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Comprehensive analysis for prediction of dust removal efficiency using twin-fluid atomization in a spray scrubber

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ABSTRACT

Wet scrubbers are very commonly used industrial equipments in removing particles from hot flue gases based on particle wetting mechanisms. Spray towers are simple and economical, hence used in small and medium scale industries for scrubbing particulate and gaseous pollutants. Even though the primary mechanisms of scrubbing of particulate are known, the exact mechanism is not understood yet. Prediction of particulate efficiency is very important for the selection of pollution control equipment. Hence verification of the overall efficiency achieved by any spray scrubbing system based on theoretical models is essential. In this paper an attempt has been made to theoretically predict the efficiency for a spray tower using single twin-fluid air-assist atomizer scrubbing wide size range (1–5 μm) of particulate matter. Results indicate that a maximum of overall theoretical removal efficiencies for the particle sizes 4–5 μm achieved by the spray tower was nearly 99.8%. A comparison of the experimental and theoretical efficiencies has been made and systematically analyzed.

1. Introduction

Literature survey reveals that particulate matter gains greater importance in the field of air pollution control among the air pollutants. Particle less than 100 μm are termed as particulate matter among which particulate less than 10 μm are considered to be highly dangerous, as they are inhalable and their health impacts on living creatures are remarkable in the history. Several epidemiological studies have indicated a strong association between elevated concentrations of inhalable particles (PM_{10}) and increased mortality and morbidity [1,2]. These particulate matters influences many atmospheric processes including cloud formation, visibility, solar radiation and precipitation, and plays a major role in acidification of clouds, rain and fog [3,4]. Particles smaller than 2.5 μm ($PM_{2.5}$) are associated with a range of respiratory and cardiovascular diseases.

In developing countries like India, sponge iron plants have been considered to be highly polluting industries in view of generation of substantial amount of air pollutants and solid wastes. During last five years, there was mushrooming growth of coal based sponge iron plants in India leading to 147 coal based units with a capacity of 11 million tones spread in all over India, making India one of the largest exporters of sponge iron in the world [5]. Due to growing environmental concern and stringent environmental regulations enforced by the legal bodies world wide on particulate emission from various sources, researchers' attention was driven to look into alternative technologies, which are simple, cost effective and have high performances in removing these particulate matter from industrial effluents. The spray column produces low-pressure drop so the dissipated power is also lower, which makes it quite economical device.

However for past few years, numerous types of conventional and non-conventional scrubbers were reported in the literature in practice for combating the particulate emissions, horizontal scrubber and theoretical analysis on particle removal efficiency [6] and modified multi-stage bubble column scrubber [7].

Thus survey of literature reveals that very few works have been done on scrubbing of the fine particulate matter in a simple counter-current spray column.

Spray column has emerged as one of the most widely used control devices for the removing of the particulates and gaseous pollutants from industrial effluent gases mainly because of its easy operation and simple construction. They gain importance in small scale and medium scale industries as they are the lowest energy scrubbers among other wet scrubbers apart from being economical. Recently technologies upgraded the spray scrubbing process in all possible ways from production of fine droplets to modification of the properties of the target particles. Air-blast atomizing has been used in many industrial applications as fineness of droplets play

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very important role in modern industrial technologies. Especially in the scrubbing process of particles, the ratio of droplet size to particle size plays an important role. The particle collection efficiency in these spray columns is based on the particle collection mechanism of primarily inertial impaction and interception, and in case of submicron particles scrubbing, diffusive and other electromotive forces also contribute to great extend [8]. The present study is an attempt to make verification on the performance study of a spray column, for removal of fine particulate matter from industrial hot flue gases with a twin-fluid air-assist atomizer. Experimental findings are verified with a theoretical model predicted for the same sets of boundary conditions.

This article reports on a systematic mathematical approach as well as detailed experimental studies on the removal of dust particles from hot gases by using a spray column with twin-fluid atomizers using water as the scrubbing medium.

2. Experimental setup and technique

The schematic diagram of the experimental setup is shown in Fig. 1. A spray column tower of height 2.4 m and diameter 1.25 cm was used to conduct the experiment, constructed of transparent, vertical perspex column, fitted with a fructo-conical top outlet. Twin-fluid assisted by air atomizer was used for producing fine droplets of size ranging from 100 to 500 μm. The dimension of the atomizer is 60 mm long and 15 mm out side diameter with a 15° angle tapering to the mouth of the nozzle of 10 mm diameter. The mouth has an integrated opening, eight holes of 0.8 mm at the periphery for water jets and at the center one hole of 1 mm diameter for air jet to atomize the liquid jet into fine droplets. The droplet size is then measured through stand still photography with the help of a known diameter of reference wire and image pro plus software. They were calculated by applying statistical method of sampling and their mean was used as droplet diameter. The Nukiyama and Tanasawa's [9] empirical equation was used for theoretical analysis of droplet diameter as follows.

$$d_o = 1920\left[\frac{1}{v_r}\sqrt{\frac{\sigma}{\rho_L}}\right] + 5.97\left[\frac{\mu_L}{\sqrt{\sigma\rho_L}}\right]^{0.45}\left[1000\frac{Q_L}{Q_G}\right]^{1.5} \quad (1)$$

$$v_r = \text{relative velocity of gas to liquid} = v_L - v_G \text{ ft/s} \quad (2)$$

$$\sigma,\ \mu_L,\ \rho_L = 72\,\text{dyn/cm},\ 0.00982\,\text{Pa s},\ 1.0\,\text{g/cm}^3\ (\text{for water})$$

$$[Q_L/Q_G] = \text{liquid to gas ratio}, \quad (3)$$

Taking standard condition:

$$d_o = \left[\frac{16291.7}{v_r}\right] + 0.284\left[\left(\frac{Q_L}{Q_G}\right)\times 10^3\right] \quad (4)$$

The particulate matter (fly ash) of size ranging from 1 to 625 μm was taken and measured using Malvern Master Size 2000 version.5.22. The fly ashes are kept in a steel hopper (400 mm × 250 mm) aided by an electric vibrator that feeds the

