# Fly-ash removal efficiency in a modified multi-stage bubble column scrubber

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## Abstract

Bubble columns are being widely used in chemical process industries for its various advantages and simplicity. A pilot plant novel multi-stage bubble column wet scrubber has been conceived, designed and fabricated. This novel scrubber has been used as dust collecting wet scrubber in presence of other gaseous and vapor pollutants. This paper reports on the detailed experimental investigations carried out on the scrubbing of fly-ash in this novel wet scrubber using water as the scrubbing medium. It has been found that the present system yielded very high efficiency for the scrubbing of fly-ash. In most cases, the fly-ash removal efficiency is more than 95% and many cases approaches 99.5%. A correlation has been developed for prediction of particulate (fly-ash) removal efficiency. The scale-up of this pilot plant in Indian thermal power plant shows excellent performance and meets the stringent pollution control standards. Attempt has also been made to install the above wet scrubber in Indian Thermal Power Plants and Ceramic Industries to combat particulate pollution control and found excellent performance.

*Keywords:* Air pollution; Wet scrubber; Fly-ash; Modified multi-stage bubble column scrubber; Percentage removal of fly-ash

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## 1. Introduction

The emission of particulate matter (fly-ash) from various industrial sources always occurs in association with sulfur dioxide, in varying composition and quantities. The effects of particulate and sulfur dioxide individually are very severe. However, several toxicological/epidemiological investigations have shown that in the presence of particulate matters synergistically modify the effects of other gases and the combined synergistic effects are much more severe than the simple additive effects of the individual pollutants. This synergism modified effects have motivated the public and private sector industries, government agencies to work out a reliable background information, enforceable regulations and viable control options for the particulate laden sulfur dioxide emission.

The increasingly stringent compliance requirements based on the synergism modified standard has put tremendous constraints on the industries to control

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**Nomenclature**

| | |
|---|---|
| $C_{\mathrm{FA,i}}$ | inlet concentration of fly-ash ($\mathrm{kg/N\,m^3}$) |
| $C_{\mathrm{FA,o}}$ | outlet concentration of fly-ash ($\mathrm{kg/N\,m^3}$) |
| $d_{\mathrm{o}}$ | orifice diameter (m) |
| $d_{\mathrm{p}}$ | diameter of fly-ash particle (m) |
| $D$ | diffusivity ($\mathrm{m^2/s}$) |
| $D_{\mathrm{C}}$ | diameter of bubble column (m) |
| $D_{\mathrm{H}}$ | diameter of expansion, contraction disks (m) |
| $D_{\mathrm{L}}$ | dispersion coefficient, liquid phase ($\mathrm{m^2/s}$) |
| $g$ | acceleration due to gravity ($\mathrm{m/s^2}$) |
| $H$ | height of the bubble column (m) |
| $H_{\mathrm{R}}$ | height to diameter ratio ($H/D_{\mathrm{C}}$), dimensionless |
| $L_{\mathrm{P''}}$ | liquid property group $[\pi g D_{\mathrm{C}}^3 \rho_{\mathrm{L}}/4Q_{\mathrm{L}}\mu_{\mathrm{L}}]$, dimensionless |
| $q$ | which penetrates into the exhaust ($q = 1 - \eta_{\mathrm{T}}$), dimensionless |
| $Q_{\mathrm{G}}$ | volumetric flow rate of gas ($\mathrm{N\,m^3/s}$) |
| $Q_{\mathrm{L}}$ | volumetric flow rate of liquid ($\mathrm{m^3/s}$) |
| $Re_{\mathrm{G}}$ | superficial gas Reynolds number ($D_{\mathrm{C}}V_{\mathrm{G}}\rho_{\mathrm{G}}/\mu_{\mathrm{G}}$), dimensionless |
| $Re_{\mathrm{L}}$ | superficial liquid Reynolds number ($D_{\mathrm{C}}V_{\mathrm{L}}\rho_{\mathrm{L}}/\mu_{\mathrm{L}}$), dimensionless |
| $Sc$ | Schimdt number based on fly-ash concentration ($\mu_{\mathrm{L}}\backslash DC_{\mathrm{FA,i}}$)) dimensionless |
| $V$ | operating scrubber volume ($\mathrm{m^3}$) |

*Greek letters*

| | |
|---|---|
| $\eta_1$–$\eta_3$ | individual stage efficiency |
| $\eta_{\mathrm{FA}}$ | removal efficiency of fly-ash, from fly-ash–air mixture |
| $\eta_{\mathrm{T(2)}}$ | overall collection efficiency, for two stages |
| $\eta_{\mathrm{T(3)}}$ | overall collection efficiency, for all three stages |
| $\mu_{\mathrm{eff}}$ | effective viscosity of liquid (kg/m s) |
| $\mu_{\mathrm{G}}$ | gas viscosity (kg/m s) |
| $\mu_{\mathrm{L}}$ | liquid viscosity (kg/m s) |
| $\rho_{\mathrm{G}}$ | gas density ($\mathrm{kg/m^3}$) |
| $\rho_{\mathrm{L}}$ | liquid density ($\mathrm{kg/m^3}$) |

*Subscripts*

| | |
|---|---|
| cal | calculated |
| exp | experimental |
| FA | fly-ash |
| FA, i | inlet concentration of fly-ash |
| FA, o | outlet concentration of fly-ash |

particulate laden sulfur dioxide to a very high degree and the existing pollution control devices like gravity settling chambers, cyclones, bag filters, electrostatic precipitators and wet scrubbers, either alone or in combination, are not fully satisfactory and/or cost effective to meet the demands of the pollution control regulations.

The various wet scrubbers used in practice offer a choice between the liquid dispersed and gas dispersed system. Because of their intrinsic pressure drop and flow rate characteristics, the bubble column may be more convenient than packed column in air pollution control applications involving particulate laden gaseous pollutants. Furthermore, EPA, US [1] has restricted the maximum discharge limits from coal based thermal power plants to $0.1634\,\mathrm{g/N\,m^3}$ for an Indian thermal power plant. Calculations show that at least 76% removal of particulate less than $2\,\mu\mathrm{m}$ in size is essential to meet the stringent standards prescribed by EPA. The existing emission standards for particulate matter in India are higher ($0.150\,\mathrm{g/N\,m^3}$) than the proposed World Bank standards of $0.050\,\mathrm{g/N\,m^3}$. Furthermore, the World Bank guidelines propose that the particulate removal efficiency should be at least 99.9% if $50\,\mathrm{mg/N\,m^3}$ are not achievable and operated at least at 99.5% efficiency. Development of high-efficiency systems, which can operate under flexible operating conditions, is thus very much demanded under the above context.

