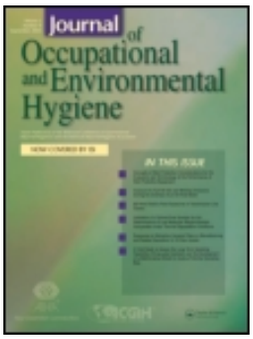

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Evaluation of the pDR-1200 Real-Time Aerosol Monitor

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The objective of this research was to characterize the ability of the pDR-1200 real-time aerosol monitor to measure aerosols of varying size, composition, and origin. Particle aspiration and transmission efficiency was characterized at airflow rates of 2 L/min, 5 L/min, and 10 L/min in a wind tunnel in both static and orientation-averaged configurations. At 10 L/min, the particle cut point for 50% penetration of particles through the device (d_{50}) was approximately 6 μm, while at 2 L/min and 5 L/min the d_{50} was significantly larger, about 9 μm ($p = 0.01$). There was no significant difference in particle penetration efficiency between facing-the-wind and orientation-averaged configurations ($p_{avg} = 0.66$). The pDR-1200 response factor, which is defined as the ratio the time-averaged, monitor-reported concentration to a gravimetric filter concentration measured directly downstream of the sensing zone, was evaluated for four aerosol types: Arizona road dust, background ambient aerosol, environmental tobacco smoke, and diesel particulate matter. These aerosols, each of varying refractive index and particle size distribution, produced significant changes in the measured response factor ($p < 0.01$). The pDR-1200 both overestimated and underestimated (up to a factor of 7) the gravimetrically determined aerosol concentration. These discrepancies further reinforce the need to calibrate the instrument in situ for each aerosol of interest. Inter-instrument variability was generally low for co-located monitors.

Keywords aspiration efficiency, light scattering, nephelometer, PM, response factor, transmission efficiency

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INTRODUCTION

A nephelometer is a type of aerosol monitor that estimates aerosol mass concentration as a function of time. Nephelometers direct a focused wavelength of light onto particles and then record the amount of scattered light using a photodetector. The detector usually is located at a specific scattering angle relative to the incident beam (e.g., 45° or 90° scattering), although some devices integrate the scattered light across a wide viewing angle.[1] The variation in scattered light intensity is assumed to be proportional to the variation in aerosol mass concentration.

Aerosol nephelometers were designed originally for area monitoring in mining applications.[1] Over time, however, they have been gradually miniaturized and are now small enough for personal monitoring applications where they can resolve an individual's personal exposure in time on the order of minutes to seconds.

Light-scattering nephelometers are useful for field measurements of aerosol mass concentration only when the intrinsic characteristics of the sampled aerosol (i.e., particle size, shape, and index of refraction) remain constant. These devices are typically factory calibrated to the mass concentration of a standard test aerosol (i.e., Arizona road dust). However, such calibration may not adequately represent aerosols encountered in the field, since variations in particle size, composition, and shape all affect the degree of scattered light and, hence, instrument response. Unfortunately, laboratory calibration often is inadequate, since laboratory-generated aerosols rarely represent the size and shape of aerosols encountered in the field. Therefore, calibration is often carried out in situ where instrument response is related to the aerosol in question by use of a co-located filter sampler as a standard reference. An aerosol-specific response factor, defined as the ratio of the average concentration reported by a nephelometer to a co-located, filter-measured concentration (gravimetric measurement), accounts for the difference between the factory calibration and field measurement. This response factor then may be used for field sampling, provided the aerosol composition and size distribution remain uniform.

Nephelometers may be biased by variations in ambient relative humidity, especially when measured aerosols exhibit hygroscopic growth.[2] Water uptake by particles may lead to a change in the degree of scattered light and, hence, instrument response. Water uptake depends on ambient relative humidity in addition to aerosol size and composition and is difficult to predict, especially when particles exhibit hysteresis due to a relative humidity change.[3] To prevent such bias, some instruments operate with a heated sensing zone to lower humidity and prevent water uptake, while other instruments are used only when relative humidity is below 60–70%.[1,4] Corrective equations have been developed to account for

the humidity bias; however, such corrections may be both instrument and aerosol specific.[5]

A third consideration involves transporting particles into the instrument sensing zone, as some airborne particles have difficulty following airflow streamlines leading into a sampler inlet. The efficiency of particle entry into a sampling device is known as *aspiration efficiency* and is a strong function of particle size. Typically, large particles (particle diameter, $d_p > 10$ μm) with sufficient inertia and settling velocity are not aspirated efficiently and therefore are not measured by the nephelometer. Additionally, aspirated particles may not reach the sensing zone, especially if the flow path is tortuous. The efficiency of particle transport through a device is known as *transmission efficiency*.

