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FLOW VELOCITY AND SURFACE TEMPERATURE EFFECTS ON CONVECTIVE HEAT TRANSFER COEFFICIENT FROM URBAN CANOPY SURFACES BY NUMERICAL SIMULATION

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Abstract: This study investigates the effect of flow velocity and building surface temperature effects on Convective Heat Transfer Coefficient (CHTC) from urban building surfaces by numerical simulation. The thermal effects produced by geometrical and physical properties of urban areas generate a relatively differential heating and uncomfortable environment compared to rural regions called as Urban Heat Island (UHI) phenomena. The urban thermal comfort is directly related to the CHTC from the urban canopy surfaces. This CHTC from urban canopy surfaces expected to depend upon the wind velocity flowing over the urban canopy surfaces, urban canopy configurations, building surface temperature etc. But the most influential parameter on CHTC has not been clarified yet. Urban canopy type experiments in thermally stratified wind tunnel have normally been used to study the heat transfer issues. But, it is not an easy task in wind tunnel experiments to evaluate local CHTC, which vary on individual canyon surfaces such as building roof, walls and ground. Numerical simulation validated by wind tunnel experiments can be an alternative for the prediction of CHTC from building surfaces in an urban area. In our study, wind tunnel experiments were conducted to validate the low-Reynolds-number k-ε model which was used for the evaluation of CHTC from surfaces. The calculated CFD results showed good agreement with experimental results. After this validation, the effects of flow velocity and building surface temperature effects on CHTC from urban building surfaces were investigated. It has been found that the change in velocity remarkably affects the CHTC from urban canopy surfaces and change in surface temperature has almost no effect over the CHTC from urban canopy surfaces.

Keywords: Convective Heat Transfer Coefficient (CHTC), CFD, flow velocity, urban canopy surfaces.

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INTRODUCTION

The Weather Research Forecasting (WRF) model coupled with UCM is to represent the transfer of heat and momentum from urban environment. This UCM provides the description of lower boundary conditions of urban area, which improves the prediction of urban momentum and heat transfer by WRF. Hence the Weather Research Forecasting (WRF) model coupled with the UCM would be considered as an effective tool for the prediction of urban heat island phenomena. The urban canopy model is responsible for predicting the heat transfer from the urban area to the overlaying atmosphere. In single layer Urban Canopy Model (Kusaka *et al.*, 2001), the local convective heat transfer from the urban canopy surfaces and its dependence on urban parameters such as building coverage ratio and building height variations are not explicitly modeled. In the UCM in WRF, the convective heat transfer coefficient from canopy surfaces are evaluated from Jurge's relation as shown in equation 1 and 2. The Jurge's relation (1924) is based on the CHTC of a heated copper square plate, which was oriented perpendicular to a uniform air flow in a wind tunnel.

$$C_w = C_G = 7.51 U_s^{0.78} \qquad (U_s > 5\text{m/s}) \qquad (1)$$

$$C_w = C_G = 6.15 + 4.18 U_s \qquad (U_s \le 5\text{m/s}) \qquad (2)$$

where Cw= CHTC of wall (W/m2^{o}C), CG= CHTC of ground (W/m2^{o}C), U_s = representative wind speed inside the canopy (m/s).

The Jurge's relation has its own limitations and may not be applied for the heat transfer from a surface of the building among the group of buildings (urban area). In this relation, the local CHTC from building walls and ground depends only on the velocity inside the canopy. However, this cannot be justified since other urban parameters also contribute to the CHTC. Moreover, this model cannot distinguish between CHTC on different wall surfaces, i.e., windward, leeward, side wall of the building and the ground, instead it expresses the CHTC generally as wall. Thus, the authors carried out wind tunnel experiments and CFD simulations to clarify this issue. Wind tunnel experiments were firstly conducted to roughly grasp the dependence of urban parameters on bulk heat transfer from an urban canopy in a thermally stratified wind tunnel. However, it is not an easy task in wind tunnel experiments to evaluate local CHTC, which vary on individual canyon surfaces such as building roof, walls and ground. Numerical simulation validated by wind tunnel experiments can be an alternative for the prediction of CHTC from building surfaces in an urban area.

