A Method for Fire Detecting by Volume and Surface Area Concentration Based on Dual Wavelengths

Xiao Xiao, Tian Deng, Ming Zhu, Shu Wang
School of Electronic Information and Communications, Huazhong University of Science and Technology, Wuhan, P.R. China

Abstract

Fire detectors trigger alarm when the concentration of measured aerosols passed the alarm threshold. However, non-fire aerosols may also reach the threshold and trigger a false fire alarm. Therefore, distinguish these two aerosols by volume and surface area concentration is considered since the traditional fire detectors measured volume concentration only. In this paper, a fire detector is designed for measuring the surface area concentration and volume concentration of aerosols with dual wavelengths sources. Thus fire aerosols in which particles are usually smaller can be differentiated from non-fire aerosols in which particles are usually larger. In this way, the false alarm ratio shall be lower than single wavelength detectors.

Keywords: Dual wavelengths, Surface area concentration, Volume concentration,

Introduction

Present photoelectric fire detectors trigger alarm by measuring the light scattering intensity of fire aerosols. Considering non-fire aerosols may also reach the concentration threshold, false alarm is inevitable. Studies show that particle size of fire aerosols is usually smaller than non-fire aerosols [1], thus it is possible to distinguish between fire and non-fire aerosols by measuring the volume and surface area concentration of the aerosols.

According to Mie scattering theory, the intensity of lights scattered by a particle with different size is related to the wavelength of incident light, the observing angle and the refractive index. Cole et al. [2] found that the ratio between infrared and blue scattering signals can be used to determine whether the particle sizes of the aerosols are larger than 1 um. However, they did not explain the mechanism by which the infrared and blue scattering signals were influenced by the particle size.

Greenberg et al. [3] established a paraxial system with a single-wavelength incident laser source and dual observing angles named MPASS (Multi-Parameter Aerosol Scattering Sensor) for fire smoke detection in spacecraft. MPASS measured the surface area concentration and the volume concentration of the aerosols with different observing angles. However, according to the general relationship between scattering intensity and particle size [4], the surface area concentration and the volume concentration of the aerosols should be measured in the regions with different ratios of particle size and wavelength of incident light; hence, the wavelengths of the incident light sources must be different to measure these two concentrations. Because MPASS adopts only a single-wavelength laser source, it cannot measure the surface area concentration and the volume concentration accurately. Moreover, the different refractive indexes of black smoke and white smoke will increase the deviation in measuring area concentration and volume concentration of fire aerosols, which makes measuring particle size in fire aerosols more difficult [5].

In this paper, we design and produce a photoelectric fire detector based on dual wavelengths light sources to measure the surface area concentration and the volume concentration of aerosols. The longer wavelength light source is used to measure the volume concentration, while the shorter wavelength source is used for the surface area concentration. Compared with the widely used photoelectric fire smoke sensor, only one LED is added in this detector, which is much simpler in mechanical structure and lower in cost than MPASS. Thus, it is very suitable for fire detection in large-scale production. The prototype fire detector shows good performance in the tests with monodisperse aerosols ranging from 200 nm to 2000 nm. Moreover we tested the detector with real smokes generated by smoldering fires and open fires. The result will be discussed in Experiment part.

Theory

Illustrated by Baron et al. [4], the scattering intensity versus particle size can be approximated to a simple function of particle size in the statistical measurement of aerosols. The scattering intensity $q(x, m, \lambda, \theta)$ is defined as the intensity of monochromatic light scattered by a single particle into a receiving aperture, where x is the particle size, m is the refractive index, λ is the wavelength of incident light, and θ is the observing angle from emitter to receiver. The intensity of light scattered by unit volume of sphere particle q_v can be expressed by:

$$q_v = \frac{q(x, m, \lambda, \theta)}{\frac{\pi}{6} x^3} \qquad \text{(Eq. 1)}$$

The general relationship [4] of q_v and ratio of x to λ is shown in Fig.1. It can be described in three regions:

I)   When $\lambda < x$, $q_v \propto x^3$, thus $q(x, m, \lambda, \theta) \propto x^6$;

II) When $\lambda \approx x$, $q_v \propto x$, thus $q(x, m, \lambda, \theta) \propto x^3$, $q(x, m, \lambda, \theta)$ is proportional to the particle volume;

