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Scattering properties of alumina particle clusters with different radius of monomers in aerocraft plume

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ABSTRACT

In this paper, diffusion limited aggregation (DLA) algorithm is improved to generate the alumina particle cluster with different radius of monomers in the plume. Scattering properties of these alumina clusters are solved by the multiple sphere T matrix method (MSTM). The effect of the number and radius of monomers on the scattering properties of clusters of alumina particles is discussed. The scattering properties of two types of alumina particle clusters are compared, one has different radius of monomers that follows lognormal probability distribution, another has the same radius of monomers that equals the mean of lognormal probability distribution. The result show that the scattering phase functions and linear polarization degrees of these two types of alumina particle clusters are of great differences. For the alumina clusters with different radius of monomers, the forward scatterings are bigger and the linear polarization degree has multiple peaks. Moreover, the vary of their scattering properties do not have strong correlative with the change of number of monomers. For larger booster motors, 25–38% of the plume being condensed alumina. The alumina can scatter radiation from other sources present in the plume and effect on radiation transfer characteristics of plume. In addition, the shape, size distribution and refractive index of the particles in the plume are estimated by linear polarization degree. Therefore, accurate scattering properties calculation is very important to decrease the deviation in the related research.

1. Introduction

In recent years, with the emergence of various new aerocraft, scattering properties of the aerocraft plume have received widespread attention. Larger booster motors use propellants with 14–20% aluminum by weight, resulting in 25–38% of the plume being condensed alumina [1]. Thus, as the main particles of plume, the characteristics of alumina particle have become the focus of researchers. There are a large number of papers to study distribution function of radius [2], refractive index [3], absorption coefficient [4,5] and number density [6] of alumina in the plume. The alumina particles can scatter radiation from other sources present in the plume, and the forward scattering of alumina is of great importance in considering how these particles can modify actual plume radiation [7]. Above researches, provide the theoretical basis for the further research about light scattering properties of alumina particles in the plume.

There are two important parameters when discussing the light scattering properties of a particle, which are scattering phase function and linear polarization degree. Scattering phase function describes the spatial distribution of light scattering energy of a particle, which is the basis of studying the radiation transfer characteristics of aerocraft plume. Linear polarization degree can be obtained by measuring, whose correlation is higher related with the shape, refractive index and particle size distribution of the particles [8]. Tishkovets et al. [9] mainly studies the scattering phase function and linear polarization characteristics of alumina particle cluster with the same radius of monomers at scattering angle 0–5° through the far field approximation method. Using multiple sphere T matrix method, Li et al. [10] studies the scattering phase function of alumina particle clusters with the same radius of monomer in aerocraft plume. Lindqvist et al. [11] studies the impact on the linear polarization characteristics by the shape, size and component of cluster particles with the same radius of monomer.

However, according to the studies of Simmons [12] and Dill [13], we know that the alumina in the plume usually aggregated as the clusters and the monomers of cluster have different radius. To our knowledge, there is no research about the scattering properties to this kind of alumina particle model at present. Moreover, the

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scattering property of alumina is of great importance in studying the radiation propagation characteristics of areocraft plume. Roblin et al. [14] introduces the alumina particle scattering phase function into radiation transfer equation, which make the success of solving the ultraviolet radiation transfer characteristic of aerocraft plume.

Therefore, this paper mainly studies the scattering properties of alumina particle clusters with different radius of monomer, and consists of the following parts. In the second part, the probability distribution function of radius of monomer is introduced into the traditional DLA algorithm. The monomers with different radius are randomly sampled, then we generate the model of alumina particle cluster in the plume adopting these monomers. In the third part, the multiple sphere T matrix method is introduced, and the basic meaning of the scattering phase function, linear polarization degree and non-spherical are expounded. The results of numerical calculations will be shown in the fourth part. The fifth part is summary and conclusion of this paper.

2. Alumina particle clusters model

Alumina particles in the plume are usually condensed clusters. According to the proportion of alumina surface's tension and shear force, when the fundamental particle number is more than 20 to 30, the alumina cluster usually rupture occurs [15]. The radius of monomer in the cluster follows with lognormal probability distribution function in the form of [13]

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

where the geometric mean r_g is 100 nm and the geometric standard deviation σ_g is 1.5 in the plume of larger booster motors.

The traditional DLA algorithm is usually used to simulate the fractal aggregate cluster particles with the same radius of monomer. [16,17]. The construction and morphology of the fractal clusters can be described by the statistical scaling law:

$$Ns = k_f \left(\frac{R_g}{a} \right)^{D_f} \tag{2}$$

$$R_g^2 = \frac{1}{Ns} \sum_{j=1}^{Ns} r_j^2 \tag{3}$$

where Ns is the number of the monomers in the cluster, a is the mean radius of the monomer, k_f is the fractal prefactor, D_f is the fractal dimension, R_g is the radius of gyration, which represents the deviation of the overall aggregate radius in a cluster, r_j is the distance from the *jth* monomer to the center of the cluster.

According the flow chart, we introduce the probability distribution function of radius into the DLA algorithm, so that the generated alumina cluster can meet the requirements of modeling. Fig. 1 is the improved DLA method with the additive steps in yellow.

Fig. 2 is scanning electron microscope pictures of collected alumina particles and some examples of the alumina particles. (a) is scanning electron microscope pictures of collected alumina particles from the plume [4] and (b) is some simulated examples of the clusters generated by ourselves. For the clusters (1)–(3), Ns is 10. For the clusters (4)–(6), Ns is 15. For the clusters (7) and (9), Ns is 20. While, the Ns of cluster (8) is 5. The radius of those monomers follows the lognormal probability distribution function that r_g is 100 nm and σ_g is 1.5.

