An Optical Fire Detector based on Polarized Fingerprint

Jin Zeng, Shu Wang, Tian Deng, Shu Yan, Ang Chen
School of Electronic Information and Communications, Huazhong University of Science and Technology, Wuhan, P. R. China

Abstract

The existing optical fire smoke detectors trigger the fire alarms when the scattering light intensity exceeds a preset threshold. Current optical detectors usually take a long time or even fail to trigger a fire alarm of black smokes, which have strong absorption efficiency and weak scattering efficiency. In this paper, a new detector with dual-wavelength and dual-angle is proposed to eliminate the effect of refractive index of fire smokes based on the polarization degree. Meanwhile, the polarized fingerprints of non-fire aerosols are also different from those of fire smokes. The simulation results show that the detector can effectively discriminate fire smokes (white smokes, black smokes) and typical non-fire aerosols (vapour, dust), and timely trigger a fire alarm of black smokes.

Keywords: Fire smokes, non-fire aerosols, polarization degree, false alarms.

Introduction

The common optical smoke detectors only use a single channel to sense the smoke concentration and usually trigger the fire alarm when the scattering light intensity exceeds a preset threshold. As described by Mie theory, the scattering light is affected by particle size and refractive index [1-3]. Therefore, these detectors are susceptible to non-fire aerosols with big particle size and insensitive to black smokes with high imaginary part of refractive index which cause nuisance alarm and missing alarm respectively. The polarized information can be used as fingerprint to estimate the difference of particle size and refractive index. Our simulation results show that the polarization characters of white fire smokes, black fire smokes and typical non-fire aerosols (vapour and dust) are different. Thus, the polarized scattering light can be used for aerosol classification and reducing the nuisance alarms and missing alarm.

In this paper, a novel method base on the polarization degree is proposed to indicate the particle sizes and the refractive indices, where the polarization degree is defined as the ratio of polarized scattering light at two different observing angles. According to the polarization degree, the aerosol samples are classified as white fire smokes, black fire smokes or typical non-fire aerosols (vapour and dust) according to the particle sizes and the refractive indices. Thus, the fire alarms can be correctly triggered with high sensitivities to black smokes and strong immunity to non-fire aerosols. A prototype sensor can be set with two wavelength (450 nm and 658 nm) and two observing channels (horizontal polarized scattering signal at 70°, unpolaried scattering signal at 95°).

Theory

According to Mie theory, the scattering light signal of a spherical particle or optical equivalent spherical particle can be described by the vertical polarization I_V , the horizontal polarization I_H , and the total light intensity I_S [4]. The polarized scattering light intensity $P_{V,}$ P_H and unpolarized scattering light intensity P_S can be calculated by Eq.1.

$$\begin{aligned} P_V &= C_N \int f(x) I_V(x,m,\lambda,\theta)dx \\ P_H &= C_N \int f(x) I_H(x,m,\lambda,\theta)dx \\ P_S &= C_N \int f(x) I_S(x,m,\lambda,\theta)dx \end{aligned} \qquad \text{(Eq.1)}$$

Where C_N is the concentration of fire smokes and non-fire aerosols, $f(x)$ denotes the particle size distribution, x is the particle diameter, λ is the wavelength of incident light, and m is the complex refractive index of fire smokes and non-fire aerosols in the air, θ is the observing angle.

$$f(x) = \frac{1}{\sqrt{2\pi} x \ln\sigma} \exp(-\frac{(\ln x - \ln\mu)^2}{2\ln^2\sigma}) \qquad \text{(Eq.2)}$$

As the polarization will cause complex structure and loss of light intensity, the number of polarization channels should be reduced as much as possible. Therefore, the combination of polarization and unpolarization will be more applicable, we define the polarization degree $R(H, S)$ as:

$$\begin{aligned} R(H,S) &= \frac{P(\lambda_H,\theta_H)}{P(\lambda_S,\theta_S)} \\ &= \frac{\mathrm{C}_N \int f(x) I_H(x,m,\lambda_H,\theta_H)dx}{\mathrm{C}_N \int f(x) I_S(x,m,\lambda_S,\theta_S)dx} \end{aligned} \qquad \text{(Eq.3)}$$

$R(H, S)$ depends on the particle size distribution $f(x)$, refractive indices m, wavelength of incident light λ and the observing angle θ. Meanwhile, $R(H, S)$ eliminates the effect of smoke concentration C_N. In this way, we can optimize the optical parameters λ, θ to set R as an optical feature to classify the aerosols.

