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激光在云雾中传输的消光特性

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摘　要:研究了大气分子和云雾粒子对入射激光的吸收与散射效应.采用 Kruse 模型、单次散射近似法和蒙特卡洛法计算了谱分布参量不同的三种云雾对 0.86 μm 波长激光的消光特性,结果表明:能见度小于 0.5 km 时,Kruse 模型不再适用于云雾消光系数的计算;能见度相同时,消光系数的单次散射近似结果大于蒙特卡洛的仿真结果,导致传输距离相同时,云雾对 0.86 μm 波长激光透过率的单次散射近似结果小于蒙特卡洛的仿真结果;同一能见度下谱分布参量不同的三种云雾,消光特性的差别较小,云雾粒子尺度分布对消光特性的影响不明显.

关键词:激光传输;云雾;消光特性;蒙特卡洛;能见度
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Extinction Characteristic of Laser Transmitted in Fog

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Abstract: The absorbing and scattering of laser beam by air molecules and fog particles were studied. Kruse model, single scattering approximation and Monte-Carlo simulation were adopted to calculate the extinction characteristics of three types of fog irradiated by near infrared laser of 0.86 μm wavelength, the results show that Kruse model is not applicable to calculate the extinction coefficient when the visibility is lower than 0.5 km. The extinction coefficient from the single scattering approximation with lower precition is larger than that from the Monte-Carlo simulation in the same visibility, which means a lower transmission at the same distance. The difference of extinction characteristic of three types of fog is so small in the same visibility that the influence of the size distribution of fog particle on it is not obvious.

Key words: Laser transmission; Fog; Extinction characteristic; Monte-Carlo; Visibility
OCIS Codes: 010.3310; 010.1615; 010.135

0 Introduction

Since its unique advantages such as high range resolution, low side lobe effect and superior ability to resist electromagnetic interference over other electromagnetic waves, laser has been used widely in the field of laser radar, laser communication systems and laser-guided weapons, etc. However, detection system based on laser has its disadvantages. Compared with microwave and millimeter wave, laser is sensitive to fog interference, which means laser is easy to be absorbed or scattered by fog particles suspended in air[1-2]. Absorbing and scattering by fog particles will lead to reduction of intensity collected by receiving systems of laser radar or laser-guided weapons, so it is significant and practical to study the extinction characteristic of laser transmitted in fog.

Although the influence of fog extinction is significant, theoretical analysis and calculation of it are not easy due to parameters that complicate the transport process, such as multi-scattering in fog, particle size distribution, volume density of particles and optical constant of incident laser[3-4], etc. During the past few decades, several methods including

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Monte-Carlo simulation, single scattering approximation and solo mean diameter method have been proved to be effective to study the extinction characteristic of fog by researchers both at home and abroad[5]. Shen[6] established the attenuation model of laser radiation of 0.532μm wavelength in fog, and the attenuation characteristic in different visibilities were simulated then. Liu[3] studied the effect of atmospheric aerosols on laser transmission attenuation, and the numerical results of different kinds of aerosols were given in his article. Both Shen and Liu adopted the method of single scattering approximation, which is not applicable in dense fog. Wang[4] studied the transmission characteristic of laser when transmitted in aerosols, but little attention was paid to the influence of particle size distribution.

In this paper, absorbing and scattering characteristics by air molecules and fog particles were studied. By using the methods of Kruse model, single scattering approximation and Monte-Carlo simulation, extinction coefficients and transmittance of laser beam of 0.86μm wavelength in fog were calculated and simulated in different visibilities. Then the results calculated by methods mentioned above were compared and analyzed. Finally, the influence of particle size distribution on extinction was also analyzed.

1 Phenomenon of fog and its particle size distribution

It is admitted in meteorology, that fog exists when the visibility is reduced to less than 1 km and the relative humidity of the air is brought to the saturation level (close to 100%). The phenomenon of fog is constituted of a huge quantity of small spherical water droplets suspended in the air. Fogs are characterized by several parameters such as liquid water content, particle size distribution, average particle size and volume density of particles. Several types of fog can be distinguished according to their formation mechanism, but generally convection fog and advection fog are the most typically encountered types in nature[7].

Convection fog appears when the air is sufficiently cool and becomes saturated, it is a fog which generally appears during the night and at the end of the day. Particle diameters of convection fog are usually concentrated around 4μm while the liquid water content varies between 0.01 g/m^3 and 0.1 g/m^3. Advection fog is formed by the movements of wet and warm air masses above colder maritime or terrestrial surfaces. It is characterized by a particle radius around 10 μm and a liquid water content higher than 0.2 g/m^3 [6].

