THE EFFECT OF MEASUREMENT VOLUME SIZE ON PHASE DOPPLER ANEMOMETER MEASUREMENTS OF GLASS MICROSPHERES[†]

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ABSTRACT

Phase Doppler Anemometry (PDA) is a widely used measurement technique capable of non-intrusively measuring a droplet diameter and up to three components of its velocity, simultaneously. PDA systems are frequently used to characterize spray nozzles and suppressant transport phenomena, which may be further used in model validation. It has been shown that the optical configuration can have a considerable effect on PDA diameter measurements. The current paper is part of an ongoing effort toward the development of a procedure to properly configure a PDA system for the best drop size measurement accuracy and reports on backscatter diameter measurements of glass microspheres using four separate measurement volume sizes. The presented data covers approximate particle to measurement volume diameter ratios from 1/25 to 1/3 which will be useful in providing guidance for the minimum ratio required to acquire backscatter diameter measurements free of errors due to measurement volume effects.

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INTRODUCTION

Phase Doppler Anemometry (PDA) is a widely used measurement technique capable of non-intrusively measuring a droplet diameter and up to three components of its velocity, simultaneously. Since the PDA technique is heavily based of light scattering theories, earlier PDA diameter measurements were reported without any indication of the measurement uncertainty. Due to the recent demand for error analysis reporting, researchers began investigating several effects that could cause a bias in PDA diameter measurements.

The current paper is part of an ongoing effort focused on the effect on PDA measurements due to varying optical parameters. Three previous works by Davis and Disimile[1-3] have reported on the effects of optical configuration on PDA diameter measurements. The first two works[1-2] showed up to a 70% difference in the arithmetic mean diameters (66% in Sauter mean diameters) between the various optical configurations evaluated and proposed an experimental selection method for choosing an optimum optical configuration. Since the proposed selection method was based off of air/water spray measurements of an unknown size, a third paper[3] was presented supporting the optical configuration selection method with measurements of glass microspheres of a known size range. However, these earlier results also showed that investigation into the effect of the ratio of particle diameter to the measurement volume diameter for back-scatter measurements was needed to further support the proposed selection method.

The ratio of the particle diameter to the measurement volume diameter is an important parameter due to the trajectory ambiguity effect (TAE), or measurement volume effect (MVE). This effect is due to the Gaussian intensity distribution of the intersecting laser beams in the measurement volume and has been investigated by a number of researchers.[4-6] Naqwi and Menon[7] presented a three step procedure for determining the important parameters of a PDA system, but these were never tested experimentally and require apriori knowledge of the diameter range to be measured.

A recently published text[8] on phase Doppler measurement techniques gives insight into the maximum allowable particle-to-measurement volume diameter ratio required to avoid MVE. In this text the authors propose a 1/3 or 1/5 ratio (particle/measurement volume) as a general rule-of-thumb in order to avoid MVE, however, stated that the required ratio is specific to the experimental conditions. In addition, Araneo et al.[9] experimentally investigated the MVE in detail and found that a 1/3 ratio was sufficient for a forward-scatter measurement configuration. As part of a PDA system commissioning test, Mulpuru et al.[10] presented PDA measurements of glass microspheres of known sizes. Although they showed excellent agreement between the measured diameters and the known microsphere sizes, their experimental data was all measured in a forward-scatter mode, and not the back-scattering mode.

The back-scattering mode is commonly used when attempting measurements in facilities with limited optical access and is distinctly different than the forward-scatter mode. Back-scatter measurements are acquired using light from the second-order refraction scattering mode. Light scattered from this mode is typically lower in intensity than forward-scattered light (reflection or refraction modes). The lowered intensity can increase the difficultly in separating second-order refraction signals from light scattered in another mode (i.e. reflection), thereby increasing the sensitivity to MVE. Therefore the need exists for data measured in the back-scatter mode with several particle-to-measurement volume diameter ratios. This data will be used to determine the ratio needed to avoid MVE for back-scatter measurements.

The current work reports on PDA diameter measurements of glass microspheres using four measurement volume diameters. Using two separate sizes of glass microspheres with each of the four measurement volume diameters, particle to measurement volume diameter ratios of approximately 1/30 to 1/3 were examined.

PHASE 2 EXPERIMENTAL STRATEGY

To allow a direct comparison of data, the general PDA setup and strategy used previously[3], was repeated for this study. With the current study focusing on the measurement volume size effects on the diameter measurements, two additional measurement volume sizes were investigated with the recent acquisition of a new 2500 focal length lens and beam expander.

A standard three-dimensional Phase Doppler Anemometry system was used to measure the diameter distribution of two separate sizes of solid glass microspheres suspended in distilled water. The glass microspheres were of a known size band classified by sieve fractions provided by the manufacturer. The upper and lower limits of the glass microsphere sieve fractions used are 25-32 µm and 45-53 µm. These size ranges will be discussed in further detail in the results section. The microspheres were constantly mixed to maintain suspension in distilled water in a rectangular glass walled test cell. The test cell can be seen in Figure 1 along with the transmitting and receiving optics.