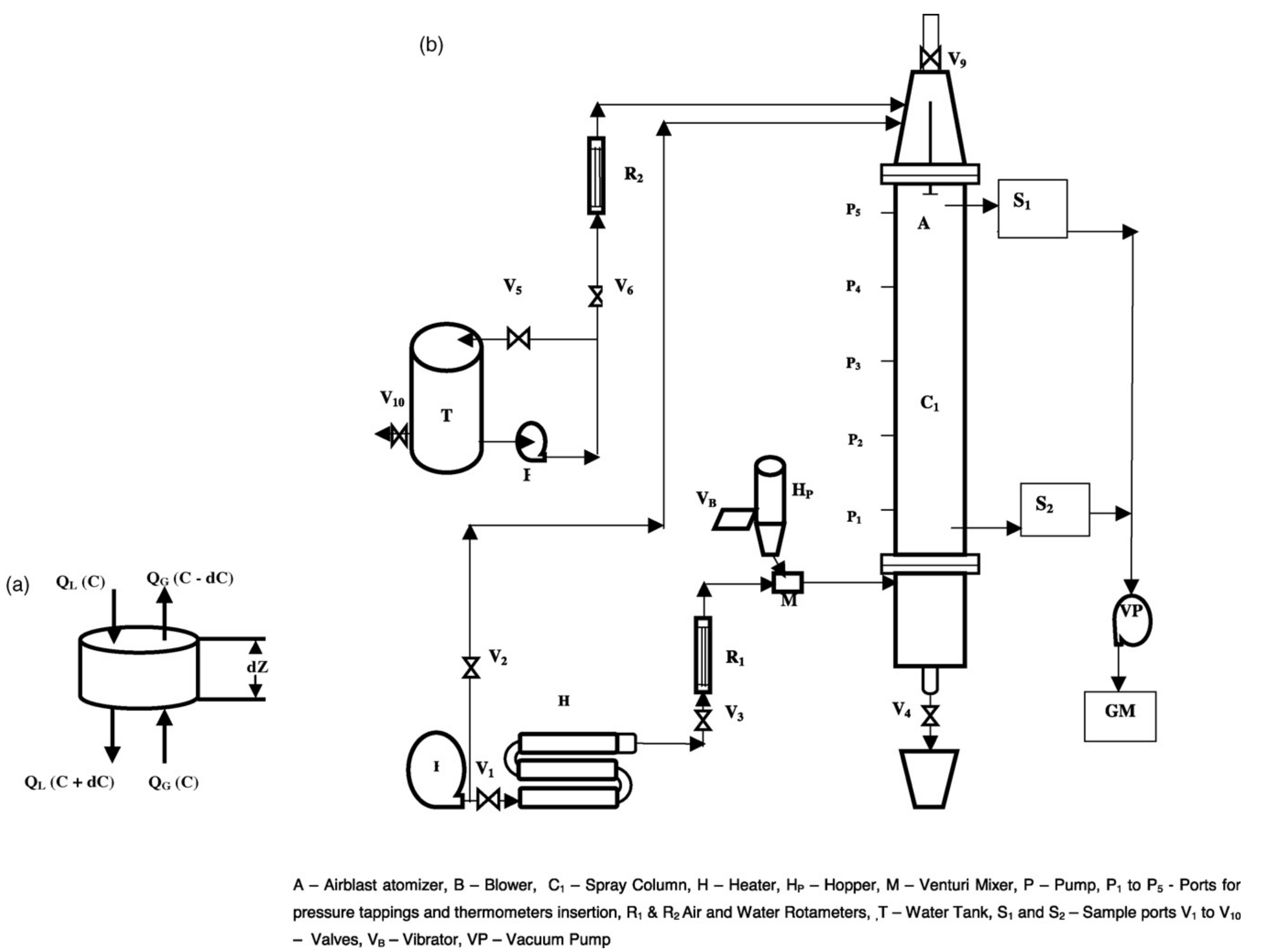

Fig. 1. (a) Schematic of the control volume for mass balance. (b) Schematic of the experimental setup for particulate scrubbing from hot flue gas.

solids into the inlet air line through a venturi-ejector for mixing the solids well with the air stream and were sent with hot flue gases from the bottom of tower ranging the flow rates from 3.084×10^{-3} to $5.584 \times 10^{-3}\,m^3/s$. The scrubbing liquid i.e. water was sent to the twin-fluid air-assist atomizer from the water tank through a 0.5 hp pump where it was sprayed into the tower with flow rates at 8.35×10^{-6}, 16.67×10^{-6}, 25.00×10^{-6}, $33.34 \times 10^{-6}\,m^3/s$. The concentrations of particulates in the inlet and outlet sampling points (S_1 and S_2) were measured by using a glass filter medium of specification GS555 MMAD. The dust-laden gas was sampled at the source points S_1 and S_2 with the help of a Glass fiber filter paper mounted on an assembly for holding the filter paper. A controlled volume of gas was allowed to pass through the filter paper using aspirator bottles. The iso-kinetic conditions were maintained during sample collection.

Percentage removal of fly ash is calculated from Eq. (5).

$$\eta_{PM} = \frac{C_{PM,\,inlet} - C_{PM,\,outlet}}{C_{PM,\,inlet}} \times 100 \quad (5)$$

2.1. Particle collection mechanism

The most dominating mechanism for particle collection efficiency in a wet scrubber is mainly dependent on particulate diameter. Fly ash collected from Kolagat thermal power plant is used as the particulate matter in the spray scrubbing process. The particle size distribution was seen to follow a log-normal distribution density function as shown in the Fig. 2. The particle diameter was defined by the mean particle diameter of the distribution function. The proposed mechanisms here include all the three mechanisms of impaction, interception and diffusion. Diffusion, interception, inertial impaction, and gravitational settling for collection of particles represent the scrubbing mechanisms. Among these mechanisms, inertial impaction remains an important mechanism for capture of particles larger than 5.0 μm, while diffusion is essential for capture of smaller particle sizes. Diffusion is the dominant collection mechanism for small particles in using wet scrubbers. Small particles attain a high diffusion coefficient

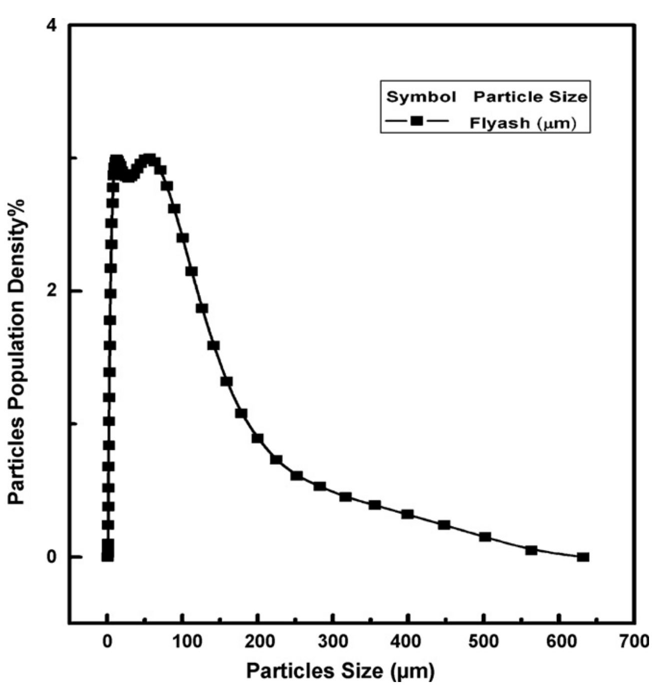

Fig. 2. Particle size distribution of fly ash.

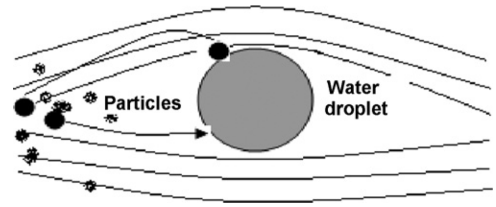

Fig. 3. Particle impaction on droplet.

because the diffusion coefficient is inversely proportional to size. Interception, even if the trajectory of a particle does not depart from the streamline, a particle may still be collected when the particle passes within one particle radius from the water droplet surface and shown in Figs. 3 and 4.

