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Performance characteristics of the particulates scrubbing in a counter-current spray-column

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Abstract

Spray scrubbers are being widely used for off gas cleaning in chemical process industries due to its various advantages like low-pressure drop and simplicity. A pilot plant counter-current spray-column wet scrubber has been conceived, designed and fabricated. Experimental investigations were conducted to quantify the performances of a counter-current spray-column for scrubbing the particulates from the gaseous waste stream. Performance characteristics of the air-blast atomizing spray-column have been evaluated on the basis of the fly-ash (particulates) collection efficiencies within the stability range of the column. A maximum efficiency of 94.23% is achieved for gas and liquid flow rate of 5.084×10^{-3} Nm^3/s and 33.34×10^{-6} m^3/s, respectively. Results further show that Inlet solid loading effects positively in increasing the collection efficiency. Experimental results were further analyzed in terms of various pertinent variables of the system and a simplified correlation has been proposed. The predicted values agreed well with the experimental data obtained. A maximum difference of 17–18% was found towards higher liquid rates, rest showing a very minimum percentage of error and standard deviations between the experimental and the predicted values.

Keywords: Scrubbing; Spray scrubber; Collection-efficiency; Fly-ash; Air pollution control

1. Introduction

Air pollution is considered to be most dangerous among pollutions of ecosystem and its control by isolation and then cleaning becomes beyond man's effort unless the pollutants are controlled at the source itself. A diverse variety of pollutants are emitted into the atmosphere by both natural and anthropogenic sources. Among them, the particulate matters (PM) are fine solids or liquid droplets that are capable of temporary suspension in air or other gases (SPM). They are composed of inert or extremely reactive materials ranging in size from 0.1 to 100 μm mostly. Particles larger than 10 μm tend to settle out of the air. PM with 10 μm in diameter and smaller is considered inhalable and dangerous. This led our special interest and attention in control of PM_{10} and $PM_{2.5}$ which are termed as PM_{10} or $PM_{2.5}$ by EPA who prescribes that their emissions should be limited to less than 150 μg/m^3 for 24 h average. Literatures reveal that most of the present particulate controls system using the dry process of removal like cyclone, ESP, bag filters are quite uneconomical due to their high operating, and initial installation cost, require frequent maintenance and cannot achieve satisfactory removal efficiency while handling very fine sub-micron sizes of the particulate matter.

Air-blast atomizing spray column has been used in many industrial applications as fineness of droplets play very important role in modern industrial technologies. They have 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 their easy operation and simple construction. They gain importance in small scale and medium scale industries, as they are the lowest energy scrubber among other wet scrubbers apart from being economical. However for past few years numerous types of conventional and non-conventional scrubbers were known to be in practice for combating the particulate emissions, viz. venturi scrubber [1], horizontal scrubber [2], modified multi-stage bubble column [3].

Critical literature survey [2–4] reveals that various works were also carried out to study the performances of the scrubbers,

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which is indeed a fundamental analysis criterion for judging their suitability and applications. Performances of these scrubbers are evaluated on the basis of the collection efficiency of the particulates from the gas solid mixtures, within their stability ranges. It is seen that high efficiency in most of these devices can be achieved only with high-energy dissipation and mechanical complications. Due to growing environmental concern and stringent environmental regulations enforced by the legal bodies' world wide on particulate emission from various sources, driven researchers' attention to look into alternative technologies, which is simple, cost effective and has high performances in removing these particulate matter from industrial effluents. Since the spray column produces low-pressure drop so the dissipated power is also lower, making it quite economical devices. Survey reveals that very few works have been done on scrubbing of the fine particulate matter in a simple counter-current spray column.

The present study is an attempt to report on the performance study of a spray column, for removal of fine particulate matter from industrial hot flue-gases. Experimental findings are also correlated to develop a suitable model for the present system, which will quantify the performance of the column. The particle collection efficiency in this spray column is based on the particle collection mechanism of primarily inertial impaction and interception by nature [4]. Since the collection efficiency is a strong dependent upon the inertial impaction mechanism, it is required to increase the energy input, which will increase the relative-velocity and other disruptive forces between the down flowing water droplets and up flowing dust laden gas. Thus, experiments were conducted with gas rate range from 3.084×10^{-3} to $5.584 \times 10^{-3}\,\mathrm{Nm^3/s}$, and four different liquid rates of 8.35×10^{-6}, 16.67×10^{-6}, 25.00×10^{-6} and $33.34 \times 10^{-6}\,\mathrm{m^3/s}$. The inlet solid loading were kept within $0–2.5 \times 10^{-3}$, 2.5×10^{-3} to 5.0×10^{-3}, 5.0×10^{-3} to $10.0 \times 10^{-3}\,\mathrm{kg/m^3}$.

