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Development and Laboratory Performance Evaluation of a Variable Configuration $PM_1/PM_{2.5}$ Impaction-Based Sampler

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ABSTRACT

This study presents the design and lab evaluation of a compact medium flow multiple round nozzle-based inertial impactor with variable head for collecting particulate matter (PM). The impactor operates at a flow rate of 175 LPM and consists of two different sets of circular acceleration nozzles designed for $PM_{2.5}$ (particle aerodynamic diameter < 2.5 µm) and PM_1 (particle aerodynamic diameter < 1 µm), either of them could be used at a time as per the objective of sampling. High vacuum grade silicone grease is used as an impaction substrate. Lab experiments were performed using a poly-disperse dolomite powder as test aerosol. The nozzle configurations selected were such that the first one provides a 50% cutpoint at 2.50 µm (aerodynamic diameter) with a pressure drop of 0.35 kPa while the second one produces a 50% cutpoint at 1.06 µm (aerodynamic diameter) with a pressure drop of 1.07 kPa. Particle losses through the nozzles were low for particle diameter upto 5.0 µm. Particle bounce-off and re-entrainment losses were found to be insignificant. Owing to its higher flow rate, it has an advantage of collecting appreciable quantity of particles (and higher number of samples) in a relatively smaller time frame as compared to other low flow rate samplers. The samples can be analyzed to obtain finely time-resolved aerosol composition which can help in a better understanding of the role of various physico-chemical processes active during different meteorological conditions (extreme dust and foggy events) that affect fate and transport of PM, especially in the Indo-Gangetic plain (IGP).

Keywords: Impactor; Particulate matter; Stokes number; Silicone grease.

INTRODUCTION

Several studies in the past have linked respirable particulate matter (PM) to the deteriorating lung and heart functioning and even reduced life expectancy (Dockery *et al.*, 1993; Koenig *et al.*, 2005). Exposure from total suspended particles (TSP), especially fine particles ($PM_{2.5}$ and PM_1) in the ambient environment is one of the major reasons for premature deaths (Massey *et al.*, 2012). Fine particles are of greater concern since they can penetrate into lung tissues and ultimately enter the blood stream (Schwartz *et al.*, 1996; Harrison and Yin, 2000; Cohen *et al.*, 2005; Kunzli and Tager, 2005; Sharma and Agrawal, 2005; Huang and Ghio, 2006).

Due to shortage of adequate natural resources, especially in the case of developing countries, people have limited availability of clean fuels and clean technologies leading to poor air quality in many of the cities of such countries (Holgate *et al.*, 1999; Dey *et al.*, 2012; Ghosh *et al.*, 2014). Therefore, measurement and regular monitoring of fine particulate matter in such places becomes important.

Inertial impactors are relatively simple devices where air laden with particle flows around an impaction substrate and is subjected to sharp change in air flow trajectory. Particles with sufficient inertia will slip across the sharply bending air streamlines and impact on the impaction surface while the finer particles will follow the bending air streamlines and move downstream of the impaction substrate (Hinds, 1999).

To measure PM concentrations of different size bins, various inertial impactors have been developed (McFarland *et al.*, 1978; Sioutas *et al.*, 1996; Demokritou *et al.*, 2001a; Misra *et al.*, 2002; Demokritou *et al.*, 2002a, b, 2004; Lee *et al.*, 2006; Singh *et al.*, 2010; Gupta *et al.*, 2011) over the years, majority of which are low flow rate, single or multi-stage impactors. With the changing ambient conditions, anthropogenic activities and introduction of newer pollution sources, especially in developing countries where air pollution is a major problem, there is a constant need for development of new impactors to cope up with such emerging challenges.

This paper presents the design, development and lab evaluation of a single stage $PM_1/PM_{2.5}$ medium flow rate multiple round nozzle-based inertial impactor. This novel

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sampler has a unique property of interchangeable nozzle assembly so as to measure PM_1 or $PM_{2.5}$ at a time as per the requirement. Recent studies performed to assess the air quality in the IGP confirm the occurrence of various physico-chemical processes that affect the PM composition. Ranging from the dust storms during pre-monsoon season to the extreme foggy events during winter season, affect the PM concentrations in different ways (Kaul *et al.*, 2011; Ram *et al.*, 2012; Ghosh *et al.*, 2014; Kaul *et al.*, 2014). The sampler developed in the current study can be used to collect filter samples over shorter time intervals (owing to its higher operating flow rate of 175 LPM) which can be analyzed later on to assess various chemical parameters. This would provide a very finely time-resolved temporal variation of PM composition which can eventually be used (in combination with meteorological data) to clearly understand the role of various physico-chemical processes active in different seasons that affect the fate and transport of PM within IGP.

