Selecting an Optimal Set of Scattering Angles and Wavelengths for Practical Photoelectric Smoke Detector

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Abstract

For a practical photoelectric smoke detector, multi-wavelength light sources and multi-angle receivers can be used to distinguish fire aerosols from non-fire aerosols and solve the false alarms problem. In order to classify the aerosol particles by using the statistical properties of the particle size distribution more effectively, a correlation method of selecting an optimal set of scattering angles and wavelengths is presented. The numerical simulation results show that the optimal selecting method is effective and the correlation coefficient is very useful as the optimization target. And the results are in good agreement with the experimental results of our previous work. Therefore, the proposed optimization strategy based on the correlation coefficient can be applied to the design of practical photoelectric smoke detector.

Keywords: Light scattering, optimal selecting method, practical photoelectric detector simulation, correlation coefficient, optimal scattering angles

Introduction

In the photoelectric fire detector based on the scattered light intensity, multi-wavelength light sources and multi-angle receivers can be used to solve the false alarms problem caused by non-fire aerosols [1]. According to the Mie scattering theory, the light intensity at the receiver is related to the particle size distribution of the aerosol, the scattering angle, and the incident light wavelength. If the scattering angle and the incident light wavelength can be optimized, the scattered light intensity at the receiver would be related to the statistical properties of the particle size distribution of the aerosol. Then the photoelectric fire detector will become an accurate aerosol sensor, which is able to classify the aerosol particles and distinguish fire aerosols from non-fire aerosols more efficiently.

Due to the different particle size distributions of fire aerosols and non-fire aerosols, their statistical properties, such as volume concentration, surface area concentration, particle size concentration and so on, cannot be exactly the same [2]. If these statistical characteristics could be obtained more accurately, it can be more effective in distinguishing fire aerosols and non-fire aerosols [3]. However, for practical photoelectric smoke detectors, it is important to reduce cost and improve reliability by using as few scattering angles and incident light wavelengths as possible. Therefore, there is a trade-off between the accuracy of classification and the number of scattering angles and incident light wavelengths. In this paper, a correlation method of selecting an optimal set of scattering angles and wavelengths for practical photoelectric smoke detector is presented.

Mathematical model of practical photoelectric smoke detector

A typical practical photoelectric smoke detector is a non-paraxial optical system. It is composed of a light emitting diode (LED) emitter and a photodiode (PD) receiver, which has the advantages of low cost, high reliability, easy to assemble and so on. But there are some constraints as follows: (1) due to the presence of the LED's angle of half intensity and the PD's angle of half sensitivity, the scattering zone is no longer a focus point; (2) the luminous efficiency of LED is varied in the range of half intensity angle, while the receiving efficiency of PD is also varied in the range of half sensitivity angle; (3) from the viewpoint of easy to assemble, small scattering angles around 0 degree should be avoided. At the same time, large scattering angles around 180 degree should also be avoided due to direct light signal interference.

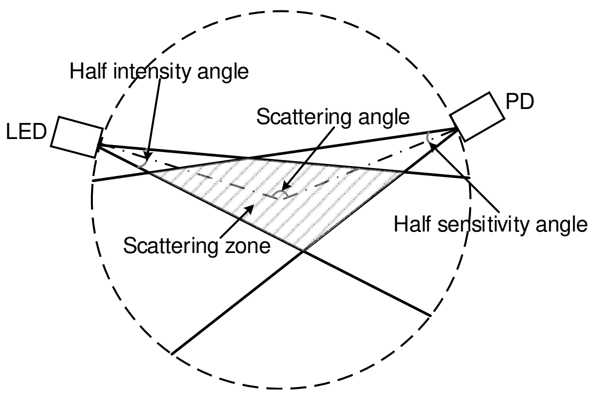

Fig. 1. Diagram of a practical photoelectric smoke detector.

Different from the ideal paraxial optical system, in order to accurately calculate the scattered light intensity on the PD receiver, it is necessary to calculate the equivalent average scattered light intensity per particle in the whole scattering zone instead of the scattered light intensity of one particle at the center of the dash line sphere. The equivalent average scattered light intensity q_w is given in [1] as follows:

$$q_w\left(x,n_p,\lambda,\theta\right)=\frac{1}{C_N\Omega}\oiiint_0^{\Omega}C_N w_E\left(\theta_E(\Omega)\right)w_C\left(\theta_C(\Omega)\right)q_p(x,n_p,\lambda,\theta)\mathrm{d}\Omega \quad \text{(Eq. 1)}$$

Where C_N is the particle number concentration, Ω is the scattering zone, w_E is the luminous efficiency, w_C is the receiving efficiency, θ_E is the half intensity angle, θ_C is the half sensitivity angle, and $q_p(x,n_p,\lambda,\theta)$ is the scattered light intensity of a particle at a fix point in the scattering zone, which is described by Mie theory. And λ is the incident light wavelength, n_p is the refractive index of the particle, θ is the scattering angle, and x is the particle size.

