LES of wind turbulence and heat environment around dense tall buildings

Tsuyoshi Nozu¹, Takeshi Kishida², Tetsuro Tamura³, Yasuo Okuda⁴, Hiroko Umakawa⁵

¹Shimizu Corporation, nozu@shimz.co.jp
²Wind Engineering Institute, kishida@wei.co.jp
³Tokyo Institute of Technology, tamura@depe.titech.ac.jp
⁴Building Research Institute, y_okuda@kenken.go.jp
⁵Pasco Corporation, haiwra9288@pasco.co.jp

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ABSTRACT

We have conducted LES (Large Eddy Simulation) simulation, focusing on local heat environment in the urban area. For estimating the reference absolute values (wind velocity and temperature) of LES, we proposed the computational model for hybrid method of LES and meso-scale meteorological model (MM5). We clarified that the heat convection as a result of mixing is active vertically and the high temperature region is recognized even at a high position in a large cavity formed behind dense tall buildings, and we showed that the hybrid method is a powerful tool for predicting of the wind turbulence and the heat environment in the urban area.

1. INTRODUCTION

For the mitigation of heat island effects on coastal cities, it is expected that the sea breeze comes into the inland area of a city, where its cold air mingles with the hotter air over and inside the urban canopies. Therefore, it is important not to allow such a sea-breeze penetration to be obstructed by large-scaled buildings and structures on the ground surface. But recently several very tall buildings have been constructed in a concentrated manner near the coast line in Tokyo, so we are concerned about that these tall buildings block a current of sea breeze into a central region of a city and amplify
a heat-island effect on whole region of an urban city as well as a restricted area around tall buildings. The area where very tall buildings are built is small, so there remain unclear whether such an effect has been spread on the whole city. But we think that at least the implementation of an appropriate heat environment on the local area based on the specified re-developing project should be advanced in view of an urban planning.

For the numerical simulation to evaluate a local thermal environment in such a part of an urban region, it is important to reproduce the complex flows among many buildings and their wakes. Especially, for estimating the mitigation of heat-island effect by the meteorological local circulation such as a sea breeze, the numerical model which can predict time sequences of unsteady flow quantities is required because the convection brought about by fluctuation behavior of turbulent flows can represent directly and strictly an intense and a range of heat transport. Hence, this study does not use the RANS (Reynolds Averaged Navier-Stokes) type modeling, but employs the LES (Large Eddy Simulation) technique for wind flow accompanied with heat around dense tall buildings existing in the urban area. Also, determination of the reference absolute values for the simulated wind velocity and temperature is supported by the numerical result obtained by the meso-scale meteorological model. The relation between the heat environment and wind turbulence around these buildings has been clarified. Accordingly we investigate details of a local thermal environment and indicate a dominant role of the surface shape and its thermal condition of a city from an environmental point of view.

The main objective of this study is to provide the new sophisticated LES model combined with the meso-scale meteorological model for predicting the wind turbulence and the heat environment in the urban area, and a new boundary treatment of heat on the urban surface using the radiation temperature distribution surveyed by aircraft. Also, availability and effectiveness of the presented numerical model are discussed in detail.

2. PROBLEM FORMULATION

2.1 Governing Equations

In this study, we carry out 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:

\[
\frac{\partial \tilde{u}_i}{\partial x_i} = 0
\]  

\[
\frac{\partial \tilde{u}_i}{\partial t} + \frac{\partial \tilde{u}_i \tilde{u}_j}{\partial x_j} = -\frac{1}{\rho} \frac{\partial P}{\partial x_i} + \frac{1}{Re} \frac{\partial}{\partial x_j} \left( \frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i} \right) - \frac{\partial \tau_{ij}}{\partial x_j} + R_{ib} \tilde{\theta} \delta_{ij}
\]  

