Design, development, calibration and field evaluation of an indigenous $PM_{2.5}$ sampler

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This note presents the development, laboratory calibration and field evaluation of a single-stage impactor (SSI) for measurement of gas-borne particulate matter (PM), for a specific cut-off diameter of 2.5 μm. The SSI was designed for a flow rate of 6 lpm, and was calibrated using standard NaCl test aerosols against a commercially available ten-stage cascade impactor (0.056–18 μm). Field evaluation of SSI for $PM_{2.5}$ measurements in ambient air was carried out by collocating SSI and the ten-stage cascade impactor. The $PM_{2.5}$ measurements by SSI during laboratory calibration and the field study were found to be 1.06–1.08 times higher than the ten-stage cascade impactor measurements, indicating a satisfactory performance.

Keywords: Impactor, particulate matter, $PM_{2.5}$, test aerosols.

Physical and chemical characterization of particulate matter (PM) in the sub-micrometre range has gained considerable importance in the past few years, with applications such as air quality assessment, control of particulate emissions, epidemiological studies, drug-delivery systems and synthesis of nano-materials. Instruments for size-specific PM measurements have been developed and are capable of measuring in different size ranges. Figure 1 shows the sizing range of various instruments and their operating principles for aerosol characterization in the nanometre to micrometre size range. Instruments based on optical light scattering principle can size and count particles > 0.09 μm in diameter in real-time. Instruments based on inertial principle like cascade impactors can measure up to half an order of magnitude smaller than the optical instruments (e.g. 0.056 μm). Instruments based on electrical mobility of particles are commercially available and they can size and count particles up to 0.003 μm (3.0 nm) in near real time.

To address air quality management issues in urban areas, characterization of PM in ambient air is critical in identifying the various sources of pollution as well as quantifying their relative contributions to overall air quality[1]. Results from source apportionment studies have been used to formulate policy guidelines for the effective control of pollution from sources at local to regional levels[2].

The focus of the present study was to design an indigenous sampler for ambient PM measurements. Single-stage impactors (SSIs) are commonly used for collecting particles of specific cut-off diameters and cascade impactors are used for determining mass size distributions of aerosols. Both these impactors have the advantage of accommodating a variety of collection substrates, which may be subsequently analysed for chemical species in the sample. A reference method for measurement of $PM_{2.5}$ has been adopted by the United States Environment Protection Agency[3].

The present study was motivated by the need for an indigenous low-cost PM sampler. The objective was to develop an SSI to determine the mass of PM with a specific cut-off diameter, and to evaluate its performance.

Methods

Design considerations for SSI

The design and calibration methods for various single stage and cascade impactors are available in the literature[4–8]. The parameter that governs the impaction of particles accelerated through a nozzle is the Stokes number (St), and is given as[9]:

$$St = \frac{\rho d_p^2 u C}{9 \mu D_n}, \qquad (1)$$

where ρ is the density of the particle, d_p the diameter of the particle, u the average nozzle exit velocity, C the Cunningham slip correction factor, μ the viscosity of the flow medium, and D_n is the diameter of the nozzle.

Other design parameters for impactors include Reynolds number, nozzle-to-plate distance, throat length of the impactor and diameter of the impaction plate[4,10]. Marple[4] recommends that (a) the nozzle-to-plate distance for impactors having a round nozzle should be larger than 0.5 times the nozzle diameter; and (b) the Reynolds number should be about 3000 for sharp cut-offs. Mercer[11] reports experimental observations to determine the effect of nozzle-to-plate distance on the collection efficiency of round-nozzle impactors, and indicates that the collection efficiency stabilizes for a nozzle-to-plate distance ~ 1.5 D_n. Sethi and John[10] used a nozzle design which is somewhat different from that by Marple[4], and state that the difference does not affect the collection performance. The various nozzle geometries are shown in Figure 2. For a cut-off diameter of 2.5 μm, at a flow rate of 6.0 lpm, the nozzle diameter based on

