J Aerosol Sci, Vol 17, No 1, pp 67–72, 1986
Printed in Great Britain

0021-8502/86 $3 00 +0 00
© 1986 Pergamon Press Ltd

PERFORMANCE OF PMS MODEL LAS-X OPTICAL PARTICLE COUNTER

W. C. HINDS and G. KRASKE

Division of Environmental and Occupational Health Sciences, UCLA School of Public Health, Los Angeles, CA 90024, U S A

(*Received* 4 *April* 1985)

Abstract—Performance characteristics of a Particle Measuring System (PMS) Model LAS-X (0.12–7 5 μm) optical particle counter were evaluated. The effect of particle refractive index was determined theoretically by calculating response curves for 32 refractive indexes Nonabsorbing organic particles with unknown refractive index have measurement errors that range from −50 to +20% Unknown particles (including absorbing particles) may have measurement errors from −60 to +250% An aerodynamic calibration of range 3 (0.12–7 5 μm) with oleic acid particles found the indicated sizes to be within ±2 channel widths of the correct aerodynamic diameters Measurements of the effect of coincidence on measured size found errors in CMD to be less than 10% for concentrations below 10,000 cm^{-3}. Experimental measurements of inlet losses showed a dependence on particle size and sample flow rate with about 50% loss of 12 μm particles at a sampling rate of 5 cm^3 s^{-1}

INTRODUCTION

This paper describes our evaluation of the PMS optical particle counter model LAS-X in three areas: the effect of particle refractive index and coincidence error on measured size, and inlet losses as a function of particle size.

The performance of PMS (Particle Measuring Systems, Inc., Boulder, CO) optical particle counters have been characterized by several investigators. Pinnick and Auvermann (1979) calculated theoretical response curves for the PMS Models CSASP, ASASP, FSSP, ASSP. They verified the response curves for Model CSASP and ASASP by experimental measurement and found the instrument's response to be sensitive to refractive index and multivalued for particles having diameters between 1 and 8 μm. Pinnick *et al.* (1981) conducted a calibration of the PMS model FSSP optical particle counter for water droplets. Garvey and Pinnick (1983) evaluated the performance of PMS model ASASP-X and gave response curves which were confirmed by experimental measurements. They concluded that the manufacturer's calibration is appropriate for nonabsorbing particles having refractive indexes between 1.5 and 1.6. They compared theoretical response curves with experimental measurements (using a single fitting constant) for particles of polystyrene, polyvinyltoluene and styrene vinyltoluene latex over the size range of 0.1–2.7 μm diameter and nigrosin dye over the range 0.18–5.0 μm diameter. They found that the instrument undersized water droplets by about 30% and undersized carbonaceous particles even more.

Chen *et al.* (1984) reported on an experimental evaluation of the Royco model 236, an instrument with optics similar to the LAS-X, using monodisperse oleic acid, di(2-ethylhexyl) phthalate (DOP) and polystyrene latex particles having sizes from 0.2 to 10 μm diameter. They found a variation in response with refractive index and a fluctuating response in the 1 5–5 0 μm diameter range

The model LAS-X and the model ASASP-X have the same optics and both come in two versions. One version has four overlapping size ranges, each with 15 equal interval channels, covering the range from 0.09 to 3.0 μm. The other has three ranges (range numbers 0, 1 and 2) which together cover the size range from 0.12 to 7.5 μm and a fourth range (range number 3) that covers the entire range, from 0.12 to 7.5 μm with unequal width channels. Each range has a 16th channel that gives a count of oversize particles, particles larger than the upper limit of channel 15, the largest channel in the range. Both versions use He–Ne laser illumination and, as shown in Fig. 1, collect light over scattering angles of 35–120° by means of a bowl-shaped parabolic mirror arranged so that a focused stream of particles passes through its focal point and the full 360° range of polarization is collected. This illuminated region is within the laser

