PREDICTION OF SENSIBLE HEAT FLUX FROM BUILDINGS AND URBAN SPACES USING A DETAILED GEOMETRY MODEL OF A SUBSTANTIAL URBAN AREA

INTRODUCTION OF A PREDICTION MODEL OF ANTHROPOGENIC HEAT INTO AN URBAN HEAT BALANCE SIMULATION MODEL

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Abstract

The present study improves an urban heat balance simulation model for urban micro-scale, so as to predict anthropogenic heat released from buildings, as well as surface sensible heat flux in an urban area. The proposed system combines the urban heat balance simulation with a building thermal simulation and a building energy simulation. The simulation system is applied to a substantial urban area in Tokyo, and the applicability of the proposed simulation model to the analysis of sensible heat flux in the area is examined.

Key words: surface heat flux, anthropogenic heat, simulation model

1. INTRODUCTION

Urban surfaces are covered with various materials, buildings with complex geometries, and vegetation. The nature of the surface and its temperature strongly affects the behavior of the lowest layers of the atmosphere. In addition, energy consumption in an urban area causes anthropogenic heat to be released into the atmosphere, and the heat and energy balance in the area are strongly related. The anthropogenic heat released from buildings depends on various factors, including building use, building thermal performance, and building equipment (such as HVAC systems). Estimating the sensible heat flux from buildings and urban spaces, taking into account the detailed conditions of urban surfaces and building energy consumption, is important when analyzing the urban thermal environment and micro-climate.

In a previous study, the authors developed a heat balance simulation model that can predict the surface temperature distribution in urban blocks using a 3D CAD (computer-aided design) system (Asawa, 2008). The previous simulation model is a micro-scale model in an urban canopy using a detailed geometry model of an urban block.

The present study improves the previous simulation model, so as to predict anthropogenic heat released from buildings, as well as surface sensible heat flux derived from convective heat transfer to/from building and ground surfaces. The proposed simulation model is expected to be applicable to the assessment of urban development and regeneration projects with respect to the urban and atmospheric thermal environments.

2. OUTLINE OF THE SIMULATION SYSTEM

2.1. Outline of the development

The proposed simulation system can treat detailed geometry and materials that exist in an urban area and can calculate heat balance and heat transfer in the urban canopy (Fig. 1). The interaction between the outdoor heat balance and building energy consumption is also considered. The proposed system is constructed based on a 3D CAD system, which can integrate various properties with a geometry model and can translate geographic information system (GIS) data into the geometry model for simulation. The subject spatial scale of the proposed simulation system is set to an ordinary urban block (within approximately 20 hectare). The applied mesh size is set to range from 200 mm to 400 mm, so as to correspond to the detailed geometry of buildings. Fig. 2 shows the structure of the proposed simulation system.

2.2. Simulation of surface temperature distribution and surface sensible heat flux

Surface temperature distribution and surface sensible heat flux are calculated by heat balance and heat
transfer simulation in an urban canopy using an urban heat balance simulation model we developed in a previous study (Asawa, 2008). The surface sensible heat flux in an urban area is estimated by summing the convective heat flux for all surfaces included in the area. The total (area-averaged) heat flux is an index for the influence of urban surfaces on the atmospheric thermal environment. The authors also proposed the heat island potential (HIP), which is expressed as the measure of a temperature, for the evaluation of surface sensible heat. The heat exchange between the urban canopy and the atmosphere above the canopy will be examined in a future study.

2.3. Simulation of building energy consumption and anthropogenic heat in an urban block

Energy consumption and anthropogenic heat in an urban block are calculated by coupled simulation of the urban heat balance simulation model and the building thermal simulation model. The calculations are implemented for each building, taking into account the building use, building thermal performance, building equipment, and surrounding conditions. This coupled simulation model considers the actual conditions of a substantial urban block and calculates the total energy consumption and anthropogenic heat in the area.

3. NUMERICAL SIMULATION MODEL

3.1. Urban heat balance simulation

Heat balance in an outdoor space affects not only the formation of the outdoor thermal environment but also the building cooling/heating load. The urban heat balance simulation model calculates heat balance and heat transfer (direct solar radiation, sky solar radiation, reflected solar radiation, atmospheric radiation, exchange of longwave radiation with the surroundings, convective (sensible) heat transfer, latent heat transfer, conductive heat transfer) for all surfaces in an urban area (Table. 1). The surface temperature distribution and surface sensible heat flux are output successively during the target days. Air temperature data, which is derived from meteorological data, and the convective heat transfer coefficient are uniformly applied to the all surfaces for heat balance simulation and estimation of the surface sensible heat flux. This is a main approximation in this simulation. The convective heat transfer coefficient is estimated by the Jurges formula. The effect of this approximation on the simulation results for surface temperature and surface sensible heat flux has been examined.

Heat transfer simulation models for rooftop greening and wall greening are incorporated into the urban heat balance simulation model. These heat transfer simulation models use the evaporation ratio as the parameter for evaporation and evapotranspiration in the estimation of latent heat flux on green-covered surfaces.

3.2. Building thermal simulation

Radiant flux data on external surface meshes (cells), calculated in the previous step (Section 3.1), are summed for each surface object. The radiant flux data are then translated to the building thermal simulation model and set for the boundary condition data of the calculation point on each surface object. At the calculation points of...
openings in buildings, incident solar radiation data (direct solar radiation, sky solar radiation, and reflected solar radiation) are also summed, so as to estimate the quantity of solar transmission into the indoor space. Solar radiation transmitted through the opening is absorbed by the walls and the floor. The building thermal simulation is implemented using the radiant flux data allotted to all external surfaces, and the cooling/heating load in the building is then calculated. One-dimensional unsteady heat conduction in building members, such as walls and roofs, is calculated by the backward-difference method. Each floor has one zone, or is divided into several zones, and calculation points of air temperature and cooling/heating load are set for each zone.