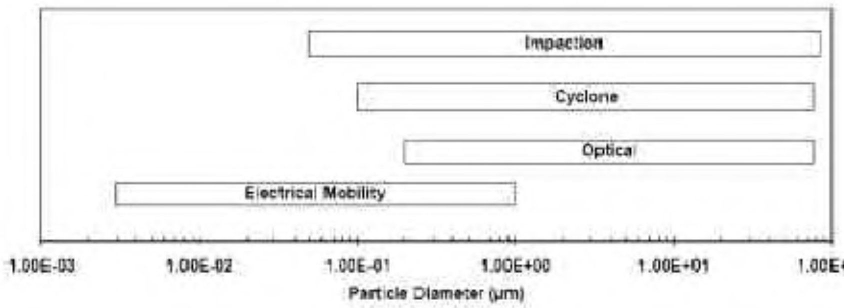

Figure 1. Sizing range of instruments and principle of operation (adapted from Hinds[9]).

Table 1. Data for design of Single Stage Impactor

Parameter	Units	Value	Remarks
Sample flow rate Q	lpm	6.0	
Viscosity of flow medium (air) μ	Pa.s	1.81×10^{-5}	
Density of flow medium (air) ρ	kg/m^3	1.205	
Diameter of the particle d_{50}	m	2.5×10^{-6}	Aerodynamic diameter
Density of particles ρ_p	kg/m^3	1000	Unit density
Cunningham slip correction factor C	#	1.0	Value assumed to be unity
Calculated Reynolds number Re	#	3016	*Re* should be about 3000 for sharp cut impactor (Marple[4])
Number of nozzles	#	1	
Calculated nozzle diameter D_n	mm	2.81	
Nozzle-to-plate distance	mm	4.2	1.5 times the nozzle diameter (Marple[4])
Throat length	mm	7.1	2.53 times the nozzle diameter (Sethi and John[10])
Diameter of impaction plate	mm	20.0	Adequate size to hold a standard size (25 mm) filter

