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Theory and procedure for measuring the solar reflectance of urban prototypes

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ABSTRACT

Solar radiation on urban surfaces is subjected to multiple reflections, which increase the solar absorption of these surfaces. Measuring the albedo of an urban area is important in order to estimate the solar absorption of the area and find engineered solutions for urban heat island mitigation. This study proposes a new approach to measure the albedo of the urban prototype. The approach measures the albedo of an urban prototype by sequentially covering a target area with a white solar-opaque mask, a black solar-opaque mask, and a black urban prototype, and the measured urban prototype, and while simultaneously measuring the incident radiation and reflected radiation over the target area. The errors of the albedo measurement depend on the albedo of the black urban prototype. The smaller this albedo is, the less the error. The proposed method can be used to measure the albedo of urban prototypes with high-reflective walls and high-reflective pavements.

1. Introduction

Urban surfaces primarily consist of building roofs, facades, and city streets. Solar radiation reaching these urban surfaces is subjected to the multiple reflections due to the three-dimensional features of the urban fabric [1–6]. In turn, this generates increased energy absorption that contributes to the urban heat island [1,7–9]. The urban surface albedo is defined as the ratio of the incoming to the outgoing shortwave radiation at the upper edge of the urban canopy layer. Measuring the albedo of an urban surface is important in estimating the solar absorption of the urban area and finding engineered solutions to mitigate the urban heat island effect [10–15].

Many numerical approaches have been proposed to simulate the albedo (or reflectivity) of the urban surface in order to characterize the solar absorption of urban areas [1,3,10,16–25]. One popular model is the SOLENE model, which was created by the CERMA Laboratory and was used to study the environmental aspects of urban and architectural projects [26–30]. This model is based on three-dimensional finite elements to calculate the albedo of different urban forms [22,27,31]. The albedo of urban surfaces can be also simulated by other sophisticated numerical methods [31–33] and other analytic approaches [25,27,34]. Due to the complexity of these numerical and analytic approaches, it is uneconomical to validate them against real-size urban models. However, it is feasible to do so by measuring the albedo of urban prototypes. Aida [35] measured the albedo of urban prototypes with different street orientations and found that the albedo of an urban prototype varied with time. Pawlak and Fortunaik [36] measured the albedo of an urban prototype and also found that the albedo of the prototype was a function of time.

The block-canyon model in the Aida's experiment is big in scale, although the experiment is expensive. While the size of Pawlak's canyon prototype is small, the measured albedo represents not only the reflectivity of the urban prototype, but also the albedo of the surroundings. To eliminate the contribution of the surrounding reflections on the measured albedo, Sailor et al. [37] proposed a techniques that used a shade ring with a diameter less than or equal to the diameter of the sample to shield the reflected radiation from the surroundings. Gattoni et al. [38] measured the albedo of an $1\,m^2$ sample by centering the sample on a standard bigger homogeneous background (e.g. $4 \times 4 m^2$). Akbari et al. [39] proposed a new method for measuring the albedo of a heterogeneous, curved, small surface by sequentially covering the surface with a white solar-opaque mask and a black solar-opaque mask, and then centering a pyranometer over the surface to read the reflected radiation. In this method, the curved surface should be bent within a limited degree

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such that the view factors from the pyranometer to the surface and to the masks (white and black) are the same. For an urban prototype, its edges are protruding so that the view factor from the lower pyranometer to the target is different from the view factor from the lower pyranometer to the prototype. Therefore, it is necessary to find a new method to measure the albedo of urban prototypes.

This study proposes a new, simplistic method to measure the albedo of the urban prototype. Different from the Akbari et al. [39] model, the proposed method introduces a black urban prototype that is the same configuration as the measured urban prototype. The albedo of the prototypes with the south-north orientation, west-east orientation, and cross-street orientation is measured, respectively. The proposed model is compared to the Akbari et al. [39] model. The application of the proposed model and the errors of the measurement are also discussed.

2. Theory

2.1. Albedo of homogeneous and heterogeneous surfaces

Albedo, or reflectivity, is quantified as the proportion of solar radiation of all wavelengths reflected by a body or a surface to the amount incident upon it. The albedo, ρ, of a homogeneous surface is

$$\rho = \frac{\int_{\lambda_0}^{\lambda_1} i(\lambda) r(\lambda) d\lambda}{\int_{\lambda_0}^{\lambda_1} i(\lambda) d\lambda} \tag{1}$$

where i represents the incident solar spectrum, W/m^2/nm; r is the spectral reflectance of the homogeneous surface; λ(m)is the wavelength; $\lambda_0 = 280$ nm and $\lambda_1 = 2500$ nm are usually considered.The albedo of a heterogeneous surface cannot be estimated by Eq. (1) alone though. If both the target model and the surroundings are Lambertian materials, the albedo of the target can be achieved by sequentially covering the surface with a white solar-opaque mask and a black solar-opaque mask [39] and by centering an albedometer over the target area to measure the reflected radiation and the incident radiation. The albedometer assembles two pyranometers back to back, with the lower pyranometer to measure the reflected radiation and the upper one to read the incident radiation. The reflections and the radiation obey

