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Study on the appropriate selection of urban heat island measure technologies to urban block properties

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A B S T R A C T

In this study, we analyzed the effects of introducing urban heat island measure technologies in a typical street canyon model to aid the selection of a suitable technology. It is appropriate to use street trees for improving the thermal environment of a sidewalk and high reflectance paint or water-retentive pavement for the reduction of surface temperature on the roadway. Reduction of solar radiation gain to the sidewalk pavement surface depends on the location and area of the street tree shadows, which are likely to occur on the northern sidewalk of an east–west road rather than an eastern (or a western) sidewalk of a north–south road. Moreover, the area of the shadow is proportional to the square of the width of tree crown (the radius) and inversely proportional to the distance between trees. Thus, it is necessary to prioritize these considerations based on the road orientation and time when the pedestrian use of sidewalk is the highest.

1. Introduction

Various urban heat island measure technologies have been proposed and the performance of each technology has been evaluated (Santamouris, 2013, in press). To appropriately select an urban heat island measures technology, the relationship between the environment where the technology has been introduced and the effect of introducing this technology must be studied. We had previously examined the relationships between the properties of urban canopy components and the radiant environment in an urban street canyon in order to understand where these technologies should be introduced (Takebayashi & Moriyama, 2012a). Consequently, we found that the best locations for implementing urban heat island measures were roofs, the northern sides of east–west roads, and the center of north–south roads. In order to determine the appropriate technique for a particular place, we analyzed the relationship between the benefits from a heat island measure technique and the place in which it was introduced. In this previous study, we used a radiation transfer and heat budget model in the urban canopy (Takebayashi & Moriyama, 2012a). Most studies have been devoted to the development of the surface energy balance model for different applications (Grimmond & Blackett, 2010). However, only a few studies focus on microscale urban surface temperature (Asawa, Hoyano, & Nakaohkubo, 2008; Krayenhoff & Voogt, 2007; Yang & Li, 2013). Our calculation model is almost same as the latest model built by Yang and Li (2013). Another our previous study (Takebayashi & Moriyama, 2012b) had pointed out that there are relatively large benefits of using objective techniques involving street trees, green walls, high reflectance paint, and water-retentive pavement. Furthermore, objective places were identified as road and wall surfaces. The roof surface is the best location for an urban heat island measure because it has the highest solar radiation gain. However, because the shading effects from the penthouse or surrounding buildings are not remarkable, the surface temperature distribution is insignificant. Thus, the benefits of applying a heat island measure technique agree with the results of a previous study conducted on a horizontal surface (Takebayashi & Moriyama, 2007). Evaluation index was defined as the surface temperature distribution on the road and wall. Surface heat budget and radiation transfer were calculated for a typical street canyon model. Street canyon parameters were orientation and width of the street.

2. Radiation transfer and surface heat budget model in the urban canopy

2.1. Outline of the calculation model

The urban canopy components—roofs, walls, and roads—were divided into grids. For each surface, direct, diffuse, and reflected solar radiation and infrared radiation were calculated. Sky view factors from each surface and view factors between the surfaces were calculated using a Monte Carlo simulation, which is a method of tracking a number of radiant flux emitted randomly from wall and road surface divided into meshes. Mutual radiation between

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the surfaces was calculated using Gebhart absorption factors. The Gebhart absorption factor gives the percentage of energy emitted by a surface that is absorbed by another surface after reaching the absorbing surface by all possible paths (Gebhart, 1971). We assumed that all surfaces were uniform diffuse reflectors and only one reflected radiation flux was included within the calculation. A sunny summer day condition was assumed, and the normal direct solar radiation was calculated using the Bouguer's equation (Yang & Li, 2013). The horizontal diffuse solar radiation was calculated using Nagata's equation which is obtained by arranging Berlage's equation (Berlage, 1928), and the infrared radiation from the sky was calculated using Brunt's equation (Philipps, 1940). The surface heat budget for each surface was calculated and the one-dimensional heat conduction equation was estimated for each wall, roof, and road. The surface heat budget for each surface is given by:

$$R_n = V + lE + A, \tag{1}$$

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

One-dimensional heat conduction equation is

$$C\gamma \frac{\partial T}{\partial t} = \lambda \frac{\partial^2 T}{\delta x^2}, \tag{2}$$

where $C\gamma$ is heat capacity (J m^{-3} K^{-1}); λ is thermal conductivity (W m^{-1} K^{-1}); T is the temperature of the wall, roof, or road (K); t is time (s); and x is the depth in the wall or road (m).