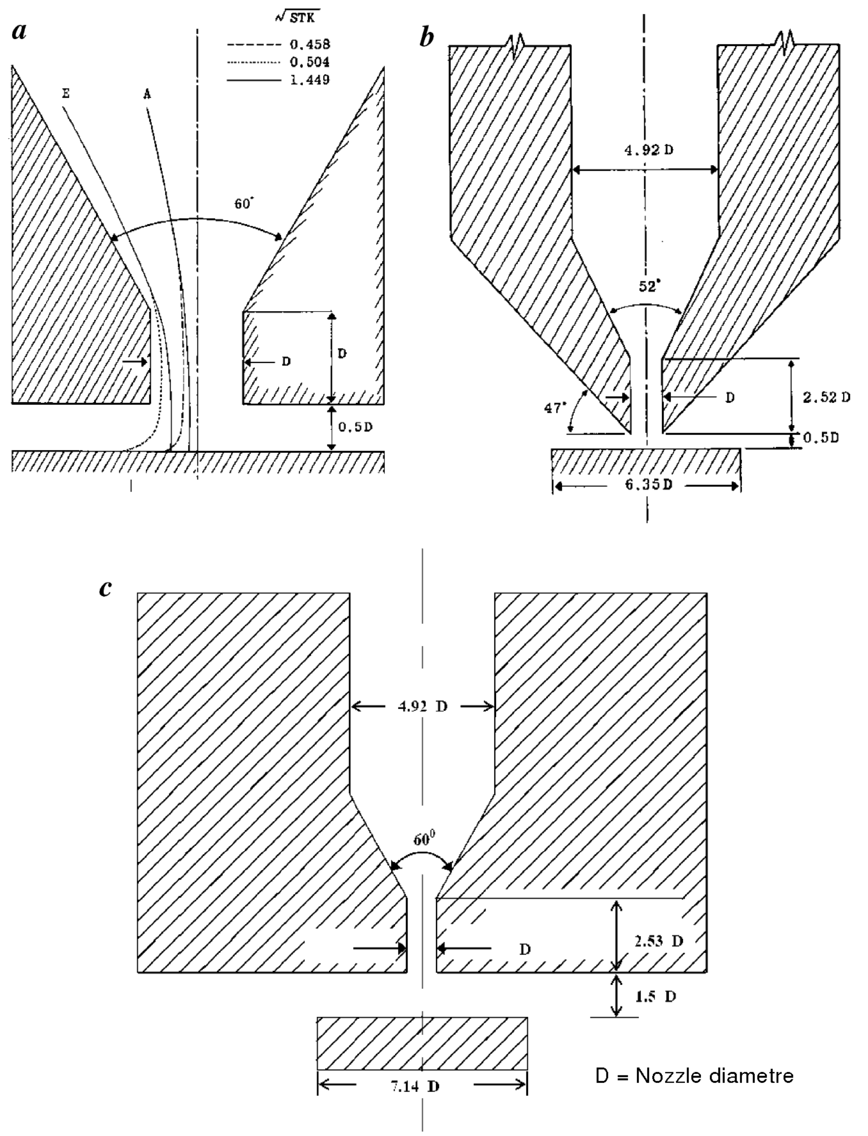

Figure 2. Comparison of various nozzle geometries. ***a***, Marple[4]; ***b***, Sethi and John[10]; and ***c***, Present work. In the present work, a nozzle-to-plate distance of 1.5 *D*, a throat length of 2.53 *D*, and a convergence angle of 60° were used.

Stokes number of 0.22 and for 50% collection efficiency was calculated to be 2.8 mm. This was arrived at iteratively after consideration of $Re \sim 3000$ as recommended by Marple[4]. A nozzle-to-plate distance of 1.5 D_n was used in the present design[11]. Design data for the impactor developed in this study are given in Table 1.

The dimensions of the fabricated impactor are shown in Figure 3 *a–f*. The body of the SSI was fabricated with aluminium, and impaction plate and filter holder assembly were made with stainless steel. The assembly diagram of SSI is given in Figure 4 *a* and a photograph of the assembly is shown in Figure 4 *b*. PM size fraction greater than 2.5 µm gets collected on the plate by impaction, and the gas stream with smaller particles is made to pass through a filter paper. The impaction plate may also be used to hold a suitable collecting substrate for gravimetric and chemical analysis of the size fraction greater than 2.5 µm.

Flow through the nozzle was monitored by measuring the pressure drop across the nozzle using the tappings provided in assembly parts I and II (Figure 4 *a*). The pressure drop (Ä*p*) across an orifice is given by[12]:

$$\Delta p = \frac{\rho u^2}{2 C_D^2}, \tag{2}$$

where *ñ* is the density of the particle, *u* the flow velocity, and C_D is the coefficient of discharge through a nozzle. A bubble meter set-up (Figure 5) was developed for calibration of flow in the SSI. The results of Ä*p* vs flow were plotted as in eq. (2) and indicates a C_D value of 0.76 (Figure 6).

