Research on infrared interference performance of carbon smoke

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Abstract: Using Lambert-Beer law, the interference characteristics of smoke composed by spheroid and spherical particles of carbon black is analyzed respectively in 10.64μm band based on the T matrix theory and Mie scattering theory in this paper. Analysis shows that whether it is spherical or non-spherical there is an optimum size (about 1.51μm) to make the interference effects of smoke best. The interference effects of smoke composed of spheroid particles are better than those composed of spherical particles. More obvious non-spherical features of spheroid is, then more better the interference effect is. When the particle size is constant, along with the thickness and concentration of smoke become larger, the interference effect becomes better.

Keywords: carbon smoke; T- matrix theory; Mie theory; infrared interference

INTRODUCTION

Smoke is a simple and effectual means of laser passive interference. It played very important role in the nearly wars. The smoke particles can absorb or scatter the incident light effectively and decay the incident light energy. The infrared smoke materials take on the better infrared extinction capability. Its interference effect depends on the smoke composition, smoke particle dimension and the incident light wavelength. The carbon black particles can absorb infrared radiation effectively and can be used to smoke material[1]. Based on the T matrix theory and Mie scattering theory[2], Lambert-Beer law was used. The interference performance of smoke composed by spheroid and spherical particles of carbon black was analyzed respectively in 10.64μm band.

BASIC THEORY

T-Matrix Theory

T-Matrix method can also call zero field method or extended boundary condition method. It is suitable for non-spheroid particle extinction parameter calculation. Its main thought is that the expansion coefficient of sacttered field vector ball harmonic function is expressed by incident field. The conversion matrix is a T-matrix [1]. Under the incident light irradiation, the particle surface produces electric current and the current formes scattered field by agitation [3]. Adopting vector spherical wave function to express the scattered field $E_{inc}(r)$ and incident field $E_{sca}(r)$:

$$E_{inc}(r)=\sum_{n=1}^{\infty}\sum_{m=-n}^{n}[a_{mn}RgM_{mn}(kr)+b_{mn}RgN_{mn}(kr)] \quad (1)$$

$$E_{sca}(r)=\sum_{n=1}^{\infty}\sum_{m=-n}^{n}[p_{mn}M_{mn}(kr)+q_{mn}N_{mn}(kr)],|r|>r_0 \quad (2)$$

In the formula: $k=2\pi/\lambda$ is wave number of ambient medium; r_0 is the external tangent spherical radius of the scattered particle. $RgM_{mn}(kr)$ and $RgN_{mn}(kr)$ are vector function.

According to the linear relationship of Maxwell equations set, the scattered field expansion coefficient p_{mn}, q_{mn} and the incident field expansion coefficient a_{mn}, b_{mn} are expressed by T-matrix as followed:

$$p_{mn}=\sum_{n'=1}^{\infty}\sum_{m'=-n'}^{n'}(T^{11}_{mnm'n'}a_{m'n'}+T^{12}_{mnm'n'}b_{m'n'}) \quad (3)$$

$$q_{mn}=\sum_{n'=1}^{\infty}\sum_{m'=-n'}^{n'}(T^{21}_{mnm'n'}a_{m'n'}+T^{22}_{mnm'n'}b_{m'n'}) \quad (4)$$

This liner relationship can be changed as following form.

$$\begin{bmatrix}p\\q\end{bmatrix}=T\begin{bmatrix}a\\b\end{bmatrix}=\begin{bmatrix}T^{11}&T^{12}\\T^{21}&T^{22}\end{bmatrix}\begin{bmatrix}a\\b\end{bmatrix} \quad (5)$$

From the relational expression above, the incident field expansion coefficient a_{mn} and b_{mn}can be obtained by known incident light electric field vector. So, as long as the conversion coefficient of T-matrix can be get, the scattered field expansion coefficient p_{mn} and q_{mn}can also be get accordingly.

