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Characterization of typical fire and non-fire aerosols by polarized lightscattering for reliable optical smoke detection

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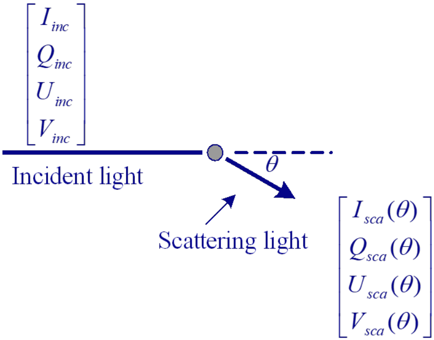
Contents

Motivation

1. Photoelectric smoke detector is the most widely used one in state-of-the-art fire protection engineering.
2. It suffers from the high false alarm rate caused by non-fire aerosols, such as dust, steam (water vapor), cook-generated aerosol.
3. There is a need to characterize the optical difference between fire and non-fire aerosols.

Stokes parameters

Light beam can be represented by four Stokes parameters, which contains full information about the light.



I	total intensity
Q	$\pm$ 90° polarization
U	$\pm$ 45° polarization
V	circular polarization

Theoretical basis

Mueller matrix

The transformation from incident light to scattering light can be represented by Mueller matrix.

Light transformation

$$I_{sca}(\theta) = F(\theta).I_{inc}(\theta) \tag{1}$$

Mueller matrix

$$F(\theta) = \begin{bmatrix} F_{11}(\theta) & F_{12}(\theta) & 0 & 0 \\ F_{12}(\theta) & F_{22}(\theta) & 0 & 0 \\ 0 & 0 & F_{33}(\theta) & F_{34}(\theta) \\ 0 & 0 & -F_{34}(\theta) & F_{44}(\theta) \end{bmatrix} \tag{2}$$

Theoretical basis

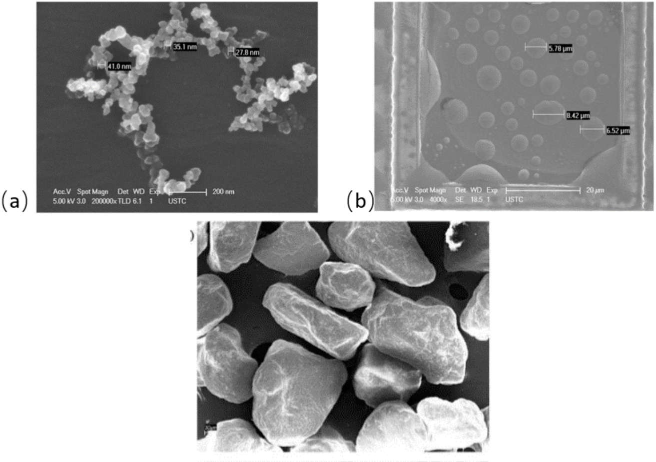
Mueller matrix

The Mueller matrix is siginificantly affected by the microscopic physical characteristics of particles (such as the size distribution, refractive index, particle morphologies and so on).

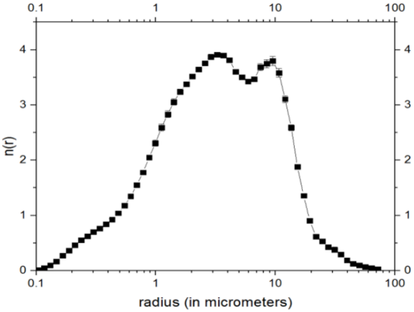
Can we distinguish fire particles using Mueller matrix?

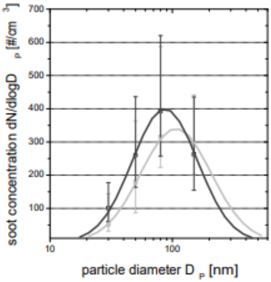
The microscopic physical characteristics can be reflected by the Mueller matrix. In principle, if the microscopic physical characteristics of fire particles are different from non-fire particles, the Mueller matrix can be used to dectect fire particles.

The difference of morpholoy between fire and non-fire aerosols



The difference of the size distribution between fire and non-fire aerosols



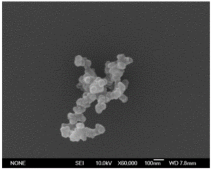


Implication

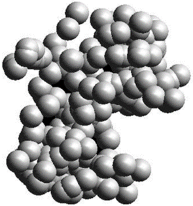
The physical characteristics of fire particles are different from non-fire particles).