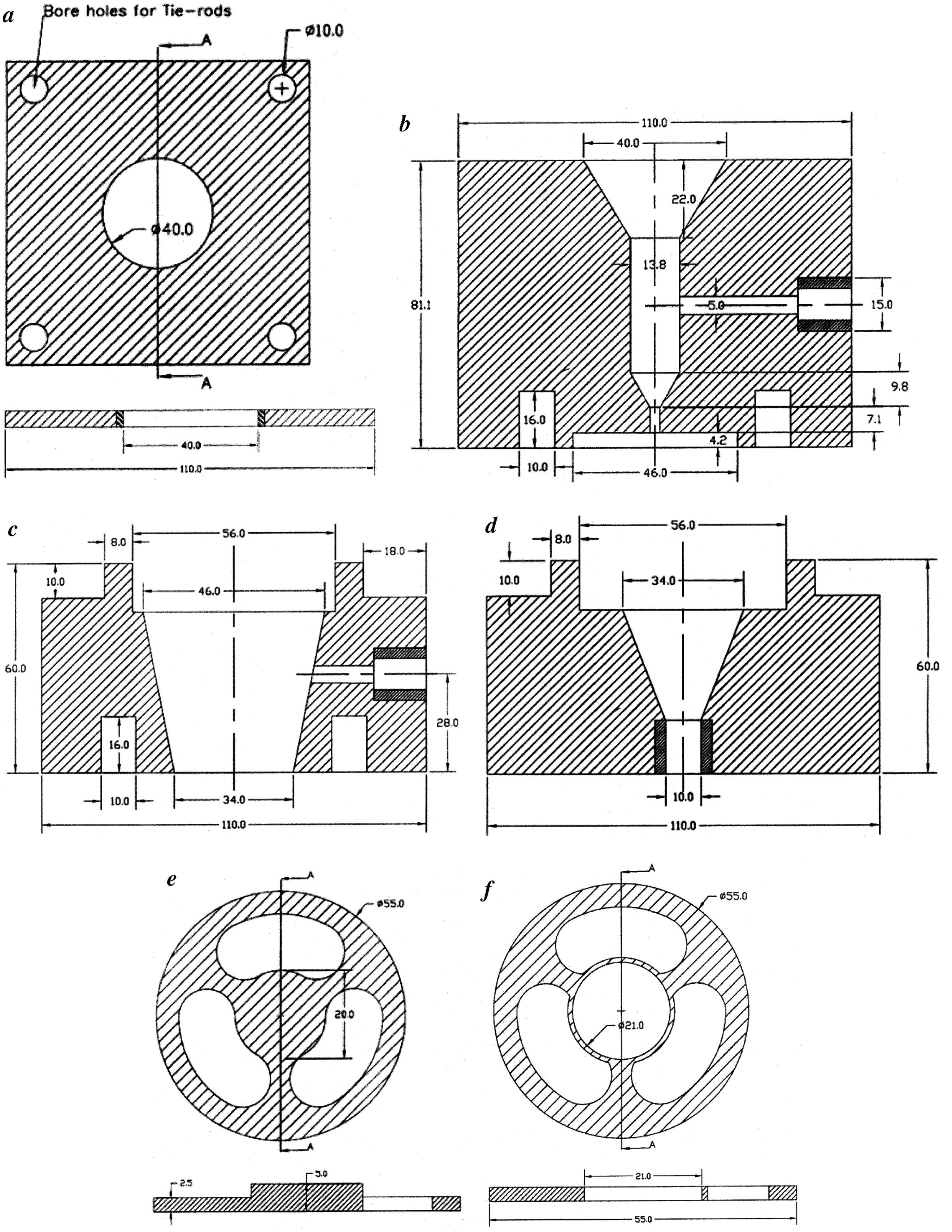

Figure 3. (*contd…*)

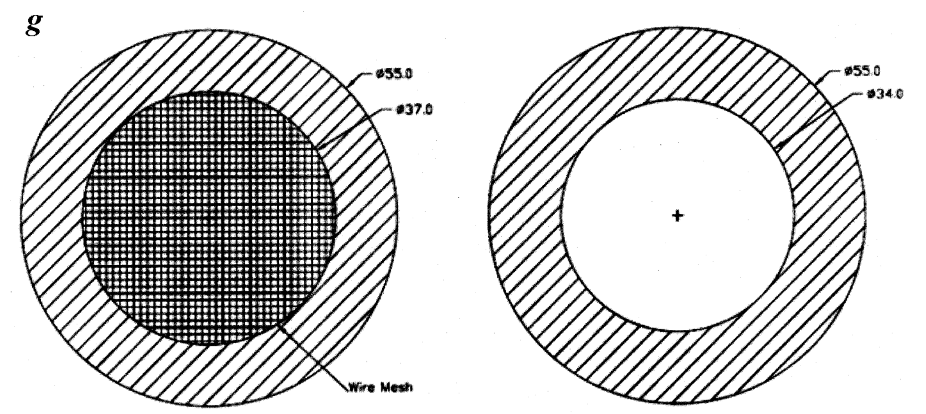

Figure 3. ***a***, Top view and sectional view (along A–A) of the inlet plate. ***b–d***, Sectional views of (***b***) SSI – Part I, (***c***) SSI – Part II and (***d***) SSI – Part III; ***e***, Top view and sectional view (along A–A) of impaction plate. ***f***, Top view and sectional view (along A–A) of impaction-plate hold ring. ***g***, Top view of after-filter holder plate with wire mesh (28 mesh cover ring).