\[
\frac{\partial \tilde{\theta}}{\partial t} + \frac{\partial \tilde{u}_i \tilde{\theta}}{\partial x_i} = \frac{\partial}{\partial x_j} \left( \frac{1}{Re Pr} \frac{\partial \tilde{\theta}}{\partial x_j} \right) - \frac{\partial h_j}{\partial x_j}
\]  

where \( t, u_i, p, \theta, Re = u_{ref} \delta / \nu, Ri_b = g \beta \Delta \theta \delta u_r^2 \) and \( Pr = \nu / \alpha \) denote time, velocity, pressure, temperature, the Reynolds number, the bulk Richardson number and Prandtl number (\( u_r \): friction velocity, \( \delta \): boundary layer depth, \( \beta \): thermal expansion coefficient, \( \nu \): eddy viscosity, \( \alpha \): coefficient of thermal diffusivity, \( g \): gravity acceleration), respectively. \( \tilde{u}, \tilde{\theta}, \tilde{p} \) are the filtered components of the velocity vector. The quantities \( \tau_{ij} \) and \( h_j \) are the subgrid-scale (SGS) stress and heat flux, respectively as follows:
\[ \tau_y = u_i u_j - \bar{u}_i \bar{u}_j , \quad h_j = u_j \bar{\theta} - \bar{u}_j \bar{\theta} \]  

(4)

2.2 Sub-grid Scale Modeling

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

\[ \tau_y - \frac{1}{3} \delta_y \tau_{kk} = -2 \nu_S \bar{S}_y = -2 C_\Delta \left| \bar{S}_y \right| \]  

(5)

\[ h_j = -\alpha_t \frac{\bar{\theta}}{\partial x_j} = -C_\theta \Delta^2 \left| \bar{S} \right| \frac{\bar{\theta}}{\partial x_j} \]  

(6)

where \( C \) and \( C_\theta \) denote the model coefficients for SGS modeling of velocity and temperature fields respectively, \( S_y \) the strain rate tensor, and \( \Delta = \left( \Delta_x, \Delta_y, \Delta_z \right) \) grid-filter width, respectively. This Smagorinsky-type model can be extended to the dynamic Smagorinsky model (Germano et al., 1991), in which the model coefficients \( C \) and \( C_\theta \) (Tamura & Mori, 2006) are evaluated dynamically using the Germano identity.

\[ C = -\frac{\left( L_y M_y \right)}{\left( M_y M_y \right)} , \quad L_y = \bar{u}_i \bar{u}_j - \bar{u}_i \bar{u}_j , \quad M_y = 2 \left( \Delta^2 \left| \bar{S}_y \right| - \Delta \bar{S}_y \right) \]

(7)

\[ C_\theta = -\frac{\left( P_j Q_j \right)}{\left( Q_j Q_j \right)} , \quad P_j = \bar{u}_j \bar{\theta} - \bar{u}_j \bar{\theta} , \quad Q_j = \Delta \left| \bar{S} \right| \frac{\bar{\theta}}{\partial x_j} - \Delta \bar{S} \frac{\bar{\theta}}{\partial x_j} \]

(8)

3. PROPOSAL OF A NEW LES-METEOROLOGY MODEL

The meso-scale simulation of the summer land and sea breeze in the Tokyo district is conducted by using MM5, and the prevailing wind direction and vertical profile of the temperature in this area are picked out. The detail model configurations used in MM5 are summarized on Table 1, and domains of simulation and terrain height are shown in Figure 1. The MM5 simulation is performed with the 2-way nesting for two domains gradually focusing on Tokyo area. The first domain size is 402km x 402km with grid resolution of 3km and the second domain size is 103km x 103km with grid resolution of 1km. The simulation period is from August 6th 2006 at 09 JST to August 11th 2006 at 09 JST. The Figure 2 shows the temperature profile of MM5 simulations under stable stratification on August 6th at 14 JST.