Mashelkar [2] reported that, bubble column scrubber (BCR) offers many advantages like, little maintenance requirement due to simple construction and no problems with sealing due to the absence of moving parts, high liquid phase content for the reaction to take place, excellent heat transfer properties and hence easy temperature control and low initial costs. Survey of the literature revealed that various wet scrubbing systems have been used for collecting particulate from waste gas streams. Literature survey also reveals

Table 1
Comparison of power consumption (pressure drop) and hydrodynamic characteristics for various gas–liquid contacting equipments with MSBCS [25,26]

| Gas–liquid contacting equipment | Gas rate, $Q_G/A_C$ ($N\,m^3/m^2\,s$) | Specific surface area, $a$ ($m^2/m^3$), $k_La$ ($s^{-1}$) | Volume fraction of gas phase, $\Phi_G$ ($m^3/m^3$ of vessel) | Power consumption, E ($W/m^3$ of vessel) |
|---|---|---|---|---|
| Plate column | 0.60 | 100–400 (0.01–0.05) | 0.9 | 1300 |
| Packed column | 0.90 | 200 (0.005–0.02) | 0.9 | – |
| Wetted wall column | 2.10 | 50 | 0.95 | – |
| Gas bubble column | 0.02 | 70 (0.005–0.01) | 0.08 | 400 |
| Stirred bubble absorber | 0.06 | 200 (0.02–0.2) | 0.15 | 2600 |
| Spray column | – | 10–100 (0.0007–0.015) | More than 0.80 | – |
| Jet (loop) | – | 1000–7000 (0.1–3.0) | 0.5 | 10–700 |
| Tubular/venturi ejector | – | 200–2000 (0.01–2.2) | Less than 0.50 | 0.8–90 |
| Multi-stage bubble column scrubber | 0.11–0.20 | 250 to 600 (0.13–0.24) | 0.21 to 0.65 | 200–450 |

that most of the work reported on the scrubbing of fly-ash, $SO_2$ and fly-ash laden $SO_2$ were used venturi scrubbers [3], spray columns [4–8] and various other columns [9–13].

Literature survey further reveals that very little work has been reported on the scrubbing of fly-ash in a bubble column. Ranz and Wong [14] undertook fundamental studies on the mechanisms of collection of dust and smoke particles, in several elementary collectors. The systems reported were rectangular and round aerosol jets impinging on flat plates, cylindrical and spherical collectors placed in aerosol streams (fibrous filters and wet scrubbers). They proposed a correlation for determining the efficiency of impaction, even under the most complicated situations.

Calvert et al. [15] reported particle collection efficiency and pressure drop for venturi and other atomizing scrubbers. Dullien and Spink [16] used a different hypothesis for the particle capture. They reported removal efficiencies of both mist and dust were in the range of 90–100% under conditions where existing theories predicted much lower efficiencies.

Bandopadhyay and Biswas [7,8] reported experimental investigation on the scrubbing of fly-ash in a spray-cum-bubble column. They reported that, experimental removal efficiency were a strong function of inlet fly-ash loading in both spray and bubble sections.

In the bubble column very limited studies on scrubbing of fly-ash have been reported. Many of the processes reported have been covered by patent protections [17–21]. In the present investigation a bubble column, operating in three stages have been designed—the staging effect being achieved through hydrodynamically induced continuous bubble generation and breakup through bubble rupture and regeneration. The system has been designed to operate with relatively large sized bubbles, so that internal circulation can be induced in the bubbles and faster transfer of gas and fly-ash can take place by turbulent diffusion through the interface of the bubbles and also due to the direct rupture of the relatively large diameter bubbles.

Detailed experimental investigations on pressure drop have been carried out on the multi-stage bubble column and reported else where [22]. In addition, the performance of the scrubber is also dependent on disperse phase hold-up, interfacial area of contact and liquid side mass transfer coefficient which have been reported by Meikap et al. [23–25]. A comparison for energy dissipation (pressure drop), interfacial area of contact and gas hold-up of various types of wet scrubber reported by Scott [26] like venturi scrubber, spray column with the present system is presented in Table 1. In the present investigation the modified multi-stage bubble column, has been used to investigate the removal of particulate (fly-ash). In the studies the effect of gas flow rate, liquid flow rate, column height and inlet fly-ash loading on percentage removal of fly-ash has been investigated from the air–fly-ash mixture with a composition similar to that of existing exhaust of an Indian coal fired thermal power plant.

## 2. Experimental setup and techniques

Fig. 1 shows the schematic diagram of the pilot plant used for removal of fly-ash. The experimental bubble

