Advanced numerical analysis on sensible heat flux from building external surfaces to the surrounding atmosphere using a heat balance simulation and CFD

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1. Introduction

Sensible heat flux from building external surfaces is one of the essential factors warming the atmosphere around buildings and causing urban heat island effects. The clarification of sensible heat flux and predict it accurately become important to discuss the method to alleviate urban heat island effects. There are many field measurements and wind tunnel experiments that have been done before. However, field measurements are difficult to cover the whole sensible heat fluxes from the building external surfaces with complex geometries and the scales of wind tunnel experiments are different from that of reality. Therefore numerical analysis is considered to be effective method for grasping the sensible heat flux on the whole building surfaces.
Surface temperature, air temperature and air flow near the building surfaces, all of which influence the sensible heat flux. Authors' group developed 3D CAD-based heat balance simulator which can calculate the detailed surface temperature distribution taking into account the building geometry (Takashi Asawa et al. 2011). Although we can predict the sensible heat flux taking into account the building geometry and material by that uses the coupled analysis of the heat balance simulation and CFD, the traditional method using high Reynolds number k-ε model (the High-Re model) can not reflect the effect of the disturbance of the boundary layer causing by surface temperature distribution and building geometry at the edge of buildings on the sensible heat flux. Therefore, it is necessary to use low Reynolds number k-ε model (the Low-Re model) to simulate inside the boundary layer to predict the sensible heat flux and Convective Heat Transfer Coefficient (CHTC) accurately by definition formula (Fig. 1). It is important to figure out prediction formula for CHTC which can be applied to the High-Re model.

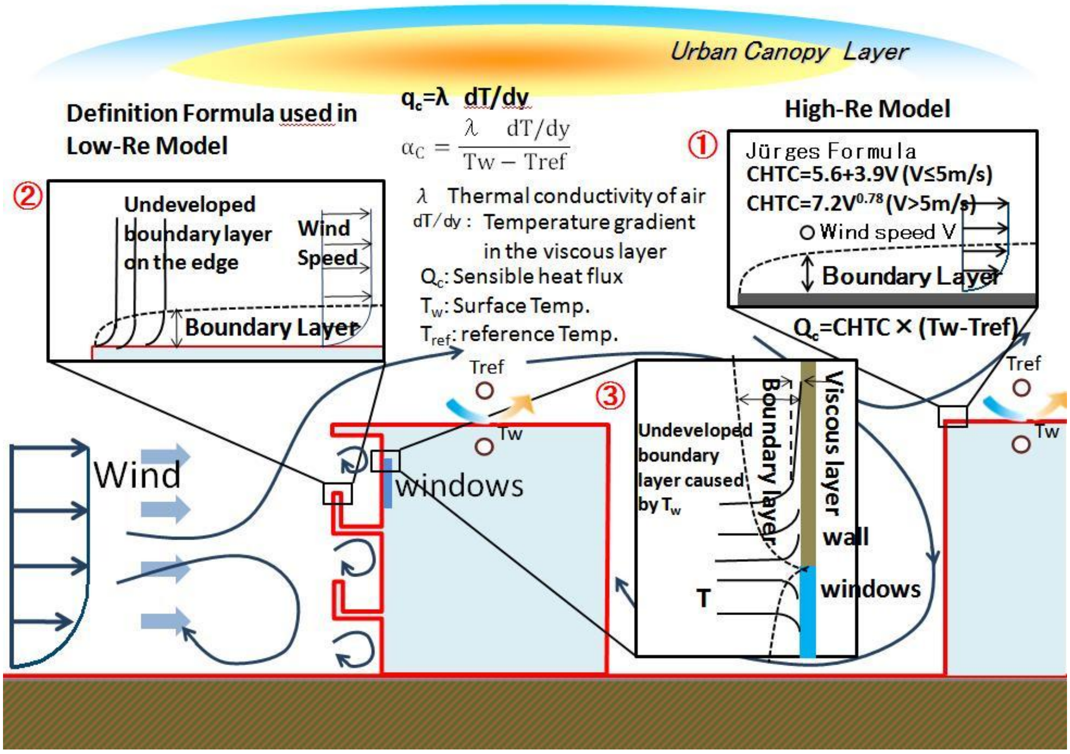

Fig. 1 Conceptual diagram of sensible heat flux from the building external surfaces to the atmosphere.