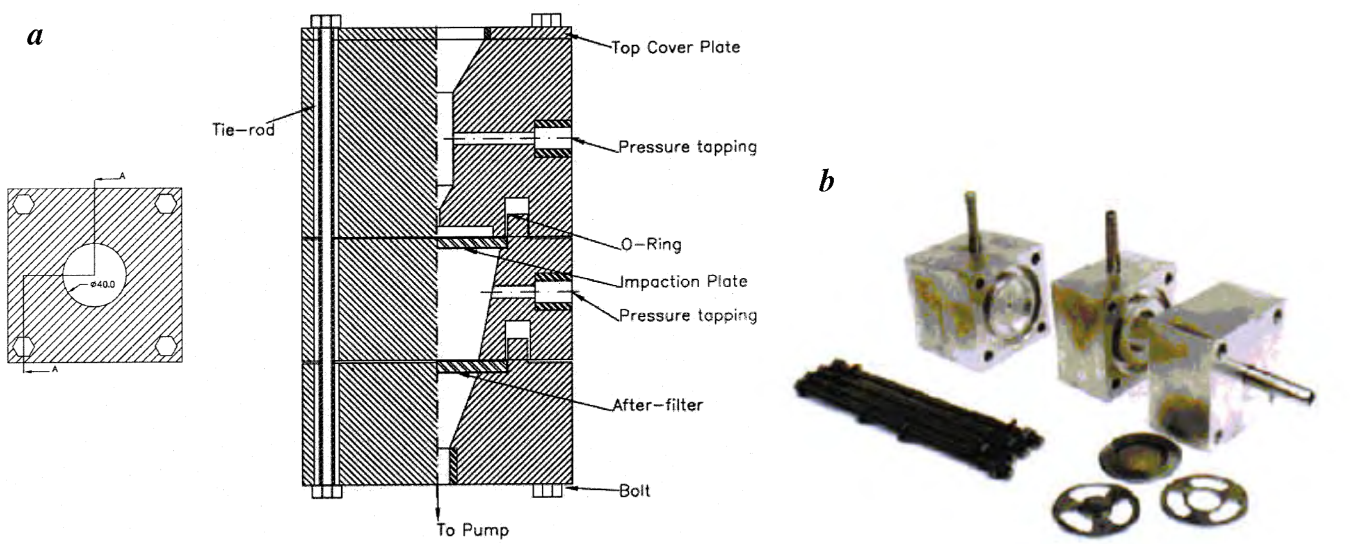

Figure 4. ***a***, Sectional view (along A–A) of complete assembly of SSI and ***b***, Photograph of SSI.

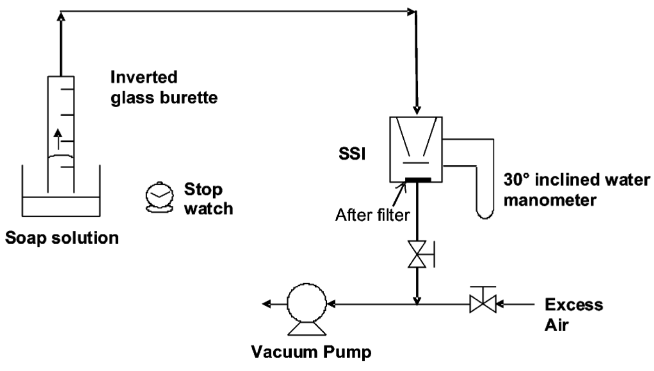

Figure 5. Experimental set-up to calibrate flow through SSI using a bubble meter.

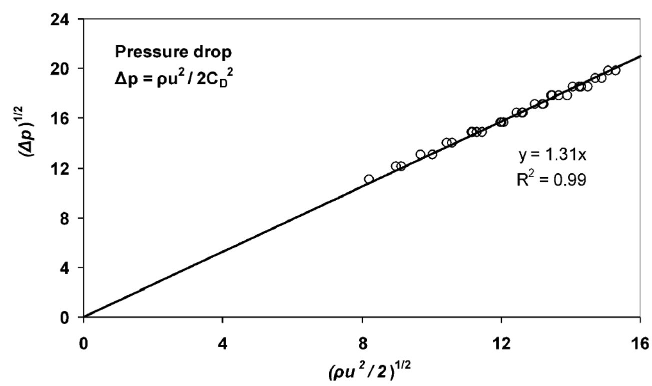

Figure 6. Results of flow calibration of SSI using bubble meter set-up. A C_D value of 0.76 was found to fit experimental data.

