SENSITIVITY TO OPTICAL NOISE OF THE MEASUREMENTS OF PARTICLE CONCENTRATION AND VOLUME FLUX WITH A PHASE DOPPLER ANEMOMETER IN DILUTE SPRAYS

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Abstract

This paper studies the effects caused by the optical losses on the calculated cross section of the measurement volume of a phase Doppler anemometer and consequently, in particle concentration and volume flux. It will be shown that as the optical losses increase, the calculated diameter of the measurement volume for the smaller particles presents an anomalous behaviour. Moreover, these small particles tend to disappear. As a consequence the particle range that the PDA can handle is restricted. A criterion to determine the minimum effective particle size that can be correctly measured is proposed.

Introduction

The particle number density is a property characterizing a spray, usually obtained by a phase Doppler anemometer (PDA). Nevertheless, its accurate determination is frequently a very difficult task as it depends, among others, on the correct determination of the measurement volume for each particle size. The dimension of the cross area of this measurement volume associated to each particle size depends, not only on the parameters of the emitter and the receiver system, photomultipliers voltage and laser power, but also on the size, scattering properties and motion direction of the particles. The dependence of the cross section on the size of the particles has been studied widely in the 1-D case ([1], [2]). Some researchers ([3], [4]) have studied the dependence of the cross section on the flow direction.

Another problem is the Gaussian intensity profile of the laser beams. This originates the trajectory error. As a rule of thumb, in order to minimize the trajectory error, it is recommended to configure the instrument for particles whose sizes are less than $1/3$ or ½ of the beam waist. However, several researchers ([5], [6], [7], [8]) have analyzed this effect, proposing some methods to its acknowledgement, elimination or minimization.

Phase Doppler anemometers generally require droplet number densities below 10^3 cm^{-3}, in the size range of 5-300 μm. The problem associated with dense spray measurements is threefold.

Firstly, PDA systems require to have only one droplet present in the measurement volume at any time. As the droplet number density increases, the probability of finding more than one particle in the measurement volume also increases. This can lead to errors in the validation of the particles detected. A detailed analysis of this problem can be found in [9].

Secondly, multiple scattering effects can become important. Particles crossing the illumination beams scatter light, which propagates forward. This radiation can eventually trigger the detector electronics, causing errors in the determination of the transit time of the particles. This problem is often seen as an increased background noise level.

Finally, the increase in the number density causes an increase in the optical length. This leads up to the attenuation on both the illumination beams and the scattered light signal. A possible bias in the diameter distribution towards the larger particles should be considered, if the smaller ones are not detected. These effects will be studied in the present paper.

As a first approach, the behaviour of the measurement volume diameter, used to evaluate the particle number density, is analyzed for a spray of low number density and low optical density, namely reference spray. Later, external shadow sprays will be used to additionally create a controlled optical length. Particularly, the effect that the optical losses have on the size of the cross section of the measurement volume and the number of detected particles during the acquisition time will be studied. Number densities calculated with the PDA have been validated using the extinction technique. This technique is also used to measure the optical lengths used in the shadow sprays.

Experimental set-up

The experimental set-up is shown in Fig. 1. Basically, it consists of an Ar-Ion multiline laser (Coherent Innova 310), a one-component conventional phase Doppler analyzer by Dantec (PDA), a system for the measurement of light extinction, and a coaxial air-blast injector supplied with compressed water and air.

