Particulate Scrubbing in a Novel Two-Stage Hybrid Scrubber

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Introduction

Scrubbers without any column internals are used more and more as particulate control devices, and are found to have promising results. Despite some of its shortcomings, the wet scrubber is the only equipment type available in today's market place, which can effectively combat the problem of particulate pollution.[1] Moreover, wet scrubber is economical and offers a very high turn down ratio, higher service factor, smaller onsite plot space, and simpler operation than electrostatic precipitator. Furthermore, the U.S. EPA[2] has restricted the maximum particulate emission limits from coal fired thermal power plants to 22.65 g per 0.294 MW, which converts to 0.1634 g/Nm^3 for an Indian thermal power plant. Calculations show that at least 76% removal of particulates with less than 2 μm in size is essential to meet the EPA's prescription of stringent standards. In the pretext of such findings, development of high efficiency systems, which can operate under flexible operating conditions, is thus, very much demanded.

The various wet scrubbers used in practice offer a choice between the liquid dispersed and gas dispersed systems. Because of their intrinsic pressure drop and flow characteristics, the spray and bubble columns are more convenient than a packed column in particulate control applications. Literature[3,4] revealed that many multistage scrubbers were attempted for particulate control. However, a hybrid scrubber using both the spray and the bubble flow regimes in two distinct stages does not seem to gain importance. An attempt has, therefore, been made in this article to report on the operation of a novel hybrid scrubber for particulate control efficiently. The literature reveals that conventional bubble columns use sparger disks, which would create cleaning problem due to the accumulation of particulates for long-term operations. To avoid the operational difficulty we have used a frustum of a cone, that is, a tapered system, rather than using a cylindrical column, for creating the bubble regime. The bubble generation, breakup and regeneration are uniformly taking place in this section. The system is designed to operate with relatively large sized bubbles (5–10 mm by visual observation, approximately). The detailed energy consumption comparison of this tapered bubble column scrubber with the existing systems is presented in Table 1. Critical analyses of the literature[5-7] indicate that efficient particulate scrubbing is strongly dependent on the droplet to particle size ratio besides other factors, viz. droplet velocity, the particle and droplet loading. Furthermore, these studies also reveal that it is very difficult to produce very small droplets ($<$ 100 μm) with uniformity in spray pattern. An attempt has, therefore, been made in this study to overcome the difficulty of generation of small drops by using an energy efficient and cost-effective two-phase critical flow atomizer without offering any noticeable pressure drop across the column. In this article, the performance of a novel two-stage hybrid (spray-cum-bubble column) scrubber for particulate removal, using water as scrubbing medium, is reported.

Experimental

The experimental setup is shown in Figure 1. The experimental column is a vertical cylindrical Perspex column, 0.1905m in dia. and 2.0 m long, fitted onto a frustoconical

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Table 1. Power Consumption Comparison of Various Gas-Liquid Contacting Equipment vs. Present System [Frustoconical Bubble Column]

Contacting Equipment	Gas Rate $Nm^3/m^2 \cdot s$	Gas Holdup m^3/m^3 of Vessel	Power Consumption W/m^3 of Vessel
Plate column	0.60	0.90	1300
Gas bubble column	0.02	0.08	400
Stirred bubble absorber	0.06	0.15	2600
Modified multistage bubble column	0.11–0.20	0.21–0.65	200–450
Frustoconical bubble column [present system]	0.18–0.31	0.16–0.20	60–100

section of mild steel. The later had a divergence angle of 7° and a height of 0.87m. Arrangements were provided in the frustoconical section by replacing a small portion with Perspex sheet for our flow visualization. At the top of the cylindrical column a critical flow two-phase atomizer developed by Biswas[8] was provided for generating sprays with different droplet size spectrum and droplet velocities. On the other hand, provision was made to feed the air-fly-ash mixture at the base of the frustoconical section tangentially. In the actual experiment, water was pumped into the column through the atomizer using low pressure (2–10 psig) air to convert the liquid into fine sprays. The liquid was withdrawn at the bottom, at such a rate that, a liquid volume of 2.7×10^{-3} m^3 could be maintained in the bubbling section. The fly-ash concentrations at the top and the intermediate sections (that is, at points S_1 and S_2) of the scrubber were measured by filtration techniques[9] matching the conditions of isokinetic sampling. The inlet fly-ash concentration at point S_3 was measured *in situ* by using a calibrated photoelectric system.[3,4] The particle-size distribution of inlet fly-ash at S_3 and at intermediate point S_2 were measured using a Malvern 3601 Sizer.[4] The typical inlet fly-ash particle-size distributions at the bubble section and the spray section are shown in Figure 2 (particle SMDs at the inlet of the bubble and spray sections were 9.82 μm and 6.38 μm, respectively).

