Theoretical analysis of stack gas emission velocity measurement by optical scintillation*

Yang Yang(杨 阳), Dong Feng-Zhong(董凤忠)†, Ni Zhi-Bo(倪志波), Pang Tao(庞 涛), Zeng Zong-Yong(曾宗泳), Wu Bian(吴 边), and Zhang Zhi-Rong(张志荣)

Anhui Provincial Key Laboratory of Photonic Devices and Materials, Anhui Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Hefei 230031, *China*

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Theoretical analysis for an online measurement of the stack gas flow velocity based on the optical scintillation method with a structure of two parallel optical paths is performed. The causes of optical scintillation in a stack are first introduced. Then, the principle of flow velocity measurement and its mathematical expression based on cross correlation of the optical scintillation are presented. The field test results show that the flow velocity measured by the proposed technique in this article is consistent with the value tested by the Pitot tube. It verifies the effectiveness of this method. Finally, by use of the structure function of logarithmic light intensity fluctuations, the theoretical explanation of optical scintillation spectral characteristic in low frequency is given. The analysis of the optical scintillation spectrum provides the basis for the measurement of the stack gas flow velocity and particle concentration simultaneously.

Keywords: optical scintillation, cross correlation, flow velocity, spectrum

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1. Introduction

With the rapid development of national economy over the last 30 years, particulate matters and air pollutions produced by industry have seriously affected the air quality and consequently human health. It has heavily counteracted the achievements of economy developments. Furthermore, this situation will continue for a long time. Therefore, the monitoring and controlling of air pollution and aerosol particles have become an arduous task for the government and local administration departments. To fulfill this task, it is needed to continually online monitor the pollution gases and particles. However, many techniques are still under development and have not fully commercialized yet. For instance, devices with high performance to online monitor gas flow velocity, particulate-mass concentration and the total pollutions produced by an individual factory are still not available.

Using optical scintillation of particulates to measure the stack gas flow velocity has great advantages compared with other traditional velocity measurement techniques, such as the Pitot tube,[1] hot wire anemometry,[2] laser Doppler velocimeter (LDV),[3] etc. The Pitot tube is a differential pressure velocimeter and can only perform single point measurement. Its measuring precision is low and the press-leading tube is easily blocked. Hot wire anemometry is widely used in turbulence measurement,[4,5] but it is brittle with poor measurement stability. The LDV is commonly used in multidimensional flow measurement,[6] but the vibration of a stack pipe easily affects the measurement accuracy. Adopting a non-intrusive optical scintillation method can measure flow velocity and particle concentration at the same time, and it has some advantages, such as easy machine maintenance, long service life, being workable in inflammable and other hazardous environments, and measurement results independent of temperature and pressure. However, although theoretical studies on atmospheric turbulence and optical scintillation in free space as well as its characteristics of particle spectroscopy have been done a lot, up to now the corresponding theory in stacks has not fully developed yet.

When a light beam is propagating through a turbulent medium, it will generate optical scintillation. This optical scintillation phenomenon has found applications ranging from particulate emission monitoring, rain-parameter determination, to wind-velocity measurement.[7–9] In the industrial stack gas, there are several primary causes to generate scintillation: particles move in or out of the view of sight in random, refractive index fluctuates in the temporal and spatial domain, and the random fluctuations of particle concentration. Chen and Shen[10] have given the relationship between the optical scintillation caused by particles moving in or out of the view of sight in random and the particle size and also the particle concentration. This kind of scintillation can be received only when the view of sight is small, the optical path is short, the particle diameter is large and the concentration is low. Yuan[11] measured the optical intensity fluctuations induced by the random distribution of particles using laser and

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†Corresponding author. E-mail: fzdong@aiofm.ac.cn