All the optical characteristics of aerosols are related to their describing parameters, among which the most important one is the particle size distribution. Generally the distribution of particle radius is different as the weather condition changes and it is usually described by analytical functions such as the lognormal distribution in the case of atmospheric aerosols and the generalized gamma distribution in the case of fog. Generalized gamma distribution is used widely to model the various types of fog and clouds while the expression is written as[8-9]

$$n(r)=a_d r^{\alpha_d}\exp(-b_d r^{\beta_d}) \tag{1}$$

where $n(r)$ equals the number of particles per volume unit and per increment unit of the particle radius r. a_d and b_d are distribution coefficients while α_d and β_d are distribution indices. For three types of fog, the distributions of them are shown in Fig. 1 and the correlative parameters are given in Table 1.

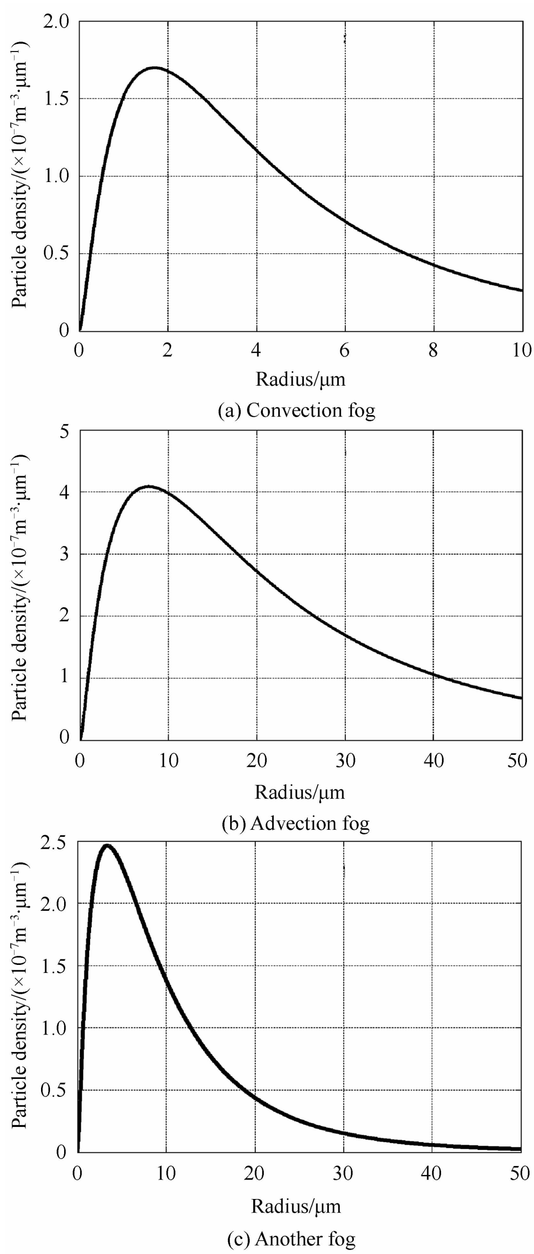


Fig. 1 Particle size distributions of three types of fog

Table 1 Correlative distribution parameters for convection fog and advection fog

Type of fog	a_d	b_d	α_d	β_d
Convection fog	500×10^6	3.5	2	0.45
Advection fog	100×10^6	2.2	2	0.40
Another fog	300×10^6	2.85	2	0.42

2 Calculation of extinction coefficient of laser transmitted in fog

The transmission of laser radiation through the atmosphere is described by the Beer-Lambert law[10-11]

$$\tau(\lambda,d)=\frac{P(\lambda,d)}{P(\lambda,0)}=\exp\left[-\mu_t(\lambda)\cdot d\right] \tag{2}$$

where $\tau(\lambda)$ is the total transmittance of laser radiation, $P(\lambda, 0)$ is the initial power emitted from the transmitter and $P(\lambda, d)$ is the measured power at distance d from the transmitter. $\mu_t(\lambda)$ is the total extinction coefficient per length unit, which represents the extinction effect on laser radiation. It is composed of the effects of scattering and absorbing which is expressed as[10-11]

$$\mu_t(\lambda)=\alpha_m(\lambda)+\beta_m(\lambda)+\alpha_a(\lambda)+\beta_a(\lambda) \tag{3}$$

in which α_m and α_a denote the molecular and aerosol absorption coefficient respectively, while β_m and β_a are molecular and aerosol scattering coefficient.