2.2. Atomization

Atomization is the process in which a certain volume of liquid is broken into many small drops generating a much increased surface area. A high relative velocity is to be created by contacting a low velocity liquid stream with a high velocity gas stream to have fine droplet size. This is termed twin-fluid or air-blast atomization [10]. In air-blast atomizers, a large quantity of gas/liquid flowing at moderate velocities (<100 m/s) is employed to disintegrate relatively slow moving coaxial liquid jets by means of aerodynamic interaction.

The tendency of air to spread the liquid volume across the spray width increases with the flow rate of air or relatively with a decrease in liquid flow rate. At very high flow rates of air, the droplets formed will be very small. The size of the droplets produced by atomizing the liquid in spray nozzles is an important parameter as there is a considerable increase in the collection efficiency with decrease in droplet size. The nozzle characteristics are important for efficient and economical operation of the scrubber. There are varieties of industrial spray nozzles for scrubbing particles; like impingement type, spiral type, spinning disc type, two liquid jet impingement, pneumatic or two fluid atomizing, sonic spray etc. [10]. As the scrubbing liquid often contains suspended solid particles, it is very important that the nozzle neither plugs nor erodes as a result of the presence of solids. Moreover the generation of fairly uniform and very fine spray at the cost of relatively little energy is difficult.

The gas–liquid ratio is another important parameter which contributes to the droplet size and thereby to the scrubbing efficiency, an optimum value of this gas–liquid ratio is the one that gives the maximum efficiency with a minimum scrubbing liquid usage [11,12]. A commercially available air-assist twin-fluid atomizer has been used to produce fine droplets of water for scrubbing the particulate matter as shown in Fig. 5. The droplet sizes are then measured through stand still photography with the help of a known diameter of reference wire and image pro plus software as shown in Fig. 6. The droplet diameters were calculated by applying statistical method of sampling and their mean was used as droplet diameter. The Nukiyama–Tanasawa [9] empirical equation was used for theoretical analysis of droplet diameter.

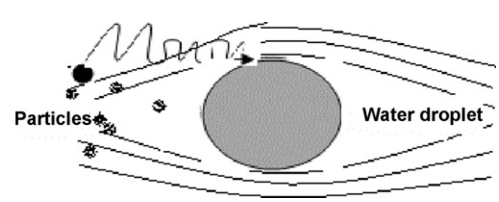

Fig. 4. Diffusion of particle on to the droplet.

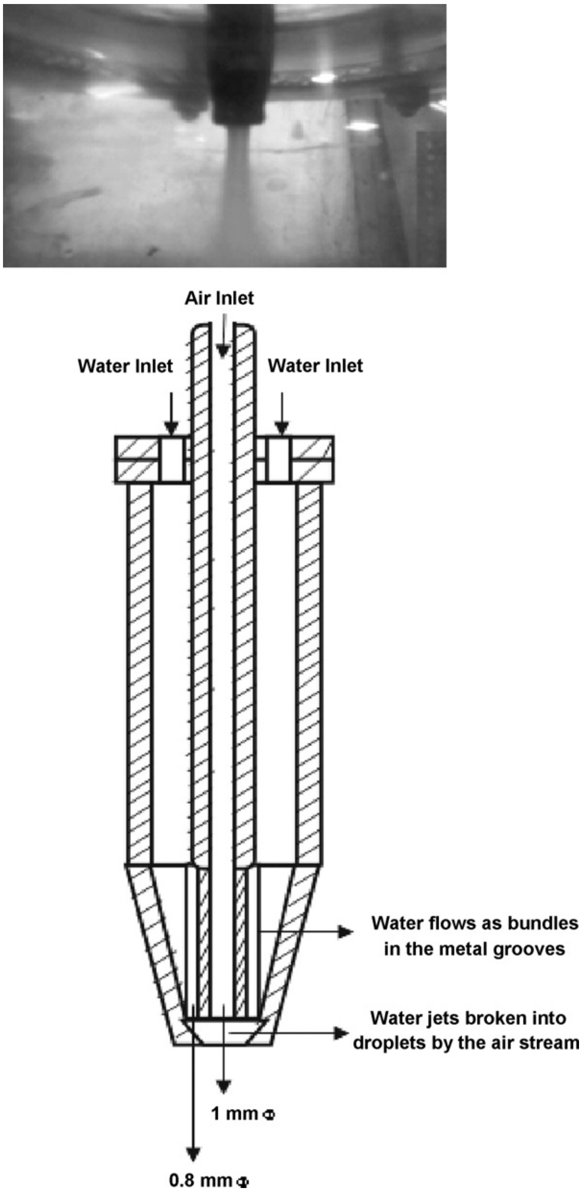

Fig. 5. Schematic and pictorial representations of air-assist twin-fluid.

2.3. *Theoretical modeling of spray tower scrubber*

A mathematical model based on mass and momentum balance has been developed over a control volume of the spay tower. The continuity equation was used to get the overall efficiency of the scrubber. Applying the continuity equation to a cylindrical element of height dz taken inside the spray column as shown in Fig. 1a, we get

Applying mass balance:

$$\text{Flux from gas to liquid} = \text{flux into liquid phase} - Q_G\,\mathrm{d}c = \left(\frac{\text{volume swept}}{\text{time}}\right) \times \text{concentration} \times \text{efficiency}$$

$$\text{Volume swept per time} = \text{number of drops swept} \times \text{drop residence time} \times \text{volumetric flux}$$

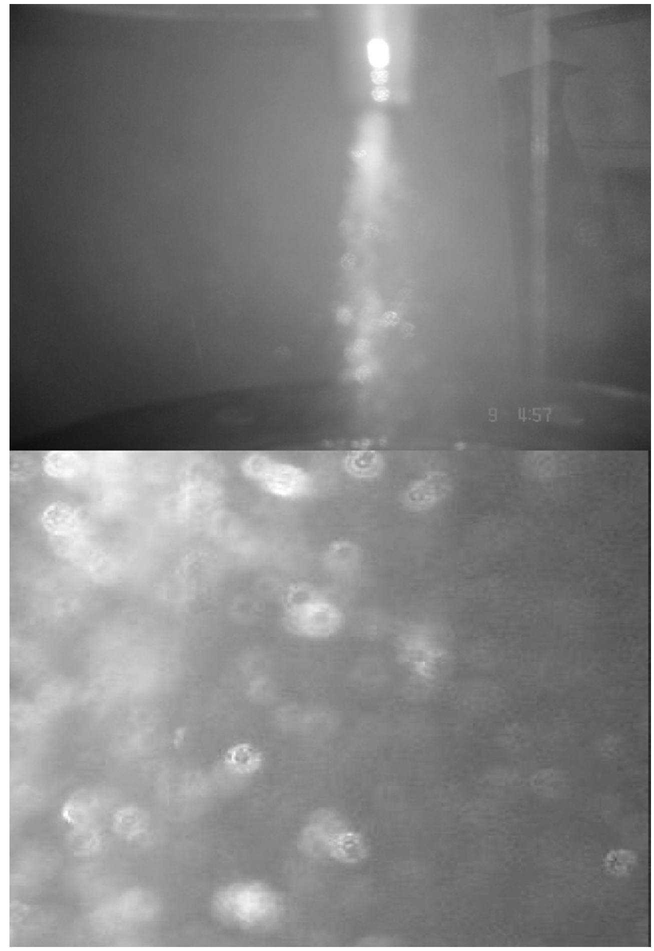

Fig. 6. Droplet diameter of spray by image pro plus.

