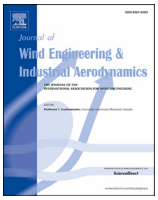
Journal of Wind Engineering & Industrial Aerodynamics 172 (2018) 170–180

Contents lists available at ScienceDirect

Journal of Wind Engineering & Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia



Numerical study of mixed convective heat transfer coefficients for building cluster

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A R T I C L E I N F O

Keywords:
Building cluster
Mixed convection
Large eddy simulations
Nusselt number
Convective heat transfer coefficient

A B S T R A C T

The convective heat transfer coefficient (CHTC) of building surfaces is an important parameter to evaluate building thermal performance, and it also affects the calculation of sensible heat in urban canopy models. In this paper, The CHTCs at different building surfaces and ground for a building cluster at high Reynolds number is studied by Large Eddy Simulations (LES) with Smagorinsky subgrid-scale model and wall damping. The forced, natural and mixed convective heat transfer cases are simulated with 6 × 3 and 3 × 3 cubes used as the model buildings respectively. The Reynolds numbers are from 3.31×10^5 to 2.65×10^6 and the Grashof numbers are from 4.42×10^{11} to 3.54×10^{12}. The results show that, the forced convection Nusselt number (Nu_F) is proportional to $Re^{0.79}$, the natural convection Nusselt number (Nu_N) is proportional to $Gr^{1/3}$ and the mixed convection Nusselt number can be calculated by $\sqrt[n]{(Nu_F)^n + (Nu_N)^n}$ with n varying from 1.9 to 3.8.

1. Introduction

The convective heat transfer is of interest for many engineering applications, such as heat exchangers (Iacovides and Launder, 1995), solar collectors (Chandra et al., 1983), building energy demand (Mirsadeghi et al., 2013), urban heat island mitigation strategy (Takebayashi and Moriyama, 2007) and so on. The convective heat transfer is usually evaluated by convective heat transfer coefficients(CHTCs) which is defined as:

$$\mathrm{CHTC} = \frac{q_w}{T_w - T_{ref}} \tag{1}$$

with q_w the heat flux normal to the wall, T_w the wall temperature and T_{ref} the reference temperature. CHTC is needed for evaluating the energy performance of buildings. The convective heat losses of external surfaces are 3–4 times as big as the radiative heat losses (Cooper, 1981; Davies, 2004), and different convective models can cause a 30% deviation for cooling energy demand (Mirsadeghi et al., 2013). Emmel et al. (2007) also showed that energy demand calculations can vary 20–40% with different convective coefficients. Therefore, the CHTC for external surfaces is an important parameter to simulate building thermal performance accurately. Moreover, the CHTC is used in urban canopy models(UCMs) (Masson, 2000; Kusaka et al., 2001; Ryu et al., 2011) to calculate the sensible heat fluxes from building surfaces and ground.

To study the CHTC for building external surfaces, many studies have been carried out including wind-tunnel experiments (Nakamura et al., 2001, 2003; Meinders et al., 1998; Meinders et al., 1999; Meinders and Hanjalić, 1999), field measurements (Hagishima and Tanimoto, 2003; Jayamaha et al., 1996; Liu and Harris, 2007; Shao et al., 2010) and numerical simulations (Emmel et al., 2007; Blocken et al., 2009; Defraeye et al., 2010; Liu et al., 2013, 2015; Montazeri et al., 2015; Allegrini et al., 2012; Defraeye et al., 2011a; Karava et al., 2011; Karava et al., 2012; Li et al., 2016; Montazeri and Blocken, 2017). All these studies provided the correlations between CHTC and wind speed. In addition, wind direction (Emmel et al., 2007; Meinders et al., 1998; Liu and Harris, 2007; Blocken et al., 2009), turbulence intensity (Hagishima and Tanimoto, 2003; Shao et al., 2010; Karava et al., 2011), building densities (Liu et al., 2013, 2015; Allegrini et al., 2012), building geometry (Montazeri et al., 2015; Karava et al., 2012; Montazeri and Blocken, 2017) and buoyancy effect (Emmel et al., 2007; Liu et al., 2015; Allegrini et al., 2012; Karava et al., 2012) have also been investigated.

