

Scrubbing of Fly-Ash Laden SO_2 in Modified Multistage Bubble Column Scrubber

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The emission of SO_2 from various chemical industries is associated with particulate (fly-ash), mostly concentrations of particulate laden sulfur dioxide in and around these plants overshoot the danger point. Prediction of fly-ash laden SO_2 removal efficiency is very important for the selection of pollution control equipment. Experimental investigations were conducted on the scrubbing of fly-ash laden SO_2 in the modified multistage bubble column scrubber using water. Experimental results show that almost zero penetration (100% removal efficiency) of fly-ash laden SO_2 can be achieved in this system. A correlation was developed for predicting the percentage collection efficiency of sulfur dioxide in the presence of fly-ash. Experimental results agreed excellently with the correlation. Enhancement of SO_2 collection due to the presence of fly-ash was also quantified.

Introduction

A review of literature on the abatement of particulate laden sulfur dioxide reveals that both sequential and simultaneous removal techniques have been practiced for the abatement of particulate laden sulfur dioxide. In sequential methods, particulate matters are removed in the first step and sulfur dioxide is removed in the subsequent step. Both gaseous and gas-borne particulate matters are removed in one single step during simultaneous removal. The sequential abatement methods, which involve separate steps for particulate and sulfur dioxide removal, have been developed extensively. For various inherent reasons, sequential or stepwise removal of particulate and gases has been shown to be deficient or problematic for industries emitting particulate laden gases. Therefore, the abatement of particulate and gases in one single step seems to be the only viable alternative to achieve techno-economic-feasibility. Tomany (1975) concluded that, despite some of its inherent shortcomings, the wet scrubber is the only equipment type available in today's marketplace which can effectively combat the problem of particulate laden SO_2 pollution when control of both of these emissions is very much demanded. Furthermore, wet scrubbers, where a liquid

phase is used to remove particulate matters, are unique in their ability to remove both particulate and gaseous pollutants. However, for such a dual duty operation, impaction and impingement of dust particles on liquid and the creation of a large surface area for gas absorption becomes important and is a controlling factor. Also, in comparison to a combination of particulate control with electrostatic precipitators and sulfur dioxide control in a separate de-sulfurization unit, wet gas scrubbers involve less investment and lower operating costs. It also offers a higher service factor, a smaller on-site plot space, and a simpler operation than an electrostatic precipitator. It also offers a very high turndown ratio.

Various wet scrubbers used in practice offer a choice between the liquid dispersed and the gas dispersed system. Because of its intrinsic pressure drop and flow rate characteristics, the bubble column may be more convenient than a packed column in air-pollution control applications involving particulate laden gaseous pollutants. Furthermore, EPA (1997) has restricted the maximum discharge limits from coal based thermal power plants to 22.65 gm per 0.294 MW, which converts to 0.1634 gm/Nm³ for an Indian thermal power plant. Calculations show that at least 76% removal of particulate less than 2 micron in size is essential to meet the EPA's prescription of stringent standards. The existing emission

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standards for particulate matter in India are higher (0.150 gm/NM³) than the proposed World Bank standards of 0.050 gm/NM³. Furthermore, the World Bank guidelines propose that the particulate removal efficiency should be at least 99.9%, if 50 mg/NM³ is 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 in demand in the above context.

A survey of literature further revealed that several wet processes have been suggested for the simultaneous abatement of particulate laden SO₂ pollution from waste gas streams. However, compared to other multiphase contactors, the bubble column reactor (BCR) offers many advantages such as 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, and excellent heat-transfer properties and, hence, easy temperature control and low initial costs. The most serious limitations of BCR as particulate control system are their low efficiency in single-stage operation and the difficulties associated with multistage operation. In fact, the literature survey did not reveal any serious attempt to exploit the possible advantages of BCR by operating a bubble column in multistage sequences and no known reference appears to exist on the simultaneous scrubbing of fly-ash laden SO₂ in bubble columns or in any type of modified bubble columns. Only a few patented systems (Baker, 1979) resemble bubble columns remotely or at least they use some that are short of gas-dispersed systems.

Bandyopadhyay and Biswas (1995, 1998) investigated and reported experimental studies on the simultaneous scrubbing of particulate laden sulfur dioxide in a hybrid column, which was comprised of a spray column and a simple bubble column using an alkaline solution. They reported 99% removal efficiency attainable within the physico-chemical variables used in their investigation by using sodium alkali as the scrubbing medium, and this was not cost-effective. In the present investigation a multistage bubble column operating

in three stages has been designed with the staging effect being achieved through hydrodynamically induced continuous bubble generation, breakup, and regeneration. The system was designed to operate with relatively large-sized (3–6 mm, approximately) bubbles, so that the internal circulation can be induced in the bubbles and a faster transfer of gas and fly-ash can take place through turbulent diffusion through the interface of the bubbles and also due to the direct rupture of the relatively large diameter bubbles. The detailed hydrodynamic characteristics including pressure drop (energy dissipation) of a multistage bubble column is presented in Table 1 (Valentin, 1967; Bandyopadhyay, 1995; Meikap, 2000; Meikap et al., 2001).