Numerical method

(1) Flame smoke particles



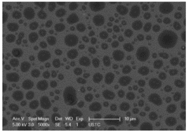
SEM Image

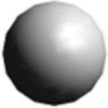


Fractal model

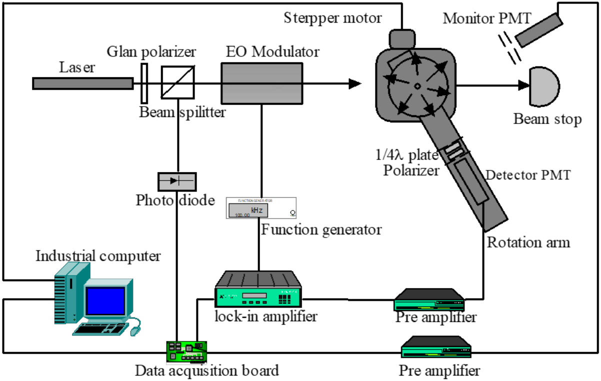
$$N = K_f \left(\frac{R_g}{a} \right)^{D_f}$$

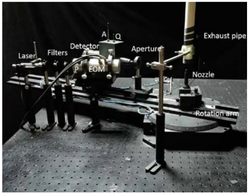
(2) Smoldering smoke particles





Experimental method





Combination	γ_P	γ_{EOM}	γ_Q	γ_A	$DC(\theta)$	$S(\theta)$	$C(\theta)$
1	90°	-45°	-	0°	$F_{11} + F_{21}$	$F_{14} + F_{24}$	$-(F_{12} + F_{22})$
2	90°	-45°	-	45°	$F_{11} + F_{31}$	$F_{14} + F_{34}$	$-(F_{12} + F_{32})$
3	90°	-45°	0°	45°	$F_{11} + F_{41}$	$F_{14} + F_{44}$	$-(F_{12} + F_{42})$
4	45°	0°	-	45°	$F_{11} + F_{31}$	$-(F_{14} + F_{44})$	$-(F_{13} + F_{33})$

Table: Combinations of Orientation Angles of Glan polarizer(P) , electrooptic modulator (EOM), quarter-wave plate (Q) and an analyzer (A) Used During Measurements

Experimental method

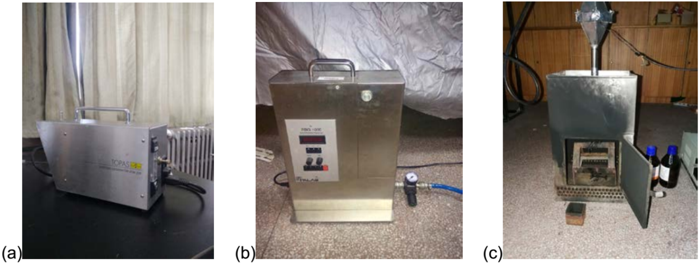


Figure: Real image of apparatus for generation of (a) water droplet, ATM-226; (b) cement dust, RBG 1000; (c) fire smoke, homemade combustion chamber.

The element studied in this work

The element commonly used in previous studies

$F_{12}(\theta)/F_{11}(\theta)$ and $F_{22}(\theta)/F_{11}(\theta)$ are commonly used in polarized light scattering in most of previous studies [4, 2, 1], while the applicability of $F_{33}(\theta)/F_{11}(\theta)$ is scarcely studied.

Why we are interested in the $F_{33}(\theta)/F_{11}(\theta)$?

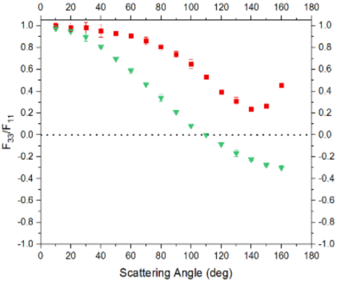
Li et al. (2017) that it is feasible to differentiate soot from other typical air particulates like salt and sand by F_{33}/F_{11} at 115°. While their experiment was conducted for particulates in air. In fire environment, the results are not available.

Why we are interested in the $F_{33}(\theta)/F_{11}(\theta)$?

The experiment conducted by our group demonstrated that the F_{33}/F_{11} of water droplet and vement dust can diviate large [3], while the results of fire particles are not available at present.