In this work, both aspiration and transmission efficiency were measured together to represent a *penetration efficiency*, defined as the ratio of particle concentration reaching the instrument sensor to the concentration in the sampled air. Penetration efficiency is affected by the instrument inlet size, shape, and orientation, the ratio of ambient air velocity to inlet velocity, and the degree of airflow turbulence.[6] Sampler orientation (relative to the direction of external wind velocity) may exacerbate the effects of inertia and gravity on particle aspiration and also must be considered. Therefore, penetration and aspiration efficiencies are usually determined in a wind tunnel under both static (i.e., facing the wind) and orientation-averaged (i.e., 360° rotation) conditions.[7]

This work describes measurements of nephelometer (model pDR-1200, Thermo Scientific Corp., Waltham, Mass.) penetration efficiency as a function of flow rate and sampler orientation, as well as measurements of instrument response factor for four common aerosols.

METHODS

Instrument Description

The pDR-1200 is a light-scattering nephelometer with a built-in filter attachment. The pDR-1200, hereafter called pDR, is part of the personalDataRAM series of instruments that measure aerosol concentration in real-time. This instrument, used with a separate pump (1–10 L/min), has an optimal response to particle diameters between 0.1 and 10 μm. The pDR weighs 0.68 kg and is approximately 160 mm in height, 205 mm in width, and 60 mm in length. The inlet consists of a circular flange designed to mount the front piece of a closed-face 37-mm filter cassette (no cassette or other size-selective device was used in the experiments described here). Concentric to the flange is a circular opening of 4.5 mm where aspirated aerosol enters the sensing zone, measuring 83 mm × 19 mm × 49 mm (L × H × W). Within the sensing zone, the pDR scatters light over the forward angle of 50–90° at a infrared wavelength of 880 nm; however, the majority of scattered light falls within ±10 degrees of the nominal scattering angle of 70°. The instrument exit consists of another 4.5-mm opening surrounded by a second flange used to mount the back piece of a 37-mm cassette. In this fashion, a filter sample may be taken immediately downstream of the pDR for subsequent gravimetric or chemical analysis.

The power source is a 9V alkaline or lithium battery; these batteries have an approximate lifetime of 20 and 40 hr, respectively. The pDR may be connected to a computer using an RS232 interface to download stored data. Data may be logged in 1-sec to 4-hr intervals with a maximum of approximately 13,300 data points. Each data point includes the average concentration, date, and time. In addition, a run summary outlines the sampling session including: overall average and maximum concentrations, total number of logged points, start time/data, and total run time. The pDR is factory calibrated in a still-air chamber using Fine Test Dust aerosolized by fluidized bed generation. The manufacturer reports this dust to have a specific gravity of 2.6 g/cm^3, index of refraction of 1.5-0i, and a mass median diameter of 2 to 3 μm.

pDR Penetration Efficiency

The penetration efficiency of the pDR was determined for both static and orientation-averaged conditions in a wind tunnel. The penetration efficiency was calculated from the relative response of an Aerodynamic Particle Sizer (APS model 3321, TSI Inc., Shoreview, Minn.) measuring particle concentration as a function of size with the pDR in-line and subsequently removed. The APS measures aerosol number concentration as a function of aerodynamic particle diameter between 0.5 and 20 μm. As discussed previously, the pDR penetration efficiency, η_p, is the product of the pDR's aspiration efficiency, η_a, and transmission efficiency, η_t:

$$\eta_{p,i} = \eta_{a,i} \cdot \eta_{t,i} = \frac{C_{in,i}}{C_{out,i}} \quad \textbf{(1)}$$

where C_{in} and C_{out} are the aerosol concentrations measured upstream (freestream) and downstream (at the sensing zone exit) of the pDR, respectively, and i denotes the particle size of interest.