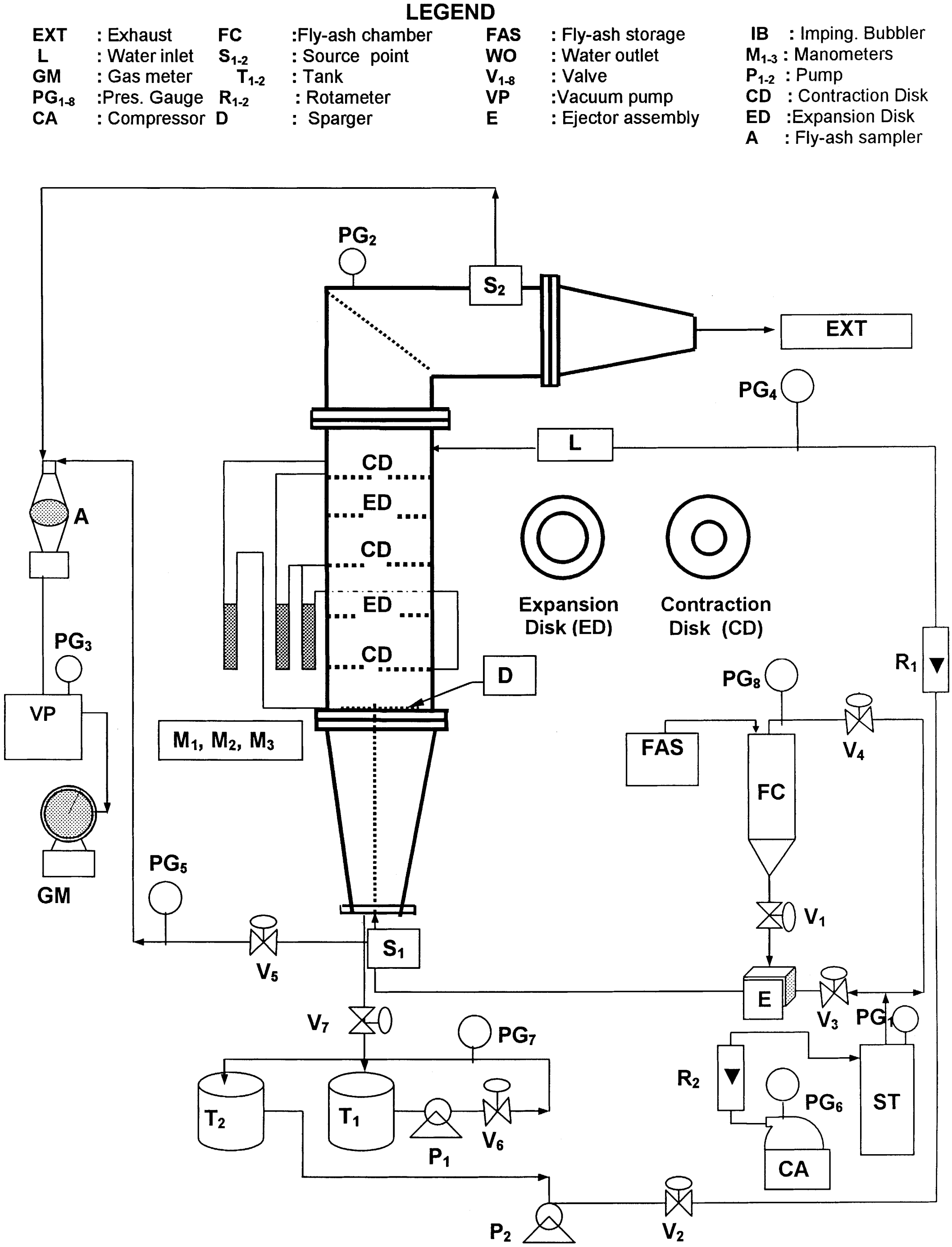

Fig. 1. Schematic diagram of the experimental setup for the scrubbing of fly-ash in a MMSBCS.

column consisted of a vertical cylindrical Perspex column, 0.1905 m in diameter and 2.0 m long, fitted onto a fructo-conical bottom of mild steel with a divergence angle of 7° and a height of 0.87 m. The minimum diameter of the fructo-conical section was 0.10 m. The vertical cylindrical column was fitted with a total of five hollow disks termed as stages (three contraction disks and two expansion disks). The expansion and contraction disks had central axial openings of 0.095 and 0.0476 m, respectively.

At the bottom most section of the cylindrical column, just above the fructo-conical cone, was fitted an antenna type of sparger [24] of 1.6 mm diameter and 144 holes for generating bubbles uniformly throughout the entire cross section of the column. The first contraction disk (known as first stage) of 0.0476 m central opening was placed at a height of 0.26 m above the sparger. The second disk (second stage) of 0.095 m central opening was fitted at a height of 0.52 m above the sparger and the third disk (third stage) was fitted at a distance of 0.78 m above the sparger. The column is divided into three distinct sections. Section 1 consists of sparger and first contraction disk of 0.26 m height, Section 2 consists of first contraction disk, first expansion disk and second contraction disk of 0.78 m height and Section 3 a height of 1.30 m. A 0.50 m clear space was provided above Section 3, for allowing time for gas–liquid separation and also to accommodate bed expansion due to bubbly flow.

Experiments were conducted both with a constant liquid batch and continuous liquid down-flow. For conducting experiments with liquid down-flow, a water inlet was provided at a height of 1.80 m as shown (L) in Fig. 1. At the bottom of the column a water outlet was provided as shown (WO). Four solenoid valves, at positions $V_1$–$V_4$ were provided at the liquid and gas inlet and outlet, respectively, for quickly trapping the flow when necessary. The liquid and gas flows into the column were controlled by valves $V_6$–$V_8$ and pressure was measured by pressure gauge $PG_1$–$PG_8$.

The air–fly-ash mixture, in composition similar to that existing in the exhaust of a coal fired thermal power plant using coal with 35% ash content, was generated by mixing air and fly-ash in an air-jet ejector (E) assembly. Compressed air from compressor (CA) was used as the motive fluid in the ejector [25] to aspirate and thoroughly mix air with the fly-ash from the fly-ash chamber (F). Compressed air was fed through the surge tank (ST) and air nozzle, at the desired motive pressure and flow rate. The air flow was regulated by a valves ($V_3$ and $V_4$) and was measured by a calibrated rotameter ($R_2$). Simultaneously, the fly-ash from fly-ash storage bin (FAS), was routed at a controlled rate through the valve $V_1$, into the ejector. Static pressure tapping ($M_1$–$M_3$) was provided in the positions shown.

In the actual experiments, the scrubbing liquor (water in this case) was pumped by a pump ($P_1$) from a storage tank ($T_2$), through the valve ($V_2$) and then fed into the column at point L. The flow rate of water was measured by the calibrated rotameter ($R_1$). The air–fly-ash mixture was fed into the bubble column scrubber through the sparger (D).

The inlet and outlet concentrations of fly-ash were measured by filtration technique [27] through a filter mounted on a filter assembly (A) and connected to a vacuum pump (VP). Glass fiber filter (99% or higher efficiency for particles 0.3 μm or larger in diameter) have been used in the experiment. The sampling flow rate was controlled by using the vacuum pump so that *iso*-kinetic sampling can be achieved. Through the sampling ports sampling probes were connected to the suction side of the vacuum pump and the samples were drawn at the same velocity as prevalent in the column. The sample flow at the desired rate was regulated by a ball valve ($V_5$). One calibrated wet-gas meter (GM) was attached with the suction pump to measure the flow rate of the sampled air stream. The fly-ash particles collected on the glass fiber filter paper was dried in an air oven at 105 °C and cooled in desiccators. The difference in weight of the filter paper containing fly-ash particles and the filter paper previously weighted alone, gave the total mass of particle collected. Samples at point $S_1$ and $S_2$ were drawn at the rate of $1–2 \times 10^{-3}\,\mathrm{N\,m^3/min}$ and the concentration of the fly-ash particles was expressed in $\mathrm{kg/N\,m^3}$. The fly-ash, in the form of slurry, was collected continuously in a settler ($T_1$). In the settler the sludge was separated at the bottom and the supernatant solution was recycled to the scrubber through a pump ($P_2$) and controlled valves ($V_6$ and $V_7$).

The analysis of inlet fly-ash used has been presented in Table 2. The particle size distribution of inlet fly-ash has been measured using a Malvern 3601 sizer using $Na_4P_2O_7$ (anhydrous) (LOBA Chemie) [28] as dispersant in a concentration of $1.0864\,\mathrm{kg/m^3}$ as shown

Table 2
Analysis of fly-ash (courtesy Kolaghat Thermal Power Plant)

| Element | Sample 1 element (%) | Sample 1 atomic (%) | Sample 2 element (%) | Sample 2 atomic (%) |
|---|---|---|---|---|
| Al | 23.38 | 29.32 | 22.74 | 28.82 |
| Si | 43.75 | 52.71 | 43.96 | 53.54 |
| K | 3.64 | 3.15 | 3.39 | 2.96 |
| Ti | 2.04 | 1.72 | 1.69 | 1.44 |
| Ca | 2.04 | 1.44 | 1.74 | 1.24 |
| Fe | 6.72 | 4.07 | 7.52 | 4.60 |
| Rb | 16.35 | 6.47 | 17.59 | 7.04 |
| Ba | 1.33 | 0.33 | 1.37 | 0.34 |
| S | 0.75 | 0.79 | – | – |

in Fig. 2, which shows the fly-ash particle distribution used for the present investigation. It is clear from the Malvern analysis that particles in the range of 2–15 μm which is important as per EPA norms were used to predict the fly-ash removal efficiency in the scrubber.

