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Relationships between the properties of an urban street canyon and its radiant environment: Introduction of appropriate urban heat island mitigation technologies

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Abstract

The relationships between the properties of urban canopy components and the radiant environment in an urban street canyon are examined considering the introduction of appropriate urban heat island mitigation technologies. Radiant heat transfers between walls and roads are calculated according to Gebhart's radiant absorption coefficients and using the Monte Carlo method. Roads are classified as either north–south or east–west; intersections are also considered. The key property of an urban street canyon is expressed by its aspect ratio W/H. A simple street canyon model and two actual urban street canyon areas are used as the objects of examination. Distributions of surface temperatures and solar radiation gains on street canyon roofs, roads, and walls are analyzed. The top priority for the implementation of urban heat island mitigation measures concerns the buildings with large roof areas. The other high-priority areas for implementing mitigation measures focus on smaller roofs and roads for which the street canyon aspect ratio W/H is greater than 1.5; the lowest-priority area is the walls.

Keywords: Urban heat island; Radiant environment; Street canyon; Urban canopy components; Urban heat island mitigation technologies; Aspect ratio

1. Introduction

A number of studies have been carried out with the aim of improving the thermal environment and air quality in urban canopy areas. The following four points were noted by Oke (1988) regarding the planning and design of urban canopies: to maximize shelter, to maximize dispersion of pollutants, to maximize urban warmth, and to maximize solar access. The importance of solar access was also studied by Arnfield (1990). Numerous studies have been conducted on the dispersion of pollutants and distribution of wind in urban canopies. Eliasson et al. (1990/1991) pointed out that some surface temperature variations in urban canyons may be explained by the sky view factor. Cristina and Souza (2007) analyzed the relationship between air temperature and sky view factor by using a GIS tool. However, it was pointed out by Robinson (2006) pointed out that the distribution of irradiation in an urban canopy was not predicted by only the sky view factor and that urban morphology should also be considered. Pearlmutter et al. (2007) noted the importance of both the aspect ratio and the directional orientation of streets. Asawa et al. (2008) presented in detail a calculation method using a 3D-CAD system; nevertheless, the application of this method to an entire city is impossible.

On the other hand, several kinds of urban heat island mitigation techniques that utilize urban canopy surface coverage components have been developed (e.g., Takebayashi and Moriyama, 2007); local authorities in

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large cities such as Tokyo and Osaka in Japan support their dissemination. However, no guidance is provided as to where these techniques should be introduced in order to utilize them most efficiently. In this study, the influence of urban canopy properties on the radiant environment in urban heat islands is analyzed, and the relative contributions of each urban canopy measurement parameter to the overall urban heat island effect are determined based on the actual conditions of the radiant environment. To mitigate the urban heat island effect, the intent is to degrade the sensible heat flux generated by the surfaces within an entire urban block. From the viewpoint of the human thermal environment, the intent is to degrade the radiation emitted from the surfaces of the urban canopy components. The dominant factor from the viewpoint of either sensible heat or radiation emissions is a reduction of the surface temperatures of the urban canopy components. Therefore, in this study, the focus is on the surface temperature distribution in urban street canyons.

2. Method

2.1. Outline of radiation transfer and heat budget model in the urban canopy

The urban canopy components—roofs, walls, and roads—are divided into grids, and for each surface, direct, diffuse, and reflected solar radiation and infrared radiation are calculated. Sky view factors from each surface and view factors between the surfaces are calculated by the Monte Carlo method. Mutual radiation between the surfaces is calculated using Gebhart's absorption factors. It is assumed that all surfaces are uniform diffuse reflectors and only one reflected radiation flux is included within the calculation. The objective condition is a sunny summer day, when the normal direct solar radiation is calculated by Bouguer's equation, the horizontal diffuse solar radiation is calculated by Nagata's equation, and the infrared radiation from the sky is calculated by Brunt's equation. The surface heat budget for each surface is calculated and the one-dimensional heat conduction equation is estimated for each wall, roof, and road.

Normal direct solar radiation (Bouguer's equation):

$$I_{DN} = I_0 P^{1/\sinh} \tag{1}$$

Horizontal diffuse solar radiation (Nagata's equation):

$$I_{SH} = \sinh(I_0 - I_{DN})(0.66 - 0.32\sinh)\{0.5 + (0.4 - 0.3P)\sinh\} \tag{2}$$

where I_{DN} is normal direct solar radiation (Wm^{-2}), I_0 is the solar constant (=1350 (Wm^{-2})), P is atmospheric transmittance (–), h is solar altitude (rad), and I_{SH} is horizontal diffuse solar radiation (Wm^{-2}).

Infrared radiation from the sky (Brunt's equation):

$$J_a - \varepsilon\sigma T_a^4(0.526 + 0.208\sqrt{f}) \tag{3}$$

where J_a is infrared radiation from the sky (Wm^{-2}), ε is emissivity (–), σ is the Stefan–Boltzmann constant (Wm^{-2} K^{-4}), T_a is air temperature (K), and f is water vapor pressure (kPa).

Surface heat budget on each surface:

$$R_n = V + lE + A \tag{4}$$

where R_n is net radiation (Wm^{-2}), V is sensible heat flux (Wm^{-2}), lE is latent heat flux (Wm^{-2}), and A is conduction heat flux (Wm^{-2}).

One-dimensional heat conduction equation:

$$C_p\gamma \frac{\partial T}{\partial t} = \lambda \frac{\partial^2 T}{\partial x^2} \tag{5}$$

where $C_p\gamma$ is heat capacity (Jm^{-3} K^{-1}); λ is thermal conductivity (Wm^{-1} K^{-1}); T is the temperature of the wall, roof, or road (K); t is time (s); and x is the distance to the wall, roof, or road (m).

2.2. Calculation conditions

A typical sunny summer day, August 5, 2010, was set for the weather conditions. It was selected from hot days Japan meteorological agency issued a warning. The criteria is more than 35 °C in daily maximum air temperature. Observation data that were recorded at the Osaka meteorological observatory (34°40.9′ N, 135°31.1′ E) were used. Local distribution of wind velocity in the urban canyon was not considered and the convective heat transfer coefficient was assumed to be a constant with a value of 12.5 Wm^{-2} K^{-1}. It can be discussed mainly the impact of radiation heat exchange in the street canyon. Initial surface and inner temperatures of each component were set at 27 °C, and the calculations were repeated twice on the same day to consider the effects of heat storage.

The walls and roofs were assumed to be 0.3 mm thick concrete and the roads were assumed to have 0.2 mm thick asphalt and 0.35 mm thick soil. Parameters regarding heat conduction are described in Table 1 based on previous results by Takebayashi et al., (2008).

2.3. Outline of the urban canyon model

The primary urban canopy properties with respect to the radiation environment within the urban canopy are the aspect ratio W/H (W is road width and H is building height) and the road direction (east–west, north–south, or intersection). Calculations were performed for a simple urban

Table 1
Parameters of each building material.

Material	Solar reflectance (–)	Emissivity (–)	Thermal conductivity (Wm^{-1} K^{-1})	Heat capacity (MJm^{-3} K^{-1})
Concrete	0.2	0.95	1.64	1.93
Asphalt	0.1	1.0	0.74	2.10
Soil			0.62	1.58