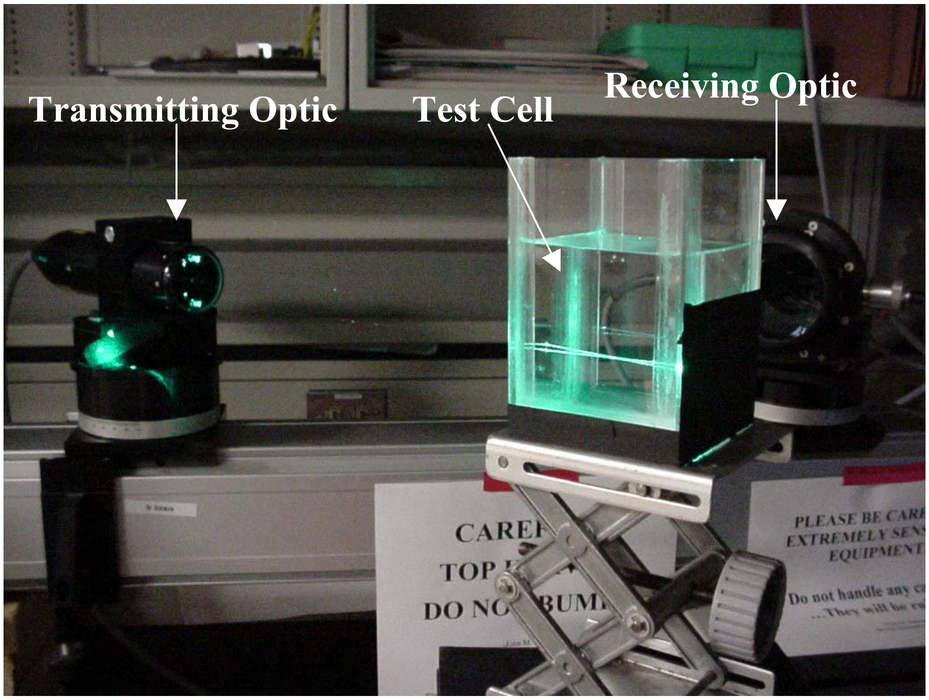

Figure 1. PDA Setup.

A 98 degree off-axis scattering angle was chosen between the transmitting and receiving optics. This angle was chosen as optimal for second-order refracted light by examination of light scattering charts for glass in water. For each measurement, 20,000 samples were acquired and diameter statistics computed. Diameter measurements were acquired for the two microsphere sizes, using four optical configurations, providing four separate measurement volume diameters.

The four optical configurations utilized during experimentation can be seen in Table 1. The measurement volume diameter is a function of the focal length of the transmitting optic, the wavelength of the transmitted beams, and the transmitted beam diameter directly after expansion. For all optical configurations, a wavelength of 514.5 nm was maintained for the transmitting beams. Therefore, the measurement volume was only varied by changing the focal length of the transmitting lens and the transmitted beam diameter. The transmitted beam diameter was varied through the use of different beam expanders. Three transmitting lenses were used with four beam expansion ratios to yield measurement volume diameters of 196, 260, 408, and 809 μm.

Table 1. Optical Configurations.

Transmitting Lens	Receiving Lens	Beam Expansion Ratio	Measurement Volume Diameter (μm)
402.5 mm	310 mm	1.00	196
1000 mm	1000 mm	1.98	260
2500 mm	310 mm	2.97	408
2500 mm	310 mm	1.50	809

Aperture masks change the diameter dynamic range of the PDA system by effectively changing the spacing between the receiving fibers in the receiving optic. Since these masks are installed in the receiving optic they only affect the received signal and therefore do not change the measurement volume diameter. However, since the aperture mask can affect the diameter measurements, each of three available masks (namely Mask A, B, and C) were utilized with the four optical configurations described above. All three masks are shown in Figure 2. Mask A had the largest aperture thus providing a smaller depth of field while Mask C has the smallest aperture, which provided a larger depth of field. Mask B's aperture fell between that of Masks A and C.

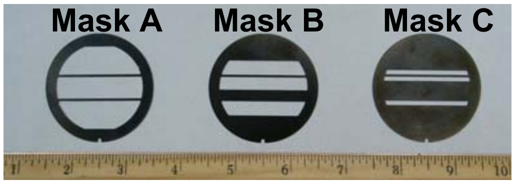

Figure 2. Aperture Masks.

The test matrix for the present study is shown in Table 2. The test number (first column) indicates the test order. The configuration number (shown in column 2 of Table 2) is an arbitrary label given to each unique optical configuration tested. Using three aperture masks with four lens combinations, 12 optical configurations could be tested. Configuration 12, corresponding to mask C with the optic configuration yielding the 809 μm measurement volume diameter, was omitted from testing. The reasoning for the omission of configuration 12 is explained below in the results section. Columns 3 - 6 of Table 2 show the optical parameters for each of the 11 optical configurations utilized.

Table 2. Test Matrix.