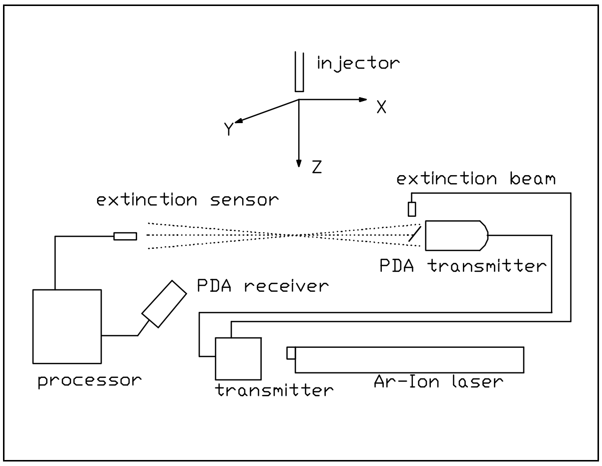

Figure 1.-Experimental set-up

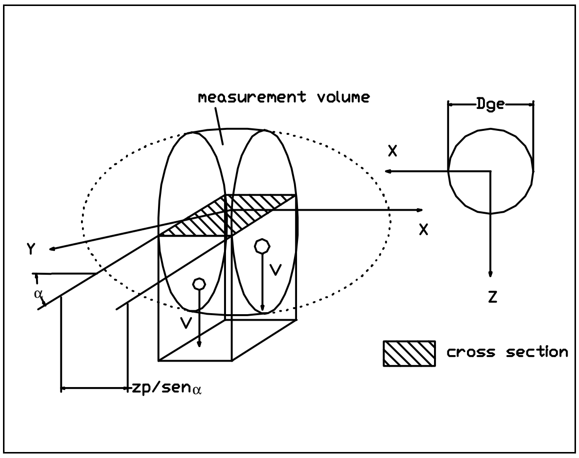

Figure 2. Measurement volume and cross section

Phase Doppler anemometer (PDA)

A multiline Coherent Innova Ar-Ion laser was used as the light source for the PDA. The green line *(514 nm)* was employed for one velocity component and size measurement. The transmitting optics has a focusing lens of *310mm* and a beam separation of *40 mm.* The resultant Gaussian control volume is an ellipsoid *1.5mm* long and *97 μm* in diameter. The receiving optics is placed at $\alpha=73^o$ from the optical axis. The pinhole placed in the image plane is a slit of *100μm* width. The signal processor is a three levels covariance detector as described in [10].

Extinction system

It measures the extinction of a collimated laser beam crossing the spray under study. The extinction beam corresponds to the blue light (488 nm) of the same laser that uses the PDA instrument (see Fig. 1). The extinction system consists of a photodiode located behind an assembly with an aperture, a microscope objective and a pinhole. The collection angle of the extinction system is 1.67 mrad. This figure remains constant in a distance from the surface aperture less than 0.6m. In this range, the apparent coefficient of extinction is larger than 1.9 for particles less than 50 μm.

Experimental techniques

Measurement of number density using the PDA

The measurement volume in a PDA is defined as the region of the space in which valid measurements can be obtained. The measurement volume is assumed to be a slit of a cylinder with a base, of diameter D_{ge}, located in a plane parallel to yOz (see Fig. 2). Its height is limited by the image of the slit of the receiver. The value of D_{ge} can be determined considering that it is twice the value of the distance, y_{max}, at which a particle could cross the measurement volume away from its centre for being detected. A particle of diameter D crossing the measurement volume will be detected only if it scatters light with an intensity exceeding the detector threshold I_{min}, that is:

$$I_{\min} = KD^2 I(y_{\max}) = KD^2 I_o \exp\left(-8\left(\frac{D_{ge}}{D_g}\right)^2\right) \qquad (1)$$

where K and I_o are constants. D_g is the e^{-2} beam waist intensity. Rearranging expression (1) and using the constant D_o^2, that include I_o, I_{min} and K, it can be written down that :

$$\left(\frac{D_{ge}}{D_g}\right)^2 = \ln\left(\frac{D}{D_0}\right) \qquad (2)$$

The expression (2) shows a logarithmic relationship between D_{ge} and the diameter D of the particle, that will be checked later. The influence of the detector appears in an implicit way in the constant D_o.

Several methods are used in the literature to determine D_{ge} ([11], [12], [13]). In the present paper, D_{ge} has been calculated by means of the transit length LT of each particle crossing the measurement volume (calculated as $LT=TT*v$, where TT is the transit time and v the instantaneous vector velocity, respectively), as proposed in [12].

The calculated D_{ge} is used to evaluate the cross section A_i for each particle size, as $A_i = D_{ge} z_p / \mathrm{sen}\alpha$, where z_p is the slit width. Then, the number density N_D can be calculated as:

$$N_D = \sum_i \frac{N_i}{A_i v_i T} \tag{3}$$

$A_i v_i T$ represents the volume containing all the particles N_i of diameter D_i, that have crossed A_i in the acquisition time T (see Fig. 2)

