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Multiple scattering of light transmission in a smoke layer

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ABSTRACT

The visibility in a fire scene decreases because of the existence of smoke produced by the flammable materials. With the growth of smoke concentration, the relationship between light and smoke becomes complicated due to the multiple scattering. In this paper, the radiative transfer equation (RTE) that considers the multiple scattering was applied to calculate the light transmission in a smoke layer. As input parameters of RTE, the single scattering albedo, asymmetry parameter and extinction cross section of single smoke agglomerate were calculated by the discrete dipole approximation (DDA) method. The effects of smoke agglomerate diameter, number density of smoke layer, and the incident light wavelength were considered. The results show that the light transmitted flux decreases with the growth of smoke diameter and number density, and increases with the growth of wavelength. The smoke diameter is dominant among the three parameters, and the light transmitted flux tends to be stable when the wavelength reaches a certain value.

1. Introduction

In a fire scene, smoke is produced by wood, clothes and other flammable materials. Smoke particles gather together to form the smoke layer and spread around the building [1]. The smoke leads to a decline of visibility. As a result, people cannot see the exit, and the rescuers cannot find the trapped people in time. In order to improve the visibility in the fire scenario, the relationship between light and smoke layer needs to be studied [2].

The smoke layer in this paper is a volumetric smoke with high concentration, which is compose of a lot of smoke agglomerates. A commonly applied equation that relates the light with the smoke layer is the Lambert–Beer law (also named the Bouguer law), as shown in Eq. (1) [3].

$$I = I_0 e^{-\tau} \quad (1)$$

where I and I_0 correspond to the incident and the transmitted intensity, respectively, and τ is the optical thickness, representing the extinction ability of smoke layer, which relates with smoke density, smoke particle diameter and so on. While, with the deepening research on the light scattering, the applicability of Lambert–Beer law has been doubted by researchers [4–8], because the Lambert–Beer law only describes the absorption characterization of transmission medium. Tam and Zardecki [4,5] applied the radiative transfer equation (RTE) to analyze the deviations of the Lambert–Beer law in the cases of a laser beam propagating in dense aerosols, such as fog, cloud and rain. Their results show that the deviations increase with the growth of optical thickness, and the maximum deviation can reach six times the calculation of Lambert–Beer law in a fog environment. Swanson et al. [6] and Piederrière et al. [7] classified the scattering characterization of the medium into three types: single scattering, for $\tau < 1$; multiple scattering, for $\tau \leq 10$; and diffusion, for $\tau > 10$. This means that the Lambert–Beer law can only be used in the region of $\tau < 1$ to ensure negligible scattering. In Wind and Szymanski's [8] work about the correction factor of the Lambert–Beer law, this region is limited to $\tau < 0.1$.

The existence and importance of multiple scattering in the smoke layer has been revealed by relevant experiments. Zhu et al. [9] found that the values of the dimensionless extinction coefficient, which is proportional to τ and also shows the extinction ability of smoke, remained nearly constant for ethane with the growth of incident laser wavelength. They attributed this phenomenon to the effect of smoke scattering (multiple scattering): any increase in the absorption coefficient with wavelength is offset by a reduction in the scattering constant. Zhu et al. [10] also measured the ratios of smoke scattering to the total extinction cross section (i.e. the extinction cross section of a volumetric smoke) at the wavelengths of 543.5 nm, 632.8 nm and 856 nm. The values are respectively 0.245, 0.195 and 0.195 for ethane smoke and 0.311, 0.228 and 0.237 for acetylene smoke.

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To the best of our knowledge, despite a lot of works on the light transmission in a smoke layer have been developed [3,11,12], little researchers considered the influence of multiple scattering. For the importance of multiple scattering in the smoke layer that has been proved above, this paper is focus to numerically study the light transmission in a smoke layer with the consideration of multiple scattering. The effects of smoke agglomerate diameter, number density of smoke layer, and the incident light wavelength will be considered, and the deviation of Lambert–Beer law will be also discussed.

As well known, an effective theoretical model to solve the multiple scattering problems is the RTE method, which has been applied in many fields, such as radiative heat transferring through the absorbing/emitting and scattering medium [13], solar light transferring through the atmosphere [14], wireless signal transferring through the clouds [15], etc. This paper extends the RTE method to calculate the light transmission in the smoke layer. Meanwhile, the discrete dipole approximation (DDA) method [16–19] is also applied to solve the optical characterizations of single smoke agglomerate, like the single scattering albedo, the asymmetry parameter and the extinction cross section, which are the input parameters of the RTE.

