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Field performance evaluation of a newly developed $PM_{2.5}$ sampler at IIT Kanpur

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ABSTRACT

In order to meet the challenges of growing air pollution for a developing nation and to measure the ambient fine particles ($PM_{2.5}$, particles having aerodynamic diameter less than 2.5 μm) on routine basis an air sampler was designed, developed and evaluated in the field. The impactor removes particles greater than 2.5 μm from the air stream via impacting them onto a vacuum grease substrate and finer particles get eventually collected on a backup filter. Various impactor nozzles with conical geometry were designed based on the published theoretical design equations. A detail parametric investigation was carried out which resulted in the optimum impactor nozzle design. For this exercise, a novel dry aerosol generator was employed in addition to the well known time-of-flight instrument, APS (Aerodynamic Particle Sizer, Model 3021, TSI Inc.). The average particle losses for the impactor nozzle as well as the sampler body were below 10% and the overall pressure drop (including a backup 47 mm filter) through the $PM_{2.5}$ sampler was only 2 in. of H_2O. This developed $PM_{2.5}$ sampler operates at a flow rate of 15 LPM. Field performance of this sampler was evaluated through co-located sampling with a high volume $PM_{2.5}$ reference sampler (HVS, GEM-BLI Model 2360, Tisch Environment Instrument) within the IIT Kanpur campus. The sampling period was 10 h long and it was carried out on six different days. The entire sets of filters were analyzed gravimetrically followed by their chemical analysis for elemental and anionic analyses. The particle mass, elemental, and anionic concentrations obtained with this newly developed $PM_{2.5}$ sampler as well as those from the reference HVS sampler showed moderate to good correlation.

1. Introduction

In the recent years, air pollution has emerged as a major problem mainly attributed to continuous emission of particulate matter, and many harmful gasses into the ambient environment, such as carbon dioxide, methane, oxides of sulfur and nitrogen. Particulate matter originates from a variety of sources, including diesel trucks, power plants, industrial processes and biomass burning among others (Chakraborty and Gupta, 2010). There is anxiety growing concern over the undesirable health effects of air pollution, especially in urban areas, where many sources of air pollutants are present. $PM_{2.5}$ has received much interest as various epidemiological and toxicological studies have shown substantial evidences of direct harmful health impacts of $PM_{2.5}$ on the human population.

Mass concentration of $PM_{2.5}$ has shown correlation with health effects in sensitive population (elderly and diseased) and measurable functional changes in the human cardiovascular and respiratory system (Pope et al. 2002). Studies conducted by Donaldson and MacNee (1998) and Ferin et al. (1999) showed that for the same amount of PM mass deposited in the lung, toxicity tends to increase as particle size decreases. This might be attributed to the increased surface area per unit mass available or to the ability of finer particles to penetrate the lung tissues and subsequently enter into 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). However, even healthy people might experience temporary symptoms from acute exposure to elevated levels of particle pollution. Also, various exposure studies have found that fine particulate matter concentrations of ambient environment and personal exposure are more closely associated, especially for certain sensitive individuals (elderly and diseased) (Rojas-Bracho et al., 2000; Sarnat et al. 2000; Demokritou et al. 2001a,b).

At this time, accurate measurement of $PM_{2.5}$ is the first step towards its effective control and abatement. Impactors are widely used for sampling and separation of air borne particulate matter due to their sharp separation, high collection abilities and relatively simple design. These 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 (Hinds, 1999). Whereas, finer particles will follow the bending air streamlines and will eventually get collected on a backup filter kept downstream of the impactor substrate. Impactors have been in existence for more than a century. Several researchers in the past have come up with theoretical equations and curves to accurately

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predict the collection of particles and nozzle design for flat impaction surfaces (Marple and Willeke, 1976; McFarland et al., 1978). These design equations were primarily based on the empirical solution of Naviers–Stokes equations for different conditions of air flow around a flat or round impaction substrate. In the past, research has also been carried out to study the effect of change in impaction surface characteristics on the collection efficiency curve and the cutpoint of the impactor (Tsai and Cheng, 1995; Huang and Tsai, 2002). Over the years, several types of inertial impactors have been developed (Marple et al., 1991; Demokritou et al., 2002a,b,c; Furuuchi et al., 2010) to measure the particulate matter and have served as a good alternative to expensive real-time optical based particle spectrometers (Liu et al., 2010). There have been many attempts previously made to carry out intercomparisons, both at laboratory scale and under different field conditions, to evaluate newer PM measurement techniques vis-à-vis the traditional inertial based sampling techniques (MacIntosh et al., 2002; Kim et al., 2004). However, there has been a constant and specific need felt for the development of new impactors for various applications (Marple, 2004) especially in the developing countries, characterized with newer sources and different ambient conditions, where air pollution has emerged as a major problem (Singh et al., 2010).