2. Experimental technique and procedure

The experimental setup is shown in Fig. 1. The spray column is constructed of transparent, vertical perspex column of 2400 mm long and 125 mm (ID) diameter, fitted with a fructo-conical top outlet. Around 565 mm, from the bottom of the column the hot-air inlet duct coming from a blower (2.2 kW) and a heater (4.5 kW) with solid mixture is fitted. The solids (fly-ash) are kept in a steel hopper (400 mm × 250 mm) aided by an electric vibrator that feeds the solids into the inlet air line through a venturi ejector for mixing the solids well with the air stream. The flow rate of the solids through the venturi mixer is controlled and calibrated rate by adjusting the needle valve of the air line and regulating the intensity of vibration by a variable rheostat connected to the power line of the vibrator. The air and the dust is allowed to flow through a venturi mixer with an angle 60° and the gas-fly-ash mixture enter the column through a gas sparger placed centrally at the bottom of the column and spread throughout the column diameter. The water used for scrubbing is pumped from the water tank through a 0.5HP pump and atomized at the top of the tower using a jet plain air-blast atomizing nozzle. Dried and moisture-free fly-ash has

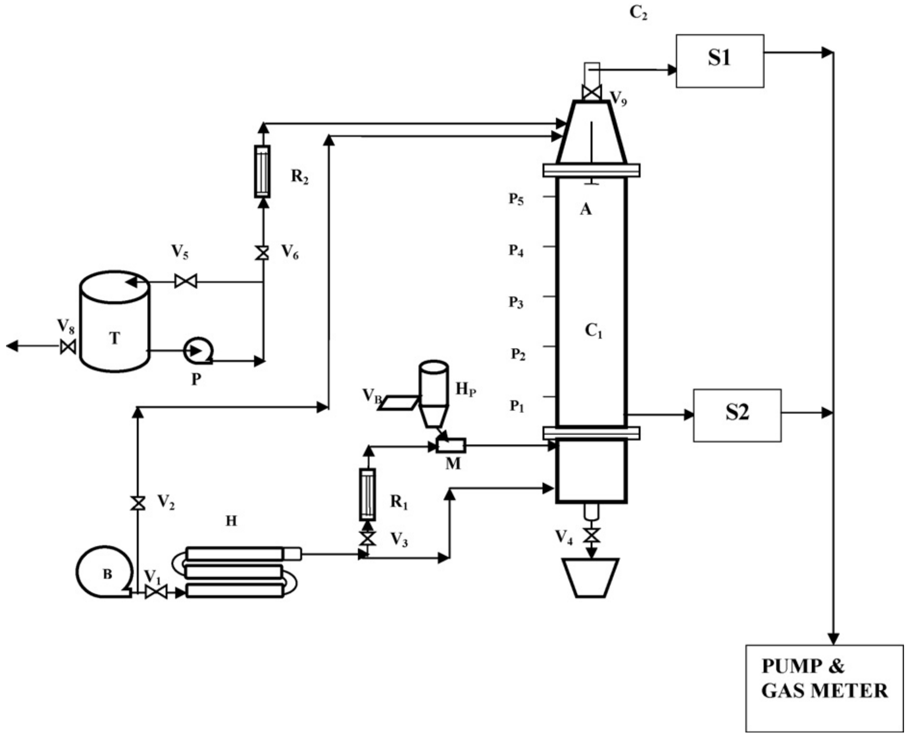

Fig. 1. Experimental set up: spray column for particulates removal. A: air blast atomizer; B: blower; H: heater; C_1: Spray-column; H_p: Hopper; $V_{1–9}$: valves; $P_{1–5}$: pressure taps; $S_{1–2}$: sample points; R_{1-2}: rotameters; T: water tank.

Table 1
The operating range of variables and the experimental conditions

Parameters	Range of values
Ambient temperature (K)	305 ± 1
Inlet temperature of the experimental hot air (°C)	70–80
Fly-ash particle size range (μm)	2–200
Liquid spray droplet size range (μm)	80–200
Gas flow rates (Nm^3/s)	3.084×10^{-3} to 5.584×10^{-3}
Liquid flow rates (m^3/s)	8.35×10^{-6} to 33.34×10^{-6}
Inlet fly-ash loading (kg/m^3)	$0–10.0 \times 10^{-3}$

been used as the particulate solids for the hot air medium. The particle size-distributions of inlet fly-ash are measured using a Malvern Master Size 2000 Ver.5.22. The operating parameters of the pilot plant studies were shown in Table 1. The inlet and the outlet concentration of the fly-ash (particulate matter) were measured by the filtration-technique [5], namely IS-5182: Part IV (1973) using a filter medium of specification GS555 MMAD. The processed gas (experimental air) samples are drawn at the rate of 3.392×10^{-3} to 5.892×10^{-3} m^3/s at isokinetic conditions. In order to collect representative samples, fly-ash samples were withdrawn at point S1 and S2 at the rate of 3.392×10^{-3} to 5.892×10^{-3} m^3/s to match the experimental gas-flow rate and the conditions of isokinetic sampling by keeping pressure drop and the velocity same as exit gases.