In most of the wind-tunnel experiment studies, the characteristic Reynolds number are relatively low (Re $\sim 10^3$ to 10^5), not conforming the similarity requirements for the building applications (Re $\sim 10^5$ to 10^7). For field measurement studies, the coming wind almost can't be controlled, so it results in the studied parameter not varying independently. A detailed review of external CHTC for wind-

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https://doi.org/10.1016/j.jweia.2017.10.025
Received 17 August 2017; Received in revised form 26 October 2017; Accepted 26 October 2017

tunnel experiments and field measurements can be found in Ref. (Mirsadeghi et al., 2013).

For the numerical research, direct numerical simulation (DNS) (Kawamura et al., 1998; Leonardi et al., 2015), large eddy simulation (LES) (Liu et al., 2013, 2015; Li et al., 2016; Iousef et al., 2017; Boppana et al., 2014; Montazeri et al., 2014; Liu and Chung, 2012) and Reynolds-averaged Navier–Stokes (RANS) (Emmel et al., 2007; Blocken et al., 2009; Defraeye et al., 2010, 2011a; Montazeri et al., 2015; Allegrini et al., 2012; Karava et al., 2011; Karava et al., 2012) are used to study heat transfer problems. As the Reynolds number of the building applications is very high, many of the wall-resolved studies were not in the Reynolds number range. To solve the flow and heat transfer with a relative coarse mesh, wall function is often adopted in high Reynolds number studies. Though Liu (Liu and Chung, 2012) showed a good agreement with an experiment by using wall function, Blocken (Blocken et al., 2009) and Boppana (Boppana et al., 2014) showed the use of wall function can cause errors up to 60% and 45% for wall heat flux. To avoid possible errors from wall function, it's better to resolve the viscous layer directly. Most of the wall-resolved numerical studies with $\mathrm{Re} \sim 10^6$ (Emmel et al., 2007; Blocken et al., 2009; Defraeye et al., 2010, 2011a; Liu et al., 2013; Montazeri et al., 2015; Liu et al., 2015; Karava et al., 2011; Karava et al., 2012) used RANS to estimate the CHTC, and only Ref. (Liu et al., 2013, 2015) used LES. However, RANS can't simulate the heat transfer for buildings very well, especially for the top and lateral surfaces (Defraeye et al., 2010; Montazeri et al., 2015) as it can't capture the unsteadiness very well, while LES is a more accurate method to resolve unsteady flow (Tamura, 2008) and estimate the CHTC (Liu et al., 2013) around buildings. The building surroundings also affect the CHTC strongly (Liu et al., 2013), however most studies only investigated an isolated building. Liu (Liu et al., 2013, 2015) studied one column of buildings with symmetry condition at the spanwise direction, but such a strong condition should not be so closed to the concerned buildings. So the CHTC of building surroundings needs further study. In addition, the CHTC at the ground are not reported in the research listed above (Emmel et al., 2007; Blocken et al., 2009; Defraeye et al., 2010, 2011a; Liu et al., 2013; Montazeri et al., 2015; Liu et al., 2015; Karava et al., 2011; Karava et al., 2012), while it is an important parameter for UCM to evaluate the land surface heat balance.

In this paper, LES with Smagorinsky subgrid-scale model is used to simulate flow around model building cluster and predict their surface CHTC. The model buildings are made of 6×3 cubes for forced and mixed convection cases, and 3×3 cubes for natural convection cases. The building area density is fixed at 0.25 and the height of cubes (H) is 10 m. A total of 24 cases with four different 10-m height inlet wind speeds (U_{10}) and four temperature differences (ΔT) are simulated. The Reynolds numbers are from 3.31×10^5 to 2.65×10^6 ($Re = U_{10}H/\nu$, ν is the kinematic viscosity), and the Grashof numbers are from 4.42×10^{11} to 3.54×10^{12} ($Gr = gH^3\beta\Delta T/\nu^2$, g is the gravitational acceleration, β is the volumetric thermal expansion coefficient). The computed Nusselt number are fitted as a correlation function of Reynolds number and Grashof number for windward, leeward, lateral, top building surfaces and the ground. The dimensional correlations for CHTC are also given as a function of U_{10}, ΔT and H.

This paper is organized as follows: In section 2, the governing equations and numerical methods are introduced. In section 3, a single cube in a turbulent channel flow is simulated numerically by LES and the results are compared with a wind tunnel experiment. In section 4, the CHTCs of model building cluster are studied numerically in forced, natural and mixing convection cases and the results are shown in section 5, followed by conclusion remarks in section 6.