In this paper, the gyration ellipsoid model is used to calculat the extinction parameter of the carbon ellipsoid particle. Its equation is:

$$r(\theta,\phi)=b\left[\sin^2\theta+\frac{b^2}{a^2}\cos^2\theta\right]^{-\frac{1}{2}} \quad (6)$$

In the equation, a is half axial length of gyration

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shaft; b is radius length of revolution. As $a/b<1$, it is flat ellipsoid. As $a/b>1$, it is prolate ellipsoid. As $a/b=1$, it is sphere. In this paper, the isopyknic radius of sphere and a/b express the size and shape of the gyration ellipsoid accordingly. The isopyknic radius of sphere is $r_v = a^{1/3}b^{2/3}$. To random orientation revolving solid particle, its extinction cross section and scattered cross section are following:

$$C_{ext} = -\frac{2\pi}{k^2}\mathrm{Re}\sum_{n=1}^{\infty}\sum_{m=-n}^{n}(T^{11}_{mnm'n'} + T^{22}_{mnm'n'}) \quad (7)$$

$$C_{sca}\frac{2\pi}{k^2}\sum_{n=1}^{\infty}\sum_{m=-n}^{n}\sum_{n'=1}^{\infty}\sum_{m'=-n'}^{n'}(|T^{11}_{mnm'n'}|^2 + |T^{12}_{mnm'n'}|^2 + |T^{21}_{mnm'n'}|^2 + |T^{22}_{mnm'n'}|^2)$$

(8)

Mie theory

To regular spheric scatterer, when the incident electromagnetic field wavelength is nearly to the scatterer length, the Mie Thoery can express the scattering process of the scatterer to electromagnetic field[5]. Its extinction cross section and scattered cross section are following:

$$C_{ext} = \frac{\lambda^2}{2\pi}\sum_{n=1}^{\infty}(2n+1)\mathrm{Re}(a_n + b_n) \quad (9)$$

$$C_{sca} = \frac{\lambda^2}{2\pi}\sum_{n=1}^{\infty}(2n+1)(|a_n|^2 + |b_n|^2) \quad (10)$$

$$C_{abs} = C_{ext} - C_{sca} \quad (11)$$

In the equation, a_n and b_n are Mie coefficient, λ is radiation wavelength.

Lambert-Beer law

Infrared smoke transmissivity can express the interfere degree of infrared smoke to image-forming system. According to the Lambert-Beer law, the transmissivity is:

$$T = \frac{I}{I_0} = \exp[-C_{ext}NL] \quad (12)$$

In the equation, I is incident intensity, I_0 is transmitted intensity, N is the smoke particle dendity, L is smoke thickness.

Spheric particle extinction cross section C_{ext} can be calculated by Mie Thoery and gyration ellipsoid particle extinction cross section C_{ext} can be calculated by T-matrix. Smoke particle concentration $N = c/(\rho V)$, c is smoke concentration; ρ is smoke particle mass density; V is the particle capacity; The smoke transmissivity can express as following:

$$T_{sphere} = \exp(-C_{ext}NL) = \exp(-3cC_{ext}L/4\pi r^3\rho) \quad (13)$$

$$T_{ellipsoid} = \exp(-C_{ext}NL) = \exp(-3cC_{ext}L/4\pi r_v^3\rho) \quad (14)$$

Carbon particle smoke infrared interfere haracteristics

Suppose smoke is single uniform dispersion system[6]. Under the condition that incident wavelength λ=1.06um, carbon particle complex refractive index $n = 3.1020 + 1.3010i$, the smoke is compesed by gyration ellipsoid and spheric scatterer particle accordingly. The smoke transmissivity is compared.

When the particle size changed, the other parameters are set as following: smoke concentration is c=0.0005kg/m^3; smoke thickness is L=10m; smoke particle mass density ρ=1500kg/m^3; gyration ellipsoid axial length ratio is a/b=1/4, a/b=1/2, a/b=2, a/b=4 accordingly. The calculation results are Fig.1.