The purpose of this study is to examine the method to predict the sensible heat flux from building external surfaces by using the coupled analyze of the heat balance simulation and CFD and figure out the appropriate prediction formula for CHTC that can be used for the prediction of heat fluxes by the High-Re model, in order to apply this method to the analysis of urban block scales.

2. Research methods

2.1 Discussion of the method to predict the sensible heat flux

CHTC is the Key parameter which influences the sensible heat flux from the building external surfaces (Aya Hagishima et al. 2004). Its behavior is difficult and there are multiple studies of predicting CHTC by numerical simulation that have been done before. Because numerical simulation inside the boundary layer where the wind speed, temperature changes rapidly near the building surfaces is difficult, they used the wind speed above the wall boundary layers near the building surfaces as the reference wind speed to calculate CHTC with the High-Re model. This method has lower computational load and is appropriate to apply to the urban block scales. However, properties of the boundary layer strongly influence the prediction of CHTC. So it is necessary to use the Low-Re model that can simulate inside the wall boundary layers to predict CHTC accurately. Then this study proposes a prediction formula which can be applied to the High- Re model. There are very few research taking into account influence inside the wall boundary layer, surface temperature and building geometry at the same time.
Blocken et al. performed 3D steady RANS CFD simulations of forced convective heat transfer at the façades of a low-rise cubic (10×10×10m^3) (Blocken et al. 2009). Then they found on the windward façade, CHTC has strong correlation with the turbulent kinetic energy K. However, in this study, only windward façade was examined. Also the detailed geometries were not reproduced. Since the sensible heat flux from whole external surfaces of buildings will influence the surrounding microclimate, we need to predict the sensible heat flux from the whole building external surfaces. Building geometry also influence the sensible heat flux, we need to take into account of typical geometry of Japanese housing complex which related to our daily lives. As the subject that this study mentioned, considering the computational load, it becomes impossible to apply the Low-Re model the high resolution cells of the urban blocks of reality. In order to predict the sensible heat flux of urban blocks more accurately, we will propose the method by deriving a specially-adapted wall functions to simulate the sensible heat flux distribution of urban blocks.

2.2 Examination of accuracy of CHTC influenced by turbulence model and coupled analysis method

This part compares the simulation results by the High-Re model and the Low-Re model to the wind tunnel experiment, so as to confirm the influence of the turbulence model on prediction accuracy of CHTC. Then, we consider the method of coupled analysis for application to the real buildings. CFD tool used in this study is OpenFOAM-2.0.

2.3 Comparison with wind tunnel experiment and CFD simulation results

Narita et al. performed wind tunnel experiments to measure the distribution of CHTC in 2D canyon that uses the filter paper evaporation method (Kenichi Narita et al. 2001). We used the High-Re and the Low-Re model to simulate under the same condition to the wind tunnel experiment and compared the results of them (Fig. 2). The Low-Re case shows similar tendency as the result of the experiment on all of the walls and grounds of the model. The difference between the experimental value and the High-Re case is relatively large. It is because the High-Re model uses a logarithmic law near surfaces for velocity distribution, the disturbed part of velocity boundary layer can't be accurately predicted. We can confirm that by using the Low-Re model the prediction accuracy in canyon space becomes higher than that of the High-Re model.