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optical fiber, and obtained the particles emission velocity by using a cross-correlation method. Commonly, in the industrial environment, the particle concentration is high, the diameter of the receiving lens is large, and it is difficult to detect the scintillation signals. Up to the present, the optical flowmeter developed by Wang[12] is the only commercial production for measuring the velocity of stack gas flow, which is based on refractive index fluctuation, i.e., the high frequency part of an optical scintillation signal. It uses one light transmitter and two identical receivers with a space of few centimeters. We have developed one device[13] with a similar design to Wang's device; the field test results indicate that it is difficult to measure velocity for some cases where the temperature field is distributed uniformly and the refractive index fluctuates weakly. The fluctuations of particle concentration field can also cause optical scintillation. In the low frequency part of optical scintillation spectra, the scintillation standard deviation shows a good linearity with particle concentration; this linearity has been used to measure particle concentration. The frequency of optical scintillation is lower in this situation, but up to now the relevant theory has not yet been found.

In this article, we introduce a new design to measure the flow velocity, which uses the optical scintillation signals of low frequency caused by particle concentration fluctuations, and adopts a structure of two parallel light paths. The principle of optical scintillation to measure the flow velocity is discussed both theoretically and experimentally. Finally, the spectral characteristics of optical scintillation signals in the part of low frequency are explained in theory.

2. Principle

The proposed structure of two parallel optical paths for stack gas flow velocity measurement is shown in Fig. 1. Each of the two identical light beams is a divergent spherical wave, both propagate along the X-axis and the origins are at $x = 0$. The diameters of the two transmitting lenses are both D_t, and the diameters of the two receiving lenses are both D_r. The distance between transmitter and receiver is L, and the distance between the two receivers is l. The direction of stack gas flow is along the Y-axis, and the mean velocity is v. The system with two point optical transmitters and two point photon receivers is assumed to be in one plane.

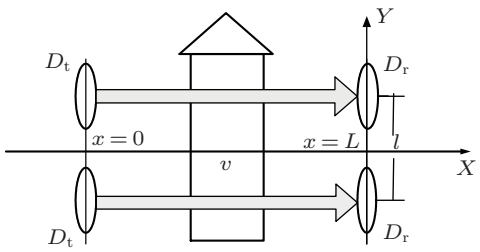


Fig. 1. Layout of optical scintillation measurement.

Suppose that the extinction coefficient of stack gas flow is $\alpha(\boldsymbol{r},t)$, and the received logarithmic light intensity is[14]

$$\ln I(t) = \ln\langle I\rangle - \int_0^L \alpha'(\boldsymbol{r},t)\,\mathrm{d}z, \tag{1}$$

where $\langle\cdot\rangle$ denotes the assemble average, $\boldsymbol{r}$ is the position vector, and $\alpha'(\boldsymbol{r},t)$ is the perturbation part.

For a homogeneous isotropic time stationary turbulence, the correlation function of the two scintillations each received by a receiver can be written as

$$C_{\ln I}(l,\tau) = \int_0^L \int_0^L R_\alpha(|\boldsymbol{r}_1 - \boldsymbol{r}_2|, \tau\,\mathrm{d}x_1\,\mathrm{d}x_2, \tag{2}$$

where τ is the time delay, and $R_\alpha(|\boldsymbol{r}_1 - \boldsymbol{r}_2|,\tau)$ is the correlation function of extinction coefficient. The stack gas moves along the Y-axis with the geometric relations as shown in Fig. 1, according to the Taylor freeze turbulence hypothesis, we have

$$R_\alpha(|\boldsymbol{r}_1 - \boldsymbol{r}_2|,\tau) = R_\alpha(x_1 - x_2, l - v\tau, 0). \tag{3}$$