Desiccated coarse Arizona road dust (ISO A4, Powder Technology Inc., Burnsville, Minn), held in a hopper, was dispersed into a wind tunnel (cross sectional area: 1 m × 1 m, length: 3.1 m) using an NBS 2 dust generator with a rotating feeder wheel. A backward-curved airfoil fan pulled the aerosol the length of the tunnel at a speed of 0.42 m/sec. This speed was chosen to render the APS inlet isokinetic with the wind tunnel freestream. Most workplace wind speeds are below 0.5 m/sec,[8] thus, this speed is appropriate for indoor exposures. Outdoor wind speeds may be considerably greater, in which case, the aspiration efficiency may change.[9] For the static orientation tests, the pDR was placed at the center of the test section, approximately 2.5 m downstream of the inlet, facing the wind. For the orientation-averaged tests, the pDR was placed on a rotating turntable capable of 360° rotation at 7 rpm. The use of a motorized turntable in conjunction with an APS allowed for rapid determination of penetration efficiency within the wind tunnel.

The velocity profile of the wind tunnel, shown in Table I, was measured at 16 cross-sectional points with a

TABLE I. Cross-Sectional Velocity Profile Measurements in Wind Tunnel (m/sec)

0.42	0.50	0.43	0.39
0.46	0.43	0.42	0.37
0.46	0.40	0.45	0.38
0.45	0.38	0.42	0.42

Note: Shaded cells indicate measurement domain. Values represent equal area measurement domains.

thermo-anemometer (model 8585, Alnor, TSI Inc.). The profile measurements were taken 6 in. upstream of the instrument test section. The velocities ranged from 0.37 m/sec to 0.46 m/sec with an average of 0.425 m/sec in the test section area. A separate aerosol monitor (DustTRAK model 8520, TSI Inc.) was located adjacent to the test section to assess the uniformity in aerosol concentration across each test.

Aerosols were drawn through the pDR at flow rates of 2, 5, and 10 L/min and into the APS. Since the APS requires a nominal flow rate of 5 L/min, bypass flows were required for the 2 and 10 L/min tests. At 10 L/min, aerosol was pulled through the pDR and immediately into a sharp-edged flow splitter. Each branch of the flow splitter operated at 5 L/min with one branch directed to the APS and a second to a filter-pump system (LelandLegacy, SKC, Inc., Eighty Four, Pa.), for a total 10 L/min through the pDR.

At 2 L/min the orientation of the flow splitter was reversed, allowing one end to pull 2 L/min from the pDR with the other end connected to a metered, particle-free airflow set to deliver an additional 3 L/min into APS. Note that any aspiration or transmission losses within the APS or flow splitter system will cancel out in Eq. 1, since these losses occurred for both the C_{in} and C_{out} measurements about the pDR.

Experiments with the pDR in-line and removed were repeated for 10 tests; each test was 120 sec in duration (60 sec with the pDR in-line and 60 sec with the pDR removed). However, only results from the three most uniform tests were analyzed at each flow condition due to instability in the aerosol mass concentrations generated by the NBS 2 generator. After sampling, the data were downloaded and imported into a Microsoft Excel spreadsheet for calculation of the penetration efficiency as a function of particle size and airflow rate (Eq. 1).

Response Factor

The ratio of the pDR-measured mass concentration (light scattering) to the filter-measured concentration (gravimetric) is defined as the pDR response factor, *RF*:

$$RF = \frac{C_{pDR}}{C_{Filter}} \quad \textbf{(2)}$$

where pDR and filter concentrations are reported in mg/m^3. The response factor was determined for four different aerosols: Arizona road dust, environmental tobacco smoke, rural background aerosol, and diesel particulate matter. Each test was conducted using three co-located pDR instruments, and each pDR had a filter sampler located immediately downstream of the optical sensing zone. Prior to sampling, pDRs were zeroed with a HEPA filter attachment and set to log aerosol concentration every second, except when otherwise stated. Gravimetric filter samples were taken on 37-mm, Teflon-coated glass fiber filters (Pallflex Fiberfilm T60A20 filters, Pall Corporation, East Hills, N.Y.) that were equilibrated at room conditions for 8 hr prior to weighing. A flow rate of 5 L/min was maintained through each sampler using calibrated sampling pumps (ACxl demo, SKC, Inc.) for all tests.

