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Numerical simulation of white double-layer coating with different submicron particles on the spectral reflectance

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ABSTRACT

The spectral selective coating is becoming more and more popular against solar irradiation not only in keeping the coated objects stay cool but also retain the appearance of the objects by reducing the glare of reflected sunlight. In this work a numerical study is investigated to design the double-layer coating with different submicron particles to achieve better performance both in thermal and aesthetic aspects. By comparison, the performance of double-layer coating with TiO_2 and ZnO particles is better than that with single particles. What's more, the particle diameter, volume fraction of particle as well as substrate condition is also investigated. The results show that an optimized double-layer coating with particles should be the one with an appropriate particle diameter, volume fraction and the black substrate.

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1. Introduction

Spectral selective coatings have a wide range of applications where it is desirable to cool objects exposed to incident irradiation from a high-temperature source. The most common situation in our daily life lies in that the exteriors of buildings have large absorption of solar irradiation mainly in the visible (VIS) and near-infrared (NIR) regions. Therefore, the interior temperature of such objects becomes high and the cooling load increases. Increased urban temperatures exacerbate the consumption of energy for cooling purposes, increase the peak electricity demand, intensity pollution problems and cause human discomfort and health problems [1,2]. Roof surfaces of the building accounts for the 20–25% of the total urban surface, hence they can potentially use to reduce the temperature of interior of buildings [3]. The spectral selective coatings are designed to achieve high spectral reflectance across the solar spectrum (0.3–2.5 μm [4,5]) and minimize heat transfer to the interior of the coated objects.

The use of cool pigmented coatings on exteriors has been widely investigated. Vargas et al. [6] considered thermal optimization of particle diameter and volume fraction, paying attention to the radiation characteristics of particles group and diffuse reflectance of titanium dioxide (TiO_2). Levinson et al. [7,8] studied the suitability of a pigment for inclusion in cool paints with solar reflectance. Baneshi et al. [9–12] investigated the performance of TiO_2 used as the pigment to maximize the reflectivity of the near-infrared (NIR) region to reduce thermal heating and minimize the visible (VIS) reflected energy received by human eyes for aesthetic appeal. It should be noted that TiO_2 is the most widely used white pigment because of its very high refractive index. In addition, Baneshi et al. [13] investigated the black-color coating with copper oxide (CuO). Just recently, Cheng et al. [14] studied the double-layer coating with CuO particles of different volume fractions.

However, dark tones, such as black, are used largely from an esthetic viewpoint or to make dirt harder to see. The conventional black pigments (carbon black, iron oxide black, or complex inorganic) are highly absorbing against sunlight. Rooms applied these dark coatings get warmer than white rooms in the summer, thus, increasing cooling loads. On the other hand, the white paint which strongly reflects the irradiation across the solar spectrum is applied to exteriors of buildings; those surfaces absorb less sunlight and thus reduce the cooling load. This type of coating is best suitable for low-slope roofs visible neither from ground level nor from taller building [15].

To the best of our knowledge, in most of the published literature available so far, there appear few papers that described the double-layer coating with different white submicron particles. This study numerically investigates the TiO_2 and ZnO particles dispersed in one coating by the DRESOR (Distribution of Ratios of Energy Scattered by the medium Or Reflected by the boundary surface) method [16–19], which has been validated the accuracy of solving the coating problem [14]. Although in reality powders of different-size particles are formed, in this study we assumed monodisperse particles in a non-absorbing matrix to more directly compare the performance of different pigments. The spectral reflectance of a pigmented coating strongly depends on the amount

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Nomenclature

d	particle diameter, μm
f_v	volume fraction distribution
g	asymmetry factor
k	extinction coefficient
L	thickness of the coating, μm
m	complex refractive index
n	refractive index
N	discrete number of elements within the medium
N_T	number density of particles
$Q_{abs,\lambda}$	absorption efficiency factor
$Q_{ext,\lambda}$	extinction efficiency factor
$Q_{sca,\lambda}$	scattering efficiency factor
R_{opt}	optimization parameter
x, y, z	normalized color coordinate
$\bar{x}, \bar{y}, \bar{z}$	color-matching function
Y	brightness of the coating

Greek letters

θ	scattering angle
κ_λ	spectral absorption coefficient, 1 /m
ρ	spectral reflectivity
σ_λ	spectral scattering coefficient, 1 /m
Φ_λ	scattering phase function

Subscripts

0	left surface
$N+1$	right surface

of absorption and back-scattering of light by suspended pigment particles [20]. The radiative properties of single TiO_2 and ZnO submicron particles in a wide range of wavelength and particle size in a non-absorbing resin are calculated based on the Mie theory [21]. The influences of arrangement of different particles in the coating, volume fraction distribution of particles, particle diameters and substrate conditions on the spectral reflectance are also investigated.

