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Transmission fluctuation method for particle analysis in multiphase flow

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ABSTRACT

The transmission fluctuations can be used for measurements on particle size and particle concentration in multiphase flows. In Gregory's method, the beam diameter is required to be much larger than the particle diameter, which limits the application seriously. In this work, we introduce a new method of the transmission fluctuation measurement, in which the beam diameter can be less, equal to and larger than the particle diameter. The theoretical analysis proves that, when the beam-to-particle diameter ratio is within the range of 0.05 and 10, the new method is able to achieve satisfying measurement results. However, Gregory's method is only suitable in the range of 5 and 10. Therefore, this new method enhances the transmission fluctuation measurements greatly.

1. Introduction

Transmission signals of narrow light beams passing through particle dispersions such as multiphase flows show significant fluctuations, which include the complete information on particle size and particle concentration. Gregory (1985) established a technique for particle characterization based on this dynamic behavior of light transmission signals. The general principle is illustrated in Fig. 1, in which the sample volume V_M is defined with the path-length L and beam cross section $A_M = \pi D^2/4$ (here D is the beam diameter), i.e. $V_M = A_M L = \pi D^2 L/4$. When the sample volume is not very large, the number of particles illuminated by the incident beam will change randomly due to the Brownian motion and hence the transmission signal shows visible fluctuations. By assuming that the variations in particle number were Poisson-distributed, Gregory obtained the expressions of the average transmission $e\{T\}$ and the standard deviation σ_T for a mono-dispersion:

$$e\{T\} = \exp\left(-\frac{e\{N\}\pi x^2 L}{4V_M}\right) \tag{1}$$

$$\sigma_T = e\{T\} \cdot \sinh\left(\frac{\sqrt{e\{N\}}\pi x^2 L}{4V_M}\right) \tag{2}$$

in which x is the particle diameter and $e\{N\}$ is the average particle number in the measuring volume. A combination of the standard deviation and the average transmission leads very simply to the particle diameter x and its volume concentration C_V, which is defined as the ratio of the particles' volume to the total volume of dispersion:

$$x = \frac{D}{\sqrt{-\ln e\{T\}}} \ln\left[\frac{\sigma_T}{e\{T\}} + \sqrt{\left(\frac{\sigma_T}{e\{T\}}\right)^2 + 1}\right] \tag{3}$$

$$C_V = -\frac{x}{1.5L} \ln e\{T\} \tag{4}$$

This method requires no information on the optical properties of the particles and employs a very simple optical setup. So it has become a very useful means of particle analysis and has been applied in many fields (Cai et al., 2005; Gabsch et al., 2007; Feller et al., 1998; Gürtler et al., 2004; Ripperger et al., 1999; Wessely et al., 1996, 2004, 2006).

However, in Gregory's technique, the Poisson distribution of the particle number implies that the measuring volume V_M should be much larger than the volume of a single particle so that it is possible for several particles existing in the measuring zone and the case of particles locating at border of the measuring volume can be omitted. In the other hand, the increase of the measuring volume diminishes the spatial resolution of the measurement and hence leads to the decrease of the signal fluctuations, which is not good for the measurement. Therefore, the measuring volume should be chosen carefully to simultaneously satisfy the assumption of the particle number distribution and make the signal fluctuations strong enough. Evidently, this technique cannot measure particles whose diameter is close to or larger than the beam diameter.

Kräuter (1995) proposed a new model of the transmission fluctuation method on the basis of a layer model. The transmission fluctuations were expressed in terms of the expectancy of transmission square $e\{T^2\} = e\{T\}^2 + \sigma_T^2$. The initial expression was obtained empirically from simulation and experimental study. Based on the assumptions of ray propagation, completely absorbent spherical particles and low particle volume concentration,

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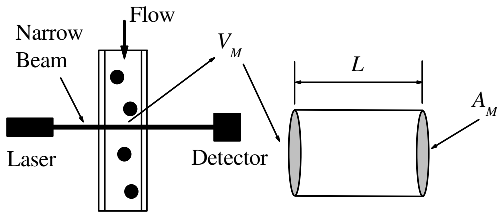

Fig. 1. Principle of the transmission fluctuation method.