Sampling duration was varied for each aerosol type to meet an established limit of quantification (LOQ) for mass capture on the filter. For these tests, the LOQ, defined as 10 times the standard deviation in weight change of multiple filter blanks, was calculated at 0.055 mg per filter. Test repetition allowed for the determination of both intra- and inter-sampler variability for both filter and PDR measurements. In addition, a particle sizing instrument (either the APS or a Scanning Mobility Particle Sizer, SMPS+C, Grimm Technologies, Inc., Douglasville, Ga.) was co-located with the pDRs to determine aerosol size distributions.

Aerosol 1: Coarse Arizona road dust, held in a desiccant chamber for 24-hr prior to use, was fed into a wind tunnel in the same manner as described for penetration efficiency tests. The sampling duration was set at 30 min per test.

Aerosol 2: Environmental tobacco smoke was aerosolized in a 1.0 m^3 still-air chamber. For each test, a lit cigarette was placed in a small enclosure fed with clean, particle-free air. The outlet of the enclosure was connected to the inlet of the chamber, providing a steady aerosol supply. Particle-free dilution air also was fed into the chamber from a separate port. A mixing fan dispersed the aerosol throughout the chamber, and excess air was vented to a laboratory hood. Aerosol residence time in the chamber was estimated at 8.5 min. Sample duration was 30 min.

Aerosol 3: Diesel soot was sampled from a dilution tunnel[10] connected to a medium-duty off-road diesel engine (4024T, John Deere, Moline, Ill). Engine exhaust was drawn through a heated sample line and diluted with clean, particle-free air. The diluted aerosol then entered a residence chamber where sampling took place. The residence time in the chamber was approximately 8 min. Sampling duration was set at 1 hr.

Aerosol 4: Background ambient aerosol was sampled from the Foothills campus west of Colorado State University in Fort Collins, Colo. This location abuts both county and state park land on the northern front range of the Rocky Mountains. Samplers were placed 4 ft above the ground and away from buildings. PM concentrations were logged every 30 sec over a 24-hr duration. Sampling periods were conducted on 2 consecutive days of varying temperature (Day 1: 6.6°C vs. Day 2: 14.9°C) and relative humidity (Day 1: 43% vs. Day 2: 28%).

Immediately after sampling, filters were removed from their cassettes, placed in a desiccant chamber for 8 hr followed by equilibration at room conditions for 8 hr, discharged on a ^{210}Polonium strip for 30 sec, and then weighed to the nearest microgram on a Mettler MX5 microbalance (Mettler-Toledo,

Columbus, Ohio). The time-weighted average gravimetric concentration, C_{Filter}, was calculated as:

$$C_{Filter} = \frac{\Delta m}{Q \cdot t} \quad \textbf{(3)}$$

where Δm represents the change in filter mass in mg, Q is the pump flow rate, L/min, and t is elapsed time, min. Concentration data from the pDRs was downloaded and exported into a Microsoft Excel spreadsheet and the response factor was determined from Eq. 2.

Statistical Analysis

Data were analyzed using R statistical software (developed by R. Gentleman and R. Ihaka, Statistics Department of the University of Auckland). Tukey pair-wise comparisons were used to determine the differences in penetration efficiency among the three flow rates, while a two-sample t-test was used to determine the effects of orientation averaging. A 3-way analysis of variance (ANOVA) was employed to detect differences between pDR response factors each aerosol type. Inter-instrument variability between co-located pDRs was determined by comparing minute-to-minute responses from each instrument. For all tests, a type I error rate of $\alpha = 0.05$ was used for the determination of statistical significance.

RESULTS AND DISCUSSION

pDR Penetration Efficiency

Particle penetration efficiencies through the pDR are shown in Figure 1 as a function of aerodynamic diameter and flow rate. In general, flow rate is inversely related to penetration efficiency. The cut point for 50% penetration through the pDR (d_{50}) at 10 L/min was approximately 6 μm, while at 2 and 5 L/min the d_{50} increased significantly to about 9 μm ($p_{avg} = 0.01$). At flow rates of 2 and 5 L/min the pDR appears to have a cut point that nearly matches the thoracic (PM_{10}) size-range. At a 10 Lp/min rate of flow, however, thoracic aerosol samples may not be measured accurately by the pDR due to inertial and gravitational losses of coarse particles during aspiration and transmission. Measurement of inhalable aerosols, covering a size range up to 100 μm, is not appropriate at any rate of flow. Sampling respirable and $PM_{2.5}$ aerosols, however, will not be biased by aspiration or transmission losses through the pDR, if taken with an appropriate size-classification device, such as a $PM_{2.5}$ impactor or respirable cyclone.[11]

No significant differences in transmission efficiency were detected between the forward-facing (i.e., facing the wind) and orientation-averaged directions for the pDR using a two-sample t-test ($p = 0.66$). While orientation averaging usually results in a reduction in aspiration efficiency (as compared with facing-the-wind orientation), this was not the case in this study (Figure 2).

