Modeling and Characterization of an Aerosol Generation Chamber

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Abstract— **An analytical study has been conducted to determine the physical dimensions (i.e. height and diameter) of a cylindrical aerosol generation chamber in which an atomizer is presumed to generate poly-disperse aerosol from a certain solution. The chamber considered here is both structurally and operationally different from most of the collection devices (e.g. gravitational settling chambers, centrifugal separators, wet scrubbers, filters, electrostatic precipitators etc. reported in the literatures. Expressions for cut-off droplet diameter and subsequently for the velocity and particle displacement history inside the chamber have been developed in this study. For a particular cut-off aerodynamic diameter the motion of the droplets has been realized to be affected by the fluid velocity through the chamber and whether the droplets are in Stoke's region or not. Finally, it has been concluded that, chamber height is to be determined by the maximum height reached by the largest droplet produced by the atomizer whereas its diameter is determined by fluid velocity within the chamber when atomization pressure and particle cut-off aerodynamic diameter are known. Several experimental results for the same configuration have been found in good agreement.**

Keywords— **Aerosol generation chamber, cut-off droplet diameter, poly-disperse aerosol, stopping distance**

I. INTRODUCTION

EXTENSIVE use of air pollution monitoring instruments in stationary sources such as stacks of industrial plants, mobile sources such as automobile exhausts, measurement of outdoor ambient particulate level, and indoor air quality assessment have forced these instruments have to be tested, evaluated and calibrated under controlled laboratory conditions and in the presence of a required velocity flow field before field applications. Such laboratory conditions require test aerosols with a pre-selected narrow band particle size distribution and a controlled flow field in terms of velocity vectors and turbulence levels. Non-availability of suitable aerosol technology and the difficulties in their implementation have, however, resulted in the inadequacy of such laboratory facilities.

Several techniques and equipments have been put into operation to produce mono-disperse test aerosol in the past. Some of these techniques include: liquid atomizer in which a liquid jet is disintegrated by the kinetic energy of the liquid itself or by exposure to high velocity air or gas or as a result of

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mechanical energy applied externally through a rotating or vibrating device [1], compressed air nebulizer where larger particles are removed by impaction within them and smaller particles are produced, ultrasonic nebulizer which produces aerosol droplets having mass mean aerodynamic diameter (MMAD) in the size range of 5 to 10 µm without the use of compressed air jet [2], vibrating orifice aerosol generator [3] which is capable of generating primary aerosol standards from a variety of solid and liquid materials, liquid suspension nebulizer harmonic electric sprayer [4], electrostatic precipitator, gravitational settling chamber etc. Among the techniques just mentioned only settling chamber employs gravitational settling principle which is also the operating principle for the elimination of the larger droplets in generation chamber except the chamber is assumed to be placed vertically. A dust tunnel of horizontal configuration has also been reported [5] which acts as a collection device for larger particles. A vertical dust settling chambers has been described [6] where the settling occurs in still air unlike to the current study as air is assumed to be moving. So, computation and selection methodology for the dimensions of the generation chamber has to be explicitly known and this work is an attempt toward that target. In the current work an analytical modeling of an aerosol generation chamber has been carried out to confirm its best physical dimensions in order to separate larger aerosol droplets from poly-disperse aerosol spray and the smaller particles are assumed to be separated in some latter stage like virtual impactor.

II. THEORETICAL MATERIALS AND MODELING

A. *Particle Flow Dynamics*

In the aerosol generation chamber, currently being studied, an atomizer is presumed to generate poly-disperse from a solution of liquid. A vacuum pump is used to draw the atomized aerosols vertically upwards and thus a uniform vertical flow of aerosols is maintained inside the generation chamber. The flow field thus may be observed to be uniform. The free body diagram of a droplet in the aerosol generation chamber is presented in Fig.1, where, V_f refers to velocity of fluid (air), V_p refers to velocity of droplet (aerosol particle), d_d indicates diameter of droplet.

