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Prediction of the radiative properties of surfaces covered with particulate deposits

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ABSTRACT

The heterogeneous particulate deposit has a significant impact on the radiative properties of surfaces. It is necessary to establish a physical model to describe the apparent spectral absorptance of surfaces covered with heterogeneous particulate deposits. In this paper, a general method combining the effective medium theory with the RTM-DRE (ray-tracing method based on the decomposition of radiation energy) method is presented to predict the apparent spectral absorptance of such surfaces. The effective optical constants of the inhomogeneous particles were determined by means of the effective medium theory, whereas the radiative properties of the surfaces were calculated by modeling the radiative transfer process based on the RTM-DRE method. Additionally, the experimental characterizations of the dust deposits were investigated to reveal the dust effect on the radiative properties of surfaces, and the experimental data and theoretical results were compared to validate the presented theoretical model. The mean relative errors lie within 11.0% of the solar band and 7.0% of the infrared waveband, which indicates the reliability of the theoretical model. Furthermore, the effect of the geometric structure parameters and material intrinsic properties on the radiative properties of the surfaces with heterogeneous particulate deposit was investigated based on the prediction model. Six main factors including the deposit thickness, particle size, bulk fraction, chemical compositions, H_2O content, and substrate reflectance were considered.

1. Introduction

The optical properties of surfaces play a critical role in determining the thermal radiation features of surfaces and are widely involved in a variety of industrial and engineering applications such as in electric power [1], chemical [2], agriculture and food [3], medical [4,5] industry, IR detection [6], and solar cell panels [7–9]. Extensive investigations indicate that the management of the optical properties of different surfaces is an effective way of meeting the requirements of different applications. In the field of solar energy utilization, solar panels are designed with a microstructure to attain strong absorption performance in the solar band and high reflective feature in the far IR band, thereby improving the capture and utilization of solar energy. In military applications, most military equipment is coated with stealth coatings to enhance the stealth performance in the IR band. However, under actual operational conditions, the solar panels are likely to be polluted or deposited upon by aerosol particles or dust due to the serious haze condition, sand storm, or flying dust weather conditions in many regions in China, thereby resulting in the decrement of the solar cell efficiency [10,11]. The surfaces of military equipment in complicated environments are commonly deposited upon by sand dust or flying dust particles from the rapid movement of equipment, which consequently impacts the original radiative properties of these surfaces and results in stealth performance loss and uncertainty of target detection and recognition. Hence, it is evident that the particulate deposits (dust, aerosol particle, coal ash, etc.) have a great impact on the radiative properties of surfaces.

Particulate deposits mainly affect the radiative properties of surfaces via two aspects. On one hand, the randomly stacked particles inside the deposit possess optical scattering and absorbing effects, thereby resulting in the variation of the radiative properties of surfaces. On the other hand, reflection from both the substrate and the upper interface of the particulate deposit complicates the radiative transfer inside the deposit and alters the radiative properties of the surfaces. Six main factors, namely the deposit thickness, particle size, bulk fraction, chemical compositions, H_2O content, and substrate

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reflectance, affect the radiative transfer process of the electromagnetic wave inside the particulate deposit. Therefore, the present study focused on the following two aspects to model the apparent radiative properties of surfaces covered with particulate deposit given that these also represented the core difficulties in this work: (1) Estimate the optical constants of the heterogeneous particles; and (2) model the radiative transfer processes within the particulate deposit. The present study, without loss of generality, categorized dust as the primary research object.

Natural dust, aerosol, and haze are generally considered inhomogeneous mediums. The optical constants, particularly the absorption index *k*, mostly depend on the chemical compositions. Approaches for the determination of the optical constant of an inhomogeneous medium can be divided into three categories: the ellipsometry method, the inversion method, and the effective medium theory. The ellipsometry method is one of the most widely used approaches for the direct measurement of the optical constants of various thin films and solid materials [12–15]. Xing et al. [16] prepared the samples on a glass substrate to form a particulate film and measured the complex refractive indices of the soot particles by the ellipsometry method. However, the reliability of the measurements primarily depended on the accuracy of the structure modeling and the material dispersion relation [17]. For particulate deposits, it is difficult to establish the physical model of the particulate film because the stacking structure of particles is randomly accumulated. Therefore, this method is unsuitable for the determination of the optical constants of particulate deposits. In addition, certain appropriate inversion models that are based on the transmittance measurements of the dilute liquid suspensions of the particles or solid pellets were proposed to deduce the optical constants of the particles. Ku and Felske [18] proposed a transmission method to determine the spectral refractive indices, size, and number density of the soot particles from the light scattering spectral extinction measurements in flames. Goodwin et al. [19,20] calculated the complex refractive indices of coal slags and fly ash from the obtained transmittance and reflectance measurements carried out on thin polished glassy slag wafers at room temperature within the visible wavelengths to infrared waveband range. Ruan et al. [21,22] presented a technique for determining the optical constants of fly ash particles from the spectral transmittance measurements, in which the complex refractive index was estimated based on the spectral transmittance distribution of a fly ash particle cloud present in potassium bromide (KBr) pellets combined with the precise Mie theory and the Kramers-Kronig (K-K) relation. Nevertheless, an inevitable multivalue complex refractive index problem limits the application of the inverse model under certain circumstances. Therefore, the effective medium theory can be applied to determine the effective optical constants of these particles only if the optical constants and the contents of the chemical compositions in the inhomogeneous particles are given. Multiple optical mixing rules were generated for the determination of the effective refractive indices of mixed systems, of which the Maxwell Garnett (MG) and Bruggeman mixing rules are commonly used [23]. Bohren and Huffman [24] investigated the refractive indices of heterogeneous particles by these two mixing rules. Freedman et al. [25] utilized the MG and the Bruggeman mixing rules to calculate the optical constants of internally mixed aerosol particles composed of dicarboxylic acids and ammonium sulfate.