Extinction technique

In order to validate the number density calculated by the PDA instrument and to characterize the optical length of the shadow sprays (that will be used later), the measurement of the extinction of a collimated laser beam traversing the reference and shadow sprays have been performed. This technique is based on the Beer-Lambert law, which describes the extinction that suffers a collimated and monochromatic beam crossing a scattering and/or absorbing media. Let P_0 be the power transmitted through a transparent media. The power transmitted through a scattering media, P, accordingly will be:

$$P = P_0 \exp(-\tau) \tag{4}$$

where τ is the optical length of the scattering media. This may be calculated using the expressions:

$$\tau = \overline{Q}\frac{\pi}{4} N D_{20}^2 = \overline{Q}\frac{\pi}{4}\left(\frac{\sum_i n_{si} D_i^2}{\sum_i n_{si}}\right) \qquad \text{where:} \qquad n_{si} = \frac{\dfrac{N_i}{A_i |v_i|}}{\sum_j \dfrac{N_i}{A_i |v_i|}}$$

In the previous expressions the coefficient $\overline{Q}$ is the mean efficiency of extinction and $\pi/4\, N_D D_{20}^2$ is the equivalent cross section for the case of a polydisperse size distribution. Note that, in order to eliminate the bias towards the faster particles, the mean square diameter, D_{20}, has been calculated with the balancing factor, n_{si}, proposed by MacLaughlin [13]. In the range of validity of the geometrical optics approximation, $\overline{Q}$ =2, which is consistent with the extinction apparatus. The attenuation is defined as $A = 1 - P/P_0$, and the transmittance Tr, which is used later, as $Tr = P/P_0$.

Experimental results and discussion

Experiments have been performed in order to study the effects that an increase in the optical length have in the calculated local number density obtained by the PDA. To do this, additional matter is placed between the measurement volume and the emitter, and between the measurement volume and the receiver of the PDA. Changes in the calculated values of D_{ge} are examined.

Measurements for a reference spray have been made at 110 mm downstream of the injector. The results are presented in the following. Fig. 3 shows the distributions of mean diameter, axial velocity and number density, and Fig. 4 the transmittance, for this spray.

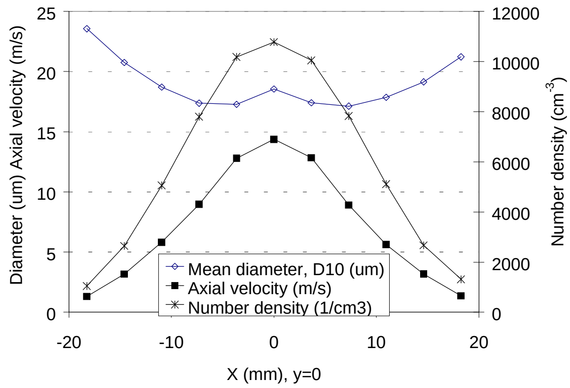

Figure 3. Distribution of mean diameter (μm), axial velocity (m/s) and number density (cm^{-3}) at 110 mm of the injector.

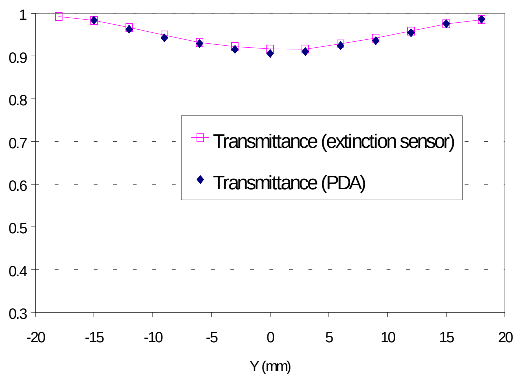

Figure 4.Transmittance measurement with the extinction system and calculated from PDA data at 110 mm of the injector .

The diameter histogram (see Fig. 5) shows that the higher size class with a representative number of particles is 50 μm, which eventually will may lead to trajectory errors. Nevertheless, trajectory effects will be neglected, since the scattering angle is the Brewster angle (minimizing the contributions of other orders of scattering) and the rate ϕ_{12}/ϕ_{13} is 2.5, which, according to Fandrey, minimize this error [14]. Fig. 6 shows the value of $(D_{ge}/D_g)^2$ for points located not further than 13 mm from the injector axis. The fact that $(D_{ge}/D_g)^2$ remains constant in all the positions of the spray lets take the assumption that, for calculating cross sectional area purposes, the reference spray can be considered one-dimensional, and not being affected by optical losses.