III) When $\lambda > x$, $q_v \propto x^{-1}$ thus $q(x, m, \lambda, \theta) \propto x^2$, $q(x, m, \lambda, \theta)$ is proportional to the particle surface area;
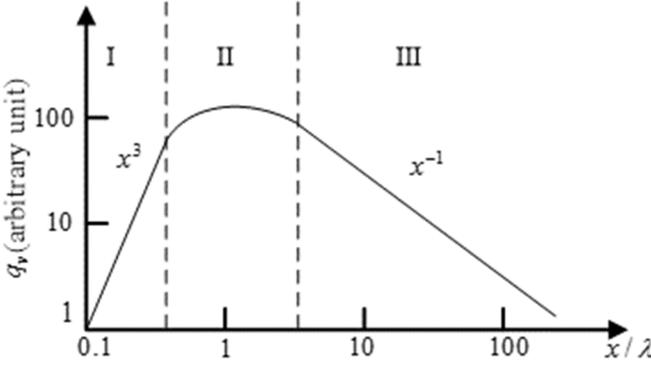

Fig.1.   The general relationship of light scattered intensity by unit volume of sphere particle q_v and x/λ.

Because an aerosol is composed of particles in different sizes, it can be characterized by particle size distribution $f(x)$ in a particle size range. The intensity of light scattered by the aerosol is given by,

$$P = C_N \int f(x)\, q(x, m, \lambda, \theta)\, \mathrm{dx} \qquad\qquad \text{(Eq. 2)}$$

where C_N is the number concentration of the aerosol. When x varies in region II, $q(x, m, \lambda, \theta) \approx \mathrm{T} \cdot x^3$, the scattering intensity P is proportional to the volume concentration of the aerosol C_V, we rewrite P as P_V.

$$P_V = \frac{6}{\pi} T_{II} C_N \int f(x) \left(\frac{\pi}{6} x^3\right) \mathrm{dx} = T_V . C_V \qquad\qquad \text{(Eq. 3)}$$

where T_V is the conversion factor of the volume concentration of the aerosol, $T_V = 6T_{II}/\pi$. T_V is the scattering intensity by unit volume concentration of the aerosol. Similarly, when x is located in region III, P is proportional to the surface area concentration of the aerosol C_V, and we rewrite P as P_V.

$$P_S = \frac{1}{\pi} T_{III} C_N \int f(x) \left(\pi\, x^2\right) \mathrm{dx} = T_S . C_S \qquad\qquad \text{(Eq. 4)}$$

where T_S is the conversion factor of the surface area concentration, $T_S = T_{III}/\pi$. T_S is the scattering intensity by unit surface area concentration of the aerosol.

Assuming that the range of aerosol's particle size distribution (PSD) is $[x_{min}, x_{max}]$, when we choose $\lambda_1 \approx (x_{min} + x_{max})/2$ as wavelength of incident light, the PSD will be mainly in region II, the intensity of scattering light is proportional to volume concentration C_V. And when we choose $\lambda_1 < x_{min}$ as wavelength of incident light, the PSD will be mainly in region III, the intensity of scattering light is proportional to surface area concentration C_S. In fire smoke detection, the range of particle sizes is mainly from 200 nm to 2000 nm. Thus, an infrared incident light with wavelength of 1100 nm can be used to measure the volume concentration, and an ultraviolet incident light with wavelength slightly less than 200 nm is suitable to measure the surface area concentration. According to the consideration of lower the cost, an infrared wavelength of 860 nm is chosen to measure C_V while the 460 nm blue incident light is chosen to measure C_S.
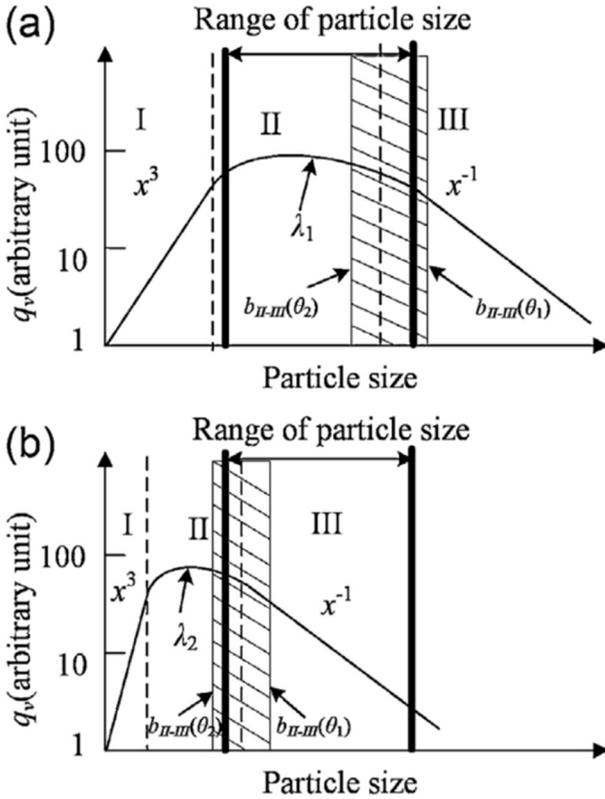