3. Methodology

3.1. Multiple sphere T matrix method

The multiple sphere T matrix method [18] has become an important numerical tool for computing the random-orientation scattering matrix of the clustered particles. The procedure for analytically calculating the T matrix for a cluster of spheres has been described in detail in Mackowski [19], only an outline of the formulation will be presented here. The scattered field from the cluster as a whole is resolved into partial fields scattered from each of the Ns sphere in the cluster, i.e.,

$$\boldsymbol{E}^{sca}(\boldsymbol{r}) = \sum_{j=1}^{Ns} \boldsymbol{E}_j^{sca}(\boldsymbol{r}) \tag{4}$$

where $\boldsymbol{E}_j^{sca}$ is the scattered flied for sphere j and $\boldsymbol{r}$ connects the origin of the common coordinate system and the observation point.

The field arriving at the surface of the jth sphere will consist of the incident field plus scattered fields that originate from all other spheres in the cluster. For the jth sphere, the incident filed $\boldsymbol{E}_j^{inc}$ is expressed as follows:

$$\boldsymbol{E}_j^{inc}(\boldsymbol{r}) = \boldsymbol{E}_0^{inc}(\boldsymbol{r}) + \sum_{l=1, l\neq j}^{Ns} \boldsymbol{E}_l^{sca}(\boldsymbol{r}), \quad j = 1, \cdots, Ns \tag{5}$$

In the above equation, $\boldsymbol{E}_0^{inc}(\boldsymbol{r})$ denotes the external incident filed. To get the T matrix of the jth sphere, the incident field and the scattered filed are expanded in vector spherical wave functions as following:

$$\boldsymbol{E}_j^{inc}(\boldsymbol{r}) = \sum_{n,m} \left[\left(a_{nm}^{j0} + \sum_{l=1, l\neq j}^{Ns} a_{nm}^{jl} \right) Rg\boldsymbol{M}_{mn}(k\boldsymbol{r}_j) + \left(b_{nm}^{j0} + \sum_{l=1, l\neq j}^{Ns} b_{nm}^{jl} \right) Rg\boldsymbol{N}_{mn}(k\boldsymbol{r}_j) \right] \tag{6}$$

$$\boldsymbol{E}_j^{sca}(\boldsymbol{r}) = \sum_{n,m} [p_{nm}^j \boldsymbol{M}_{mn}(k\boldsymbol{r}_j) + q_{nm}^j \boldsymbol{N}_{mn}(k\boldsymbol{r}_j)], \quad j = 1, \cdots, Ns \tag{7}$$

where k is the wave number of the medium. Owing to the linearity of Maxwell's equations and boundary conditions, the relationship between the scattered field expanding coefficients and the incident field expanding coefficients are given by $\boldsymbol{T}^j$ matrix:

$$\begin{bmatrix} \boldsymbol{p}^j \\ \boldsymbol{q}^j \end{bmatrix} = \boldsymbol{T}^j \left(\begin{bmatrix} \boldsymbol{a}^{l0} \\ \boldsymbol{b}^{l0} \end{bmatrix} + \sum_{l\neq j} \begin{bmatrix} \boldsymbol{A}(kr_{lj}) & \boldsymbol{B}(kr_{lj}) \\ \boldsymbol{B}(kr_{lj}) & \boldsymbol{A}(kr_{lj}) \end{bmatrix} \begin{bmatrix} \boldsymbol{p}^l \\ \boldsymbol{q}^l \end{bmatrix} \right), \quad j = 1, \cdots, Ns \tag{8}$$

where $\boldsymbol{r}_{lj} = \boldsymbol{r}_l - \boldsymbol{r}_j$ connects the origins of the lth and jth local coordinate systems. Inversion of the above equation gives:

$$\begin{bmatrix} \boldsymbol{p}^j \\ \boldsymbol{q}^j \end{bmatrix} = \sum_{l=1}^{Ns} \boldsymbol{T}^{jl} \begin{bmatrix} \boldsymbol{a}^{l0} \\ \boldsymbol{b}^{l0} \end{bmatrix}, \quad j = 1, \cdots, Ns \tag{9}$$

where the matrix $\boldsymbol{T}^{jl}$ transforms the coefficients of the incident filed expansion centered at the lth origin into the jth-origin-centered expansion coefficients of the partial field scattered by the jth component. Finally, the cluster T matrix is given by

$$\boldsymbol{T} = \sum_{j,l=1}^{Ns} \begin{bmatrix} Rg\boldsymbol{A}(kr_{j0}) & Rg\boldsymbol{B}(kr_{j0}) \\ Rg\boldsymbol{B}(kr_{j0}) & Rg\boldsymbol{A}(kr_{j0}) \end{bmatrix} \boldsymbol{T}^{jl} \begin{bmatrix} Rg\boldsymbol{A}(kr_{0l}) & Rg\boldsymbol{B}(kr_{0l}) \\ Rg\boldsymbol{B}(kr_{0l}) & Rg\boldsymbol{A}(kr_{0l}) \end{bmatrix} \tag{10}$$

Then, we can obtain the random orientation scattering matrix elements.

In the standard {I, Q, U, V} representation of polarization, the normalized Stokes scattering matrix has the well-known block-