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VIRTUAL IMPACTORS: A NOBLE DEVICE TO GENERATE HIGH CONCENTRATION MONODISPERSE AEROSOLS

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ABSTRACT

A solid or liquid particle suspended in a gas which is usually air is called an aerosol. Dust, fume, smoke, mist, fog, smog, and cloud are all examples of aerosols found in nature. One of the important applications of aerosol technology is the production of monodisperse test aerosols used for aerosol research, calibration, testing and development of air-cleaning and air-sampling equipments and pollution abatement. The characteristics of an ideal aerosol generator are a constant and reproducible generation of monodisperse, stable, uncharged, spherical aerosol particles whose size and concentration can be easily controlled. Atomization produces aerosols with sufficient mass concentration but the generated aerosols are highly polydisperse. Therefore, polydisperse aerosols produced by atomization should be subsequently segregated to narrow size range so as to obtain aerosol appropriate for use as a test aerosol. A monodisperse aerosol is usually defined as one that has a geometric standard deviation of less than 1.2. An aerosol having geometric standard deviation from 1.2 to 1.5 is said to be narrowly distributed. Polydisperse aerosols have geometric standard deviation greater than 2.0. Virtual impactors are widely used in the sampling of particles because they generate high concentration aerosols. This technology is new in Bangladesh. This paper describes the technical aspects of virtual impactor so as to introduce the reader with this new technology. Results of experimental studies performed with an improved virtual impactor have also been described. It was possible to generate narrowly distributed aerosols with the improved virtual impactor employed.

Keywords: Aerosols, Virtual impactors, Monodisperse.

1. INTRODUCTION

A monodisperse virtual impactor type aerosol generator is used for various purposes, e.g., instrument calibration, aerosol research, development and testing of air-cleaning and air-sampling equipments, inhalation tests etc. Various devices have been employed to produce aerosol droplets (Hinds 1982; Berglund and Liu 1973), namely liquid atomizer, compressed air nebulizer, vibrating orifice aerosol generator, spinning disk generator (Simpkins 1997) and condensation generator. Liquid atomizers produce polydisperse aerosols of high mass concentration whereas the other aerosol generators produce monodisperse aerosols of very low mass concentration (Chein 1994). However, characteristic of an ideal monodisperse aerosol generator is a constant and reproducible output of single-sized, spherical aerosol droplets which are electrically neutral and whose size and concentration can be easily controlled. The virtual impactor is a device which is used for the inertial separation of airborne particles (Loo et al. 1976; Dzubay et al. 1975). In a conventional type of virtual impactor, particle laden air is accelerated through a nozzle and then impinges into a collection probe that is slightly larger in diameter than the nozzle. The particles larger than the cut off size have enough inertia to penetrate deep into the receiving tube and follow the minor flow (Marple et al. 1990) which is usually about 5-10\% of the mainstream flow. The major flow, containing particles smaller than the cut off size, makes a sharp turn around the collection probe and exits. However, the minor flow would still contain a small amount of fine particles. An improved virtual impactor employs a central clean air flow to reduce or eliminate the fine particle contamination in the minor flow (Masuda et al. 1979; Chen et al. 1986). The clean air core prevents small particles from entering the center of the acceleration nozzle and, therefore, small particles can follow the major flow better. Recently, it was experimentally determined (Li and Lundgren 1997) that to reduce fine particle contamination in the minor flow, the clean air core diameter should be at least twice the converging nozzle diameter and that the clean air core should be positioned so that the ratio of the clean air flow velocity to the aerosol flow velocity ranges from 1.5 to 5.0 at the outlet of the clean air tube. A well-designed virtual impactor should have good separation characteristics like no fine particle contamination in the coarse particle flow (minor flow) and few or no internal losses (Asgharian and Godo 1997).