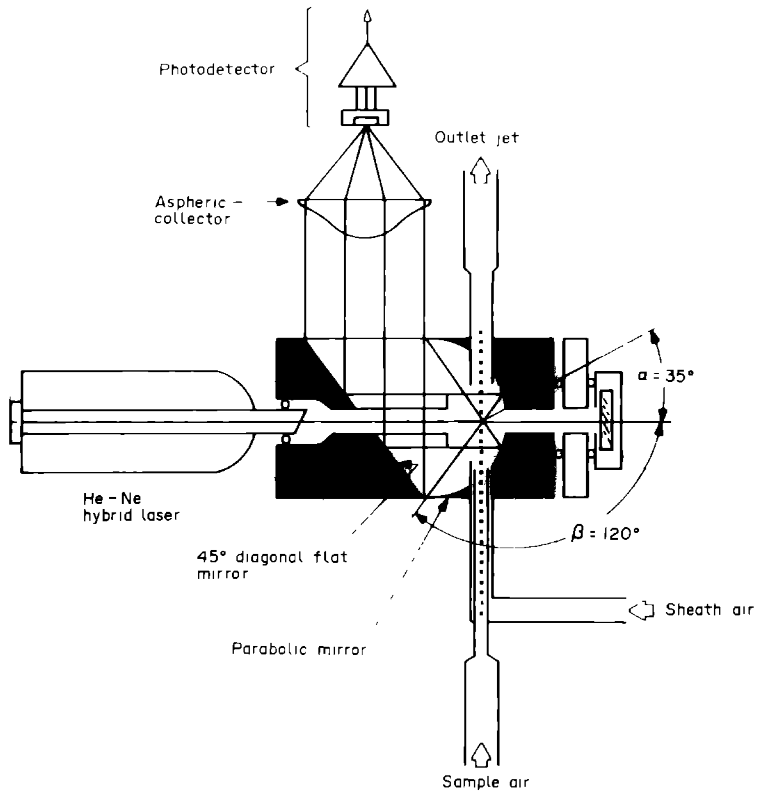

Fig 1 Schematic diagram of PMS model LAS-X Optical Particle Counter

cavity so illumination is equal in the forward and backward directions. Earlier work by Garvey and Pinnick (1983) evaluated the response characteristics of the 0.09–3.0 μm version, we present here our evaluation of the 0.12–7.5 μm version

EFFECT OF REFRACTIVE INDEX

The effect of refractive index on indicated particle size was evaluated theoretically by calculating the relative signal produced by 170 particle sizes over the size range of 0.05–37.8 μm diameter for each of 32 refractive indexes The refractive indexes used are shown in Table 1. Signals were calculated using the light scattering calculation subroutine DBMIE, written by Dave (1968). Relative output signals were determined by combining the scattering amplitudes produced by forward and backward illumination for both polarizations and integrating over all scattering angles As pointed out by Garvey and Pinnick (1983) it is the scattering amplitudes rather than the scattering intensities that must be combined because the scattered light from the forward and backward illumination are not independent. Thus the relative signal R has the form

$$R = \mathrm{K}\int_{35^\circ}^{120^\circ} (|S_1(\theta)+S_1(\pi-\theta)|^2+|S_2(\theta)+S_2(\pi-\theta)|^2)\sin\theta\,\mathrm{d}\theta, \qquad (1)$$

where K is a constant, θ is the scattering angle and S_1 and S_2 are the scattering amplitudes in the horizontal and vertical polarizations and the straight brackets indicate complex conjugation.

The instrument calibration curve, a line relating relative signal to indicated size (output size from the PMS instrument), was obtained by first combining manufacturer's data for the different ranges into a single curve on a log–log plot. A single constant relating all relative signals calculated by equation (1) and the instrument calibration was then determined by a

Table 1 Refractive indexes used

1 3		1 5905	PSL
1 333	Water	1 6	
1 35		1 65	
1 4		1.7	
1.45		1.8	
1.4582	Oleic acid	1 7	
1.471	Mineral oil	2 0	
1.48		1 50 − (0.1, 0 3, 0.5, 0 7, 1 0, 1 5, 2 0) i	
1 485	DOP	1 51 − 1 63i	Iron
1 5		1 55 − 0 6i	Methylene blue
1 54		1 59 − 0 66i	Carbon
1 544	NaCl, Quartz	1 67 − 0 26i	Nigrosin
1 55		1 67 − 0 6i	

least squares fit between the manufacturer's experimental calibration data for nine polystyrene latex particle sizes and the calculated theoretical response curve for $m = 1.5905 - 0.0i$, where $i = \sqrt{-1}$

The calculations ignore the effect of standing waves in the laser cavity, that is, the average amplitudes in both directions and for both polarizations are used This is equivalent to the anti-nodal average as given by Solderholm and Salzman (1984) but differs little from the average of all possible intersection points in the standing wave, the most likely physical case. Since this error is constant for all curves, it is eliminated in the process of fitting the manufacturer's experimental calibration points to the theoretical curves.

