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A numerical simulation tool for predicting the impact of outdoor thermal environment on building energy performance

Jiang He *, Akira Hoyano, Takashi Asawa

Interdisciplinary Graduate School of Science and Engineering, Tokyo Institute of Technology, Yokohama 226-8502, Japan

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ABSTRACT

A building affects its surrounding environment, and conversely its indoor environment is influenced by its surroundings. In order to obtain a more accurate prediction of the indoor thermal environment, it is necessary to consider the interactions between the indoor and outdoor thermal environments. However, there is still a lack of numerical simulation tools available for predicting the interactions between indoor and outdoor microclimate that take into account the influences of outdoor spatial conditions (such as building forms and tree shapes) and various urban surface materials. This present paper presents a simulation tool for predicting the effect of outdoor thermal environment on building thermal performance (heating/cooling loads, indoor temperature) in an urban block consisting of several buildings, trees, and other structures. The simulation tool is a 3D CAD-based design tool, which makes it possible to reproduce the spatial forms of buildings and constructed surface materials in detail. The outdoor thermal environment is evaluated in terms of external surface temperature and mean radiant temperature (MRT). Simulated results of these temperatures can be visualized on a color 3D display. Building heating/cooling loads and indoor air temperature (internal surface temperature) can also be simulated. In this study, a simulation methodology is described, and a sensitivity analysis is conducted for a wooden detached house under different outdoor conditions (building coverage, adjacent building height, surrounding with trees or no-trees). Simulation results show that the simulation tool developed in this study is capable of quantifying the influences of outdoor configurations and surface materials on both indoor and outdoor environments.

1. Introduction

A number of simulation tools, such as EnergyPlus, DOE-2, and TRANSYS, have been developed to predict building thermal performance and energy use [1]. The analysis domains for these simulation tools are almost all limited to indoors. However, in reality, a building affects its surrounding environment and conversely, its indoor environment is influenced by its surroundings. To provide a more accurate prediction of indoor thermal environment and building energy performance, it is necessary to consider the interactions between the indoor and outdoor thermal environments. However, there is still a lack of numerical simulation tools available for predicting the interactions between indoor and outdoor microclimate that take into account the influences of outdoor spatial conditions (such as building forms and tree shapes) and various urban surface materials.

A number of previous studies have focused on numerical prediction of interactions between indoor and outdoor thermal environments [2–8,15,16]. In one recent study, Zhu et al. [8] used a coupled urban-building energy evaluation system based on a one-dimensional canopy model (AUSSSM) to analyze the influence of urban canopy configurations on outdoor thermal comfort under conditions of different building coverage, indoor air-conditioning setpoints, etc. However, in these previous studies, the spatial forms and construction materials of buildings were simplified. In reality, an urban block is composed of trees, buildings and other structures that have complicated spatial forms and are made of various materials. It is well known that spatial forms and construction materials affect the formation of both outdoor and indoor thermal environments. Moreover, the simulation tools used in the previous studies were not developed to be used by general designers (architects, developers, etc.), so there was no tool to integrate the tools into a 3D-CAD system to reproduce spatial forms of buildings and other structures in detail.

To create a 3D CAD-based design tool that can be used to support the prediction of the interaction between indoor and outdoor thermal environments in an urban block, we have developed a simulation method that integrates the building heat load simulation program into a 3D-CAD thermal environment simulator (a 3D CAD-based simulation system) previously developed by our research group [9]. The simulation tool has been integrated into

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* Corresponding author. Tel.: +81 45 9245510; fax: +81 45 9245553.
E-mail address: kakohe.j.aa@m.titech.ac.jp (J. He).