In this "Filtration Technique" the difference in the weight of the filter paper containing the collected fly-ash particles (dried and moisture-free), and the filter paper weighed alone gives the total mass of the particles collected. The fly-ash concentrations at the inlet and outlet are drawn at sample ports S_1 and S_2 as shown in Fig. 1 using the above technique. The percentage removal efficiency of the particulate matter (fly-ash) is calculated from:

$$\eta_{\mathrm{PM}} = \frac{C_{\mathrm{PM,inlet}} - C_{\mathrm{PM,outlet}}}{C_{\mathrm{PM,inlet}}} \times 100 \tag{1}$$

where η_{PM} is the collection efficiency of the particulates, $C_{\mathrm{PM,inlet}}$ the concentration of particulates at inlet (kg/m^3), and $C_{\mathrm{PM,outlet}}$ is the concentration of particulates at outlet (kg/m^3).

The experimentation is carried for different gas, liquid and solid flow conditions and the experimental results were analyzed to check the performance of the spray column. The fly-ash concentration at the bottom inlet and top outlet is respectively measured from at points S_1 and S_2 using the above technique, at varied conditions and the experimental results were analyzed. From the size-distribution differential data the average size of the fly-ash particles within the analyzed size ranges was found to be 8.409 μm (SMD).

3. Results and discussion

The trend of variation of percentage removal particulates is discussed in the following sections for various inlet loadings of fly-ash and for various operating and flow variables for liquid droplet and dust laden gas interactions within a spray column.

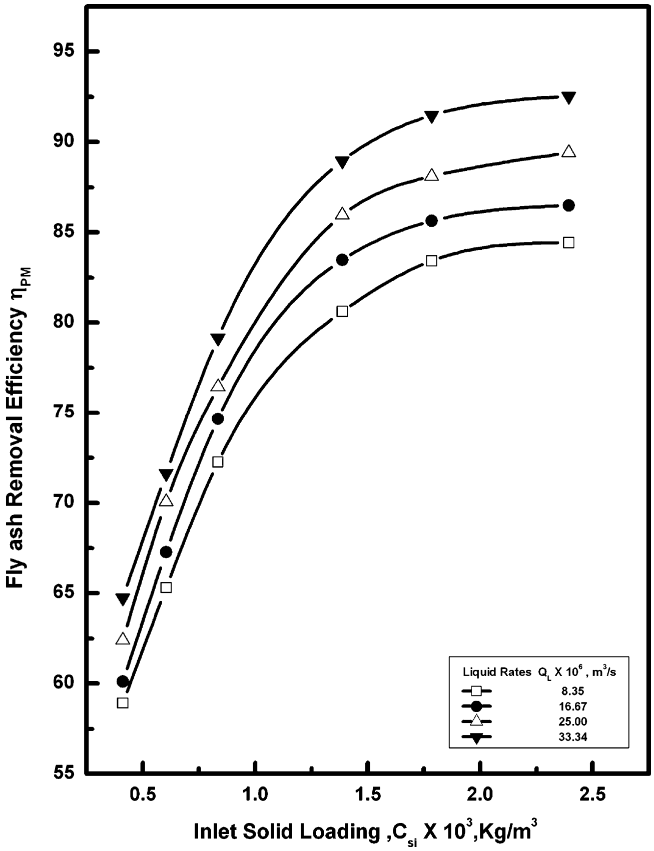

Fig. 2. Effect of solid loading from 2.5 to 5.0×10^3 kg/m^3 on fly-ash removal efficiency at constant liquid ranging rate from 8.35 to 33.34×10^6 m^3/s.

3.1. *Effect of inlet fly-ash loading*

It can be seen from Fig. 2 that the percentage removal efficiency of fly-ash increases with increase in fly-ash loading ranging from 0 to 2.5×10^{-3} kg/m^3 at constant liquid rate ranging from 8.35 to 33.34×10^{-6} m^3/s. This may be due to the fact that inertial impaction or interception are highly efficient for large population density of particles that leads to more probability of impaction and interception between particles and droplets when the inter-particle spacing is very low, thus enhances collection. So higher inlet solid loading progressively decreases the inter-particle spacing, which contributes positively to the removal efficiency of the particulates.