2.1 Extinction of air molecules

As mentioned in Eq. (3), extinction caused by air molecules includes the effects of scattering and absorbing simultaneously. Since air molecules are small compared with the wavelength of the incident laser, molecular scattering can be calculated by using the Rayleigh scattering theory[12]

$$\beta_m(\lambda)=1.33\times10^{-5}\left(\frac{\lambda}{0.532}\right)^{-4} \tag{4}$$

As the wavelengths of laser used in practice are usually in the near-infrared and IR spectrum, molecular scattering coefficients are quite small for these wavelengths. For example, at $\lambda=0.86$ μm, we obtain $\beta_m=1.95\times10^{-6}$ m^{-1}, while for the visibility of 30 km, the aerosol extinction coefficient referred in Ref. [13] equals 1.30×10^{-4} m^{-1}. The aerosol extinction coefficient largely predominates over the molecular scattering coefficient, even for good visibility conditions, so the contribution of molecular scattering could be neglected without affecting the precision.

Laser radiation is also absorbed by air molecules in narrow spectral bands with a selective absorption coefficient. For a typical application, air molecular absorption is negligible in the spectrum area mostly used in laser-designated systems, since the wavelengths of them belong to the transmission window of air generally [13].

2.2 Extinction of fog particles

As mentioned in introduction, several methods have been used to study the extinction of fog by researchers. In the following sections, three methods will be referred to calculate the extinction of fog particles, while the advantages and disadvantages of them are both discussed.

2.2.1 *Extinction and meteorological conditions*

In order to predict the extinction of laser radiation in air, the Kruse formula has been used widely in many literatures. The model sets up the relationship between extinction and meteorological conditions, which is expressed as[14]

$$\mu_t(\lambda)\approx\beta_a(\lambda)=\frac{3.912}{V}\left(\frac{\lambda}{0.532}\right)^{-q} \tag{5}$$

In visible and near-infrared up to about 2.5μm, the formula relates extinction to visibility at a given wavelength λ. The coefficient q has been subject of many theoretical discussions and experimental works while it depends on the visibility condition. Applying this formula means a significant advantage for longer, IR wavelengths, which seem to be less attenuated in fog in low visibility condition. This empirical formula, however, originally was intended for applications in geodesy or meteorology, where dense fog conditions were out of scope[15].

2.2.2 *Single scattering approximation*

The extinction of laser radiation by fog particles is related not only to the chemical characteristic, but also to the distribution and density of them. The multi-scattering effect could be neglected when the density of particles is rather low, while the contribution of single scattering is only considered. The total extinction, scattering and absorbing coefficients of fog particles with distribution $n(r)$ are[4]

$$\mu_i=\int_0^\infty\sigma_i(r)n(r)\mathrm{d}r=N\int_0^\infty\sigma_i(r)p(r)\mathrm{d}r,\quad (i=\mathrm{t,s,a}) \tag{6}$$

where σ_t, σ_s and σ_a are extinction, scattering and absorbing cross section respectively of single fog particle. N is the volume density of fog particles while p represents the Probability Density Function (PDF) of the distribution. Generally it is hard to measure the value of density directly in practice. Fortunately, volume density can be derived by the visibility of the air. When the wavelength is 0.532 μm, relationship between visibility and extinction coefficient is written as

$$V=\frac{3.912}{\mu_t(0.532)} \tag{7}$$

Combining Eqs. (6) and (7), the density N can be derived by the following expression from[4]

$$N=\frac{3.912}{V\int_0^\infty\sigma_{t0.532}(r)p(r)\mathrm{d}r} \tag{8}$$

Once we have got the density of fog particles in different visibilities, extinction coefficients could be calculated by Eq. (6).

2.2.3 *Multiple scattering based on Monte-Carlo simulation*

Monte-Carlo method has been used widely to simulate the transmission process of photons in random medium[16-17]. The method statistically models the behavior of photon propagation and scattering in random medium, while the key idea is to simulate the multi-scattering process as a succession of elementary events whose probability laws are known. Each photon has its own random trajectory in the process of transmission. Based on a large number of simulated photons, we obtain the expected characteristic of light transmitted in random medium.