Table 2. Description of various instruments used in the study

Name	Specification	Details
Atomizer	Orifice diameter	~0.3 mm
	Operating parameters	3 lpm at 240 kPa (35 psig)
Diffusion dryer	Length	1 m
	Inner diameter	25 mm (wire gauge)
	Outer diameter	100 mm
	Desiccant	Silica gel self-indicating (blue)
Dilution chamber	Material (volume)	Acrylic (7000 cm^3)
Manometer – 1	Type	U-tube, mercury
	Range	0–20 cm Hg
Manometer – 2	Type	30° inclined, water
	Range	0–10 cm H_2O (inclined)
Rotameter – 1	Flow range	1–10 lpm
Rotameter – 2	Flow range	5–50 lpm
Vacuum pump – 1	Type	Reciprocating dual-piston
	Vacuum performance	0 inch Hg – 165 lpm
	(Hg inch vs lpm)	10 inch Hg – 75 lpm
Vacuum pump – 2	Type	Diaphragm
	Vacuum performance	0 inch Hg – 50 lpm
	(Hg inch vs lpm)	10 inch Hg – 28 lpm
Weighing balance	Make and model	Sartorius BP 210D, Germany
	Least count	10 µg

Description of test aerosol set-up

Test aerosols were generated using a compressed air atomizer[9]. In this type of atomizer, compressed air is passed through an orifice. The liquid is aspirated from a reservoir and sprayed as a jet. Larger droplets are removed by impaction within the atomizer, and the smaller droplets flow out with the air stream as aerosol. The atomizer was operated at a flow rate of 3 lpm and a pressure of 240 kPa (35 psig).

NaCl solution is routinely used for generation of test aerosols. The solution droplets are dried using a 'diffusion dryer'[13]. In a diffusion dryer, the aerosol passes through a screen tube surrounded by a desiccant. Droplets lose moisture as they pass through the diffusion dryer, and result into dry particles of salt at the exit. A diffusion dryer was fabricated in a PVC pipe and fitted with a cylindrical wire mesh (20 mesh) to separate the desiccant from the aerosol stream (Table 2). Silica gel (self-indicating blue, 6–20 mesh) was used as the desiccant and the device was tested for flow rates up to 10 lpm and pressures up to 138 kPa (20 psig).

Three different test aerosols were generated using three concentrations of aqueous solution of sodium chloride in the atomizer. The NaCl droplet aerosol (6 lpm at one atmosphere) was diluted 7–8 times using 36–42 lpm of dry filtered air. Detailed specifications of various instruments used in this study are given in Table 2.

Calibration of ten-stage cascade impactor and SSI

The experimental set-up is shown schematically in Figure 7. The apparatus consists of the test aerosol generation system and the particle sampling system. A commercially available ten-stage cascade impactor (non-rotating MOUDI™, MSP Corporation, Minneapolis, MN, USA) was calibrated, and the SSI was collocated for comparison.

The cut-off stages in the cascade impactor were 18, 10, 5.6, 2.5, 1.8, 1, 0.56, 0.32, 0.18, 0.10, and 0.056 µm. Flow rate of 30 lpm through the cascade impactor was maintained by monitoring the pressure drop between stages 7 and 9 as 13.4 cm Hg. Aluminium foils were used as substrates in the impaction stages of the ten-stage cascade impactor, and glass fibre filter was used as the after filter.

For SSI, aluminium foil was used as substrate in the impaction stage and Nuclepore membrane was used as the after filter. Flow rate of 6 lpm in SSI was maintained by monitoring the pressure drop across the nozzle as 5.7 cm H_2O using an inclined manometer.