3.2. *Effect of the gas flow rate*

Fig. 3 shows effect of the gas flow rate at constant liquid flow rate, for four different liquid rates of 8.35×10^{-6}, 16.67×10^{-6}, 25.00×10^{-6} and 33.34×10^{-6} m^3/s and inlet solid loading were kept within $0–2.5 \times 10^{-3}$ kg/m^3. The figure reveals that with increase in gas flow rate the collection efficiency increases. As the relative velocity between the gas and falling spray droplets increases, the impaction between the droplet and dust particles within the continuous gas phase also increases and there by increasing the collision rate and probability of interception (capturing) [6]. Therefore higher collection efficiencies are obtained with higher gas velocities. Meikap et al. reported [2]

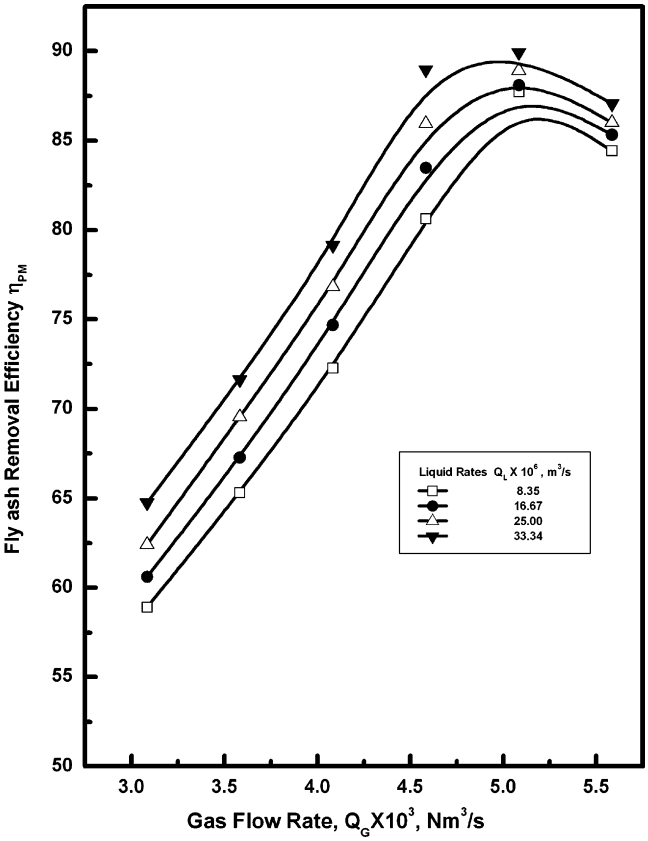

Fig. 3. Effect of gas rate on fly-ash removal efficiency at constant liquid rate from 8.35 to 33.34 × 10^6 m^3/s and inlet solid loading of 5.0–10.0 × 10^3 kg/m^3.

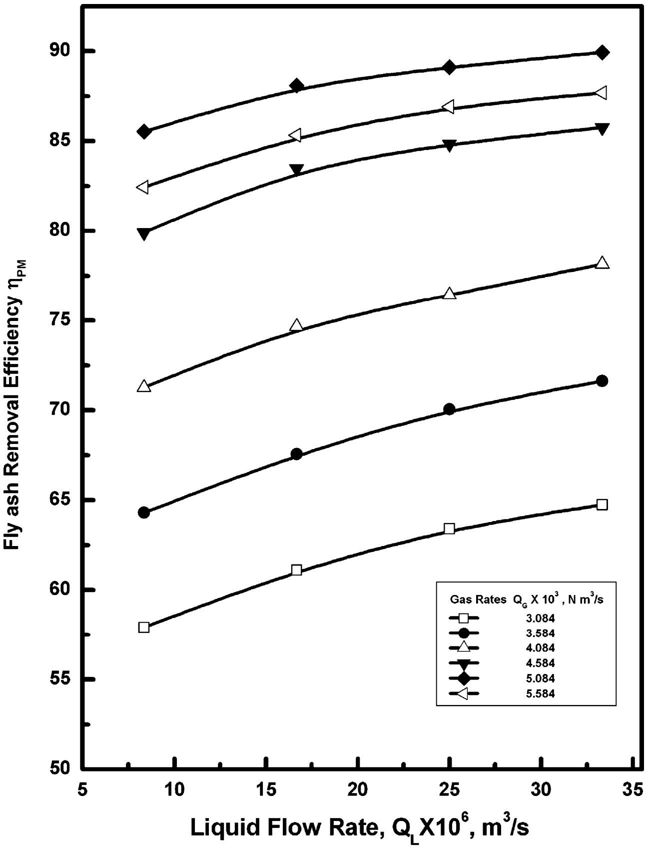

Fig. 4. Effect of liquid rate on fly-ash removal efficiency at constant gas rate with inlet solid loading of 0–2.5 × 10^3 kg/m^3.

too that higher gas rate effects positively in increasing particulate removal efficiency in multi-stage bubble regime. However at a very high gas rate, above 5.084 × 10^{-3} Nm^3/s, the particulate removal efficiency tends to decrease. This may be due to the considerable carryover (entrainment) of fine droplets and due to particle elutriation along with the scrubbed gas that may not collect the particles in the spray column.