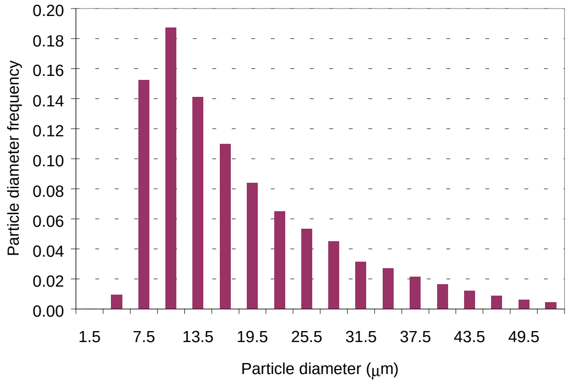

Figure 5. Particle diameter relative frequency histogram in (x,y)=(0, 0).

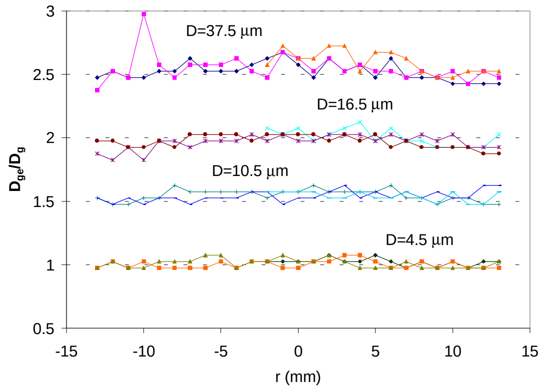

Figure 6 Distribution of $(D_{ge}/D_g)^2$ at 110 mm of the injection plane. Measurements points are located not further than 13 mm from the injector axis.

<u>Optical losses in illumination beams and transmitted beam</u>

Let a Gaussian beam be crossing a particulate media of optical length τ. Under the assumptions of simple scattering, the transmitted beam intensity I^* may be written as:

$$I^* = I_0 \exp(-\tau)\exp\left(-8\left(\frac{y}{D_{ge}}\right)^2\right) \tag{5}$$

Proceeding as in (2), but now considering that the intensity of the illumination beams is I^*, the relationship between D_{ge}^* and D_{ge} is:

$$\left(\frac{D_{ge}^*}{D_g}\right)^2 = \ln\left(\frac{D}{D_o}\right) - \frac{\tau}{2} \tag{6}$$

where D_{ge}^* is the value of D_{ge} for the case of optical losses in the illumination beams.

In order to check the validity of expression (6), which allows to investigate the effects of optical losses in the calculation of the number density, two different configurations have been studied. The experimental arrangements are shown in Fig. 7, where a shadow spray is used to generate optical losses in a controlled manner. The shadow spray was located in either of the positions A (transmission) or B (reception), but never in both of them. The locations of the measurement points, for each configuration are shown in Fig. 8.

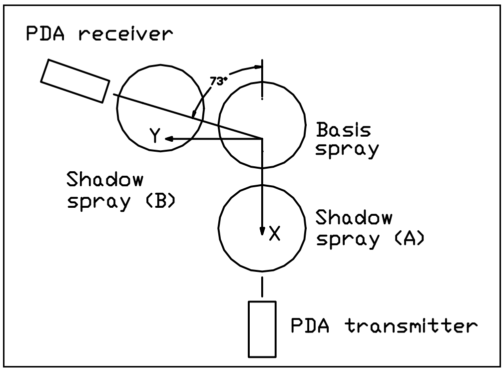

Figure 7. Experimental configurations.

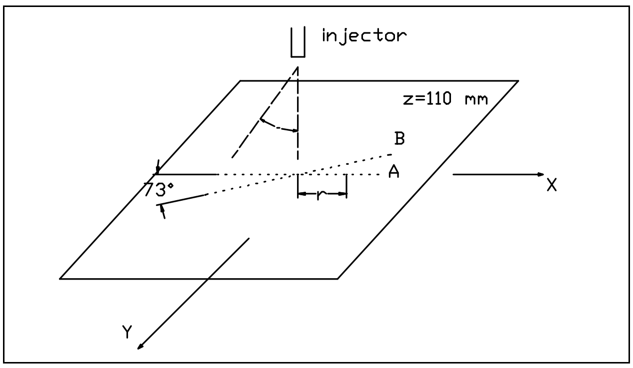

Figure 8. Location of the measurement points in both configurations, A and B.