Response curves were plotted along with the manufacturer's calibration curve to show departures of the scattered signal from the calibration curve for a given particle size and refractive index as shown in Fig. 2. In such a plot the meaning of the abscissa scale is different for the response curves and the calibration curve. For the theoretically determined response curves it is the true particle size; for the calibration curve it is the indicated size (the instrument output particle size associated with a particular relative signal) and is assumed to be a continuous function.

While Fig. 2 can be used to determine output correction factors for particles of known refractive index, a more useful presentation is to plot true particle size versus indicated size, as shown in Fig 3 for oleic acid and methylene blue. In many situations aerosols of unknown or mixed refractive index are present and it is often useful to know the extent of the error in

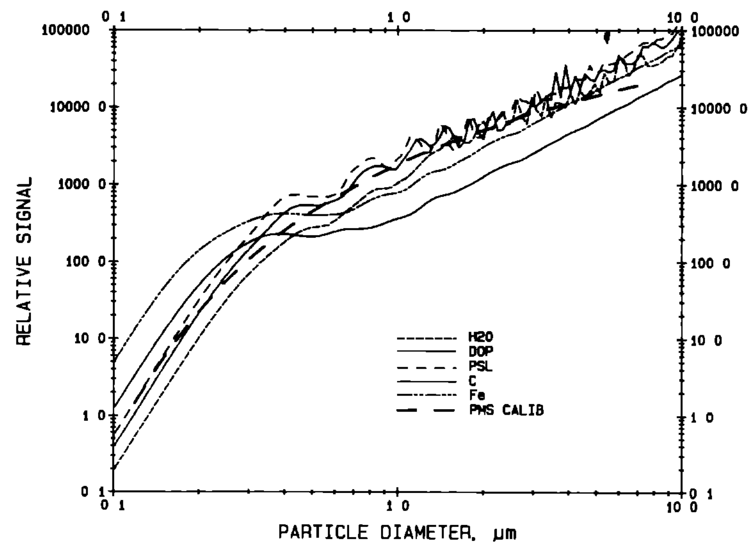

Fig 2. Theoretical response curves for water, di(2-ethylhexyl)phthalate, polystyrene latex, carbon, and iron and instrument calibration curve for PMS Model LAS-X

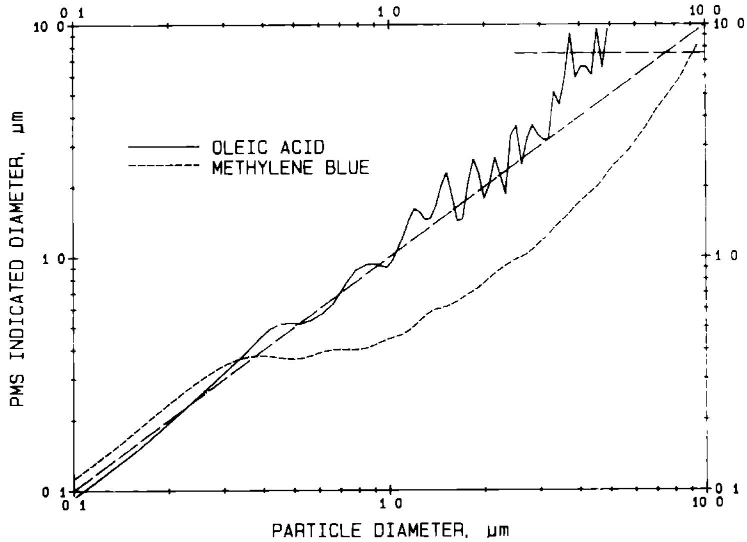

Fig 3 PMS Model LAS-X calibration curve for oleic acid and methylene blue.

