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LES ESTIMATION OF ENVIRONMENTAL DEGRADATION AT THE URBAN HEAT ISLAND DUE TO DENSELY-ARRAYED TALL BUILDINGS

Tetsuro Tamura*, Junichi Nagayama, Kenichi Ohta, Tetsuya Takemi, and Yasuo Okuda[1]
Tokyo Institute of Technology, Yokohama, Japan
[1]Building Research Institute, Tukuba, Japan

1. INTRODUCTION

For the mitigation of heat island effects on coastal cities, it is sometimes expected that the sea breeze come into the inland area of a city, where its cold air mingles with the hotter air over and inside the urban canopies. In the downtown of Tokyo, there exists a coastline at the southeast boundary, so the sea breeze is observed to reach into about 20 km inland. But recently several very tall buildings have been constructed at Shiodome near this coast line between the center of Tokyo and the Tokyo bay. We are concerned about that these tall buildings block a passage of sea breeze into the downtown of Tokyo.

Of course, it is generally thought that the size of heat island phenomenon itself ranges to several tens square kilo-meters with meso-scale behavior, which is ten times larger than the Shiodome area of some square kilo-meters. Such a large discrepancy tends to introduce this local effect to be not serious but trivial. Therefore the treatment to aspect of the ground surface has been thus far very poor. But for the analysis of the heat island, the surface treatment and the area considered should be selected by a significance of phenomenon that each issue encompasses. In such a convection-dominant phenomenon at Shiodome, it is important to focus on details of the very local flow characteristics inside both of the roughness layer and the urban canopies, and to clarify the effect of cold air contained within the sea breeze on heat environment in the downtown of Tokyo.

To solve this issue, we have to formulate the physical model or the numerical model which represents correctly aspect of the ground surface condition consisting of buildings, structures and vegetation et al. In order to get the data for building shapes in a local area, the electronic mapping information is utilized. The present study uses height data of surface roughness and expresses directly surface shapes of urban area for the numerical simulation. The previous numerical simulation of the boundary layers usually has employed the log law model, or sometimes a little sophisticated version such as the wall layer model for the treatment of the ground surface condition. It means that the integral quantities are utilized for representing total boundary effects, but not local effects. Recent data for building height determining the surface roughness are much improved and have a horizontal resolution with about 2 or 2.5 m, so it might be enough to simulate roughness shapes, even an individual residential house, placed on the ground surface in urban areas.

Further, in the case of the numerical simulations for winds in urban canopies, which need to deal with details of existing flows throughout spaces between buildings, so the RANS (Reynolds averaged Navier-Stokes) technique might have advantage to compute the flow field highly resolved by the grid from standpoints for computer capacity. However, in the case that we focus on the roughness layer or inside the urban canopies, the flow in this near-wall region is very complicated and unsteady due to separation, vortex-shedding, rapid flow contraction and extension among roughness elements. Nevertheless, the complete RANS modeling of turbulence has not been developed yet for such a complex flow. Also, for the estimation of mitigation of heat island effect by utilizing the local area circulation, the numerical model which can predict time sequential turbulence is appropriate, because the convection by fluctuating behavior of turbulent flows represents directly and strictly a scale or a range of heat transport. Hence this study employs the LES (large eddy simulation) technique, which is applied to the wind flow over actual roughened ground surface in Tokyo area. For the horizontal inflow boundary condition of the computational domain at the Shiodome area of 1 km by 1.5 km, turbulent flow data such as wind velocity or temperature are imposed by taking into consideration existence of the sea upstream. For the generation of inflow turbulence, we additionally set up the driver domain of 1 km by 2.5 km and solve a spatially developing turbulent boundary layer over smooth sea surface by applying the quasi-periodic condition based on the rescaling technique for smooth wall without any surface deformation.

According to the previous study, the field measurement around the Shiodome area showed that the extreme reduction of wind velocity behind a group of tall buildings. We compare the LES results with these field measurement data and validate the LES model.