Thus,

$$\left(\frac{Q_L}{\pi d^3/6}\frac{\mathrm{d}z}{(v_t - v_G)}\right)\frac{\pi}{4}{d_o}^2 v_t \tag{6}$$

$$-Q_G\mathrm{d}c = \left(\frac{Q_L}{\pi d^3/6}\frac{\mathrm{d}z}{(v_t - v_G)}\right)\frac{\pi}{4}{d_D}^2 v_t c \eta_{SD} \tag{7}$$

Integrating Eq. (7) gives

$$\frac{c}{c_0} = \exp\left[-\frac{3}{2}\frac{Q_L}{Q_G}\frac{h}{d_o}\frac{v_t}{(v_t - v_G)}\eta_{SD}\right] \tag{8}$$

$$\eta_{overall} = 1 - \frac{c}{c_0} = 1 - \exp\left[-\frac{3}{2}\frac{Q_L}{Q_G}\frac{h}{d_D}\frac{v_t}{(v_t - v_G)}\eta_{SD}\right] \tag{9}$$

where Q_L: liquid flow rate (m^3/s), Q_G: gas flow rate (m^3/s), v_t: terminal settling velocity of droplets (m/s), v_G: gas velocity in tower (m/s), h: height of the tower (m), d_D: droplet diameter (m), η_{SD}: single droplet collection efficiency

Assumptions.

(1) There is no evaporation of undergoing in tower of water droplets.
(2) No entrainment of gas in droplets in water gas.
(3) No coalescence occurs in between the droplets.
(4) Waste gas follows ideal gas law.
(5) Droplets are assumed spherical.
(6) Particle size distribution is uniform and droplet sizes are same.
(7) Particles in the droplets prior to scrubbing.

Thus the overall efficiency can be obtained if the values of all the variables in the Eq. (9) are known. Although the single droplet collection efficiency was predicted based on the three primary mechanisms, yet the exact mechanisms involved are not fully understood. The theoretical equations were used for predicting the single droplet efficiency by considering all the three mechanisms. Particle collection by diffusion mechanism is dominant for submicron particle size in wet scrubbers [7]. Small particles attain a high diffusion coefficient because the diffusion coefficient is inversely proportional to size. The diffusive collection efficiency of a single liquid sphere, which includes the effects of induced internal circulation inside a liquid droplet, is given by Kim et al. [6].

$$\eta_{\mathrm{diff}} = 0.7\left\{\frac{4}{\sqrt{3}}\left(\frac{1-\alpha}{J+\sigma K}\right)^{1/2} Pe^{1/2} + 2\left(\frac{\sqrt{3}\pi}{4Pe}\right)^{2/3}\left[\frac{(1-\alpha)(3\sigma+4)}{J+\sigma K}\right]^{1/3}\right\} \quad (10)$$

where α is the packing density (liquid holdup), σ is the viscosity ratio of water to air,

$$J = 1 - \frac{6}{5}\alpha^{1/3} + \frac{1}{5}\alpha^2, \quad (11)$$

$$K = 1 - \frac{9}{5}\alpha^{1/3} + \alpha + \frac{1}{5}\alpha^2, \text{ and} \quad (12)$$

$$Pe = \frac{\mathrm{DU}}{D_{\mathrm{diff}}} \quad (13)$$

Pe is the Peclect number. For the diffusion coefficient, D_{diff}, appearing in the Peclect number, the following form is used:

$$D_{\mathrm{diff}} = \frac{kTC}{3\pi\mu d_{\mathrm{p}}}, \quad (14)$$

where k is the Boltzmann constant, T is the absolute temperature, μ is the viscosity of the air, d_{p} is the particle diameter, and C is the Cunningham slip correction factor which is a strong function of mean free path of the particles (λ) and particle diameter d_{p}. Here the value of C is obtained by the following equation:

$$C = 1 + \frac{6.21\times 10^{-4}}{d_{\mathrm{ps}}}T \quad (15)$$

where T: absolute temperature (K) and d_{ps}: Stokes diameter (13×10^{-6} m).

Even if the trajectory of a particle does not depart from the streamline, a particle may still be collected when the particle passes within one particle radius from the water droplet surface. This phenomenon is known as interception mechanism of particle removal. Jung and Lee [11] derived the following collection efficiency of a single liquid sphere due to interception mechanism:

$$\eta_{\mathrm{int}} = \frac{(1-\alpha)}{(J+\sigma K)}\left[\left(\frac{R}{1+R}\right) + \frac{1}{2}\left(\frac{R}{1+R}\right)^2(3\sigma+4)\right] \quad (16)$$

where

$$R = \frac{d_{\mathrm{p}}}{d_{\mathrm{o}}} \quad (17)$$

Rearranging for R

$$\eta_{\mathrm{int}} = \left[\frac{(1-\alpha)}{(J+\sigma K)}\frac{1}{d_{\mathrm{o}}}\right]d_{\mathrm{p}} + \left[\frac{(1-\alpha)}{(J+\sigma K)}\frac{(3\sigma+4)}{2d_{\mathrm{o}}^2}\right]d_{\mathrm{p}}^2 \quad (18)$$

The particle collection efficiency due to impaction of the particles on to the droplets and getting adhered to the droplets is dominant for particles larger than 5 μm and is a function of stokes number, defined as

$$\eta_{\mathrm{imp}} = \left(\frac{\mathrm{Stk}}{(\mathrm{Stk}+0.35)}\right)^2 \quad (19)$$

where Stk, the stokes number is expressed as

$$\mathrm{Stk} = \frac{\rho_{\mathrm{p}} d_{\mathrm{p}}^2 (U_{\mathrm{sd}} - U_{\mathrm{si}})}{18\mu D}, \quad (20)$$

here, ρ_{p} is the particle density, and U_{sd} and U_{si} are droplet falling velocities relative to the gas and settling velocities of particle, respectively.

The overall collection efficiency by a single droplet (η_{SD}) is sum of the above three collection efficiencies, as the collection efficiencies are assumed to be additive by Kim et al. [6] and Sarkar et al. [12].

Hence,

$$\eta_{\mathrm{SD}} = \eta_{\mathrm{diff}} + \eta_{\mathrm{inter}} + \eta_{\mathrm{imp}} \quad (21)$$

3. Results and discussions

The experimentation on fly ash scrubbing in a spray tower with single twin-fluid air-assist atomizer was conducted with variations in liquid–gas ratio, loading rates and droplet distributions. The values of the variables are used in the theoretical estimation of single droplet efficiency in the prediction of overall efficiency. The developed mathematical model equations were simulated by matlab programme for the theoretical overall efficiency as reported by Sarkar et al. [12]. The program was simulated for variable like liquid–gas ratios, particle sizes and height of the spray tower. Thus Eq. (9), which includes all the Eqs. from (10) to (21), was estimated for the specified boundary conditions. The results are plotted and the values estimated for the parameters in Eqs. from (9) to (21) are presented.

