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The statistical average of optical properties for alumina particle cluster in aircraft plume

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ABSTRACT

We establish a model for lognormal distribution of monomer radius and number of alumina particle clusters in plume. According to the Multi-Sphere T Matrix (MSTM) theory, we provide a method for finding the statistical average of optical properties for alumina particle clusters in plume, analyze the effect of different distributions and different detection wavelengths on the statistical average of optical properties for alumina particle cluster, and compare the statistical average optical properties under the alumina particle cluster model established in this study and those under three simplified alumina particle models. The calculation results show that the monomer number of alumina particle cluster and its size distribution have a considerable effect on its statistical average optical properties. The statistical average of optical properties for alumina particle cluster at common detection wavelengths exhibit obvious differences, whose differences have a great effect on modeling IR and UV radiation properties of plume. Compared with the three simplified models, the alumina particle cluster model herein features both higher extinction and scattering efficiencies. Therefore, we may find that an accurate description of the scattering properties of alumina particles in aircraft plume is of great significance in the study of plume radiation properties.

1. Introduction

Recently, with the emergence of various new aircraft types (e.g., hypersonic vehicle and subsonic vehicle), the radiative properties of aircraft plume have received widespread attention. Rialland et al. [1] studied the infrared radiation model of aircraft plume and compared it with the infrared measurement results. Gimelshein et al. [2] established a UV radiation model for high-temperature two-phase aircraft plume, and compared the simulation results with UV measurement data. Kim et al. [3] discussed a heat radiation model of aircraft plume. Blanc et al. [4] and Devir et al. [5] also analyzed the UV and infrared radiation features of aircraft plumes and compared them with the experimental results. Zhang and Chen [6] discussed the infrared radiation properties of solid rocket engine plume. Huang et al. [7] investigated the UV radiation properties of missile plume.

An aircraft plume is a medium that is capable of emitting, absorbing and scattering, and its scattering has a great influence on the detected intensity [8]. When studying the UV radiation properties of plume, Neele and Schleijpen argued that ignoring the scattering properties of alumina particles in the tail flame will result in an underestimation of the visibility of plume [9,10]. In simulating the UV radiation properties of aircraft plume, Robert et al. concluded from the experimental data that the radiance of the alumina particles accounted for 25% of the total radiance, indicating that particle scattering should not be neglected when researching the properties of the aircraft's UV radiation [11]. Gimelshein et al.'s research shows that the alumina and soot particles have a significant effect on the scattering process of plume, posing a great influence on the prediction of UV radiation properties [2]. Based on the above conclusions, we may find that an accurate description of the scattering properties of alumina particles in aircraft plume is of great significance to studying the plume radiation properties.

In modeling the radiation properties of aircraft plume, the closer the alumina particle model is to the real status of alumina particles in the plume, the more accurate the simulation results of the radiation properties are. In earlier studies, alumina particles in plume were often simplified to spheres [12,13]. However, according to alumina particles scanning electron microscopy results [14], we will know that the alumina particles in plume often agglomerate into clusters. Moreover, both the number and radius of monomer for the alumina particle clusters in plume conform to logarithm normal distribution [15,16]. Based on different algorithms (e.g., Monte Carlo method [17], Discrete coordinate method

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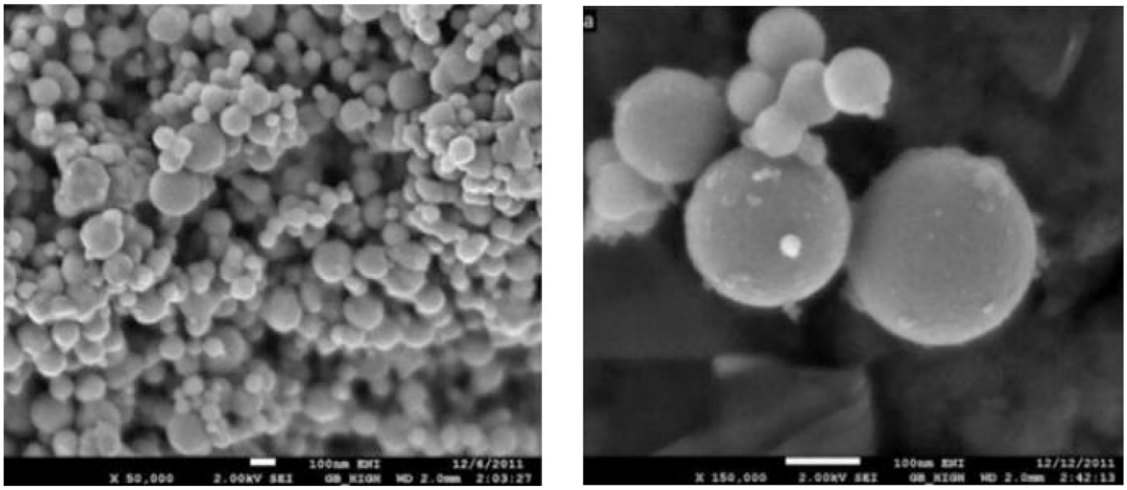

Fig. 1. Scanning electron microscope pictures of collected alumina particle clusters [23].