Fig.2. Boundary of region II and III (the shaded area) varies by adjusting the observing angle θ. (a) Expand region II at θ_1 to measure the volume concentration. (b) Expend region III at θ_2 to measure the surface area concentration.

In standard fire experiment, we compare the result of volume concentration C_V and surface area concentration C_S measured by the detector with reference instrument SMPS (Scan Mobility Particle Sizer 3936, TSI). SMPS is combined by Electrostatic Classifier and Condensation Particle Counter (CPC). Given a polydisperse input of aerosol, the Electrostatic Classifier can output a stream of monodisperse of known particle size [6] while CPC can enlarge the particles in this stream into droplet with the condense of n-butanol and count the number of these particles by laser [7].

According to Mie theory, the deviations result from the refractive index m, the wavelength of incident light λ and the observing angle θ. As discussed above, the wavelength of the incident light can be selected in the principle for measuring the volume concentration and surface area concentration, the refractive index will be discussed in Experiment part, the deviation of measurement mainly comes from the observing angle θ. As shown as the shaded area in Fig. 2, the variation of observing angle would change the boundary between region II and region III. For a range of particle sizes to be measured, we select λ_1 and adjust the observing angle to θ_1 to set the whole range of particle size into region II for the measurement of volume concentration, as shown in Fig. 2(a). Similarly, we select λ_2 and adjust the observing angle to θ_2 to set the whole range of particle size into region III for measurement of the surface area concentration as shown in Fig. 2(b).

Experiment

In our experiments, we tested the prototype fire detector using four kinds of standard fire which are smoldering cotton wick and wood smokes (white smokes), open fire of n-heptane and polyurethane smokes (black smokes). Meanwhile we also use SMPS to measure C_V, C_S and of the smokes as reference values. As shown in the table 1, the detector gives a correct value of C_V and C_S compared with SMPS3639 when measuring the white smokes while the value of C_V and C_S in black smokes is much smaller than reference value. In n-heptane fire smoke, the C_V and C_S measured by the detector is as low as 33.8 % and 33.1 % of reference value respectively. And in polyurethane fire smoke, the C_V and C_S is as low as 33.2 % and 38.3 % respectively.

The measurement errors of black smokes are caused by using the conversion factors of smoldering fire smokes, from scattering power to volume and to surface area concentrations. The difference of refractive indexes between white smokes and black smokes is the dominant reason that cause the deviations of conversion factors. The white smokes scatter most of incident lights while the black smokes absorb parts of incident lights, thus the scattered intensity of black smokes is lower than in white smokes. Since the same conversion factor is used in both white smokes and black smokes, the measuring results of black smokes are lower than reference.

Table 1. Experiment result of C_V and C_S by prototype fire detector and SMPS.

Test Fire	Prototype Fire Detector		SMPS	
	C_V (E+12 nm³/m³)	C_S (E+10 nm²/m³)	C_V (E+12 nm³/m³)	C_S (E+10 nm²/m³)
Smoldering cotton wick	5.45	14.51	5.89	14.63
smoldering wood	4.58	7.45	4.26	7.41
open fire of n-heptane	14.17	15.30	41.90	46.22
open fire of polyurethane	1.96	3.47	5.91	9.06

According to the experiment results, we find that the response of the detector to black smoke is about 1/3 of reference value from SMPS [5]. However, the simulation shows that the decrease was the same for volume concentration and surface area concentration in black smoke. Thus, the general description of particle scattering for white smokes and black smokes is described by Fig.3.
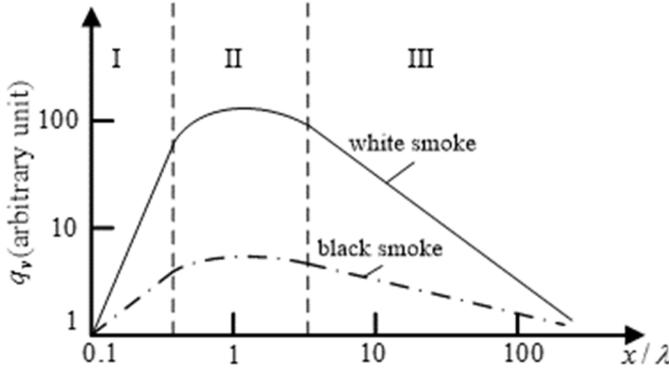

Fig.3. The general relationship of q_v and x/λ in white smoke and black smoke.