Test No.	Conf. No.	Transmitting Lens (mm)	Receiving Lens (mm)	Beam Expansion Ratio	Aperture Mask	M.V. Diam. (μm)	Microsphere Size (μm)	Particle to M.V. Diam. Ratio
1	1	402.5	310	1.00	A	196	25 - 32	0.145
2	2	402.5	310	1.00	B	196	25 - 32	0.145
3	3	402.5	310	1.00	C	196	25 - 32	0.145
4	1	402.5	310	1.00	A	196	45 - 53	0.250
5	2	402.5	310	1.00	B	196	45 - 53	0.250
6	3	402.5	310	1.00	C	196	45 - 53	0.250
7	4	1000	1000	1.98	A	260	25 - 32	0.110
8	5	1000	1000	1.98	B	260	25 - 32	0.110
9	6	1000	1000	1.98	C	260	25 - 32	0.110
10	4	1000	1000	1.98	A	260	45 - 53	0.188
11	5	1000	1000	1.98	B	260	45 - 53	0.188
12	6	1000	1000	1.98	C	260	45 - 53	0.188
13	7	2500	310	2.97	A	408	25 - 32	0.070
14	8	2500	310	2.97	B	408	25 - 32	0.070
15	9	2500	310	2.97	C	408	25 - 32	0.070
16	7	2500	310	2.97	A	408	45 - 53	0.120
17	8	2500	310	2.97	B	408	45 - 53	0.120
18	9	2500	310	2.97	C	408	45 - 53	0.120
19	10	2500	310	1.50	A	809	25 - 32	0.035
20	11	2500	310	1.50	B	809	25 - 32	0.035
21	10	2500	310	1.50	A	809	45 - 53	0.061
22	11	2500	310	1.50	B	809	45 - 53	0.061

The measurement volume diameter, microsphere size, and particle to measurement volume diameter ratio are shown in columns 7, 8, and 9 of Table 2, respectively. The particle to measurement volume ratio shown is approximate and was calculated by dividing the mean value of the microsphere size range by the measurement volume diameter.

RESULTS

The measurements of the two microsphere sizes using the 11 optical configurations shown above are presented herein. Configuration 12 was omitted, as stated earlier, due to the fact that aperture mask C cuts a large amount of light in the received signal. In addition, the overall light intensity in the measurement volume is decreased as the measurement volume size is increased. If the measurement volume is not sufficiently powered, diameter measurements could be biased toward larger particles (larger particles reflect and refract more light than smaller particles). Combining the decreased light intensity in the measurement volume for configuration 12 with the decrease in the received signal using mask C, configuration 12 required the use of a higher powered laser to sufficiently illuminate the measurement volume. Attempted tests using configuration 12 confirmed that with the maximum available laser power was not sufficient and thus the measurements were biased towards the upper range of the sieve fraction. A higher powered laser was not available for this investigation thus configuration 12 was omitted.

It should also be noted that based on the sieving procedure used to separate the microspheres, an error band of ±15% of the sieve fraction was specified by the manufacturer. Therefore, the arithmetic mean diameter (D10) of the measurements should fall within the 21.25 - 36.80 µm range for the smaller microspheres and 38.25 - 60.95 µm for the larger microspheres.

25 µm to 32 µm Microsphere Measurements

The measured arithmetic mean diameter (D10) for the 25-32 µm microspheres using the 11 optical configurations (described in Table 2) are plotted in Figure 3. From the microsphere manufacturer's suggestion, the arithmetic mean diameter measurements of the 25-32 µm microspheres are expected to fall in the 21.25 - 36.80 µm range. The limits of this range are shown in Figure 3 as red dashed lines. The red solid lines in Figure 3 represent the upper and lower sieve fraction limits, however, these are shown for comparison purposes only as any diameter measured between the dashed red lines must be deemed acceptable. Repeated measurements for configurations 1, 2, 4, and 7 are also shown in Figure 3. The repeated measurements provide insight into the measurement repeatability.