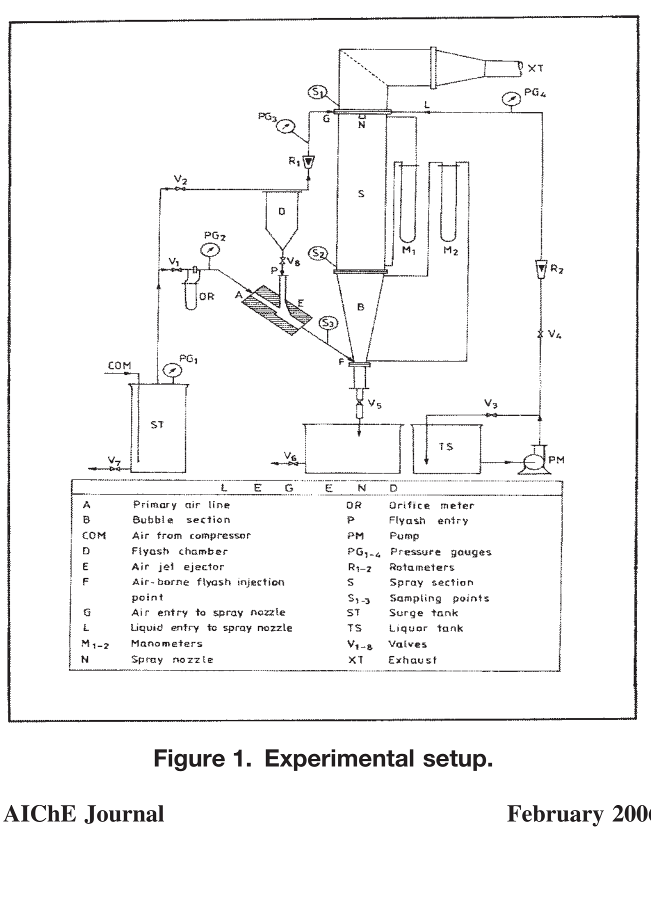

Figure 1. Experimental setup.

Results and Discussion

Experiments on the particulate scrubbing have been conducted at various process conditions, which are presented in Table 2. The trend of variation of percentage removal are discussed in the following sections for various inlet loading of fly-ash as well as various operating and flow variables for bubble, spray and combined modes of operation.

Effect of Inlet Fly-Ash Loading and Gas Flow Rate

The effect of inlet fly-ash loading and gas flow rate on percentage removal of fly-ash for the bubble section is shown in Figure 3 at a constant liquid flow rate. It can be seen from the figure that the increase in fly-ash loading decreases the removal efficiency. It also appears from the figure that the percentage removal of fly-ash increases with the increase in gas flow rate. The rate of increase is slow initially and beyond a gas flow rate of approximately 4.5×10^{-3} m^3/s the increase becomes insignificant. Furthermore, it can be seen, from Figure 2 that this section collects the relatively coarser particles (20 μm to 100 μm, approximately) while releasing the finer particles. The effect of inlet fly-ash loading and gas flow rate on the percentage removal for the spray section is shown in Figure 4 at a

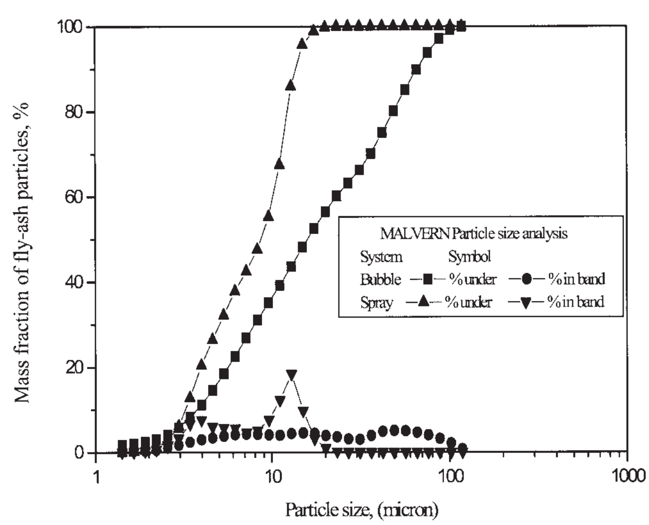

Figure 2. Typical particle size distribution of fly-ash at the inlet of the bubble and the spray sections (Courtesy: Kolaghat Thermal Power Station).