METHODOLOGY

Theoretical Consideration for Impactor Nozzle Design

In an impactor, whether a particle impacts depends on the drag force on the particle, particle momentum and effective transit time across the substrate plate. Impactor theory combines these factors into a dimensionless parameter called Stokes number (Stk). The cut point of the impaction stage with multiple accelerating nozzles can be calculated by using the Stokes equation, as follows (Baron and Willeke, 2001):

$$Stk = \frac{\rho_p d_p^2 U C_c}{9\eta D_j} \quad (1)$$

where, ρ_p is the particle density (kg/m^3), η is the dynamic viscosity of air (Pa.s), d_p particle diameter (µm), U jet velocity through single impactor nozzle (m/s), D_j nozzle diameter (m), and C_c Cunningham slip correction factor which is given by the following equation (Baron and Willeke, 2001):

$$C_c = 1 + \frac{1}{Pd_p}[15.60 + 7.00\exp(1 - 0.059Pd_p)] \quad (2)$$

where P is the absolute pressure (kPa). Conversion from optical diameter to aerodynamic diameter was an important factor in this study because the optical particle counter (PAS 1.108, Grimm GmbH) was employed for aerosol concentration measurement. This conversion can be carried out using the following equation (Hinds, 1999):

$$d_a = d_{op}(\rho_p/\rho_0\,\chi)^{1/2} \quad (3)$$

where d_a and d_{op} are aerodynamic and optical diameter (µm), respectively, ρ_0 is the standard density (1000 kg/m^3) and χ is the dimensionless dynamic shape factor for particle. Stokes equation is used to find out the nozzle dimensions. The theoretical d_{50} is calculated using the equation (Hinds, 1999):

$$\left(d50\sqrt{C_c}\right)^2 = \left[\frac{9\pi\eta n D_j^3\left(Stk_{50}\right)}{4\rho_p Q}\right] \quad (4)$$

where Q is the air stream flow rate (m^3/s) and n is the number of round nozzles. This equation works well for flat surfaces. The impaction substrate is kept 0.40 cm thick and the surface is made flat and smooth using a razor blade so as to minimize particle bounce off. The theoretical value of $\sqrt{Stk_{50}}$ was taken as 0.50 while designing the round nozzle impactor (Marple and Willeke, 1976; Marple *et al.*, 1987). The nozzle Reynolds number (Re) was calculated using the following equation:

$$Re = \frac{\rho_{air} U D_j}{\eta} \quad (5)$$

where ρ_{air} is the air density (kg/m^3), U is the flow velocity (m/s). The sharpness of the efficiency curve is evaluated on the basis of the geometric standard deviation which can be calculated using the following equation (Hinds, 1999):

$$\sigma_g = [d_{84}/d_{16}]^{1/2} \quad (6)$$

where d_{84} and d_{16} are the size of particles corresponding to a collection efficiency of 84.1% and 15.9%, respectively.

Experimental Setup

Various impactor nozzles were designed with target cutpoint of 1 µm and 2.5 µm in the flow range of 100–200 LPM, based on the Eqs. (1)–(5). The impactor nozzles along with impaction substrate unit were tested individually using a laboratory testing rig setup as shown in Fig. 1. An improved dry aerosol generator was employed using dolomite powder to produce a stable flow of polydisperse aerosol (Gupta *et al.*, 2011; Singh *et al.*, 2014). The dolomite powder had been sieved through 45 µm mesh and the finer fraction was used as test aerosol in order to avoid clogging of air inlets and nozzles in the aerosol dispersion chamber. The generated aerosol enters the mixing chamber where it is mixed and diluted with dried ambient air. Then the diluted aerosol enters into a cylindrical duct of sufficient length on the upstream side of impactor assembly to ensure complete mixing and uniform concentration of aerosol at the sampling point. A high flow rate vacuum pump was employed to generate the desired range of flow rates. The flow rate was monitored by a rotameter which had been calibrated with a mass flowmeter (TSI Inc. Model 4040). A portable aerosol spectrometer (PAS 1.108, Grimm GmbH) was used to test the performance of the impactor. Since PAS gives optical diameter of the particles so Eq. (3) was used to convert to aerodynamic diameter with density and shape factor of dolomite used as 2840 kg/m^3 and 1.10, respectively (Deelman, 1999; Alkuwairan, 2012).