Response Factor

The response factors for rural background aerosol, environmental tobacco smoke, Arizona road dust, and diesel particulate matter are reported in Table II. Each aerosol type produced significant changes in the pDR response factor ($p_{avg} = 0.005$), except those between diesel particulate matter and Arizona road dust ($p = 0.99$). The pDR overestimated

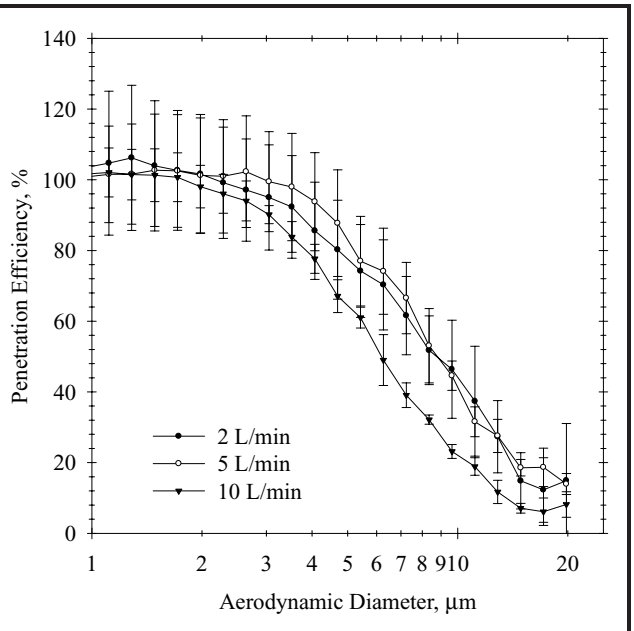

FIGURE 1. Penetration efficiency of the pDR as a function of flowrate for static, facing-the-wind orientation. Note: Error bars represent one standard deviation.

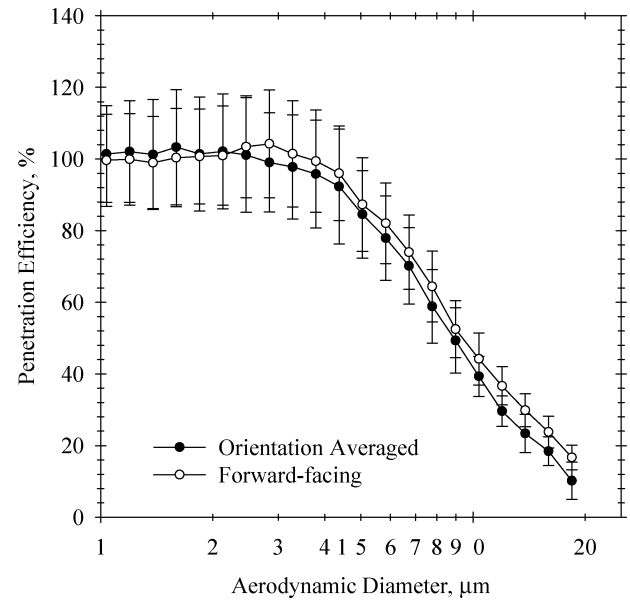

FIGURE 2. pDR penetration efficiency at 5 L/min for orientation-averaged and static conditions. Note: Error bars represent one standard deviation.