3.3. *Effect of the liquid rate and liquid spray droplet sizes*

As revealed in Fig. 4, the collection efficiency also increases with increase in liquid rates of 8.35 × 10^{-6}, 16.67 × 10^{-6}, 25.00 × 10^{-6} and 33.34 × 10^{-6} m^3/s and inlet solid loading were kept within 0–2.5 × 10^{-3} kg/m^3. This increase is attributed to the large number of droplets produced for accommodating a greater volume of liquid in higher ranges of liquid rates. Almost similar view was expressed by Beig and Taheri [7], showing higher liquid rates effecting positively by increasing the collection efficiency. But this increasing trend cannot go on indefinitely as with higher liquid rates the spray droplet sizes also increases, which enhances their terminal settling velocity. In that case the droplets with reduced residence time might not get effective impaction and interception. As a result their increasing trend will go down slightly thereafter. Same way the higher sizes of the droplets does not affect favorably in increasing the efficiency [8–12].

For the present system, excellent collection efficiency is achieved under feasible operating conditions and the maximum efficiency achieved is 94.23%, which is quite efficient considering the fact that it is a spray regime. Muller [13] in droplet column claimed to have achieved 96.0% for finer dusts and lower ranges of liquid rates. Dullien and Spink [14] achieved a removal efficiency of both dust and mist of submicron sizes in the range of 90–100% using Caldyn nozzle that can produce droplets having diameter ranging from 5 to 50 μm. Pilate et al. [15] in their studies on the effect of diffusiophoresis and thermophoresis on particle collection efficiency by spray droplets revealed that the effect of thermophorosis affects the collection efficiency than diffusiophorosis as diffusiophorosis contributes only 2% and that too for particles of submicron levels. Johnson [16] also reported a similar operating experience with integrated particulate and sulfur dioxide scrubbing in a power plant.

4. Development of correlation for predicting removal efficiency

In order to quantify the performances of the spray column, we tried to develop an empirical model, by dimensional analysis, in order to predict the removal efficiency from directly measurable parameters. The experimental result show, that the conceivable variables which could possibly affect the collection efficiency of the particulates, η_{PM}.

Geometrical parameters namely—(i) droplet Sauter mean diameter: d_{O}, (ii) particle Sauter mean diameter, d_{p}; flow conditions namely: (iii) droplet slip velocity: V_{L}, (iv) superficial gas velocity: V_{G}, (v) inlet solid concentration: C_{si}; design aspect namely—(vi) spray-column diameter: D_{C}, (vii) spray-column height, H_{C}; physical parameters namely—(viii) droplet density: ρ_{L}, (ix) gas density: ρ_{G}, (x) particle density: ρ_{p}, (xi) gas viscosity, μ_{G}. The efficiency thus becomes a function of eleven sensitive parameters, each of them trying to exerts it influences:

$$\eta_{\mathrm{PM}} = f(V_{\mathrm{G}}, V_{\mathrm{L}}, d_{\mathrm{O}}, d_{\mathrm{P}}, \rho_{\mathrm{G}}, \rho_{\mathrm{L}}, \rho_{\mathrm{P}}, \mu_{\mathrm{G}}, C_{\mathrm{si}}, D_{\mathrm{C}}, H_{\mathrm{C}}) \tag{2}$$

The variables in the above equation can be grouped into dimensionless groupings by employing the Buckingham's π-Theorem, and the equation can be reduced to

$$\eta_{\mathrm{PM}} = k_0[Re\mathrm{G}]^a[Re\mathrm{L}]^b\left[\frac{d_{\mathrm{O}}^2\rho_{\mathrm{L}}}{d_{\mathrm{P}}^2\rho_{\mathrm{P}}}\right]^c\left[\frac{C_{\mathrm{si}}}{\rho_{\mathrm{G}}}\right]^d\left[\frac{d_{\mathrm{O}}}{D_{\mathrm{C}}}\right]^e \tag{3}$$

where Re_{L} is the liquid Reynolds number and Re_{G} is the gas Reynolds number.