The impactor nozzles having conical shape and diameter range of 3 mm to 6 mm were designed and fabricated. The nozzles were tested with flow rates ranging between 100 to 200 LPM using the dry aerosol generation system for different S/W ratios. To obtain the best possible PM collection efficiency and separation curve for the desired cutpoint of

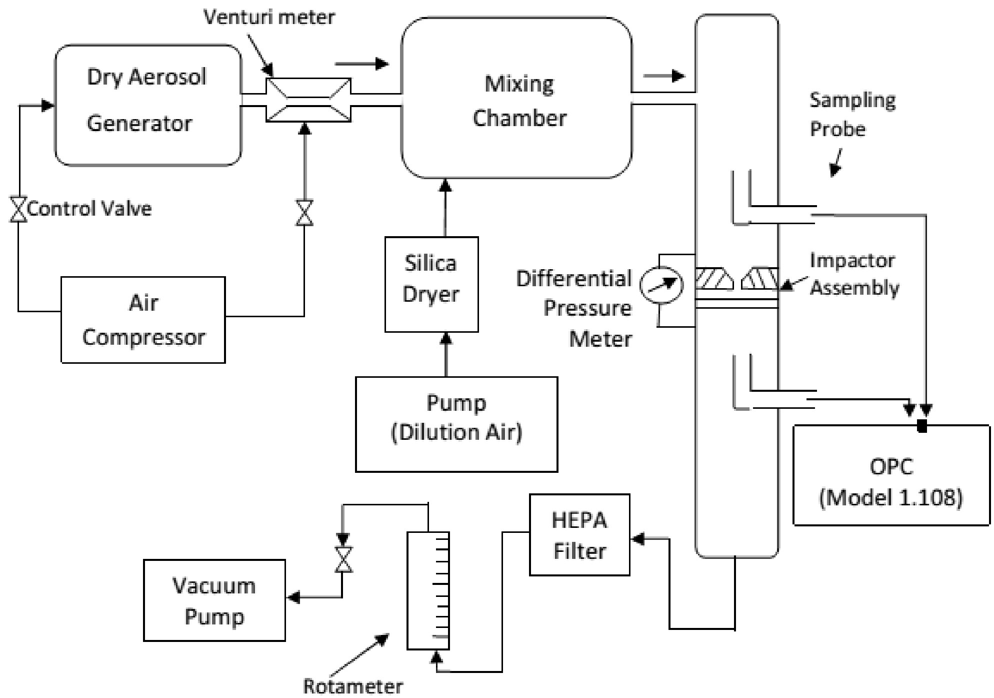


Fig. 1. Experimental setup for impactor characterization in the laboratory.

1.0 µm and 2.5 µm, critical design parameters such as S/W (ratio of distance between nozzle exit to substrate surface and nozzle diameter), Re were investigated using impactor nozzles of different diameters and varying airflow rates through the impactor as a part of a rigorous parametric investigation (Gupta *et al.*, 2011). An optical particle counter was used to alternatively sample between upstream and downstream of the impactor for a time interval of 4 min each. The difference in particle concentration was then calculated for the upstream and downstream flows to determine the collection efficiency of each impactor set. Each experiment consisted of at least 4 sets of upstream and downstream samples. In addition, each configuration was repeatedly tested for at least 4 times. The final optimized nozzle configuration for PM_1 was with 8 nozzles of 3 mm diameter each while $PM_{2.5}$ consisted of 4 nozzles having 6 mm diameter each (Fig. 2). The finer particles, after passing through the impactor assembly, get collected onto a standard 47 mm diameter filter paper.