the analytical expression was later achieved by Breitenstein and Shen (Breitenstein, 2000; Shen, 2003; Shen et al., 2003):

$$e\{T\} = (1 - PC_V)^{1.5L/(P\cdot x)}$$
$$e\{T^2\} = [1 - PC_V \cdot (2 - \xi) + (PC_V)^2 \cdot (1 + \varepsilon)]^{1.5L/(P\cdot x)} \tag{5}$$
$$\xi = \int_0^\infty F_S \frac{2J_1^2(u)}{u} \mathrm{d}u \tag{6}$$
$$\varepsilon = \int_0^\infty F_S \frac{2J_1^2(u)}{u} F_{ML} \mathrm{d}u \tag{7}$$

where $\Lambda = D/x$ is the beam-to-particle diameter ratio, $P \geqslant 1.5$ is the structural parameter dependent on the flow condition. F_S is a factor describing the beam profile. For a circular uniform beam $F_S = [2J(u\Lambda)/u\Lambda]^2$ and for a Gaussian beam $F_S = \exp[-(u\Lambda/2)^2]$. F_{ML} is a factor describing the dispersion structure. A detailed description can be found in literature (Shen and Riebel, 2004).

With a combination of the average transmission and the expectancy of transmission square, the particle size and particle volume concentration can be obtained from Eq. (5).

In this work, the different methods of transmission fluctuations are studied by means of theoretical analysis, simulation and experiments.

2. Comparison of the methods theoretically

The term $(PC_V)^2 \cdot (1 + \varepsilon)$ in the expectancy of transmission square $e\{T^2\}$ is in the high order of the volume concentration C_V and hence can be omitted when the particle dispersion is low concentrated. Thus the average transmission and the expectancy of transmission square can be approximated to

$$e\{T\} \approx \lim_{PC_V \to 0} \left[(1 - PC_V)^{-\frac{1}{PC_V}}\right]^{-\frac{1.5L}{x}C_V} = \exp\left(-\frac{1.5L}{x}C_V\right)$$
$$e\{T^2\} \approx \lim_{PC_V \to 0} [1 - PC_V \cdot (2 - \xi)]^{1.5L/(P\cdot x)} = \exp\left(-\frac{1.5L}{x}C_V(2 - \xi)\right) \tag{8}$$

Therefore, the standard deviation of the transmission signals can be obtained from the average transmission and the expectancy of transmission square

$$\sigma_T = \sqrt{e\{T^2\} - e\{T\}^2} \approx e\{T\} \cdot \sqrt{e\{T\}^{-\xi} - 1} \tag{9}$$

When the extinction E is used (defined as the negative logarithm of the average transmission $E = -\ln e\{T\}$), Eqs. (8) and (9) can be further rewritten as

$$e\{T\} \approx \exp(-E)$$
$$e\{T^2\} \approx \exp[-E(2 - \xi)] \tag{10}$$
$$\sigma_T \approx \exp(-E) \cdot \sqrt{\exp(E\xi) - 1} \tag{11}$$

The function ξ is given in Eq. (6) and it can be calculated numerically. The numerical results ξ for a circular uniform beam and a Gaussian beam are shown in Fig. 2. So Eq. (11) shows the dependence of the standard deviation σ_T on the extinction E and the beam-to-particle diameter ratio Λ.

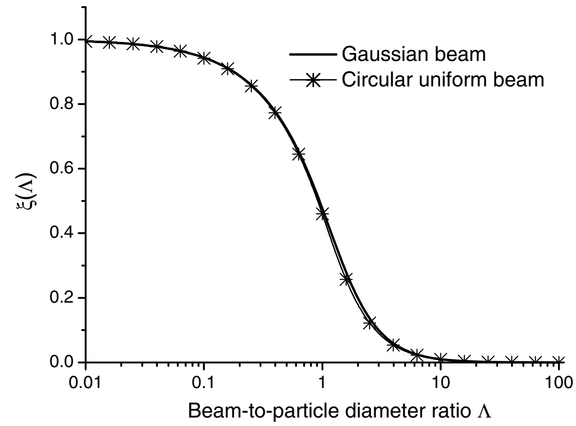

Fig. 2. Numerical result on the function ξ.

Now, we introduce the measuring volume $V_M = \pi D^2 L/4$ into Eqs. (1) and (2) and add the subscript G in the expression of the standard deviation:

$$e\{T\} = \exp\left(-\frac{e\{N\}\pi x^2 L}{4V_M}\right) = \exp\left(-\frac{1.5L}{x}C_V\right) = \exp(-E) \tag{12}$$
$$\sigma_{T,G} = e\{T\} \cdot \sinh\left(\sqrt{-\ln e\{T\}}/\Lambda\right) = \exp(-E) \cdot \sinh\left(\sqrt{E}/\Lambda\right) \tag{13}$$

The numerical results on the standard deviation σ_T calculated at different values of the beam-to-particle diameter ratios Λ and extinctions E are shown in Fig. 3, in which the solid lines are obtained with Eq. (11) and the dashed ones are with Eq. (13). It can be found that the standard deviations calculated with both methods decrease when the beam-to-particle diameter ratio increases. This means an additional spatial average of the transmission signals over the beam cross section, which is unexpected in the transmission fluctuation measurements. Thus one has to always keep in mind that the beam diameter should be narrow enough in order to make the transmission signals fluctuate violently.

