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SIMULATION OF HEAT TRANSFER FROM CANOPY SURFACES USING LOW-REYNOLDS NUMBER k-ε MODEL

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Abstract: This study focuses on the Convective Heat Transfer Coefficient (CHTC) from urban building surfaces by numerical simulation. The heat transfer effects because of various geometrical and physical properties of urban areas exhibits a differential heating and uncomfortable environment compared to rural regions called as Urban Heat Island (UHI) phenomena. Investigation of Convective heat transfer coefficient becomes more important in the study of urban heat island phenomena. Experimental simulation of urban area with various urban canopy cases in thermally stratified wind tunnel is employed for the heat transfer kind of investigations in urban area. But, it is not an easy task in wind tunnel experiments to evaluate local CHTC, which vary on individual canyon surfaces transfer 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, Water evaporation technique used in wind tunnel experiment for the evaluation of convective heat transfer coefficient and naphthalene sublimation technique conducted by other researchers are used 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 both water evaporation technique and naphthalene sublimation experimental results. It is found that the low-Reynolds-number k-ε model is reliable for the investigations pertaining to heat transfer from urban canopy.

Keywords: Convective Heat Transfer Coefficient (*CHTC*), CFD, low-Reynolds-number k-ε model, urban canopy surfaces

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INTRODUCTION

Experimental investigation of urban canopy type set ups with different urban configurations was done by many researchers all over the world. Especially some of the experimental technique viz. water evaporation, naphthalene sublimation method was explored in the last decade. Experiments with different urban canopy configurations were also done by many researchers. Yoshie *et al.* (2008) investigated the ventilation performance of various configurations of urban areas by wind tunnel experiments and they found that non-uniformity in building height greatly improves ventilation performance and reduces air temperature in urban canopies due to the "vertical ventilation path", i.e., the effect of vertical advection and vertical turbulent diffusion. Oke (1988) demonstrates a number of useful relationships exist between the geometry and the microclimate of urban street canyons. They are potentially helpful to the establishment of guidelines governing street dimensions for use by urban designers. He classified the flow behavior over the different configurations of urban canopy as skimming flow, wake interference flow and isolated roughness flow.

The change in flow pattern would also change the heat transfer behavior of building surfaces. Barlow *et al.* (2004) investigated the mass transfer from street canyon surfaces by naphthalene sublimation technique in wind tunnel. The naphthalene sublimation technique was used to quantify scalar vertical fluxes out of a street canyon under neutral conditions. They did the experiment for various building coverage ratios and found that the fluxes from the roof and downstream wall were considerably larger than the fluxes from the street and upstream wall.

Narita (2007) also evaluated mass transfer from individual wall surfaces in an urban canyon using water evaporation technique in wind tunnel. This paper describes a method involving water evaporation from filter paper to measure the convective mass fluxes from urban canyon surfaces. He obtained the "convective transfer velocity" from all the individual urban canyon surfaces for different building coverage ratios and found that the "convective transfer velocity" was varying on each canyon surfaces for different canopy configurations. 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.

Urban canopy type wind tunnel experiments are being widely used in acquiring knowledge about the flow and thermal behavior inside and over the urban canopy. But the alternate for doing complex experiments is simulating the case using suitable simulation tool. The authors conducted CFD simulation with a low-Reynolds-number k-ε model to evaluate the convective heat transfer from canyon surfaces. In order to check the reliability of the simulation, the Calculated CFD results were compared with the experimental results obtained from water evaporation technique by Narita etal and naphthalene sublimation technique conducted by Barlow *et al.* (1995).

CFD SIMULATION

General outline of numerical simulation and boundary conditions

The simulation was carried out with a 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. Fig 1 shows the experimental set up, in which aluminum blocks with dimensions 0.05m (W) ×0.05m (D) ×0.05m (H) are used for the generation of block arrays.

Simulation was performed for 25% 11%, 6%, Building Coverage Ratio (hereafter referred to as BCR) with uniform height building blocks. The inflow velocity and temperature of the air at the computational domain inlet were uniformly maintained at 1.9m/s and 7.8°C throughout the cross section. The floor temperature was maintained at 53°C to simulate the unstable thermal environment. These conditions were adopted for all simulation cases.