Figure 3 illustrates a schematic of the computational model for hybrid method of LES and meso-scale meteorological model (MM5) concerning an urban heat island. For generating turbulent boundary layer under stable stratification based on the sea breeze characteristics, we set up the driver region that consists of two domains (Domain1 and Domain2). Domain1 generates the neutral turbulent boundary layer over rough wall by using re-scaling technique (Lund et al. 1998; Nozawa & Tamura, 2002). Rough wall is covered with roughness blocks which are represented by the forcing technique (Goldstein et al., 1993). Domain2 generates thermally stably-stratified turbulent boundary layer developing over the sea surface by using the temperature profile calculated by MM5. Domain3 reproduces the main region in Tokyo area of 1.75 km by 1.0 km and the boundary condition at ground surface is set with the GIS data, which can represent the realistic urban aspect with tall buildings in Tokyo. Table 2 shows the domain size, grid points and grid size for the computational domain.
Table 1: Model configuration and input data used in MM5.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Details</th>
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</thead>
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<tr>
<td>Meteorology model</td>
<td>PSU/NCAR MM5 version 3.7.2</td>
</tr>
<tr>
<td>Period</td>
<td>09JST on 6 to 09JST on 11 August 2006</td>
</tr>
<tr>
<td>Input data</td>
<td>JMA 6-hourly 10km x 10km Meso Analysis</td>
</tr>
<tr>
<td>Elevation data</td>
<td>USGS 30-sec (inner grid)</td>
</tr>
<tr>
<td>Sea surface temperature</td>
<td>Weekly NOAA OI SST V2</td>
</tr>
<tr>
<td>Computational domain</td>
<td>Domain 1:402km (3km)</td>
</tr>
<tr>
<td></td>
<td>Domain 2:103km (1km)</td>
</tr>
<tr>
<td>Vertical layer</td>
<td>28 vertical sigma levels (Surface to the 100hPa)</td>
</tr>
<tr>
<td>Vertical turbulence</td>
<td>Modified Mellor–Yamada level 2.5 closure scheme</td>
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<tr>
<td>Cloud microphysics</td>
<td>Reisner</td>
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<tr>
<td>Soil model</td>
<td>5-layer soil model</td>
</tr>
<tr>
<td>Atmospheric Radiation</td>
<td>Dudhia (Short and long wave radiation)</td>
</tr>
</tbody>
</table>

Figure 1: MM5 domain configuration and terrain height.

Figure 2: Temperature profile on August 6\(^{th}\) at 14 JST.
For setup of temperature boundary conditions on the ground and building surface, the radiation temperature measured by aircraft is utilized (see Figure 4). By filtering the surface temperature field and quantifying approximately it based on the near-ground air measurement temperature, the temperature boundary conditions on the ground and building surfaces are given.

Wind and temperature fields with the urban scale can be simulated by the meso-scale meteorological model, while turbulent flow fields over and inside the urban canopy can be computed by LES that incorporates explicitly the effects of the actual shape for buildings and structures. Generally, LES can estimate the relative value for the wind flow to the reference value but cannot evaluate the absolute value. So, by using the simulated results of MM5, we give a temperature profile at inlet of the stable turbulent boundary layer in Domain2 and estimate a level of the actual wind velocity.

Figure 3: Schematic of the computational model for hybrid method of LES and meso-scale meteorology model concerning urban heat island.

Table 2: Computational domain, grid points and grid size.

<table>
<thead>
<tr>
<th></th>
<th>Streamwise(x)</th>
<th>Vertical(y)</th>
<th>Spanwise(z)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computational domains</td>
<td>5.0δ + 4.1δ + 3.5δ</td>
<td>1.6δ</td>
<td>2.0δ</td>
</tr>
<tr>
<td>Grid points</td>
<td>156 + 151 + 700</td>
<td>100</td>
<td>400</td>
</tr>
<tr>
<td>Grid size (wall unit)</td>
<td>18.9 + 18.9 + 2.95</td>
<td>2.95–26.6</td>
<td>2.95</td>
</tr>
</tbody>
</table>
4. RESULTS

Figure 5 shows the time history of field measurement data and results of MM5 simulation at about 200m height. On the whole, the wind velocity and wind direction simulated by MM5 are in good agreement with the field measurement data, but the measurement wind velocity at rooftop of the tall building is smaller than other data in the wind direction affected by its own building.