When the beam-to-particle diameter ratios Λ is small (say $\Lambda \leqslant 1$), the standard deviations obtained from different methods differ largely from each other. The difference decreases gradually as Λ increases and it becomes invisible when Λ is larger than 5.0. So both the methods can explain the transmission fluctuations for the case $\Lambda \geqslant 5$.

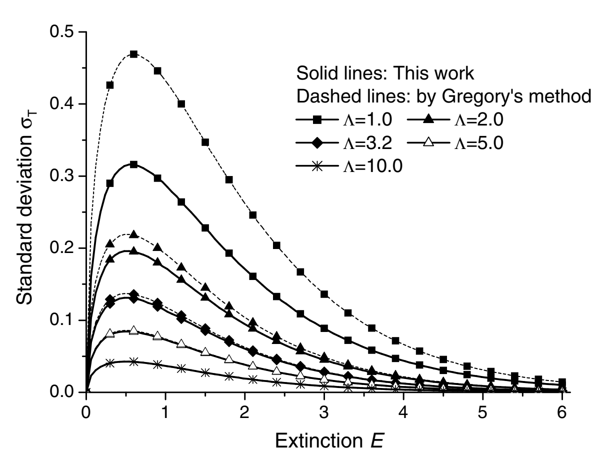

Fig. 3. Numerical results on the standard deviations at variant beam-to-particle diameter ratios Λ and extinctions E, calculated with Eqs. (11) and (13).

The equivalence of the methods at big beam-to-particle diameter ratios can be proved easily. Numerically, when $\Lambda \geqslant 5$, ξ is roughly equal to Λ^2. So if the extinction E is not too big (i.e. the particle volume concentration is not high), the product of E and ξ is close to zero and hence the further approximation can be made in Eq. (11):

$$\sigma_T \approx \exp(-E) \cdot \sqrt{\exp(E\xi) - 1} \approx \exp(-E) \cdot \sqrt{E\xi} \approx \exp(-E) \cdot \sqrt{E}/\Lambda \quad (14)$$

Similarly, $\sinh\left(\sqrt{E}/\Lambda\right) \approx \sqrt{E}/\Lambda$. So Eq. (13) may be approximated to

$$\sigma_{T,G} = \exp(-E) \cdot \sinh\left(\sqrt{E}/\Lambda\right) \approx \exp(-E) \cdot \sqrt{E}/\Lambda \quad (15)$$

Nevertheless, up to here, we are unable to tell which method is the more proper one to describe the transmission fluctuations for the small beam-to-particle diameter ratios (i.e. $\Lambda < 5$). This will be done in the following section by simulations and experiments.

3. Simulations and experimental evidences

Simulations are performed on basis of the same assumptions with the theory. The light beam propagating in the particle dispersion obeys the geometric optics. The particles are spherical and completely absorbent. In order to investigate the transmission fluctuations in a wide range of particle volume concentrations and that of the beam-to-particle diameter ratios, the particle dispersion is simulated under different conditions.

In the following simulations, the pathlength of the dispersion is $5x$, $10x$, $20x$, $30x$ or $40x$ respectively. The dimensions of the dispersion perpendicular to the incident beam are very large (say several hundreds larger than the particle diameter) to avoid deviation from the statistics (see Fig. 4). The extinction varies from 0.05 to 4.0 (corresponding to the average transmission from 0.95 to 0.018), which can be realized by controlling the number of particles in the dispersion. The narrow beam moves randomly and the transmission signals are simulated accordingly.

It should be pointed out that, for a fixed value of the extinction, a shorter pathlength corresponds to a higher particle volume concentration. When the pathlength is $5x$ and the extinction is larger than 2, the particle volume concentration is very high and the average separation of the particle pair is small so that the spatial interaction between particles should be accounted for while multiple scattering can be excluded. A detailed discussion can be found in literatures (Shen and Riebel, 2004; Riebel and Shen, 2004). Paying attention to this, we also simulate the particle dispersion with a very long pathlength. It is realized with a particle dispersion in which the particles can intersect into each other freely (i.e. there is no interactions between particles).