Blocken *et al.* (2009) conducted CFD simulations to evaluate CHTC on the surfaces of a low-rise building with low–Reynolds-number model and found that the flow around the building varies the CHTC values on the windward facade. They found that CHTC is a power law correlation of wind speed at every "façade". They also reported the non-suitability of standard wall functions for CHTC calculation on the wall surface. Defraeye *et al.* (2010) performed CFD simulations using a low-Reynolds-number model to evaluate the forced convective heat transfer at the surfaces of a cube immersed in a turbulent boundary layer. The CFD simulation was validated by comparison with wind-tunnel measurements. The CHTC obtained from the low-Reynolds-number model showed satisfactory agreement with the experimental data. They also found that standard wall functions, which are frequently used for high-Reynolds-number flows, overestimated the CHTC significantly compared to the low-Reynolds-number model.

The authors conducted CFD simulation with a low-Reynolds-number k-ε model to evaluate the convective heat transfer from canyon surfaces. Calculated CFD results showed good agreement with experimental results. Further in order to assess the major parameter that affecting the CHTC was studied by CFD simulation. The effect of flow velocity and surface temperature was analyzed. The results from this study will be helpful in choosing the parameter for generalizing the CHTC from urban canopy surfaces.

WIND TUNNEL EXPERIMENT

Outline of wind tunnel experiment

The experiments were carried out in a thermally stratified wind tunnel at Tokyo Polytechnic University as shown in **Fig. 1**. The dimensions of the wind tunnel are 1.0 m (height) × 1.2 m (width) × 9.4 m (length). The experimental setup consisted of an aluminum cubic block array to model different cases of urban canopy. The array continued upstream of the measured section to model the fetch, which is responsible for the development of the turbulent thermal boundary layer on the urban canopy. **Figure 2** shows the experimental set up, in which aluminum blocks with dimensions 0.05m (W) ×0.05 m (D) ×0.05 m (H) are used for the generation of block arrays.

Experiment was carried out for 25% Building Coverage Ratio (hereafter referred to as BCR) with uniform height building blocks. The inflow velocity and temperature of the air at the wind tunnel inlet were uniformly maintained at 1.9m/s and 7.8oC throughout the cross section. The floor temperature was maintained at 53oC to simulate the unstable thermal environment. These conditions were adopted for all experimental cases. The surface temperatures of ground and block roof were observed using thermo-camera pictures taken during the experiments. The block roof temperature reached nearly 50^{o}C because of the higher thermal

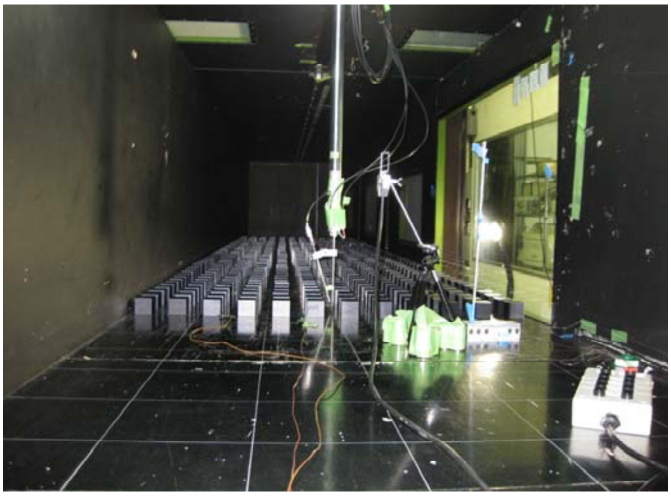


Fig. 1 Wind Tunnel experimental setup.

conductivity of the aluminum. The X-direction wind velocity component and the temperature were measured in the measuring section (outlet) shown in **Figs 2** and **3** shows the measuring points (within the moving limit of the traverse system) at the measuring cross section. We used more measuring points more closely spaced near the floor as shown in **Fig. 3** (right side). A split film probe and a thermocouple were used to measure the velocity and the temperature, respectively. The velocity and temperature measurements were made behind the blocks and along the flow passages, as shown in **Fig. 3**.