RESULTS AND DISCUSSION

Stability of the Aerosol Generation System

The performance and stability of the dry aerosol generator is shown in Fig. 3. The plot shows the variation in aerosol generation (average aerosol number concentration with a variation of one standard deviation) upstream and downstream of impactor assembly in one of the representative tests conducted during sampler development. A maximum variation of ± 6% in the aerosol number concentration at the upstream and downstream of the impactor nozzle was observed during the experiments carried out to evaluate particle losses and other impactor characterization.

Results of the Parametric Investigations for Impactor Characterization

Table 1 summarizes the results of the parametric investigations carried out on different round nozzle impactors before arriving at the optimum. There are several outcomes of the interaction of the collision between particles and collection substrate viz. particle is collected on the substrate, particle bouncing off of the surface and getting reentrained in the airstream, colliding with previously collected particle and getting reentrained in the airstream again or coarse particles breaking apart and getting reentrained in the airstream (Kavouras *et al.*, 2000). The only favorable option is the first outcome and to accomplish that a thick and smooth grease coating of 0.40 cm was used in all the impactors tested which is in accordance with earlier studies (Turner and Hering, 1987; Pak *et al.*, 1992; Hill *et al.*, 1999; Demokritou *et al.*, 2001b).

Varied combinations of flow rate and number of nozzles were tested (using Eq. (4)) in order to obtain the desired cut off sizes. With a fixed number of nozzles and diameter, increasing flow rate results in lower cutoff sizes. In Table 1, the last column shows the σ_g values of the efficiency curves for different tests. In real impactors, the jet flow velocity is uniform in the central region of the nozzle but reduces to zero at the nozzle wall. Such varying cross-sectional velocity profile affects the sharpness of the efficiency curve (Marple and Liu, 1974, 1975). This effect is more pronounced in nozzles with larger diameter and can be clearly noticed in the Table 1. Previous studies on development of impactor theory suggest that sharp efficiency curve can be obtained for Re values between 500 and 3000 (Marple and Willeke, 1976). In general, the higher Re values obtained in the presented tests could also probably explain the higher σ_g values.

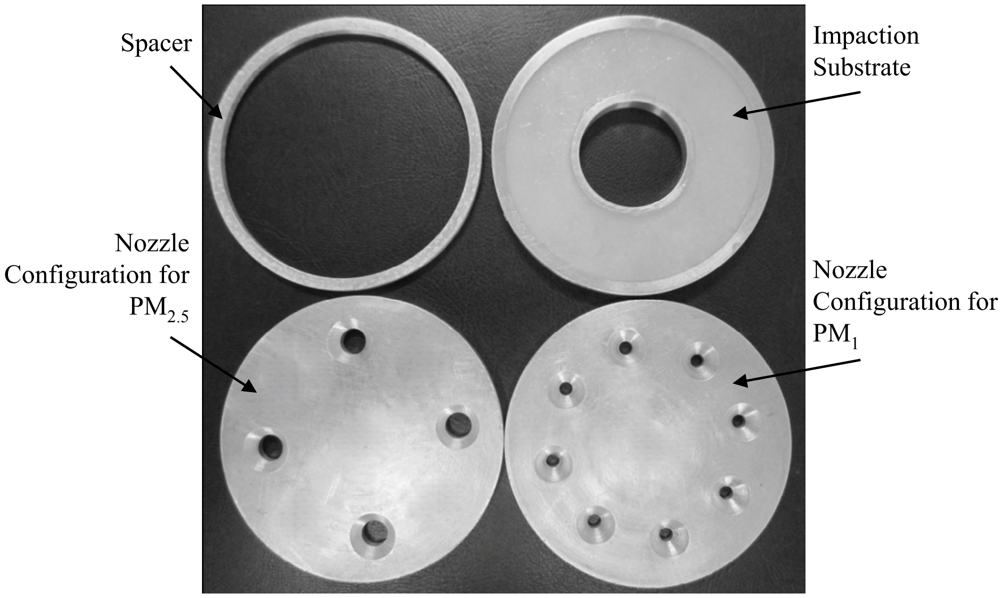


Fig. 2. Components of the optimum PM_1/$PM_{2.5}$ impactor assembly.