This article reports on detailed experimental studies on the simultaneous absorption of SO₂ and scrubbing of fly-ash, from a particulate-laden SO₂–Air mixture in a modified multistage bubble column scrubber (MMSBCS) using water as the scrubbing medium.

Experimental Setup and Technique

Figure 1 shows the experimental setup. The experimental column is a vertical cylindrical Perspex column, 0.1905 m in diameter and 2.0 m long, fitted onto a frusto-conical bottom of mild steel. The latter had a divergence angle of 7° and a height of 0.87 m. The vertical cylindrical column was fitted with a total of five hollow disks (three contraction disks and two expansion disks (Figure 2)). The expansion and contraction disks had central axial openings of 0.095 m and 0.0467 m, respectively. The vertical Perspex column has been constructed in three vertical stages, which, in effect, operate in series. The lowest stage of the column is a simple bubble column, where the bubbles are generated by passing the gas at relatively high velocities through an antenna type sparger (Figure 2). At the end of this stage, the bubbles have been ruptured and coalesced by imposing a flow disturbance on the bubble swarm by positioning a horizontal disk with a rela-

Table 1. Power Consumption and Hydrodynamic Characteristics: Various Gas-Liquid Contacting Equipment vs. Present System*

Contacting Equipment	Gas Rate, Q_G/A_G , Nm ³ /m ² ·s	Specific Surface Area, a , m ² /m ³	Vol. Fract. of Gas Phase, Φ_G , m ³ /m ³ of Vessel	Power Consumption, E , W/m ³ of Vessel
Plate column	0.60	100–400 (0.01–.05)	0.9	1,300
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	2,600
Spray column	—	10–100 (0.0007–.015)	More than 0.80	—
Jet (loop)	—	1,000–7,000 (0.1 to 3.0)	0.5	10–700
Tubular/Venturi ejector	—	200–2,000 (0.01–2.2)	Less than 0.50	0.8–90
Modified Multistage Bubble Column	0.11 to 0.20	250 to 600 (0.13–0.24)	0.21 to 0.65	200 to 450

*K_La values within the bracket.

tively small diameter single axial opening (contraction disk). The gas-in-liquid dispersion passing through the disk opening is subjected to dynamic instabilities in the form of flow expansion followed again by flow contraction. The flow expansion after stage 1 has been achieved by positioning a relatively large diameter hollow disk (expansion disk) above the first contraction disk. Also, contraction of the two-phase dispersion has been achieved by using a second contraction disk, positioned co-axially above the expansion disk. The column section consisting of an expansion disk positioned between

the two contraction disks comprises one stage. At the end of each stage, bubbles lose their individual identities and new bubbles are regenerated at the beginning of each stage.

The air-SO₂ fly-ash mixture, with a composition similar to that existing in the exhaust of a coal fired thermal power plant using coal with 35% ash and 0.5% sulfur content, was generated by mixing air, fly-ash, and SO₂ in an air-jet ejector (E) assembly. Compressed air from the compressor (CA) was used as the motive fluid in the ejector to aspirate and thoroughly mix air with the SO₂ and fly-ash from the SO₂ gas