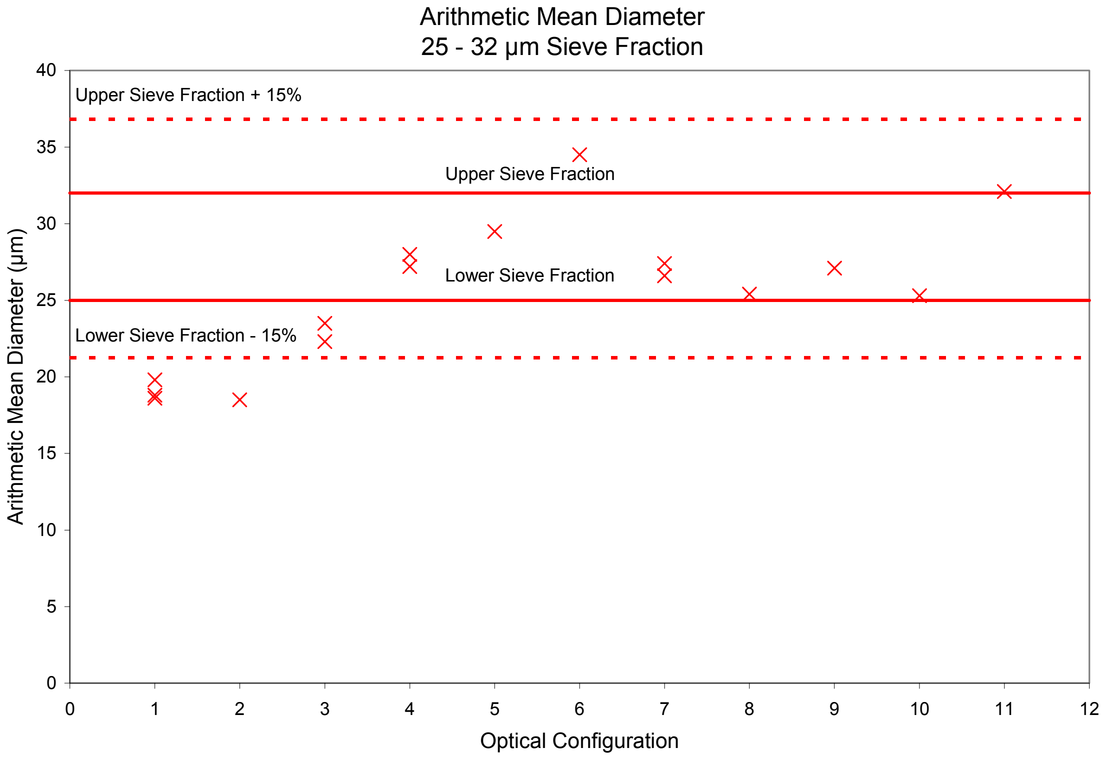

Figure 3. 25 µm to 32 µm Microsphere D10 Measurements, All Configurations.

It can be seen that the measurements for all configurations except 1 and 2 fall within the expected limits (red dashed lines). Therefore, configurations 3 - 11 can be said to be acceptable configurations for the given measurement condition, based solely on the data shown in Figure 3.

Recall that configurations 1, 2, and 3 all have the smallest measurement volume diameter. It could be initially thought that since the data measured with configuration 3 is within the acceptance band and configurations 1 and 2 share the same measurement volume size as configuration 3, the measurement volume size is not the main parameter causing the discrepancy in the D10 measurements. However, mask C cuts the most light of the three receiving aperture masks. Since larger particles scatter more light than smaller particles it is possible that the data acquired using configuration 3 is biased towards the larger particles thus giving the impression that configuration 3 is an acceptable configuration. Inspection of the diameter distributions (not shown) provides evidence of a bias toward the larger particles for configuration 3. Thus the change in the measurement volume size could still be a main factor in the difference between the diameters measured with configurations 1 and 2 and those measured with configurations 4-11.

The effect of the measurement volume diameter on the diameter measurements is better illustrated by plotting the measured D10 diameters against the measurement volume diameter for each aperture mask separately. This is shown in Figure 4 and Figure 5 for masks A and B, respectively. The particle to measurement volume ratio plotted on the abscissa was calculated by dividing the median value of the given sieve fraction by the measurement volume diameter. This is an approximate value since the actual microsphere sizes can fall anywhere in the provided range. Due to the biasing effect with mask C (described above), only the data for configurations using masks A and B will be examined.

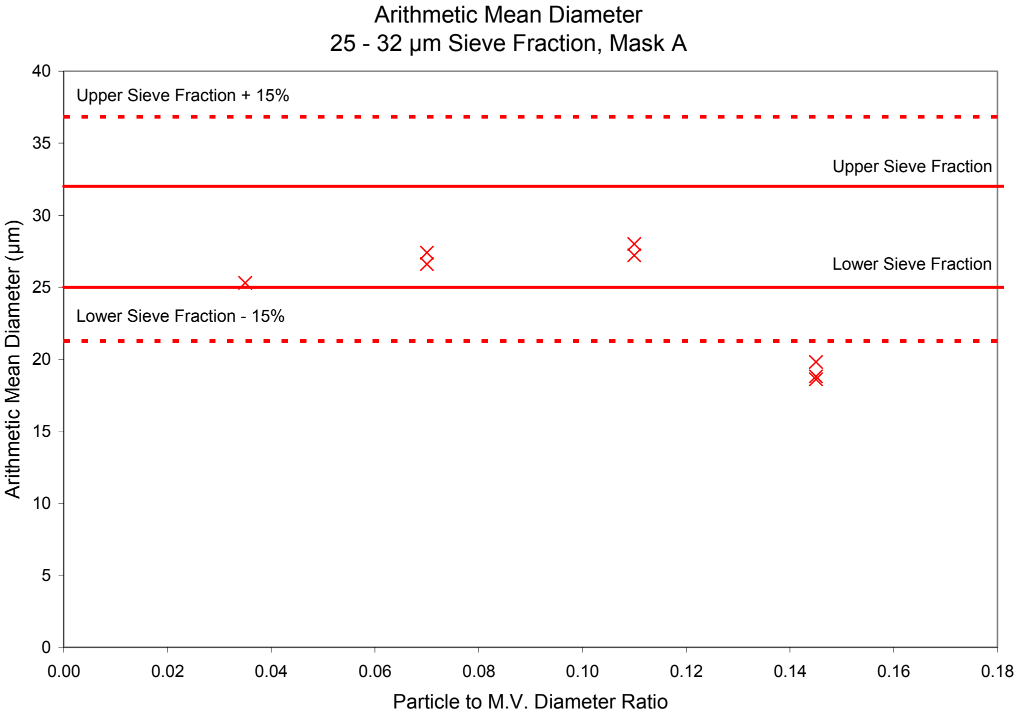

Figure 4. 25 μm to 32 μm Microsphere D10 Measurements, Mask A.