In order to eliminate the deviation of concentration in black smoke, we calculate the Sauter mean diameter $\overline{D}_{Sauter}$ by equation below:

$$\overline{D}_{Sauter} = 6 \cdot C_V / C_S \qquad \text{(Eq. 5)}$$

Thus, the Sauter mean diameters measured by the detector have a consistent value with SMPS. As shown in the Fig.4, the relative standard deviation of Sauter mean diameters of the detector to SMPS is only 6.04 %. In this way, we can obtain the Sauter mean diameter with high accuracy despite the influence of refractive index.
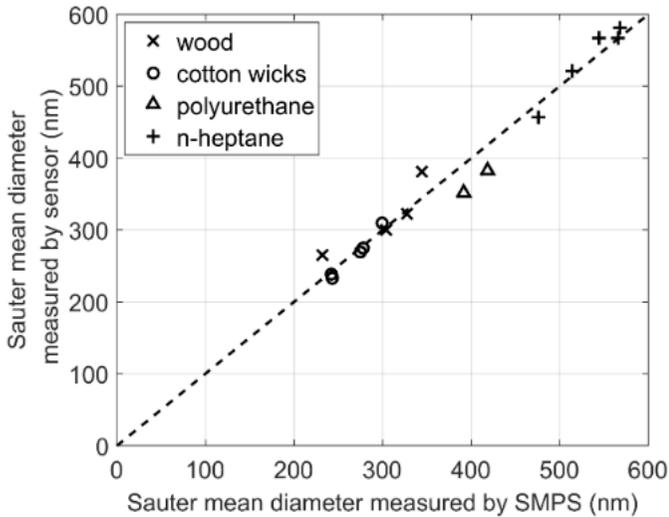
Fig.4.   Sauter mean diameter measured by the prototype fire detector versus SMPS in fire smoke tests.

Conclusion

According to the general relationship of particle scattering given by Baron et al, we promote dual wavelengths technology to measure the volume concentration and surface area concentration of aerosols. In combination of volume and surface area concentration, it is possible to distinguish fire smoke from non-fire aerosols, and resist nuisance fire alarm. A prototype fire smoke detector was manufactured base on dual wavelengths technology. The test results showed that the measurements of volume concentration and surface area concentration for white smokes were consistent with reference values by SMPS, but the measurement result for black smokes were lower than reference values. In order to eliminate the effect of refractive indices, the Sauter mean diameter, as the ratio of volume concentration and surface area concentration, is introduced as an auxiliary parameter to distinguish fire smokes from non-fire aerosols correctly.

References

[1]   TSI Incorporated, "*Particle Size*", TSI Technical Notes (2013),

[2]   M. Cole, "*Aerosol characterisation for reliable ASD operation*", 14th Int. Conf. Auto. Fire Detect. AUBE'09, Duisburg, Germany, 2009.

[3]   P.S. Greenberg, D.G. Fischer, N. Glenn, "*Advanced Particulate Sensors for Spacecraft Early Warning Fire Detection*", 40th Int. Conf. Environ, (2010) 1–10.

[4]   P. Baron, K. Willeke, "*Aerosol Measurement: Principles, Techniques, and Applications",* 2nd Edition, New York: John Wiley & Sons, 2005.

[5]   T. Deng, S. Wang, M. Zhu, "*Dual-wavelength optical sensor for measuring the surface area concentration and the volume concentration of aerosols ",* Sensors and Actuators B: Chemical, Volume 236, 29 November 2016, Pages 334–342.

[6]   TSI Incorporated, "*Series 3080 Electrostatic Classifiers, Operation and Service Manual"*, Shoreview, USA, May 2012.

[7]   TSI Incorporated, "*Model 3775 Condensation Particle Counter, Operation and Service Manual",* Shoreview, USA, July 2011.