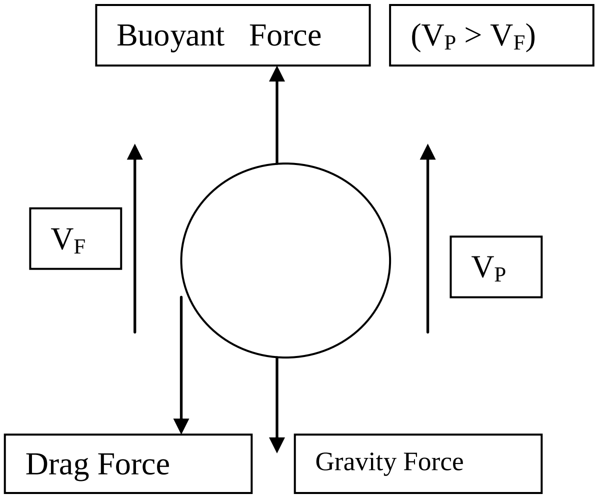

Fig.1: Free body diagram of a droplet in aerosol generation chamber

The resulting force acting on the droplet can be expressed in terms of Newton’s second law of motion as below:

-Gravity force + Buoyant force- Drag force= ma

$$-\rho_p \frac{\pi}{6} d_d^3 g + \rho_f \frac{\pi}{6} d_d^3 g - C_D \frac{\pi}{8} \rho_f d_d^2 (V_p - V_f)^2 = ma \ldots (1)$$

Where ρ_p and ρ_f are densities of liquid particle (droplet) and fluid (air) respectively, g is the gravitational acceleration and C_D is the drag coefficient. Neglecting buoyant force [7], for droplets with Reynolds number, $R_e \leq 1$, Stokes drag coefficient, $C_D = \frac{24}{R_e}$ [where $R_e = \frac{(V_p - V_f) d_d \rho_f}{\mu}$ and μ is the coefficient of dynamic viscosity of fluid (air)], may be used [8].

Equation (1) thus takes the form:

$$\rho_p \frac{\pi}{6} d_d^3 g - 3\pi\mu d_d \left(V_p - V_f\right) = ma \ldots\ldots\ldots\ldots\ldots.\ldots\ldots\ldots..(2)$$

B. *Chamber Modeling*

During the motion of the droplet within the chamber, the acceleration of the aerosol droplet becomes zero and hence it can be treated as uniform terminal velocity *(V_{TP})*. Under this circumstance, V_p will be less than V_f and the direction of drag force will be opposite to that of gravity force. For the foregoing condition, V_p is replaced by droplet terminal velocity *(V_{TP})* and Eq. (2) gives:

$$V_{TP} = V_f - \frac{g d_d^2 \rho_p}{18\mu} \; (R_e \leq 1) \ldots\ldots\ldots\ldots\ldots\ldots..\ldots\ldots\ldots.(3)$$

To take into account for small particles whose size approaches the mean free path of the air, introducing the slip correction factor, C_f, into the above equation yields:

$$V_{TP} = V_f - \frac{C_f g d_d^2 \rho_p}{18\mu} \; (R_e \leq 1) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

Where, $C_f = 1 + \frac{2.52\lambda}{d_a}$ for particles up to 0.1 µm and for particles up to 0.01 µm in diameter,

$C_f = 1 + \frac{\lambda}{d_a}\left[2.514 + 0.8 exp\left(-0.55\frac{\lambda}{d_a}\right)\right]$. Here, λ represents the particle's mean free path.