Optimization strategy

Based on the Mie scattering theory, the simulation data of the scattered light intensity of the practical photoelectric smoke detector are obtained under the influence of the above factors. Assuming that the particle size distribution function of the aerosol is $f(x)$, then the scattered light intensity P at the scattering angle θ can be expressed as:

$$P=C_N\int f(x)q_w\left(x,n_p,\lambda,\theta\right)\mathrm{d}x \quad \text{(Eq. 2)}$$

Where C_N is the particle number concentration, and $q_w(x,n_p,\lambda,\theta)$ is the equivalent average scattered light intensity shown in Eq. 1. The statistical properties of the aerosol can be obtained by the particle size distribution function $f(x)$, that is, the i order moment M_i can be expressed as:

$$M_i=\int x^i f(x)dx \quad \text{(Eq. 3)}$$

Where the zero order moment M_0 denotes the particle number concentration, the first order moment M_1 denotes the particle size concentration, the second order moment M_2 denotes the particle surface area concentration, and the third order moment M_3 denotes the particle volume concentration of aerosol.

The correlation coefficient $R_n(M_i)$ between the i order moment of aerosol M_i and the scattered light intensity $P_n([\theta,\lambda])$ with the combination of the scattering angle θ and the incident light wavelength λ is defined by l_2 norm, and can be expressed as:

$$R_n(M_i)=\frac{M_i P_n([\theta,\lambda])^T}{\|M_i\|_2\|P_n([\theta,\lambda])\|_2} \quad \text{(Eq. 4)}$$

The correlation coefficient r_{mn} between two received light intensities at different scattering angles and incident light wavelengths combinations $P_m([\theta,\lambda])$ and $P_n([\theta,\lambda])$ is defined by l_2 norm, and can be expressed as:

$$r_{mn}=\frac{P_m([\theta,\lambda])P_n([\theta,\lambda])^T}{\|P_m([\theta,\lambda])\|_2\|P_n([\theta,\lambda])\|_2} \quad \text{(Eq. 5)}$$

Taking the i order moment M_i of aerosol as the optimization target, the optimization strategy of choosing the first set of the optimal combination of scattering angles and incident light wavelengths is defined as:

$$max\, R_n(M_i),\ \ for\ all\ n\ in\ the\ set\ of\ [\theta, \lambda] \qquad \text{(Eq. 6)}$$

Under the condition that the former n-1 sets of the optimal combination of scattering angles and incident light wavelengths are known, and taking the i order moment M_i of aerosol as the optimization target, the optimization strategy of choosing the nth (greater than or equal to 2) set of the optimal combination of scattering angles and incident light wavelengths is defined as:

$$min \sum_{m=1}^{n-1} r_{mn}\ AND\ max\, R_n(M_i),\ \ for\ all\ n\ in\ the\ set\ of\ [\theta, \lambda] \qquad \text{(Eq. 7)}$$

This means that the newly selected combination of scattering angles and incident light wavelengths brings the maximum amount of information, while it is most relevant to the i order moment of aerosol.

Numerical simulations

It is generally believed that most of fire aerosol particles are distributed within the range of 1000 nm. And considering the feasibility of practical photoelectric smoke detector, the particle size distributions in numerical simulations are assumed to satisfy the lognormal distributions with the means μ ranging from 100 to 1000 nm with the discrete step size of 25 nm and the variances δ ranging from 1.5 to 2 with the discrete step size of 0.1.

There are two LED light sources employed, including an infrared LED with the light wavelength of 950 nm and a blue LED with the light wavelength of 450 nm. And the scattering angles only ranging from 30 to 150 degree with the discrete step size of 5 degree are available. So there are total 50 combinations of scattering angles and incident light wavelengths. Moreover, there are only two particle refractive indexes used, including 1.55 +0.02i and 1.55 +0.5i, which are correspond to the grey smoke and the black smoke in the standard test fire aerosols, respectively.

In order to investigate the effect of particle refractive index on the optimization results, we change the real and imaginary parts of the refractive index, and calculate the correlation coefficient of the obtained optimal combination sets. Considering the particle refractive indexes of fire aerosols and non-fire aerosols causing false alarm, the real parts of particle refractive indexes are selected ranging from 1.3 to 2 with the discrete step size of 0.05 and the imaginary parts of particle refractive indexes are only selected from the discrete set of [0, 0.005, 0.01, 0.02, 0.05, 0.1, 0.2, 0.5, 1].

Table 1 shows the largest correlation coefficient sets of the single combination of scattering angles and incident light wavelengths with the particle volume concentration as the optimization target for two different refractive indexes. And table 2 shows the largest correlation coefficient sets of the single combination of scattering angles and incident light wavelengths with the particle surface area concentration as the optimization target for two different refractive indexes.