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Nomenclature

a, b	constant in Brunt's formula
a_{su}	solar absorptivity
$A_I(i,j)$	area of internal surface j in room i (m^2)
$A_F(i)$	area of the floor in room i (m^2)
A_{mesh}	area of a mesh (m^2)
$A_O(i)$	total area of internal surfaces in room i (m^2)
A_{sm}	area of external surface m (m^2)
$A_W(i,l)$	area of window l at external surface m in room i (m^2)
c	cloud amount ($0 \leqq c \leqq 10$)
c_p	specific heat capacity (J/(kg K))
c_{pi}	specific heat capacity of indoor air (J/(kg K))
e	water vapor pressure near the ground (Pa)
F_i	view factor from a point to face i
F_{sky}	view factor from a point to the sky
H_C	convection heat (W/m^2)
H_E	latent heat (W/m^2)
H_G	conductive heat flux (W/m^2)
H_i	removed/required heat for room i (W) (H_i is air-conditioning load when air-conditioned. $H_i = 0$ when not air-conditioned)
H_L	net longwave radiation (W/m^2)
H_S	absorbed solar radiation (W/m^2)
I_{DR}	direct solar radiation (W/m^2)
I_{RR}	reflected solar radiation (W/m^2)
I_{SR}	sky solar radiation (W/m^2)
$I_{sum(m)}$	total solar radiation on external surface m (for openings) (W)
I_{TR}	total solar radiation on mesh i at external surface m (for openings) (W/m^2)
k	mass transfer coefficient (kg/(m^2 s (kg/kg(DA))))
L	thickness of a wall or roof (m)
m_c	coefficient of cloud altitude
Mr_i	heat capacity of room i (indoor air + furniture) (J/K)
MRT	mean radiant temperature (K)
N_s	total number of surrounding surfaces
$N_I(i)$	number of internal surfaces in room i
N_m	number of meshes at external surface m
N_w	number of surrounding buildings and ground
N_{WI}	number of windows in room i
Q_i	internal sensible heat source in room i (W)
$Q_{LI}(i,j)$	longwave radiation absorbed by internal surface j in room i (W/m^2)
Q_m	mean absorbed radiation by external surface m (W/m^2)
$Q_{SI}(i,j)$	solar radiation absorbed by internal surface j in room i (W/m^2)
R_{La}	atmospheric radiation (W/m^2)
R_{Lw}	longwave radiation from surrounding buildings and ground (W/m^2)
$R_{mesh(m,i)}$	total radiation absorbed by mesh i at external surface m (W/m^2)
$R_{sum(m)}$	total radiation absorbed by external surface m (W)
T	internal temperature (K)
T_a	outdoor air temperature (K)
T_{ri}	internal air temperature in room i (K)
T_s	external surface temperature (K)
$T_{sI}(i,j)$	surface temperature of internal surface j in room i (K)
T_{sm}	mean surface temperature of external surface m (K)
T_w	surface temperature of surrounding buildings and ground (K)
t	time (s)
V_a	amount of ventilation (m^3/s)
x	three components of coordinates (m)
X	absolute humidity (kg/kg(DA))
$\alpha_{cI}(i,j)$	convection coefficient for internal surface j in room i (W/(m^2 K))
α_o	overall heat transfer coefficient (W/(m^2 K)) (its value is assumed to be 9.3 W/(m^2 K))
β	evaporation efficiency
ε	emissivity
θ	incident angle of direct solar radiation (rad)
ι	latent heat (J/kg)
$\eta(i,j)$	solar transmittance of window j in room i
λ	thermal conductivity (W/(m K))
ρ	density (kg/m^3)
ρ_i	density of indoor air (kg/m^3)
σ	Stefan-Boltzmann constant (W/(m^2 K^4))
τ_l	solar transmittance of window l
Subscripts	
a	atmosphere
s	surface

commercial 3D-CAD software (VectorWorks) on a PC, and a Japanese-version called ThermoRender is commercially available in Japan.

In order to demonstrate the usefulness of the proposed simulation method, this study has conducted a sensitivity analysis for a wooden detached house located at a residential area with various outdoor conditions (building coverage, adjacent building height, surrounding with trees or no-trees, etc.). The methodology of the simulation tool is described below.

2. Methodology

The simulation process is outlined in Fig. 1. The simulation is performed using 3D-CAD models (shown at the upper left in Fig. 1) for buildings, trees and other structures in the area being analyzed. As shown at the top right corner of Fig. 1, three-dimensional spatial forms of buildings, trees and other structures, and two-dimensional ground surfaces are divided into mesh grids. Thermophysical data of construction materials such as albedo, conductivity, and solar transmittance are assigned to the grids. An automatic mesh-dividing process with a spatial resolution of 0.05–5 m (a practical size is 0.1–0.4 m) has been designed and only uniform mesh can be used in the present version of the tool. A uniform mesh size of 0.2 m was used in this study.

Three-dimensional radiation (solar radiation and longwave radiation) from surroundings (the sky, ground and surroundings) was considered in the heat balance calculation for each mesh. Conduction heat was assumed to be transferred in one direction which is normal to the mesh surface. The following assumptions were also used in the thermal simulation. Ambient air temperature and wind velocity are uniformly distributed in the outdoor spaces at an analysis time. Indoor air temperature is uniform in a room at an analysis time. The effect of heat bridges is not considered in the building heat load simulation.

2.1. External surface temperature simulation

The energy balance equation at each mesh surface can be written as Eq. (1). The left term of Eq. (1) is the conductive heat at the mesh. The first right term is the absorbed shortwave (solar) radiation by the mesh. The second right term is the net longwave radiation. The third right term is the convective heat transfer from