$$I_w = [\rho_w F + \rho_s (1-F)] I_{hw} \tag{2}$$

$$I_b = [\rho_b F + \rho_s (1-F)] I_{hb} \tag{3}$$

$$I_t = [\rho_t F + \rho_s (1-F)] I_{ht} \tag{4}$$

where I_w(W/m^2), I_b (W/m^2), and I_t(W/m^2) are the reading reflected radiation when the pyranometer is centered over the white mask, the black mask, and the target area, respectively; and I_{hw}(W/m^2), I_{hb}(W/m^2), and I_{hb} (W/m^2) are the horizontal global irradiance incident on the upper pyranometer, respectively. F is the view factor from the lower pyranometer to the target area. ρ_w, ρ_b, and ρ_s are the albedo of the white mask, of the black mask, and of the surroundings, respectively. The albedo of the target area, ρ_t, can be found by solving Eqs. (2)–(4).

2.2. Albedo of an urban prototype

Measuring the albedo of a real-size urban surface is not economical, but it is feasible to measure the albedo of an urban prototype, which is highly rough and heterogeneous so its albedo cannot be estimated by Eq. (1). Eqs. (2)–(4) cannot be directly used to measure the albedo of an urban prototype, either. The reason is that the edge of the prototype is protruding to a certain height so that the view factor, F', from the lower pyranometer to the prototype is different from F in Eqs. (2)–(4). That is, the new Eq. (4) is

$$I_t = [\rho_t F' + \rho_s \left(1-F'\right)] I_{ht} \tag{4}$$

In Eq. (4), the surrounding albedo ρ_s is found by solving Eqs. (2)–(3), both F' and ρ_t are unknown so ρ_t cannot be solved. To find ρ_t, we can introduce another equation by covering the target area with a black prototype that has the same configuration as the urban prototype. Assuming the albedo of the black urban prototype is ρ_{tb}, one has

$$I_{tb} = [\rho_{tb} F' + \rho_s \left(1-F'\right)] I_{htb} \tag{5}$$

where I_{tb} (W/m^2) is the reflected radiation received by the down-facing pyranometer; I_{htb} (W/m^2) is the global horizontal solar irradiance received by the up-facing pyranometer.

Solving for ρ_t, one gets

$$\rho_t = \frac{\left(\frac{I_t}{I_{ht}} - \frac{\rho_{bt} - \frac{I_{tb}}{I_{htb}}}{\rho_{bt} - \rho_s}\rho_s\right) \times (\rho_s - \rho_{tb})}{\frac{I_{tb}}{I_{htb}} - \rho_s} \tag{6}$$

where

$$\rho_s = \frac{\rho_w I_b / I_{hb} - \rho_b I_w / I_{hw}}{(\rho_w - \rho_b) - \left(I_w/I_{hw} - I_b/I_{hb}\right)} \tag{7}$$

The albedo of the black urban prototype, ρ_{tb}, is unknown because of the solar trapping effect of the urban prototype. However, multiple reflections are minimized because the black surface is highly absorptive. According to Berdahl et al. [40], the albedo of the black urban prototype is

$$\rho_{tb} = \frac{1 - p\rho}{\rho_{bm}} \tag{8}$$

where ρ_{bm} is the albedo of the surface of the blakc urban prototye (estimated by Eq. (1)) and p is the probability that a photon leaving a rough surface returns to it. p can be estimated from

$$p = 1 - S_1/S_2 \tag{9}$$

where S_1 is the nominal area of the surface and S_2 is the full exposed surface of the rough surface. The errors caused by this assumption will be examined in Section 5.

3. Experiments

Urban prototypes were prepared by anchoring 5 cm-cubic wood blocks on a 1 m × 1 m flat wood board. For comparison, a flat wood board without anchoring blocks was also prepared. To avoid the heterogeneous wood texture on the albedo measurement, the flat model and the urban prototype with unicolor was painted. The cubic wood blocks were arranged to a north-south orientation, a west-east orientation, and a cross-street orientation (Fig. 1). For the urban prototype at any orientation, the ratio of building height to street width was 1.0 and the width of the rooftop of the prototype was the same as the street width. Therefore, the corresponding p value of both north-south and west-east orientation prototypes was 0.5, and p value of the cross-street orientation was also 0.5.

The BADESE lacquer, a Chinese paint brand for building inner and outer walls, was used to paint the urban prototypes. Pigments can be added to the lacquer for different colors, including blue, green, yellow, black, white, and others colors. All painted surfaces were matte. The black urban prototype was painted with the dark-colored lacquer. The unicolor-painted wood blocks, as well as the black block, were submitted to a spectrophotometer Lamda 750 to test its spectral reflectance as shown in Fig. 2. Other than the black urban prototype, white and black masks were needed. Both