## 3. Results and discussions

In the scrubbing experiments, studies were conducted to determine the effect of gas and liquid flow rates on the percentage removal of fly-ash particles using water as scrubbing medium and to determine the effects of inlet fly-ash loading on the percentage removal of fly-ash and the effect of inlet fly-ash loading on outlet fly-ash loading. Experiments have been conducted with liquid flow rates of $34.5 \times 10^{-6}$, $69.0 \times 10^{-6}$, $103.5 \times 10^{-6}$, $138.0 \times 10^{-6}$, $172.5 \times 10^{-6}$ and $207.0 \times 10^{-6}\,\mathrm{m^3/s}$. Corresponding to each liquid flow rate, gas flow rates of $3.0 \times 10^{-3}$, $3.6 \times 10^{-3}$, $4.2 \times 10^{-3}$, $4.9 \times 10^{-3}$, $5.5 \times 10^{-3}$ and $6.0 \times 10^{-3}\,\mathrm{N\,m^3/s}$ were used. The gas velocities were so selected as to generate bubbles in the size range of 2–5 mm (by visual observation). For each liquid flow rates the inlet fly-ash loading was varied from 13.6 to $27.3\,\mathrm{g/N\,m^3}$ in five stages, e.g. 13.6, 17.3, 20.9, 24.6 and $27.3\,\mathrm{g/N\,m^3}$. The inlet loading was determined by gravimetric method. The scrubbing liquid in these sets of experiments was water. To quantify the effects of expansion and contraction disks data have been generated for particulate collection efficiency as a function of column height as well as for the entire column. Percentage removal of fly-ash have been calculated for each run by the formula:

$$\eta_{\mathrm{FA}} = \frac{C_{\mathrm{FA,i}} - C_{\mathrm{FA,o}}}{C_{\mathrm{FA,i}}} \times 100 \qquad (1)$$

The trend of the variation of percentage removal of fly-ash has been plotted in Figs. 3 and 4 for various inlets loading of fly-ash, and various operating and flow variables for the modified multi-stage bubble column scrubber (MMSBCS) and along the height of the scrubber.

### *3.1. Effect of gas flow rate and fly-ash loading on percentage removal of fly-ash*

The percentage removal of fly-ash, $\eta_{\mathrm{FA}}$ at different inlet fly-ash loading and for constant heights of the bubble column scrubber, has been plotted against gas flow rates in Fig. 3. It can be seen from this figure that the percentage removal of fly-ash in the MMSBCS is very high, even at a very low gas flow rate. This high efficiency is due to the unique particulate collection mechanism in the MMSBCS. Increased turbulence resulting from vigorous bursting, formation and regeneration of bubbles in the gas phase enhances the probability of inter-particle and particle–water-film collisions in the bubble column. Furthermore, during bubble breakup and reformation fly-ash particles are directly captured by the water due to their higher wettability, thereby increasing the efficiency of collection. Breakup of the bubbles in the liquid continuum, entraps the solid particles in water, which are continuously washed out by the stream of downward flowing liquid. Particulate not collected in the lower section of the column are carried over by the upwardly moving gas stream, in the form of regenerated bubbles. Bubbles bursting induced in the subsequent contraction disks, collect the residual particulate matter. As the gas flow increases intensity of bubble bursting, regeneration and re-bursting increases which leads to higher particulate collection. However, beyond a gas flow rate of approximately $4.2 \times 10^{-3}\,\mathrm{N\,m^3/s}$, bubble reformation is hindered due to faster coalescence which reduces the removal efficiency.

This plot also includes the effects of inlet fly-ash loading and it is seen from the figures that the increase in fly-ash loading increases the percentage removal of fly-ash $\eta_{\mathrm{FA}}$. Low inlet loading hinders particle collection in bubble column due to lower

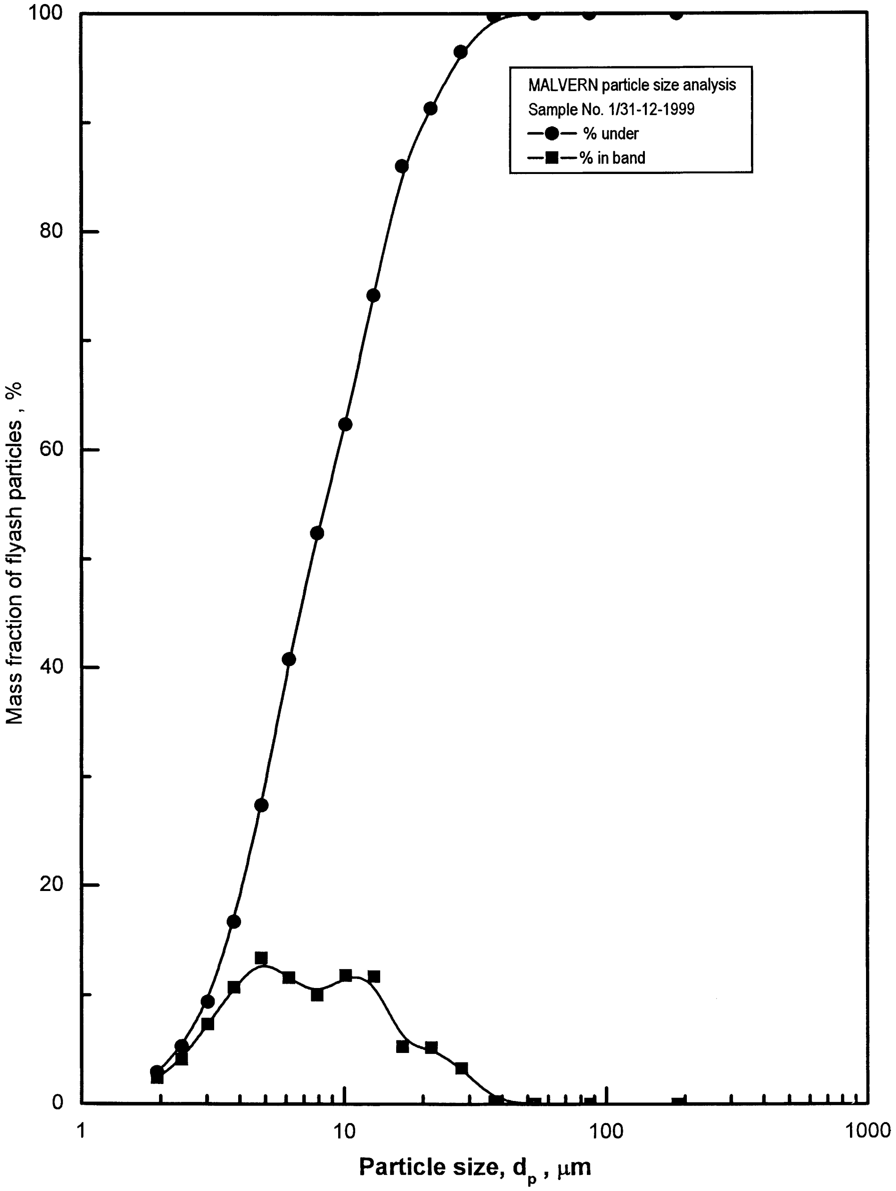

Fig. 2. Particle size distribution of fly-ash (courtesy Kolaghat Thermal Power Station).

particle–particle interaction. Increased particle loading increases particle–particle interactions which contribute positively to the removal of particulate [16]. In addition, at high inlet loading of fly-ash, the impact of fly-ash inside the bubbles increase due to enhanced Brownian motion, which may also lead to enhanced collection efficiency at high dust loading. However, the increase in efficiency is not appreciable amount, which is within 0.80% for entire inlet loading.