Simulated results are given in Fig. 5, comparing with the theoretical results calculated with Eqs. (6) and (11). It can be found that

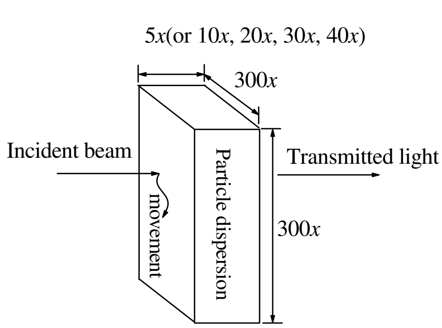

Fig. 4. Scheme of the simulation.

all the simulated results agree well with those obtained from Eq. (11) and deviate from Gregory's method largely, especially for small beam-to-particle diameter ratios. When the extinction increases, the simulated results gradually deviate from the theory, depending on the value of the beam-to-particle diameter ratio. When $\Lambda = 0$ and 0.1, the deviation is almost invisible. However, when $\Lambda = 3.2$, the deviation grows very fast along with the increase of the extinction. This is because that Eq. (11) is only an approximation at low particle concentrations so that effects from particle interaction are not considered (Shen and Riebel, 2004; Riebel and Shen, 2004). Another possible reason is that the dimensions of the dispersion in the perpendicular direction are fixed for all the simulations. So, compared to the beam cross section, the irradiated area of the dispersion becomes smaller when the beam-to-particle diameter ratio increases. This leads to the number of transmission signals decrease and hence the deviation from the statistics increases.

The experimental setup is schematically shown in Fig. 6. The beam from a He–Ne laser ($\lambda = 0.6328$ μm, TEM00 mode) is expanded and then focused with convex lenses. The waist lies in the middle of the measuring zone. The average beam diameter is about 50 μm in the measuring zone and the optical pathlength is about 5.5 mm. In order to ensure constant measurement conditions, the particle dispersion is cycled in the circuit driven by a hose pump. The transmitted light intensity or transmission is focused by a convex lens onto a photodiode. The signal is amplified and is then fed to a low-pass filter to get the average transmission. Meanwhile, the amplified signal is fed into a high-pass filter followed by a RMS chip to get the standard deviation of the transmission signal. The cutoff frequencies of the filters are about 50 Hz.

The measurements are performed on mono-dispersed glass beads and SiC. The samples are prepared carefully and are measured with a diffractrometer produced by Sympatec. The mean diameters of glass beads measured are 25 μm, 40–45 μm, 130 μm, 265 μm and 350–400 μm. The mean diameters of SiC are 18 μm, 35 μm, 50 μm and 80 μm. The particle volume concentration varies in a very wide range by controlling the weight of the samples in the closed particle dispersion. The corresponding value of the extinction varies from 0.2 to 5.0. Some of the experimental results are plotted in Fig. 7. The fit of the measurements with the theory is evaluated by the root mean square (RMS) of the standard deviations measured at different values of extinction and the corresponding theoretical ones, which is defined as

$$\mathrm{RMS} = \left[\frac{1}{m}\sum_{i=1}^{m}\left(1 - \frac{\sigma_{T,\mathrm{meas},i}}{\sigma_{T,\mathrm{theory},i}}\right)^2\right]^{\frac{1}{2}} \quad (16)$$

whereby the subscript i denotes the measurement point. The values of RMS are respectively 0.0449, 0.0397, 0.0168, 0.0437, 0.0499 and 0.0466 for particles with mean diameters of 18 μm, 25 μm, 40–45 μm, 80 μm, 195–210 μm and 350–400 μm. Once again, the results give satisfactory agreement with the theory introduced in this work in a wide range of particle volume concentration. The measurement on particles whose mean diameter is 50 μm and the beam-to-particle diameter ratio is close to 1 gives the best fit with the theory, which will be further discussed later.

With the experimental results on the extinction and the standard deviation, the mean particle diameter and the corresponding volume concentration can be simply achieved. To do this, Eq. (11) can be rewritten as

$$\xi = \frac{1}{E}\ln[\sigma_T^2 \exp(2E) + 1] \quad (17)$$

Once the measured value of ξ is obtained, the beam-to-particle diameter ratio can be found on the curve in Fig. 2. Combining with

