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Urban canyon albedo and its implication on the use of reflective cool pavements

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ABSTRACT

Solar irradiance to an urban canyon is subjected to multiple reflections, a process that increases solar absorption and contributes to the unban heat island. The absorption depends on the urban structures, and the day of the year, and the albedos of the walls and pavement. This study develops a numerical model to predict the urban canyon albedo (UCA) and validates the model with experimental observations. It estimates whether increasing the pavement albedo can raise the UCA effectively. It evaluates the reflective diffuse radiation from the pavement to adjacent building walls. It is found the ratio of building's height to the road's width, or called the aspect ratio, controls the UCA while other factors play secondary roles. Reflective pavements in an urban canyon reflect a sizable additional diffuse radiation to the adjacent walls during summertime. It is recommended that reflective pavements can be used only if an urban canyon has an aspect ratio no greater than 1.0.

1. Introduction

Urban structures consist of building, roof, walls, and street. Buildings at both side of the street create a canyon-like environment that is called street canyon or urban canyon. Solar irradiance to any surfaces in the canyon is absorbed or reflected. Unlike the reflections from a flat and open surface, the reflections from one surface in an urban canyon tend to be intercepted by other surfaces and then be subjected to multiple reflections. While some diffuse radiation escapes to the sky, these multiple reflections increase the radiation absorption of the canyon and contribute to the development of urban heat island.

Many studies have contributed to understand the albedo of the street canyon (this study treats albedo and reflectivity are interchangeable) [1–7]. Aida [4,5] experimented the albedo of different street orientations under different seasons and found that the albedo of street orientations varied with time. On the basis of this experiment, several numerical models have devoted to understand the street canyon's albedo [8], the energy–weight albedo of a street urban [9], and the daily variation of albedo of a street canyon [1]. These studies have been found that the street canyon's albedo is significant lower than the albedo of the street and the walls. One geo-engineering idea is to make the pavements more reflective than conventional pavements and to reflect more radiation back to the sky [10–12]. Conventional asphalt pavements can be more reflective by using chip seal techniques (sealing the surface with light-colored aggregates) [13,14], by coating the surface with high near-infrared radiation reflectance [15–17], and/or by doping the surface with reflective pigments [18,19]. Conventional concrete pavements can be more reflective by filling concrete with white filler [20], by using light-colored cementitious mixture [21,22], and by whitetopping techniques [23]. Reflective pavements can have albedo of 0.20 to 0.80 [20], depending on the surface materials and the aging of the materials. Experiments have confirmed that reflective pavements effectively decrease the pavement surface temperature. However, these experiments observed either the temperatures of the flat brick samples or those of pavements in open areas [12,24,25]. It remains unknown whether increasing the albedo of the urban street can effectively reduce the solar absorption of the street canyon.

This study proposes a numerical model to predict the UCA and validates the model with experimental observations. The model considers the multiple reflections between different surfaces in the urban canyon. Applications of the model are centered on two topics: (1) if increasing the pavement albedo effectively raises the albedo of the street canyon; and (2) if a reflective pavement

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reflects a sizable additional diffuse radiation to adjacent buildings' walls.

2. Model development

2.1. Solar position

The solar position determines when the street and the building walls are shaded or sunlit. It varies with the solar declination angle, the solar zenith angle, the solar azimuth angle, and the hour angle. The solar declination angle, δ (rad), is

$$\delta = 0.409\sin\left(2\pi\frac{N+284}{365}\right) \tag{1}$$

where N is the number of the day with January 1 as $N = 1$.

The solar zenith angle, θ (rad), is determined from

$$\cos\theta = \sin\delta\sin\phi + \cos\delta\cos\phi\cos\omega \tag{2}$$

where ϕ (rad) is the latitude of the observer on the earth surface; ω (rad) is the solar hour angle.

The solar hour angle is $-\pi/2$ at sunrise, 0 at noon and $\pi/2$ at sunset. The time of sunrise and sunset can be derived as:

$$\cos\omega = -\tan\delta\tan\phi \tag{3}$$

where the sunset time is the positive value and the sunrise time, the negative value.

The solar azimuth angle, γ (rad), is given by

$$\sin\gamma = \frac{\cos\delta\sin\omega}{\sin\theta} \tag{4}$$

If $\left|\sin\ \gamma\right| > 1$ or if $\left|\sin\theta\right|$ is infinitesimal, the solar azimuth angle cannot be calculated. The solar azimuth angle has to be estimated by:

$$\cos\gamma = \frac{\cos\theta\sin\phi - \sin\delta}{\sin\theta\cos\phi} \tag{5}$$

It is noted that when $\theta = 0$, the denominators in Eqs. (4) and (5) are zero. For computational convenience, it is advisable to discrete the time frame from sunrise to sunset as even number elements so that the discrete time serial from sunrise to sunset does not have $\theta = 0$. The albedo at noontime ($\theta = 0$) can be interpolated from the simulated albedo around the noontime.