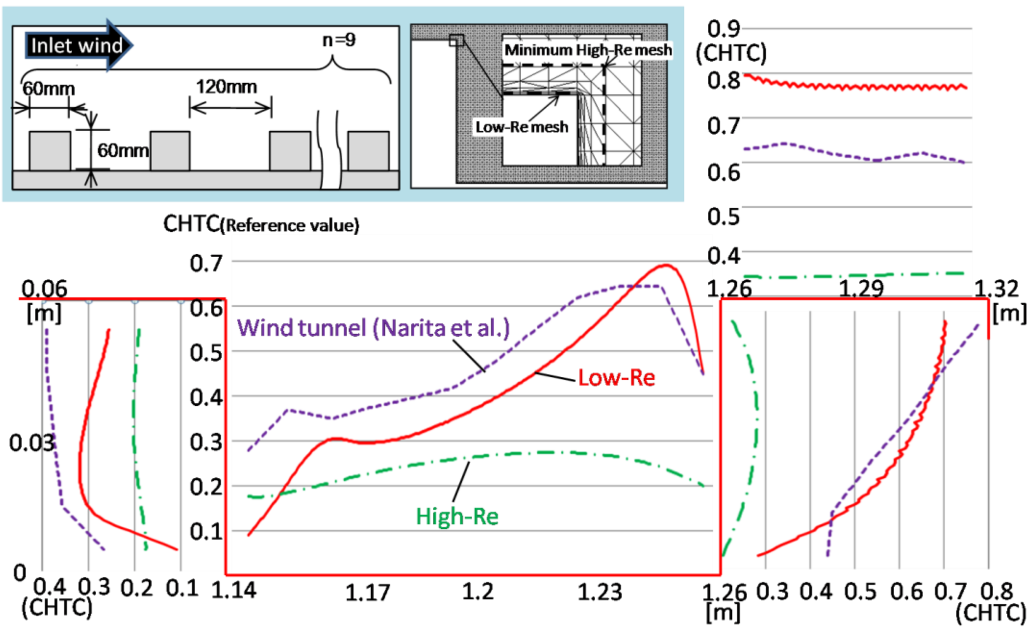

Fig. 2 Comparison with wind tunnel experiments using the simple buildings model.

2.4 Flow of coupled analysis and necessary steps of it

Flow chart of the coupled analysis is shown in Fig. 3. First, we calculate surface temperature distribution by heat balance simulation. Then, we use the result as the boundary condition of CFD and calculate CHTC distribution. We use calculated CHTC as boundary condition of the heat balance simulation to simulate surface temperature distribution considering the wind speed and temperature distribution near the surfaces. Finally, we repeat the same operation until the coupled analysis converged.

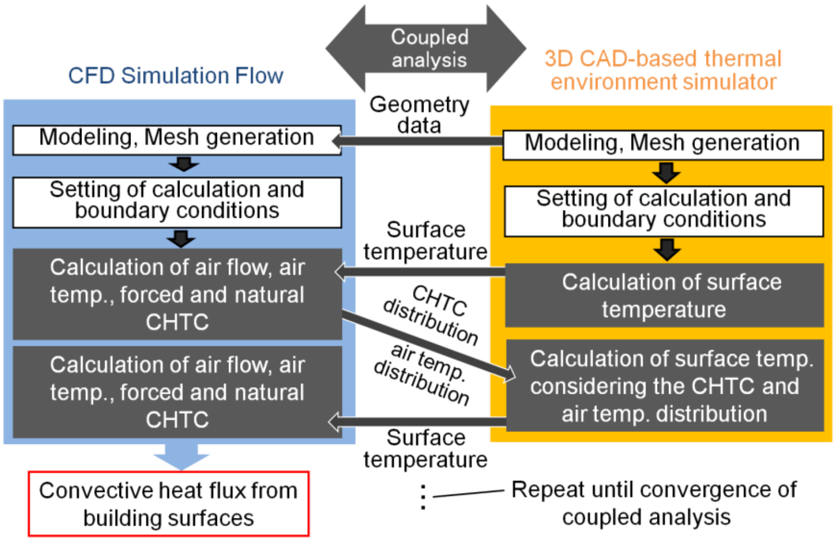

Fig. 3 Flow chart of coupled analysis.