Insert Eq. (3) into Eq. (2), according to the identical equation, which is established for any even function:

$$\int_0^L \int_0^L f(x_1 - x_2)\,\mathrm{d}x_1\,\mathrm{d}x_2 = 2\int_0^L (L-x) f(x)\,\mathrm{d}x, \tag{4}$$

equation (2) can then be written as

$$C_{\ln I}(l,\tau) = 2\int_0^L (L-x) R_\alpha(x, l - v\tau)\,\mathrm{d}x, \tag{5}$$

where

$$R_\alpha(x, l - v\tau) = \iiint_0^\infty \cos(\kappa_2(l - v\tau) + \kappa_1 x)\varphi_\alpha(\boldsymbol{\kappa})\,\mathrm{d}\kappa_1\,\mathrm{d}\kappa_2\,\mathrm{d}\kappa_3, \tag{6}$$

with $\boldsymbol{\kappa}$ being the spatial wavenumber, $\kappa^2 = \kappa_1^2 + \kappa_2^2 + \kappa_3^2$, $\varphi_\alpha(\boldsymbol{\kappa})$ being the three-dimensional (3D) power spectrum of extinction coefficient fluctuations.

For a stationary random process, the correlation function can be expressed as

$$C_\mathrm{f}(r) = \frac{1}{2}[D_\mathrm{f}(\infty) - D_\mathrm{f}(r)], \tag{7}$$

where f is a stationary random function.

Suppose that the particle concentration is a conservational and passive scalar quantity, for sufficiently developed turbulence, the extinction coefficient structure function is

$$D_\alpha(r) = C_\alpha^2 r^{2/3}, \quad l_0 \ll r \ll L_0, \tag{8}$$

where C_α^2 is the structure constant of the extinction coefficient and r is the distance between two arbitrary points in the turbulence field, l_0 and L_0 are the inner-scale and outer-scale of the turbulence respectively.

Replace ∞ with the outer-scale L_0 of the turbulence in Eq. (7), and insert Eq. (8) into Eq. (7), then we will easily obtain

$$R_\alpha(x, l-v\tau) = \frac{1}{2}C_\alpha^2(L_0^{2/3} - r^{2/3}), \tag{9}$$

where $r = \sqrt{x^2 + (l-v\tau)^2}$, while $r > L_0$, $R_\alpha = 0$.

Insert Eq. (9) into Eq. (5), then we will have

$$C_{\ln I}(l,\tau) = C_\alpha^2 \int_0^L (L-x)(L_0^{2/3} - r^{2/3})\,\mathrm{d}x. \tag{10}$$

Carrying out the numerical simulations of Eq. (10), the result is shown in Fig. 2. The time delay at the peak of the cross-correlation function is 0.5 second, which is just equal to l/v. It illustrates that it is feasible to calculate the velocity by the optical scintillation cross-correlation function.

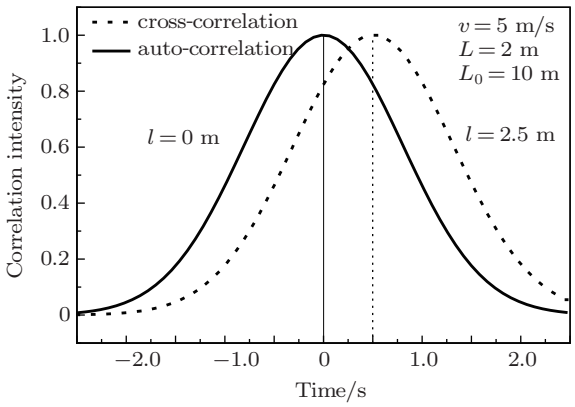


Fig. 2. Numerical computer simulations.

Considering the aperture smoothing effects[15,16] of the transmitting lens and the receiving lens, the correlation function of the optical scintillation can be written as

$$\begin{aligned} &C_{\ln I}(l,\tau) \\ &= 2\int_0^L \mathrm{d}x \int_0^\infty \mathrm{d}\kappa \cdot (L-x) R_\alpha(x, l-v\tau) \\ &\times \left\{ \frac{2\mathrm{J}_1\left(\frac{\kappa D_\mathrm{r} x}{2L}\right)}{\frac{\kappa D_\mathrm{r} x}{2L}} \right\}^2 \left\{ \frac{2\mathrm{J}_1\left[\frac{\kappa D_\mathrm{t}}{2}\left(1-\frac{x}{L}\right)\right]}{\frac{\kappa D_\mathrm{t}}{2}\left(1-\frac{x}{L}\right)} \right\}^2, \end{aligned} \tag{11}$$

where J_1 is the first-order Bessel function.