Eqs. (1)–(5) can be used to estimate when a surface in the street canyon is shaded or sunlit. A typical urban canyon is schematically shown in Fig. 1. The beam irradiation causes a shaded area extending to a length of x_0 (m), which is

$$x_0 = h\tan\theta\cos(\gamma - \gamma_c) \tag{6}$$

where h (m) is the height of the building; and γ_c (rad) is the orientation of the canyon, in which 0 is for the west–east orientation, and $\pi/2$ for the north–south orientation.

At low sun, x_0 is greater than the width of the street, w (m). The road is fully shaded and the wall is partially sunlit. The height of the sunlit wall, z (m), can be computed by:

$$z = h - \frac{x_0 - w}{\cos(\gamma - \gamma_c)\tan\theta}, \quad x_0 = w \tag{7}$$

At high sun, x_0 is less than the width of the street so that one wall is fully sunlit and the road is partially sunlit. The length of the sunlit road is

$$x = w - h\tan\theta\cos(\gamma - \gamma_c)\ x_0 < w \tag{8}$$

It is noteworthy that during the daytime, one wall is always shaded and the other wall is either fully or partially sunlit. For convenience, it is advisable to compute the absolute of z and x and then to estimate the sign of $\tan\theta$ and $\cos(\gamma - \gamma_c)$ to determine which parts of the wall and road are sunlit. For a symmetric street canyon, using the absolute values is sufficient to estimate the solar absorption and reflection of an urban canyon.

2.2. Beam radiation and diffuse radiation

Solar irradiation to the ground surface is fractioned into beam radiation and diffuse radiation. This fraction has been the subject of many documented models [6,9,26]. Among them, one well-cited model is the Orgill and Hollands model [28], which is

$$\frac{I_d}{I} = \begin{cases} 1.0 - 0.249k_T, & k_T < 0.35 \\ 1.557 - 1.84k_T, & 0.35 \le k_T \le 0.75 \\ 0.177 & k_T > 0.75 \end{cases} \tag{9}$$

where I_d (W/m^2) is the diffuse radiation, and I (W/m^2) is the total irradiance, I_b (W/m^2) is the beam irradiance ($I_b = I - I_d$), and k_T is the sky cleanness coefficient, with 1.0 for a clean day and 0 for a cloudy day.

The solar irradiation during a day approximately follows a cosine wave with zenith at noon time and zero at both sunrise and sunset time, which is

$$I = I_0\cos\theta \tag{10}$$

The daily zenith solar irradiation, I_0, can be estimated by [27],

$$I_0 = S_0\tau^{1/\cos\gamma} \tag{11}$$

here τ is a constant varying from 0.62 to 0.81 with a cloudless day as 0.81; S_0 is solar constant, 1367 W/m^2.

2.3. View factor

The reflection from a surface can be either diffuse or mirror. For building materials, the reflection is diffuse; i.e., the intensity of the emitted radiation is independent to direction. The decisive factor to the diffuse energy flux is the view factor. The view factor from one surface to other surfaces and to the sky is crucial to the solar absorption in an urban canyon. The view factor of the road to the wall $F_{w\to h}$ and to the sky $F_{w\to s}$ can be calculated by Eqs. (12a) and (12b) (the subscript w = road, s = sky, h = wall; these subscripts are used through this paper)

$$F_{w\to s} = \frac{\left(\sqrt{w^2+h^2} - h\right)}{w} \tag{12a}$$

$$F_{w\to h} = 0.5\frac{\left(w - \sqrt{w^2+h^2} + h\right)}{w} \tag{12b}$$

The view factors of one wall to the sky, the road, and the opposing wall are

$$F_{h\to s} = 0.5 - 0.5\left(\sqrt{\frac{w^2+h^2-w}{h}}\right) \tag{13a}$$

$$F_{h\to h} = \left(\sqrt{\frac{w^2+h^2-w}{h}}\right) \tag{13b}$$

$$F_{h\to w} = 0.5 - 0.5\left(\sqrt{\frac{w^2+h^2-w}{h}}\right) \tag{13c}$$

Eqs. (12a), (12b) and (13a)–(13c) counts for the view factor of the whole wall and the street. The view factor of these surfaces to the sky determines the diffuse irradiance arriving at these surfaces.