We compared the result of the sensible heat flux by coupled analysis between first step, second step and third step (Fig. 4). We find that the difference of the sensible heat flux between first and second step is large, second and third step is small. The reason is first step uses the wind speed in the sky as the wind speed near the building surfaces, so underestimation of the sensible heat flux and surface temperature occurs. The difference between second and third step is only 5%. We can consider it has converged at the second step and the necessary number of step is two.

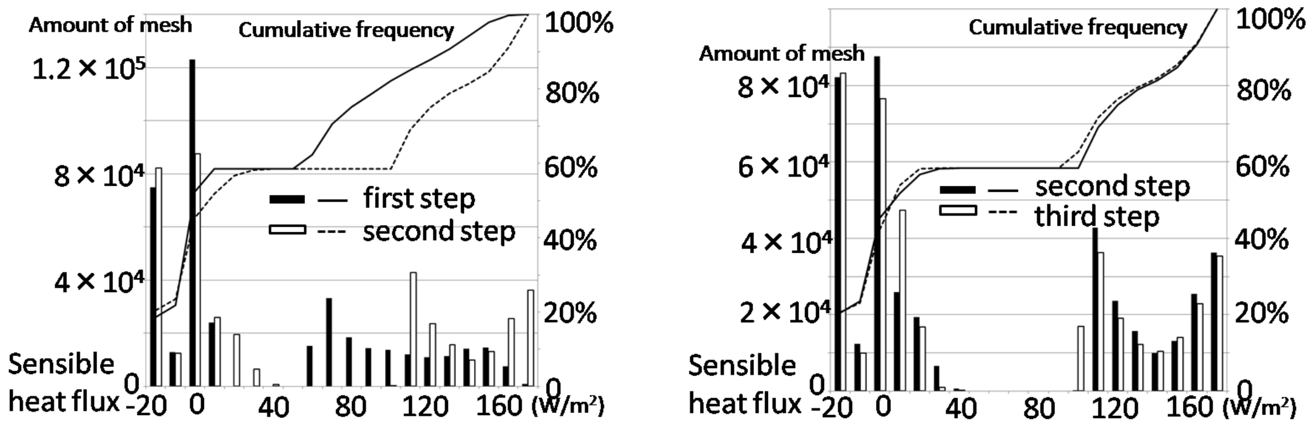

Fig. 4 Comparison of the frequency distribution difference for sensible heat flux due to the number of steps by coupled analysis.

2.5 Outline of simulation examination of prediction formula of CHTC to be applied to High-Re model

The object of simulation is a single apartment of a housing complex located in Tokyo. Since it is desired to reflect the influence of the boundary layer, we used the Low-Re model which finely divided grid near the walls (Fig. 5). Simulation condition is as Table 1 shows. The temperature distribution and wind velocity vector distribution around the building are shown in the Fig. 6.

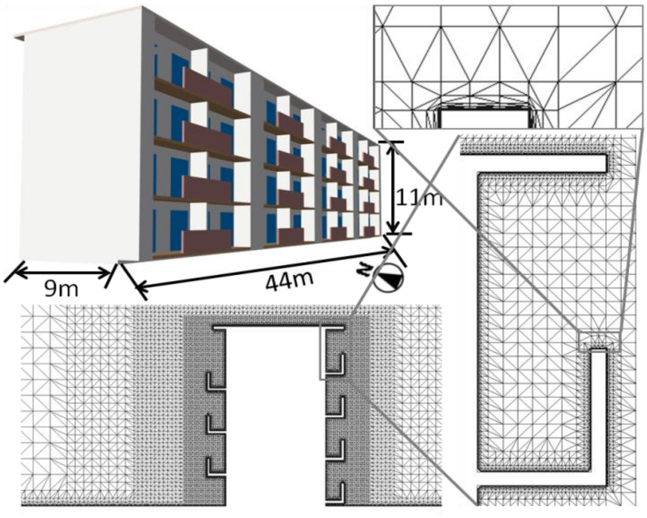

Fig. 5 Grid near the walls of the building in the Low-Re Model.