Controlling the size of the aerosols in the minor flow is very important to obtain the test aerosols. No work has yet been reported showing the effect of controlling parameters on which the size of the output aerosols. The present study is an attempt to investigate the effect of solution concentration and minor flow rate on the size of aerosol particles in the minor flow and also to prescribe the relationship between them. The type of aerosol generator described in this study has the ability to produce a high concentration of monodisperse aerosols. It has two stages - a generation chamber stage and a virtual impactor stage as explained in experimental procedure. An atomizer is used to produce polydisperse aerosols at the bottom of the aerosol generation chamber. The larger droplets are removed by gravitational settling as the polydisperse aerosol travels vertically through the generation chamber. Droplets smaller than cut off size are subsequently eliminated in the virtual impactor stage.

2. THEORY

The size of monodisperse aerosols generated in the aerosol generator can be controlled by controlling minor flow rate and solution concentration used.

2.1 Particle size variation with the concentration of solution

The size of monodisperse aerosols can be controlled by changing the concentration of liquid solution according to the relation:

$$C_c = \frac{V_p}{V_d} = \frac{{d_p}^3}{d_d^3} \qquad (1)$$

where, C_c = solution concentration, V_p= Volume of solute from which final particles are formed, V_d= Volume of solvent from which initial droplets are formed, since the volume of solute is negligible compared to the volume of solvent d_p= diameter of particle and d_d= diameter of droplet. The value of the cut off diameter of droplets in the generation chamber and can be determined from the analytical studies (Nevers 1995). Cut off diameter in the generation chamber is always fixed since the flow rate through the generation chamber is fixed. Hence, depending on the final particle diameters d_p, the solution concentration, C_c is varied to obtain it.

The particle diameter is related to aerodynamic diameter as follows:

$$d_p = D_{pa}\left(\frac{\rho_a}{\rho_p}\right)^{\frac{1}{2}} \qquad (2)$$

where, D_{pa} = aerodynamic diameter of the particle, ρ_a = water density and ρ_p = particle density. Aerodynamic diameter may be defined as the diameter of unit density particle whose settling velocity is the same as original particle. Since the solute DOP (di-octyl phthalate) density is very close to water (unit) density, therefore, the relationship can be used here also. Subsequently, Eq. (1) yields:

$$C_c = \frac{D_{pa}^3}{d_d^3}\left(\frac{\rho_a}{\rho_p}\right)^{\frac{3}{2}} \qquad (3)$$

Eq. (3) exhibits the relationship between aerodynamic diameter of the particle and solution concentration of solution strength.

In a real impactor, the nozzle flow divides equally into two flows due to impaction on the flat plate placed at right angles to the nozzle flow. Hence, the flow field is uniform in a real impactor provided the flow rate (Q_1) through the nozzle is constant. But in a virtual impactor, this is not the case. Here, keeping the total flow rate (Q_1) through nozzle constant, the minor flow rate (Q_m) through collection probe can be changed by changing the major flow rate (Q_2) operating the vacuum pump.

So, in a virtual impactor, the effective velocity responsible for pushing the particles into minor flow is the difference of velocities ($V_1 - V_2$), V_1 and V_2 being the velocities in nozzle (total) flow and major flow respectively. Stokes number for a virtual impactor is given by:

$$S_{tk} = \frac{\tau(V_1 - V_2)}{D/2},$$

where, τ is the relaxation time of the particle. Putting

$\tau = \frac{\rho_p d_p^2}{18\mu}$ in the above equation gives

$$9\mu D(S_{tk})_{50} = \rho_p d_{p50}^2\left\{\frac{Q_1}{A_1} - \frac{Q_1 - Q_m}{A_2}\right\} \qquad (4)$$

Where $S_{tk/50}$ and d_{50} are stoke number and cut-off diameter respectively at 50% collection efficiency, A_1 and A_2 are areas of totals and major flows respectively and Q_2=(Q_1- Q_m).

The collection efficiency may be defined as the ratio of the number of particles collected in the minor flow to the total number of particles delivered by the atomizer. Keeping Q_1 to be constant and separating the constant terms, Eq. (4) yields:

$$d_{p50}^2 = \frac{C}{Q_m} \qquad (5)$$

where C is a constant. Hence the cut off diameter of generated particles is inversely proportional to the square root of minor flow rate. Thus, by varying the minor flow rate, the desired particle size can be produced.