Flow of droplets with higher terminal (settling) velocity *($Re > 1$)* is beyond the Stokes region *($Re \leq 1$)* and the correlation for C_D is given by [8]

$C_D = \frac{24}{R_e^{0.646}}$ For $1 < R_e \leq 400$, which gives:

$$V_{TP} = V_f - \left[\frac{g d_d^{1.646} \rho_p}{18\mu^{0.646} \rho_f^{0.354}}\right] (1 < Re \leq 400) \ldots\ldots\ldots\ldots\ldots(5)$$

The deceleration of different sized droplets is analyzed by assuming that these are released with the same initial velocity in air stream by the atomizer. Initially, droplets while emerging from the atomizer are outside the Stokes region because of their high initial velocity and then reach to Stokes region very shortly. The time taken to reach droplets terminal velocities and the nature of deceleration process of the droplets has been estimated as follows:

For the droplets within Stoke's region, Eq. (2) takes the following differential form:

$$m\frac{dV_p}{dt} = 3\pi\mu d_d \left(V_f - V_p\right) - mg \ldots\ldots\ldots\ldots\ldots.\ldots\ldots\ldots\ldots.(6)$$

Where, $m = \rho_p \frac{\pi}{6} d_d^3$ and t is the elapsed time of the droplet. Performing integration and substitution, droplet velocity in the Stokes region and non-Stokes region can be characterized by the following expressions [9]:

$$V_{p3} = V_{TP} + \left(V_{p2} - V_{TP}\right)\exp\left(\frac{t_2 - t_3}{\tau}\right) \quad (R_e \leq 1) \ldots\ldots.(7)$$

$$V_{p1} = V_f + \frac{V_i - V_f}{\left\{1 + 0.354 A t_1 \left(V_i - V_f\right)^{0.354}\right\}^{2.825}} \ldots\ldots\ldots\ldots\ldots(8)$$
$$(1 < R_e \leq 400)$$

Where, $A = \frac{18\mu^{0.646}\rho_f^{0.354}}{\rho_p d_d^{1.646}}$, V_i the initial droplet velocity emerging from atomizer, V_{p3} is the velocity of the droplet in the Stoke's region, t_1 is the time taken by the droplet to reach V_{p1}, t_2 elapsed time to reach transition, t_3 the total elapsed time, and the relaxation time of the droplet, $\tau = \frac{m}{3\pi\mu d_d}$.

Likewise, general expressions for the droplet displacement within the generation chamber during Stokes and non-Stokes region can be characterized by the following expressions:

$$S_2 = (t_3 - t_2)V_{TP} + \tau(V_{TP} - V_{p2})\left[\exp\left(\frac{t_2 - t_3}{\tau}\right) - 1\right] \ldots (9)$$

$$(\text{Re} \leq 1)$$

$$S_1 = V_f t1 - \frac{1}{0.646A}\left[\frac{(V_i - V_f)^{0.646}}{\left\{1 + 0.354At1(V_i - V_f)^{0.354}\right\}^{1.825}} - (V_i - V_f)^{0.646}\right](1 < R_e \leq 400) \ldots\ldots (10)$$

Hence, total distance travelled by droplets in the aerosol generation chamber is presented by:

$$S_t = S_1 + S_2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (11)$$

III. RESULTS AND DISCUSSION

The values of aerosol droplet diameters d_d which satisfy both Eq. (3) and Eq. (5) are found to be about 78 µm at 25^o for the same velocity of air through the aerosol generation chamber. Hence, transition diameter for terminal velocity from Stokes to non-Stokes region occurs at about 78 µm aerodynamic diameter of the droplet.

A. *Droplet Terminal Velocity:*

In Fig. 2, cut-off aerodynamic diameters of the droplet are the point corresponding to $V_{TP} = 0$. The figure demonstrates that for any fluid velocity, V_{TP} starts at a value equal to V_f for extremely small droplets and decreases as droplet size increases. Fig. 2 also presents an interesting point that, if the value of V_{TP} is zero for a particular size of droplet and fluid velocity, aerosol droplets greater than that size, indicated by negative terminal velocities, will settle down in the aerosol chamber and smaller ones, for which V_{TP} is positive, will be carried upward by the fluid to the virtual impactor section of the aerosol generator.