3.3. Building energy simulation

The energy consumption elements calculated in the present study include HVAC systems, lighting, electrical appliances, hot-water supplies, and kitchen equipments. The energy consumption by a building HVAC system is calculated using the cooling/heating load data estimated by the building thermal simulation (Section 3.2) and the coefficient of performance (COP) of the HVAC system. The total energy consumption for lighting and electrical appliances is estimated by the unit demand schedule data in the database for each building-use type and the floor area data, which is directly obtained from the building 3D CAD model. Energy simulation that includes district heating and cooling (DHC) plants will be considered in the future.

3.4. Calculation of anthropogenic heat released from buildings

Anthropogenic heat released from buildings consists of heat emission from heat source equipment, outdoor units of HVAC systems (such as cooling towers), and mechanical ventilation and hot-water supply systems (e.g., Ashie, 2002, kametani, 1996). These quantities are estimated based on the energy consumption data calculated in the previous section (Section 3.3). The proportion of sensible heat to latent heat differs in each HVAC system (the dependence on gas supply or electrical supply) as well as with the type of outdoor unit (air-cooled or water-cooled). In the present study, anthropogenic heat generated by automobile traffic is not considered.

4. APPLICATION RESULTS

4.1. Subject urban area and calculation conditions

The proposed simulation model was applied to the prediction of total sensible heat flux from the buildings and outdoor spaces in a substantial urban area. A business/residential area with massive and tall buildings in the center of Tokyo was selected as the subject site. The specifications of the urban block and buildings are listed in Table 2 and Table 3. The unit demand data for lighting, electrical appliances, and hot-water supplies per building floor area for each building-use type were set according to measurement data (e.g. Ojima laboratory, 1995). The heat source equipments of HVAC systems are an absorption refrigerator (with a cooling tower) and air-cooled heat pump chiller for office buildings and a room air conditioner for residential buildings. The indoor air temperature of air-conditioned room was 26 °C. The meteorological conditions used in the calculation were for a summer day with a clear sky (August 5th). Each simulation was continued for five days in order to obtain a periodic steady-state solution for the subject day.

4.2. Simulation results

Figure 3 shows the simulation results for the surface temperature distribution of the urban block at 3 p.m. The surface temperatures of the western wall of the

Table 4 Comparison of anthropogenic heat between the simulation results and previously reported values (quantity per unit floor area)

<table>
<thead>
<tr>
<th>Build. No. (HVAC)</th>
<th>Sensible heat [kW/m²]</th>
<th>Latent heat [kW/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1 (AR)</td>
<td>0.45</td>
<td>1.69</td>
</tr>
<tr>
<td>B2 (AR)</td>
<td>0.43</td>
<td>1.70</td>
</tr>
<tr>
<td>B3 (HC)</td>
<td>1.11</td>
<td>0.058</td>
</tr>
<tr>
<td>*1 (AR)</td>
<td>0.427</td>
<td>0.979</td>
</tr>
<tr>
<td>*2 (HC)</td>
<td>1.10</td>
<td>0.061</td>
</tr>
</tbody>
</table>

AR: Absorption refrigerator
HC: Air-cooled heat pump chiller
buildings B1 and B2 increase to over 40 °C due to strong direct solar radiation from the west, as well as the temperature increase of the flat roofs and asphalt-paved road. The cooling loads of these buildings are larger than that of building B3, which is shaded by these tall buildings during the afternoon. The surface temperatures of the window panes are relatively low due to the air cooling in the building and the low solar absorptivity of the glass surface. On numerous glass surfaces, the sensible heat flux is a negative value. Outdoor parking lots and parks are shaded by neighbor buildings and tall trees, and the ground surface temperature ranges from approximately 30 °C to 40 °C. At night (8 p.m.), the surface temperatures of the buildings and roads remain higher than the air temperature as a result of heat storage during the daytime. Figure 4 shows the results for anthropogenic heat released from each building. The buildings with cooling tower (water-cooled) release a large quantity of latent heat compared with sensible heat. The amount and proportion of anthropogenic sensible heat obtained in the present estimation correspond approximately to previously reported values by Ashie (2002) (Table 4). For latent heat flux, the calculated values in this study are larger than that of the previously reported values. Figure 5 shows the results for area-averaged sensible heat flux including surface heat flux and anthropogenic heat flux. The peak value of anthropogenic sensible heat flux from buildings is almost equal to the surface sensible heat flux in this area. The high density of building energy consumption in the area cause the quantity of the anthropogenic sensible heat flux, although the office buildings have cooling towers for heat release and latent heat flux occupies a significant portion of the total heat flux. At night, the surface sensible heat flux remains over 30 W/m² due to heat storage in buildings and roads. These results show the applicability of this simulation model to the analysis of sensible heat flux from an urban area, taking into account the spatial geometry, materials, and building-use types in the area. The examination using a broader range of examples of urban areas will be conducted in a future study.

5. CONCLUSION

A simulation system to predict surface sensible heat flux and anthropogenic heat from buildings in an urban area was developed for the assessment of urban development with respect to the urban and atmospheric thermal environments. The proposed system combines the urban heat balance simulation with the building thermal simulation and the building energy simulation. The simulation system was applied to a substantial urban area in Tokyo, and the applicability of the proposed simulation model to the analysis of sensible heat flux in the area was examined.

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References