planting is discussed, which could provide a reference for evaluating the building energy-saving potential of urban vegetation design.

Keywords: convective heat transfer coefficient, wind direction, tree planting

1. INTRODUCTION

The convective heat transfer of building external surfaces is of great interest for many engineering applications, as it is closely related to building energy consumption, building thermal performance, and outdoor thermal comfort. The convective heat transfer coefficient (CHTC), which represents the intensity of heat transfer on building facades, is usually defined as

$$CHTC = q_c/(T_w - T_{ref}) \tag{1}$$

where $q_c\,[W/m^2]$ is the convective heat flux of local surface, $T_w\,[K]$ is the surface temperature, and $T_{ref}\,[K]$ is the reference temperature. The CHTC of building external facades is influenced by a wide range of parameters including wind patterns, building surroundings, and temperature pressures i.e. (Liu et al., 2013; Mointazeri et al., 2015). Many correlations of it have been provided by previous researchers, however, most of them focus on single buildings. The street canyon, which is a typical and basic component in modern cities, needs additional attention. In this study, the forced convective heat transfer coefficients of a full-scale street canyon are investigated with the effect of wind directions and tree plantings being considered. A validated computational fluid dynamic (CFD) model is used to conduct simulations of wind flow and convective heat transfer around the street canyon. New CHTC expressions for the building facades in the street canyon will be driven from a series of simulations and then compared with that of single buildings.

2. LIST OF CASES

In the current study, the research target is a full-scale street canyon formed by two long building blocks, which have a dimension of length (L) × depth (D) × height (H) = 120 × 12 × 12m^3. The distance between two buildings is 24m resulting in an aspect ratio (H/W) of 0.5. To investigate the effect of tree planting, a tree-free (TF) canyon and a canyon with two-side-lines trees (TSL) are considered at the same time, the dimension of tree plantings are shown in Fig. 1(a). The angle between inflow wind and the normal direction of wall A varies from 0° to 90°. The temperature difference between inflow air and building walls fixes on 10K since only forced convective is considered in this study.

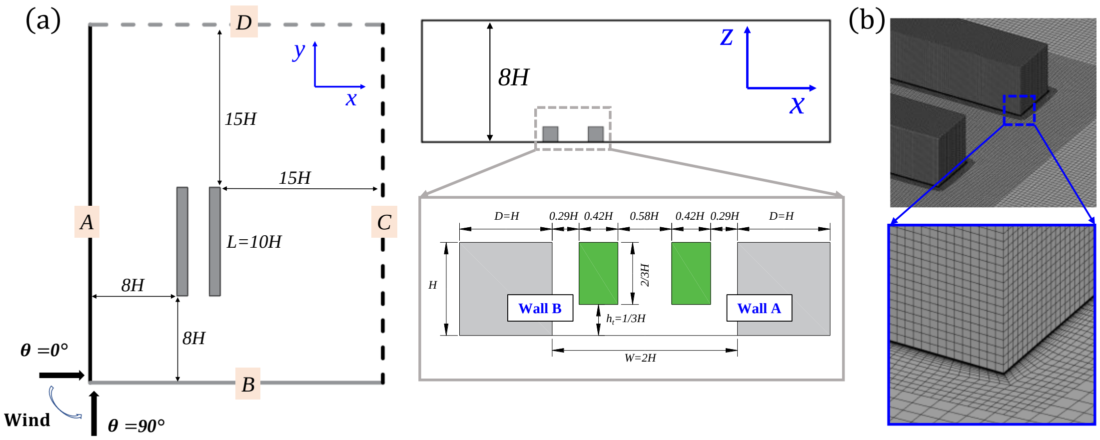

Figure 1. Schematic diagram of (a) street canyon geometry and computational domain, and (b) grid.

3. CFD SIMULATION SETUP

3.1. Numerical method

Steady Reynolds-averaged Navier-Stokes (RANS) simulations are conducted with realizable $k - \varepsilon$ turbulence model used for closure. For near wall treatment, low-Re model is selected to resolve the viscous layer directly since it could provide more accurate results for surface heat transfer problems than the standard wall function (Blocken et al., 2009). The performance of the current model was validated by reduced-scale experiments of Meinders et al. (1999). To reflect the aerodynamic effect of tree plantings, the tree canopy model shown in Eq (2) to Eq (4) is used. The drag coefficient C_d is 0.8 and the leaf area density S_{LAD} is 1.17 m^2/m^3, while other model constants are determined according to Zhong at al. (2022). Experimental measurement data provided by the Japanese Architecture Society (Mochida et al., 2008) has been used to validate the accuracy of this model.

$$S_{u,i} = -\rho C_d S_{LAD} \times U\boldsymbol{u_i} \tag{2}$$

$$S_k = \rho C_d S_{LAD}\left(\beta_p U^3 - \beta_d kU\right) \quad (3)$$

$$S_\varepsilon = \rho C_d S_{LAD}\frac{\varepsilon}{k}\left(C_{\varepsilon 4}\beta_p U^3 - C_{\varepsilon 5}\beta_d kU\right) \quad (4)$$

3.2. Computational domain and grid

The computational domain is shown in Fig. 1(a). For cases with $\theta = 0°$ (90°), plane A (B) and C (D) are used as inlet plane and outlet plane respectively. For cases with $\theta \neq 0°$, plane A and B are the inlet plane while plane C and D are the outlet plane. A high-resolution grid with the height of building wall adjacent cells equal to 1mm is used in this study, as shown in Fig. 1(b).