In order to establish the fundamental relationship between the removal efficiency η_{PM} and the various dimensionless groupings, a multiple linear regression analysis has been carried out to evaluate the constant and coefficients of the equation. The optimum equation which yield's minimum percentage of error and minimum standard deviation, gives the best possible correlation of fractional efficiency as

$$\eta_{\mathrm{PM}} = 4.2\times10^{-3}[Re\mathrm{G}]^{0.5000}[Re\mathrm{L}]^{0.0045}\left[\frac{d_{\mathrm{O}}^2\rho_{\mathrm{L}}}{d_{\mathrm{P}}^2\rho_{\mathrm{P}}}\right]^{-0.4675} \times\left[\frac{C_{\mathrm{si}}}{\rho_{\mathrm{G}}}\right]^{-0.2727}\left[\frac{d_{\mathrm{O}}}{D_{\mathrm{C}}}\right]^{-0.0325} \tag{4}$$

The variance σ^2 of estimates $S^2(Y)$ and the correlation coefficients of the above equations are 0.5490 and 0.99676 respectively for a t-value 1.711 at 0.05 probabilities and 95% confidence range.

The form of the equation can be rearranged to give the penetration of the particulates through the spray droplet medium, given as

$$q = 1-\eta_{\mathrm{PM}} = 1-4.2\times10^{-3}[Re_{\mathrm{G}}]^{0.5000}[Re_{\mathrm{L}}]^{0.0045} \times\left[\frac{d_{\mathrm{O}}^2\rho_{\mathrm{L}}}{d_{\mathrm{P}}^2\rho_{\mathrm{P}}}\right]^{-0.4675}\left[\frac{C_{\mathrm{si}}}{\rho_{\mathrm{G}}}\right]^{-0.2727}\left[\frac{d_{\mathrm{O}}}{D_{\mathrm{C}}}\right]^{-0.0325} \tag{5}$$

where q is the penetration index of particle.

Fig. 5 shows a comparative study between the predicted model and the experimental data obtained. It reflects an excellent agreement with minimum error percentage. While Fig. 6 shows the variations of the deviations of the model and experimental values, the maximum deviation is within 17–18%.

To characterize the power–efficiency characteristics a comparative chart has been constructed as shown below Fig. 7. will be useful in optimizing the operating parameters. Thus the total operating cost of the column would be an additive function of initial installation cost and regular cost incurred due to power dissipation.

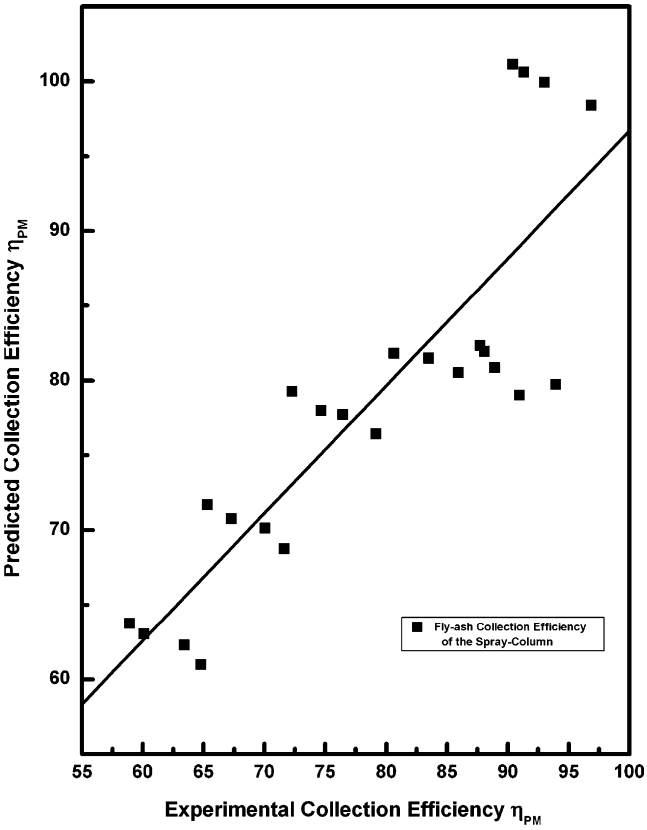

Fig. 5. Comparison of the experimental and predicted values of collection efficiency of the fly-ash scrubbing in spray-column.

It has been found that the maximum energy loses in the column is 105.5 W/1000 m^3 for a pressure loss of 350 N/m^2 equivalent to 24 W/m^3 vessel, which is quite low compared to the other kind of wet scrubber available. Since the power dissipated is low the regular cost always low which makes it a very economical devices and there is no problem in targeting at the higher efficiency. A correlation has been developed to quantify the performance of the column in removing the particulates. The experimental results agree well with the correlation developed, with a correlation coefficient of 0.99679 (with a minimum error) and the minimum standard deviations of errors. The fly-ash particle size distribution were measured by Malvern Master Size 2000 Ver.5.22 and shown in Fig. 8. It is found that the size of fly-ash lies in between 1 and 500 μm.

