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Eliminating the effects of refractive indices for both white smokes and black smokes in optical fire detector

Tian Deng, Shu Wang, Xiao Xiao, Ming Zhu*

School of Electronic Information and Communications, Huazhong University of Science and Technology, Wuhan 430074, Hubei, China

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ABSTRACT

Existing optical fire smoke detectors would take more time or even fail to trigger alarms of black smokes because the optical scattering efficiencies of black smokes are much lower than those of white smokes. In this paper, we design an optical fire smoke detector with consistent response to white smokes and black smokes based on dual-wavelength technology and multiple scattering signals. The proposed detector utilizes the incident lights of dual wavelengths to measure the surface area concentration and volume concentration of fire smokes respectively. The particle size distribution of the smokes can be estimated by these concentrations. The refractive indices are deduced by the third scattering signal and more observing angles are helpful to reduce the measurement errors. As a result, a 4-channel detector [140°–950 nm, 45°–950 nm, 140°–450 nm, 45°–450 nm] is developed, which can accurately measure the concentrations of both smoldering cotton (white smoke) and open fire of polyurethane (black smoke).

1. Introduction

Optical fire smoke detectors are widely used in household and industries fire detection due to their simplicity in production and low cost [1,2]. Existing optical fire smoke detectors measure the power of scattering light as an indicator of smoke concentration and trigger fire alarms when the power of scattering light exceeds a threshold value [3]. However, the scattering efficiencies (scattering power per smoke concentration) of black smokes would be much lower than those of white smokes, because the black smokes absorb part of incident light, while the white smokes scatter most of incident light [3,4]. Thus, existing optical fire smoke detector will underestimate the concentration values of black smokes and may take more time or even fail to trigger the alarms. Therefore, it is an emergency to develop an optical fire detector with consistent responses to both white smokes and black smokes.

Efforts were made to balance the response of detector to white smokes and black smokes. Comparing with the forward scattering (the observing angle from emitter to receiver larger than 90°), the backward (the observing angle less than 90°) is helpful to mitigate the difference of responses to white and black smokes in a certain degree [5,6]. However, it cannot solve the problem of lower scattering efficiency caused by black smokes essentially and the difference between the responses of white smokes and black smokes still exist. Some works reported that optical smoke detectors with empirical multiple observing angles or/and multiple incident light wavelengths can distinguish a few different types of smokes by pattern recognition, but the reasons to select wavelengths and observing angles are not explained [7–12]. According to Mie theory, the intensity of the light scattered by smoke depends on the wavelength of incident light, the observing angle, the refractive index and the particle size distribution. These works do not derive the refractive indices and particle size distributions of fire smokes from the scattering signals with multiple wavelengths and observing angles. Thus, they are not general design methods for fire detectors with consistent responses to both white smokes and black smokes.

In this paper, we propose a general design method to develop optical fire smoke detectors with dual wavelengths and multiple observing angles to measure the surface area concentration and volume concentration for both white smokes and black smokes. By applying dual wavelength technology [13], the surface area concentrations and volume concentrations of fire smokes can be obtained, and the particle size distributions are estimated. After that, the third observing angle is utilized to confirm the refractive indices of the fire smokes, the measurement errors would be reduced by the scattering signals from more observing angles. A 4-channel fire smoke detector with dual wavelengths and two observing angles is designed in consideration of performance and cost, which has simple optical structure and only a few optical components. And then the design scheme is verified by 5000 kinds of random gener-

* Corresponding author.
E-mail address: zhuming@mail.hust.edu.cn (M. Zhu).

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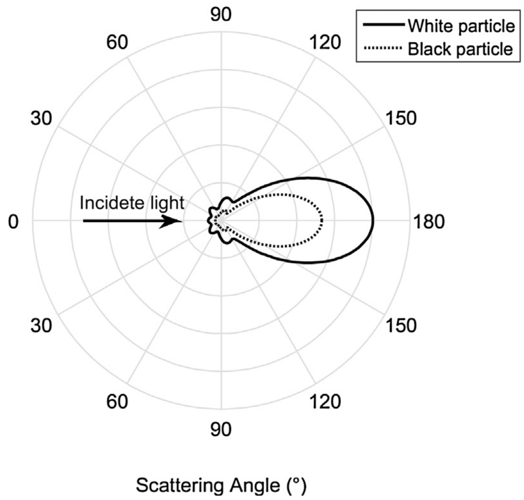

Fig. 1. Scattering efficiency of white smoks versus black smokes.

ated fire smokes via simulation. A sample optical fire detector with the four channels is manufactured and used to measure the concentrations of the smoldering cotton (white smoke) and open fire of polyurethane (black smoke) with the maximal deviation only by 13.01%.

The following paper is organized into four sections. Section 2 introduces the general design method of fire smoke detector with dual wavelengths and multiple observing angles. Section 3 shows the simulation results for optimization in fire detections to both white smokes and black smokes. Section 4 shows our sample optical fire detector with four scattering signal channels and the experiment results for smoldering cotton (white smoke) and polyurethane open fire (black smoke). Section 5 concludes the whole paper.