2. Methodology

2.1. Radiative properties of single particles of TiO_2 and ZnO

Obeying the Mie theory, the radiative properties of the particles, such as phase function, extinction efficiency factor $Q_{ext,\lambda}$ and scattering efficiency factor $Q_{sca,\lambda}$ can be calculated [21]. The spectral distributions of complex refractive index of TiO_2 [22] and ZnO [23] particles in the range of 0.3–2.5 μm with a logarithmic scale are shown in Fig. 1, which is important for the calculation of the radiative properties.

After the radiative properties of a single particle are obtained, the scattering and absorption coefficients for a group of monodispersed particles can be easily computed assuming independent scattering regime as follows [9]:

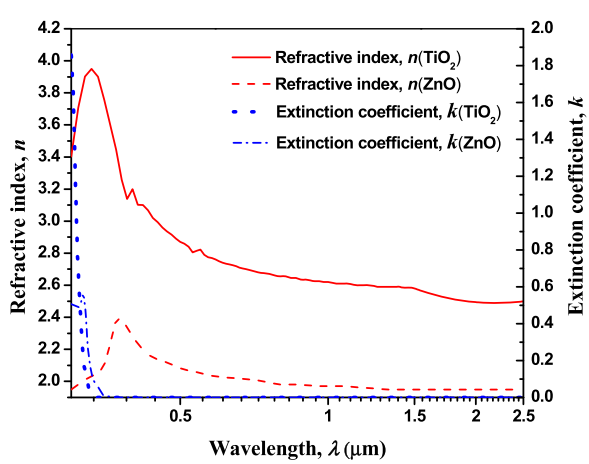

Fig. 1. Real and imaginary parts of the complex refractive index of TiO_2 and ZnO.

$$\sigma_\lambda = N_T \frac{\pi d^2}{4} Q_{sca,\lambda}, \tag{1}$$

$$\kappa_\lambda = N_T \frac{\pi d^2}{4} Q_{abs,\lambda}, \tag{2}$$

$$f_{v,cal} = N_T \left(\frac{\pi d^3}{6} \right), \tag{3}$$

where d is the particle diameter, $f_{v,cal}$ is the particle volume fraction and N_T is the number density of particles.

2.2. Definition of the optimization parameter and color evaluation

In order to reduce the glare or brightness of a pigmented coating system, it is necessary to reduce the reflectance throughout the VIS region from 0.38 to 0.78 μm. Based on this, the aesthetic performance is defined using the following equation:

$$\rho_{VIS} = \frac{\int_{0.38}^{0.78} \rho(\lambda)\bar{y}(\lambda)I(\lambda)d\lambda}{\int_{0.38}^{0.78} I(\lambda)d\lambda}. \tag{4}$$

Here, $I(\lambda)$ is the solar irradiation, $\bar{y}(\lambda)$ is one parameter in color matching function [24] and $\rho(\lambda)$ is the spectral reflectance of the pigmented coating.

The performance parameter of pigmented coating for the total spectral reflectance (TSR) in the solar spectrum region is proposed as follows:

$$\rho_{TSR} = \frac{\int_{0.30}^{2.50} \rho(\lambda)I(\lambda)d\lambda}{\int_{0.30}^{2.50} I(\lambda)d\lambda}. \tag{5}$$

After ρ_{TSR} and ρ_{VIS} are obtained, the optimization parameter can be calculated as follows:

$$R_{opt} = \frac{\rho_{TSR}}{\rho_{VIS}}. \tag{6}$$

In order to have an optimized coating, the parameter R_{opt} should be maximized.

For color characterization, we conducted a color analysis according to the International Commission on Illumination (CIE) system, which consists of a luminance parameter Y and two color coordinates x and y. The coordinates are found from the following

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