TABLE II. pDR Response Factors (±1 standard deviation) and Relative Standard Deviation Between Co-Located pDRs for Four Aerosol Types

Aerosol Type	C_{pDR} (mg/m^3)	Aerosol Size MMAD,[A] GSD[B]		Response Factor C_{pDR}/C_{filter}	RSD[C] (%)
Environmental tobacco smoke	9.85	0.13	1.43	6.94 ± 0.88	7.0
Rural background aerosol	0.03	0.10	2.21	1.92 ± 0.73	41
Diesel particulate matter	0.29	0.09	1.78	0.62 ± 0.16	6.0
Coarse Arizona road dust	8.19	1.69	1.67	0.71 ± 0.08	11

[A] Mass median aerodynamic diameter (MMAD), μm.
[B] Geometric standard deviation (GSD)
[C] Relative standard deviation (RSD) between three co-located *p*DRs based on 1-min averages.

mass concentrations of environmental tobacco smoke and rural background aerosol by factors of 6.9 and 1.9, respectively. The pDR underestimated both diesel particulate matter and Arizona road dust by factors of 0.62 and 0.71, respectively. Response factors were repeatable between repeat tests of the same aerosol, with the exception of the rural background aerosol tests. Instrument-to-instrument variability was low, as time-averaged concentrations reported by co-located pDRs were not significantly different ($p_{avg} = 0.82$). The minute-to-minute (i.e., real-time) variability between co-located pDRs was also low. This real-time variability is shown qualitatively in Figures 3–5 and quantitatively in Table II, is represented by the relative standard deviation (RSD) of 1-min averages between co-located pDRs during each measurement run.

Only the rural background aerosol tests demonstrated high variation between co-located pDRs and across repeat tests. The cause of this variability is unclear; however, several factors may have contributed to this result. First, only two instruments were available for sampling during the background ambient aerosol tests. Second, very low concentrations were measured during these tests, on the order of 20 μg/m^3. At such low concentrations, even a small amount of drift in laser intensity, factory calibration, or optics contamination may produce substantial differences between co-located instruments. Finally, although these instruments were placed only several feet apart, there may have been small differences in the sampling microenvironment (e.g., temperature, humidity, windspeed, etc.) that were not controlled for, as was done during the laboratory tests. While some variability may also be attributed to the gravimetric method (i.e., filter weighing), the mass detected on each filter sampler for these tests exceeded the established LOQ of 0.055 mg.

All pDRs are calibrated initially by the manufacturer using fine Arizona road dust in a still-air chamber using fluidized bed generation. Because the pDR was factory calibrated using a dust similar to the coarse test dust used in this study, a response factor of 1 was expected for the coarse Arizona road dust. However, the pDR underestimated the test dust concentration by a factor of 0.71. This discrepancy may be

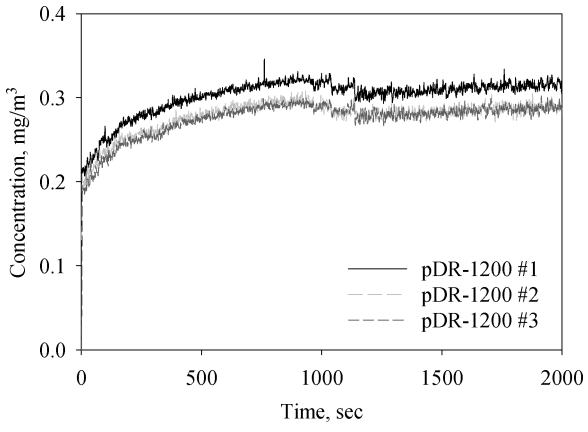

FIGURE 3. pDR inter-instrument comparison with diesel particulate matter

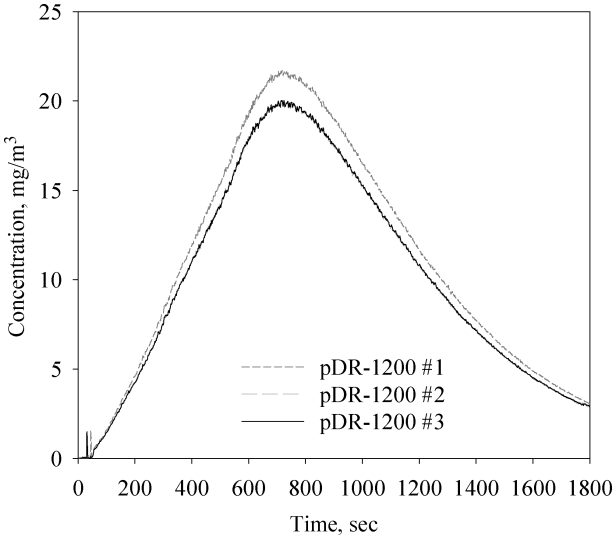

FIGURE 4. pDR inter-instrument comparison with environmental tobacco smoke. Note: The pDR-1200 #1 and #2 signals closely overlap.