2. The design method for eliminating the effects of refractive indices of smokes

2.1. Optical scattering and 'Three regions' law of white smokes and black smokes

In the early stage of combustion, there is commonly only one comburent as the source of fire, which would simply generate single type of fire smoke and in a low concentration. Based on refractive indices, the fire smokes generally can be divided into two kinds, white smokes and black smokes. The main differences of the white and black smokes are the imaginary parts of their refractive indices, which indicate the absorption efficiency of incident light by the smokes. As the changes of refractive indices with wavelengths are very small in fire detection, the typical value of refractive indices of the white smoke is 1.55 + 0.02i, while that of the black smokes is 1.55 + 0.5i [14–16]. The black smokes would absorb part of incident light and thus the scattering efficiency is weakened significantly. The white smokes scatter most of incident light, so the scattering efficiency would be much stronger [3]. As an optical fire detector based on the scattering signal power of scattering light, the alarm sensitivities of black smokes would be as low as 1/4 of those of white smokes in the experiments of standard test fire [4]. We simulated the scattering efficiencies of the white particle and the black particle based on Mie theory in Fig. 1, where the wavelength of incident light is 950 nm and the particle size is 570 nm. As the dot line of black particle is surrounded by the solid line of white particle completely, Fig. 1 shows that the scattering efficiency of black particle is always weaker than that of white particle.

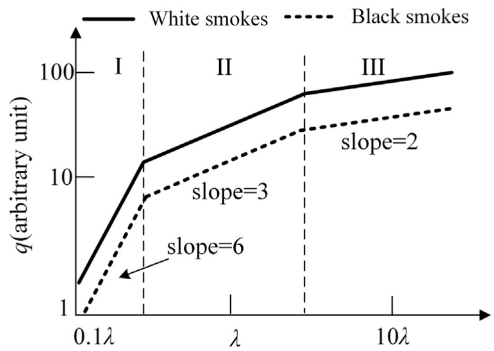

Fig. 2. The general relationship between scattering intensity and particle size in a log-log coordinate for white smokes and black smokes.
(a) The simulation result of volume concentration. (b) The simulation result of surface area concentration.

In order to solve the imbalance response for white and black smokes, the detector should eliminate the effects of the refractive indices of fire smokes. As described in [17], the scattering signal P with wavelength of incident light λ and observing angle θ can be described by:

$$P = C_N \int f(x)q(x, m, \lambda, \theta)dx, \tag{1}$$

where C_N is the number concentration of the aerosol, $q(x,m,\lambda,\theta)$ describes the intensity of monochromatic light scattered by a single particle into a receiving aperture based on Mie scattering theory, m is the refractive index and $f(x)$ is the particle size distribution. Since the Mie scattering theory is complicated, it is hardly to eliminate the effect of m independently from $f(x)$. Baron et al. [18] utilized the 'Three regions' law to describe the general relationship between scattering intensity P and particle size x, which promotes a potential way to analyze the refractive index m and the particle size distribution $f(x)$ independently. As shown in Fig. 2. We have $q(x,m,\lambda,\theta) \approx T_I \cdot x^6$ in region I, $q(x,m,\lambda,\theta) \approx T_{II} \cdot x^3$ in region II and $q(x,m,\lambda,\theta) \approx T_{III} \cdot x^2$ in region III. Where T_I, T_{II} and T_{III} are the conversion factors of x and q in each region, which are related to refractive index m and observing angle θ. Obviously, the conversion factors of white smokes would be higher than those of black smokes, as shown in Fig. 2.

If the wavelength of incident light is close to the particle size as in region II, $q(x,m,\lambda,\theta) \approx T_{II} \cdot x^3$ can be taken into Eq. (1) and thus the scattering signal P_V is proportional to volume concentration C_V:

$$P_V = \frac{6}{\pi} T_{II} \cdot C_N \int f(x)(\frac{\pi}{6}x^3)dx = T_V \cdot C_V, \tag{2}$$

where T_V is the conversion factor of the volume concentration and scattering power, i.e. the volume concentration response sensitivity of fire smokes, $T_V = 6 \cdot T_{II}/\pi$. Similarly, if the wavelength of incident light is much smaller than x as in region III, $q(x,m,\lambda,\theta) \approx T_{III} \cdot x^2$, thus the scattering intensity P_S is proportional to surface area concentration C_S:

$$P_S = \frac{1}{\pi} T_{III} \cdot C_N \int f(x)(\pi x^2)dx = T_S \cdot C_S, \tag{3}$$

where T_S is the conversion factor of the surface area concentration and the scattering power, i.e. the surface area concentration response sensitivity of fire smokes, $T_S = T_{III}/\pi$.

According to the 'Three regions' law, we promote dual wavelengths technology to measure the volume concentration and surface area concentration of fire smokes [13]. By adjusting the wavelength of incident light, the optical scattering signals of fire smokes are proportional to the volume concentration or surface area concentration in different regions. In this way, a short