Next, we show the wind flow characteristics around tall buildings at the Shiodome area. Especially

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* *Corresponding author address*: Tetsuro Tamura, Dept. of Environmental Science and Technology, Tokyo Institute of Technology, G5-7, 4259 Nagatuda, Midori-ku, Yokohama 226-8502, Japan; e-mail: tamura@depe.titech.ac.jp

we bring into focus the turbulence structures in the roughness layer and the urban canopies.

Finally, based on these results at the Shiodome area, we investigate the environmental aspects at the urban heat island due to densely-arrayed tall buildings.

2. PROBLEM FORMULATION

2.1 *Governing Equations*

In this study, we carry out large-eddy simulation (LES) analysis of spatially-developing turbulent boundary layers. Under the Boussinesq approximation, the filtered governing equations consist of the Navier-Stokes equations, the continuity equation and the temperature equation for three dimensional incompressible stratified flow as follows:

$$\frac{\partial \bar{u}_i}{\partial t}+\frac{\partial \bar{u}_i\bar{u}_j}{\partial x_j}=-\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_j}+\frac{1}{Re_\tau}\frac{\partial}{\partial x_j}\left(\frac{\partial \bar{u}_i}{\partial x_j}+\frac{\partial \bar{u}_j}{\partial x_i}\right)-\frac{\partial \tau_{ij}}{\partial x_j}+Ri_b\bar{\theta}\delta_{i3}, \tag{1}$$

$$\frac{\partial \bar{u}_i}{\partial x_i}=0 \quad , \quad \frac{\partial \bar{\theta}}{\partial t}+\frac{\partial \bar{u}_j\bar{\theta}}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\frac{1}{Re_\tau}\frac{1}{Pr}\frac{\partial \bar{\theta}}{\partial x_j}\right)-\frac{\partial h_j}{\partial x_j} \quad ,$$

where t, u_i, p, θ, $Re_\tau=u_\tau\delta/\nu$, $Ri_b=\nu\beta\Delta\theta\delta/u_\tau^2$ and $Pr=\nu/\alpha$ denote time, velocity, pressure, temperature, the Reynolds number, the bulk Richardson number and Prandtl number (u_τ : friction velocity, δ : boundary layer depth, β : thermal expansion coefficient, ν : eddy viscosity, α :coefficient of thermal diffusivity, g : gravity acceleration), respectively. $\bar{u}_i=(\bar{u},\bar{v},\bar{w})$ are the filtered components of the velocity vector. The quantities τ_{ij} and h_j are the subgrid-scale (SGS) stress and heat flux, respectively as follows:

$$\tau_{ij}=\overline{u_iu_j}-\bar{u}_i\bar{u}_j \quad , \quad h_j=\overline{u_j\theta}-\bar{u}_j\bar{\theta} \quad . \tag{2}$$

2.2 *Sub-grid Scale Modeling*

In this study, the SGS closure is performed by a Smagorinsky-type concept for eddy viscosity (ν_t : turbulent viscosity, α_t : turbulent thermal diffusivity) as follows:

$$\tau_{ij}-\frac{1}{3}\delta_{ij}\tau_{kk}=-2\nu_t\bar{S}_{ij}=-2C\bar{\Delta}^2\left|\bar{S}\right|\bar{S}_{ij} \quad , \tag{3}$$

$$h_j=-\alpha_t\frac{\partial \bar{\theta}}{\partial x_j}=-C_\theta\bar{\Delta}^2\left|\bar{S}\right|\frac{\partial \bar{\theta}}{\partial x_j} \quad , \tag{4}$$

where C and C_θ denote the model coefficients for SGS modeling of velocity and temperature fields respectively, S_{ij} the strain rate tensor, and $\bar{\Delta}=\left(\bar{\Delta}_x\bar{\Delta}_y\bar{\Delta}_z\right)^{1/3}$ grid-filter width, respectively. This Smagorinsky-type model can be extended to the dynamic Smagorinsky model, in which the model coefficients C and C_θ are evaluated dynamically using the Germano identity.