Examination of Figure 4 shows that the data measured with a particle to measurement volume diameter ratio of 0.145 (approximately a 1:7 ratio) was not within the acceptable limits for the 25-32 µm microspheres. The diameters measured for the three configurations at or below a ratio of 0.110 all fall within expected limits. This suggests that the measurement volume size is affecting the data. Although it cannot be confirmed at this time, it seems a maximum particle to measurement volume diameter for minimal error exists between 0.110 and 0.135 for the given measurement condition. The data for mask B (see Figure 5) shows a similar trend which further suggests that a maximum ratio likely exists in the range of 0.110 to 0.135.

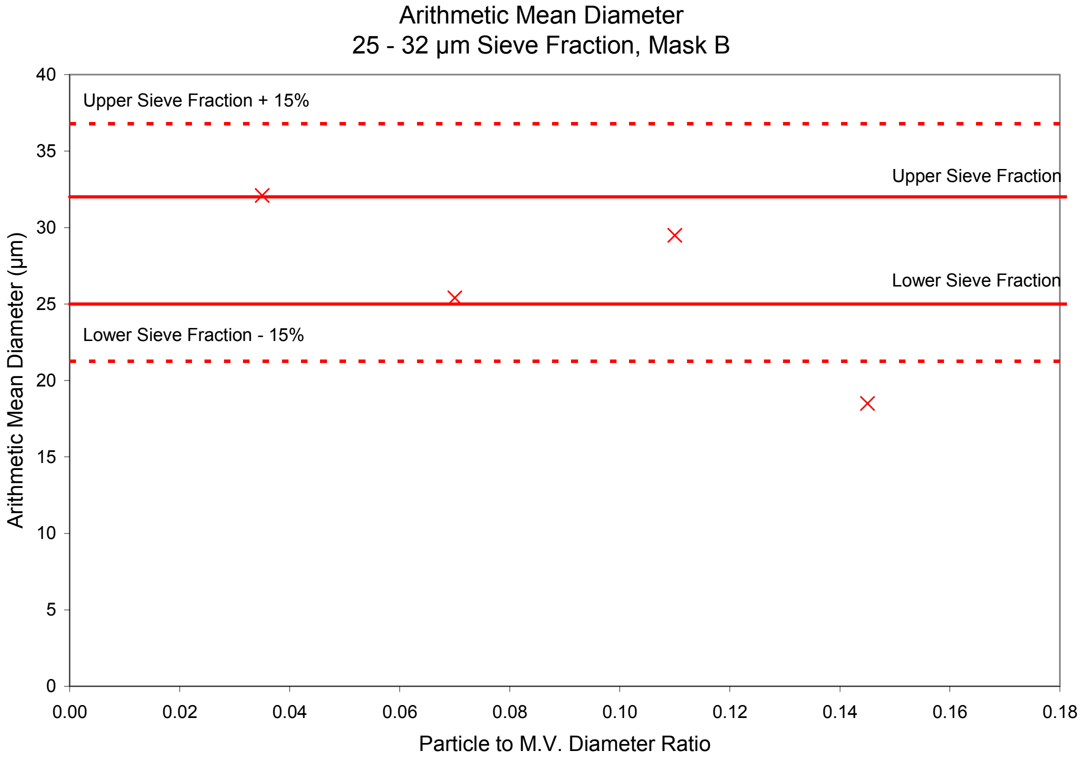

Figure 5. 25 - 32 µm Microsphere D10 Measurements, Masks B.

45 µm to 53 µm Microsphere Measurements

Figure 6 is similar to Figure 3 except plotted for the 45-53 µm microsphere measurements. It can be seen that all configurations except configurations 1, 3, and 4 are measuring diameters within the expected range. However, the measurement repeatability shown in configurations 7 and 10 indicates the measurements close to the lower expected limit (dashed blue line) cannot accurately be concluded to be either acceptable or unacceptable. However, Figure 6 clearly shows that the diameter measurements are affected by the optical configuration utilized.