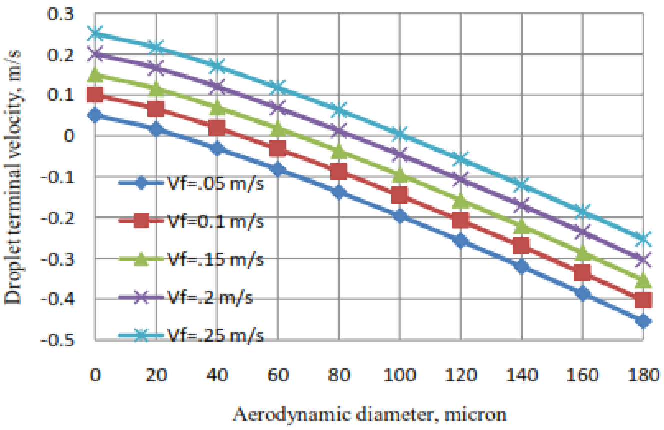

Fig.2: Droplet terminal velocity Vs aerodynamic diameter

B. *Fluid Velocity& Cut-Off Aerodynamic Diameter:*

The variation of fluid velocity with aerodynamic cut-off diameter of DOP and alcohol solution is explicitly illustrated in Fig. 3. This plot has been used to determine cut-off aerodynamic diameter of aerosol droplets for a particular fluid velocity. Alternately, if the cut-off aerodynamic diameter of aerosol droplet is known or selected, the fluid velocity through the chamber for which all droplets larger than D_{CO} will settle down in the chamber and the rest will flow to the virtual impactor section can be determined. Hence, the chamber will act analogous to a low-pass filter with respect to droplet size.

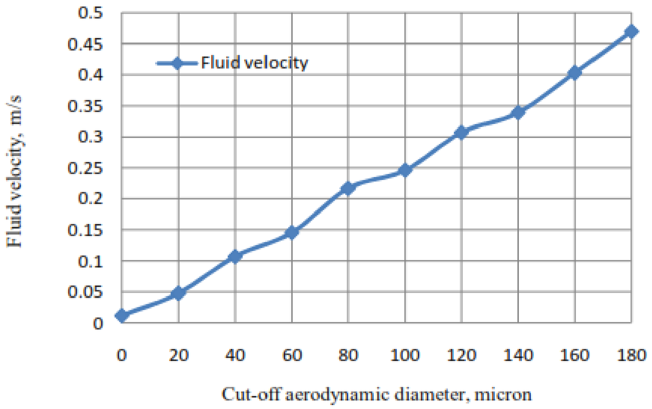

Fig. 3: Variation of fluid velocity with cut-off aerodynamic droplet diameter

C. *Droplet Velocity:*

Equation (7) & Eq. (8) is used to describe the droplet velocity variation with elapsed time in Stokes and non-Stokes region respectively for a given droplet initial velocity (V_i) and fluid velocity (V_f). Figure 4 shows plot of these for droplet of DOP in alcohol of three different sizes at $V_{I=}20$ m/s and V_f=.05 m/s. For these conditions the D_{CO} is very close to 40 µm. Following the approach specified by Lefebvre [7], for an atomization pressure of 200 kp_a for atomized DOP spray (specific gravity of 0.983) at a flow rate of 36 ml/min, largest droplets of 168.3 µm diameter can be produced. Hence this diameter has been chosen for comparison. Fig. 4 also dictates that, 10µm, 40µm and 168.3µm diameter droplets reach their transition velocities (Vp_2) of 1.49m/s, 0.41m/s and 0.13m/s at times (t_2) of 0.000535 s, 1.0111 s and 0.214 s respectively. From Fig. 4 it is also observed that droplets with D_{CO} will reach zero velocity after about 0.05 s, whereas, smaller droplets with diameter 10µm will reach a constant upward velocity of about 0.046 m/s after about 0.003 s as evident from Fig.4 and the largest droplets with 168.3 µm diameter will reach a constant negative velocity of 0.43 m/s after 0.5 s.