The experimental results obtained for $(D^*_{ge}/D_g)^2$ are shown in Figs. 9 and 10. The continuous lines show the calculated $(D^*_{ge}/D_g)^2$ according to (6). There is a good agreement between the theoretical and the experimental results. Note that, in all the cases it exists a minimum particle size at which the theoretical logarithmic behaviour is lost. But when the optical losses increase, this minimum particle size also increase.

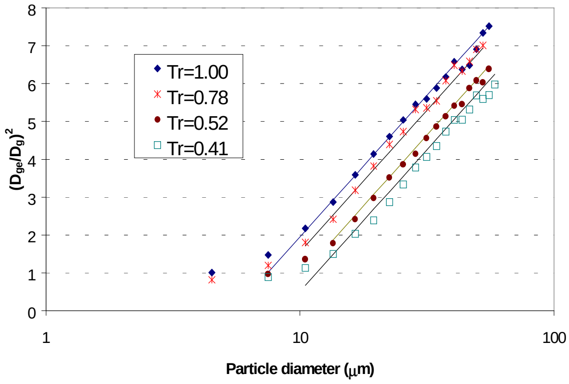

Figure 9. $(D^*_{ge}/D_g)^2$ for different optical losses in illumination beams.

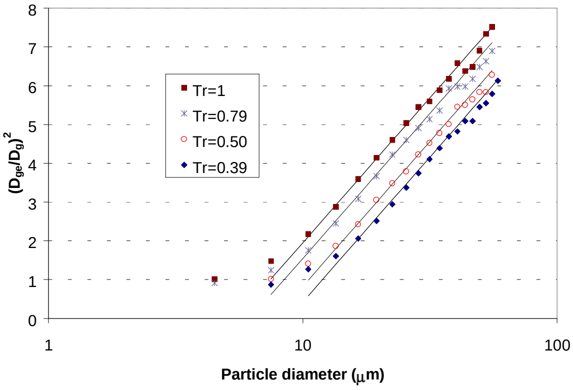

Figure 10. $(D^*_{ge}/D_g)^2$ for different optical losses in transmitted beams.

On the other hand, changes in the detected number of particles, as the optical losses increase, have also been detected. Figs. 11 and 12 show the particle diameter frequency for various sizes and optical losses. It is seen, for example, how particles of 10.5 μm in diameter and smaller ones tend to vanish at transmittances below 0.65.

The acquisition system used is based in intensity level. This means that only the particles that scatter light with a intensity above the detector threshold level will be detected. Therefore, particles smaller than a given minimum diameter D_{min} will not be detected. It is expected that the value of D_{min} will increase with the attenuation.

The experimental results of Figs. 11 and 12 show a different behaviour. It can be seen how to each transmittance level a minimum particle size D_{min} can be matched. Particles larger than D_{min} are always detected. However, particles with sizes smaller than D_{min} are also detected, although their number decrease progressively with the increase in attenuation. This behaviour has also been detected in a dense spray.

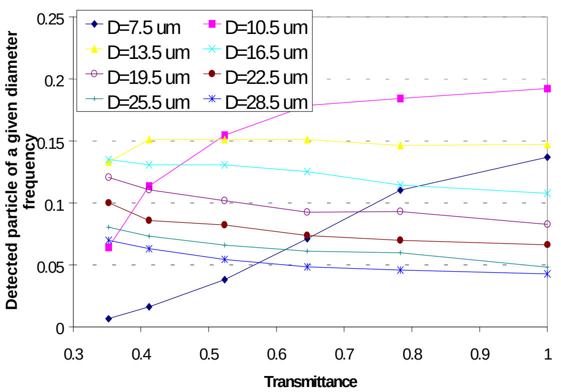

Figure 11. Particle diameter frequency for different optical losses in illumination beams.

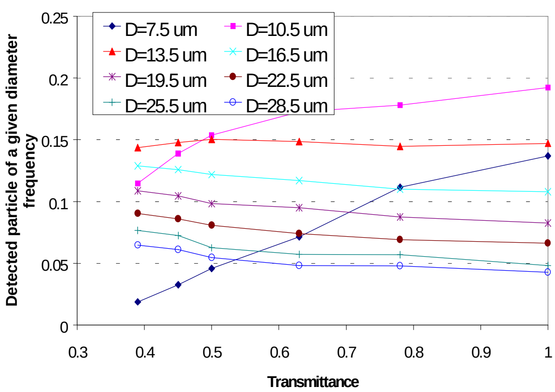

Figure 12. Particle diameter frequency for different optical losses in transmitted beams.