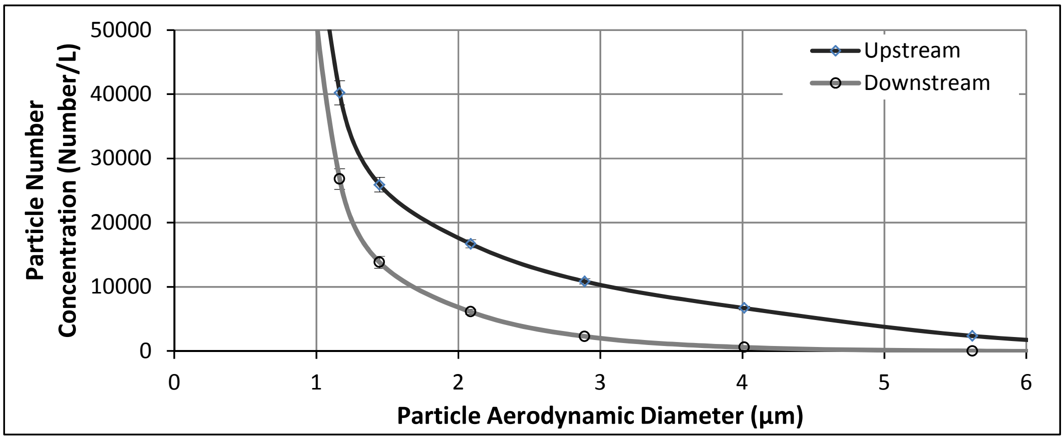


Fig. 3. Size distribution variation from a representative test.

Table 1. Results of the Initial Parametric Investigations for Multiple Round Nozzle Impactors.

Q (L/min)	Nozzle Dia (mm)	Number of Nozzles	S/W	$d_{50\ exp}$ (μm)	$\sqrt{Stk_{50exp}}$	Re	σ_g
175	6	6	2.0	3.88	0.51	6836	1.57
			2.4	4.04	0.54	6836	2.11
140	6	4	2.0	3.40	0.49	8204	2.62
			2.4	3.41	0.50	8204	2.08
175	6	4	2.0	2.50	0.41	10255	2.14
			2.4	2.52	0.41	10255	2.12
200	6	4	2.4	2.21	0.38	11720	2.12
108	3	8	2.0	1.55	0.40	6329	1.94
			2.4	1.53	0.39	6329	1.87
175	3	8	2.0	1.06	0.34	10255	1.40

The collection efficiency curves obtained for the optimized impactor nozzles for the PM_1/$PM_{2.5}$ are shown in Fig. 4. The variation in collection efficiency between different sets of experiment (n = 5) is depicted as error bars (one standard deviation). The experimentally determined cut points (d_{50}), sharpness of the collection efficiency curves (σ_g) and pressure drop (ΔP) are presented in Table 2. A configuration of 8 round nozzles of 3 mm each was used for PM_1 stage. The experimentally determined cut point for this stage was 1.06 μm, which corresponds to $\sqrt{Stk_{50}} = 0.34$. The sharpness of the collection efficiency curve was 1.40, which indicates good separation of particles larger than the cut point from the