2. Theoretical background

The RTE describes a monochromatic light transferring through a plane-parallel medium, shown as Eq. (2) [20,21]. The first item u in the right side is the light intensity at point (τ, μ, φ). The second item S represents the contribution of multiple scattering from other particles and the thermal emission of medium, which can be described as Eq. (3). If S is removed, the RTE equals to the Lambert–Beer law. Thus, the Lambert–Beer law is just a special case of RTE where the scattering effect is not considered.

$$\mu \frac{du(\tau, \mu, \varphi)}{d\tau} = u(\tau, \mu, \varphi) - S(\tau, \mu, \varphi) \tag{2}$$

where τ is the optical thickness of plane medium, μ is the cosine of polar angle, and φ is the azimuthal angle.

$$S(\tau, \mu, \varphi) = \frac{\omega}{4\pi} \int_0^{2\pi} d\varphi' \int_{-1}^{1} d\mu' P(\tau, \mu, \varphi; \mu', \varphi') \times u(\tau, \mu', \varphi') + Q(\tau, \mu, \varphi) \tag{3}$$

where ω is the single scattering albedo, P is the phase function, (μ', φ') is the direction of the light coming, and Q has different expression in different cases:

$$\begin{cases} Q = (1-\omega)B(T), & \text{thermal emitting medium} \\ Q = \dfrac{\omega I_0}{4\pi} P(\tau, \mu, \varphi; -\mu_0, \varphi_0) e^{(-\tau/\mu_0)}, & \text{nonemitting medium} \end{cases} \tag{4}$$

where $B(T)$ is the Plank function at temperature T, I_0 is the incident light, and (μ_0, φ_0) is the direction of I_0.

The phase function P in Eq. (3) describes the probability of the light in the direction (μ', φ') transferring to (μ, φ), and is commonly simplified by the Henyey–GreenStein phase function [22]:

$$P(\langle \mu, \varphi; \mu', \varphi' \rangle) = \frac{\omega}{4\pi} \times \frac{1-g^2}{\left(1+g^2-2g\ \cos\langle \mu, \varphi; \mu', \varphi' \rangle\right)} \tag{5}$$

where g is the scattering asymmetry parameter that defines the shape of probability density. $g > 0$ represents that forward scattering is dominant, $g < 0$ represents that backward scattering is dominant, and $g = 0$ denotes a uniform distribution.

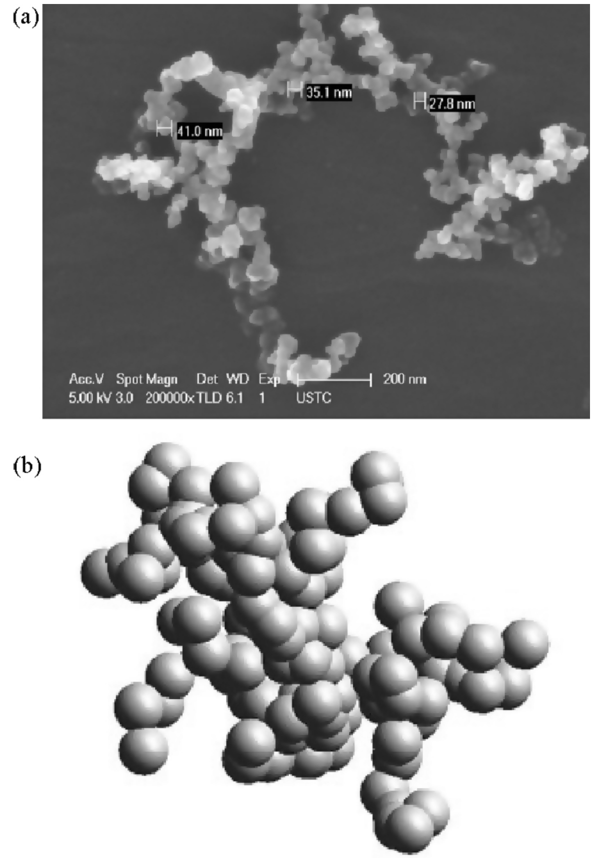

Fig. 1. (a): the SEM image of a single smoke particle from n-heptane fire; (b) the simulated fractal-shaped aggregate of smoke particle with $N = 117$, $D_f = 1.85$ and $K_f = 3.77$ [23].

The single scattering albedo ω represents the scattering ability of medium, given as

$$\omega = \frac{C_{sca}}{C_{ext}} \tag{6}$$

where C_{sca} is the scattering cross section, and C_{ext} is the extinction cross section.

The optical thickness τ represents the dimensionless path length of optical transmission, expressed as

$$\tau = \rho_n C_{ext} L \tag{7}$$

where ρ_n is the number density of medium, and L is the path length.

So far, the unknown parameters in RTE are g, ω, C_{sca}, C_{ext}, ρ_n, L and T. Four of them, g, ω, C_{sca} and C_{ext}, are the characteristics of single smoke particle, and the morphology of smoke particle needs to be known to calculate these parameters. Zhang et al. [23] used the scanning electron microscope (SEM) to observe the morphology of smoke particles from an n-heptane fire and found that the smoke particle is the fractal-shaped agglomerate, which is shown in Fig. 1(a). The morphology of fractal-shaped agglomerates can be expressed by Eq. (8).

$$N = K_f \left(\frac{R_g}{d_p} \right)^{D_f} \tag{8}$$

where N is the number of primary spheres in agglomerate, K_f is the prefactor, R_g is the gyration radius of entire agglomerate, d_p is the diameter of primary spheres, and D_f is the fractal dimension. Basing on Eq. (8) and the SEM image, Zhang et al. [23] rebuilt the smoke aggregate as shown in Fig. 1(b).