Fire Sensing Method based on Particle Size Distribution

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Abstract

An unsolved challenge for fire detectors is how to avoid the nuisance alarm of non-fire aerosols. Herein, a particle size distribution sensing method with four optical channels is proposed for fire detection. According to the simulation results of our sensing method, the relative standard deviation of count median diameter is 9.39 %, while that of the geometric standard deviation $\sigma$ is 5.13 %. According to the differences of particle size distributions, a fire alarm can be timely trigger for both white smokes and black smokes, while the nuisance alarm caused by non-fire aerosols can be eliminated.

Keywords: Fire sensing, particle size distribution, count median diameter, geometric standard deviation, feature vector

Introduction

With the advantages of simple structure and low cost, optical fire detectors are widely used in fire protection. Common optical fire smoke detectors trigger fire alarm based on the intensity of scattering light, which is considered to be proportional to the concentration of fire smokes. Nevertheless, there is still one technology gap need to be well filled, that is the nuisance alarm caused by non-fire aerosols.

To enhance the robustness of optical fire detectors, kinds of methods have been developed to improve the technical defect. As an important characteristic, there is a gap of particle size between fire smokes and non-fire aerosols at about 1 μm. Cole [1] et al. made use of the ratio between two wavelength scattering signals to evaluate whether the particle sizes of the aerosols are larger than 1 μm, and then determine whether there is a fire occurred. S. Wang [2] et al. use the Sauter mean diameter as the basis for fire judgment instead of aerosol concentration. Thus, the interference of the concentration measurement error of black smokes caused by its absorption effect could be eliminated. By this way the omitting alarm rate of optical fire detectors could be eliminated.
Similarly, R. Zheng [3] et al. used the ratio of the forward and backward scattered light signals at two wavelengths to classify fire smokes and non-fire aerosols. In addition, in order to obtain more optical features of aerosols, polarization information is also used to classify aerosols [4]. As discussed above, the core of existing methods is how to set up a reasonable optical channel to collect the optical feature corresponded to the particle size of each aerosol. In other words, the particle size can be used as the key characteristic to solve the problem of nuisance alarm and omitting alarm. The way to estimate particle size directly may help to identify fire and non-fire more finely.

In this paper, a method with four optical channels \{[450 nm, 45°]_1, [950 nm, 45°]_2, [450 nm, 140°]_3, [950 nm, 140°]_4\} is promoted to directly estimate the particle size distribution of aerosols with lognormal distribution model. According to the simulation results, the relative standard deviation of count median diameter is 9.39 % while that of the geometric standard deviation \(\sigma\) is 5.13 %. Based on this method, fire smokes could be classified finely from more types of non-fire aerosols according to the discrimination of particle size distribution. Thus, the risk of nuisance alarms would be further reduced.

**Theory**

According to Mie theory [5], the optical features of aerosols are different mainly due to their differences of particle size and refractive index. The particle size is one of the most distinctive feature to discriminate fire smokes from non-fire aerosols. Therefore, the particle size distribution sensing method is proposed by determining the unique optical feature corresponding to each aerosol. Based on this method, fire smokes could be classified finely from non-fire aerosols.

As described by Hulst et al. [5], the scattering light signal \(P\) of the optical channel \(i\) can be calculated by Eq. 1:

\[
P([\lambda, \theta]_i) = C_N \int f(x)q(x, m[\lambda, \theta]_i)dx \quad i = 1,2,3...
\]

Where \(C_N\) is the number concentration of the aerosol, \(x\) is the particle size. \(q(x, m[\lambda, \theta]_i)\) 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 \([\lambda, \theta]_i\) denotes the wavelength of incident light and observing angle of measurement channel \(i\) respectively, \(f(x)\) is the particle size distribution. As illustrated in [6], the particle size distribution of aerosols can be described by the lognormal distribution as:

\[
f(x) = \frac{1}{\sqrt{2\pi x \ln \sigma}} \exp \left[ -\frac{(\ln x - \ln \mu)^2}{2 \ln^2 \sigma} \right]
\]

(Eq. 2)
Where the $\mu$ is count median diameter in which the particle number with size above $\mu$ are as many as that below $\mu$ in aerosols. The term $\sigma$ denotes the geometric standard deviation, whereas $\ln \sigma$ is commonly referred to as the mode width. Therefore, the estimation of the particle size distribution is converted into the $\mu$ and $\sigma$.

Then, a feature vector $F$ is defined to classify each aerosol, where the value of each channel is normalized by the value of 1st channel to eliminate the influence of number concentration $C_N$.

$$F = (\frac{P_2}{P_1}, \frac{P_3}{P_1}, ..., \frac{P_i}{P_1}) \quad i > 1$$  \hspace{1cm} (Eq. 3)

According to Eq. 1 and Eq. 3, the feature vector $F$ only relates to the incident light wavelength $\lambda$ and the observation angle $\theta$ except for the influence of particle size and refractive index changes. Therefore, we can classify the aerosols by selecting appropriate incident light wavelength $\lambda$ and observation angle $\theta$ to establish an unique feature vector $F$ for each aerosol. Then, the particle size distribution corresponding to feature vector of different aerosols can be estimated. If the measurement value of particle size distribution belongs to the range of fire smokes, it is determined that a fire has occurred. In this way, a fire smoke detection method by sensing the particle size distribution of aerosols is promoted.