### *3.2. Effect of liquid flow rate and fly-ash loading on the percentage removal of fly-ash*

The effect of liquid down-flow rate, $Q_L$, on the percentage removal of fly-ash, $\eta_{FA}$, is presented in

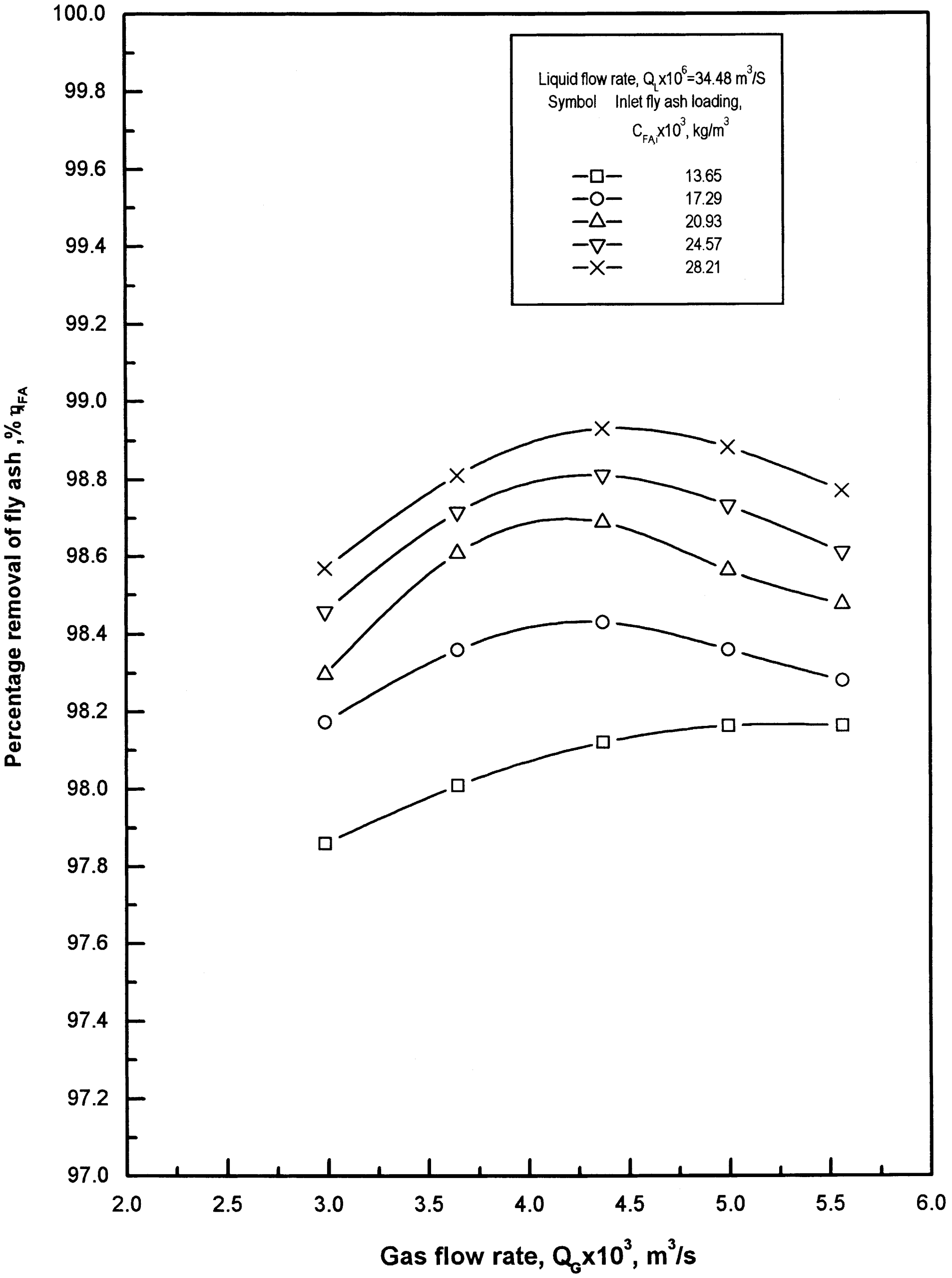

Fig. 3. Effect of gas flow rate on percentage removal of fly-ash, at constant liquid flow rate and for various inlet fly-ash loading.

Fig. 4, at various inlet fly-ash loading, and for constant gas flow rate. It can be seen from the figure that $\eta_{FA}$ increases as the liquid flow rate is increased. In the present investigation, as the liquid flow rate is increased the dispersed phase hold-up and interfacial contact area increases [25]. As a result of this the percentage removal increases with the increase in liquid flow rate. Present investigation supports the observation made by Calvert et al. [15], who reported that when enough contact area is available, the cut