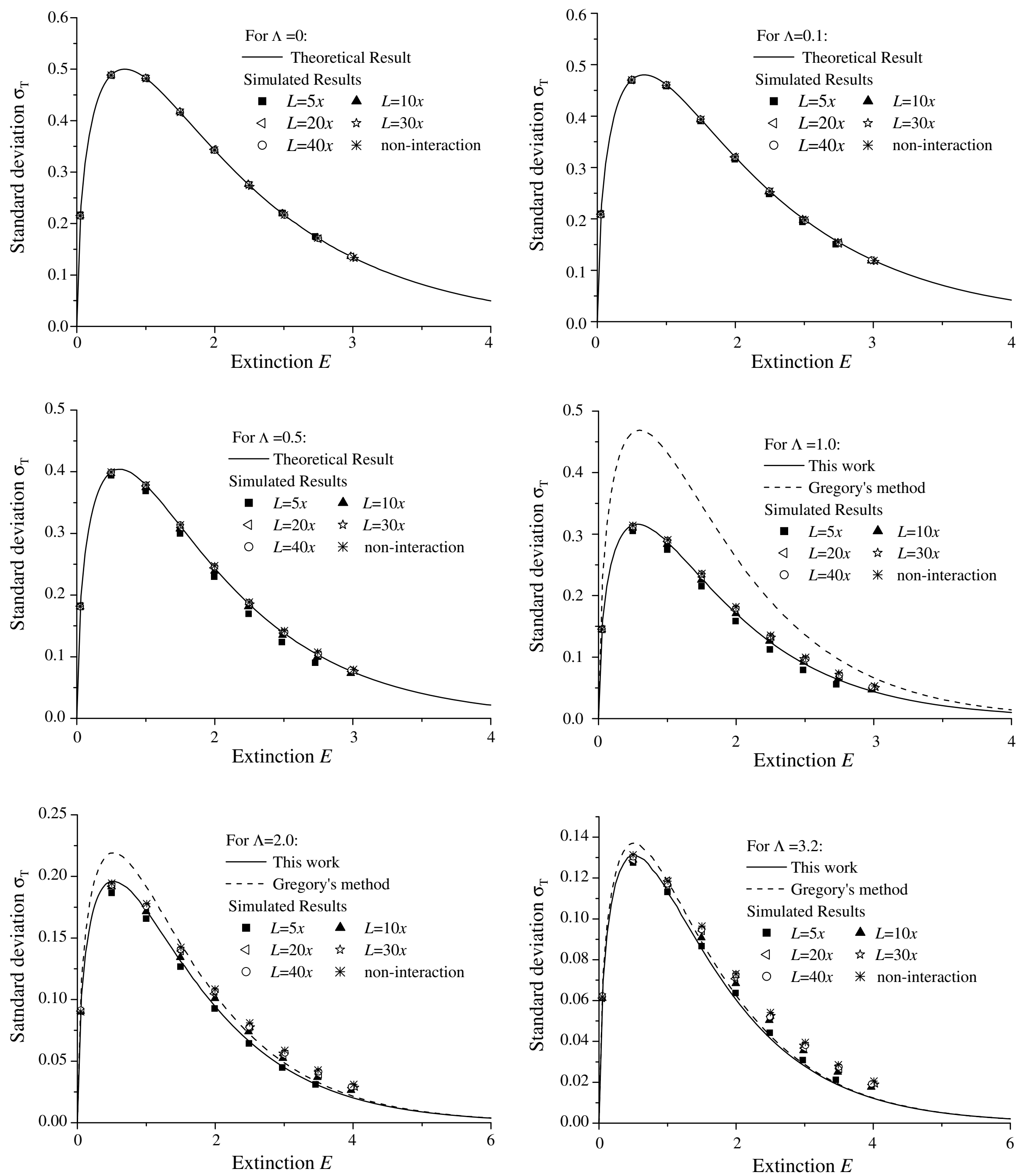

Fig. 5. The standard deviation for different beam-to-particle diameter ratios and extinctions. The theoretical results are plotted in lines and the simulated ones in dots.

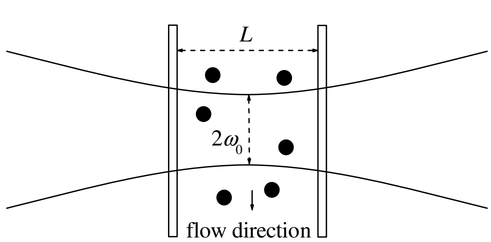

Fig. 6. Optical arrangement for measurements.

the beam diameter, the particle size and the volume concentration are obtained:

$$C_V = \frac{E \cdot x}{1.5L} \tag{18}$$

As examples of this, experimental results on particle size and concentration of the glass beads 40–45 μm and SiC 18 μm are given in Tables 1 and 2. The particle diameters measured with the transmission fluctuation method are quite comparable with those measured with the diffractrometer. As to the measurement on particle volume concentration, the results with the transmission fluctuation method agree well with those by weight of the glass beads. However, the measured volume concentrations of SiC are much higher than what we know. This is because that the volume concentration is calculated with Eq. (18) in which the particles are assumed to be spherical. So it is not surprising that the measurements on the non-spherical SiC would give higher results on the volume concentrations. The sphericity of SiC particles measured in this work is about 2.44. Similar results can be found in literatures (Guo and Riebel, 2005; Shen and Riebel, 2003).