Many methods have been suggested or demonstrated for wind measurements by the temporal cross correlation of the optical scintillation,[17] such as the peak technique, slope technique, frequency technique, Briggs technique, and covariance technique. Among these methods, the peak technique is more resistant to interference, and easy to implement.[18] The average velocity of the optical path can be obtained by the formula:

$$\bar{v} = \frac{l}{\tau}. \tag{12}$$

3. Practical measurement results

The measurement schematic diagram is shown in Fig. 3. Two identical LED light sources transmit spherical waves each with a wavelength of 630 nm and an output power of 1 W. The receiver is the silicon photoelectric diode. The received signals are magnified after having passed through the low-pass filters, and then collected by an acquisition card. Finally the signal processing device gets the digital signals to be processed. It should be pointed out here that the beam wave front of the selected LED light source must be close to the ideal spherical surface in the far field, the closer the better. Zeng *et al.*[19] have analyzed the effects of beam quality on measurements of scintillation intensity and flow velocity.

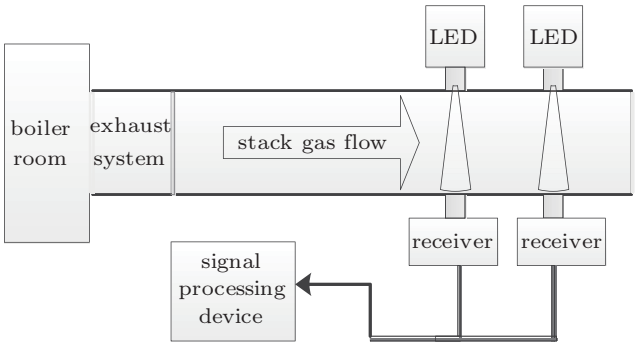


Fig. 3. Schematic diagram of flow velocity measurement.

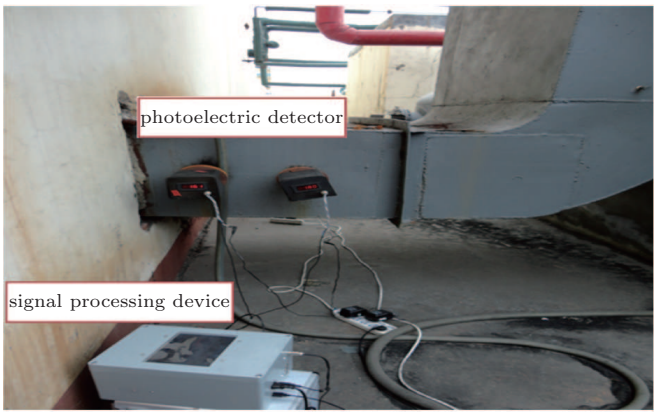


Fig. 4. (color online) Photo of an experimental field test.

The measurement is carried out at a chemical factory in Weifang of the Shandong Province in December 2012. A rectangular stack with a length of 2 m and a width of 0.55 m is used, as shown in Fig. 4. The distance between the transmitter and the receiver is the length of the stack, and the spacing between the two receivers is 0.38 m. The aperture diameters of the transmitter and the receiver are both 30 mm. The velocity of the stack gas flow is about 7 m/s. The stack gas is produced from the burning of coal.

The continuous measurement of the stack gas flow velocity is performed by using an optical method and the Pitot tube synchronously. Figure 5 shows the results obtained by

the two methods. It is observed that they are in good consistency with each other, and the small difference is due to the fact that the Pitot tube measures one point velocity, while the optical method measures the average velocity of the optical path.