Bulk convective heat transfer from urban canopy

Heat flow by advection at the measuring section (outlet) can be calculated from the velocity and temperature data using the following equation:

$$Q = \sum_{i=1}^{n} \rho C_p U_i T_i A_i \tag{3}$$

where Q = heat flow (W), ρ = density of air (kg/m³), Cp = specific heat of air (J/kg°C), Ui = mean wind velocity at measuring point i (m/s), Ti = mean temperature of air at measuring point i (°C), Ai = control area around measuring point i (m²), and n = number of measuring points.

The difference between the inlet heat flow (at X=0) and the outlet heat flow (at measuring section in **Fig. 2**) was considered to be the bulk heat convected from all over the urban canopy surfaces (ground, walls and roofs).

$$\Delta Q = Q_{UC} = Q_{out} - Q_{in} \tag{4}$$

where $\Delta Q = Q_{UC}$ = heat convected from all over the urban canopy (W), Q_{out} = heat flow at the outlet (measuring section in **Fig. 2**)(W), and Q_{in} = heat flow at the inlet (W) in **Fig 2**.

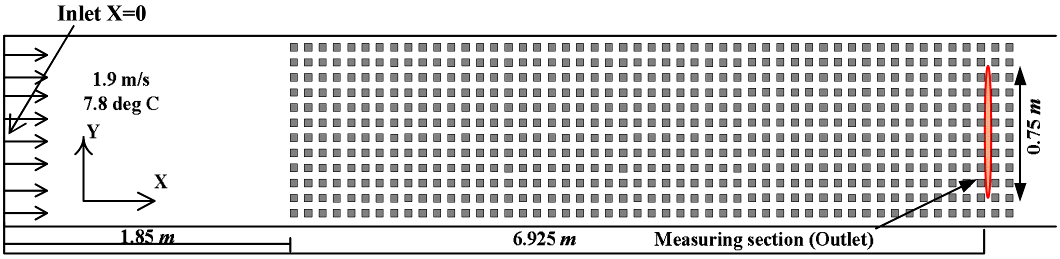


Fig. 2 Wind Tunnel experimental setup (25% BCR).

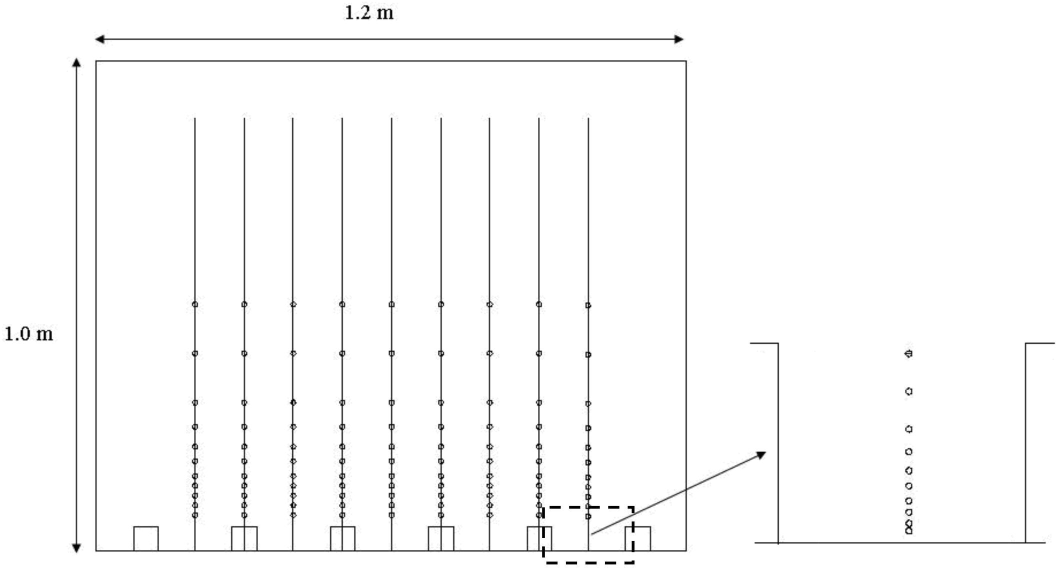


Fig. 3 Measuring points in wind tunnel cross section (ex: BCR- 6%).