3. EXPERIMENTAL PROCEDURE

The experimental set up is shown in Fig. 1. A simplex, solid-cone atomizer (Delavan, Model DLN 29713-2) was installed at the bottom of a vertical perspex generation chamber 0.15 m in diameter and 1.5 m height. The atomizer generates clouds of aerosols from a liquid solution of 10% DOP in ethyl alcohol at a constant atomizing air pressure of about 117 kPa Polydisperse aerosols move upwards in the generation chamber of the aerosol generator and enter the mixing box placed at the top of the chamber. From there, the aerosols move downwards and enter the improved virtual impactor of the generator. The improved virtual impactor separates larger diameter particles from the aerosol stream by virtual inertial impaction into the collection probe. Improved virtual impactors have been discussed in the literature in terms of their design philosophy by Chen and Yeh (1987). Two sets of improved virtual impactor has been designed, fabricated and one set has been used for size control by varying the solution concentration and the other set has been employed for size control by controlling the minor flow rate. Secondary air flow is supplied at the bottom of the generation chamber so that the flow rate through the chamber is maintained constant at 50 lpm in case of size control by varying the solution concentration and 40 lpm in case of size control by controlling the minor flow rate. Clean air at a flow rates of 16 lpm and 17 lpm is also supplied through the clean air tube at the center of the acceleration nozzle in case of size control by varying solution concentration and minor flow rate respectively. A vacuum pump was employed to extract most of the aerosols through the major flow line and the rest of the coarse aerosols passed through the outlet pipe as minor flow. The minor flow was diluted with clean air and a small portion of it was ejected by a mechanism followed by further dilution to the allowable concentration before entering the Optical Particle Counter, LASAIR-2500 (Particle Measuring System Inc., USA). The sampling time was set to 30 minutes. To have statistically meaningful data, at least 28000 particles were measured by LASAIR-2500 during each sampling.

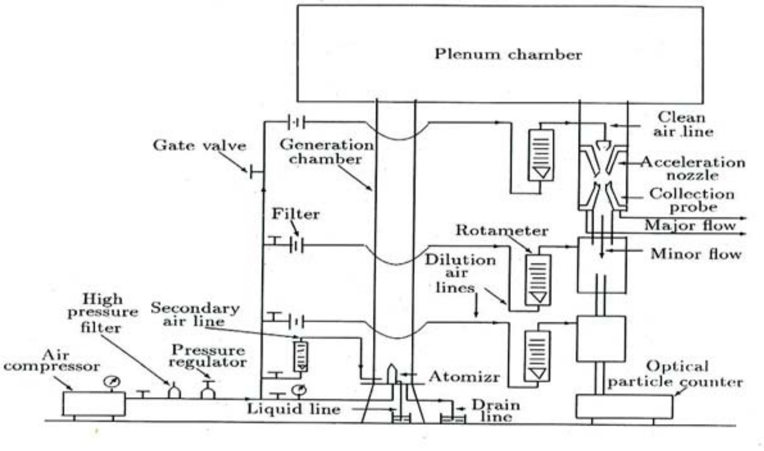

Fig 1. Experimental set up

During this experiment, the liquid pressure was maintained at atmospheric pressure (liquid surface maintained at atomizer entrance height). The conditions in the laboratory were fairly stable during the tests with the ambient pressure and temperature being 760 mm of Hg and 33^0C respectively. So, all pressures and flow rates mentioned in this work are relative to the above.

3.1 Effect of solution concentration

During the tests for investigating the effect of solution concentration on the particle size in the minor flow, all flow rates were kept constant and only the solution strength (concentration of DOP in ethyl alcohol) was varied. The minor flow rate was kept at 10% of total flow rate. The solution concentration was varied from 5% to 100%.