Figure 6 illustrates the profile of wind velocity. The wind velocity near the ground of MM5 simulation is smaller than those of other cases, because the MM5 simulation has used a constant roughness length for representing roughness effect and that can not fully reproduce the roughness effect of buildings in an urban area. However, it is expected that the wind velocity simulated by MM5 can be reproduced at higher position above the urban canopy. Therefore, we determined a reference absolute wind velocity of LES at a height of about 300m for coupling LES and MM5. On the other hand, LES profile is in good agreement with the profile of the field measurement data.

Figure 5: Time history of field measurement data and MM5 on August 6th - 10th, 2006.
Figure 6: The profile of wind velocity on August 6\textsuperscript{th} at 14 JST.

Figure 7 illustrates the LES results for instantaneous streamwise velocity and temperature fields in a vertical section of around dense tall buildings. In this figure, it can be confirmed that dense tall buildings block a current of sea breeze into the urban area and a kind of large cavity region is formed behind these tall buildings. In this cavity region, the heat convection as a result of mixing is active vertically and the high temperature region is recognized even at a high position.

Figure 7: Instantaneous streamwise velocity and temperature field in the roughness layers over the actual city.
Figure 8 shows time-averaged streamwise velocity field and temperature field in vertical section and horizontal section at 60m height. It is recognized that the high temperature region behind a single tall building is small because of a small wake formed behind that, but the high temperature region behind a group of tall buildings is very large because of a merging large wake formed behind such an assembly. The extent of the impact for the heat environment reaches at about 300m downstream behind dense tall buildings and is nearly equal to the height of the buildings. While, at the side of the group of tall buildings, the cooling effect by sea breeze can be seen because of the high wind speed.

Figure 9 shows time histories of the wind velocity and temperature in various local points at 65m height. Temperature is transformed to dimensional temperature by comparison of maximum/minimum value between the filtered radiation temperature (see Figure 4(b)) and the field measurement data (Tanaka & Mikami; Mikami & Tanaka, 2005). Above low and medium-rise buildings (outside dense tall buildings), the wind velocities are higher than those inside dense tall buildings, and temperatures are lower than those inside ones. In contrast, inside dense tall buildings,
the penetration of a sea breeze between buildings does not advance efficiently in spite of a sufficiently large wind speed fluctuation. Accordingly the temperature magnitudes become higher and their fluctuations are relatively small, as a result of the small heat convection and diffusivity. On the other hand, in the wake behind dense tall buildings, the wind speed level and its fluctuation are very small and the temperature maintains the highest value as a result of heat stagnation.

Figure 10 illustrates instantaneous temperature fields in some vertical sections. It is confirmed that the thermal boundary layer with high temperature develops as the cold wind comes into inside of the city. However, the large green area at left side of windward inhibits the growth of thermal boundary layer with high temperature.

![Figure 9: Time histories of the wind velocity and temperature in various local points at 65m height](image)

![Figure 10: Instantaneous temperature fields in some vertical sections.](image)
5. CONCLUSIONS

In this study, we provided the new sophisticated LES model combined with the meso-scale meteorological model and a new boundary treatment for temperature on the ground and building surfaces. The obtained results are summarized as follows.

1. It was shown to be able to set up easily the temperature boundary conditions of the various land cover surfaces in urban area by using the radiation temperature measured by aircraft.
2. We found that the high temperature region behind a group of tall buildings was very large because of a merging large wake formed behind these tall buildings and the extent of the impact for the heat environment reached at about 300m downstream behind dense tall buildings.
3. We showed it possible to clarify exactly the physical mechanism of the interaction of the effect of the meteorological local circulation such as a land-sea breeze and that of exhaust heat from urban area by using the hybrid method of LES and meso-scale meteorological model.

REFERENCES

Tanaka H., Mikami T. Private Communication