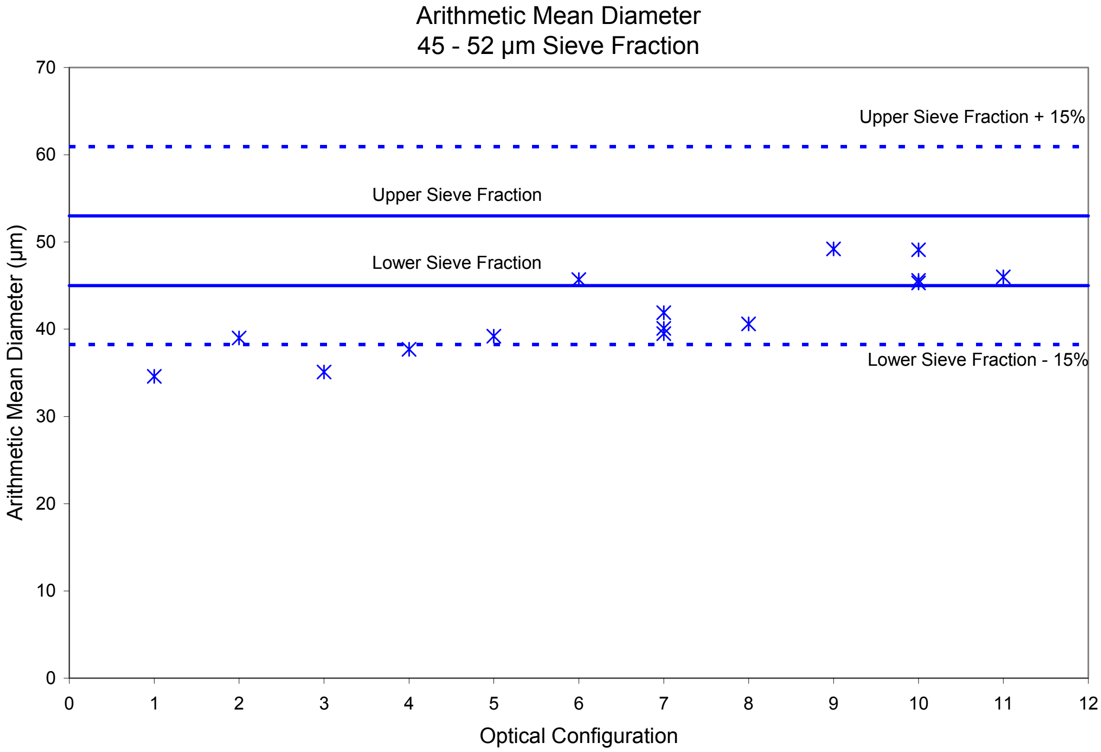

Figure 6. 45 µm to 53 µm Microsphere D10 Measurements, All Configurations.

A better indication of the affect of the measurement volume diameter on the diameter measurements is shown by again plotting the measured diameters against the ratio of the particle to measurement volume diameter for each mask separately (see Figure 7 and Figure 8). The data in Figure 7 suggest a maximum particle to measurement volume diameter ratio for minimal error might exist between approximately 0.120 and 0.180. However, the data in Figure 8 does not support this assumption with all the measurements falling within the expected range. Again, due to repeatability, the points close to the lower limit of the expected range cannot be determined to be acceptable or unacceptable. Thus, although it appears that a maximum ratio needed to minimize error possibly exists in the range of 0.120 - 0.180, this cannot be concluded due to the wide acceptance band in which the measurements could fall.