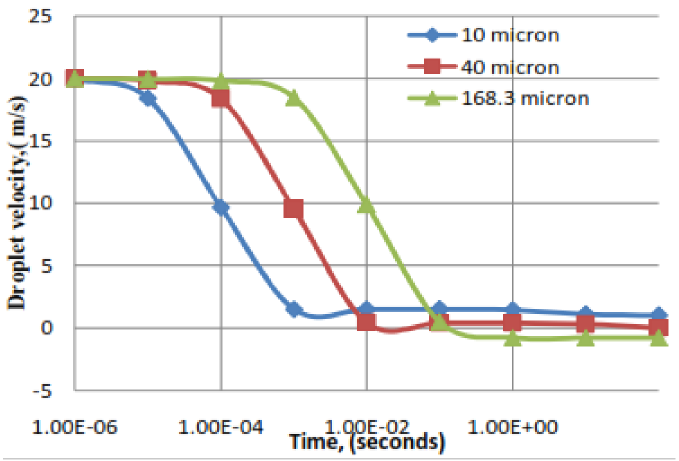

Fig.4: Droplet velocity vs. time diagram

D. *Droplet Displacement:*

Equation (9) and Eq. (10) describe the vertical droplet displacement in terms of elapsed and relaxation times (t and τ) when droplet initial velocity and fluid velocity are fixed which in this analysis are of 20 m/s and .05 m/s respectively. Fig. 5 clearly displays that the droplets of sizes 10 µm, 40 µm and 168.3 µm travel distances of 1.00313 m, 1.0357 m and 0.3964 m in non-Stokes region from their generation to the transition times of 0.000535 s, 1.0111 s and 0.214 s respectively. It is also seen from Fig. 5 that within a very short time, the droplet with D_{CO} reaches a height of about 4 cm and is suspended at that height because of zero terminal velocity. The droplet with smaller diameter reaches a low constant positive V_{TP} within a short time (Fig. 4) and that is aptly demonstrated by the slow but steady increase of the distance travelled by the droplets after about 0.003 s. Finally, the maximum height reached by the largest droplet was found to be 40 cm after about 0.23 s from the initial discharge. If, the chamber height is less than the maximum height reached by the largest droplet (i.e. 40 cm) then these droplets will move out of the chamber to the virtual impactor stage. Hence, in determining the height of the chamber, the maximum height reached by the largest droplet was considered.

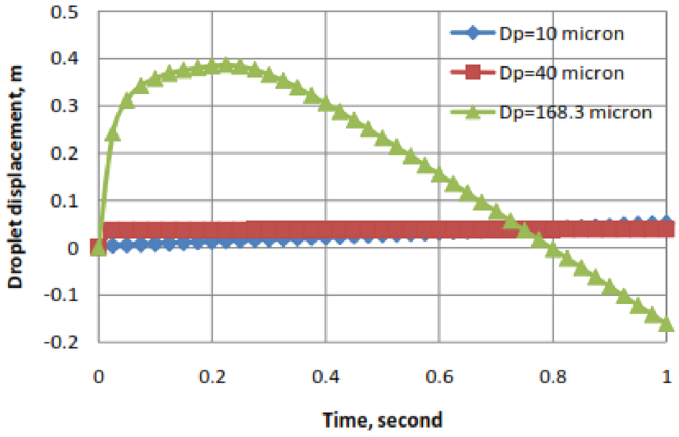

Fig.5: Variation of droplet displacement with time

IV. CONCLUSION

This work identified the critical parameter to determine the physical dimensions (i.e. height and diameter) of the cylindrical generation chamber of mono-disperse aerosol generator for a certain flow rate of air. The particle terminal settling velocity for a particular size of droplet and for a given fluid velocity has been found to be a dominating parameter to characterize the motion of the aerosol particle inside the generation chamber. The height of the chamber has been found and concluded to be affected by the maximum height reached by the largest possible aerosol droplet size within the chamber.

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