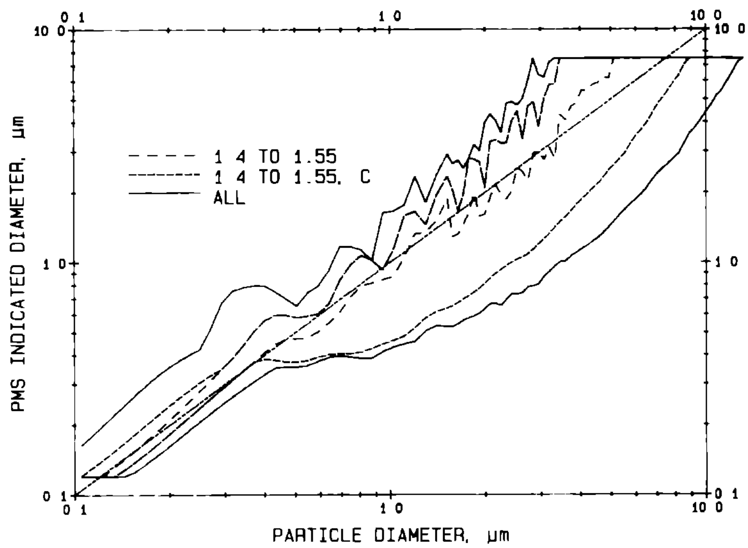

Fig 4 Response boundaries for three ranges of refractive index

measurement of particle size that is introduced by the range of refractive indexes present. This is shown in Fig. 4 which gives response boundaries and hence errors for three refractive index ranges The ranges are: (1) 1 40–1.55, a range representing most nonabsorbing organic particles; (2) the same as (1) with the addition of carbon, and (3) the full refractive index set given in Table 1. On such a graph the intercepts of a horizontal line give the range of true size that may be present for a given indicated size. The intercepts of a vertical line give the range of instrument responses (indicated sizes) for particles of the same size but different refractive index (within the specified refractive index range). Data have been truncated at 7.5 μm even though larger particles are counted in the oversize channel For nonabsorbing particles oversizing or positive errors are greater than negative errors (undersizing). The presence of absorbing particles greatly increases the magnitude of potential undersizing errors. All refractive index groups show the potential for significant oversizing error for particles larger than about 3.0 μm

The instrument response for a material having a particular refractive index can be checked

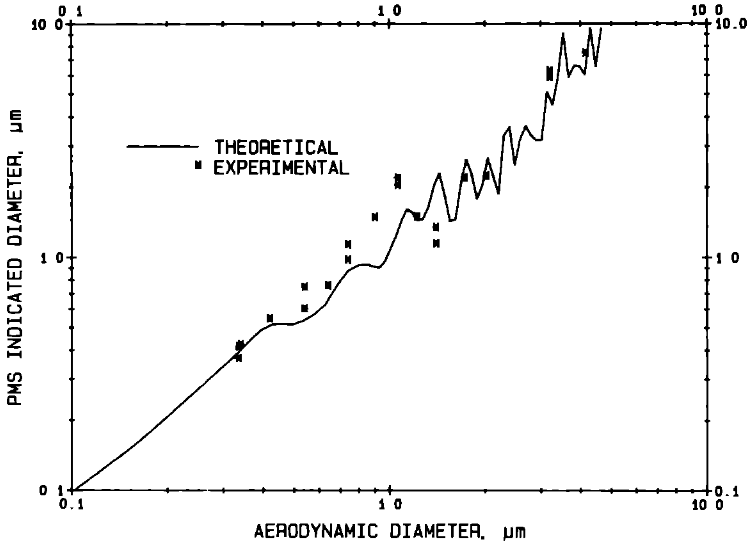

Fig. 5 PMS Model LAS-X aerodynamic calibration for oleic acid

by performing an aerodynamic calibration with a single stage impactor. A polydisperse aerosol is sampled upstream and downstream of a single stage impactor operated at a known aerodynamic cut-off size. The indicated 50% efficiency point, determined by interpolation of the PMS output data, provides an instrument calibration point at a known aerodynamic diameter. This was done for oleic acid (density = 0.893 g cm^{-3}) at 19 points over the aerodynamic diameter range 0.3–7.5 μm using a Sierra Model 290 cascade impactor modified for single stage operation. The results, shown in Fig. 5, agree reasonably well with theoretically predicted values except for unexplained differences in the neighborhood of 1 μm.

EFFECT OF COINCIDENCE ON CMD

In earlier work (Hinds *et al.*, 1983) the effect of coincidence on measured size distribution was evaluated by measuring the size distribution of a submicrometer DOP aerosol at different dilutions. Computer fitting was used to determine the best fitting lognormal distribution for each measured size distribution. For number concentrations less than 10^4 cm^{-3} there was less than a 10% error in CMD. Errors were calculated assuming that the low concentration plateau in CMD was the correct CMD. Similar measurements made with monodisperse polystyrene latex spheres showed less than a one channel width (average channel width is 10.6% of the lower limit) shift in the peak size for concentrations up to 10^4 cm^{-3}.

