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Numerical simulation of convective heat transfer coefficients at the external surfaces of building arrays immersed in a turbulent boundary layer

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ABSTRACT

The convective heat transfer is an important component in the total energy balance for arrays of buildings immersed in a turbulent boundary layer. This study examines convective heat transfer coefficients (CHTC) at the external windward, leeward, lateral and top surfaces of buildings. This study uses Large Eddy Simulations (LES) with Smagorinsky–Lily model to predict CHTC and then compares the simulation results with experimental data. In addition, steady RANS including the realizable k–ε and the shear stress transport k–ω turbulence models are also validated with the experimental data. However, both of these RANS models overestimated CHTC values for arrays of buildings in contrast to LES predictions. Regular arrays of cubic buildings are modeled to investigate CHTC in an urban environment, which are arranged according to different plan area densities (λ_p = 0.44, 0.25, 0.16, 0.11, 0.063 and 0.04). This morphological parameter (λ_p) represents different urban neighborhoods and it is used to characterize different flow regimes in an urban environment. The CHTC distributions are independent of the Reynolds number based on different incoming wind velocities at a height of 10 m above the ground (U_{10}) for windward, leeward, lateral and top building surfaces. Furthermore, CHTC distributions for different λ_p and U_{10} = 5 m/s are compared with flow characteristics in building arrays. Finally, the CHTC correlations as a function of λ_p and U_{10} were obtained, where λ_p varies from 0.04 to 0.25 and the Reynolds number ranges from 7×10^5 to 5×10^6. With the increase of the plan area densities from 0.04 to 0.25, CHTCs increases 15% for the leeward surface and decreases 16% for the lateral surfaces. Consequently, a total energy balance and the energy consumption predictions for a building need to take into account the urban density of the building surroundings.

1. Introduction

The convective heat transfer coefficients (CHTC) on external surfaces of a building are crucial parameters for accurate evaluations of building thermal performance and associated building energy consumption [1]. Several studies have demonstrated that the simulated energy consumption can vary from 20% to 40% due to different choices of CHTC values for internal building surfaces [2–4]. In addition, another study has also shown that an uncertainty of 15% for CHTC at external building surfaces can result in a corresponding uncertainty of 20% in heat flux calculations throughout the envelope [5]. Furthermore, for external surfaces, the overall heat flux sensitivity to CHTC is even greater because the outdoor surface velocities are equal or much greater than the indoor surface velocities. For example, CHTCs are especially relevant to studies on solar collectors [6], green roofs [7] and urban heat island mitigation strategies [8]. CHTC is also an important parameter in the total energy balance for a building in an urban environment, especially when the building enclosure materials have a relatively low thermal resistance, resulting in a relatively high sensitivity of the total energy balance to CHTCs [9]. In summary, accurate predictions of CHTCs enable accurate calculations of the heat losses or gains for an external building surface.

To obtain better predictions of the CHTC at the external surfaces of buildings, a large number of studies have been carried out by means of wind-tunnel experiments [10–12], numerical simulations [9,13–16] and field measurements [17–22]. In all of these studies, CHTCs were correlated to the reference mean wind speed at a height of 10 m above the ground with the incoming wind profiles typically defined as logarithmic or power-law correlations. The influences of the wind direction have also been studied by developing different CHTCs for windward and leeward surfaces. However, the majority of the existing studies were limited to a building roof and/or vertical walls of a single isolated building, or to a certain location of a single building surface.

Existing CHTCs are not suitable for a deployment to an entire neighborhood of buildings due to the complex building geometries

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and airflow patterns that are not all accounted for in the previous studies. Nevertheless, the existing CHTC correlations are a good starting point to develop a comprehensive set of correlations for applications to an actual urban neighborhood. A recent study performed by Saneinejad et al. [23] showed that numerical simulations were able to predict the CHTCs in the windward and leeward walls of a street canyon. The study analyzed the spatial variation of CHTC in 2D urban areas. However, the accuracy of the simulation results was limited due to the flow limitations to upward and downward directions in 2D urban canyons, which differs from an actual 3D urban area [24]. Furthermore, Narita [25] developed a water evaporation technique to study the distribution of convective heat transfer coefficients in urban environments. However, 2D street canyon models were still employed. Both studies gave a general recommendation that the use of 3D building models is needed.

It should be noted that wind played a significant role in predicting existing correlations for the CHTC, which can also be strongly impacted by the buildings' surroundings. In an urban environment, a building's surroundings create a shelter effect that can reduce local wind speeds. This sheltering effect has been first taken into consideration in building infiltration studies [26–28]. More recently, Lovely et al. [18] presented the concept of sheltering effects when predicting the CHTCs for external building surfaces. This study provided an important contribution although it primarily focused on the angle of wind incidence affecting the values of CHTCs for windward or leeward building surfaces.

Despite complex vortex and flows in urban area, the morphological parameters, such as the building plan area density (λ_p) and frontal area density (λ_f), have been shown to be important in predicting urban airflow patterns [29]. Additionally, the values of surface roughness height (z_0) in many meteorological and wind-engineering problems, especially in regular obstacle arrays, is an important factor in modeling environmental wind effects [30]. Therefore, when estimating the CHTC values at the external surfaces for arrays of cubes representing buildings immersed in a turbulent boundary layer, taking into account the morphological parameters and features of the atmospheric boundary layer is necessary.