3.2 Effect of minor flow rate

The variation in minor flow rate was made by changing the major flow rate (drawn by the vacuum pump) keeping all other flow rates constant and at a constant concentration of 10% of DOP. The major flow rate was varied in such a way so that the minor flow varied from 3 lpm (4.47% of total flow) to 11 lpm (16.41% of total flow).

4. RESULTS AND DISCUSSION

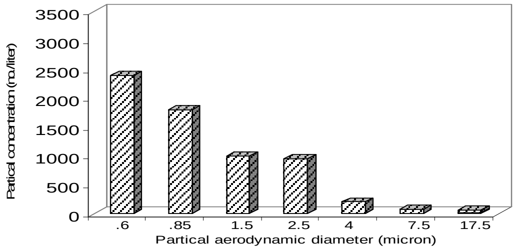

Fig 2. Particle size distribution for an atomizing air pressure of 17.1 kPa and chamber flow rate of 40 lpm

Fig. 2 shows the DOP particle size distribution histograms measured by LASAIR-2500 at an atomizing pressure of 117 kPa and chamber flow rate of 40 lpm. The size distribution has an number mean aerodynamic diameter (NMAD) of 1.23 μm , geometric mean aerodynamic diameter (GMAD) of 1.02 μm and geometric standard deviation (GSD) of 1.77. Thus the particles generated by the atomizer at the atomizing pressure and chamber flow rate is fairly polydisperse in nature and ready for subsequent separation in the improved virtual impactor to monodisperse (GSD<1.5) test aerosols.

4.1 Size control by varying the solution concentration

The DOP particle size distribution in the minor flow measured by LASAIR-2500 for solution concentrations of 5%, 10%, 25%, 50%, 75% and 100% DOP in ethyl alcohol have been shown in Fig. 3. They have NMADs of 1.41, 1.78, 2.57, 3.02, 3.54 and 4.07 respectively. This shows that as the solution strength increases, the particle size increases validating the theoretical predictions. All the size distributions mentioned above have GSD<1.5 indicating monodisperse aerosol.

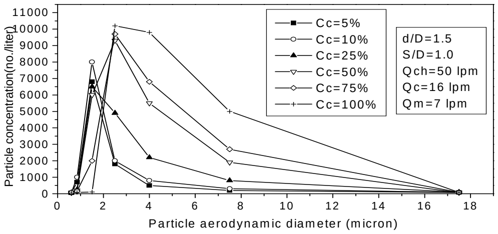

Fig 3. Variation of particle aerodynamic diameter with particle concentration for various solution concentrations.

4.2 Size control by varying the minor flow rate

Graph showing the variation of DOP particles size distribution in minor flow as measured by the optical particle counter for different minor flow rates is given in Figure 4; the corresponding minor flow rates were 11 lpm, 9.5 lpm, 8 lpm, 7 lpm, 5.5 lpm and 3 lpm respectively. They have NMADs of 1.90, 1.98, 2.18, 2.63, 3.00 and 3.86, respectively with GSD less than 1.5 in all the cases ensuring acceptable monodispersity for the final output aerosols.

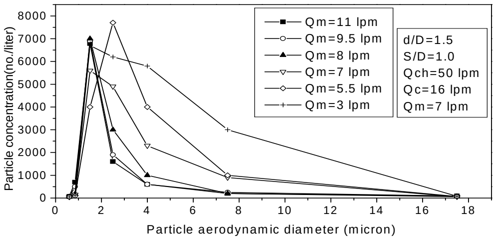

Fig 4. Variation of particle aerodynamic diameter with particle concentration for various minor flow rates.

5. CONCLUSIONS

Size control of generated monodisperse aerosols of DOP in minor flow of a virtual impactor type aerosol generator has been achieved by controlling the concentration of liquid solution (DOP in ethyl alcohol) atomized and the minor flow rate. By varying the solution strength from 5% to 100%, NMADs of DOP particles from 1.41 to 4.07 μm have been achieved; while changing the minor flow rate from 11 lpm to 3 lpm produced a change in NMADs of DOP particles from 1.90 to 3.86.

6. ACKNOWLEDGEMENT

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