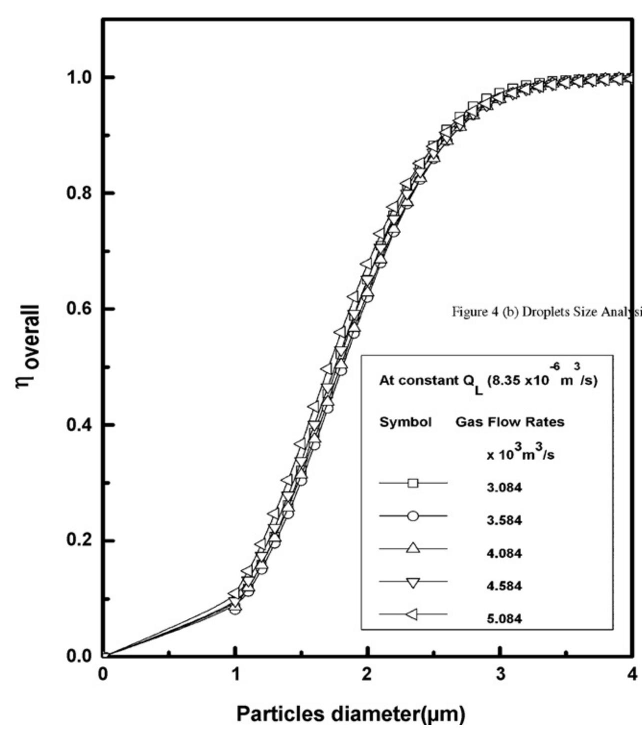

Fig. 7. Overall theoretical efficiency with respect to particle size at different gas flow rates and at constant liquid flow rate (8.35×10^{-6} m^3/s).

Fig. 7 represents the matlab simulated results on the effect of particle size on overall collection efficiency at different gas flow rates and at constant liquid flow rate. As the particle size increases the overall efficiency also increases steadily and reaches the maximum, 1 for a particle of 4.6 μm for a gas flow rate of 3.084×10^{-3} m^3/s and liquid flow rate of 8.35×10^{-6} m^3/s. As the particle size increases above 1 μm the Stokes number in the impaction mechanism and the *R* value in the interception mechanism increase and contribute to maximise the overall collection efficiency. Whereas the estimated values of the efficiency due to diffusion mechanism is found to be very less for these particle sizes as predicted Kim et al. [6]. When the gas flow rate increases the collection efficiency drops for the increase in particles size. For the gas flow rate of 5.584×10^{-3} m^3/s and liquid flow rate of 8.35×10^{-6} m^3/s, the maximum, 100% collection efficiency was achieved for 5.7 μm particle size. As the gas flow rate increases for a constant liquid flow rate, the collection efficiency decreases slightly in spite of increase in the droplet size. Thus the overall collection efficiency of the spray column decreases when the amount of gas and its velocity increases for a given liquid rate.

Fig. 8 presents the effect of particle size on the theoretical overall efficiency with different liquid flow rates ($1–50 \times 10^{-6}$ m^3/s) at constant gas flow rate (3.084×10^{-3} m^3/s). As the particle size increases the overall collection efficiency increases. A maximum of 39.8% theoretical efficiency was achieved for 1 μm particle size at the liquid flow rate of 50×10^{-6} m^3/s. As the liquid flow rate increases from 1×10^{-6} to 50×10^{-6} m^3/s the overall theoretical collection efficiency also increases markedly. The difference in the efficiency between 1×10^{-6} and 10×10^{-6} m^3/s flow rates of liquid was found to vary distinctly; the trend also seemed to be bit different from other flow rates with respect to the slope of the curve. Compared to effect of gas flow rates, the effect of liquid flow rate is much significant for the given range of particle sizes. Fig. 9 shows the effect of liquid flow rate on the overall theoretical efficiency at constant gas flow rate (3.084×10^{-3} m^3/s) for different particle sizes.

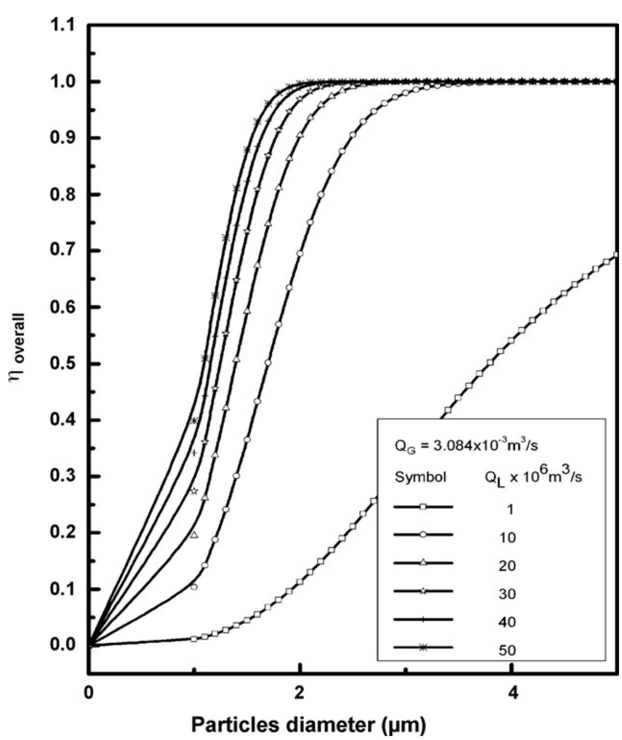

Fig. 8. Effect of particle size (d_p) on the overall theoretical efficiency at different liquid flow rates and at constant gas flow rate (3.084×10^{-3} m^3/s).

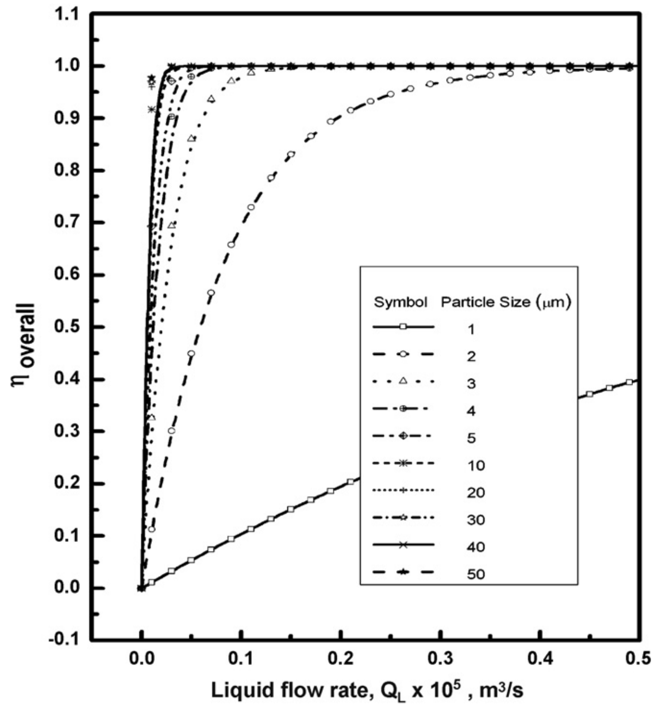

Fig. 9. Effect of liquid flow rate on the overall theoretical efficiency with different liquids at constant gas flow rate (3.084×10^{-3} m^3/s) for different particle sizes up to 50 μm.