This paper presents the design, development, and field performance evaluation of a newly developed $PM_{2.5}$ air sampler that utilizes silicone vacuum grease as an impaction substrate. In the past, researchers have found that silicon vacuum greased coating with a thickness of a few microns can rapidly become ineffective. This is likely due to the fact that the particles accumulate onto the surface and subsequent incoming particles bouncing off as they hit the previously deposited particles. Thick and smooth grease coating of 0.22 cm or greater can rectify this problem and can withhold the collected particles on the surface of the grease more effectively (Hill et al., 1999). This kind of impaction substrate was found to be very effective in eliminating particle bounce-off as particles were rather deeply embedded into the grease and silicone oil wetted their surface soon after impaction onto the grease substrate (Turner and Hering, 1987; Demokritou et al., 2001b). The new $PM_{2.5}$ sampler presented here includes a single impaction stage containing vacuum grease and a backup filter to collect particles below 2.5 µm. The developed $PM_{2.5}$ sampler was subjected to field evaluation by co-locating it with a popular HVS sampler. In addition to the gravimetric data, chemical compositions of the collected particles with the two samplers were quantitatively compared.

2. Theoretical consideration

According to the impaction theory, the cut point of the impaction stage can be calculated by using the dimensionless Stokes number (Stk). Stk is the main governing parameter that is responsible for impaction which is defined as follows:

$$Stk = \frac{\rho_p d_p^2 U C_c}{9 \eta D_j} \tag{i}$$

Where, ρ_p is the particle density (kg/m^3), η is the air dynamic viscosity (Pa.s), d_p particle diameter (µm), U jet velocity in the impactor nozzle (m/s), D_j nozzle diameter (m), and C_c Cunningham slip correction factor, and P is absolute pressure (kPa) (Baron and Willeke, 2001).

$$C_c = 1 + \frac{1}{Pd_p}\left[15.60 + 7.00\ \exp\left(-0.059Pd_p\right)\right] \tag{ii}$$

The theoretical d_{50} (cut point) can be calculated by using the following equation (Hinds, 1999):

$$d_{50}\sqrt{C_c} = \left[\frac{9\pi\eta D_j^3 (Stk_{50})}{4\rho_p Q}\right]^{1/2} \tag{iii}$$

This equation works fairly well for flat surfaces. The Reynolds number can also be calculated by using the following equation:

$$Re = \left(\rho_{air} U D_j\right) / \eta \tag{iv}$$

Where ρ_{air} is the air density (g/m^3), U is the flow velocity (m/s).

3. Materials and methods

3.1. Impactor design and fabrication

Various impactor nozzles were designed based on the Eqs. (i)–(iv). A dry aerosol generator was employed using talcum powder to produce a stable flow of polydisperse aerosol (Fig. 1). These impactor nozzles (along with impaction substrate unit) were tested individually using a laboratory setup as shown in Fig. 2. A time-of-flight based instrument (Aerodynamic Particle Sizer, Model 3021, TSI Inc.) was employed to test the performance of the impactor. Since, APS directly provides the particle aerodynamic diameter so density of the talcum powder was not required for any calculations. Parametric investigations were carried out using impactor nozzles of different diameters, varying overall airflow rates through the impactor, in order to obtain the best possible PM collection efficiency and separation curve for the desired cutpoint of 2.5 µm. Ratio of nozzle to substrate distance and nozzle width (S/W) was kept constant at 1.3 as suggested from the past studies (Demokritou et al., 2001a; Demokritou et al., 2002a,b).

The sampler was fabricated from the metal aluminum as this metal is corrosion resistant, light weight; there is no problem of static charge and easy to machine as per design specifications. Also, it can be artificially or naturally (via atmospheric oxidation) anodized to prevent corrosion and minimize mechanical wearing of sampler parts and cut down the overall sampling losses. The main impactor consisted of one round impactor nozzle, which was actually conical in shape, one spacer and impaction substrate plate. For the impaction stage, a smooth layer of silicone vacuum grease (2 mm thick) was used as an impaction substrate. This was necessary to minimize bounce-off and break-up losses of large particles. A smooth impaction substrate layer was created from vacuum-grade silicon grease, using a razor blade (Demokritou et al., 2002a,b). The sampler also had a rain cover at the inlet. Fig. 3 shows the developed air sampler as well as its internal components in the sequence in which they are arranged inside it including a 47 mm filter holder inside it.

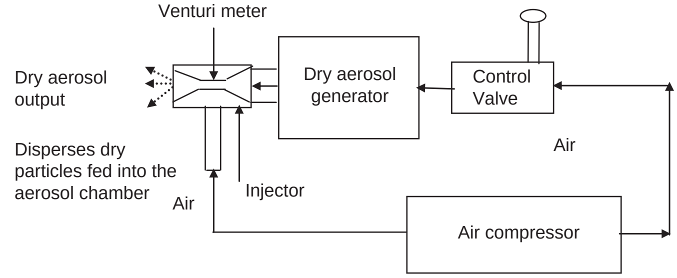

Fig. 1. Detailed schematic of dry aerosol generator.