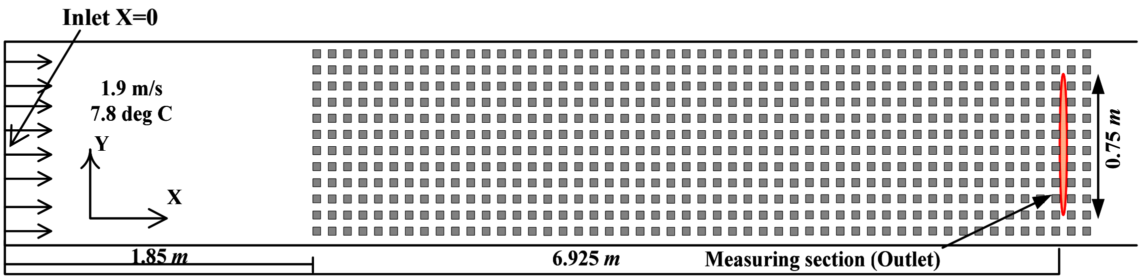

Fig 1. Computational domain with building array (25% BCR).

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.

Figs 1(a) and **1(b)** show the grid arrangement in the horizontal plane and vertical section (For example: BCR-11% case with uniform height buildings), respectively. As shown in **Figs 2** and **3**, 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

$$y^+ = \frac{u_* y}{\nu} \tag{1}$$

where u_* = 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 (m^2/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.

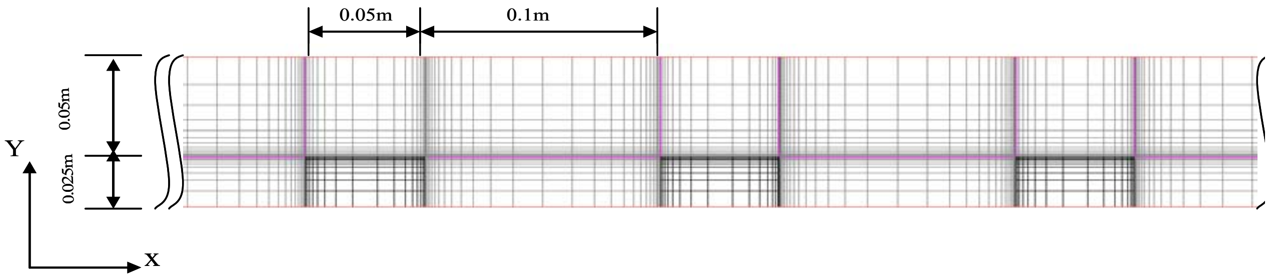

Fig 2. Grid arrangement in horizontal plane (ex : uniform height, BCR-11% case).

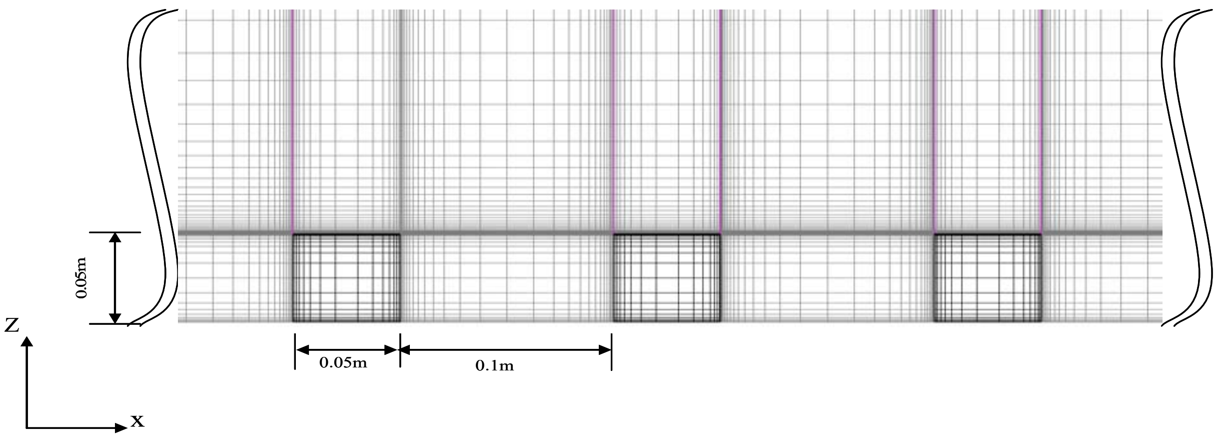

Fig 3. Grid arrangement in vertical section (ex : uniform height, BCR-11% case).