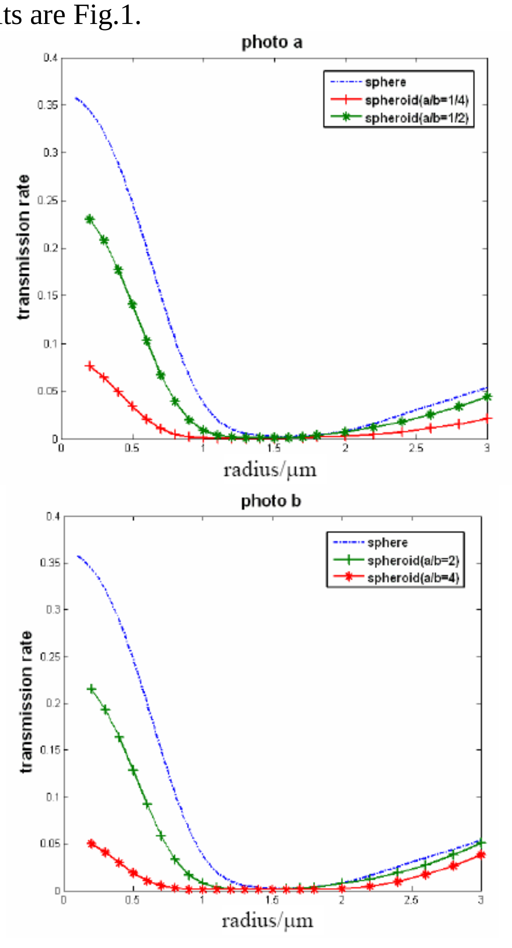

Fig. 1. The influence on transmissivity of carbon black smoke screen with particle radius change

From Fig.1 above, whatever gyration ellipsoid or spheric scatterer, the smoke transmissivity changes with particle radius. The interference effect is best when the particle radius in the 1-2um. In Fig.1 photo(a), The interference effect of gyration ellipsoid axial length ratio a/b=1/4 is better than a/b=1/2 and they are both better than spheric scatterer. In Fig.1 photo (b), The interference effect of gyration ellipsoid axial length ratio a/b=4 is better than a/b=2 and they are both better than spheric scatterer.

To compare the gyration ellipsoid interference effect in different axial length directly, put axial length ratio a/b=4 and a/b=1/4 curve in one figure and axial length ratio a/b=2 and a/b=1/2 curve in the other figure. The results are Fig.2.

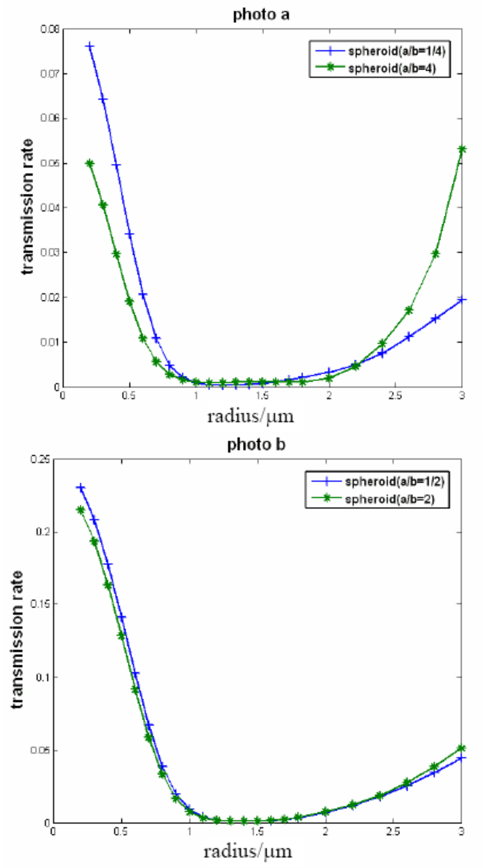

Fig. 2. The comparison of transmission rate for different a/b of spheroid

From Fig.2, the difference of interference effect is very small. To gyration ellipsoid, when its axial length ratios are reciprocal each other, the interference effect is nearly similar.

When the smoke concentration changed, the other parameters are set as following: particle radius is $r=r_v=1.5$um; smoke thickness is L=15m; smoke particle mass density $\rho=1550\text{kg/m}^3$; gyration ellipsoid axial length ratio is a/b=1/4, a/b=1/2, a/b=2, a/b=4 accordingly. The calculation results are Fig.3.

From Fig.3 above, whatever gyration ellipsoid or spheric scatterer, the smoke transmissivity changes with particle radius. The interference effect of gyration ellipsoid particle smoke is better than the spheric scatterer particle smoke.

