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A new approach to optimizing pigmented coatings considering both thermal and aesthetic effects

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ABSTRACT

Pigmented coatings with high reflectivity against solar irradiation can be used to control unwanted thermal heating that occurs as materials absorb sunlight such as heat in buildings that increases cooling loads. However, these surfaces produce glare that is unpleasant to the eye, and the coatings themselves can damage the appearance of the coated object. We introduce a new optimization method that embraces both thermal and aesthetic requirements. Our proposed coatings maximize the reflectivity of the near infrared (NIR) region to reduce thermal heating, while for aesthetic appeal they also minimize the visible (VIS) reflected energy received by human eyes, especially at wavelengths where eye sensitivity is high. The optimization parameter is defined as the ratio of the total reflected energy in the NIR region to that in the VIS region weighted by human eye sensitivity. Titanium dioxide is used as the pigment, and databases of its radiative properties are constructed using the Mie theory. To compute reflectivity, nongray radiative heat transfer in an anisotropic scattering monosized pigmented layer, with independent scattering, including direct and diffuse solar irradiations, is analyzed using radiation element method by ray emission model (REM^2). Colors are calculated and optimization parameter is evaluated by using spectral reflectivity. Finally, the optimum values of particle size, volume fraction of pigment, and coating thickness are obtained.

1. Introduction

High-intensity solar irradiation can potentially raise temperatures inside cars and buildings when their exterior surfaces absorb solar energy. Such unwanted heating increases cooling loads. To overcome this problem, the use of cool pigmented coatings on exterior surfaces has been proposed. Various technological applications use pigmented coatings to increase diffuse reflectance under illumination with visible (VIS) or near infrared (NIR) radiation.

Johnson et al. [1] optimized the grain size distribution of zinc oxide pigment in a thermal control coating (TCC) used for spacecraft walls in order to attain maximize diffuse solar reflectance at a lower film thickness, and reduce the pigment volume concentration. Moreover, Vargas [2] considered thermal optimization of particle diameter and volume fraction paying attention to the radiation characteristics of a particle group and to diffuse reflectance of titanium dioxide pigmented coating. Dombrovsky et al. [3] studied the infrared radiative properties of a polymer containing hollow glass microspheres used for the development of heat-insulating coatings to reduce night time heat loss from the walls of buildings.

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Solar-reflective nonwhite surfaces and their applications to residential roofing materials were studied by Levinson et al. [4].

Those studies dealt mainly with radiation from the viewpoint of heat transfer. On the other hand, in the pigmented coatings that those studies examined, optimization is concerned only with thermal performance by maximizing solar reflectance in the NIR region or in both the VIS and NIR spectra. However, the glare that such coatings reflect, such as on cars and rooftops, can be unpleasant to the eye, and the coatings themselves may be visually unappealing.

Conventionally, dark tones, such as black, are used abundantly from an esthetic viewpoint or to make dirt harder to see. However, since black's absorptivity to sunlight is high, dark rooms get warmer than white rooms in the summer, thus increasing cooling loads. On the other hand, when white paint, which strongly reflects both VIS and NIR radiation, is applied to exterior surfaces such as roofs, those surfaces absorb less sun and relatively reduce the cooling load. However, white paint reflects visible light (VIS), and the glare can offend the eye and make the object less appealing to look at. The remedy to this problem is to minimize the reflected sunlight. Thus we are simultaneously dealing with two subjects: increasing reflectance to reduce unwanted heating and decreasing glare to improve aesthetic appeal. The authors aim to develop a method for optimization both the thermal and aesthetic aspects of pigmented coatings.

Approximately 40% of sunlight energy is NIR light and it is possible to reduce sunlight absorption of outer wall materials sharply by reflecting this light. Also, although the ultraviolet (UV) rays in sunlight account for about 5% of solar energy, they destroy the molecular bond of organic matter, such as plastic, and this degrades paint film. In addition, when sunlight is strong, air conditioning becomes more efficient by the transmission of long-wavelength infrared (IR) rays with a wavelength of about 10 μm emitted from the body surface of a building, car, etc. From this background, our desired coating reflects UV and NIR radiation well, decreases the reflectance of VIS radiation, and transmits long-wavelength infrared radiation as shown in Fig. 1. Here we only consider the optimization of pigmented coatings against the VIS and NIR regions which contain 95% of sunlight. We introduce a parameter, R, as the ratio of solar reflected energy in the NIR region to the reflected energy in the VIS region weighted by the standard visual sensitivity of the human eye. To achieve an optimum coating, this parameter should be maximized.

This paper aims to realize a pigmented coating that controls radiation by optimizing the size, volume fraction and film thickness of particles. Since the purpose of this paper is just to introduce a new method of optimizing of pigmented coatings both thermally and aesthetically, a simple coating made of monosized spherical pigments in a nonabsorbing matrix with independent scattering is considered. Also, titanium dioxide, a common pigment used in paints, is used as the pigment.

To calculate the radiative properties of a titanium dioxide particle, Maxwell equations must be solved at each wavelength and diameter [5]. This process requires a particularly long CPU time. Hence, as proposed by Maruyama et al. [6], at first we construct databases of the radiative properties of titanium dioxide over a wider range of wavelength and diameter. When nongray radiative heat transfer analysis is conducted, the radiative properties can be obtained quickly by interpolating the values from these databases [6]. Next, in order to find the reflectivity of the coated system against solar irradiation and to examine the influences of effective parameters on it, we conduct a radiation thermal analysis using the radiation element method by ray emission model (REM^2) [7–9]. Finally, the tristimulus values and corresponding color coordinates [10] are calculated. The effects of particle diameter, volume fraction and film thickness on optimization parameter R and on the color coordinates are discussed for titanium dioxide pigmented coatings.

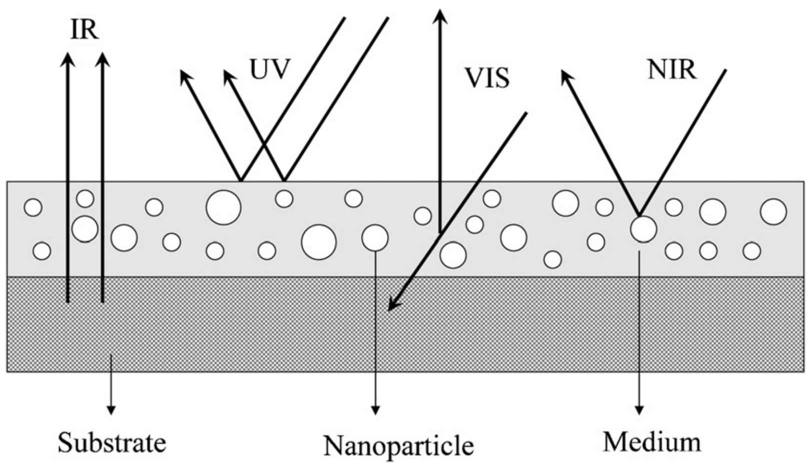

Fig. 1. Schematic diagram of a pigmented coating using nanoparticles to maximize the reflectance of UV and NIR regions of sunlight, minimize the reflectance of VIS region, and transmit IR wavelengths.