5. Liquid spray droplet characterization

The generation of fairly uniform and very fine spray at the cost of relatively little energy is difficult. Hence, determination of droplet size and their distribution becomes necessary. Both visual and photographic observation reveals that the whole column can be sub divided two distinct zones under steady state operation. The upper intense atomizing zone which extends down almost 0.75 m from nozzle tip where the fine droplets gets uniformly distributed over the up flowing dirty hot gases. The

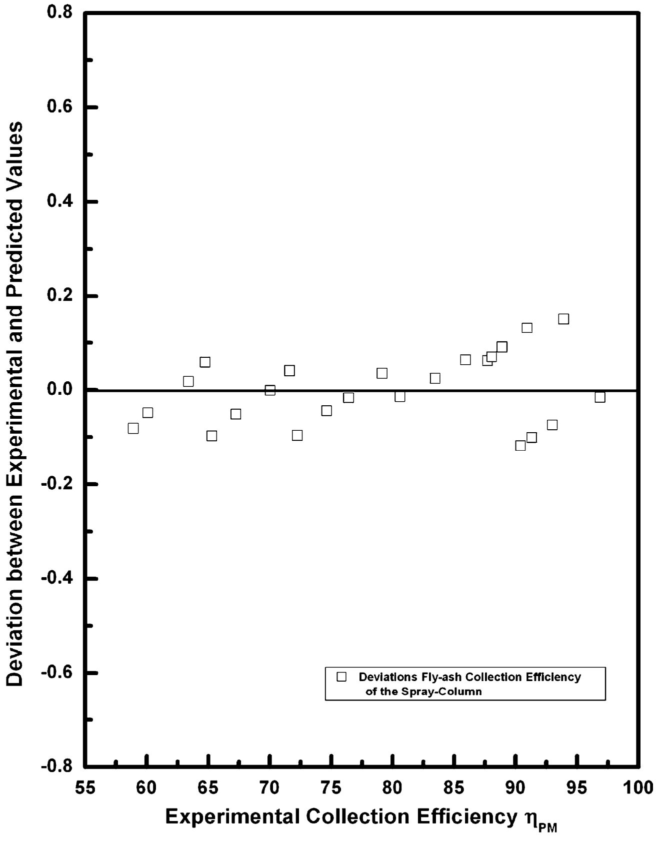

Fig. 6. Deviation between experimental and predicted values of collection efficiency.

bottom zone, which comprises the rest of column where the dust captured droplets falls freely or coalesce, combine and settles. They are also seen to flow down as ripples over the column wall. Altogether a very fine uniform distribution of finer droplets was noted.

It is evident from Fig. 9 showing an effect of gas rate 3.084×10^{-3} to 5.584×10^{-3} Nm^3/s on droplet size of spray at different liquid rate of 8.35×10^{-6}, 16.67×10^{-6}, 25.00×10^{-6} and 33.34×10^{-6} m^3/s and inlet solid loading were kept within 0–2.5×10^{-3} kg/m^3. droplet size decreases uniformly with increase in gas rate. This is primarily due to the fact that higher air flow rates promotes more efficient disintegration mechanism within the liquid by the growth of interface aerodynamic forces due to increased gas–liquid relative velocity at an enhanced gas rate. It is also noticed from the same figure that for a fixed gas rate droplet sizes increases but moderately with increase in liquid velocity. It is quite obvious as higher liquid rates offers greater liquid volume and enhances the counter-disruptive forces of surface-tension and viscosity producing bigger size drops and assisting in increase in coalesce rate of finer drops. The sizes of the droplets being produced mostly ranges from 80 to 200 μm,

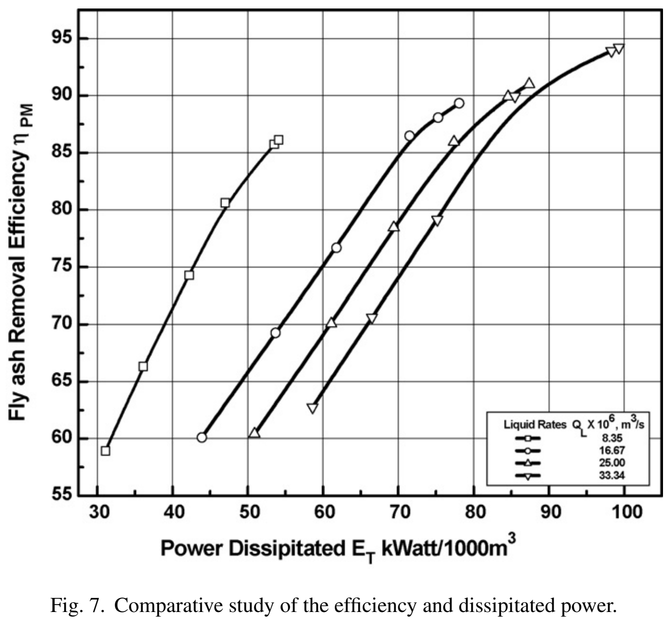

Fig. 7. Comparative study of the efficiency and dissipitated power.