Table 1. Combination of scattering angles and wavelengths with the particle volume concentration (the third moment M_3) as the optimization target.

	Grey smoke (1.55 +0.02i)			Black smoke (1.55 +0.5i)		
	Wavelength (nm)	Angle (degree)	Correlation coefficient	Wavelength (nm)	Angle (degree)	Correlation coefficient
1	950	150	1.0000	450	150	0.9903
2	950	140	0.9981	450	140	0.9898
3	950	130	0.9954	450	130	0.9891

Table 2. Combination of scattering angles and wavelengths with the particle surface area concentration (the second moment M_2) as the optimization target.

	Grey smoke (1.55 +0.02i)			Black smoke (1.55 +0.5i)		
	Wavelength (nm)	Angle (degree)	Correlation coefficient	Wavelength (nm)	Angle (degree)	Correlation coefficient
1	950	75	0.9997	450	150	0.9998
2	950	70	0.9997	450	140	0.9998
3	950	90	0.9996	450	130	0.9997

From table 1 and table 2, we can see: (1) for gray smoke, the scattered light intensity of the infrared light source at the forward scattering angle (150 degree) is most related to the volume concentration, while that at the backscattering angle (75 degree) is most related to the surface area concentration; (2) for black smoke, the scattered light intensity of the blue light source at the forward scattering angle (150 degree) is most relevant to the volume concentration or the surface area concentration.

The effects of particle refractive index on the correlation coefficients of the particle volume concentration and the particle surface area concentration for the obtained optimal combination sets are showed in Fig. 2 and Fig. 3, respectively. As the imaginary part of refractive index is increased from 0 to 1 and the real part of refractive index is increased from 1.3 to 2, the correlation coefficients of the obtained optimal combination sets containing 950 nm wavelength are decreased, where the amplitudes of change are very small. At the same time, those sets containing 450 nm wavelength are decreased first and then increased, where the amplitudes of change slightly are greater than the formers.

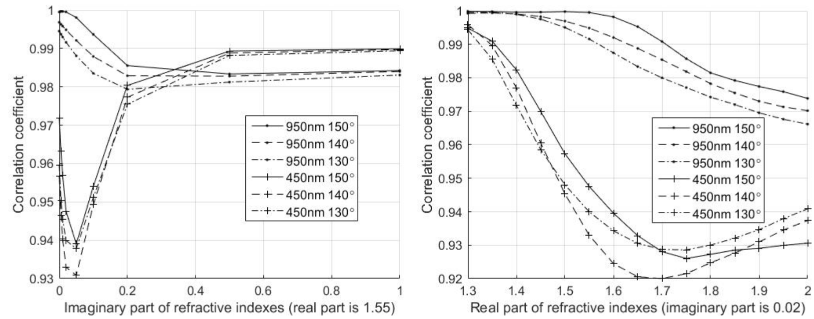

Fig. 2. The correlation coefficient of particle volume concentration versus: (a) imaginary part of refractive indexes; (b) real part of refractive indexes.

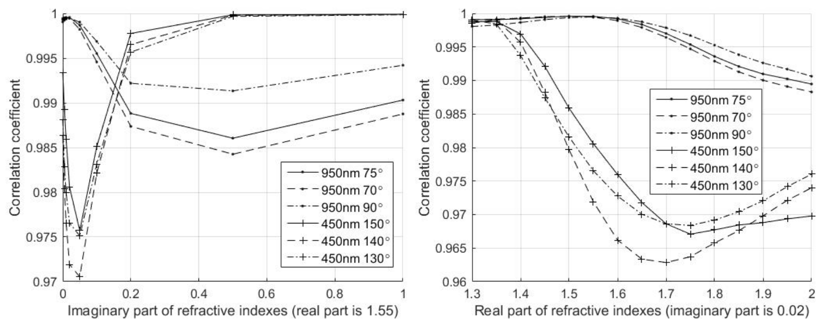

Fig. 3. The correlation coefficient of particle surface area concentration versus: (a) imaginary part of refractive indexes; (b) real part of refractive indexes.

For a set of two combinations of scattering angles and incident light wavelengths, the optimal target can be expressed as the second order statistical characteristic of aerosol, that is, the ratio of two different order moments. For example, the ratio of particle volume concentration and particle surface area concentration is defined as the Sauter mean diameter (SMD). Thus, taking the SMD as the optimization target, the optimization strategy of choosing a set of two optimal combinations of scattering angles and incident light wavelengths is defined as:

$$max\, R_n(\text{SMD}) = \frac{\frac{M_3}{M_2}\left(\frac{P_m([\theta,\lambda])}{P_n([\theta,\lambda])}\right)^T}{\left\|\frac{M_3}{M_2}\right\|_2 \left\|\frac{P_m([\theta,\lambda])}{P_n(\theta,\lambda)}\right\|_2}$$

$$for\ all\ m, n\ (m \neq n)\ in\ the\ [\theta,\lambda]\ set \qquad \text{(Eq. 8)}$$

Table 3 shows the largest correlation coefficient sets of two combinations of scattering angles and incident light wavelengths with SMD as the optimization target for two different refractive indexes.