The filters were conditioned for 24 h in a desiccator before weighing on a microbalance having a least count of 10 µg (Sartorius BP 210D, Germany).

Field study

Performance of the SSI for ambient air sampling was carried out at a National Ambient Air Quality Monitoring Program site, which is categorized as a 'commercial' location in Mumbai. The ten-stage cascade impactor was collocated with the SSI. Eight-hourly samples were collected continuously for one week in February 2005 for the study.

Results and discussion

The results of calibration of the ten-stage cascade impactor are plotted in Figure 8. Cumulative mass percentages have been plotted against the average diameter for

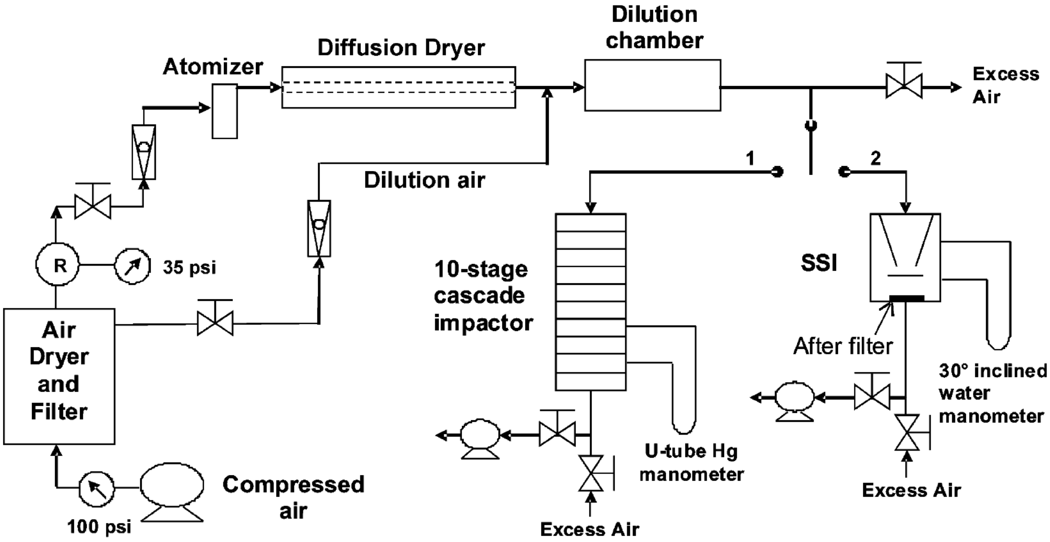

Figure 7. Experimental set-up for comparison of SSI and ten-stage cascade impactor using a standard NaCl aerosol. Connection (1) was used to calibrate the ten-stage cascade impactor.

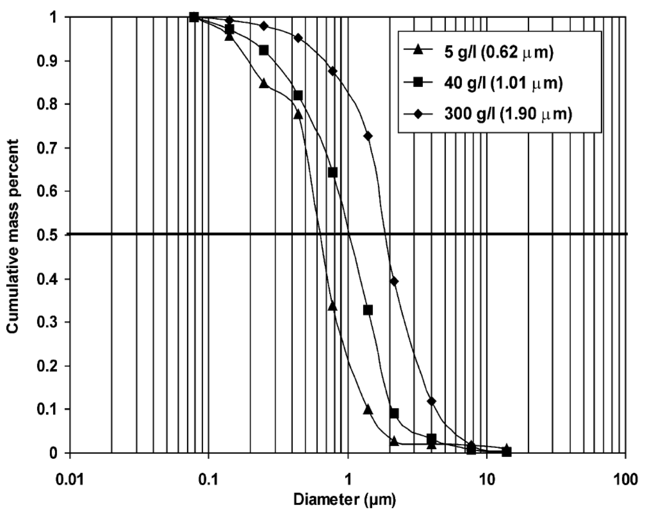

Figure 8. Results of ten-stage cascade impactor calibration using NaCl test aerosols. Three NaCl concentrations result in three MMADs (shown in brackets), each approximately doubled for nearly eight times increase in concentration.