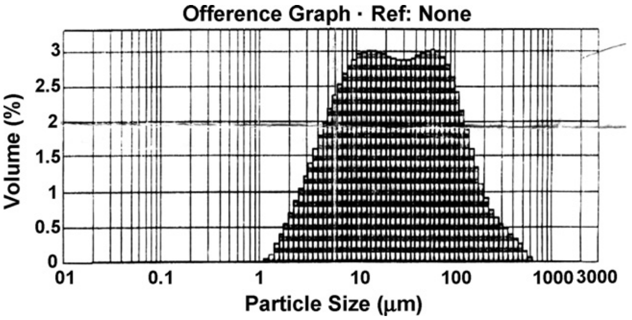

Fig. 8. Particle size distribution of fly-ash measured using Malvern Master Size 2000 Ver.5.22.

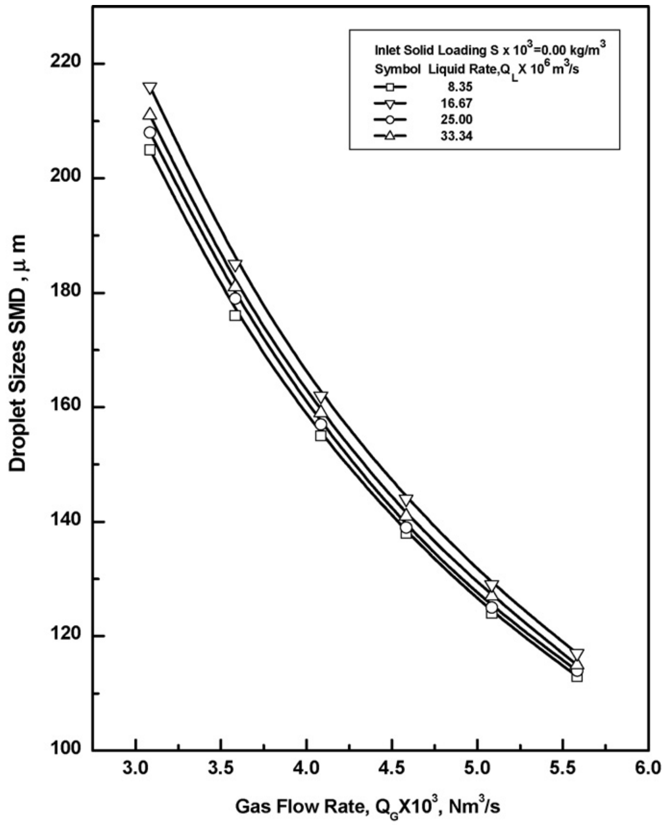

Fig. 9. Effect of gas rates on droplet sizes for different liquid rates and solid loading of 0–2.5×10^3 kg/m^3.

varying immensely with gas and liquid flow rates. The final optimal operating conditions of gas rate of 5.084×10^{-3} Nm^3/s, liquid rate of 33.34×10^{-6} m^3/s and inlet solid loading ranging in $5.0–10.0 \times 10^{-3}$ kg/m^3 are best suitable for such system.

6. Conclusion

The performance studies on the scrubbing of the fly-ash (particulate) in counter current spray-column are summarized as follows:

(1) Removal efficiency is a strong function of the inlet fly-ash loading rate. An excellent efficiency is achieved under the feasible operating conditions and a maximum efficiency of 94.23% was achieved for a gas rate of 5.084×10^{-3} Nm^3/s and a liquid rate of 33.34×10^{-6} m^3/s while the inlet solid loading ranging in $5.0–10.0 \times 10^{-3}$ kg/m^3.
(2) Experiments conducted on hydrodynamics shows that the maximum energy loses in the column is 105.5 W/1000 m^3 for a pressure loss of 350 N/m^2 equivalent to 24 W/m^3 vessel, which is quite low compared to the other kind of wet scrubber available. Fairly good liquid economy is achieved with liquid to gas ratio of 1.59–10.81 m^3 per 1000 actual cubic meter (ACM) where both the gas and liquid flow rates effects positively in increasing the dispersed phase hold ups.
(3) Considering that world-wide energy sector, iron and steel and other industries are prime generator of particulates from their gaseous wastes emissions, can incorporate at their downstream these kind of economical and effective devices. All these makes the present spray column the most economical and simplest means of devices with high recycle value and high efficiency to combat against the particulate pollution and provide a much cleaner and safe environment, which we are missing day by day.

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