Results

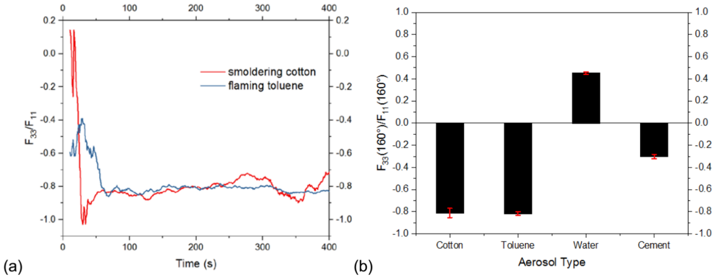
Our experiment results show that F_{33}/F_{11} can deviate largely for different non-fire aerosols. In addition, the difference is most obvious at 160°. Therefore, we want to use F_{33}/F_{11} at 160°.



Other questions need to be disposed

Whether the F_{33}/F_{11} at 160° of fire particles are different from non-fire particles? Whether the F_{33}/F_{11} at 160° of different fire particles do not deviate largely?

Results



Findings

F_{33}/F_{11} at 160° of fire particles do not deviate with each other, while F_{33}/F_{11} at 160° of fire particles are significantly different from non-fire particles? Therefore, It is feasible to detect fire particles using F_{33}/F_{11} at 160°.

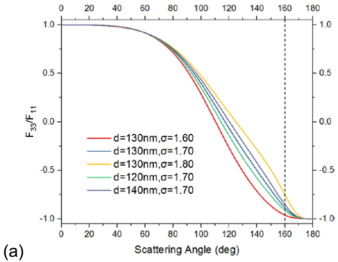
Another question

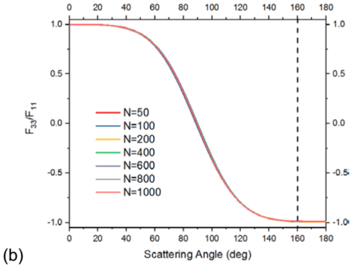
As the experiment is not likely to be conducted for all circumstances, one may doubt that whether the conclusion is applicable for all fire particles (eg. whether F_{33}/F_{11} at 160° of fire particles do not deviate largely when changing their size.)

Solution

Numerical results are used as supplement to verify that the findings are applicable for most fire particles.

Results





Findings

F_{33}/F_{11} at 160° of fire particles do not change largely with the size. That is to say, in most cases, different fire particles can be classified into a single type using F_{33}/F_{11} at 160°. Therefore, we can conclude that it is feasible to detect fire particles using F_{33}/F_{11} at 160°.

Results

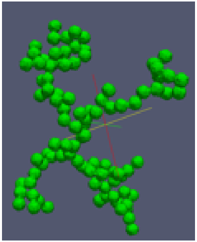
Note

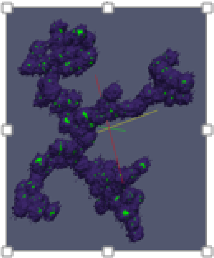
Here we only consider the variation of the size of fire particles, while the variations of refractive index and morphology are not considered. This is because that the refractive index and morphology of freshly emitted fire particles is commonly given, and the measurements are commonly within a relative narrow range.

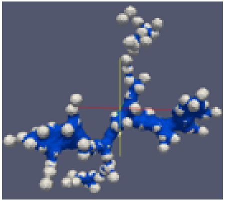
Note

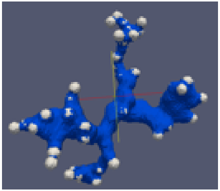
Therefore, it is acceptble to simulate fire particles in different environments by just changing the size distribution.

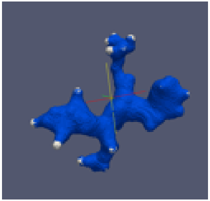
Future work: aged smoke particles











Summary and conclusions

1. F_{33}/F_{11} of non-fire and fire aerosols are studied combining experimental and numerical methods.
2. F_{33}/F_{11} at 160° is proposed as an indicator for discrimination between typical fire and non-fire aerosols.
3. F_{33}/F_{11} at 160° of fire particles does not deviate largely from each other. However, F_{33}/F_{11} at 160° of fire particles is significantly different from non-fire aerosols.
4. The universality of the findings are verified using numerical methods.

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Thanks for your attention!

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