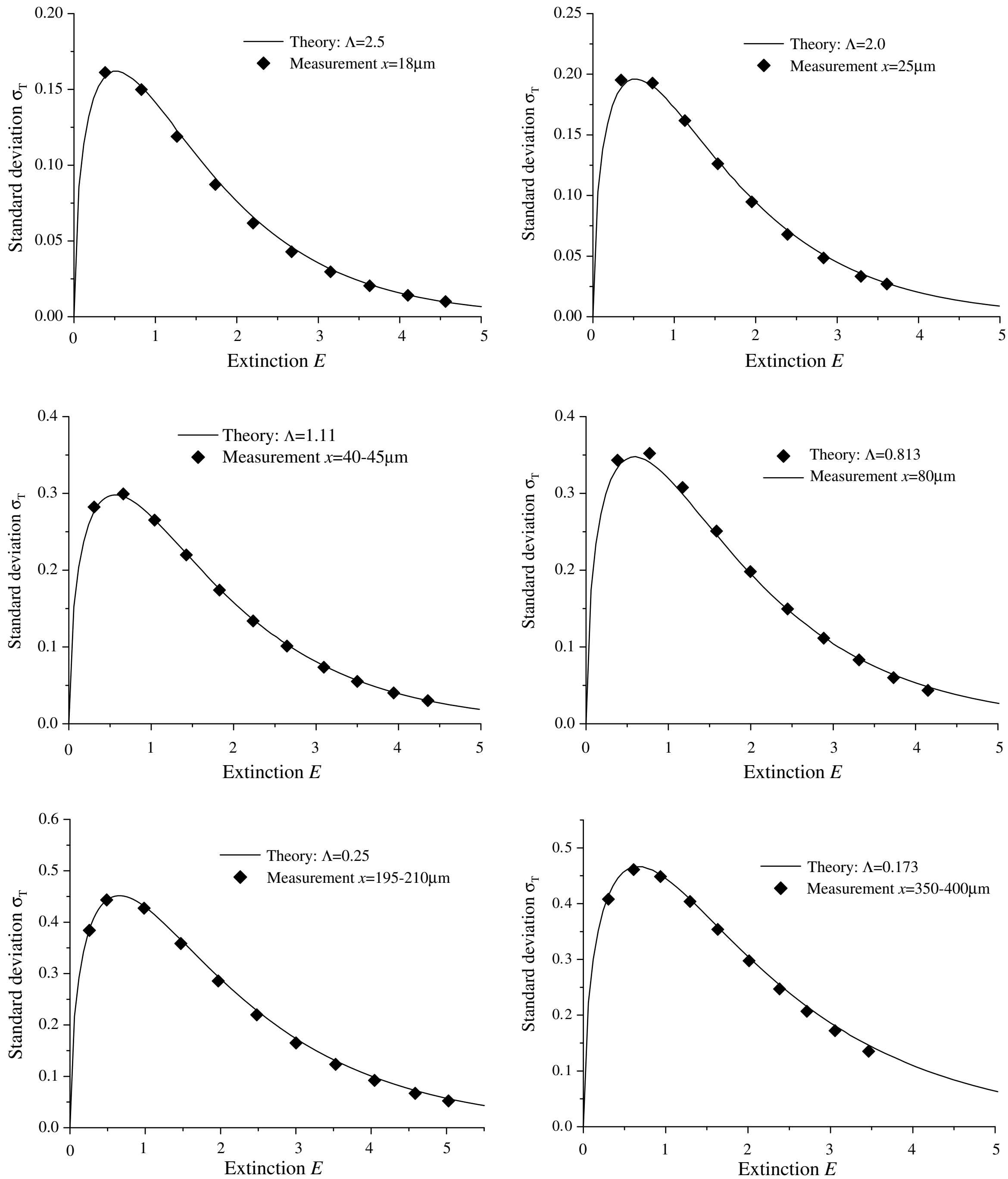

Fig. 7. Measurements on standard deviations for different beam-to-particle diameter ratios and extinctions. The theoretical results are plotted in lines and the experimental ones in dots.