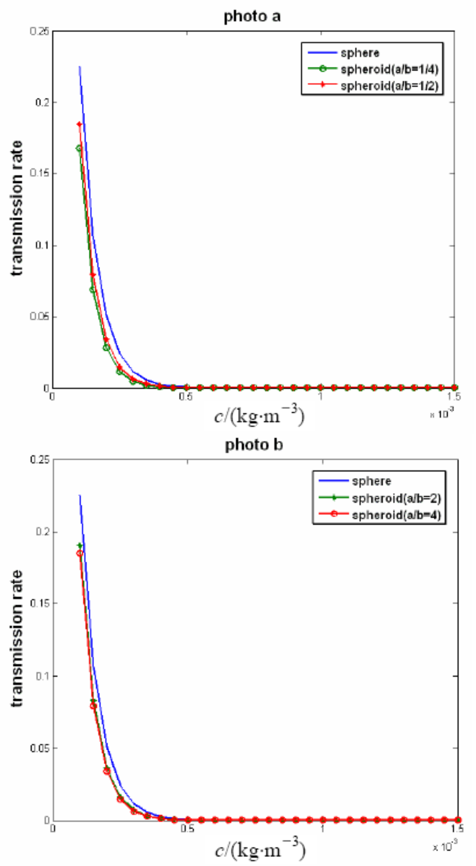

Fig. 3. The influence on transmission rate of carbon black screen with smoke concentration change

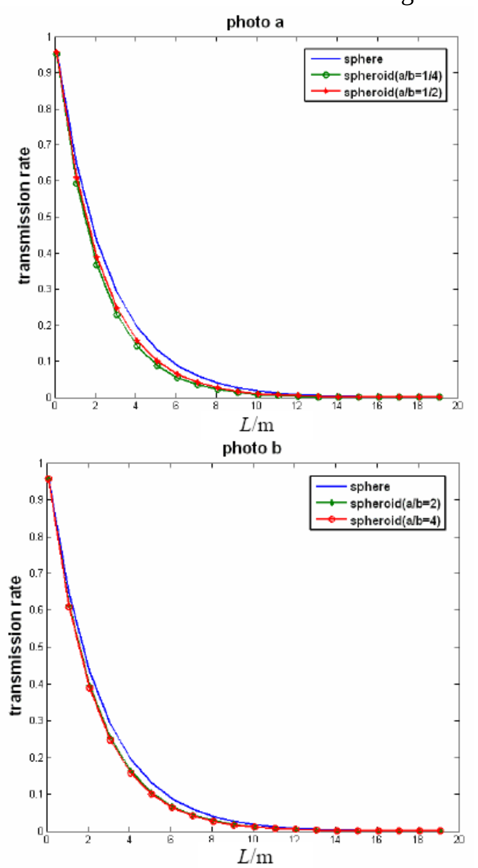

Fig. 4. The influence on transmission rate of carbon black screen with smoke thickness change.

The gyration ellipsoid axial length ratio is different, but the interference effect is similar. The interference effect of gyration ellipsoid axial length ratio a/b=1/4 is better than a/b=1/2 and a/b=4 is better than a/b=2.

When the smoke thickness changed, the other parameters are set as following: particle radius is $r=r_v=1.5um$; smoke particle mass density $\rho=1550kg/m^3$; smoke concentration is $c=0.0004kg/m^3$; gyration ellipsoid axial length ratio is a/b=1/4, a/b=1/2, a/b=2, a/b=4 accordingly. The calculation results are Fig.4.

From Fig.4 above, the smoke transmissivity reduces with smoke thickness increaing. The interference effect of gyration ellipsoid particle smoke is better than the spheric scatterer particle smoke. The gyration ellipsoid axial length ratio is different, but the interference effect is similar. The interference effect of gyration ellipsoid axial length ratio a/b=1/4 is better than a/b=1/2 and a/b=4 is better than a/b=2.

CONCLUSION

Based on the T-Matrix Thoery and Mie Theory, the smoke interference effect of gyration ellipsoid and spheric scatterer are calaulated by Lambert-Beer law. The conclusion is that there is an optimal particle size (about 1.5um), the smoke interference effect is best. To gyration ellipsoid, under axial length ratio a/b<1, the more small the axial length ratio is, the better the interference effect is. Under axial length ratio a/b>1, the more large the axial length ratio is, the better the interference effect is. The interference effect of gyration ellipsoid particle smoke is better than the spheric scatterer particle smoke under the condition of this paper. When the particle size is invariant, the better the smoke interference effect is, the larger smoke density and thickness is.

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