In Fig. 10 simulation was done for the range of gas flow rates in such way that it covers the experimental gas flow rate range. From the Fig. 9 it is clear that the effect of gas flow rate on the theoretical overall efficiency is almost nil for particles above 3 μm. For particles of sizes 1 and 2 μm, the effect is not that much appreciable but is found to increase with increase in the gas flow rate at a very marginal level, from 0.08 to 0.12 and 0.65 to 0.70 respectively for the gas flow rates ranging from 0.001 to 0.005 m^3/s. But in case of particles above 2 μm, the theoretical efficiency was found to decrease with increase in the gas flow rate which is also marginal.

Fig. 11 reveals the effect of the gas flow rate on the overall theoretical efficiency for particles size ranging from 1 to 5 μm at constant liquid flow rate of 16.67×10^{-6} m^3/s. For particles with 1 μm size, the efficiency seemed to increase with increase in the gas flow rate very gradually. In case of particles with size of 2 μm, the efficiency drops for few increments of gas flow rates and again increases gradually with the gas flow rate. Similar trend was also observed for 3 μm particle size. For particle size 4 μm and above the efficiency remains 1 for the given values of gas flow rate at this liquid flow rate.

Fig. 12 represents the effect of gas flow rate on the overall theoretical efficiency for particle size ranging from 1 to 5 μm at 8.35×10^{-6} m^3/s. For particle of 1 μm the overall theoretical efficiency increases with increase in the gas flow rate at very marginal level, from 0.083 to 0.121. For particle of 2 μm size the overall theoretical efficiency decreases initially from 0.65 to 0.061 for increasing gas flow rate from 0.001 to 0.0022×10^{-3} m^3/s and further increase in the gas flow rate increases the efficiency up to 0.70 while the gas flow rate is being increased to 0.0059×10^{-3} m^3/s.

Fig. 13 represents the overall theoretical efficiency of the spray scrubber with respect to its height. Since the experimental setup is 1.96 m high, the simulation is done for height starting from 0 to 1.96 m at constant liquid (8.35×10^{-6} m^3/s) and gas flow rates

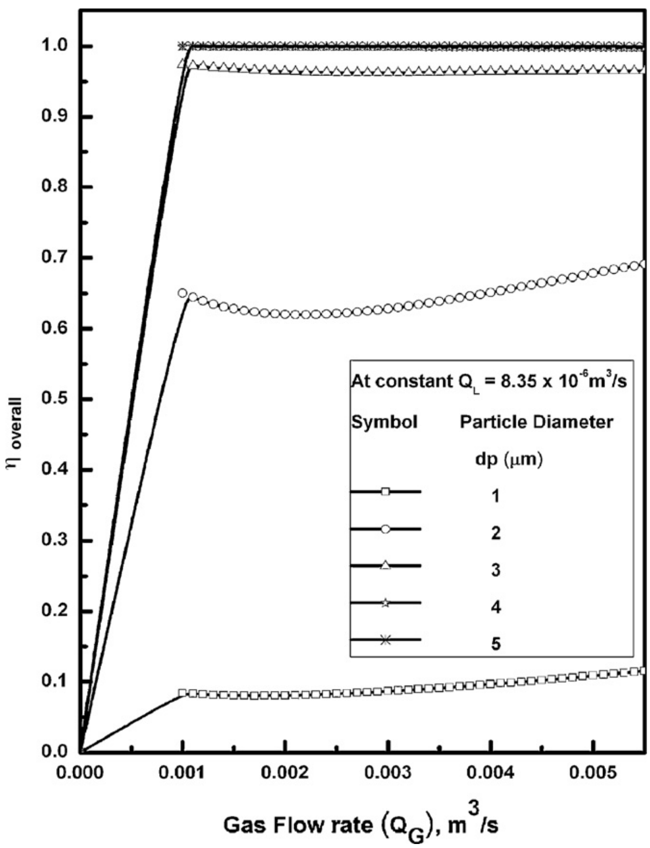

Fig. 10. Effect of gas flow rate on the overall theoretical efficiency of the spray tower at constant liquid flow rate (8.35×10^{-6} m^3/s) and at different particle sizes.

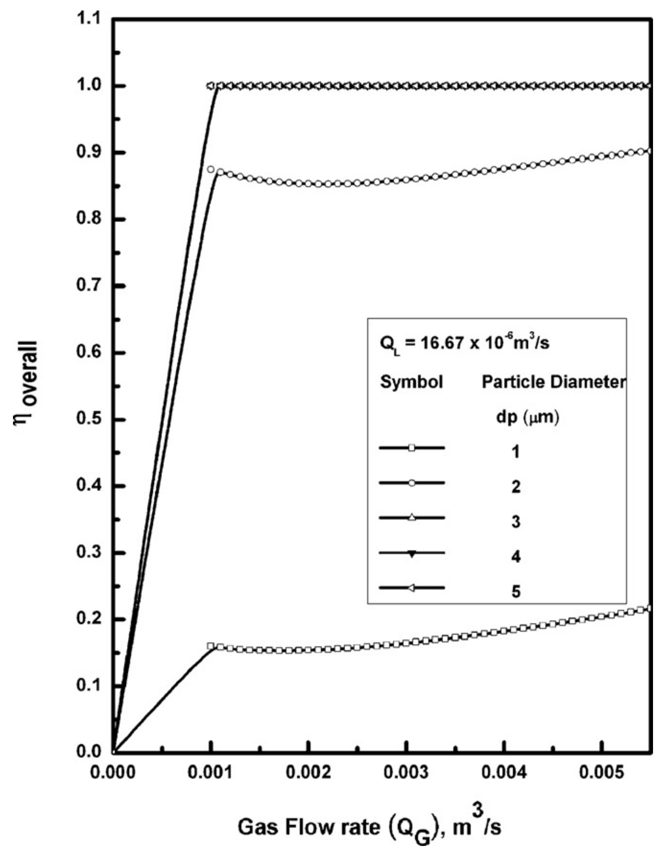

Fig. 11. Effect of gas flow rate on the overall theoretical efficiency of the spray tower at constant liquid flow rate (16.67×10^{-6} m^3/s) and at different particle sizes.