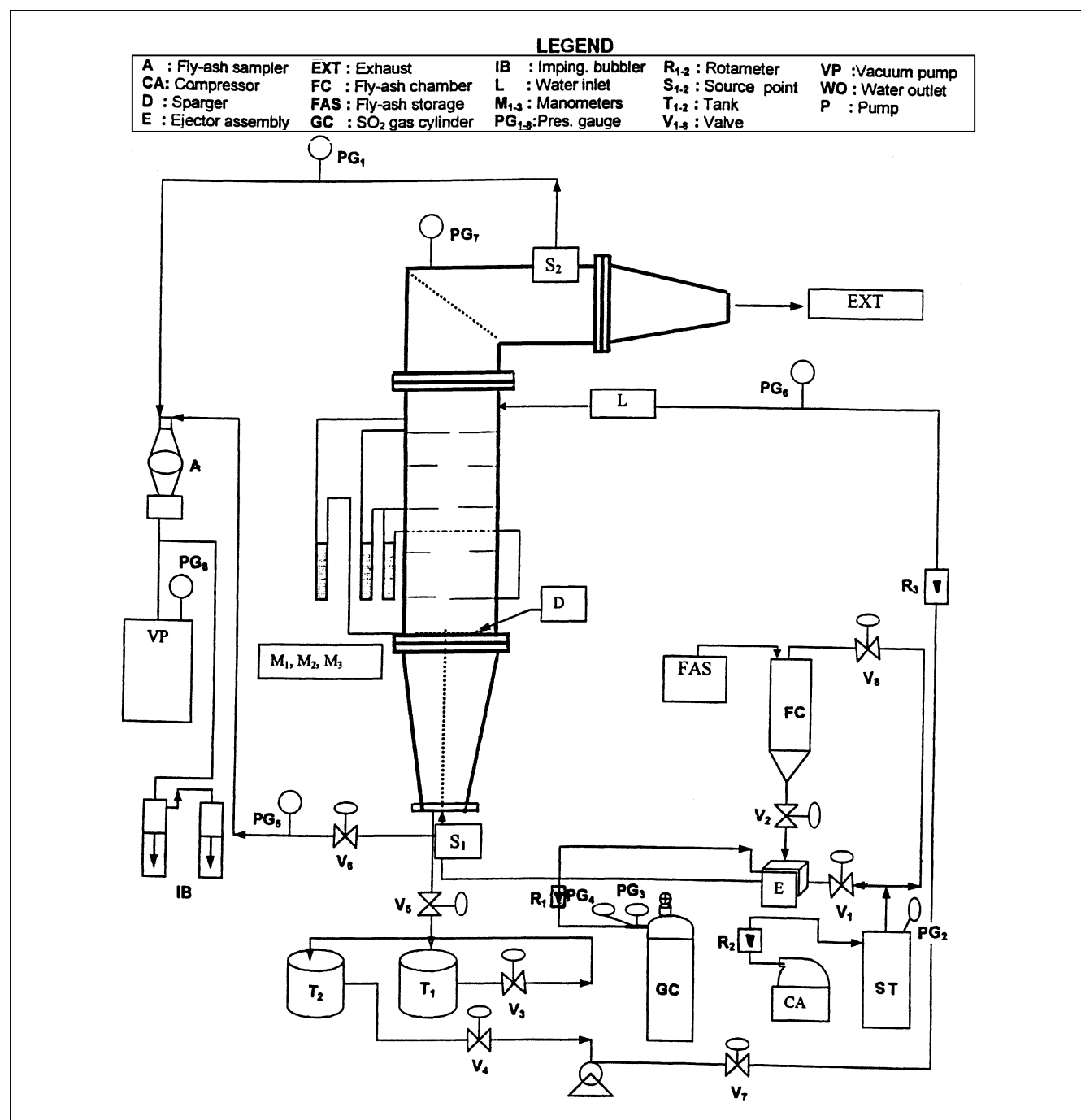


Figure 1. Experimental setup for scrubbing fly-ash laden SO₂ in water in a MMSBCS.

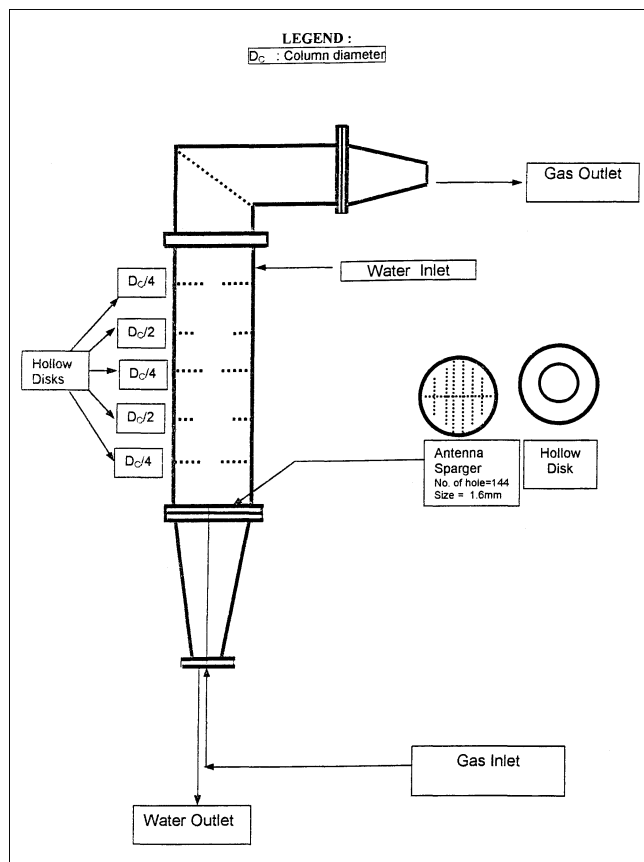


Figure 2. Column, hollow disks, and antenna sparger.