Method

According to our former experiment results and relevant reports, the count median diameter of fire smokes normally ranges from 100 nm to 1000 nm and the geometric standard deviation *σ* ranges from 1.4 to 2.0 [5-7]. The typical refractive indices of the black and white smokes are 1.55+0.5*i* and 1.55+0.02*i*, respectively. Meanwhile the count median diameter of non-fire aerosols normally ranges from 1000 nm to 2500 nm (While considering the simulation accuracy and enough to describe the characteristics of fire smokes and non-fire aerosols, the gap of count median diameter set as 100 nm) and the geometric standard deviation *σ* ranges from 1.4 to 2.0. The typical refractive indices of the vapour and dust are 1.33 and 1.55+0.02*i*, respectively. As discussed above, the key parameters of fire smokes and typical non-fire aerosols for simulation are listed in Table 1.

Table 1. Key parameters of fire smokes and non-fire aerosols

Particle size distribution	Count mean diameter(μ)(nm)	Geometric standard deviation(σ)	Reflective index(m)	
Lognormal distributed	100:100:1000	1.4:0.1:2.0	White smokes	Black smokes
			1.55+0.02i	1.55+0.5i
Lognormal distributed	1000:100:2500	1.4:0.1:2.0	Dust	Vapour
			1.55+0.02i	1.33

Once the parameters of fire smokes and non-fire aerosols are confirmed, the polarization degree gap of the sensor can be simulated. Due to cost and availability, the wavelength of incident light are selected from 450 nm, 658 nm, which are the most commonly used incident light in fire detection. Meanwhile, in consideration of the mechanic limination and stray light, the observing angles of the scattering light are set between 30° and 150° (As considering the complexity of the structure and the accuracy of the actual detector, the observation angle interval of 5° can meet the requirements). As mentioned above, the optical parameters of smoke sensor for simulation are listed in Table 2.

Table 2. Optical parameters for optimal simulation

Wavelengths of incident lights (nm)	Observing angles H	Observing angles S
450/658	30°:5°:150°	30°:5°:150°

As illustrated by Eq.3, the polarization degree contains the information of particle size and refractive index. Therefore, we define the scattering polarization degree of white smokes, black smokes, dust, and vapour. $\boldsymbol{R_i}$ and $\boldsymbol{R_j}$ represent the polarization degree of aerosol sample i and aerosol sample j, respectively. The polarization degree gap G_{ij} between $\boldsymbol{R_i}$ and $\boldsymbol{R_j}$ is defined as:

$$\begin{aligned} &G_{ij} = \min(abs(\boldsymbol{R}_i - \boldsymbol{R}_j)) \quad if\ \boldsymbol{R}_i \cap \boldsymbol{R}_j = \varnothing\ (i \neq j) \\ &G_{ij} = 0 \quad if\ \boldsymbol{R}_i \cap \boldsymbol{R}_j \neq \varnothing\ (i \neq j) \end{aligned} \qquad \text{(Eq.4)}$$

Where i, j = {vapour, dust, black smokes, white smokes}. For example, vapour can be discriminated for the other aerosols while $G_{1j} > 0$, and then the wavelength of incident light λ_{1j} and the observing angles θ_{H1j} and θ_{S1j} can be obtained.

$$[\lambda, \theta_H, \theta_S]_{1j} = \arg\ G_{1j}([\lambda, \theta_H, \theta_S]_{1j}) > 0 \qquad \text{(Eq.5)}$$

Eq.5 obtain the optical parameters of detector, which can distinguish the vapour from the other aerosols. Similary, the optical parameters can be obtained to distinguish dust, black and white smokes. Thus, all four types of aerosols can be discriminated by the intersection of $[\lambda, \theta_H, \theta_S]$ as shown in Fig.1. Furthermore, higher value of *G* can provide higher robustness for discrimination against the measurement errors.