2. Governing equations and numerical methods

In the present study, Large Eddy Simulations (LES) with Smagorinsky subgrid-scale model is used to simulate the flow and Boussinesq approximation is used to represent the buoyancy effect.

The filtered continuity, momentum and temperature equations for incompressible flows are as follows:

$$\frac{\partial \overline{u}_i}{\partial x_i} = 0 \tag{2}$$

$$\frac{\partial \overline{u}_i}{\partial t} + \frac{\partial\left(\overline{u}_i\overline{u}_j\right)}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} + \nu\frac{\partial^2 \overline{u}_i}{\partial x_j \partial x_j} + \frac{\partial \tau_{ij}}{\partial x_j} + g_i\left[1-\beta\left(\overline{T}-T_0\right)\right] \tag{3}$$

$$\frac{\partial \overline{T}}{\partial t} + \frac{\partial\left(\overline{T}\overline{u}_j\right)}{\partial x_j} = \frac{\nu}{Pr}\frac{\partial^2 \overline{T}}{\partial x_j \partial x_j} + \frac{\partial h_j}{\partial x_j} \tag{4}$$

Here $\overline{u}_i$ and $\overline{T}$ are filtered velocity and temperature, g is gravity acceleration given $-9.81\mathrm{m/s^2}$ in the vertical direction, T_0 is the reference temperature for calculating buoyancy and given 20 $^\circ C$, Pr is the Prandlt number, β is the expansion coefficient and their specific values are given in section 3.3 and section 4.1. $\tau_{ij} = \overline{u}_i\overline{u}_j - \overline{u_i u_j}$ and $h_j = \overline{T}\overline{u}_j - \overline{T u_j}$ are the sub-grid scale stress and heat flux. The Smagorinsky subgrid-scale model is used to calculate τ_{ij}:

$$\tau_{ij} - \frac{1}{3}\tau_{kk}\delta_{ij} = \nu_{sgs}\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right) = 2\nu_{sgs}\overline{S}_{ij} \tag{5}$$

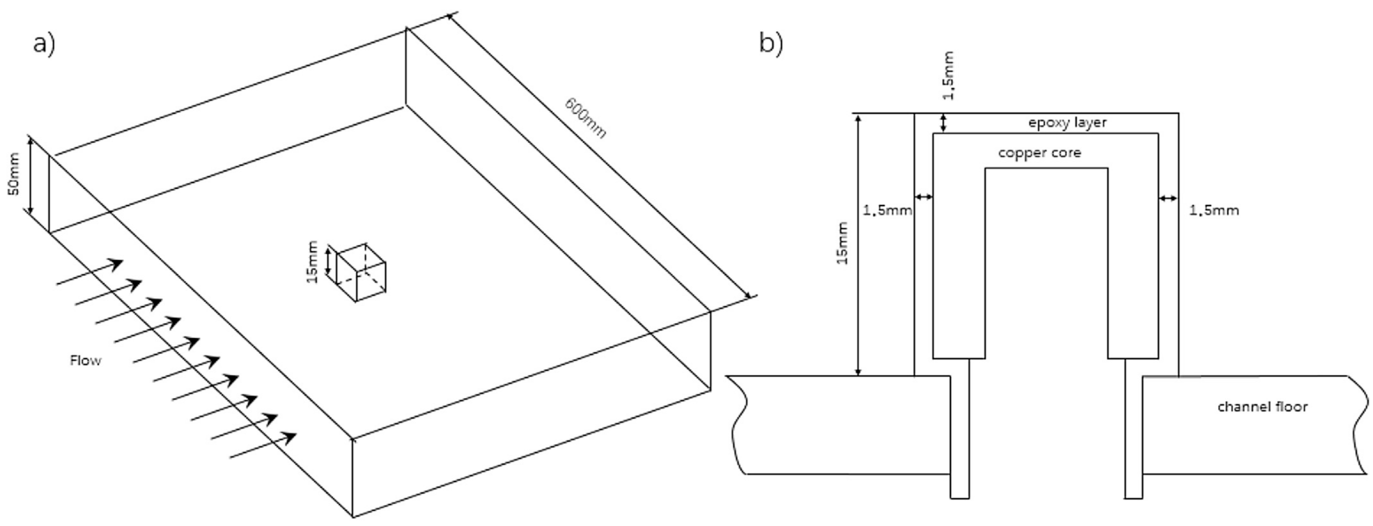

Fig. 1. The diagrammatic sketch of (a) the wind tunnel and (b) the cube.