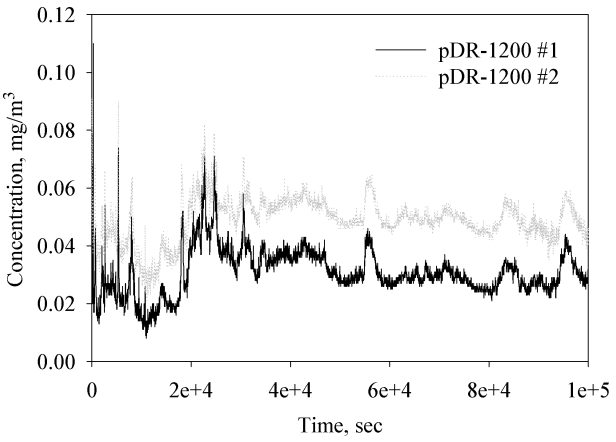

FIGURE 5. pDR inter-instrument comparison with background ambient aerosol

due to differences in the particle size distribution generated between the two experimental setups, as the present study used coarse Arizona road dust (vs. fine) aerosolized with an NBS-2 dust generator (vs. fluidized bed) in a wind tunnel, whereas the factory calibration was conducted in a still-air chamber using fine Arizona test dust aerosolized by a fluidized bed generator.

The pDR underestimated mass concentrations of diesel particulate matter by a factor of 0.62. This underestimation is somewhat expected, since the pDR is calibrated with particles that generally scatter but do not absorb light. Since diesel particulate matter contains a large portion of light-absorbing elemental carbon, this aerosol will likely scatter less light, resulting in an underestimation of the gravimetric diesel particulate matter concentration. Additionally, particle size effects may play a role.

Filters are inefficient retainers of environmental tobacco smoke, which contains a large amount of semivolatile organic material. These semivolatile compounds are likely to evaporate from the filter surface during collection, desiccation, and equilibration, leading to an underestimation of the actual concentration. This phenomenon could explain why the nephelometer overestimated the filter by such a large degree. Environmental tobacco smoke contains thousands of semivolatile organic compounds; compound-specific evaporation rates depend on many factors, such as humidity, temperature, flow rate, and filter equilibration time. Consequently, such losses are difficult to quantify.

Some drift in inter-instrument variability over a wide concentration span is evident in Figures 3–5. Instrument #1 drifted to higher concentrations of diesel particulate matter, whereas #2 and #3 stayed in close proximity across the sampling period. The same result was apparent during ETS sampling. Only two pDR monitors were used during background ambient sampling, and again, pDR #1 drifted to higher concentrations than #2. Before each use, the pDRs were cleaned and zeroed with particle-free air using a zeroing kit from the manufacturer, and attached pumps were pre- and postcalibrated using a venturi flow meter. Because pDR #2 and #3 demonstrated similar responses over each of the tests, it is likely that this drift could be an error in factory calibration of pDR #1.

CONCLUSIONS AND RECOMMENDATIONS

The relative response of light scattering nephelometers is strongly dependent on the sampled aerosol. Since several particle characteristics affect instrument response, notably the size, shape, and refractive index, these instruments should be calibrated in situ (i.e., alongside a gravimetric filter sampler) to account for the intrinsic and extrinsic properties of the sampled aerosol. However, once the relative response factors to a variety of aerosols are established, subsequent sampling may help determine the nature of the sampled aerosol, as reported response factors may be indicative of the aerosol source. This hypothesis has yet to be tested in the field.

The particle penetration efficiency of the pDR indicated that an increased flow rate restricted the entry of some particles into the instrument. Because the d_{50} for particle transmission at 2 and 5 L/min was about 9 μm, the instrument will likely miss a small fraction of sampled PM_{10} or *thoracic* aerosols. The measurement of *inhalable* aerosol (i.e., particle sizes up to 100 μm in aerodynamic diameter) by the pDR is wholly discouraged, regardless of flow rate, as particles larger than 10 μm will not effectively enter the instrument. Despite these findings, light-scattering nephelometers are useful instruments for detecting relative changes (i.e., peaks) in aerosol concentrations through time (Figures 3–5). Such capability makes nephelometers useful as survey meters during industrial hygiene evaluations, especially when an emphasis is placed on control.

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