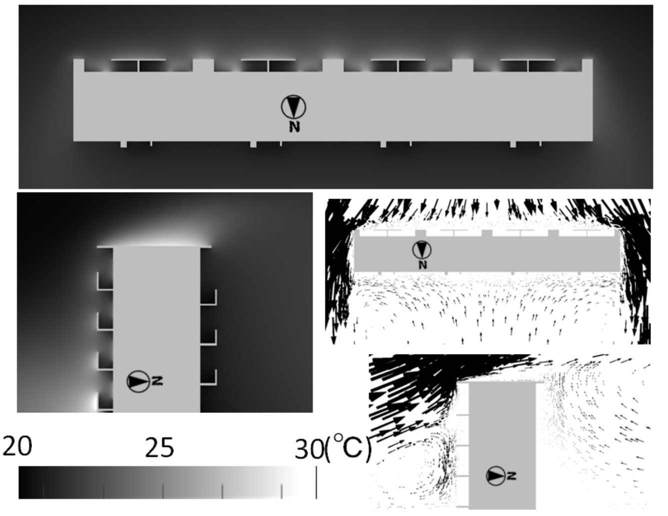

Fig. 6 Air temperature and wind speed horizontal (above ground 6m) and vertical plane (near the center of the building).

Table 1 Simulation conditions.

items \ cases	Case without detail geometries	Case with detail geometries
turbulence model	Lounder-Sharma model	
the number of meshes on the surfaces	about 4 million	about 25 million
mesh size of the vicinity	6.1e-5m	
boundary conditions of ground and walls	No-slip	$q_c=\lambda \ dT/dy$
Algorithm of CHTC	definition formula: $CHTC = \frac{\lambda \ dT/dy}{Tw - Tref}$	
Weather condition	12:00 Nov. 5th 2004 Temp. 20.2°C wind speed at 1.8 times height of the building 2.0m/s	

3. Result

3.1 Influence of the building geometry on the prediction of CHTC and sensible heat flux

We compared the case with detailed geometry and that without detailed geometry. Fig. 7 shows the surface temperature distribution of the windward surfaces on the left and CHTC distribution in the middle and sensible heat flux distribution on the right. In both cases, there is a tendency that CHTC increases from the center bottom of the building to the periphery. By taking into account detail geometry, ventilation in veranda space surrounded by obstacles such as eaves is deteriorated. CHTC of the walls is small. On the vertical eaves of verandas, CHTC is larger than center due to the disturbance of the boundary layer of the edge portion. By taking into account building's material, the surface temperature of wall is higher than that of the windows. The sensible heat flux distribution reflects the effect of both CHTC and surface temperature, so it has the tendency of both CHTC and surface temperature distribution.