Table 2. Experimental Conditions for Fly-Ash-Air-Water System

Liquid flow rate	$1.11 \times 10^{-5} - 3.11 \times 10^{-5}$ m^3/s
Gas flow rate	$3.75 \times 10^{-3} - 6.20 \times 10^{-3}$ m^3/s
Fly-ash loading	$11.5 \times 10^{-3} - 25.0 \times 10^{-3}$ kg/m^3
Droplet SMD	72.2 μm — 139.8 μm (by PDA method)
Droplet velocity	20 to 30 m/s (by LDV method)
Bubble SMD	5–10 mm (visual observation)

constant liquid flow rate. It can be seen from the figure that the percentage removal increases with the increase in inlet fly-ash loading. It can also be seen from the figure that at higher gas flow rates the removal efficiency increases. Figure 3 also includes the effect of inlet fly-ash loading and gas flow rate on percentage removal for the two-stage hybrid scrubber at a constant liquid flow rate. It can be seen from the figure that the removal efficiency increases with the increase in inlet fly-ash loading and gas flow rate.

The decrease in removal efficiency at high inlet loading of fly-ash in the bubble section might be attributed to the increased particle-particle interaction leading to their carry over by the uprising bubbles. On the other hand, the increase in removal efficiency with the increase in gas flow rate might be due to the capture of particles resulting from the bubble bursting, regeneration and rebursting, as well as the cyclonic action created by the tangential entry of the inlet gas into the bubble section. In the spray section, the increase in inlet loading of fly-ash might have increased the particle-particle interaction which resulted in increased removal efficiency.[4] The increase in removal efficiency at higher gas flow rate might be attributed to the enhanced interception and impaction of particles in droplets caused due to increased relative velocity between the droplet and the particle. The overall performance of the two-stage hybrid scrubber indicates that the removal efficiency of fly-ash was increased with the increase in inlet fly-ash loading and gas flow rate similar to that observed in the spray section.

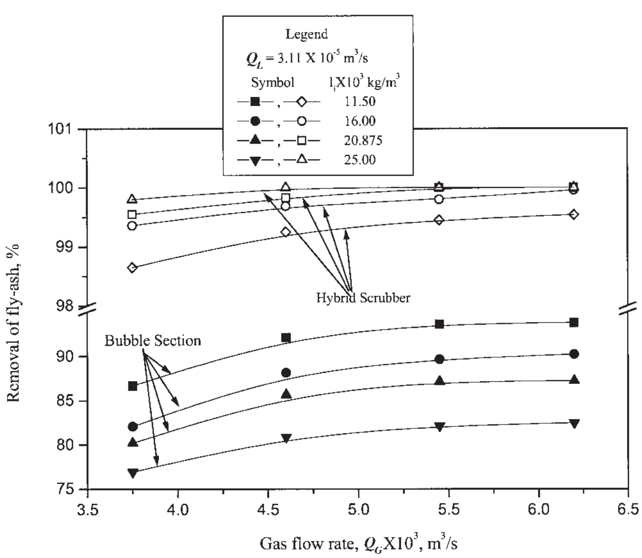

Figure 3. Effect of inlet fly-ash loading and gas flow rate on percentage removal at constant liquid flow rate in the bubble section, and in the hybrid scrubber.

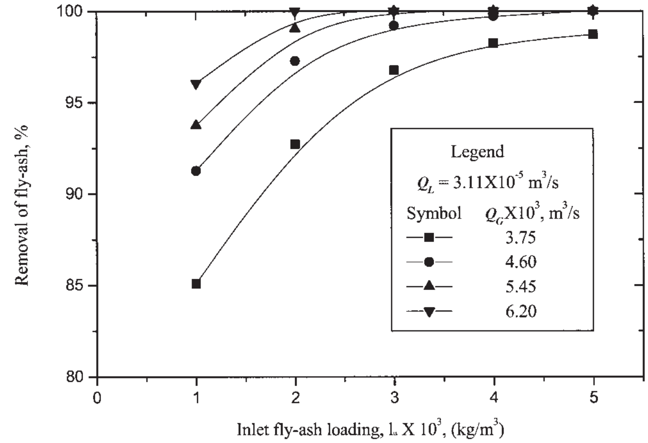

Figure 4. Effect of inlet fly-ash loading and gas flow rate on percentage removal at constant liquid flow rate in the spray section.

Therefore, the behavior of the hybrid scrubber was dominated by the spray scrubbing.