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

Computational domain	9.35 m (x) × 0.075 m (y) × 0.8 m (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)

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 simulation cases were obtained from the thermo camera pictures taken during the experiment. 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 CFD and experiment results

Recently, the convective heat transfer coefficient *(CHTC)* of building surfaces has been regarded as an important parameter in discussions not only the thermal load of the building, but also the urban pedestrian environment, since *CHTC* is very important in estimating convective heat flux from the building surfaces. The convective heat exchange at an building surface, due to air flow over the surface, is usually modeled by convective heat transfer coefficients *(CHTC)* which relates the convective heat flux from the building surface to the difference between the surface temperature at the surface and a reference temperature. Convective heat transfer coefficient can be obtained from CFD simulation using the following expression

$$CHTC = (h_C)_S = \frac{\sum_{j=1}^{m} q_j A_j}{S \cdot (T_S - T_R)} \quad (2)$$

where $(h_c)_s$ = convective heat transfer coefficient (W/m^2°C), q_j = surface heat flux on individual cells on ground and block surfaces (W/m^2), A_j = area of individual cells on surfaces, m = number of cells on ground and block surfaces, T_S = area weighted average temperature of ground or block surfaces (°C), T_R = reference temperature (temperature at the boundary layer) (°C), S = area of the individual surfaces like ground, roof, windward wall, leeward wall and sidewall (m^2). Here the suffix *s* denotes the convective heat transfer coefficient from the individual surfaces like ground, roof, windward wall, leeward wall and sidewall.

Comparison of CFD results with Water Evaporation Technique

The CHTC varies for individual canopy surfaces in a same case of BCR. **Figures 4(a)** and **4 (b)** show the CHTC variation of individual canopy surfaces for BCR

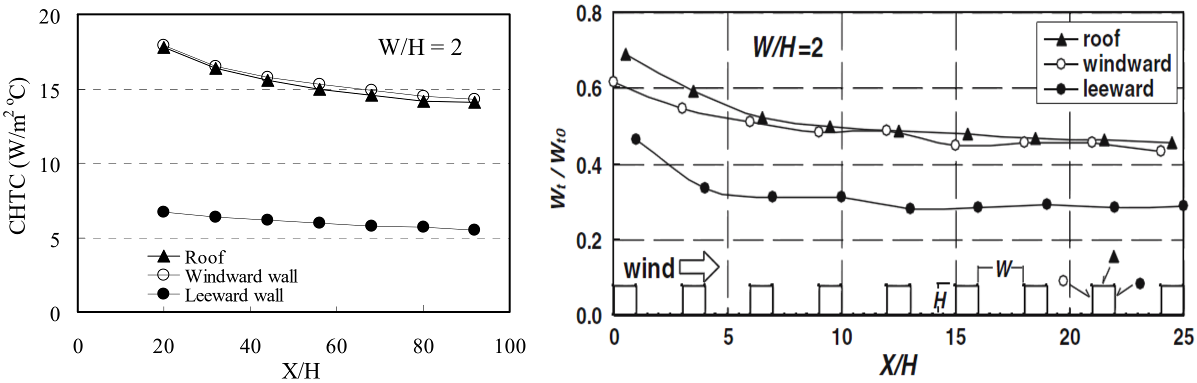

Fig. 4 (a). CHTC of individual canopy surfaces for 11% BCR, (b) Stream wise transfer velocity for individual canopy surfaces for 11% BCR with uniform height buildings (Narita *et al.*, 2007).

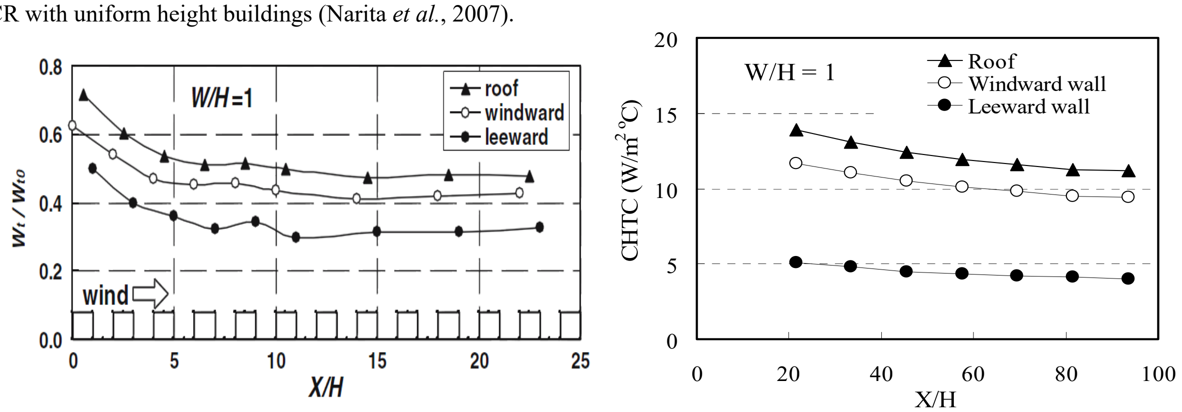

Fig. 5 (a). CHTC of individual canopy surfaces for 25% BCR with boundary layer height temperature as reference temperature for uniform height buildings, (b). Stream wise transfer velocity for individual canopy surfaces for 25% BCR with uniform height buildings (Narita *et al.*, 2007).