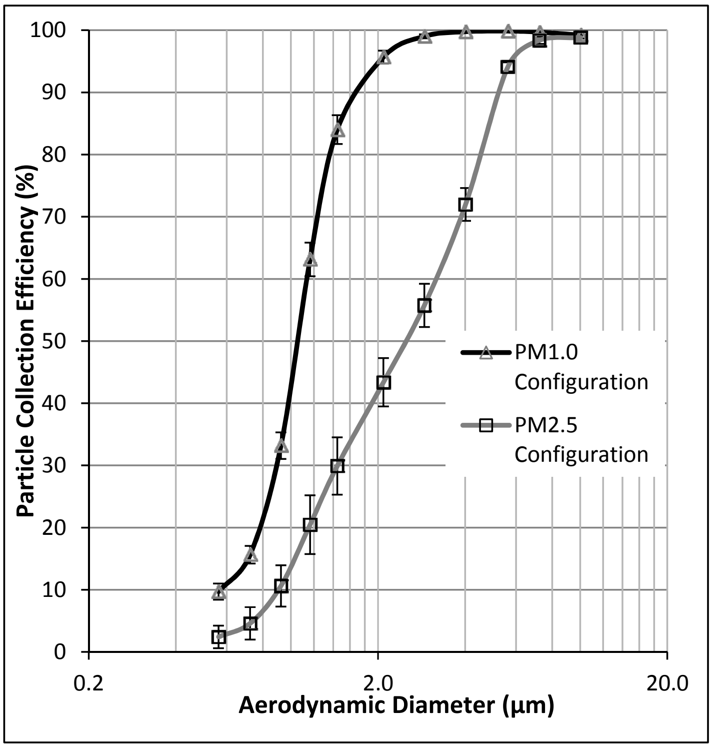


Fig. 4. Collection efficiency curves for optimum $PM_1/PM_{2.5}$ impactors.

Table 2. Design parameters and experimentally calculated characteristics of optimum impactor configurations.

Configuration	$PM_{2.5}$	PM_1
Physical Parameters		
Number of Nozzles	4	8
Nozzle Diameter (cm)	0.60	0.30
S/W	2.0	2.0
Theoretical Calculations		
U (cm/s)	258	515
Re	10255	10255
Experimental Results		
d_{50} (µm)	2.50	1.06
$\sqrt{Stk}$	0.41	0.34
ΔP (kPa)	0.35	1.07
σ_g	2.14	1.40

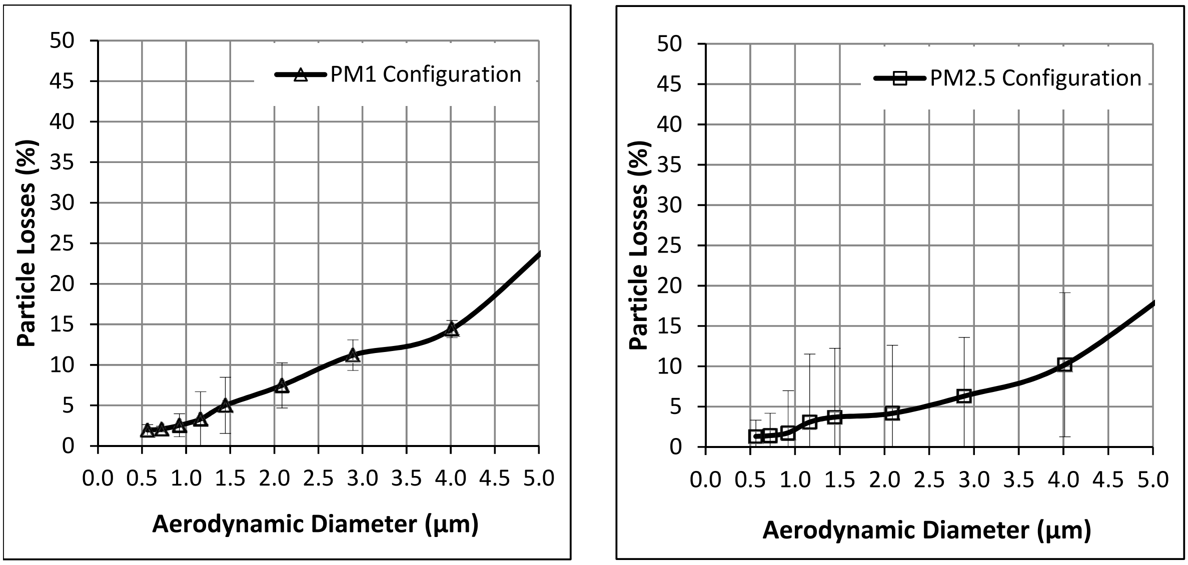
airstream. For particles above 2.0 µm the collection efficiency was higher than 94% which suggests that coarse particle bounce-off and re-entrainment losses were insignificant. Pressure drop was 1.07 kPa (4.3 inches of H_2O) which was fairly low.

A configuration of 4 round nozzles of 6 mm each was used for $PM_{2.5}$ stage. The experimentally determined cut point for this stage was 2.50 µm, which corresponds to $\sqrt{Stk_{50}} = 0.41$. Though the cutpoint was very precise, the sharpness value of the collection efficiency curve was a bit on the higher side with a value of 2.14 considering the efficiency ranges from 2.5% to 98% over the range of particle aerodynamic diameter considered. Pressure drop was 0.35 kPa (1.4 inches of H_2O) which was very low.