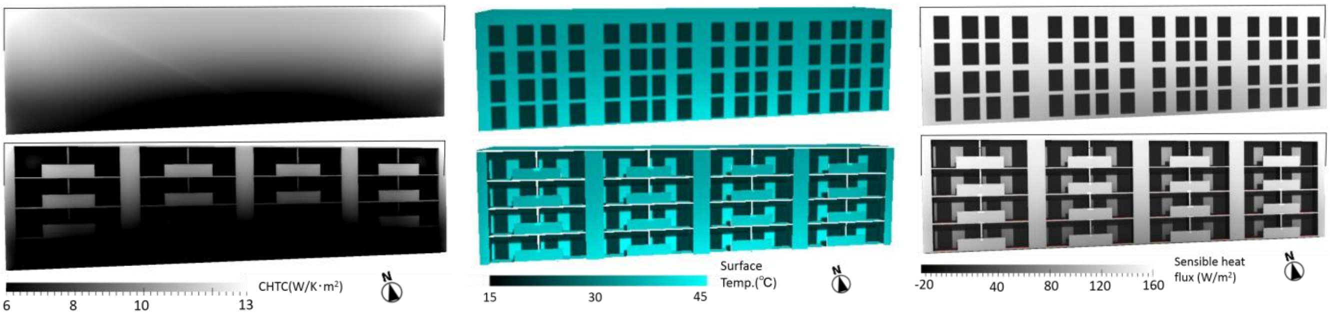

Fig. 7 From left to right, surface CHTC distribution, temperature distribution, sensible heat flux distribution, from top dawn, cases without detail geometries, cases with detail geometries.

Examine on prediction accuracy of CHTC prediction formula

In order to apply for the High-Re model, we examined the relationship between CHTC of building surfaces and the effective wind speed ($U_k=\sqrt{U_x^2+U_y^2+U_z^2+2k}$) (k: Turbulent Energy) above the wall boundary layer which can reflect the disturbance of the wind speed. In situation that forced convection is dominated, the correlation between CHTC and U_k is relatively high. It is because that forced convection derived from wind speed dominates the convective heat transfer on the surfaces. The prediction formula is shown on Fig. 8 and can be applied to the High-Re model.

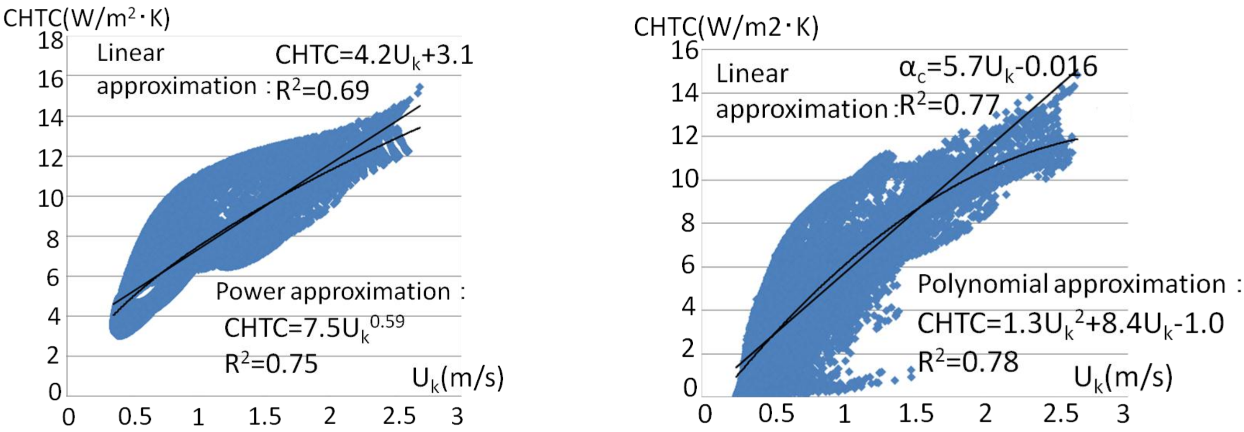

Fig. 8 the relationship between CHTC and Uk, case without detail geometries (left), case with detail geometries (right).

4. Conclusion and Implications

In this study,

1) Firstly, we validated the prediction accuracy of sensible heat flux using the Low-Re model. Then, we examined the prediction method of the sensible heat flux by simulate the target building with full scale. In addition, we confirmed the influence of building geometry on the prediction of sensible heat flux.
2) For CHTC prediction formula, we obtained a relatively high correlation in the forced convection dominated cases. In this situation, the experimental approximation formula obtained from the analysis is considered to be appropriate for the heat flux prediction using the High-Re model for urban block scales, when the wind speed is high so that forced convection is dominated.

References

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