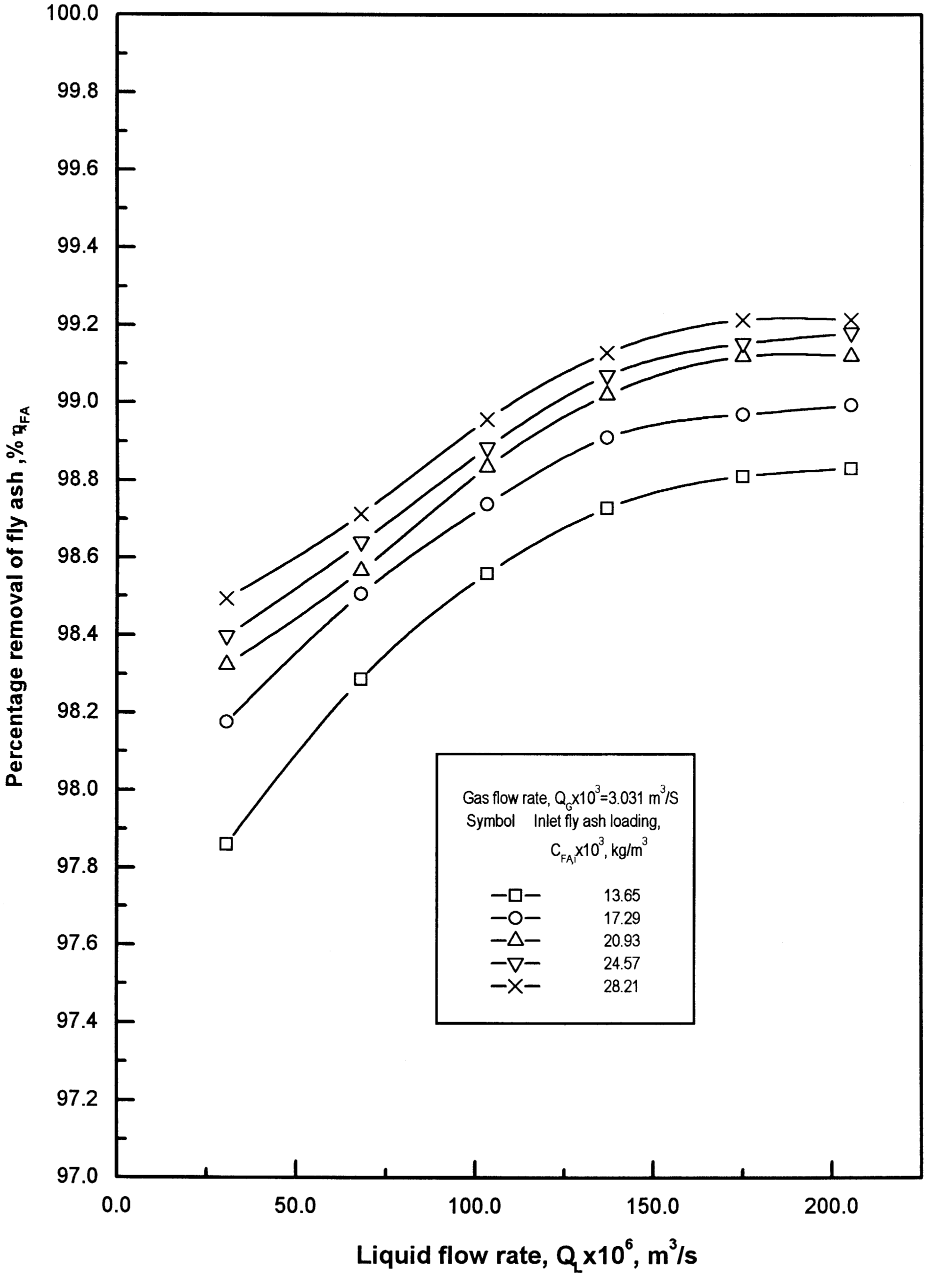

Fig. 4. Effect of liquid flow rate on percentage removal of fly-ash, at constant gas flow rate and for various inlet fly-ash loading.

diameter is more dependent on the efficiency of individual collecting surface than the total collecting surface (number of bubbles). Thus, the increase in liquid flow rate may not increase the total number of bubbles but it still affect positively the efficiency of individual bubbles, as very high total interfacial area is available in the system. It is also revealed from Fig. 4 that at liquid flow rate 170 × $10^{-6}$ m$^3$/s the percentage removal almost reaches 99.3% at a gas flow rate of 3.0 × $10^{-3}$ N m$^3$/s and at inlet fly-ash loading of 28.2 × $10^{-3}$ kg/N $m^3$. The 100% collection efficiency appears to be fascinating. Douglas et al. [29] observed removal efficiencies of both dust and mist in the range of 90–100% under conditions where existing theories predict lower efficiencies. Furthermore, the higher the inlet fly-ash loading the higher is the efficiency of collection. This may be attributed to the fact that low inlet loading hinders particle collection in bubble column due to lower particle–particle interaction.

### *3.3. Effect of column height on percentage removal of fly-ash*

Fig. 5 is a typical plot of percentage removal of fly-ash, $\eta_{FA}$, achieved at the different height of the

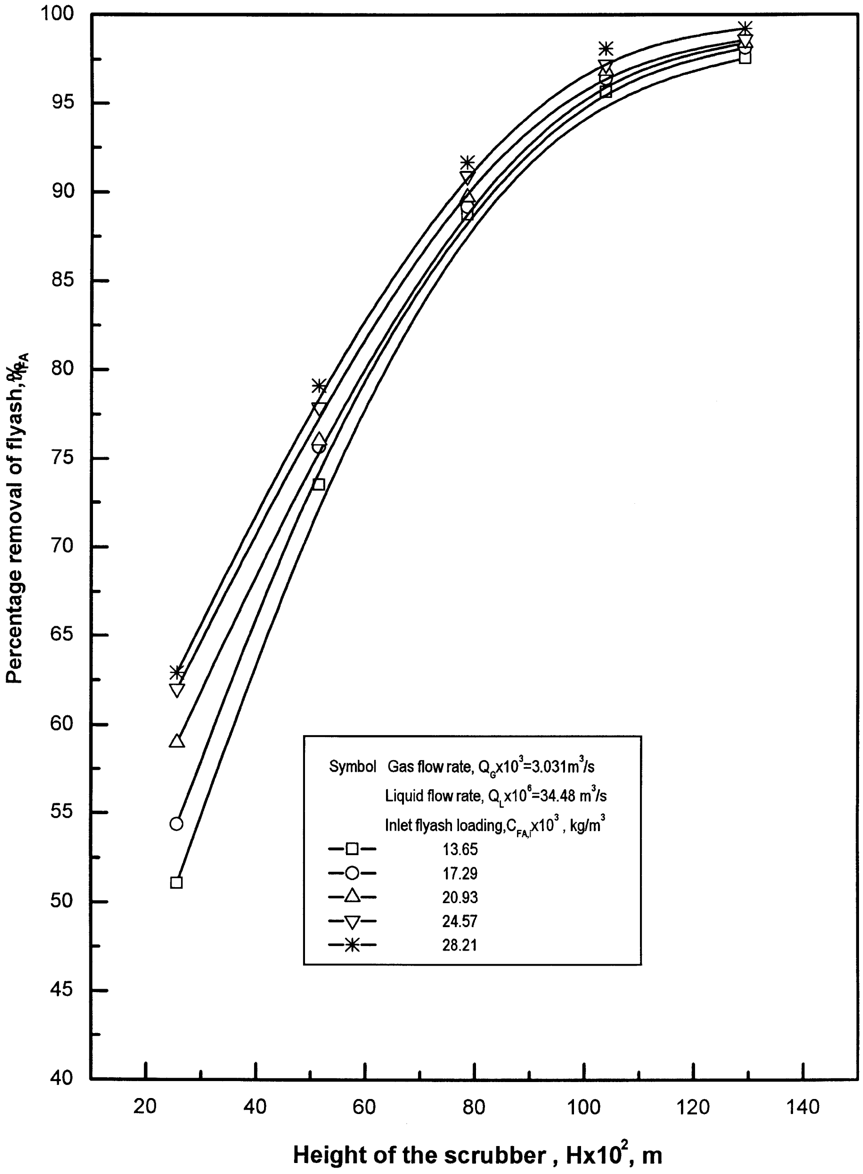

Fig. 5. Effect of scrubber height on the percentage removal of fly-ash for various fly-ash loading.