4. RESULTS

In this part, the effect of wind direction and tree planting on CHTC is discussed. The results with reference velocity at 10m height U_{10} equal to $3m/s$ are presented here.

4.1. The effect of wind direction on CHTC

The CHTC distributions of wall A and wall B for TF cases are shown in Fig. 2. Since the heat transfer patterns in building facades are strongly dependent on the complicated flow structures inside the street canyon, the variation of canyon flow patterns under three typical wind directions are provided in Fig. 3 simultaneously. When the inflow stream is perpendicular to wall A and B, cross vortices form inside the canyon. The maximum value of CHTC appears in the upper part of both ends of wall A due to the lateral air entrainment. When $\theta = 45°$, the airflow spirals through the canyon. An obvious stratification distribution of CHTC is found in wall A while its distribution in wall B is relatively uniform. When the incoming flow is parallel to wall A and B, the vortex structure disappears and the CHTC distributions are completely consistent under the channeling flow pattern. The surface averaged CHTC ($CHTC_{avg}$) are compared in Fig. 4(a). It can be seen that the variation of wind direction has an obvious effect on $CHTC_{avg}$. When θ changes from 0° to 45°, The $CHTC_{avg}$ of wall A and wall B increases by 53% and 63% respectively.

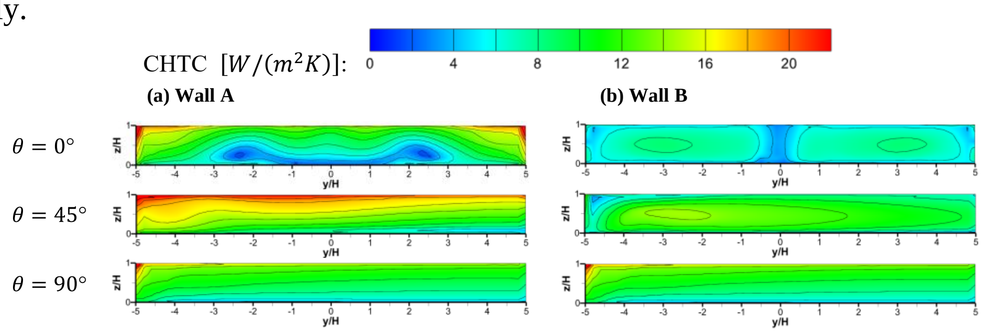

Figure 2. CHTC distributions of TF cases under different wind directions: (a) wall A, and (b) wall B.

4.2. The effect of tree planting on CHTC

The $CHTC_{avg}$ of building facades in the street canyon with the existence of two-side-lines trees is shown in Fig. 4 (b). Compared with that of TF cases, the surface averaged CHTC of wall A and wall B reduces by 13% ~ 59%. It is mainly due to the aerodynamic drag effect of tree plantings, which slows the airflow inside the street canyon.

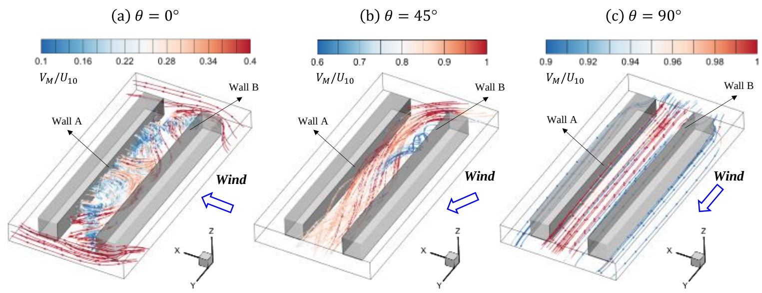

Figure 3. Flow patterns of the tree-free street canyon: (a) $\theta = 0$, (b) $\theta = 45$, and (c) $\theta = 90°$.

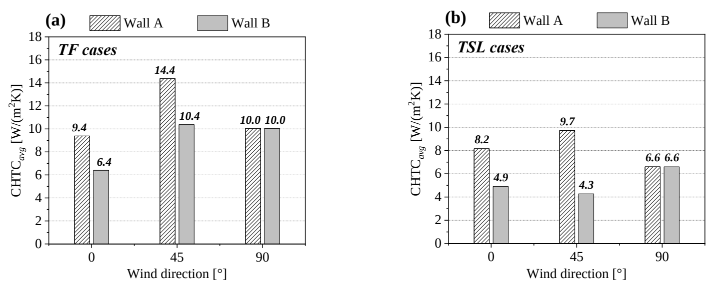

Figure 4. Surface averaged CHTC values in the street canyon: (a) TF cases, and (b) TSL cases.

5. CONCLUSION

The current study discusses the effect of wind directions and tree plantings on CHTC of external building facades in the street canyon. By conducting full-scale simulations with high-resolution grids and low-Re model, the key findings are:

- In the street canyon, both the distribution and surface averaged value of CHTC are sensitive to the direction of inflow air. New CHTC correlations with wind directions being considered are needed for accurate building performance simulation.
- The aerodynamic drag effect of tree plantings weakens the convective heat transfer inside the street canyon. From this perspective, the design of vegetation structures is a potential method for building energy saving.

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