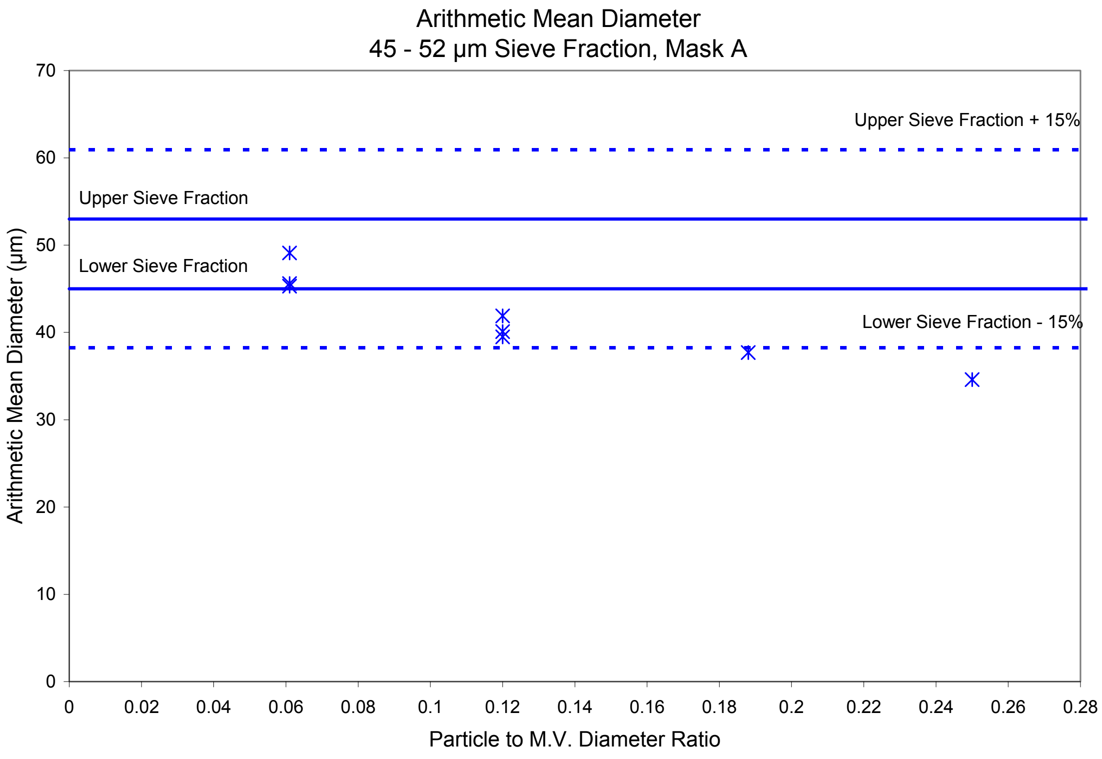

Figure 7. 45 µm to.53 µm Microsphere D10 Measurements, Mask A

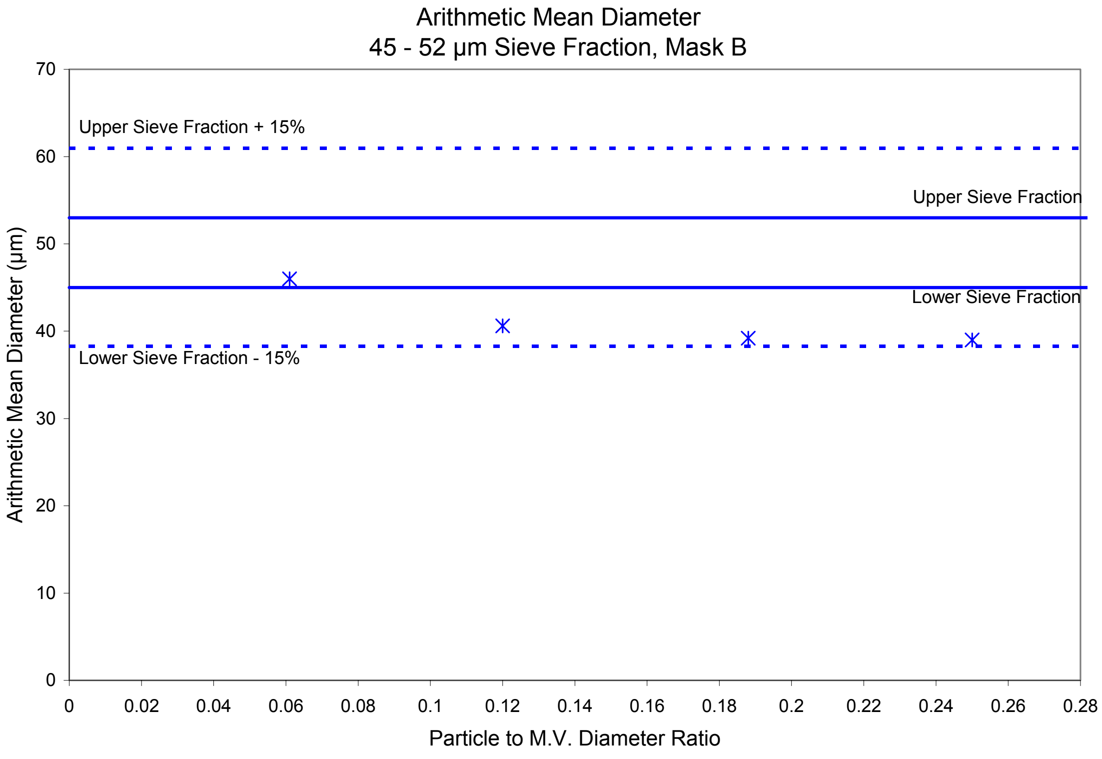

Figure 8. 45 µm to 53 µm Microsphere D10 Measurements, Mask B.

Combined Particle to Measurement Volume Diameter

Since the above data indicated that a maximum ratio between the particle and measurement volume diameter needed to minimize diameter measurement error might exist, additional data was acquired using microspheres of a 75-90 µm sieve fraction. These measurements were combined with the two sets of measurements described above. Individual plots of the 75-90 µm microsphere measurements did not provide any further insight and thus are not presented.

The combination of the 75-90 µm microsphere measurements with the 25-32 µm and 45-53 µm measurements is shown plotted against the particle to measurement volume diameter ratio in Figure 9 for configurations using mask A only. To allow a direct comparison of the data from different size microspheres, the arithmetic mean diameters were normalized by the median value of the sieve fraction range. Thus a normalized arithmetic mean of 1 represents a D10 diameter measured at the median value of the sieve fraction range.

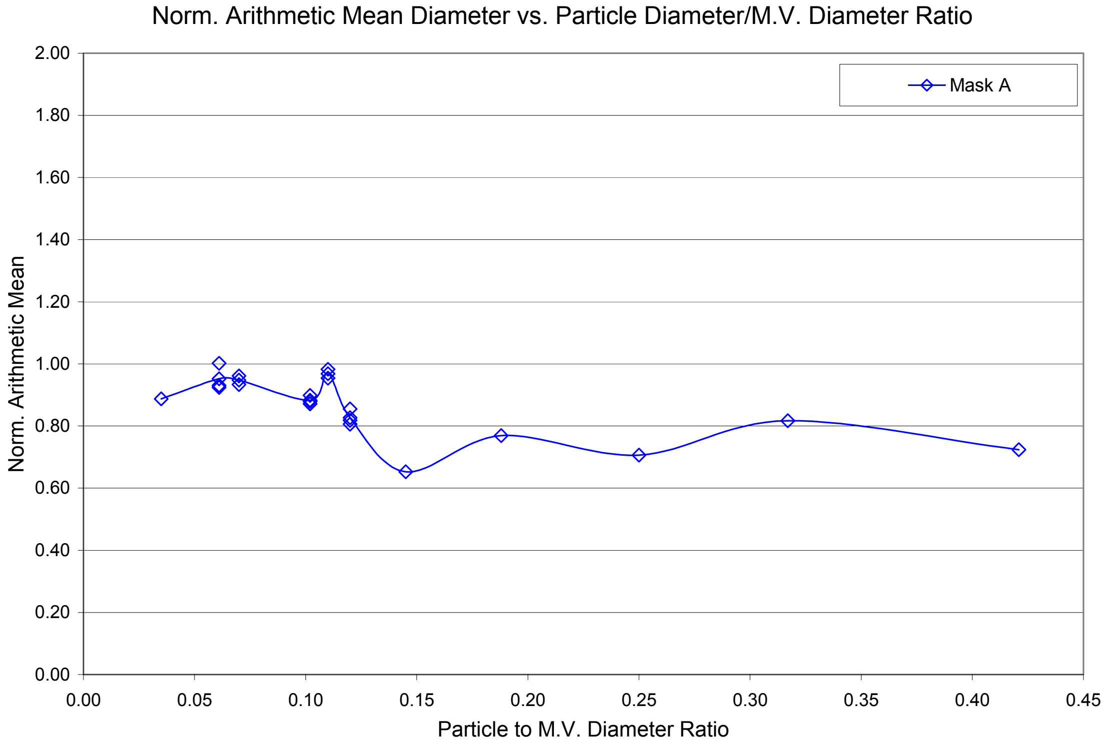

Figure 9. Normalized D10 Measurements, Mask A.