2.3 *Numerical Model*

Figure 1 illustrates a numerical model for the simulation of urban boundary layers at Shiodome area, where the south-southeast inflow corresponding to the sea breeze is given. A large eddy simulation of the spatially developing smooth-wall turbulent boundary layer, which has no pressure gradient, is formulated utilizing the technique of the quasi-periodic boundary condition (Lund et al. 1998[1]). In this model, we set up the computational domain which consists of two parts: one is a main region for the simulation of the flow field over the Siodome area, where many high-rise buildings densely locate at the center of the main region; and the other is a driver region for the auxiliary simulation for generating inflow turbulence for the main region. In the driver region, the variables at a single y-z section are rescaled according to the development ratio of the boundary layer thickness and friction velocity along the streamwise direction and reintroduced at the inflow boundary. The velocity profile at the inflow boundary is reset based on the law of the wall in the inner region or defect law in the outer region. This process allows the generation of spatially developing neutral turbulent boundary layer with a small computational domain. The driver computational region is set to be $5\delta_0$*$1.6\delta_0$*$2\delta_0$ (δ_0 =500[m] is the boundary layer thickness at the inflow boundary.), with corresponding grid numbers of 156, 100 and 400 in the streamwise (x), wall-normal (z) and spanwise (y) directions, respectively. The mesh widths are (Δx^+, Δz^+, Δy^+) = (18.9, 2.95 ~ 26.6, 2.95). The main computational region is set to be $3\delta_0$, $1.6\delta_0$, $2\delta_0$ in x, z and y directions, with the same resolutions as those for the driver region except for Δx^+ = 2.95.

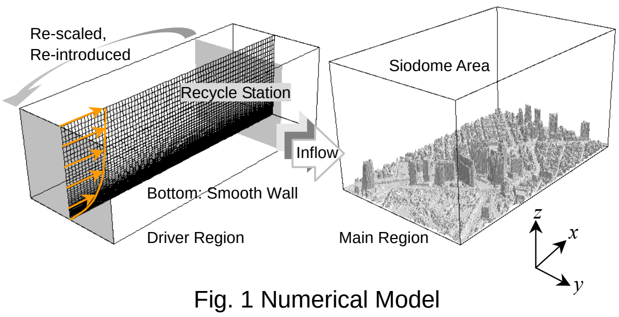

Fig. 1 Numerical Model

As a first step we assume that temperature is dealt with a passive scalar and hence buoyancy effects are neglected. It is because we find out how the heat generated from the building group moves by the sea breeze at the Siodome area. In the main region, the passive scalar with a value of unity is given at the surfaces of a group of high-rise buildings as a boundary condition. Accordingly we set Ri_b to be zero and Pr=0.5. Also, we set Re_τ to be 590.

2.4 *Numerical Method*

The numerical method used is based on a MAC method for the main region and a fractional step method for the driver region. For a time advancing, the Adams-Bashforth method for convection terms and the Crank-Nicolson method for diffusion terms are employed. The spatial derivatives are approximated by the second-order central difference for the driver region and fourth-order central difference for the main region. The boundary conditions for velocity and passive scalar are shown in Table1.

Table1 Boundary conditions

Velocity	Driver	Main
Bottom	No-slip	No-slip
Top	$\partial u/\partial z=0$, $w=U_\infty d\delta^*/dx$	Free-slip
Spanwise	Periodic	Periodic
Inflow	Rescaled velocity	Velocity at x/δ= 4.8 in the driver region
Outflow	$\partial/\partial t+c\partial/\partial x=0$	$\partial/\partial t+c\partial/\partial x=0$

Passive Scalar

All of Boundary	Neumann Condition

where, δ^* is the displacement thickness, c is taken to be the bulk velocity.