Since both the impactor stages have the same Re and S/W values, the difference in the sharpness of the efficiency curves could probably be due to the cross-sectional velocity of the air jet at the nozzle exit. $PM_{2.5}$ stage has double the nozzle diameter compared to the PM_1 stage, hence has higher chances of occurrence of non-uniform jet velocity profile across the nozzle diameter which affects the efficiency curve. On the other hand, using high volume impactors (Q higher than 500 LPM) have inherent disadvantage because of the possibility of loss of some amount of semi-volatile fraction and certain labile species (e.g., NH_4NO_3) (Zhang and McMurry, 1992; Cheng and Tsai, 1997). While a low flow rate sampler would be needed to run for longer durations. The impactor stages developed in this study have low pressure drop at adequately high flow rate and therefore could avoid such losses.

Jet-to-Jet Interaction and Cross-Flow Parameter

Flow fields and particle impaction characteristics are more complicated in multi-nozzle impactors than in single-nozzle impactors, since the divided jet of air has to penetrate cross-flowing air from different nozzles to impinge on the impaction plate. A study previously done by Fang *et al.* (1991) describes a cross-flow parameter expressed as a function of the geometric parameters for the multi-nozzle impactor to evaluate the role of cross-flow of jet streams on impactor characteristics ($nD_j/4D_c$ where n is the number of nozzles, D_j the nozzle diameter and D_c the outermost nozzle cluster diameter). The study further indicates that satisfactory collection characteristics can be obtained when the value of cross-flow parameter is less than 1.2. In the present study, the multiple-nozzle design was carried out in accordance with the above criteria to avoid jet-to-jet



(a) (b)

Fig. 5. Overall particle losses in the impactor for (a) PM_1 and (b) $PM_{2.5}$ configuration, respectively.

interactions and obtain better collection characteristics. The value of $nD_j/4D_c$ was well below the stated for both PM_1 and $PM_{2.5}$ configurations (= 0.12 for both configurations).

Nozzle and Wall Losses

It is also important to note that the collection efficiency curves shown in Fig. 4 include particles collected on both the impaction substrate and particles lost on the impactor walls and acceleration nozzle. Inertial particle losses within the impactor assembly, especially at the flow turns may be caused by the turbulent flow in the acceleration nozzle region considering the fact that the Reynolds number is on the higher side (Demokritou *et al.*, 2002a, b). Particle losses were quantified by measuring particles upstream and downstream of the impactor nozzles without employing the impaction substrate. Fig. 5 illustrates the particle losses (combined nozzle and wall losses) for both cases ($PM_1/PM_{2.5}$) as a function of the particle aerodynamic diameter. PM_1 configuration has higher jet velocity in the nozzle exit region which could be the reason for higher losses (especially larger particles) as compared to the $PM_{2.5}$ configuration. For PM_1 configuration, collection efficiency reaches above 90% for particle size 2 µm (Fig. 4) hence particle losses beyond 2 µm is of least concern. Similarly for $PM_{2.5}$ configuration, particle losses are well below 10% for particle diameter less than 3.5 µm. As evident from Fig. 3, the particle concentration was very low beyond 5 µm hence Fig. 5 was shown only upto 5 µm.

CONCLUSIONS

This study involved the design and development of an air sampler, which is capable of selectively removing the particles greater than 1.0 µm/2.5 µm on a greased impaction substrate at an operating flow rate of 175 LPM and collects the finer particles onto a standard 47 diameter filter paper. Validation of the developed impactors needs to be carried out against EPA approved samplers available at our campus before they can be employed in field studies. Once a successful validation has been done, the impactors could prove to be a very effective setup to selectively monitor $PM_1/PM_{2.5}$ on a routine basis and study finely time-resolved temporal variation of PM composition. This information can provide better insight into the various physico-chemical processes involved in fate and transport of PM during extreme dust and foggy events prevalent in the IGP. Such an impactor provides advantage over: a) impactors operating at very high flow rates which are prone to loss of certain amounts of semi-volatile fraction and labile species, b) low flow rate samplers which require long sampling durations.

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