Effect of Liquid to Gas Flow Rate Ratio

Figure 5 is a typical plot of percentage removal of fly-ash vs. liquid to gas flow rate ratio for Stage 1 (bubble section), Stage 2 (spray section), and combined-staged operation (hybrid scrubber) for a fixed inlet fly-ash loading and for fixed gas flow rates. It can be seen from the figure that the percentage removal of fly-ash increases with the increase in Q_L/Q_G ratio in the bubble section, spray section and hybrid scrubber. It can also be seen from the figure that almost 100% removal efficiency (zero penetration) was achieved at a Q_L/Q_G ratio of 3.0 m^3/1000 ACM [$Q_G = 6.20 \times 10^{-3}$ m^3/s and $l_{ib} = 20.875 \times 10^{-3}$ kg/m^3] in the spray section and in the two-stage hybrid scrubber as well.

In the bubble section, the increase in removal efficiency with the Q_L/Q_G ratio might be attributed to the faster removal of fly-ash particles by the downward flowing liquid at higher rate, possibly due to reduced particle-particle inter-

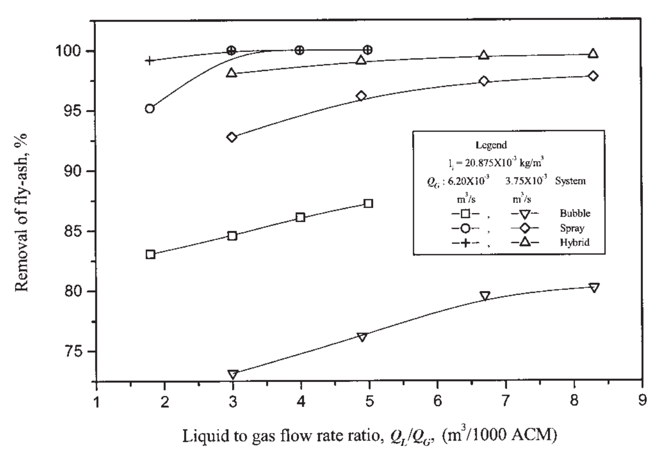

Figure 5. Effect of liquid to gas flow rate ratio on percentage removal at constant inlet fly-ash loading.

action as discussed earlier. The energy performance of this frustoconical bubble section is more favorable than the other existing systems (Table 1). In the spray section, as the Q_L/Q_G ratio for a constant gas flow rate is increased, the drop diameter increases, and the total drop cross-sectional area to sweep the air stream also increases.[4] Thus, the change in the Q_L/Q_G ratio for a constant gas flow rate, that is, the change in the liquid flow rate, might not affect the total number of drops, but it positively affected the efficiency of individual drops. The total interfacial area available in the system was adequate to cause effective impaction and interception of particles, and hence the percentage removal was increased with the increase in the Q_L/Q_G ratio. This agrees reasonably well with the observation made by Calvert et al.[5] Furthermore, almost 100% removal efficiency of fly-ash was achieved at a Q_L/Q_G ratio of 3.0 m^3/1000 ACM. Dullien and Spink[6] also achieved a removal efficiency of both dust and mist in the range of 90–100% using a Caldyn nozzle comparable to the atomizer used in this study. However, a Caldyn nozzle requires more energy than this atomizer to generate droplets having comparable spray hydrodynamics.[8] For example, to generate droplets with an SMD of 40 μm, this atomizer requires energy of 2.5 kJ/kg – H_2O/h at a liquid loading of 20 kg/h, compared with 15 kJ/kg – H_2O/h for a Caldyn nozzle. It indicates that the energy performance of this atomizer is more favorable than the Caldyn nozzle under the same hydrodynamic conditions. This two-stage hybrid scrubber achieved almost 100% removal of fly-ash particles with much lower hydraulic loading (Q_L/Q_G ratio of 3.0 m^3/1000 ACM), than that one obtained by Meikap et al.[10] in MMBCS (Q_L/Q_G ratio of 5.5 m^3/1000 ACM). The overall performance of the two-stage hybrid scrubber is energetically favorable compared to the existing systems, as discussed earlier. Hence, the novelty of the system is achieved.

Analysis of the Collection Efficiency

An attempt has been made to develop empirical correlations in order to predict the removal efficiencies of particulate from the directly measurable parameters for bubble and spray regimes separately. The overall efficiency of collection of the two-stage hybrid scrubber can be calculated with the help of the performance equations of two individual stages by the following equation

$$\eta_{FA,O} = \eta_{FA,B} + \eta_{FA,S}(1 - \eta_{FA,B}) \qquad (1)$$

The parameters, which could possibly affect the particulate collection efficiency in the bubble section, $\eta_{FA,B}$, are (a) geometrical parameters, namely, bubble Sauter mean diameter (d_b), particle Sauter mean diameter (d_p); (b) flow parameters, namely, bubble slip velocity (u_b), gas flow rate (Q_G), liquid flow rate (Q_L), fractional gas holdup (ε_g); (c) physical parameters, namely, particle density (ρ_p), gas bubble density (ρ_g), liquid density (ρ_L), gas viscosity (μ_g), inlet particle concentration (l_{ib}). The dimensional analysis may be simplified to

$$\eta_{FA,B} = f[\{(\rho_g d_b^2)(\rho_p d_p^2)\}(l_{ib}/\rho_L)(Q_L/Q_G)\varepsilon_g] \qquad (2)$$