3. COMPARISON WITH OBSERVATION DATA

Here, there is the observational data[2] [3] obtained by casting up the pilot balloon at three observation points (see Fig.2). Wind velocity was measured by trajectory of the ascending pilot balloon in daytime, sunny, July 28, 2005. The surface aspect of the Siodome area has different type at three locations: the south location where the influence of the building group on the wake flow is insignificant, the west where the influence is considered to be significant, and the north where the influence is so strong and wind field is much changed.

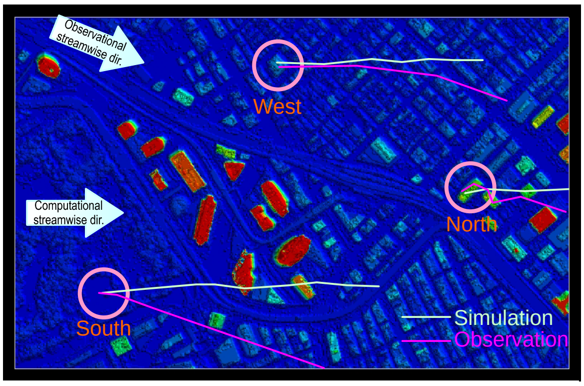

Fig. 2 Trajectory of pilot balloon in the main region

To compare our computed result with this observational data, we also calculated the trajectory of the balloon according to the following motion equations, and obtained the instantaneous velocity at each height where balloon exists:

$$\begin{aligned} m\ddot{x} &= \rho(u-\dot{x})v_r A C_D/2 \quad , \\ m\ddot{y} &= \rho(v-\dot{y})v_r A C_D/2 \quad , \\ m\ddot{z} &= -mg+\rho(w-\dot{z})v_r A C_D/2 + B \quad , \end{aligned} \tag{5}$$

where $x, y, z, mg, \rho,$ $v_r=\sqrt{(u-\dot{x})^2+(v-\dot{y})^2+(w-\dot{z})^2}$ A, C_D=0.4, B=mg-$W_t^2\rho A C_D/2$, denote the balloon