Table 3
Calculated stage efficiencies for water scrubbing of fly-ash

| $\eta_T$ (3) | $\eta_T$ (2) | $\eta_1$ | $\eta_2$ | $\eta_3$ |
|---|---|---|---|---|
| 0.9758 | 0.8878 | 0.510 | 0.755 | 0.798 |
| 0.9814 | 0.8921 | 0.544 | 0.763 | 0.828 |
| 0.9841 | 0.9043 | 0.590 | 0.766 | 0.834 |
| 0.9860 | 0.9089 | 0.620 | 0.760 | 0.850 |
| 0.9865 | 0.9110 | 0.627 | 0.761 | 0.840 |

scrubber for a constant gas flow rate and constant liquid flow rate. These data have been collected to emphasize the effect of staging, on the performance of the MMSBCS. It may be seen from the figure that for a constant inlet loading of fly-ash, the percentage removal of fly-ash, $\eta_{FA}$, increases almost exponentially with the increase in height of the scrubber. A closer look reveals that the collection efficiencies in the range of 50–65% were achieve1.6d in stage 1 (a bubble section on which a sudden flow disturbance was imposed). In stage 2 of the column the efficiencies increased from about 60 to 90%, due to vigorous bubble breakup and reformation induced by the presence of the contraction and expansion disks. Efficiencies above 90% (between 90 and 100%) were achieved in the final stage. Assuming that the stages act in series (the section of the column which has an expansion disk positioned between two contraction disks is called one stage), the following Eq. (2) should represent the overall efficiency of scrubbing achieved in column with three stages:

$$\eta_T = \eta_1 + (1-\eta_1)\eta_2 + [1-(\eta_1 + (1-\eta_1)\eta_2)]\eta_3 \tag{2}$$

Using the experimental data, values of $\eta_1$, $\eta_2$, and $\eta_3$ have been calculated [30] and tabulated in Table 3 at various gas and liquid flow rate. It is seen from this table that the efficiency of scrubbing remains almost uniform through out the length of the column. The somewhat lower value obtained in the first stage is due to the lower volume of the bubble column between the sparger and the first contraction disk. It was shown [24] that due to bubble coalescence in a simple bubble column the dispersed phase hold-up and interfacial area decrease along the height of the bubble column. However, uniform dispersion achieved in the MMSBCS led to the improved performance. The column section between two contraction disks gives improved performance of the scrubber, due to continuous bubble breakup, and bubble reformation. Even at the lowest stage of the column, the performance is modified due to presence of the contraction disk which induces vigorous bubble bursting. Furthermore, it may be seen from the figure that at a constant height of the column, $\eta_{FA}$, increases with the increase in inlet fly-ash loading. This may be attributed to the fact that low inlet loading hinders particle collection in bubble column due to lower particle–particle interaction. Increased particle loading increases particle–particle interactions which contribute positively to the removal of particulate [16]. However, direct comparison with a simple bubble column could not be made as even in the lowest stage the performance was modified due to the presence of the first contraction disk.

## 4. Correlation of particulate collection efficiency in the modified multi-stage bubble column scrubber

In order to predict the particle collection efficiencies in the MMSBCS from the directly measurable parameters, an attempt has been made to develop an empirical correlation, by multiple linear regression analysis method. The parameters which could possibly affect the collection efficiency, $\eta_{FA}$, are:

(a) geometrical parameters, namely, bubble sauter mean diameter ($d_o$), diameter of the column ($D_C$), height of the column ($H$);
(b) flow parameters, namely gas velocity ($V_g$), liquid velocity ($V_l$);
(c) physical properties, namely, particle density ($\rho_p$), gas density ($\rho_g$), liquid density ($\rho_d$), gas viscosity ($\mu_g$), inlet particle loading ($C_{FA,o}$), gravitational acceleration ($g$), surface tension of the liquid ($\sigma_L$) and diffusivity ($D_L$).

The particle collection efficiency thus becomes a function of 13 parameters:

$$\eta_{FA} = f_1(d_o, D_C, H, V_g, V_l, \rho_p, \rho_g, \rho_d, \mu_g, \sigma_L, D_L, C_{FA,i}, g) \tag{3}$$

In the present experiments due to the presence of the contraction and expansion disks, the percentage fly-ash removal, $\eta_{SO_2}$ become a function of height, $H$. Thus, $H$ was incorporated as an independent variable.

The variables in Eq. (3) can be grouped into dimensionless numbers by employing Buckingham's $\Pi$ theorem.

It can be seen that the following equation, which yields the minimum percentage error and minimum standard deviation, present the best possible correlation among the family of equations mentioned in the Table 4.

$$\eta_{FA} = 1 - 2.24 \times 10^{-3}[L_{P''}]^{0.294}[Re_G]^{-0.042} \times [Sc_{''}]^{-0.50}[H_R]^{-2.86} \quad (4)$$