In order to establish the functional relationship between percentage removal of particulate and the various dimensionless groups in Eq. 2, multiple linear regression analysis has been used to evaluate the constant and coefficients of the equation. The following equation presents the best possible correlation having the minimum percentage error and the minimum standard deviation of percentage error

$$\eta_{FA,B} = 1.17723[\{(\rho_g d_b^2) \times (\rho_p d_p^2)\}^{0.02561}(l_{ib}/\rho_L)^{-0.16675}(Q_L/Q_G)^{0.06327}\varepsilon_g^{1.19082}] \qquad (3)$$

The parameters, which could possibly affect the particulate collection efficiency in the spray section, $\eta_{FA,S}$, are (a) geometrical parameters, namely, droplet sauter mean diameter (D_d), particle sauter mean diameter (d_p); (b) flow parameters, namely, gas velocity (v_g), droplet velocity (v_d), and (c) physical parameters, namely, particle density (ρ_p), gas density (ρ_g), droplet density (ρ_L), gas viscosity (μ_g), inlet particle concentration (l_{is}). The dimensional analysis may be simplified to [4]

$$\eta_{FA,S} = f[\{(\rho_L D_d^2)/(\rho_p d_p^2)\}(v_g/v_d)(l_{is}/\rho_g)] \qquad (4)$$

In order to establish the functional relationship between percentage removal of particulate the various dimensionless groups in Eq. 4, multiple nonlinear regression analysis has been used to evaluate the constant and coefficients of the equation. The following equation presents the best possible correlation having the minimum percentage error and the minimum standard deviation of percentage error

$$\eta_{FA,S} = 1 - 2.658 \times 10^{-7}[\{(\rho_L D_d^2)/(\rho_p d_p^2)\}^{-0.75}(v_g/v_d)^{-1.89}(l_{is}/\rho_g)^{-1.03}] \qquad (5)$$

Various statistical tests have been carried out to test the acceptability of the correlations and determined at 99.1% confidence level, which reveal that the correlations are highly functional.

Conclusions

Experimental results indicate that removal efficiency is a strong function of inlet particulate loading. In the bubble section, higher inlet loading leads to lower efficiency of particulate collection while, in the spray section, higher inlet loading leads to higher efficiency of particulate collection. It is also found from the experimentation that almost 100% collection (that is, zero penetration) of particulate can be achieved in the novel two-stage hybrid scrubber for Q_L/Q_G ratio of 3.0 m^3/1000 ACM. The overall collection efficiency of the two-stage hybrid scrubber can be well predicted using the correlations developed for the two separate sections. The experimental results are in excellent agreement with the correlations. The energy and hence the cost performance of this system is found to be highly favorable. As the particulate collection efficiency of the hybrid scrubber is more than 99.5%, and since the fly-ash particles used in this system contains less than 10% of the total particles of diameter of less than 2.0 micron, the standards prescribed by EPA is, thus, met.

Notation

d_b = bubble Sauter mean diameter, m
D_d = droplet Sauter mean diameter, m
d_p = particle Sauter mean diameter, m
f = functions of variables, dimensionless
l_i = inlet fly-ash loading, kg/m^3
l_{ib} = inlet fly-ash loading in the bubble section, kg/m^3
l_{is} = inlet fly-ash loading in the spray section, kg/m^3
Q_G = gas flow rate, m^3/s
Q_L = liquid flow rate, m^3/s
u_b = bubble slip velocity, m/s
v_d = droplet velocity, m/s
v_g = superficial gas velocity, m/s

Greek letters

$\eta_{FA,B}$ = fly-ash removal efficiency in the bubble section, dimensionless
$\eta_{FA,O}$ = fly-ash removal efficiency in the two-stage hybrid scrubber, dimensionless
$\eta_{FA,S}$ = fly-ash removal efficiency in the spray section, dimensionless
μ_g = viscosity of gas, kg/m s
ρ_g = density of gas, kg/m^3
ρ_L = density of liquid, kg/m^3
ρ_p = density of fly-ash particles, kg/m^3
ε_g = fractional gas holdup, dimensionless

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