In order to simulate the extinction of laser radiation in fog, the diagram of multi-scattering effect and random transmission process is shown in Fig. 2. Suppose a cylinder with unit cross section and length L locates along the z axis, and the incident laser is along the positive direction of z axis. Each photon′s spatial migration can be uniquely described by five variables: three spatial coordinates for the position and two direction angles θ and φ. Here θ denotes the angle between scattering direction and incident direction, and φ denotes the angle between the projection of scattering direction in xoy plane and x axis. We describe the photon′s spatial position with three Cartesian coordinates and the migration direction with three direction cosines from two direction angles. The direction cosines are specified by taking the cosines of the angles that the photon′s direction makes with each of the x, y, and z axes, respectively.

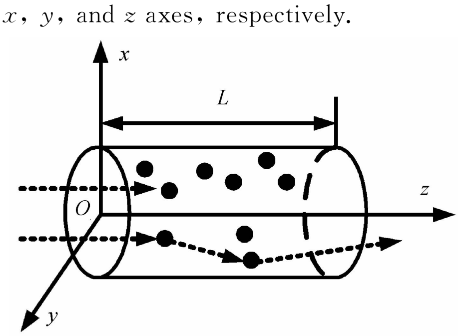


Fig. 2 Diagram of multi-scattering effect and random transmission process

As showed in Fig. 2, the initial direction cosines of every photon are specified by $\mu_x=0$, $\mu_y=0$ and $\mu_z=1$. Since fog particles are distributed randomly in the cylinder, the distance between scattering interactions is given by the random variable[17]

$$\Delta L=-\frac{\ln\xi}{\mu_t} \tag{9}$$

where ξ is a uniform random variable between zero and one, μ_t is the extinction coefficient calculated by Eq. (6). For a photon located at (x_i, y_i, z_i) travelling a distance ΔL in the direction (μ_x, μ_y, μ_z), its coordinates are updated according to the 3-dimensional geometry by

$$\begin{cases} x_{i+1}=x_i+\mu_x\Delta L \\ y_{i+1}=y_i+\mu_y\Delta L \\ z_{i+1}=z_i+\mu_z\Delta L \end{cases} \tag{10}$$

The new direction after collision is determined by the normalized phase function which describes the angular intensity of scattered light. The one which is frequently used in literature is Henyey-Greenstein phase function, in which the scattering angle θ is generated to satisfy the following [18]

$$\theta=\arccos\left\{\frac{1}{2g}\left[(1+g)^2-\left(\frac{1-g^2}{1-g+2g\xi_\theta}\right)^2\right]\right\} \tag{11}$$

where g is the asymmetric factor calculated by Mie theory. The azimuth angle φ is a uniform random variable between zero and 2π, so it is generated to satisfy[17]

$$\varphi=2\pi\xi_\varphi \tag{12}$$

Here, ξ_θ and ξ_φ are uniform random variables between zero and one. If a photon is scattered at angles (θ, ψ) offset from the incoming direction with direction cosines (μ_x, μ_y, μ_z), the new direction cosines are easily calculated according to geometry and specified by[17]

$$\begin{cases} \mu_x'=\dfrac{\sin\theta}{\sqrt{1-\mu_z^2}}(\mu_x\mu_z\cos\varphi-\mu_y\sin\varphi)+\mu_x\cos\theta \\ \mu_y'=\dfrac{\sin\theta}{\sqrt{1-\mu_z^2}}(\mu_y\mu_z\cos\varphi+\mu_x\sin\varphi)+\mu_y\cos\theta \\ \mu_z'=-\sin\theta\cos\varphi\sqrt{1-\mu_z^2}+\mu_z\cos\theta \end{cases} \tag{13}$$

Based on Monte-Carlo method, the probability that a photon successfully passed through the cylinder from the location of the ith collision is written as[4]

$$P_n^i=\begin{cases} w_i\exp\left(-\mu_t\dfrac{L-x_i}{\mu_{zi}}\right), \mu_{zi}>0 \\ 0, \mu_{zi}\leqslant 0 \end{cases} \tag{14}$$

where w_i is the assigned survival probability with initial value $w_0=1$. The relationship of two neighboring w_i is expressed as[4]

$$w_i=w_{i-1}\exp(-\mu_a\Delta L) \tag{15}$$

in which μ_a represents the absorption coefficient calculated by Eq. (6). If the photon′s survival probability diminishes sufficiently or the photon gets out of the cylinder, the simulation of the photon terminates. Otherwise, we compute the location of the next collision. Once we have finished the migration simulation of all photons, the estimate of transmittance is obtained from the contribution of the total emitted photons

$$\tau=\frac{1}{N_p}\sum_{n=1}^{N}P_n=\frac{1}{N_p}\sum_{n=1}^{N}\sum_{i=1}^{M}P_n^i \tag{16}$$

where N_p is the total number of all emitted photons, and M represents the total collision times of the nth photon. Once we have got the transmittance τ, the extinction coefficient could be calculated by Eq. (2).