**Optimization Strategy**

As discussed above, the scattering light signal $P$ is related to particle size distribution $f(x)$ and refractive index $m$ of the aerosol sample, as well as the wavelength of the incident light $\lambda$ and the observation angle $\theta$. In order to determine the unique feature vector of aerosol, we need to analyse the scattering light signal differences of all aerosol types.

**Table 1. Parameters of fire smokes and typical non-fire aerosols.**

<table>
<thead>
<tr>
<th>Typical aerosols</th>
<th>count median diameter $\mu$(nm)</th>
<th>Geometric standard deviation ($\sigma$)</th>
<th>Reflective index ($m$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fire smokes</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smoldering smokes</td>
<td>100:50:1000</td>
<td>1.5:0.1:2.0</td>
<td>1.55+0.02i</td>
</tr>
<tr>
<td>Open fire smokes</td>
<td>100:50:1000</td>
<td>1.5:0.1:2.0</td>
<td>1.55+0.5i</td>
</tr>
<tr>
<td><strong>Non-fire aerosols</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cooking smokes</td>
<td>25:25:100</td>
<td>1.5:0.1:2.0</td>
<td>1.55+0.02i/0.5i</td>
</tr>
<tr>
<td>Vapor / fog</td>
<td>1000:50:2500</td>
<td>1.5:0.1:2.0</td>
<td>1.33</td>
</tr>
<tr>
<td>Dust</td>
<td>1000:50:2500</td>
<td>1.5:0.1:2.0</td>
<td>1.55+0.02i</td>
</tr>
</tbody>
</table>
According to related literatures [2,7,8] and our experimental measurements, particle size and refractive index parameter of fire smokes and typical non-fire aerosols are listed in Table 1. The count median diameter range of fire smokes is considered to be 100 nm to 1000 nm, while that of cooking smoke is set with [25, 100). Given that aerosols with large particles are difficult to enter the measurement chamber of the fire detector placed at a high place due to the effect of sedimentation and airflow inertial, the range of other typical non-fire aerosols is tentatively considered to be (1000, 2500).

Meanwhile, the geometric standard deviation \( \sigma \) of aerosol samples is from 1.5 to 2.0. The refractive index of cooking smoke and fire smoke is set to 1.55+0.02i and 1.55+0.5i while that of vapor/fog is 1.33 and dust is 1.55+0.02i. As listed in Table 1, aerosols are divided into 624 types for simulation by discretizing the count median diameter and geometric standard deviation. The count median diameter interval of cooking smokes is set to 25 nm, and that of fire smokes and other non-fire aerosols is 50nm while the geometric standard deviation varies from 1.5 to 2.0 in the step of 0.1 of all aerosols.

Combination Eq. 1, the deviation \( \text{Div}_{A&B} \) of scattering light signal in all of the optical channels for any two kinds of 624 aerosols A and B is defined as:

\[
\text{Div}_{A&B} = \max \left\{ \frac{\text{averaged} \sum_i \frac{P^A_{\lambda i}([\lambda, \theta_i])}{P^B_{\lambda i}([\lambda, \theta_i])}}{\frac{P^A_{\lambda i}([\lambda, \theta_i])}{P^B_{\lambda i}([\lambda, \theta_i])}} \right\} \times 100\% \quad i = 1, 2, 3, \ldots
\]

(Eq. 4)

According to Eq. 4, we can calculate the optical signal deviation among all aerosols. If the deviation between one aerosol and all other aerosols is greater than a threshold, the feature vector of this aerosol is unique and can be accurately distinguished from other aerosols. The threshold is related to measurement accuracy of the hardware system, which is selected to be 5 % in this paper. On the other hand, if the deviation between an aerosol and some aerosols is less than the threshold, the feature vectors of these aerosols are not unique and these aerosols cannot be distinguished from each other. In order to distinguish aerosols as many as, the optical parameters need to be selected reasonably. In consideration of particle size is the main characteristic difference between fire smokes and non-fire aerosols, we take use of the evaluation error of count median diameter as the optimization indicator in the process of selecting optical parameters. The relative standard deviation \( \text{RSD}_{\text{CMD}} \) of count median diameter is defined as:
\[ RSD_{CMD} = \sqrt{\frac{1}{N} \sum \frac{(CMD_{real} - CMD_{test})^2}{CMD_{real}^2}} \] 

(Eq. 5)

Where \( CMD_{real} \) is the count median diameter true value of aerosols listed in Table 1, \( CMD_{test} \) is the test value of simulation experiment, \( N \) is the number of aerosol samples with different particle size distributions and refractive indices. In our simulation experiment, if the feature vector of one aerosol is unique, we take the real \( \{\mu, \sigma\} \) value of aerosol samples as the simulation test value. On the other hand, if the feature vectors of some aerosols is coincided, these aerosols cannot be distinguished from each other and then taken the average value of the real \( \{\mu, \sigma\} \) of these aerosols as the test value. In addition, the interpolation process could be used to solve the aerosols not listed in Table 1 according to the continuity of particle size. By calculating the \( RSD_{CMD} \) of all optical parameter groups with different wavelengths and observation angles, the group with the smallest \( RSD_{CMD} \) is taken as the optimal optical parameter, as described in Eq. 6.