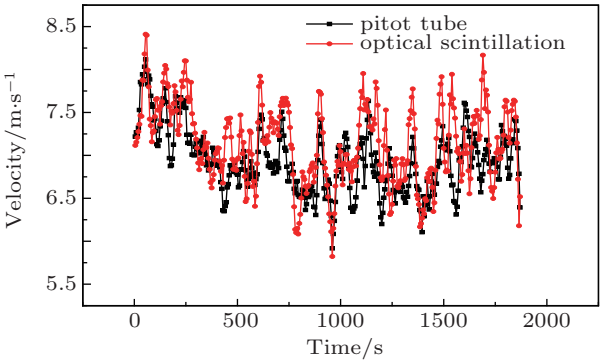


Fig. 5. (color online) Variations of velocity of the stack gas flow with time.

Figure 6 shows a set of received optical scintillation signals in a time period of 5 s. The shapes of the two path signals are very similar obviously, just with a difference in time delay. The low frequency of optical scintillation caused by stack gas flow is relative to the random particle concentration fluctuations. The power ratio of the optical scintillation spectra in part of the low frequency is $-8/3$ (Fig. 7).

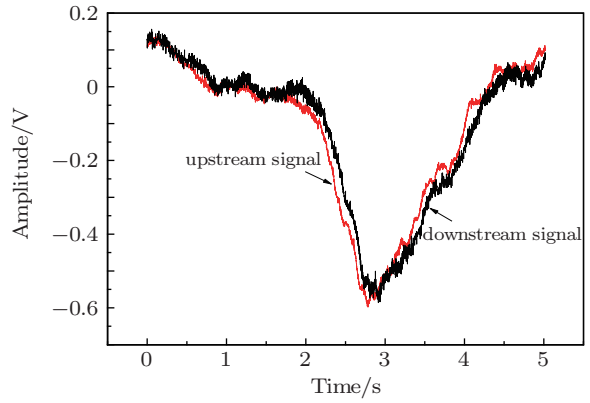


Fig. 6. (color online) Received time-dependent signals of light intensity fluctuations.

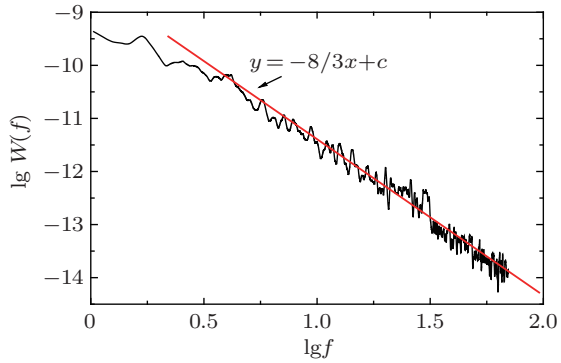


Fig. 7. (color online) Low frequency part of the optical scintillation spectrum.

The cross correlation of the received optical scintillation signals is shown in Fig. 8. The time delay at the peak of the cross-correlation is 0.07 s. According to Eq. (12), the velocity of stack gas flow is 5.43 m/s.

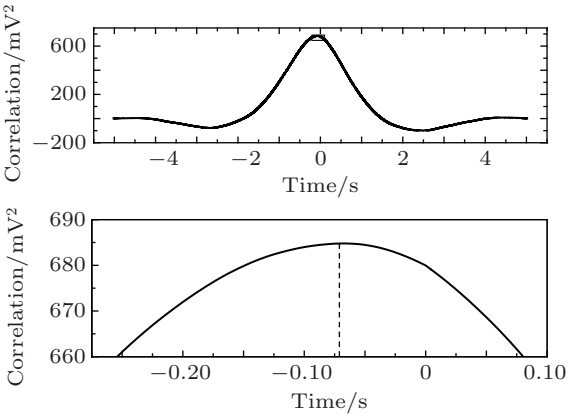


Fig. 8. Cross-correlation of the optical scintillation.