11% with boundary layer height temperature as reference temperature (to compare with water evaporation experiment) and transfer velocity of surfaces for BCR 11% of water evaporation experiment of Narita et al (2007) in 2D street canyon respectively. The horizontal axis in these figures represents the distance from the windward surface of the first block to the representative canopies normalized with the height of the block. The CHTC for windward wall is almost same with roof and which are higher than the leeward wall. This shows the same tendency exhibited by the results of water evaporation experiment, which is shown in **Figs 4(a)** and **4(b)**. Similarly, **Figs 5(a)** and **5(b)** show the CHTC variation of individual canopy surfaces for BCR 25% with boundary layer height temperature as reference temperature and transfer velocity of surfaces for BCR 25% of water evaporation experiment of Narita et al (2007) in 2D street canyon respectively. The CHTC for roof is higher than the windward wall and leeward wall. This shows the same tendency exhibited by the results of water evaporation experiment, which is shown in **Figs 5 (a)** and **5 (b)**.

Comparison of CFD results with Naphthalene Sublimation Technique

Figures 6(a) and **6(b)** show the CHTC variation of individual canopy surfaces with boundary layer height temperature as reference temperature for various canyon aspect ratio H/W (H = height of the block, W = distance between two blocks) and transfer coefficient of surfaces for various canyon aspect ratio of naphthalene sublimation technique of Barlow et al (2004) in 2D street canyon respectively. The CHTC of roof and windward wall is higher than the leeward wall and ground for H/W=1 (corresponds to BCR-25%). This shows the same tendency exhibited by the results of naphthalene sublimation technique of Barlow et al (2004), which is shown in **Figs 6(a)** and **6(b)**.

The velocity over the surfaces of roof, windward wall, and side wall is higher and the temperatures over these surfaces (near the first mesh cell) are lower. But the velocity is lower and the temperature is higher over the surfaces (near the first mesh cell) of leeward wall and ground. This is the reason for higher CHTC for roof, windward wall and side wall than the other surfaces like leeward wall and ground. The nature of flow over the canopy surfaces is because of the BCR and the flow direction. This was explained with the velocity and temperature contour over these surfaces in the next section. For the entire canopy surfaces the CHTC decreases with the horizontal distance in the windward direction because of higher air temperature in the downstream canopies.

CONCLUSION

Convective heat transfer from various urban canopy cases for different building coverage ratios with uniform building heights were investigated by CFD simulation.

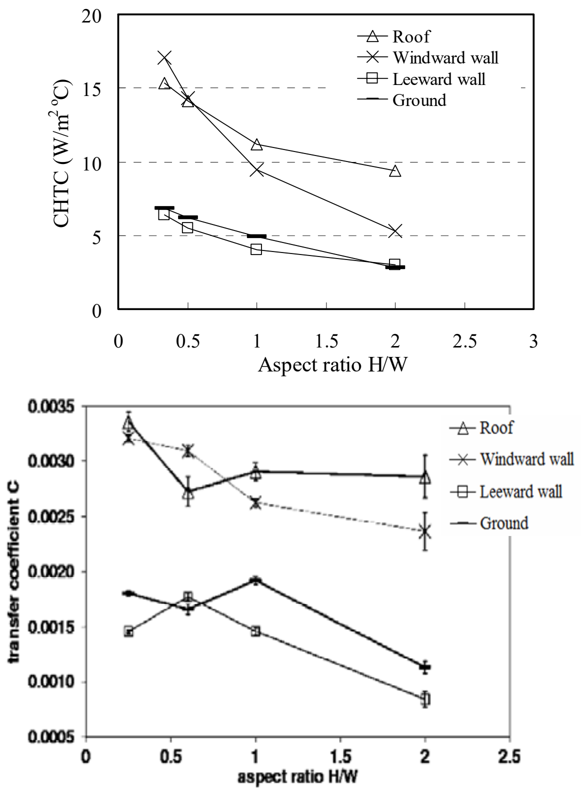

Fig. 6 (a) CHTC of individual canopy surfaces for various canyon aspect ratios H/W for uniform height buildings, (b). Transfer coefficient for individual canopy surfaces for various canyon aspect ratio with uniform height buildings (Barlow et al, 1995).

Low-Reynolds number turbulence model validated by the authors using experimental data obtained from water evaporation technique and naphthalene sublimation technique. The main conclusions of this study are as follows

1. Prediction of CHTC by CFD simulation with Low-Reynolds number k-εmodel is satisfactory when compared with the experimental results obtained from water evaporation technique and naphthalene sublimation technique.

2. Low-Reynolds number k-εmodel simulation is reliable for the investigations pertaining to heat transfer from urban canopy.

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