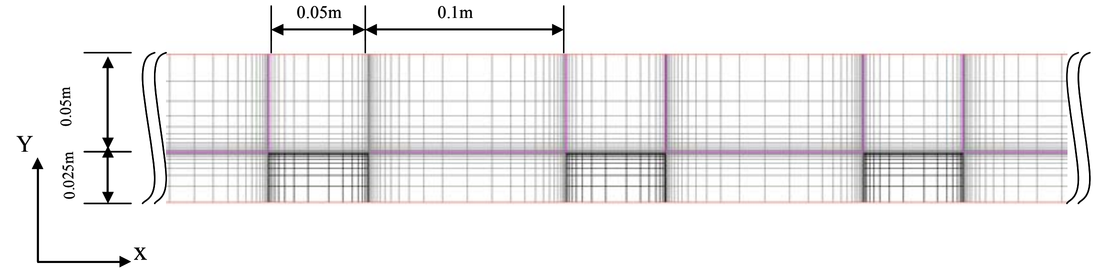


Fig. 4a Grid arrangement in horizontal plane (ex : uniform height, BCR-11% case).

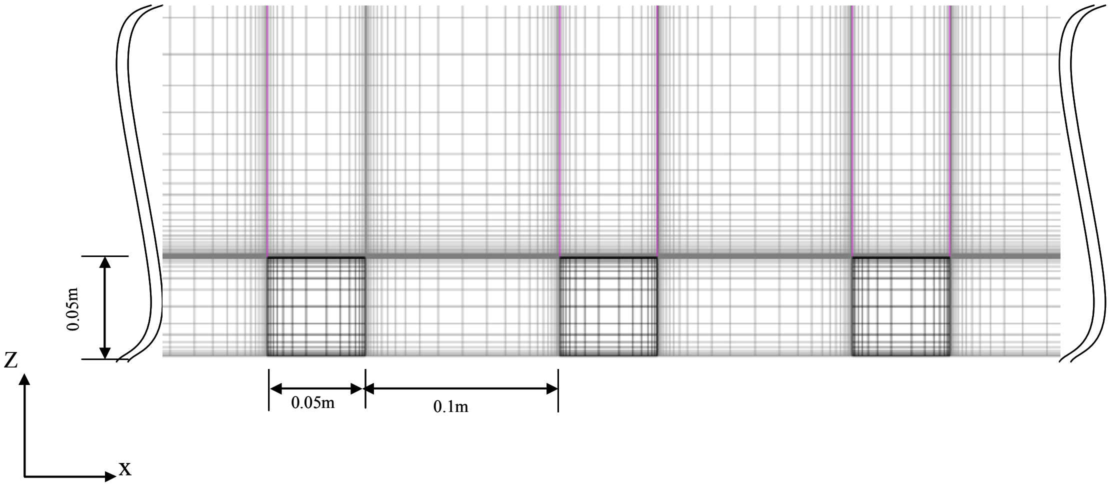


Fig. 4b Grid arrangement in vertical section (ex : uniform height, BCR-11% case).

CFD Simulation

General outline of numerical simulation and boundary conditions

For the calculation of complex turbulent flows with separation and heat transfer, Abe *et al.* (1994, 1995) developed a new low-Reynolds number turbulence model for flow field and thermal field. This model quite successfully predicts the separating and reattaching flows in the downstream of a backward-facing step, which involve most of the important physical phenomenon of complex turbulent flow around obstacles. Thus, the authors considered this Low Reynolds number k-ε model was suitable for urban canopy simulations.

Figures 4a and **4b** shows the grid arrangement in the horizontal plane and vertical section (For example: BCR-11% case with uniform height buildings), respectively. The computational domain was an exact replica of the wind tunnel in windward length and vertical height. Minimum width was selected by considering symmetry in the Y direction. As shown in **Figs 4a** and **4b** the domain has structured grids with very fine mesh near the wall surfaces. Distance between wall surface and first mesh line was 0.2 mm. As a result, non-dimensional distances from the wall surfaces Y+ were below 1.0 for most of the first fluid cells close to the wall surfaces. y+ is defined as follows:

$$y^{+} = \frac{u_{*} y}{\nu} \qquad (5)$$

where = frictional velocity at the surface (m/s), y=distance between the wall surface and the first fluid cell (m), and ν=kienematic viscosity of air (m2/s). The maximal value of y+ was in the range of '2' at edge of the windward wall, sidewall and roof of the first block in the upstream region where the frictional velocity at the surface is higher (higher wall shear stress). We conducted grid sensitivity analyses using fine mesh (1939(x)×30(y)×67(z) = 3 897 390) and coarse mesh (1378(x)×20(y)×59(z) = 1 626 040) for BCR25% uniform case. The differences between wind velocities and temperature profiles and convective heat transfer for the calculated results of the fine mesh and the coarse mesh were extremely small. Thus we judged that the grid resolution of the fine mesh was sufficient, and after that grids with similar resolution to the above fine mesh were used for other calculation cases.

Calculation conditions (For example: BCR-11% case with uniform height buildings) are shown in **Table 1**. No slip boundary conditions were applied for wall shear stress. For thermal boundary conditions, surface temperatures were prescribed and heat conduction boundary condition was applied for heat flux on the wall surfaces. The surface temperature for various

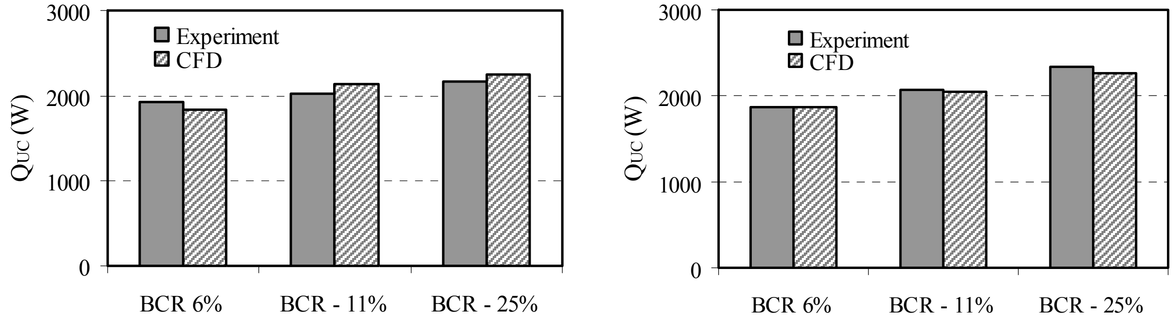
Table 1. Calculation conditions for low Reynolds number k-ε model (For ex: BCR-11% case with uniform height buildings)

Computational domain	9.35m(x) × 0.075m(y) ×0.8m(z)
Grid resolution	1564(x) × 33(y) × 100(z) = 5 161 200 mesh
Boundary conditions for wall shear stress	
Wall and roof of blocks	No slip condition
Wind tunnel floor	No slip condition
Wind tunnel ceiling	Symmetric plane
Lateral sides of computational domain	Symmetric plane
Inflow boundary condition	Velocity U = 1.9 m/s, Temperature T = 7.8°C Turbulent kinetic energy k= 0.0016m^2/s^2 (Corresponds to turbulence intensity = 2%)
Outflow boundary condition	Zero gradient condition
Thermal boundary conditions	
Block roof surface	Surface temperature 48.5°C, heat conduction (No slip condition)
Wind tunnel floor surface	Surface temperature 53°C, heat conduction (No slip condition)
Block wall surface	Surface temperature 50°C (average of above two surface temperatures), heat conduction (No slip condition)

simulation cases were obtained from the thermo camera pictures (roughly 300 pictures for each experiment) taken during the experiments. The average temperature obtained from the thermo-camera pictures were defined as the heat transfer boundary condition over the surface (ground and roof temperature). Lateral sides (in the Y direction) and the ceiling (in the Z direction) of the computational domain were taken as symmetry plane. Inflow of the computational domain has the uniform velocity and temperature condition as same as the wind tunnel experiment. Turbulent kinetic energy at the inflow corresponds to the 2% turbulence intensity of the wind tunnel. Outflow was defined as zero gradient condition. For the discretization schemes for the advection term, a second order upwind scheme was used for the transport equation of momentum, heat, turbulent kinetic energy and dissipation rate. The convergence criteria for the residual was set at 10^{-10}, which is much smaller than the default value of 10^{-3}, and the convergence was assessed by comparing the results (velocity and temperature profile) of the latest iteration and considerable previous iteration.