4. Optical scintillation spectra in part of low frequency

At any time t, logarithmic light intensity fluctuation is

$$(\ln I)' = \int_0^L \alpha'(r)\,\mathrm{d}x. \tag{13}$$

Let $S(r) = S(x,y,z) = (\ln I)'$, while $x = L$,

$$\begin{aligned} &S(L,y_1,z_1) - S(L,y_2,z_2) \\ &= \int_0^L [\alpha'(x,y_1,z_1) - \alpha'(x,y_2,z_2)]\,\mathrm{d}x, \end{aligned} \tag{14}$$

then

$$\begin{aligned} &\langle [S(L,y_1,z_1) - S(L,y_2,z_2)]^2 \rangle \\ &= \int_0^L \mathrm{d}x_1 \int_0^L \mathrm{d}x_2 \langle [\alpha'(x_1,y_1,z_1) - \alpha'(x_1,y_2,z_2)] \rangle \\ &\cdot \langle [\alpha'(x_2,y_1,z_1) - \alpha'(x_2,y_2,z_2)] \rangle. \end{aligned} \tag{15}$$

According to the identical equation, we have

$$\begin{aligned} &\langle [\alpha'(x_1,y_1,z_1) - \alpha'(x_1,y_2,z_2)] \\ &\times [\alpha'(x_2,y_1,z_1) - \alpha'(x_2,y_2,z_2)] \rangle \\ &= \frac{1}{2}\langle [\alpha'(x_1,y_1,z_1) - \alpha'(x_2,y_2,z_2)]^2 \rangle \\ &+ \frac{1}{2}\rangle [\alpha'(x_1,y_2,z_2) - \alpha'(x_2,y_1,z_1)]^2 \rangle \\ &- \frac{1}{2}\langle [\alpha'(x_1,y_1,z_1) - \alpha'(x_2,y_1,z_1)]^2 \rangle \\ &- \frac{1}{2}\langle [\alpha'(x_1,y_2,z_2) - \alpha'(x_2,y_2,z_2)]^2 \rangle, \end{aligned} \tag{16}$$

for the homogeneous isotropic turbulence,

$$\begin{aligned} &\langle [\alpha'(x_1,y_1,z_1) - \alpha'(x_2,y_2,z_2)]^2 \rangle \\ &= \langle [\alpha'(x_1,y_2,z_2) - \alpha'(x_2,y_1,z_1)]^2 \rangle \end{aligned}$$

$$= D_\alpha(\sqrt{(x_1-x_2)^2+(y_1-y_2)^2+(z_1-z_2)^2}, \quad (17)$$

and

$$\begin{aligned}&\langle[\alpha'(x_1,y_1,z_1)-\alpha'(x_2,y_1,z_1)]^2\rangle\\ &= \langle[\alpha'(x_1,y_2,z_2)-\alpha'(x_2,y_2,z_2)]^2\rangle\\ &= D_\alpha(|x_1-x_2|), \end{aligned} \quad (18)$$

where D_α is the extinction coefficient structure function. Therefore, Eq. (15) can be written as

$$\begin{aligned}&D_{\ln I}(\rho)\\ &= \int_0^L \mathrm{d}x_1 \int_0^L \mathrm{d}x_2 \{D_\alpha(\sqrt{(x_1-x_2)^2+(y_1-y_2)^2+(z_1-z_2)^2}\\ &\quad -D_\alpha(|x_1-x_2|)\}, \end{aligned} \quad (19)$$

where $\rho=\sqrt{(y_1-y_2)^2+(z_1-z_2)^2}$.

By properly designing the spacing between two parallel beam paths (as shown in Fig. 1) to satisfy the Taylor freeze turbulence hypothesis, it can be obtained that $y_1-y_2=l-v\tau$ and $z_1=z_2$. In order to calculate the optical scintillation spectrum, let $l=0$, then $\rho=v\tau$. According to Eq. (4), Eq. (19) turns into

$$D_{\ln I}(\rho)=2\int_0^L (L-x)\times[D_\alpha(\sqrt{x^2+\rho^2})-D_\alpha(x)]\mathrm{d}x. \quad (20)$$

Insert Eq. (8) into Eq. (20), then we will have

$$D_{\ln I}(\rho)=2C_\alpha^2\int_0^L (L-x)\times[(x^2+\rho^2)^{1/3}-x^{2/3}]\mathrm{d}x. \quad (21)$$