In this paper, Computational Fluid Dynamics (CFD) based on Reynolds-Averaged Navier–Stokes (RANS) equations and Large Eddy Simulation (LES) with the Smagorinsky–Lily subgrid model are firstly carried out to predict CHTCs in a 3D cubic array. Comparisons against wind tunnel experimental results reveal the predictive accuracy of currently used models. As a relatively more accurate simulation method, LES is then used to simulate flow field for the regular arrays of buildings and calculate the CHTCs for windward surfaces, leeward surfaces, lateral surfaces and rooftops, with different cube layouts defined by six different plan area densities (λ_p = 0.44, 0.25, 0.16, 0.11, 0.063 and 0.04) .

2. Governing equations and turbulence models

In the present study, the realizable k–ε turbulence model [31] and the shear stress transport (SST) k–ω turbulence model [32] are applied with RANS to simulate CHTCs for external surfaces of buildings. In addition to these two RANS models, LES with Smagorinsky–Lily model [33] is also used to validate the simulation results with experimental data.

2.1. Reynolds-Averaged Navier–Stokes model

The governing equations of continuity, momentum and energy for steady incompressible flows and heat transfer with negligible radiation and buoyancy effects are expressed as follows:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial (u_i u_j)}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_j}\left(\frac{\mu}{\rho}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \overline{u_i' u_j'}\right) \tag{2}$$

$$\frac{\partial (u_i T)}{\partial x_i} = \frac{1}{\rho c_p}\frac{\partial}{\partial x_i}\left(\lambda \frac{\partial T}{\partial x_i}\right) + \frac{\partial}{\partial x_j}\left(-\overline{u_j' T}\right) \tag{3}$$

where $-\overline{u_i' u_j'}$ is the Reynolds stress tensor, and $-\overline{u_j' T}$ is the turbulent heat flux. By relating the stress tensor and turbulent heat flux to the mean strain-rate and mean temperature gradients, respectively, the two unknowns can be solved as follows:

$$-\rho\overline{u_i' u_j'} = \mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\rho\delta_{ij}k \tag{4}$$

$$-\rho c_p \overline{u_j' T} = q_c = \lambda_t \frac{\partial T}{\partial z} \tag{5}$$

where μ_t is the turbulent dynamic viscosity, λ_t is the turbulent thermal conductivity ($\lambda_t = C_p \mu_t / Pr_t$), which is proportional to μ_t since the turbulent Prandtl number, Pr_t, ranges from 0.7 to 0.9 depending on the laminar Prandtl number of the fluid [34]. For the two used RANS turbulence models, μ_t is related to the turbulent kinetic energy (k) and turbulent dissipation rate (ε) or the specific dissipation rate (ω). As a consequence, in order to solve Eq. (4) and (5), two additional closure equations are required to enable the computation of the Reynolds stress tensor and turbulent heat fluxes.

More details about the two transport equations and corresponding parameter settings for both the realizable k–ε turbulence model and the SST k–ω turbulence model can be found in Shih et al. [31] and Menter [32]. For the former model, near-wall treatment is taken into consideration for the viscous sublayer, which in other words is a low-Reynolds number model, used instead of the wall functions. This enhanced wall treatment is a near-wall modeling method that employs the one-equation model of Wolfshtein [35] to resolve the viscosity-affected in the near wall region, in which the turbulent Reynolds number, $Re^* = \rho y k^{1/2}/\mu$, is smaller than 200. Accordingly, the dimensionless wall distance, $y^+ = \rho u^* y^p / \mu$, at the wall-adjacent cell should be on the order of $y^+ \approx 1$. The SST k–ω turbulence model itself is available as the low-Reynolds number model, which treats the wall boundary condition in the same way as the enhanced wall treatments [36]. In that case, a smaller y^+ value at the wall-adjacent cell ($y^+ \approx 1$) is also required.

2.2. Large Eddy Simulation

In LES, the continuity, momentum and energy equations for incompressible flows and heat transfer are filtered as follows:

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \tag{6}$$

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial (\bar{u}_i \bar{u}_j)}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \nu\frac{\partial^2 \bar{u}_i}{\partial x_i \partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j} \tag{7}$$

$$\frac{\partial \bar{T}}{\partial t} + \frac{\partial (\bar{u}_j \bar{T})}{\partial x_j} = \frac{\nu}{\Pr}\frac{\partial^2 \bar{T}}{\partial x_i \partial x_j} - \frac{\partial h_j}{\partial x_j} \tag{8}$$

where $\tau_{ij} = \overline{u_i u_j} - \bar{u}_i \bar{u}_j$ and $h_j = \overline{u_j T} - \bar{u}_j \bar{T}$ are the subgrid-scale stress tensor and subgrid-scale heat flux, respectively. Both of them are unresolved and need to be modeled. Therefore, the Smagorinsky–Lily subgrid model is applied. In this model, the subgrid-scale tensor with the eddy viscosity hypothesis is given as:

$$\tau_{ij} - \frac{1}{3}\tau_{kk}\delta_{ij} = \nu_{sgs}\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right) = -2\nu_{sgs}\bar{S}_{ij} \tag{9}$$