4. Further discussions

The dependence of the standard deviation σ_T on the extinction and the beam-to-particle diameter ratio is given in Eq. (11) and is plotted in Figs. 5 and 7. The maximum of the standard deviation $\sigma_{T,\max}$ can be calculated by letting $d\sigma_T/dE = 0$:

$$\left.\frac{d\sigma_T}{dE}\right|_{\sigma_T=\sigma_{T,\max}} = 0$$
$$E|_{\sigma_T=\sigma_{T,\max}} = -\frac{1}{\xi(\Lambda)}\ln\left(1-\frac{\xi(\Lambda)}{2}\right) \tag{19}$$

Since the value of ξ varies from 0 to 1, so we may expect that the maximum of the standard deviation $\sigma_{T,\max}$ will occur within the range of the extinction from 0.5 to ln2 (as is plotted in Fig. 8). In order to get a good measurement on the transmission fluctuations, it is better to get a bigger value of the standard deviation of the transmission signal. So the extinction should be controlled in the range of 0.5 and ln2, according to the beam-to-particle diameter ratio (as given in Fig. 8 whereby an empirical expression is also given). The corresponding average transmission is between 0.5 and 0.607. This can be realized with a by-pass in the real application.

Table 1
Experimental results of glass beads 40–45 μm

E	σ_T	x (μm)	$C_{V,\text{mass}}$ (%)	C_V (%)
0.307	2.82e−1	46.8	0.22	0.19
0.660	2.99e−1	45.7	0.45	0.41
1.042	2.65e−1	44.9	0.67	0.63
1.426	2.20e−1	44.7	0.90	0.85
1.827	1.74e−1	44.3	1.12	1.08
2.237	1.34e−1	44.3	1.35	1.32
2.648	1.01e−1	43.8	1.57	1.55
3.095	7.36e−2	43.8	1.80	1.82
3.500	5.52e−2	43.8	2.02	2.05
3.941	4.02e−2	44.3	2.25	2.32
4.356	3.01e−2	45.1	2.47	2.61

Table 2
Experimental results of SiC 18 μm

E	σ_T	x (μm)	$C_{V,\text{mass}}$ (%)	C_V (%)
0.383	1.61e−1	20.4	0.04	0.09
0.828	1.50e−1	19.8	0.08	0.20
1.266	1.19e−1	19.3	0.13	0.30
1.736	8.72e−2	19.1	0.17	0.40
2.200	6.18e−2	18.8	0.21	0.50
2.673	4.29e−2	18.7	0.25	0.61
3.151	2.97e−2	18.9	0.29	0.72
3.630	2.04e−2	19.2	0.34	0.85
4.101	1.42e−2	19.7	0.38	0.98
4.564	1.00e−2	20.5	0.42	1.13

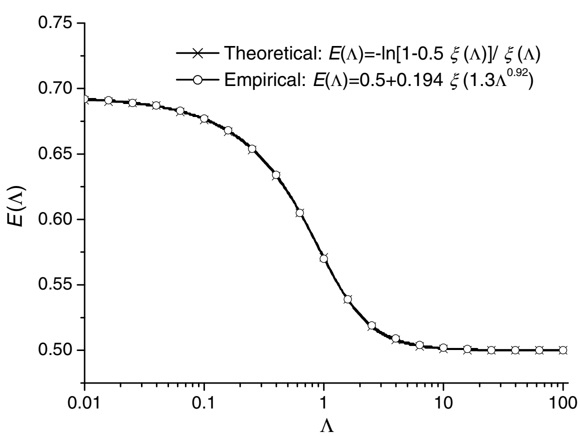

Fig. 8. Dependence of the extinction on the beam-to-particle diameter ratio for the maximum of the standard deviation.

Instituting Eq. (19) into Eq. (11), the relationship between the maximum of the standard deviation $\sigma_{T,\max}$ and the beam-to-particle diameter ratio Λ can be achieved (see Fig. 9):

$$\sigma_{T,\max} \approx \left(\frac{2-\xi(\Lambda)}{2}\right)^{\frac{1}{\xi(\Lambda)}} \sqrt{\frac{\xi(\Lambda)}{2-\xi(\Lambda)}} = 2^{-\frac{1}{\xi(\Lambda)}}(2-\xi(\Lambda))^{\frac{1}{\xi(\Lambda)}-\frac{1}{2}}\xi(\Lambda)^{\frac{1}{2}} \qquad (20)$$

An empirical expression of Eq. (20) is given as

$$\sigma_{T,\max}(\Lambda) = 0.5 \cdot (1 + 0.89\Lambda + \Lambda^{2.46})^{-0.439} \qquad (21)$$

The maximum of the standard deviation $\sigma_{T,\max}$ decreases gradually as the beam-to-particle diameter ratio Λ increases. From this point of view, it seems better to have a small beam-to-particle diameter ratio. However, this is not a good idea if one pay attention to the relationship between ξ and Λ. In Fig. 2, the slope of the curve (i.e. $d\xi/d\Lambda$) is very small when $\Lambda < 0.1$ so that an tiny error of the measurement on ξ would lead to a very large measurement error of the

