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Dual-wavelength optical sensor for measuring the surface area concentration and the volume concentration of aerosols

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ABSTRACT

The surface area concentration and the volume concentration of aerosols can be used to detect fire smoke. However, existing optical sensors with a single wavelength source cannot measure these two concentrations accurately. In this paper, we design a sensor to measure these two concentrations with dual wavelength sources, based on the phenomenon that the surface area concentration and the volume concentration of aerosols are proportional to the scattering intensity of the different wavelength incident lights. The prototype sensor is tested by monodisperse aerosols with particle sizes ranging from 200 nm to 2000 nm. The standard measurement deviations of the surface area concentration, volume concentration and Sauter mean diameter are 11.6%, 21.9% and 9.4%, respectively, which are better than the results of sensors with a single wavelength source. Moreover, the Sauter mean diameter of fire smokes measured by our sensor are consistent with calibration instruments, which is helpful to resist false alarm in fire detection. With simple mechanical structure and high accuracy, this sensor is promising in fire detection and atmosphere environment monitoring.

1. Introduction

Optical sensors are widely used in fire smoke detection and industries due to their simplicity in production and low cost. Existing fire sensors trigger an alarm when the smoke density exceeds a threshold value. However, the density of non-fire aerosols may also exceed this threshold and trigger a false fire alarm. Studies show that the particle size of smoke aerosol is usually smaller than non-fire aerosols [1–5], thus, it is possible to distinguish fire and non-fire smoke to verify fire alarm by measuring particle size of the aerosols. Most existing instruments measure the particle size by dividing particle size range into different channels with electrical mobility, aerodynamics or other methods [6–10]. However, these channel-dividing technologies require precise instruments with complicated structure and high-cost, which cannot be embedded in a simple and low-cost sensor. Therefore, to detect fire smoke with sensors, it is more practical to obtain the statistical particle size of the aerosols (Sauter mean diameter) by measuring the surface area concentration and the volume concentration [11].

According to Mie scattering theory [12], the intensity of light 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. [13] 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 μm. However, they did not explain the mechanism by which the infrared and blue scattering signals were influenced by the particle size. Greenberg et al. [11,14,15] 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 [6], 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.

In this paper, we design and produce an optical sensor based on dual-wavelength light sources to measure the surface area concentration and the volume concentration of the aerosols. The longer wavelength light source is used to measure the volume concentration, while the shorter wavelength source is used for the surface

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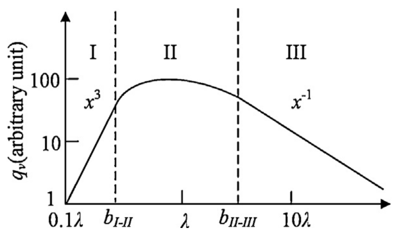

Fig. 1. The general relationship of light scattered intensity by unit volume of sphere particle q_v and particle size x with wavelength of incident light λ.

area concentration. Next, the Sauter mean diameter of the aerosols is calculated by the ratio of the volume to the surface area [16]. This sensor is a non-paraxial optical system with two LEDs and one PD (photodiode). Compared with the widely used optical fire smoke sensor [17], only one LED is added in our sensor, which is much simpler in mechanical structure and lower cost than MPASS. Thus, it is very suitable for fire detection in large-scale production. The prototype sensor shows good performance in the tests with monodisperse aerosols ranging from 200 nm to 2000 nm. Moreover, we tested the sensor with real smokes generated by smoldering fires and open fires, the sensor was found to measure the smoke particle sizes accurately. Because our sensor obtains the Sauter mean diameter with high accuracy, it can be used to verify a fire alarm in fire detection.

The following paper is organized into four sections. Section 2 introduces the method using sources of two different wavelengths to measure the surface area concentration and the volume concentration of aerosols. Section 3 describes the scattering model of aerosol in the sensor and gives the strategy to optimize the observing angles. The prototype sensor is designed based on the angle optimization principle. Section 4 shows the test results of the prototype sensor for monodisperse aerosols and real smoke aerosols. Section 5 concludes the whole paper.