[18] and spherical harmonic discrete coordinate method [19]) for solution of radiative transfer equation, the optical properties of particle (e.g., scattering phase function, asymmetry factor, single scattering albedo and extinction coefficient) are used. During the calculation process, the optical properties of the particle are chosen in one of the following two ways: one is choosing optical properties of a single particle in plume, the other is choosing the statistical average optical properties of the particles in plume. When the optical properties of single particles are chosen for finding the plume radiation properties, the simulation is closer to the actual situation. However the number of alumina particles is very numerous (more than one million particles [20]). In that case, if only a small number of particles are chosen, it is difficult to come to an effective conclusion. Yet, if a larger number of particles are chosen, the calculation will take a long time. Therefore, the choice of using statistical average optical properties of alumina particles can substantially reduce required computational time [21]. However, to the best of our knowledge, no literature has yet calculated the statistical average optical properties of the alumina particle cluster which the radius and number of monomer both follow lognormal distribution at present. Therefore, we mainly study the statistical average of optical properties for alumina particle clusters in plume in this thesis, which will lay a foundation for further study on the radiative transfer properties of plume.

This thesis falls into four parts. In the second part, a model for lognormal distribution of monomer radius and number of alumina particle clusters in plume is established based on the experimental measurement results. Moreover, an algorithm for finding the statistical average optical properties in the model is given. In the third part, the statistical average of optical properties for alumina particle clusters following different distribution are discussed, and the effect of common detection wavelengths on such properties is analyzed. Then comparison is made between the statistical average optical properties in this alumina particle cluster model and the statistical average optical properties in the three simplified models. The fourth part is the conclusion of this study.

2. Methodology

2.1. Model for alumina particle clusters with monomer radius and number meeting a lognormal distribution

Alumina particles in plume often agglomerate into clusters. According to the proportion of alumina surface's tension and shear force, when the fundamental particle number is more than 20, the alumina cluster usually rupture occurs [16]. Fig. 1 shows the experimental collection of alumina particle clusters in plume as well as their electron microscope pictures. The number of the monomer Ns follows the lognormal distribution, its probability density function $P_n(Ns)$ is expressed as follows:

$$P_n(Ns) = \frac{1}{\sqrt{2\pi}\,Ns\ln(\sigma_g)}\exp\left[-\left(\frac{\ln(Ns)-\ln(N_g)}{\sqrt{2}\ln(\sigma_g)}\right)^2\right] \quad (1)$$

where the number geometric mean N_g is 10, the number geometric standard deviation σ_g is 1.5 in the plume of larger booster motors. The radius of monomer r follows a lognormal distribution with the radius geometric mean r_g being 100 nm and the radius geometric standard deviation σ_g being 1.5, its probability density function $P_r(r)$ is expressed as follows [22]:

$$P_r(r) = \frac{1}{\sqrt{2\pi}\,r\ln(\sigma_g)}\exp\left[-\left(\frac{\ln(r)-\ln(r_g)}{\sqrt{2}\ln(\sigma_g)}\right)^2\right] \quad (2)$$

2.2. Algorithm for finding statistical average optical properties of alumina particle cluster

Studies by Simmons [24] have shown that a large number of alumina particle clusters are distributed in aircraft plume, and both the monomer radius and number in these clusters follow a lognormal distribution. Therefore, in order to investigate the statistical average of optical properties for alumina particle clusters, we first need to find the optical properties of a single alumina particle cluster, and then based on the distribution of monomer radius and number, we find the statistical average of optical properties for alumina particle clusters. Detailed calculation steps are shown in Fig. 2.

Step 1: Calculate the optical properties of a single alumina particle cluster

According to the improved DLA algorithm in reference [15], we can obtain a model for a single alumina particle cluster in plume. The structure and morphology of each alumina cluster can be described by the following formula:

$$Ns = k_f\left(\frac{R_g}{a}\right)^{D_f} \quad (3)$$

$$R_g^2 = \frac{1}{Ns}\sum_{j=1}^{Ns} r_j^2 \quad (4)$$

$$a = \frac{1}{Ns}\sum_{k=1}^{Ns} r_k \quad (5)$$