From table 3, when taking the SMD as the optimization target, the following conclusions can be drawn: (1) the set of the infrared light source at the forward scattering angle (100 degree) and the blue light source at the backscattering angle (65 degree) is optimal for gray smoke; (2) the set of the infrared light source at the forward scattering angle (125 degree) and the blue light source at the backscattering angle (45 degree) is also suboptimal for black smoke; (3) the set of the infrared light source at the forward scattering angle (110 degree) and the blue light source at the backscattering angle (40 degree) is optimal for two kinds of smoke.

Table 3. Two combinations of scattering angles and wavelengths with the SMD as the optimization target.

		The first combination		The second combination		
		Wavelength (nm)	Angle (degree)	Wavelength (nm)	Angle (degree)	Correlation coefficient
Grey smoke	1	950	100	450	65	0.9995
	2	950	115	450	100	0.9995
	3	950	95	450	65	0.9995
Black smoke	1	950	30	950	55	0.9964
	2	950	30	950	60	0.9957
	3	950	125	450	45	0.9940
Any smoke	1	950	110	450	40	0.9936
	2	950	115	450	40	0.9934
	3	950	130	450	45	0.9931

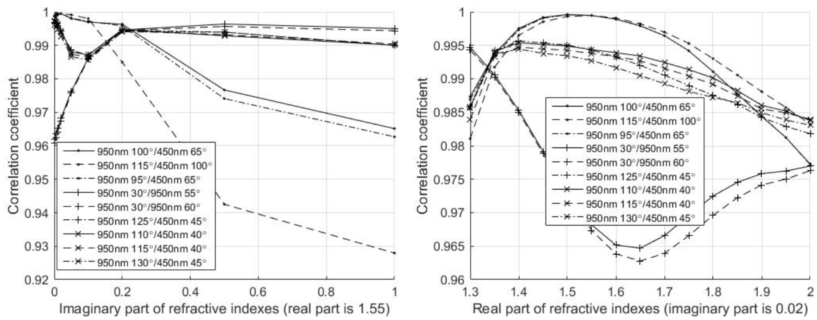

Fig. 4. The correlation coefficient of SMD versus: (a) imaginary part of refractive indexes; (b) real part of refractive indexes.

The effects of particle refractive index on the correlation coefficients of SMD for the obtained optimal combination sets are showed in Fig. 4. As the imaginary part of refractive index is increased from 0 to 1, the correlation coefficients of the obtained optimal combination sets, which are optimal for two kinds of smoke, are more stable than others, but they are not monotonically reduced or increased. As the real part of the refractive index is increased from 1.3 to 2, the amplitudes of change of the correlation coefficients for the obtained optimal combination sets containing 950 nm and 450 nm wavelength are small than others.

In our previous work [1], the experimental results of the monodisperse DEHS aerosols (refractive index is 1.45 +0i) show that the ratio of the scattered light intensity of the infrared light source at 45 degree to that of the blue light source at 120 degree is close to the SMD of DEHS aerosols. Our simulation results of the correlation coefficient of SMD for the DEHS aerosols are shown in Fig. 5, and the same conclusion could be drawn.

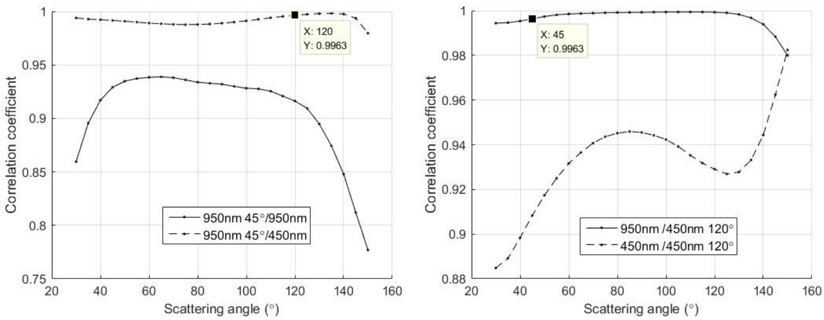

Fig. 5. The correlation coefficient of SMD versus: (a) scattering angles of the second combination; (b) scattering angles of the first combination.

Conclusion

The above results are in good agreement with the experimental results of practical photoelectric smoke detectors in our previous work. Therefore, the proposed optimization strategy can be applied in the design of practical photoelectric smoke detector to efficiently distinguish fire aerosols from non-fire aerosols.

References

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