SAMPLING EFFICIENCY

Because this version of the PMS Model LAS-X measures particles up to 7.5 μm and registers particles greater than 7.5 μm in the oversize channel, it is of interest to identify size-selective particle losses in the inlet and associated tubing. Monodisperse methylene blue particles having aerodynamic diameters of 1.8, 6.3 and 12.5 μm (aerodynamic diameters were calculated using a density of 1.26 g cm^{-3} for methylene blue) were generated with a vibrating orifice aerosol generator. The instrument was cleaned and aligned according to the manufacturer's instruction. The standard PMS inlet tube (stainless steel; 3.2 mm o.d., 2.1 mm i.d. and 100 mm length) was positioned so that 28 mm protruded into a 115 mm diameter chamber. The aerosol passed through a neutralizer and flowed vertically downwards through a chamber at a velocity of about 1 cm s^{-1}. Simultaneous samples were taken with the PMS instrument and with a 13 mm open face filter holder positioned at the same level and 4 cm

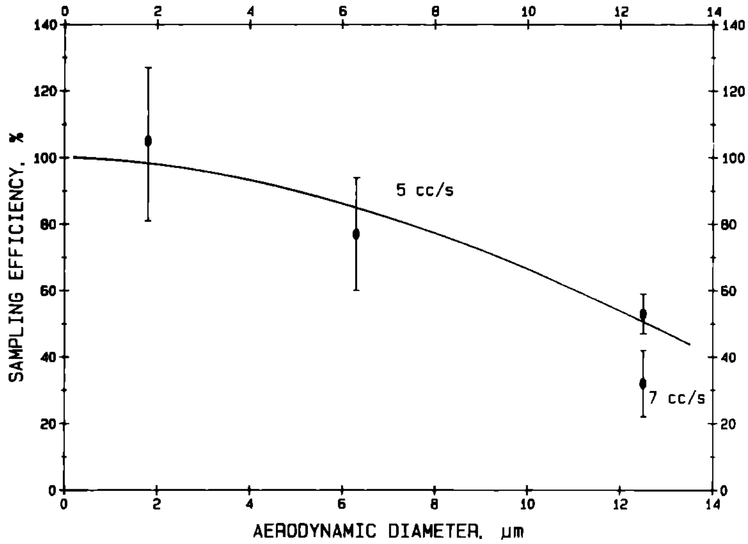

Fig. 6 Sampling efficiency versus particle size for PMS Model LAS-X

away from the PMS inlet tube. The chamber velocity is sufficiently low that sampling is equivalent to still air sampling for both samplers (Hinds, 1982).

Results based on microscopic counting of filter samplers for a sampling flow rate of 5 cm^3 s^{-1} are shown in Fig. 6 with the mean and plus or minus two standard deviations given for each point. Two measurements at 7 cm^3 s^{-1} are also given for 12 5 μm diameter particles. The latter gives an indication of the effect of sampling flow rate on sampling efficiency. Other measurements of losses as a function of sampling rate for 12 μm oleic acid particles found the optimum sample flow rate to be 4 cm^3 s^{-1} with substantially lower counts at < 2 and > 6 cm^3 s^{-1}. Increasing sheath air flow rate from 20 to 50 cm^3 s^{-1} reduced the count of > 4.5 μm particles by a factor of two. Frequent (every few hours) cleaning of the inlet tube assembly is required when sampling liquid particles larger than 8 μm. The sampling efficiency measured here does not differentiate between inlet losses, internal losses, and counting losses.

Acknowledgement—This research was supported in part by NIH (NIOSH) Grant No 1 RO1 OH01595-01.

REFERENCES

Chen, B T, Chang, Y. S and Yeh, H. C. (1984) *J Aerosol Sci.* **15,** 457

Dave, J V (1968) Subroutines for Computing the Parameters of Electromagnetic Radiation Scattered by a Sphere, Report No. 320-3237 IBM Scientific Center, Palo Alto, CA.

Garvey, D M. and Pinnick, R G. (1983) *Aerosol Sci. Technol* **2,** 477.

Hinds, W C (1982) *Aerosol Technology Properties, Behaviour, and Measurement of Airborne Particles.* Wiley Interscience, New York

Hinds, W. C, Macher, J M and First, M W (1983) *Am. ind Hyg Ass. J* **44,** 495

Pinnick, R. G and Auvermann, H. J (1979) *J. Aerosol Sci* **10,** 55

Pinnick, R. G, Garvey, D. M and Duncan, L D. (1981) *J appl Meteorol* **20,** 1049

Solderholm, S. C. and Salzman, G. C (1984) Laser spectrometer theory and practice In *Aerosols* (Edited by Liu, B Y H, Pui, D. Y. H. and Fissan, H J.) Elsevier, New York