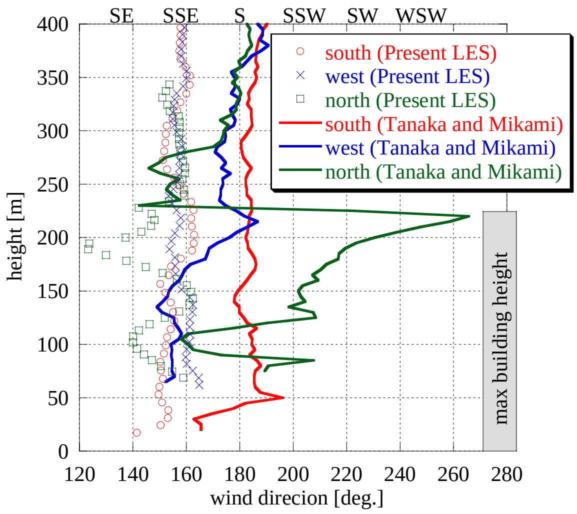

Fig. 3 Vertical profile of wind direction

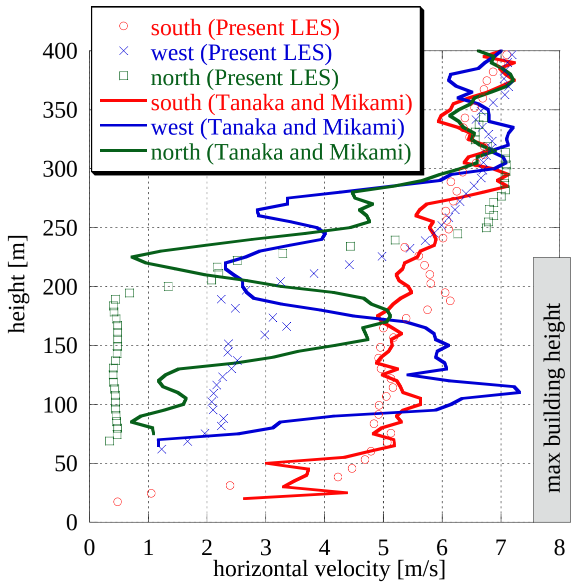

Fig. 4 Vertical profile of horizontal velocity

position, the gravity force, the air density, relative velocity of the balloon to the wind velocity, the cross section area of the balloon, the drag coefficient and buoyant force. W_t is assumed to be 2.5 [m/s] as the constant ascending (or terminal) velocity.

Figures 3 and 4 show the profile for the wind direction and horizontal velocity respectively, together with the observational result. In spite of the difference of the inflow between the observation and the simulation, the vertical profiles of the simulated wind directions and horizontal velocity are reasonably consistent with the observation results at the south of the building group. On the LES results at the west side and the north side, both velocity and direction of the wind are much decreasing around a top of tall buildings like the observation data. But below the maximum building height both of the LES and the observation data are relatively different from each other. Especially, in the LES results, the inflow is completely shielded by the buildings and the velocity extremely decreases to about 8 % and is almost constant below the buildings height at the leeward region. On the other hand, the observation data shows a rapid increase of velocity in the limited location. At the west side, the horizontal velocity fluctuates more unsteadily than LES results.

4. WIND FLOW CHARACTERISTICS

Based on the flow visualization, it can be seen that very complicated but specified wind flow patterns are formed in the wake of a group of tall buildings, and these patterns vary in the vertical direction. These flow patterns may be thought to strongly affect the formation of thermal environment.

Figure 5 illustrates the LES results for instantaneous streamwise velocity field in various cross-sections. We can find that all buildings at Siodome are completely embedded in the turbulent boundary layer. Figure 6 and 7 illustrate instantaneous streamwise velocity in a vertical (shown by a broken line in Figure 7) and horizontal cross section of a group of tall buildings at the altitude of 90 meters. It can be recognized that the streamwise velocity entirely decreases on the leeward of buildings. But we also find a path with strong wind among the building group. So, this means instantaneous strong wind sometimes happens in the wake. It can be seen in the horizontal section that there is a widely extending region with a low velocity inside of the building group and high velocity region among a complex arrangement of buildings.

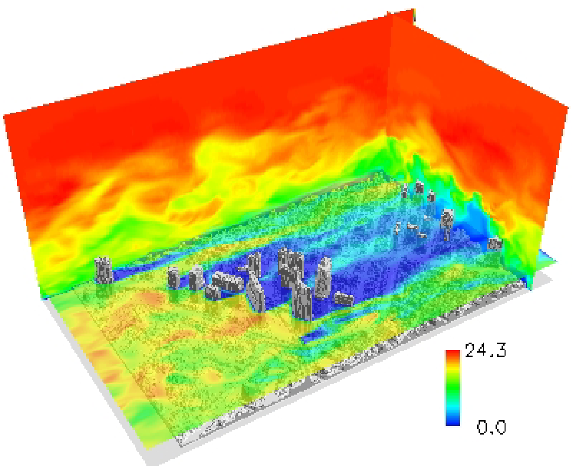

Fig. 5 Turbulent boundary layer over Shiodome area

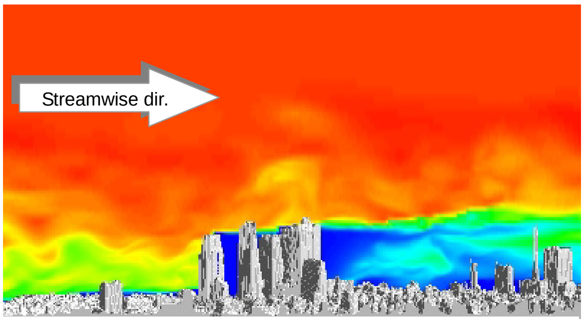

Fig. 6 Instantaneous streamwise velocity in a vertical cross section of tall buildings