Comparison between experiment and CFD results

Figures 5a and **5b** compares the bulk heat transferred (QUC) from urban canopy for experiment and CFD simulation for different canopy configuration cases with uniform and non-uniform building heights respectively. As discussed in section 2.3, the difference between inlet heat flow (**Fig. 2**) and outlet heat flow (at measuring section in **Fig. 2**) was considered to be the bulk heat transferred from all over the urban canopy surfaces (ground, walls and roofs). The QUC from urban canopy obtained by the experiments and the CFD simulations shows good agreement with each other. In addition, the vertical profiles of wind velocity and temperature (at measuring section) calculated by CFD simulations agreed very well with those of the experiments (Sivaraja *et al.*, 2010). Thus, the authors considered that CFD simulations are appropriate for estimation of convective heat transfer coefficient from building surfaces for further studies.



(a) Uniform height case (b) Non-uniform height case

Fig. 5 Comparison between experiment and CFD simulations: Bulk heat transferred (Q_{UC}) from urban canopy for various BCR.

Table 2. Various cases of thermally stratified environment with different flow velocities

Cases	Inflow velocity (m/s)	Reference velocity, U_R (m/s)	$(T_R - T_S)$ (°C)	Ri_b
Case 1	1.9	2.1	–45.2	–0.13
Case 2	1	1.15	–45.2	–0.5
Case 3	0.75	0.85	–45.2	–0.9

Thermal stratification effects on CHTC of canyon surfaces (with change in flow velocity)

The effect of thermal stratification in urban atmosphere has been studied with the help of numerical simulation. The unstable thermal environment in real urban area favors the urban heat island phenomena. Hence we opted the study of heat transfer coefficient variation due to the change in the stratification effects in a unstable thermal environment. This urban thermal stratification has been characterized by Bulk Richardson's number. Bulk Richardson number can be expressed like the following

$$Ri_b = \frac{gH \times (T_R - T_S)}{(T_0 + 273) \times U_R^2} \tag{5}$$

where Rib = Bulk Richardson number, H = Reference height (m), TR = temperature at ref height above the canopy (oC), (center position of the canopy), and TS = Surface temperature (°C), T0 = Average Inflow temperature (°C), and UR = Velocity at reference height above the canopy (m/s), at the boundar layer height.

The stable and neutral environment not much important considering diurnal heat island phenomena, hence three cases of weakly unstable, unstable and strongly unstable cases of urban thermal environment of 25% building coverage ratio with uniform height building case were examined. This various Rib values can be achieved by change in the inflow velocity and the surface temperature. But for the first investigation the Rib was achieved by only changing the flow velocity which is shown clearly in **Table 2**. The temperature difference between the surface and reference position is same for all the cases. The value of Rib for weakly unstable condition is -0.13 termed as case1, for unstable condition it is -0.5 termed as case2 and for strongly unstable it is -0.9 termed as case3.

Figures 6a–6d shows the CHTC profile in horizontal direction for roof, windward wall, leeward wall, and ground respectively. From the figures it has been inferred that the CHTC is higher for all the canopy surfaces in weakly unstable environment than the other cases of thermally stratified environment. This shows that the flow velocity influences much on the all the urban canopy surfaces. Thus weakly unstable environment favors the mitigation of the urban heat island phenomena in urban area rather than the other cases of urban thermal stratification. This shows the dependence of convective heat transfer coefficient from the building surfaces on the thermal stratification attained with the change in flow velocity over the canopy in the urban area.