The definite integral in Eq. (21) contains two parts, one is $L[(x^2+\rho^2)^{1/3}-x^{2/3}]$ (the first term), and the other is $x[(x^2+\rho^2)^{1/3}-x^{2/3}]$ (the second term on the right-hand side). Actually, it is easy to obtain that in a range from 0 to L, the first term on the right-hand side is a monotonically decreasing function, and the second term is a monotonically increasing function (shown by differentiating the formula). When $x=L$, the two formulas are equal. So the second term can be neglected, Eq. (21) will be reduced to

$$D_{\ln I}(\rho)\approx 2C_\alpha^2 L\int_0^L[(x^2+\rho^2)^{1/3}-x^{2/3}]\mathrm{d}x. \quad (22)$$

When x is large enough, then

$$(x^2+\rho^2)^{1/3}-x^{2/3}\approx x^{2/3}\left[1+\frac{\rho^2}{3x^2}-1\right]=\frac{\rho^2}{3x^{4/3}}\to 0. \quad (23)$$

So the upper limit of the integral of Eq. (22) can be replaced with infinity without bringing in a large error,

$$D_{\ln I}(\rho)=2L\int_0^\infty [D_\alpha(\sqrt{x^2+\rho^2})-D_\alpha(x)]\,\mathrm{d}x. \quad (24)$$

Owing to[20]

$$D_\alpha(\sqrt{x^2+\rho^2})-D_\alpha(x)$$

$$= 2\iint_{-\infty}^{+\infty}[1-\cos(\kappa_2\eta+\kappa_3\zeta)] \times F_\alpha(\kappa_2,\kappa_3,x)\,\mathrm{d}\kappa_2\,\mathrm{d}\kappa_3, \quad (25)$$

where $\rho^2=\eta^2+\zeta^2$, $F_\alpha(\kappa_2,\kappa_3,x)$ is the two-dimensional (2D) spectrum of extinction coefficient fluctuations, suppose that $\Phi_\alpha(\kappa_1,\kappa_2,\kappa_3)$ is a 3D spectrum, then there will be a relationship between $F_\alpha(\kappa_2,\kappa_3,x)$ and $\Phi_\alpha(\kappa_1,\kappa_2,\kappa_3)$,

$$\int_0^\infty F_\alpha(\kappa_2,\kappa_3,x)\,\mathrm{d}x=\pi\Phi_\alpha(0,\kappa_2,\kappa_3). \quad (26)$$

Insert Eqs. (25) and (26) into Eq. (24), then we will have

$$\begin{aligned}D_{\ln I}(\rho) &= 4L\iint_{-\infty}^{+\infty}[1-\cos(\kappa_2\eta+\kappa_3\zeta)]\,\mathrm{d}\kappa_2\,\mathrm{d}\kappa_3\\ &\quad\times\int_0^\infty F_\alpha(\kappa_2,\kappa_3,x)\,\mathrm{d}x\\ &= 2\iint_{-\infty}^{+\infty}[1-\cos(\kappa_2\eta+\kappa_3\zeta)]2\pi L\\ &\quad\times\Phi_\alpha(0,\kappa_2,\kappa_3)\,\mathrm{d}\kappa_2\,\mathrm{d}\kappa_3. \end{aligned} \quad (27)$$

Because of

$$\begin{aligned}D_{\ln I}(\rho) &= 2\iint_{-\infty}^{+\infty}[1-\cos(\kappa_2\eta+\kappa_3\zeta)]\\ &\quad\times F_{\ln I}(\kappa_2,\kappa_3,0)\,\mathrm{d}\kappa_2\,\mathrm{d}\kappa_3, \end{aligned} \quad (28)$$

where $F_{\ln I}(\kappa_2,\kappa_3,0)$ is the 2D spectrum of logarithmic light intensity fluctuations, a comparison of Eq. (27) with Eq. (28) yields

$$F_{\ln I}(\kappa_2,\kappa_3,0)=2\pi L\Phi_\alpha(0,\kappa_2,\kappa_3). \quad (29)$$