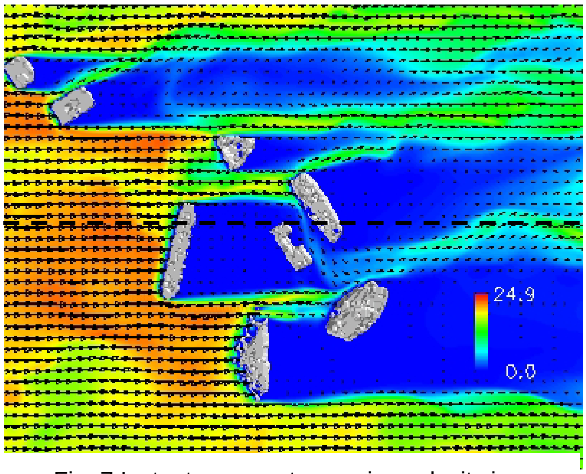

Fig. 7 Instantaneous streamwise velocity in a horizontal cross section of tall buildings

5. CONVECTION AND DIFFUSION OF HEAT

In view of accurate estimation for Heat Island degradation, it is necessary to discuss the convection and diffusion of heat. As the first stage, we used a passive scalar in which the buoyancy is not considered, and set it on the surface of the building group as heat sources. Figure 8 shows a location of the setting passive scalar at initial stage. Figure 9 depicts the heat (passive scalar) transfer. It can be seen that the passive scalar is convected far away at a higher position. While a below the buildings, passive scalar is not transported so much by the effect of the blocking sea breeze. Also we can see that a passive scalar

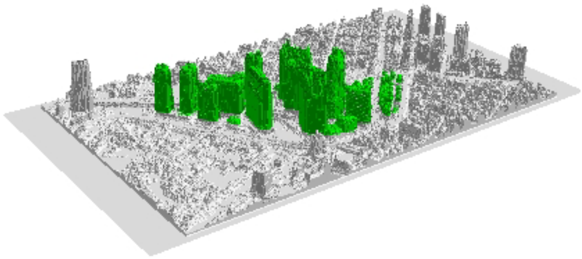

Fig. 8 Initial stage of passive scalar on the surface of tall buildings

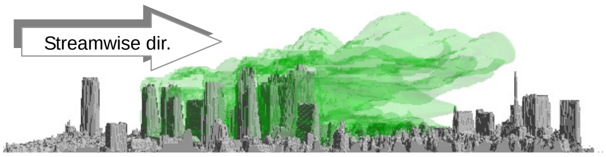

Fig. 9 Aspect of the heat (passive scalar) transfer

has stagnated in the building group because the cavity region is formed among the building group. In spite of no effect of the buoyancy, passive scalar diffuses largely in the upward as well as the streamwise direction.

6. CONCLUSIONS

In this study, for the estimation of environmental degradation at the urban heat island due to densely arrayed tall buildings, we conducted LES for turbulent flow and temperature fields around a group of tall buildings near the sea. The following results are obtained.

In comparison with field measurement data, we have validated that the reasonably good results can be obtained by the present LES method.

According to the LES results for turbulent flows in the roughness layer over a city and the urban canopies, it is recognized that the flow velocity extremely decreased behind the building blocks. Accordingly we can easily imagine the occurrence of the environmental degradation for the thermal condition due to densely arrayed tall buildings. Also, we can find the very special aspect such as the steady patterns of a path with strong wind in the wake of a group of tall building.

By the passive scalar (temperature) analysis from the heat sources on the surface of the building blocks, we can find the heat has been convected and diffused largely behind a group of tall buildings. For the accurate estimation of thermal environment, we need the detailed analysis, for example, the buoyancy effect incorporated.

7. REFERENCES

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