The apparent radiative properties, particularly the absorptance or emittance, of surfaces covered with particulate deposit have been experimentally and theoretically studied. Baxter et al. [26] examined the spectral emission characteristics of coal collected from narrowly sized classified samples of coal and graphite placed on a heated NaCl window in temperatures ranging from 120 to 200 °C using Fourier transform infrared (FTIR) spectroscopy. Saljnikov et al. [27,28] measured the thermal radiation properties of ash deposits on the pulverized coal boiler of an electric power plant. The observed ash powder layers were opaque under infrared radiation and the spectral emittance increased with increasing wavelength increments. Boow and Goard [29] measured the emittance of the glass powder and laboratory-prepared boiler ashes of different sizes, and derived an empirical formula to describe the relationship between the optical properties and the particle diameter. Bhattacharya et al. [30] developed a novel approach based on the discrete ordinates method (DOM) to predict the spectral emittance of semi-transparent and opaque particulate deposits. Furthermore, Bhattacharya et al. [31] investigated the influence of optical constants and particle size on the radiative properties and heat transfer involving ash clouds and deposits by considering the true nature of the ash cloud and deposit based on the DOM. However, they neglected the dependent scattering of particles, which is generated from the scattering between adjacent particles. Ruan et al. [32] applied the Monte Carlo (MC) method to calculate the radiative transfer in a non-gray medium using the spectrally radiative exchange factor.

In this work, a general approach combining the effective medium theory with RTM-DRE (ray-tracing method based on decomposition of radiation energy) is presented to simulate the apparent spectral absorptance of surfaces covered with particulate deposit and evaluate the effects of the dust on the radiative properties of the surface. The article is organized as follows. Firstly, the effective medium theory in the forms of the MG and the Bruggeman mixing rules is applied to derive the effective optical constants of dust particles of multiple compositions, in which the composition contents are analyzed precisely by XRF technique. Thereafter, a novel physical model combined the RTM-DRE with the MIE and effective medium theories is established to estimate the apparent spectral absorptance of particulate-deposited surface. The particulate deposit is treated as an effective medium. The experimental radiative properties of the dust-deposited surface are then measured to simultaneously validate the prediction model of the apparent absorption properties of surfaces with particulate deposits. Lastly, the impacts of the deposit thickness, size distribution, particulate bulk fraction, Fe_2O_3 content, H_2O content, and substrate reflectance on the radiative properties of the surface are theoretically investigated.

2. Experimental characterization of dust particles and deposits

2.1. Characterization of dust particles

Three types of dust samples listed in Table 1 were collected in Nanjing and Fengyang in China, respectively. Moreover, the chemical compositions of the dust samples were measured at the State Key Laboratory for Mineral Deposits Research, Nanjing University using the ARL 9900 X-ray Fluorescence (XRF) Spectrometer (Thermo Fisher, Inc., Waltham, MA, United States). The abbreviated terms of the dust samples, namely NJES-D, NJEC-D, and AHFY-D, represent street dust from East Nanjing, the construction site dust from East Nanjing, and the flying dust driven by the running vehicle from the wild fields of Fengyang, Anhui, respectively. It is evident from [19] that the components analyzed from the XRF in Table 1, such as Al_2O_3, Fe_2O_3, CaO, MgO, and MnO, were taken as the chemical compositions of the coal slags. Nevertheless, for the numerical determination of the optical constants of the coal slags and aerosol particles, SiO_2, Al_2O_3, Fe_2O_3, and CaO were treated as the dominant oxide components [22,31]. However, these particles invariably contain the composition of the organic substance, which can be treated as the loss on ignition (LOI) in the XRF test. The present study assigned LOI as one of the dominant dust