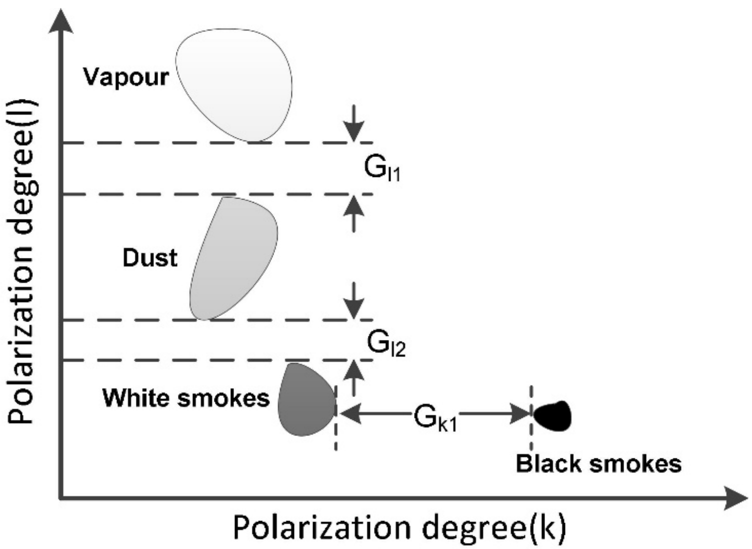

Fig.1. The polarization degree gap *G* between vapour, dust, white smokes and black smokes.

The simulation results of fire smoke detector

According to the optimal target described by Eq.4 and Eq.5, the optimized angle and wavelength can be obtained. The optimal optical parameter is selected as [450nm/658nm, H:70°, S:95°] and the polarization degree results as show in Table 3.

Table.3 The simulation results of polarization degree

Classification / R	Vapour	Dust	Black smokes	White smokes
$R_{(450nmH/450nmS)}$	2.1990-2.7604	1.6486-2.0599	0.1998-1.1698	0.5086-2.1254
$R_{(450nmH/658nmS)}$	3.9218-4.4076	2.4157-2.9039	0.4089-1.8091	2.9150-5.2230

According to the simulated polarization degree in Table 3, the polarization degree gap between two different aerosols can be further obtained. The results are shown in Table 4, where 0 means indistinguishable (G <= 0), 1 means distinguishable (G > 0), if one of the G1,G2 equal to 1, which means the two different aerosols can be distinguished from each other with using the polarization degree gap.

Table.4 The simulation results of polarization degree gap

G_1,G_2	Vapour	Dust	Black smokes	White smokes
Vapour	[0,0]	[1,0]	[1,1]	[1,0]
Dust	[1,1]	[0,0]	[1,1]	[0,1]
Black smokes	[1,1]	[1,1]	[0,0]	[0,1]
White smokes	[1,0]	[0,1]	[0,1]	[0,0]

As shown in table 4, fire smokes and non-fire aerosols can be discriminated. The simulation results show that the detector can effectively distinguish fire smokes (white smokes, black smokes) from typical non-fire aerosols (vapour, dust), and the black smokes can also be distinguished from white smokes.

Conclusion

In this paper, we propose a new polarization degree based method to distinguish fire smokes and non-fire aerosols, and different types of aerosols can be classified. According to the simulation results, the prototype sensor can be realized with only dual-wavelength and two measurement channels which in a low cost. The polarization degree sensing aerosol size and refractive index, and then classify the aerosols. With using this method, it can reduce both cause nuisance alarm and missing alarm respectively, and has higher performance. Unfortunately, we did not conduct prototype testing due to the influence of COVID-19, and this work will be completed in the future.

Acknowledgements

This work was supported by National Key Technologies R&D Program of China [Grant No. 2016YFC0201101].

References

[1] L Marcius, T. Schultze, W. Krüll, I. Willms, Design of a Polarimetric Scattering based Aerosol Classifying Detevtor Prototype, Proceeding of the 16th International Conference on Automatic Fire Detection AUBE '17, 2017.

[2] Thorsten Schultze, Lea Marcius, Wolfgang Krüll, Polarised Light Scattering Analyses for Aerosol Classification, Proceedings of the 16th International Conference on Automatic Fire Detection AUBE '17, 2017.

[3] Wilhelm Dunkhorst, Peter Lipowicz, Weiling Li, Casey Hux, Qiang Wang &Wolfgang Koch. In-situ characterization of e-cigarette aerosols by 90°-light scattering of polarized light. Aerosol Science and Technology. (2018)717-724. http://www.tandfonline.com/loi/uast20.

[4] BOHREN C F, HUFFMAN D M. Absorption and scattering by a sphere [M]. Absorption and Scattering of Light by Small Particles, 1983.

[5] Shu Wang, Xiao Xiao, Tian Deng. A Sauter mean diameter sensor for fire smoke detection. Sens.Actuators B: Chem. 281 (2019) 920–932.

[6] HULST H C v.c Light scattering by small particles[M]. Dover Publications, 1981.

[7] TSI Incorporated, "Particle Size, TSI Technical Notes," http://www.tsi.com/uploadedFiles/_Site_Root/Products/Literature/Technical_Notes/Particle_Size.pdf.