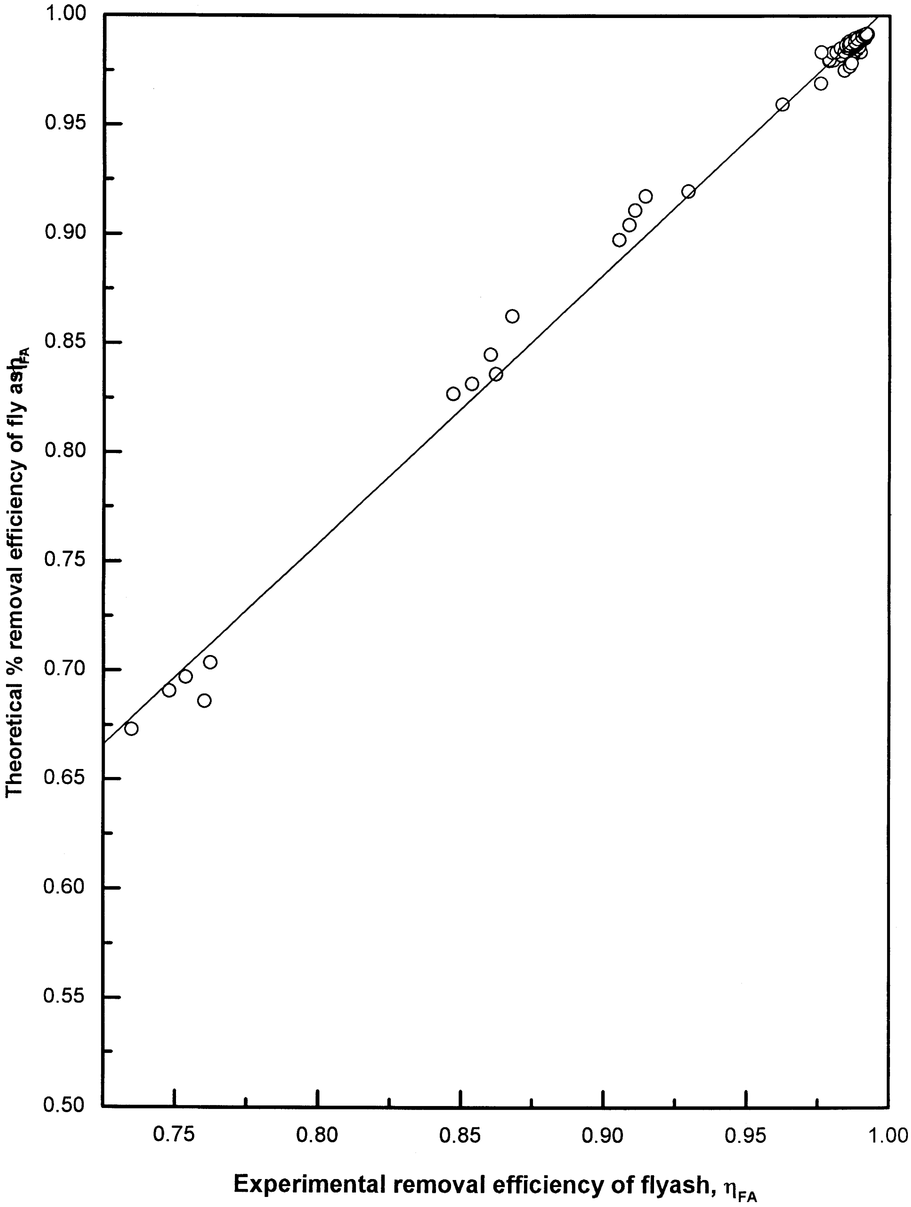

Fig. 6. Comparison of experimental percent removal efficiency of fly-ash.

Table 4
Different forms of equation with their standard deviation and regression co-efficients for percentage removal efficiency of fly-ash, $\eta_{\mathrm{FA}}$

| Different forms of equation | $S$ | B1 | B2 | B3 | B4 | Regression coefficient | Standard deviation of percentage error |
|---|---|---|---|---|---|---|---|
| $\eta_{\mathrm{FA}} = S[L_{\mathrm{P}''}]^{\mathrm{B1}}[Re_{\mathrm{G}}]^{\mathrm{B2}}[Sc_{''}]^{\mathrm{B3}}[H_{\mathrm{R}}]^{\mathrm{B4}}$ | 0.626 | 0.0015 | −0.012 | −0.01 | 0.27 | 0.95 | 3.43 |
| $\eta_{\mathrm{FA}} = 1 - S[L_{\mathrm{P}''}]^{\mathrm{B1}}[Re_{\mathrm{G}}]^{\mathrm{B2}}[Sc_{''}]^{\mathrm{B3}}[H_{\mathrm{R}}]^{\mathrm{B4}}$ | $2.24 \times 10^{-3}$ | 0.294 | −0.042 | 0.50 | −2.86 | 0.995 | 0.95 |
| $\eta_{\mathrm{FA}} = S\exp[-[L_{\mathrm{P}''}]^{\mathrm{B1}}[Re_{\mathrm{G}}]^{\mathrm{B2}}[Sc_{''}]^{\mathrm{B3}}[H_{\mathrm{R}}]^{\mathrm{B4}}]$ | 1.0 | 0.294 | 0.034 | 0.50 | −2.98 | 0.970 | 2.85 |
| $\eta_{\mathrm{FA}/(1-\eta_{\mathrm{FA}})} = S[L_{\mathrm{P}''}]^{\mathrm{B1}}[Re_{\mathrm{G}}]^{\mathrm{B2}}[Sc_{''}]^{\mathrm{B3}}[H_{\mathrm{R}}]^{\mathrm{B4}}$ | 1.761 | 0.002 | −0.034 | −0.03 | 1.45 | 0.972 | 2.3 |

Eq. (4) describes the percentage removal of fly-ash in the MMSBCS which is an important parameter for assessing the performance of the bubble column from the stand point of air pollution control.

The form of equation can be rearranged to:

$$q = 1 - \eta_{\mathrm{FA}} = 2.24 \times 10^{-3}[L_{\mathrm{P}''}^{0.294} Re_{\mathrm{G}}^{-0.042} Sc_{''}^{-0.50} H_{\mathrm{R}}^{-2.86}] \quad (5)$$

Eq. (5) actually describes the particle penetration through the bubble column which is an important parameter for assessing the performance of the bubble column from the stand point of air pollution control.

The values of percentage removal of fly-ash, $\eta_{\mathrm{FA}}$ predicted by Eq. (4) have been plotted against the experimental values of percentage removal of fly-ash, $\eta_{\mathrm{FA}}$ in Fig. 6. The percentage deviation between the experimental data and those of predicted by Eq. (4) have been calculated and found that the percentage deviation is quite low (within ±5%).

## 5. Scale-up of the scrubber

An attempt was made at Indian Thermal Power Plant located at Burdwan, West Bengal to use the designed data obtained in the multi-stage bubble column scrubber for their particulate (fly-ash) pollution control. The scale-up of the laboratory model pilot plant was done by taking into consideration of volumetric flow rate of the flue gas and accordingly dimensions (diameter, height, gap between the disks, number of disks, etc.) of the scaled-up scrubber was determined. On a trial basis part of the flue gas was used to pass through the scrubber and found more than 98.5% removal efficiency. An attempt has also been made to install the above wet scrubber in Allied Ceramic Industries to combat particulate pollution control and found excellent performance. The implementation work of the wet scrubber is in progress and not yet completed.

## 6. Conclusions

This article dealt with the detailed studies on the scrubbing of fly-ash, the findings of which may be summarized as follows.

Experimental results show that almost zero penetration (100% removal efficiency) of fly-ash can be achieved, at a liquid to gas flow rate ratio of 5.5 $\mathrm{m}^3$/1000 actual cubic meter per minute (ACMM) of gas flow rate, in the present system. Removal efficiency has been found to be a strong function of inlet fly-ash loading in the modified multi-stage bubble column scrubber. Stage efficiencies in the range of 50–60 were obtained in the bubble stage and 80–90% in stages 2 and 3, which indicates the efficacy of the contraction–expansion disks. Higher inlet fly-ash loading lead to higher efficiency of collection. Results also indicate that higher gas flow rate results in higher fly-ash collection efficiency.

Furthermore, a dimensionless correlation has been developed for predicting the fly-ash collection efficiencies in the MMSBCS. Experimental results are in excellent agreement with the correlation (correlation coefficient 0.99). The present pilot plant data was used to scale-up the scrubber in the Indian Thermal Power Plant and Allied Ceramic Industries which operates successfully with a removal efficiency of 98.5% which meets the regulation of pollution control board.

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