3 Results and analysis

Based on the three methods introduced in section two, numerical results of extinction coefficient for both convection fog and advection fog are calculated in different visibilities. Results of extinction coefficients of convection fog by Kruse formula and single scattering approximation are given in Table 2 and Table 3 respectively.

Table 2 Numerical results of μ_t (km^{-1}) by Kruse formula

Wavelength/μm \ Visibility/km	0.02	0.05	0.1	0.5	1
0.41	195.6	78.24	39.12	7.82	4.53
0.86	195.6	78.24	39.12	7.82	3.13
1.06	195.6	78.24	39.12	7.82	2.82
3.00	195.6	78.24	39.12	7.82	1.68

Table 3 Numerical results of μ_t (km^{-1}) by single scattering approximation

Wavelength/μm \ Visibility/km	0.02	0.05	0.1	0.5	1
0.41	193.8	77.51	38.76	7.75	3.88
0.86	200.5	80.19	40.09	8.02	4.01
1.06	203.2	81.28	40.64	8.13	4.06
3.00	212.6	85.05	42.53	8.51	4.25

According to the results shown in Table 2 and Table 3, we come to the conclusion that the extinction coefficients decrease as the visibility increases gradually. As shown in Table 2, extinction coefficients remain the same as the wavelength changes when the visibility is lower than 0.5 km. In fact, neither Kruse formula nor single scattering approximation resolves the extinction coefficient accurately, as multi-scattering effect are both neglected in the two models. So, neither one of the two methods is accurate in condition of dense fog.

Extinction coefficient and transmittance of convection fog calculated for laser with the wavelength of 0.86μm in different visibilities are shown in Fig. 3. As shown in (a) and (b), errors exist between the methods of single scattering approximation and Monte-Carlo simulation. When laser transmits a distance of 1 km, as can be seen in (b), the transmittance from Monte-Carlo simulation is larger than that from single scattering approximation. This phenomenon can be explained by the result that the extinction coefficient from Monte - Carlo simulation is less than that from single scattering approximation, which is caused by the multi-scattering effect considered in Monte-Carlo simulation.

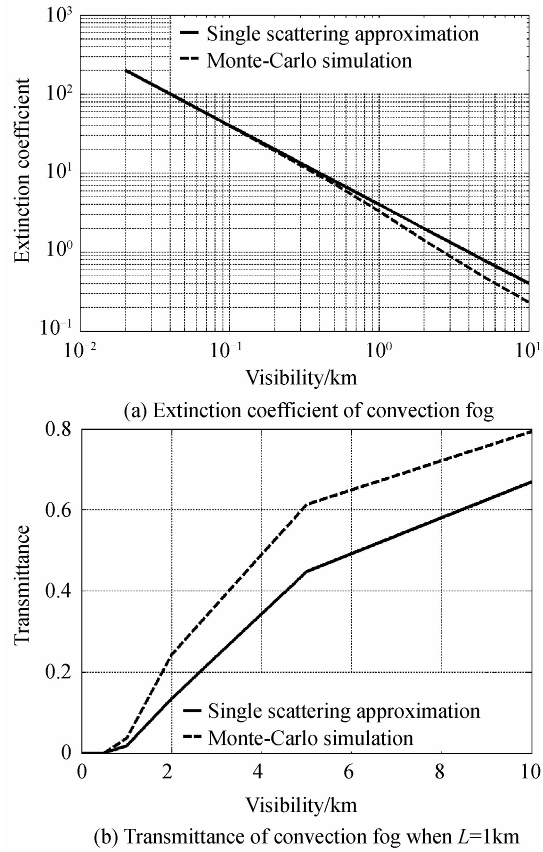
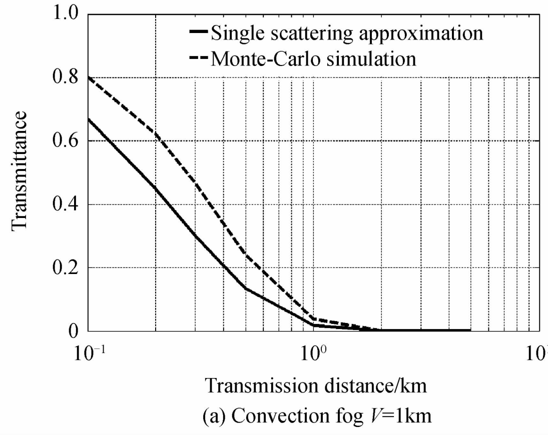
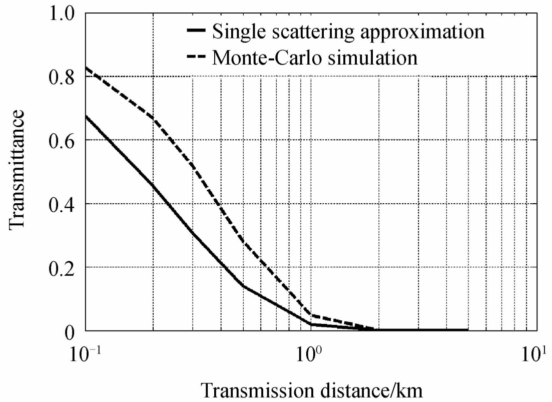


