Energy and Buildings 114 (2016) 214–220

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Investigating performance prediction and optimization of spectral solar reflectance of cool painted layers

Shinichi Kinoshita*, Atsumasa Yoshida

Department of Mechanical Engineering, Osaka Prefecture University, l 1-1 Gakuen-cho, Naka-ku, Sakai 599-8531, Japan

A R T I C L E I N F O

Article history:
Received 24 April 2015
Received in revised form 29 June 2015
Accepted 30 June 2015
Available online 3 July 2015

Keywords:
Urban heat island
Painted layer
Reflectance
Numerical analysis
Radiative heat transfer

A B S T R A C T

The air temperatures are generally found to be higher in the urban areas in comparison with the suburban or rural areas. One of the countermeasures to mitigate this urban heat island is to coat the surfaces of buildings with paint that has higher solar reflectance; the method is commonly referred to as "cool painting". It is important to evaluate the solar reflectance of the paints used for such paintings. Though solar reflectance can be measured by a spectrophotometer with an integrating sphere, accurate numerical prediction of reflective properties of the painted layer including arbitrary pigments can contribute to further development of the cool paint material. The effect of diffuse reflection in the painted layer is more significant than that of specular reflection on the painted surface. It is also important to evaluate the scattering properties of pigments, which are related to the reflection performance. For evaluating the scattering properties of a pigment in a medium, anisotropic scattering should be considered. In this study, we applied the radiation element method for predicting the solar reflectance of a painted layer. The hemispherical spectral reflectance of a painted layer, including TiO_2, ZnO or Al_2O_3, was evaluated. Our results showed that spectral reflectance of a painted layer with arbitrary values of particle sizes, volume fraction of pigment, and coating thickness can be calculated by this method. Further, the validity of this numerical method was evaluated by comparison with the reflective property of the actual painted layer by means of spectrophotometry.

1. Introduction

In recent years, the heat island phenomenon, wherein the air temperature in the urban areas becomes higher than in the suburban and rural areas during summers, has resulted in problems such as a general decline in comfort, negative health effects and an increase in the energy consumption. As a countermeasure to tackle the heat island phenomenon and a reduction in the air-conditioning load, materials with high solar reflectance, the so-called "cool materials," are coated on building skins or road surfaces. Cool materials can decrease the sensible heat load to atmosphere and thermal storage in the building frames due to the solar radiation. Therefore, the cool paints with high solar reflection performance are typically applied to the roof surfaces. Santamouris [1] reviewed about the effect of control for urban heat island and improvement of comfort by applying reflective mitigation technology. It is very important to measure the solar reflectance of painted layer in order to evaluate its effects on the outdoor thermal environment. Synnefa et al. [2,3] evaluated the performance of cool paintings in the urban outdoor environments by measuring surface temperature of many samples coated with cool paints, containing different kinds of pigments, during daytime and nighttime. The performance was also evaluated from a long-term perspective by comparing the measured results for every month. Bretz et al. [4] measured the surface temperature and heat flux of the buildings where cool paint had actually been applied, and evaluated its effect in terms of power saved through air conditioning and the resulting economic benefits. Painted materials are often customized for the color tone or reflection performance as requested by the customers or depending on the surface of the object where they need to be applied. The solar reflectance can be measured by a spectrophotometer with an integrating sphere. A high precision numerical evaluation of the reflection performance of the painted layer, before its actual application, through simulation techniques is expected to contribute the progress and optimization of reflection performance of cool paints.

Solar radiation is affected by specular reflection, scattering, absorption and emission by the painted layer. The effect of diffuse reflection in the painted layer is generally higher than that of specular reflection at the surface of the layer. Therefore, it is very important to know the scattering properties of the pigment in order

* Corresponding author.
E-mail address: kinosita@me.osakafu-u.ac.jp (S. Kinoshita).

http://dx.doi.org/10.1016/j.enbuild.2015.06.072
0378-7788/

Symbol	Quantity [SI unit]
a_1	Forward scattering parameter [–]
d_p	Particle diameter [μm]
I_λ	Spectral radiation intensity [W/(μm m^2 sr)]
$I_{b\lambda}$	Spectral blackbody radiation intensity [W/(μm m^2 sr)]
k	Absorptive index of n [–]
m	Complex index of refraction ($n = m - ik$) [–]
n	Refractive index [–]
r	Position [m]
S	Geometric path length [m]
$\hat{s}$	Direction vector (unit vector) [–]
T	Temperature [K]
x	Size parameter of particle medium [–]
β_λ	Spectral extinction coefficient [1/μm]
β^*	Apparent extinction coefficient [1/μm]
$\phi(\hat{s}' \to \hat{s})$	Phase function from $\hat{s}'$ to $\hat{s}$ [–]
λ	Wavelength of electromagnetic wave [μm]
μ	Direction cosine [–]
Ω	Solid angle [sr]
ω_λ	Spectral scattering albedo [–]
ω_D	Corrected scattering albedo [–]