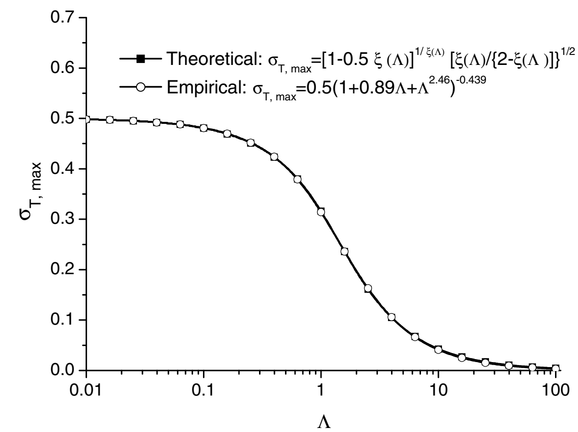

Fig. 9. Dependence of the maximum of the standard deviation on the beam-to-particle diameter ratio.

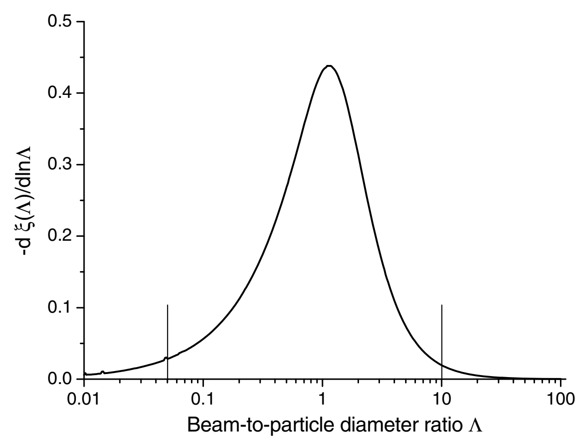

Fig. 10. The slope of ξ for a Gaussian beam.

particle diameter. Same is the case for $\Lambda > 10$. Fig. 10 gives the slope of the curve ξ for a Gaussian beam. Obviously, when $0.05 \leqslant \Lambda \leqslant 10$, the transmission fluctuation method can offer a satisfying resolution of particle size.

Based on the discussions above, we may conclude that the measurement on the transmission fluctuations depend closely on the range of the extinction and the beam-to-particle diameter ratio. In order to get a good measurement result, it is better to keep the beam-to-particle diameter ratio close to 1 or within the range from 0.05 to 10 and the value of the extinction should be in the range from 0.5 to ln 2.

5. Conclusions

In this work, the transmission fluctuation methods are compared with simulations and measurements. It is proved that the standard deviation σ_T decreases gradually as the beam-to-particle diameter ratio Λ is increasing. When Λ is larger than 10, the standard deviation σ_T is too small to make a good measurement. Theoretical analysis denotes that Gregory's method is only suitable for large beam-to-particle diameter ratios (i.e. $\Lambda > 5$). Therefore, Gregory's method is only suitable for $5 \leqslant \Lambda \leqslant 10$. However, the new method introduced in this work can work properly when $0.05 \leqslant \Lambda \leqslant 10$. The range of measurable particle size corresponds to the average beam diameter within the measuring zone. For example, if a narrow beam with the average diameter of 50 μm is used in the measurement, the method would be capable to measure the particles ranging from 5 μm to 1000 μm. It is proved that both the methods give the same results when the beam-to-particle diameter ratio is larger than 5. Due to the fact that the highest slope value of $\xi(\Lambda)$ is found in the vicinity of $\Lambda \approx 1$, the new method can reach the best condition for the transmission fluctuation measurements while Gregory's method cannot.

In order to make a good measurement on the particle diameter and particle volume concentration, it is much better to control the extinction in the range of 0.5 and $\ln 2$ so that the standard deviation is close to its maximum.

It should be pointed out that the dependence of the transmission fluctuation measurement on the extinction efficiency is not discussed. In this work, it is simply taken as 1. A detailed discussion can be found in literature (Shen and Riebel, 2001).

Finally, the transmission fluctuation method developed in this work can apply to measure the particle size and the particle concentration. Therefore, it is suitable to measure the mono-dispersions only. While a poly-dispersion is measured, the mean particle size would be obtained and thus the particle concentration would possibly deviate from the real one, depending on how wide the particle size distribution is. However, the method may also be developed into the transmission fluctuation spectrometry in which band-pass filters or variable beam diameters are employed to draw information on particle size distribution and particle volume concentration (Shen et al., 2007). The further study will be published later.

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