(3.084×10^{-3} m^3/s) for particle size ranging from 1 to 5 μm. As the height increases the overall theoretical efficiency increases gradually and was found to be linear for particle of 1 μm size. A maximum efficiency of 0.08 was achieved for a height of 1.96 m for the given gas and liquid flow rates. For 2 μm particle size (d_p), the overall theoretical efficiency was to found to increase from 0.21 to 0.62 with a steady increase as we go from bottom of the spray tower. The changes occurring in the overall theoretical efficiency for 2 μm d_p were found to be very distinct when compared to the 1 μm size d_p. Similarly for the 3 μm size d_p also the overall theoretical efficiency was found to increase even at still higher rate, starting from 0.064 to 0.962 as we go above from 0.1 to 1.96 m of the spray tower. The increasing trend was found to change from linear to parabolic as we increase the particle size from 1 to 5 μm along the height of the spray tower. For particle sizes of 4 and 5 μm the overall theoretical efficiency was found to climb much steeper than the lower sized particles and reached 0.90 and 0.97 at a height of 0.72 m itself. A maximum of 0.998 and 0.999 values of overall theoretical efficiencies for the particle sizes 4 and 5 μm was achieved at the end of the spray tower.

The effect of gas flow rate on the overall theoretical efficiency of the spray tower for 5 μm particle size at a constant liquid rate along height of the spray tower is presented in Fig. 13. An exponential increase in the collection efficiency was observed for all five flow rates of gas with respect to the height of the tower at a constant liquid flow rate of 8.35×10^{-6} m^3/s. Almost by one-fourth (0.52 m) height of the spray tower an overall theoretical efficiency of 0.90 was achieved by all the gas flow rates for d_p size of 5 μm at the given liquid flow rate. As the gas flow rate increases a very marginal decrease in the overall theoretical efficiency was observed without disturbing the trend. From this figure it can be inferred that gas flow

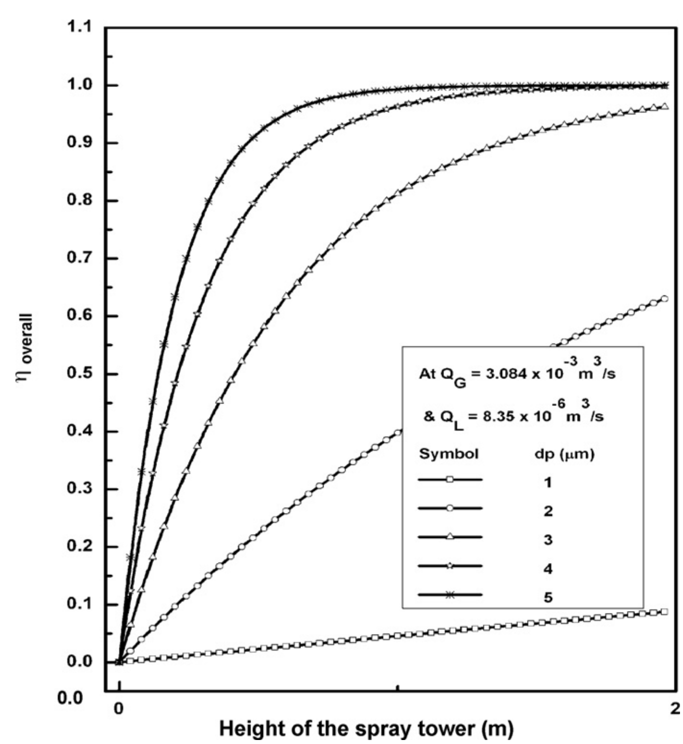

Fig. 12. Overall theoretical efficiency of the spray tower with respect to height of the tower at constant gas and liquid flow rate and at different particle sizes.

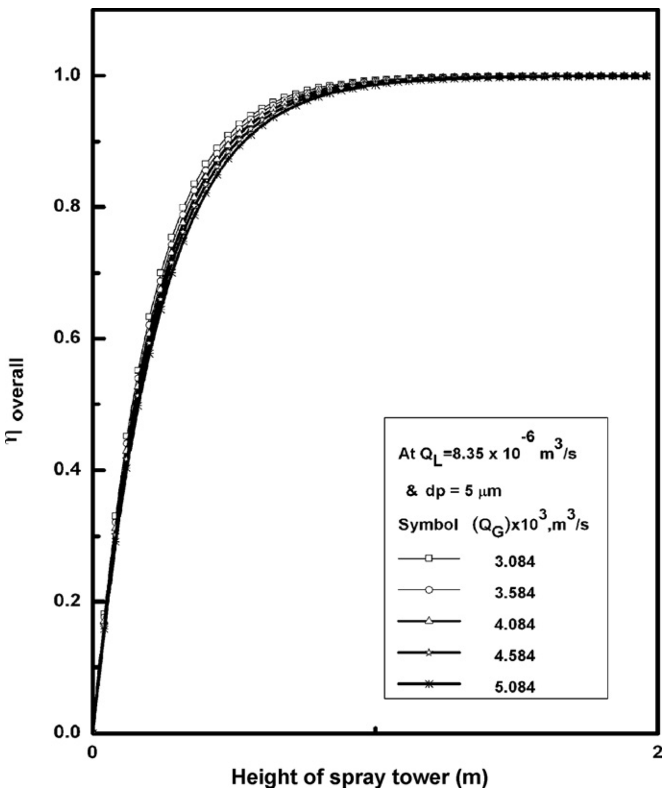

Fig. 13. Overall theoretical efficiency of the spray tower with respect to the height of the spray tower at constant liquid flow rate (8.35×10^{-6} m^3/s) and different gas flow rates for 5 μm particles size.

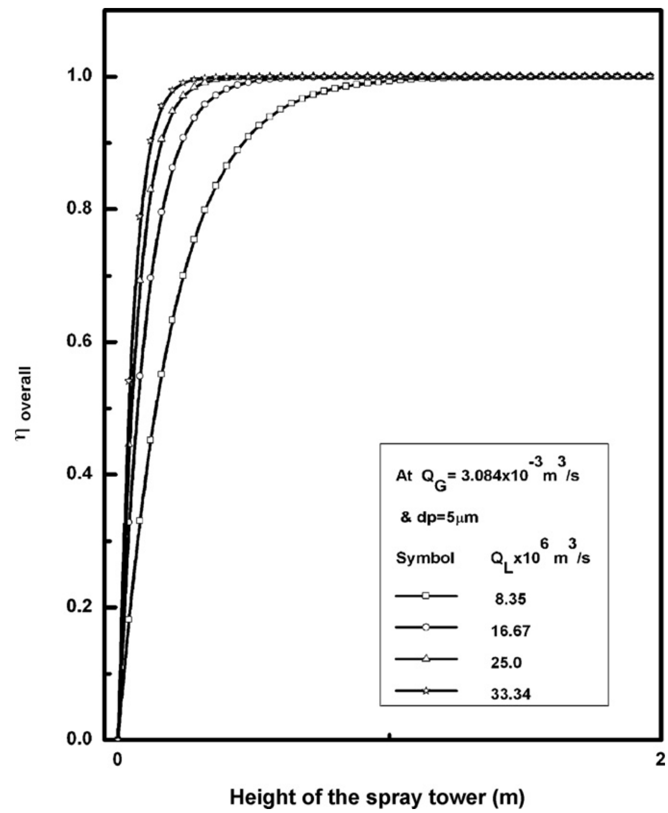

Fig. 14. Overall theoretical efficiency of the spray tower with respect to the height of the spray tower at constant gas flow rate (3.084×10^{-3} m^3/s) and different gas flow rate for 5 μm particles size.

rate has very marginal effect on the overall theoretical efficiency for particles close to 5 μm. Since the experimentation is done for the single outlet concentration of the fly ash of the spray scrubber, there are no experimental results to compare the efficiency of the spray tower with respect to its height with the theoretical results.