2. The surface area concentration and the volume concentration measurement by dual wavelengths

2.1. General relationship of scattering light versus particle size

Illustrated by Baron et al. [6], 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:

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

Based on Ref. [6], the general relationship of q_v relating to x and λ is shown in Fig. 1. The relationship can be described in three regions:

I) When $x < \lambda$, $q_v \approx A_I \cdot x^3$, thus $q(x,m,\lambda,\theta) \approx T_I \cdot x^6$;
II) When $x \approx \lambda$, $q_v \approx A_{II} \cdot x^0$, thus $q(x,m,\lambda,\theta) \approx T_{II} \cdot x^3$, $q(x,m,\lambda,\theta)$ is proportional to the particle volume;
III) When $x > \lambda$, $q_v \approx A_{III} \cdot x^{-1}$, thus $q(x,m,\lambda,\theta) \approx T_{III} \cdot x^2$, $q(x,m,\lambda,\theta)$ is proportional to the particle surface area.

where A_I, A_{II} and A_{III} are the conversion factors of x and q_v in each region, and $T_I = \pi \cdot A_I/6$, $T_{II} = \pi \cdot A_{II}/6$ and $T_{III} = \pi \cdot A_{III}/6$ are the conversion factors of x and q, which are related to refractive index m and

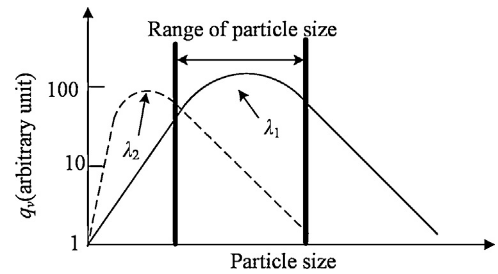

Fig. 2. Dual wavelength measurement technology, where the longer λ_1 (solid line) is used to measure the volume concentration and the shorter λ_2 (dash line) is used to measure the surface area concentration.

observing angle θ. As a continuous curve, we have $A_I \cdot b_{I\text{-}II}{}^3 = A_{II} \cdot b_{I\text{-}II}{}^0$ and $A_{II} \cdot b_{II\text{-}III}{}^0 = A_{III} \cdot b_{II\text{-}III}{}^{-1}$, where $b_{I\text{-}II}$ is the boundary between region I and II, $b_{II\text{-}III}$ is the boundary between region II and III, it can be inferred that $b_{I\text{-}II} = (A_{II}/A_I)^{1/3}$ and $b_{II\text{-}III} = A_{III}/A_{II}$.

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,

$$P = C_N \int f(x)q(x, m, \lambda, \theta)dx \tag{2}$$

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

$$P_V = \frac{6}{\pi} T_{II} \cdot C_N \int f(x)(\frac{\pi}{6}x^3)dx = T_V \cdot C_V \tag{3}$$

where T_V is the conversion factor of the volume concentration of the aerosol, $T_V = 6 \cdot T_{II}/\pi$. 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_S, and we rewrite P as P_S.

$$P_S = \frac{1}{\pi} T_{III} \cdot C_N \int f(x)(\pi x^2)dx = T_S \cdot C_S \tag{4}$$

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.

2.2. Dual-wavelength selection principle

According to Section 2.1, the volume concentration C_V and the surface area concentration C_S are proportional to the scattering intensity in regions II and III, respectively. The boundaries of the regions are determined by the ratio of particle size x and wavelength of incident light λ. To measure C_V and C_S, the wavelengths of incident lights should be selected to make the ratio x/λ in region II or III. To measure C_V, the wavelength should be selected as the middle value of particle size range, such as λ_1 (solid line) shown in Fig. 2, setting x/λ into region II. To measure C_S, the wavelength should be smaller than the minimum value of x, e.g., λ_2 (dashed line) in Fig. 2, setting x/λ into region III. Consequently, the wavelength to measure C_V must be different from the wavelength to measure C_S for the same aerosol.

In fire smoke detection, the range of particle sizes is mainly from 200 nm to 2000 nm. This range includes most of fire aerosols and some of non-fire aerosols that float in the air. Thus, an infrared incident light with wavelength of 1100 nm can be used to measure the volume concentration, and an ultraviolet incident light with