Let $\kappa=\sqrt{\kappa_2^2+\kappa_3^2}$,

$$F_{\ln I}(\kappa,0)=2\pi L\Phi_\alpha(\kappa). \quad (30)$$

If the structure function is

$$D(r)=C^2r^p, \quad (0<p<2), \quad (31)$$

then the corresponding one-dimensional (1D) spectrum[20] is

$$W(\kappa)=\frac{\Gamma(p+1)}{2\pi}\sin\frac{\pi p}{2}C^2\kappa^{-(p+1)}, \quad (32)$$

and the corresponding 3D spectrum is

$$\Phi(\kappa)=\frac{\Gamma(p+2)}{4\pi^2}\sin\frac{\pi p}{2}C^2\kappa^{-(p+3)}, \quad (33)$$

where $\Gamma(\cdot)$ is the Gamma function.

It has been supposed that the extinction coefficient structure function is

$$D_\alpha(r)=C_\alpha^2 r^{2/3}, \quad l_0\ll r\ll L_0. \quad (34)$$

According to Eq. (33), the corresponding three-dimensional spectrum is

$$\Phi_\alpha(\kappa)=\frac{\Gamma(8/3)\sin(\pi/3)}{4\pi^2}C_\alpha^2\kappa^{-11/3}=0.033C_\alpha^2\kappa^{-11/3}. \quad (35)$$

Insert Eq. (35) into Eq. (30), then we will have

$$F_{\ln I}(\kappa,0) = 0.21LC_\alpha^2\kappa^{-11/3}. \tag{36}$$

There is a relationship between the structure function and the two-dimensional spectrum as follows:

$$D(\rho) = 4\pi\int_0^\infty [1-\mathrm{J}_0(\kappa\rho)]F(\kappa,0)\kappa\,\mathrm{d}\kappa. \tag{37}$$

Insert Eq. (36) into Eq. (37), then we will obtain

$$D_{\ln I}(\rho) = 2.91C_\alpha^2 L\rho^{5/3}. \tag{38}$$

Because $\rho = v\tau$, so

$$D_{\ln I}(\tau) = 2.91LC_\alpha^2 v^{5/3}\tau^{5/3}. \tag{39}$$

According to Eq. (32), the power ratio of the spectrum, whose time structure function is satisfied by Eq. (39), is $-8/3$,

$$W(\omega) = 0.348LC_\alpha^2 v^{5/3}\omega^{-8/3}. \tag{40}$$

So, the theoretical inference is consistent with the actual measurement result.

5. Conclusion

The reasons for optical scintillation caused by a light beam passing through a stack gas flow are very complex. Particles moving in or out of the view of sight at random will induce optical intensity fluctuations, but it is hard to receive the scintillation signals in the industrial environment. Turbulence causes the optical scintillation, and the frequency of this kind of scintillation commonly reaches hundreds or thousands of Hz. The scintillation signals of this frequency range can be used to measure the velocity of stack gas flow. This method has limitations: when the temperature field is distributed uniformly and the refractive index fluctuates weakly, it is difficult to measure velocity. Particle concentration fluctuations at random will also induce optical scintillation. In the low frequency part of the optical scintillation spectra, the scintillation standard deviation shows good linearity with particle concentration, and almost all the particle concentration measuring methods using optical scintillation are based on this empirical relationship, but up to now the relevant theory has not yet been found.

Adopting the proposed architecture of separate parallel double light paths, the stack gas flow velocity can be measured by a peak technique. The measuring results accord well with those obtained by the Pitot tube. According to the random fluctuations of the particle concentration field, we obtain a power ratio of $-8/3$ in part of the low frequency, and give the expression of the cross-correlation function. However, the industrial environment is very complex, and many reasons will cause optical scintillation besides what we have mentioned. To measure velocity and particle concentration, then thereby to realize the objective of real-time monitoring the total emissions, further work needs to be done and the relevant results will be published in the near future.

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