Similarly Fig. 14 reveals that when the liquid flow rate is varied from 8.35×10^{-6} to 33.34×10^{-6} m^3/s for a constant gas flow rate of 3.084×10^{-3} m^3/s, the overall theoretical efficiency was found to follow the same trend as that of the previous figure but with marked difference with respect to the liquid flow rates, so that the effect of liquid flow rate over overall theoretical efficiency can be clearly seen rather than the effect of gas flow for particle of size of 5 μm. The particle removal by water droplet may be due to surface weathering of particle in addition to particle–particle interaction [13]. An efficiency value of almost 1 is achieved for by liquid flow rates at half of the tower height itself. A further increase in the particle size might lead to an efficiency value of 1 still at a lower height of the tower.

Fig. 15 represents the effect of overall collection efficiency obtained experimentally when the fly ash particles of surface mean diameter of 11 μm have scrubbed at different liquid flow rates in the spray tower. As the gas flow rate increases the efficiency increases initially reaching a maximum value and later drops. Similar trend was followed by efficiencies obtained with respect to the gas flow rate at higher level of liquid flow rates. But in case of theoretical efficiencies as given in Figs. 10 and 11, the effect of gas flow rate also seemed to increase the overall efficiency for particles of sizes 1 and 2 μm in a very gradual manner and decreases for particles of sizes 3–5 μm. Since the particle range scrubbed in the spray tower is of the order ranging from 1 to 500 μm and surface mean diameter is 13 μm, whose efficiency is supposed to be one according to theoretical prediction for the same boundary conditions. Thus for such

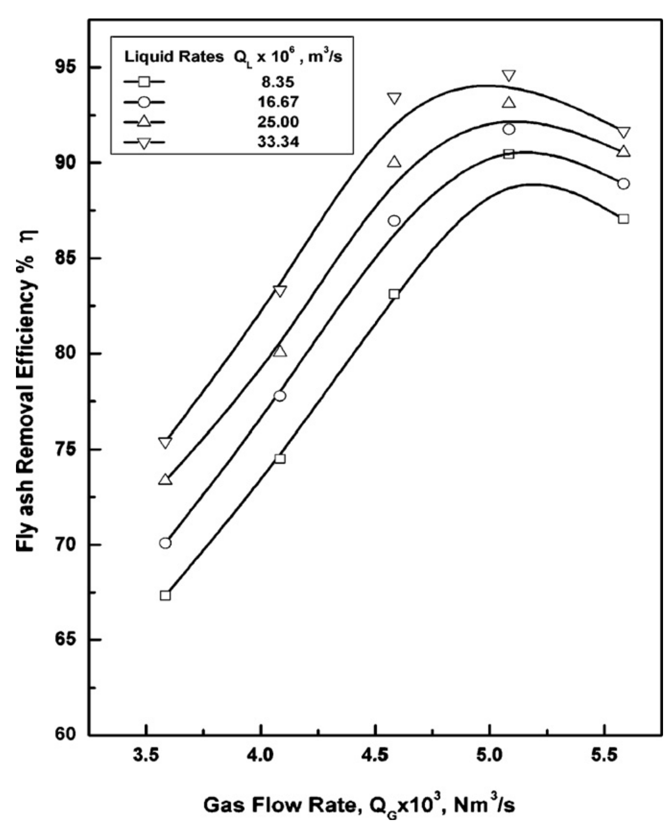

Fig. 15. Effect of gas flow rate on the overall efficiency of the spray tower at different liquid flow rates.

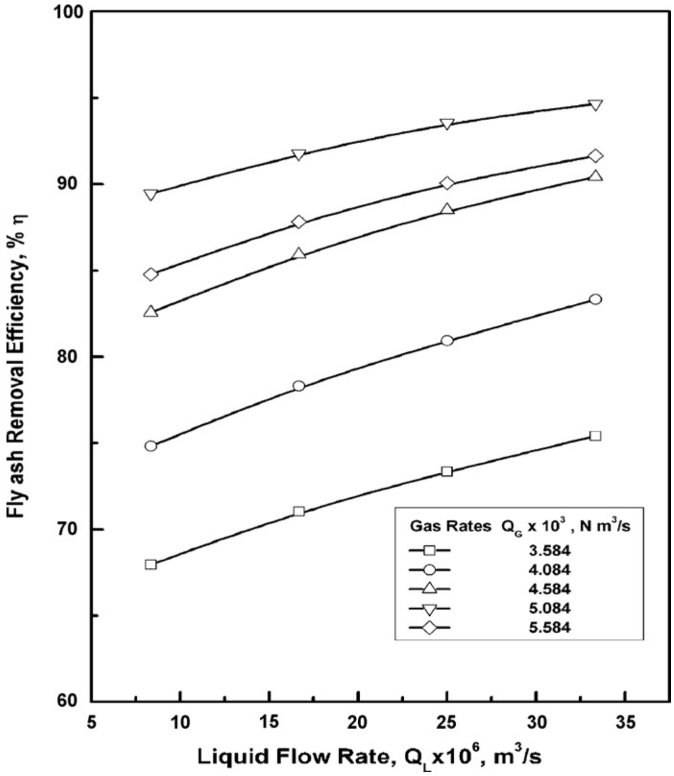

Fig. 16. Effect of liquid flow rate on the overall theoretical efficiency of the spray tower at different gas flow rates.

a wide range of particle size and the unknown exact mechanism, it is bit difficult to idealize the experimental results to that of the theoretical results. Fig. 16 reveals the effect of liquid flow rate on the overall efficiency of the spray tower at different gas flow rates where the increase in the liquid flow rate increases the efficiency gradually which is rapid in case of theoretical results. Hence there is a distinct difference in the experimental and theoretical results for the spray scrubbing process when a wide range of particle size is being scrubbed in a spray scrubber using single spray twin-fluid air-assist atomizer.

4. Conclusion

Particle collection efficiency of a spray column using twin-fluid atomizer has been theoretically investigated with a comprehensive analysis of model and experimentally verified for various droplet sizes of air-blast atomizer. The outcome of the results are summarized as follows:

(1) A mathematical model based on mass balance, momentum balance and continuity equation to a cylindrical element has been developed to predict droplet collection efficiency.
(2) The experimental values of particle removal efficiencies are compared with the theoretically predicted values. It has been found that the particle collection efficiencies are greatly dependent on the droplet size of the spray, gas flow rate and liquid flow rate under operating conditions.
(3) The experimental results show that an optimum collection efficiency of 96% for particulates was achieved at a gas flow rate of 5.25×10^{-3} m^3/s. The results also indicate that a maximum overall theoretical collection efficiency for the particle sizes 4–5 μm was 99.8%.

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