Assuming that the D10 diameter should ideally be close to the median value of the sieve fraction (normalized values close to 1) the data in Figure 9 suggests that a maximum ratio needed to minimize error occurs around 0.11. Data measured with a configuration providing a ratio lower than 0.11 appears to level off close to a normalized mean diameter value of 1. Above the 0.11 ratio the data appears to level off to a normalized value of closer to 0.80. A similar plot showing the data for masks B and C is shown in Figure 10. Again it appears that a maximum ratio for minimized error possibly occurs around 0.11. This corresponds to an approximate ratio of 1:9 between the particle size and the measurement volume diameter.

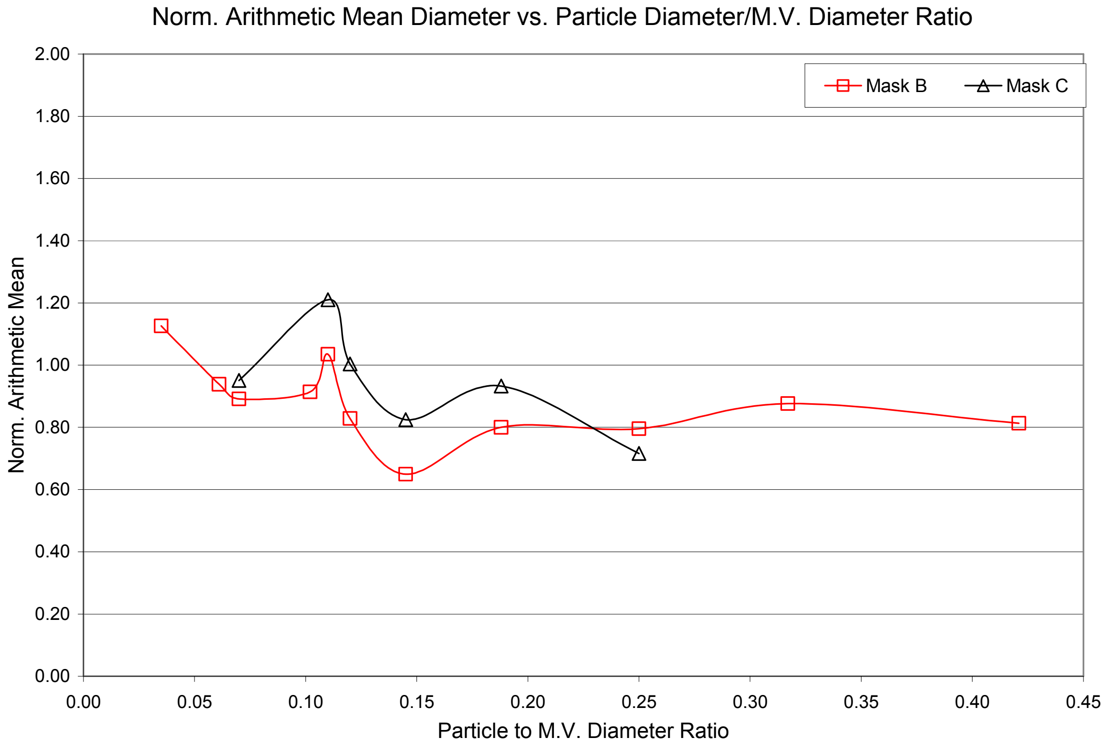

Figure 10. Normalized D10 Measurements, Mask B and C.

Figure 9 and Figure 10 are the result of a preliminary method pf representing the data. Since the D10 diameters could fall in a relatively large range, it cannot be confirmed that the measurement volume should be 9 times greater in size that the expected measured particle size to minimize error in the diameter measurements (as suggested above by a 1:9 ratio). However, the data is showing signs that a ratio between the particle diameter and measurement volume diameter possibly exists to allow diameter measurements with minimal error.

SUMMARY

It was shown that that the chosen measurement volume diameter, more importantly the ratio between the particle and measurement volume diameter, affects the arithmetic mean diameter measurements. Previous literature suggested that a maximum ratio of 1/3 to 1/5 be kept for forward-scatter scenarios to minimize error in the diameter measurements due to MVE. The data presented herein is suggesting that a maximum ratio also exists in a back-scatter arrangement. This ratio for back-scatter configurations appears to occur at approximately 1/9, which would require that the measurement volume diameter be maintained at a size 9 times greater than the expected maximum particle size to be measured. However, with the broad range in which the diameter measurements were deemed acceptable, further investigation using microspheres with a tighter range is needed to confirm the suggestion of a 1/9 ratio for back-scatter measurements.

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