to evaluate the painted layer; pigments are generally considered to be isotropic in terms of scattering properties. However, existing numerical solutions often do not consider isotropic scattering in the medium. For example, one of the most popular continuum models is the two-flux theory introduced by Schuster [5] and popularized by Kubelka and Munk [6]. The Kubelka-Munk model describes the one-dimensional, bidirectional propagation of diffuse light through a film. Levinson et al. [7] suggested a model for deriving scattering and absorption coefficients from spectral transmittance and reflectance measurements. Details of the angular dependence of the radiative transfer are neglected. Kunitomo et al. [8–12] evaluated the radiative performance of a painted layer by solving the radiation transfer equation with precision. For example, radiative properties of painted layers containing spherical particle are analyzed in the case of normal incidence [8] and in the cases of oblique and hemispherical incidences [9]. Other such examples of the numerical simulations include evaluation of the reflection properties of optically thick medium in the case of normal incidence [10] and painted layer with two-layer structure [11], and the scattering and absorption characteristics of fine-particle disperse medium [12].

In this study, Radiation element method [13] was used to predict solar reflectance because it is a simple method and can consider various conditions including isotropic scattering. In this method, the computation time is short and thermal radiation field can be analyzed under flexible boundary conditions. By taking into account the anisotropy of the scattering medium, we intend to improve the accuracy of our analysis. In addition, the applicability of the numerical method was evaluated by comparing the results of spectral reflectance of actual painted layer by means of spectrophotometry. One of the goals of this study is to analyze the painted layers that have several pigments or multilayer structure and to realize the optimal design for the painted layer.

2. Numerical method

2.1. Fundamental equations

In this analysis, the participating medium in a plane-parallel system is applied. The spectral radiation intensity I_λ at position $\boldsymbol{r}$ in direction $\hat{s}$ can be expressed as follows.

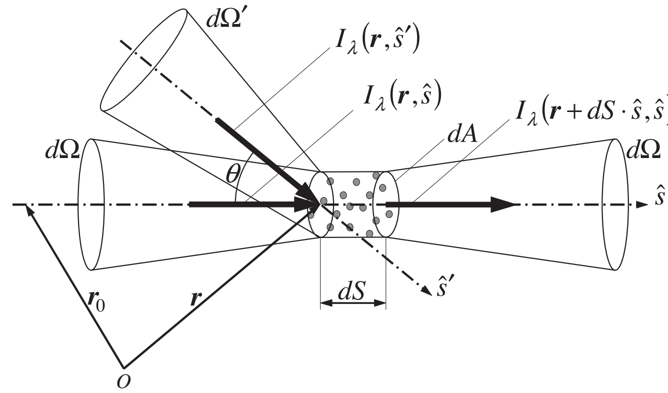

Fig. 1. Schematic diagram for radiation energy balance in a local volume element.

$$\frac{dI_\lambda}{dS} = \beta_\lambda \left[-I_\lambda(\boldsymbol{r}, \hat{s}) + (1-\omega_\lambda) I_{b\lambda}(T) + \frac{\omega_\lambda}{4\pi} \int_{4\pi} I_\lambda(\boldsymbol{r}, \hat{s}') \phi_\lambda(\hat{s}' \to \hat{s}) d\Omega' \right] \quad (1)$$

where β_λ and ω_λ are the spectral extinction coefficient and the scattering albedo of the medium, respectively. S is the path length in the direction $\hat{s}$, $\phi_\lambda(\hat{s}' \to \hat{s})$ is the phase function from the direction $\hat{s}'$ to $\hat{s}$, which is the angular distribution of light intensity by a particle and is given at scattering angle based on the incident light (Fig. 1). $I_{b\lambda}(T)$ is the blackbody radiation intensity; Ω is the solid angle; and T is temperature of the medium. As plane-parallel system has circumferential symmetry, Eq. (1) can be transformed as

$$\frac{dI_\lambda(z, \mu)}{dS} = \beta_\lambda \left[-I_\lambda(z, \mu) + (1-\omega_\lambda) I_{b\lambda}(T) + \frac{\omega_\lambda}{2} \int_{-1}^{1} I_\lambda(z, \mu') \phi_\lambda(\mu') d\mu' \right] \quad (2)$$

where μ is the direction cosine, $\mu \equiv \cos\theta$, and $\mu' \equiv \hat{s}' \cdot \hat{s}$.

2.2. Mie theory and anisotropic scattering

The radiative properties of a single homogeneous spherical particle are calculated according to Mie theory. These properties depend on complex refractive index ($m = n - ik$) and diameter d_p of the pigment particles and the wavelength of the incident electromagnetic wave λ. The size parameter x is defined as follows.

$$x = \frac{\pi d_p}{\lambda} \quad (3)$$

From these parameters, spectral extinction coefficients, albedos and phase functions of the particles can be obtained. To perform the Mie calculation, the ratio method [14] is used. In this study, the results of the Mie calculation were corrected in order to consider anisotropic scattering in media. Then forward scattering parameter a_1 was defined as follows.

$$a_1 = \frac{3}{2} \int_{-1}^{1} \phi_\lambda(\mu) \mu d\mu \quad (4)$$