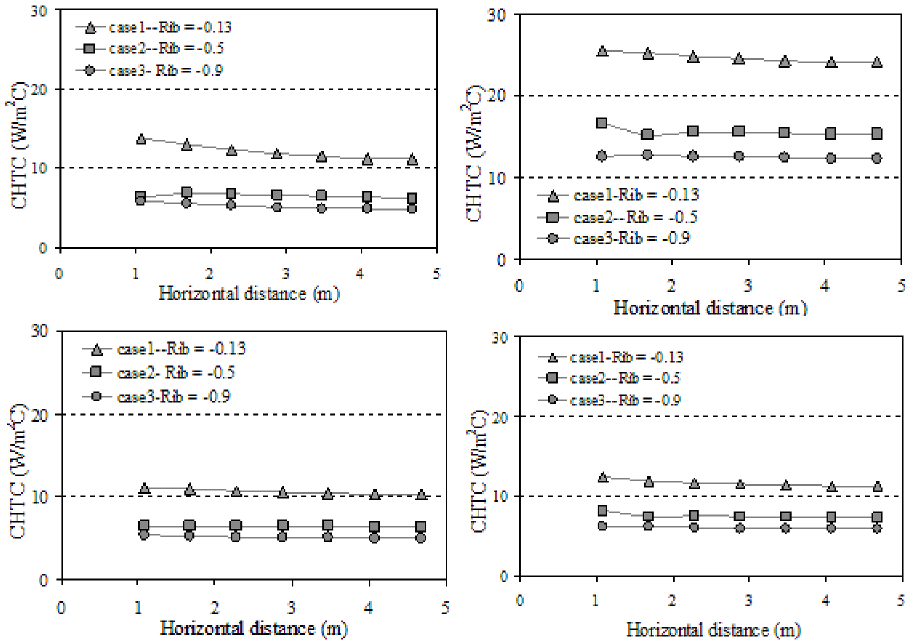


Fig. 6 (a) CHTC profile for roof in different thermally stratified environment (with change only in flow velocity); (b) CHTC profile for windward wall in different thermally stratified environment (with change only in flow velocity); (c) CHTC profile for leeward wall in different thermally stratified environment (with change only in flow velocity); and (d) CHTC profile for ground in different thermally stratified environment (with change only in flow velocity).

Table 3. Various cases of thermally stratified environment with surface temperatures

Cases	Inflow velocity (m/s)	Reference velocity, U_R (m/s)	$(T_R - T_S)$ (°C)	Ri_b
Case 1	1.9	2.1	-45.2	-0.13
Case 2	1.9	2.1	- 67.2	-0.19
Case 3	1.9	2.1	-92.2	-0.28

Thermal stratification effects on CHTC of canyon surfaces (without change in flow velocity)

Thermal stratification effect in urban area can be characterized by Bulk Richardson number. In the above section the various cases of bulk Richardson number has been achieved by both the change in inflow velocity. In this section three cases of bulk Richardson number effects on the CHTC of canopy surfaces were investigated. Here the bulk Richardson number was achieved by change in building surface temperature and not the change in inflow velocity. The inflow velocity is maintained constant and the surface temperature was changed which is clearly shown in **Table 3**. The value of Rib for case1 is –0.13 termed, for case2 it is –0.19 and for case3 it is –0.28.

Figures 7a–7d shows the CHTC profile in horizontal direction for roof, windward wall, leeward wall and ground respectively. These figures illustrates that the there is no variation in the CHTC from the canyon surfaces for the change in bulk Richardson number achieved by change in building surface temperature by keeping the flow velocity as a constant one.

This shows the CHTC from the surfaces predominantly depends on the flow velocity over the surface irrespective of the surface temperature. Thus change in Bulk Richardson number will not affect the CHTC from the surfaces unless the scenario (Rib) achieved by change in flow velocity.

Conclusion

Convective heat transfer from various urban canopy cases for different building coverage ratios with uniform and non-uniform building heights were investigated by wind tunnel experiments and CFD simulation. Low-Reynolds number turbulence model validated by the authors using experimental data was adopted for further investigations in CFD simulations. Our main purpose was to clarify the most influential parameter on Convective Heat Transfer Coefficient (CHTC) from the urban canopy surface. The main conclusions of this study are as follows:

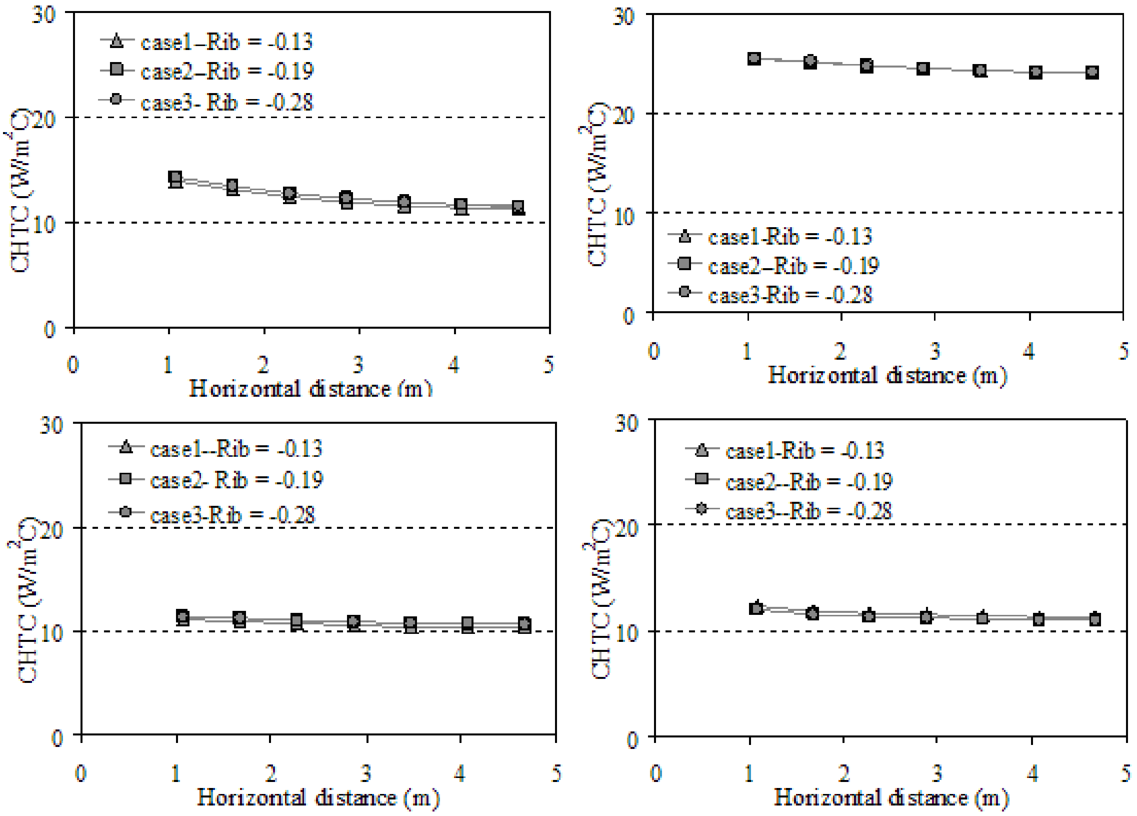


Fig. 7 (a) CHTC profile for roof in different thermally stratified environment (with change only in surface temperature), (b) CHTC profile for windward wall in different thermally stratified environment (with change only in surface temperature), (c) CHTC profile for leeward wall in different thermally stratified environment (with change only in surface temperature), and (d) CHTC profile for ground in different thermally stratified environment (with change only in surface temperature).

1. Prediction of bulk heat transfer by CFD simulation with Low-Reynolds number k-εmodel is satisfactory when compared with the experimental results.

2. It has been found that the change in velocity over the canopy remarkably affects the CHTC from urban canopy surfaces and change in surface temperature has almost no effect over the CHTC from urban canopy surfaces.

3. For the generalization of CHTC for urban canopy surfaces, velocity has to be considered in priority and which was found to be the most influential parameter affecting CHTC from the surfaces.

4. Convective heat transfer coefficient (CHTC) from individual canyon surfaces will be generalized for various urban canopy cases with the help of the parametric studies performed by CFD simulation (future work). The different cases for parametric studies will be selected by varying the Building Coverage Ratio (BCR), the height of the buildings, Reynolds number and Bulk Richardson number (by varying inflow velocity). Various simulation case results will be employed to generalize the CHTC from the canyon surfaces. The CHTC expressed as local Nusselt number will be generalized with variables like local canopy velocity expressed in local Reynolds number, building coverage ratio, height ratio) and canopy Richardson number. Inclusion of this generalized expression for individual urban canopy surfaces in UCM will be expected to increase the prediction accuracy of urban heat transfer by WRF.

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