The weather conditions on a typical sunny summer day, August 4, 2011, was chosen for the study. This day was selected from the hot days for which the Japan Meteorological Agency issued a warning. The criterion for such a warning is a maximum air temperature greater than 35 °C. Observation data recorded at the Kobe meteorological observatory (34°41.8′ N, 135°12.7′ E) was used. The local distribution of wind velocity in the urban canyon was not considered and the convective heat transfer coefficient was assumed constant at 12.5 W m^{-2} K^{-1}. The discussion primarily focuses on the impact of radiation heat exchange in the street canyon. Initial surface and inner temperatures of each component were set at 27 °C and calculations were repeated twice on the same day to consider the effects of heat storage.

The walls and roofs were assumed to be made of 0.3-mm-thick concrete, whereas the roads were assumed to be made of 0.2-mm-thick asphalt and 0.35-mm-thick soil. Heat conduction parameters were set on the basis of the results of a study we conducted previously (Takebayashi & Moriyama, 2012c). Solar reflectance, emissivity, thermal conductivity, and heat capacity of concrete were 0.2, 0.95, 1.64 W m^{-1} K^{-1}, and 1.93 MJ m^{-3} K^{-1}, respectively. For asphalt, these values were, in the same order, 0.1, 1.0, 0.74 W m^{-1} K^{-1}, and 2.1 MJ m^{-3} K^{-1}. Furthermore, the thermal conductivity and heat capacity of soil were 0.62 W m^{-1} K^{-1} and 1.58 MJ m^{-3} K^{-1}, respectively.

2.2. Outline of the urban canopy model and heat island measure techniques

From the results of a previous study, the characteristics of road surface temperature in the street canyon can be explained using a typical two-dimensional street canyon model representing the building height and road width. It was necessary to distinguish the east–west and north–south roads. The thermal characteristics of both roads were overlaid on the intersection. In this paper, north–south and east–west roads of widths 20 m (narrow), 30 m (moderate), and 50 m (wide) were selected as the objective roads. These were treated as two-dimensional street canyons. The building height was kept constant at 30 m by referring to a typical urban block of Kobe city. We assumed the street trees were planted continuously along the road in the two-dimensional street canyon model. The effect of changing the arrangement interval between two street trees is discussed in the next chapter. The outline of the street canyon model with a street tree and green wall is shown in Fig. 1. Both side buildings with 30-m height were located 1 m away from the road, and the sidewalk with 3-m width was in front of them. A street tree with 2 m width was located between the roadway and sidewalk. The widths of the roadway were 10, 20, and 40 m, and the roadways were equally divided into three for analysis. The mesh interval for calculation was maintained constant in both horizontal and vertical directions at 0.5 m.

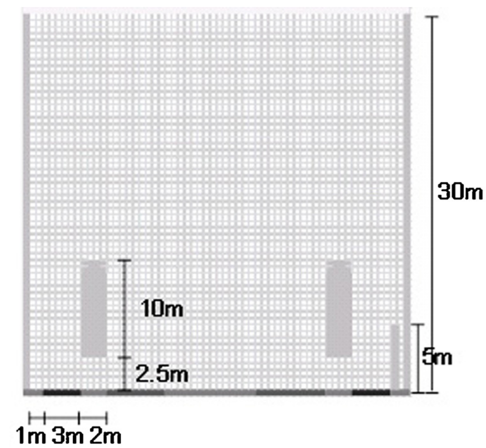

Fig. 1. Outline of the street canyon model with a street tree and green wall.

Objective heat island measure techniques examined in this study were a street tree, a green wall, high reflectance paint, and water-retentive pavement. The height of a street tree, the height under the tree crown, solar radiation shielding factor of leaves, and evaporative efficiency of leaves were 10 m, 2.5 m, 0.8, and 0.3, respectively. The green wall was 5 m high and 0.5 m away from the concrete wall. Solar radiation shielding factor and evaporative efficiency of leaves were 0.8 and 0.3, respectively. The reflectance of high reflectance paint was 0.4, and it was painted on the asphalt road surface. The evaporative efficiency of the water-retentive pavement was 0.3, which was different from that of the asphalt road surface. The pavement was assumed to be of a continuous water supply type with irrigation equipment.

2.3. Calculation results

The daily mean surface temperature was averaged along each sidewalk, each side roadway, and the center of each roadway, from the calculation results of introducing the countermeasure technology. Furthermore, the daily mean wall surface temperature is used to examine the green wall. Depending on the location, the benefits of each technology occurred at different times. Some technologies influenced night temperature owing to the thermal storage capacities of road and wall materials. In this study, we assumed that the daily mean surface temperature represented both the thermal environment during the day and the heat storage effect during the night. For example, the benefit from the high reflectance paint was approximately 7 K during the day and approximately 0.5 K during the night at the center of the north–south road, resulting in a daily average of approximately 1 K.

The daily average surface temperature reduction caused by the street tree is shown in Fig. 2. The benefit on the northern sidewalk of the east–west road and the eastern and western sidewalk of the north–south road were observed to be the greatest. This meant that the improvement of the thermal environment of the pedestrian space was remarkable.