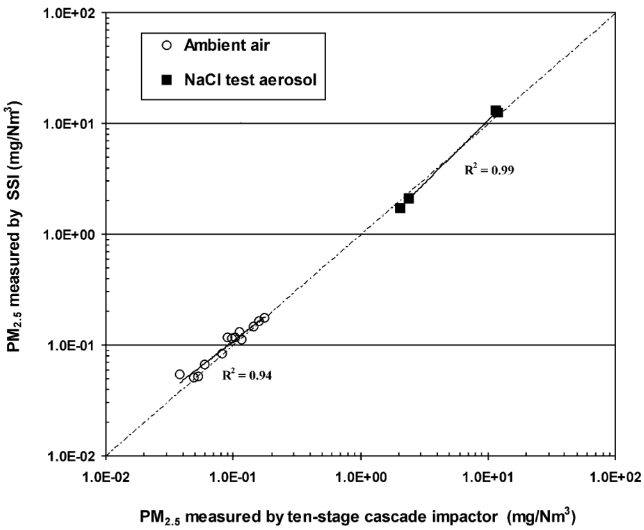

Figure 9. Comparison of SSI with ten-stage cascade impactor measurements of $PM_{2.5}$.

every size interval of the ten-stage cascade impactor for the three mass size distributions of NaCl solution concentrations. Mass median aerodynamic diameter (MMAD) of dry particle size is directly proportional to the solute concentration. When solution concentration is increased eight times, MMAD is expected to increase by a factor of two. The results indicate a near-twice increase in MMAD as expected with eight times increase in NaCl concentration for 5 to 40 g/l and 40 to 300 g/l step increases in the concentration.

Figure 9 shows results from laboratory calibration and field evaluation of SSI. To compare the < 2.5 µm size fraction of SSI with the ten-stage cascade impactor, the masses collected at all stages below stage 4 (i.e. stage 5 to the after filter) were added. The *r*-squared values for calibration and field evaluation studies were 0.99 and 0.94 respectively. For the NaCl test aerosols, $PM_{2.5}$ as measured by SSI was found to be 1.08 times greater than that measured by the ten-stage cascade impactor. For ambient air measurements, $PM_{2.5}$ measurements by SSI were 1.06 times greater than that of the ten-stage cascade impactor measurements. These results indicate satisfactory performance of SSI for $PM_{2.5}$ measurements.

Chemical characterization of ambient aerosols is helpful in the identification of various sources of pollution in an area. Different collecting substrates (membrane filters, quartz filters, glass fibre filters) can be used as the after filter in SSI depending upon the analytical method and/or chemical species to be analysed[14]. The impaction plate can also hold a suitable collecting substrate for gravimetric and chemical analysis of the $>PM_{2.5}$ fraction.

Summary and conclusions

This note is an attempt to make available a relatively simple PM-measuring instrument. The proposed instrument has been evaluated for performance against a commercially available ten-stage cascade impactor. Detailed machine drawings of SSI have been given to facilitate replication of this effort as needed. Simple calibration techniques such as a bubble meter set-up and a test aerosol generation system using NaCl solutions have been described as alternatives to the otherwise relatively expensive approaches of using PSL particles and/or mono-disperse particle generation using instruments like vibrating orifice aerosol generator. Further, the proposed design of the SSI can be used for sizing particles other than 2.5 µm. A cut-off diameter range of 2.5–6 µm can be selected based on Reynolds number range[4] of 500–3000 for the corresponding flow rates of 6.0 to 1.0 lpm.

At a flow rate of 6 lpm and ambient air sampling duration of 24 h, the sample collected on the filter substrate is adequate for gravimetric and chemical analyses. For particular sampling requirements which need higher time resolution, such as peak-hour traffic sampling, and episodic sampling, a higher flow rate is required in order to collect an adequate sample. The present design may be extended in the development of a high flow rate multi-nozzle impactor.

While the evaluation reported here has been restricted to test NaCl aerosols and ambient PM, similar performances for source measurements of PM (e.g. exhaust sampling from diesel and petrol combustion engines, producer gas from thermal biomass gasifiers), and indoor air measurements have also been successfully measured by SSI in some of our other studies[15].

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