Fig. 3 Extinction coefficient and transmittance of convection fog in different visibilities

Relationships between transmittance and transmission distance for both convection fog and advection fog are shown in Fig. 4. As shown in Fig. 4, The transmittance of laser radiation decreases quickly as the distance increases. The results from Monte-Carlo simulation are larger than that from single scattering approximation at the same distance, which is also caused by the multi-scattering effect in Monte-Carlo.

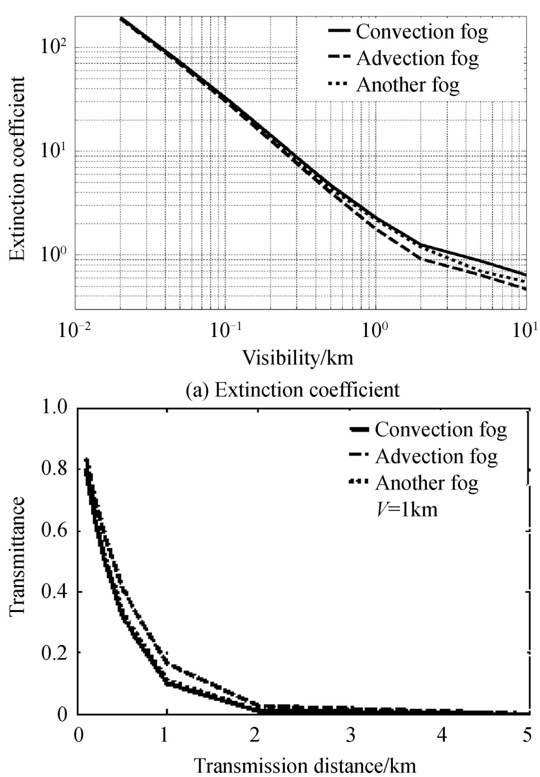




(b) Advection fog V=1km

Fig. 4 Relationship between transmittance and transmission distance

Fig. 5 shows the difference of extinction coefficient and the difference of transmittance among three types of fog under the same condition. As shown in Fig. 5, the difference of extinction coefficient in the same visibility and the difference of transmittance at the same distance are rather small among three types of fog. So, the difference is not obvious among three types of fog, which means the extinction characteristics are nearly the same under the same condition. In other words, the influence of the variation of particle size distribution on extinction characteristic is not obvious in the same visibility.



(b) Transmittance

Fig. 5 Extinction coefficient and transmittance of three types of fog

4 Conclusions

The extinction characteristic of laser transmitted in fog is an important issue that must be considered for applications in laser engineering. To solve the problem of extinction of laser transmitted in fog, absorbing and scattering by air molecules and fog particles are studied in this paper. Compared with the extinction by fog particles, the extinction by air molecules could be neglected as analyzed in section two. Based on the methods of Kruse model, single scattering approximation and Monte-Carlo simulation, the extinction coefficient and transmittance of laser with the wavelength of 0.86 μm are calculated in different visibilities. By comparing the results from different methods with each other, we come to the following conclusion that Kruse model is not applicable to calculate the extinction coefficient when the visibility is lower than 0.5 km. The extinction coefficient from single scattering approximation is larger than that from Monte-Carlo simulation in the same visibility, which means a lower transmission at the same distance. The influence of particle size distribution of fog on extinction characteristic is not obvious from the fact that the extinction coefficient and transmittance of three types of fog are nearly the same in the same visibility. These results are beneficial to evaluate the extinction effect of fog on laser transmission, which will promote the application of laser radar, laser communication systems and laser-guided weapons, etc.

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