\[ \{[\lambda, \theta]_1, [\lambda, \theta]_2, \ldots, [\lambda, \theta]_k\} = \text{arg min} \ RSD_{CMD}(\lambda, \theta) \quad i = 1, 2, 3... \] 

(Eq. 6)

**Simulation results and discussion**

As listed in Table 2, the wavelengths of incident light source are selected as 450 nm, 650 nm, and 950 nm. Meanwhile, because of the limitation of mechanical design and the interference caused by stray light, the observing angle is restricted from forward 40° to forward 140° with a stride of 5°.

<table>
<thead>
<tr>
<th>Wavelengths of incident light ( \lambda ) (nm)</th>
<th>Observing angle ( \theta ) (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>{450,650,950}</td>
<td>Forward 40:5:140</td>
</tr>
</tbody>
</table>

Table 2. Optical parameters of simulation.

Due to the optical channel is greater than 1 according to Eq. 3, the measurement channel \( i \) is set to start from 2 in our simulation experiment. When the measurement channel \( i=2 \): The optimal channels is \{[450 nm,85°], [950 nm,135°]\}, and the corresponding error \( RSD_{CMD} \) of count median diameter is 48.27 %. The comparison between the real value \( CMD_{real} \) of count median diameter and the simulation test value \( CMD_{test} \) is shown in Fig. 1a. The simulation results imply that the measurement error is still too high to measure the count median diameter. Therefore, it is essential to further increase the number of measurement channels. When the measurement channel \( i=3 \): The optimal channels is \{[450 nm,45°], [650 nm,140°], [950 nm,60°]\}, and the corresponding error \( RSD_{CMD} \) of count median diameter is 13.55 %. According to the simulation results in Fig. 1b, the addition of an optical channel significantly reduces the measurement error of CMD compared to Fig. 1a.
Fig. 1. The optimum simulation results of CMD with different numbers of measurement channels.

(a) the measurement channel \( i=2 \)

(b) the measurement channel \( i=3 \)
Besides, a diode integrating two wavelengths is used as the light source instead of a monochromatic photodiode considering the feasibility of the method to avoid the structure from being too complicated when further increasing the optical channel. Therefore the optimal channels of \{[450 nm,45°]_1, [950 nm,45°]_2, [450 nm,140°]_3, [950 nm,140°]_4\} is selected while the corresponding error $RSD_{CMD}$ of count median diameter is 9.39 %. Compared with the 3-channel simulation results, the 4-channel measurement error has not been significantly reduced.

(a) the results of CMD

(b) all aerosols in the vector space

Fig. 2. The optimum simulation results in the measurement channel $i=4$. 
So we did not increase the number of measurement channel further and take use of this optimal channels as the final choice. In addition, due to the deviation threshold that we choose is fairly enough to cover the measurement deviation from scattering light intensity to electrical signal during the optimization process according to Eq. 4, the measurement error of particle size distribution can be further improved if the measurement accuracy of scattering light is increased. Fig. 2a shows the final result between the real value $CMD_{real}$ of count median diameter and the simulation test value $CMD_{test}$ of the channels of $\{[450 \text{ nm},45^\circ]_1, [950 \text{ nm},45^\circ]_2, [450 \text{ nm},140^\circ]_3, [950 \text{ nm},140^\circ]_4\}$.

As shown in Fig. 2b, all aerosol samples are separated in the vector space according to their feature vector $F$, which implies that the aerosols could be discriminated from each other well. Where each dot indicates an aerosol with certain particle size distribution, meanwhile the aerosols with different types are marked in different colors. Therefore, we can estimate the particle size distribution based on the feature vector $F$. After further calculation in this channel, $RSD$ of the geometric standard deviation $\sigma$ is $5.13\%$ which is evaluated more accurate than count median diameter. Therefore we can define the fire judgment method based on these simulation results as: if $CMD \in [100,1000]$, then trigger alarm. In this way, fire smokes can be classified well from non-fire aerosols.

**Conclusion**

In this paper, the method with 4 optical channels $\{[450 \text{ nm},45^\circ]_1, [950 \text{ nm},45^\circ]_2, [450 \text{ nm},140^\circ]_3, [950 \text{ nm},140^\circ]_4\}$ is proposed to estimate the particle size distribution of fire smokes and non-fire aerosols. According to the simulation results, the relative standard deviation of count median diameter is $9.39\%$, while that of the geometric standard deviation $\sigma$ is $5.13\%$. Based on this method, fire smokes could be classified finely from non-fire aerosols according to the discrimination of particle size distribution. Unfortunately, we did not conduct prototype testing due to the influence of COVID-19, and this work will be completed in the future.

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**References**