In order to study the possible relationship between the detection faults and the anomalous behaviour of $(D^*_{ge}/D_g)^2$, the inter-arrival times between particles have been studied. For the case of an ideal spray [9], the probability of finding n particles in a time period is a Poisson process:

$$P_t(n) = \frac{1}{n!}\left[\int_0^T \lambda(\bar{x},t)dt\right]^n \exp\left(\left[\int_0^T \lambda(\bar{x},t)dt\right]\right)$$

And for a stationary spray:

$$P_t(n) = \frac{1}{n!}\lambda(\bar{x})\exp(-\lambda(\bar{x})t)$$

where the intensity λ is the expected number of particles that arrive at the measurement volume. Fig. 13 shows the inter-arrival time histograms for the case of non-optical losses and important optical losses, either in transmission and in reception. The Poisson behaviour can be observed in all of them. Fig. 14 shows the inter-arrival time histograms for particles of diameter equal to 10.5 µm, for the same cases as in Fig. 15. This particle size presents an important percentage of non-detected particles (see Figs. 11 and 12). However, the Poisson behaviour still remains, but with a lower intensity (see Fig. 14).

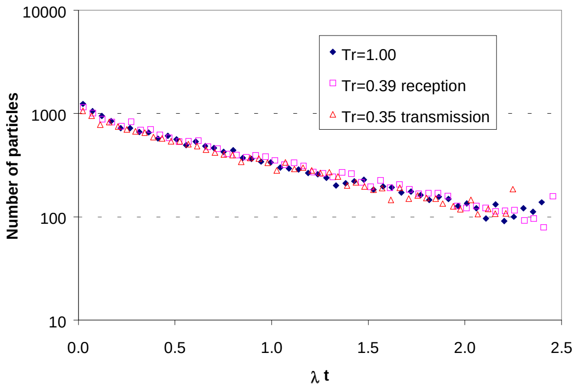

Figure 13. Inter-arrival time histograms for two extremely cases of optical losses and all the sizes.

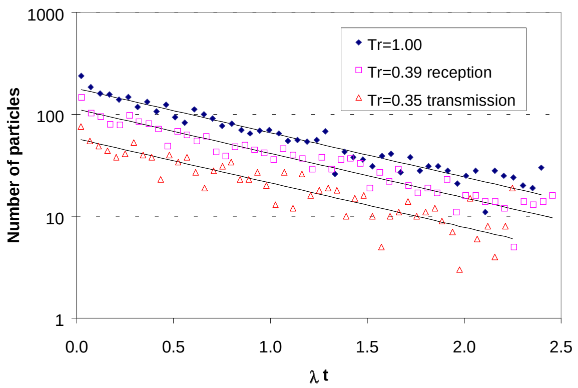

Figure 14. Inter-arrival time histograms for two extremely cases of optical losses (10.5 µm particle size).

There is then a progressive loss of small particles, even though the detection system is triggered by intensity level. The detection of the small particles, in high attenuation conditions, may be attributed then to the optical noise, and the results obtained from these acquired particles should be considered with care. As it has been observed in Fig. 9 and Fig. 10, the values of D_{ge} are overpredicted for the smaller particles, which according to (3) will give an underestimation of the calculated number particle concentration.

Therefore, it has been shown that the optical loses (in the transmission and the reception path) may squeeze the size range of particles that can be correctly measured and the corresponding number density associated with these small diameters.

The minimum measurable diameter can be determined observing the tendency of $(D^*_{ge}/D_g)^2$: it will correspond to the diameter beyond which the logarithmic behaviour disappears.

Conclusions

The effects of the optical losses on the size of the cross section of the measurement volume of a phase Doppler anemometer have been studied. These losses have an effect on the size range that the instrument can measure, as the small particles are not properly counted. Moreover, the calculated values from these small particles may be erroneous. The new minimum particle size that the instrument can detect accurately can be determined by inspection of the calculated diameter of the measurement volume for each particle size.

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