cylinder (GC) and fly-ash storage vessel (FAS), respectively. To ensure an axially symmetrical jet, the ejector was mounted with a downward slope of 30° with the air nozzle perfectly aligned along the axis of the ejector throat. The air nozzle was fixed at a projection ratio (which is the ratio of the distance between the nozzle tip and the beginning of the parallel throat to the throat diameter) of 3.78, determined experimentally for obtaining the highest possible mass ratio of the aspirated gas. Compressed air at the desired motive pressure and flow rate was forced through the air nozzle at a regulated flow rate using the valve (V_1) and the rotameter (R_2). Simultaneously, the SO_2 and fly-ash was routed at a controlled rate through the SO_2 gas regulator, through the valve (V_9) and the rotameter (R_1) and fed into the ejector at point P. The air, fly-ash, and SO_2 gas mixed intensely in the mixing throat of the ejector and the mixture was fed into the sparger at the bottom of the vertical column.

In the actual experiment, water was continuously fed at the top of the column through valve (V_7) and rotameter (R_3) and withdrawn at the bottom at such a rate that a particular liquid height and bubble volume (gas-liquid dispersion volume) can be maintained in the column. In order to collect representative samples, fly-ash laden SO_2 gas samples were withdrawn at an approximately isokinetic rate. Samples at point S_1 and S_2 were drawn at the rate of 1 to $2 \times 10^{-3} \text{ Nm}^3/\text{min}$ to match the experimental gas-flow rate and the conditions of isokinetic sampling. The fly-ash laden SO_2 absorption experi-

ments were conducted at gas-flow rates of 1.20 to $5.46 \times 10^{-3} \text{ Nm}^3/\text{s}$ and a liquid flow rates of 34.48 to $175 \times 10^{-6} \text{ m}^3/\text{s}$. Under steady-state operating conditions, the SO_2 and fly-ash samples were collected simultaneously by drawing the samples first through the filtering unit and then passing them through the impingers (IB), as shown in figure. Samples were collected at source point S_1 and S_2 . Sulfur dioxide samples were collected with the help of midget impingers and aspirator bottles (Meikap, 2000) and analyzed by the "Tetrachloro-mercurate Method" (Indian Standards, 1969, part VI). The fly-ash concentrations at point S_1 and S_2 were measured at point (A) by the filtration techniques (Indian Standards, 1973, part IV).

The fly-ash particle-size (average particle size diameter, 7.52 micron) distribution (Figure 3) has been measured using a Malvern 3601 sizer, using $\text{Na}_4\text{P}_2\text{O}_7$ (anhydrous) [LOBA Chemie] as dispersant in a concentration of 1.0864 kg/m^3 , as shown in Figure 1.

In the scrubbing experiments, detailed studies were conducted to determine the effect of gas-flow rates, liquid flow rates, inlet loading of fly-ash and sulfur dioxide, height of the scrubber on the simultaneous removal of fly-ash, and sulfur dioxide using water as the scrubbing medium.

Results and Discussions

Experiments on the simultaneous absorption of sulfur dioxide in the presence of fly-ash have been conducted at various process conditions which are presented in Table 2.

The percentage removal of SO_2 have been calculated in each run by the formula,

$$\eta_{\text{SO}_2} = \frac{C_{\text{SO}_2 - \text{FA},i} - C_{\text{SO}_2 - \text{FA},o}}{C_{\text{SO}_2 - \text{FA},i}} \times 100 \quad (1)$$

The trend of the variation of percentage removal have been plotted in Figure 4 for various inlet loading of SO_2 and various operating and flow variables for the MMBCS and along the height of the scrubber.

Effect of gas-flow rate and SO_2 loading on percentage removal of SO_2

The percentage removal of SO_2 , $\eta_{\text{SO}_2 - \text{FA}}$, at different inlet SO_2 loading, and for a constant height of the bubble volume, has been plotted against gas-flow rates in Figure 4. It can be seen from this figure that, even in the presence of fly-ash, the percentage removal of SO_2 in MMBCS increases with the increase in the gas-flow rate, for a constant liquid flow rate. However, the rate of absorption of fly-ash-laden SO_2 is very high and increases very slowly with the increase in gas-flow rates. To compare the percentage removal of SO_2 in the presence of fly-ash and also in its absence, plots of percentage removal of SO_2 have been prepared for both conditions (that is, for SO_2 -water and fly-ash- SO_2 -water systems) under identical conditions of gas and liquid flow rates and inlet concentrations. It is seen from these plots (Figure 5) that the presence of fly-ash particles enhances the percentage removal of sulfur dioxide marginally. This enhancement may be due to three basic reasons, namely:

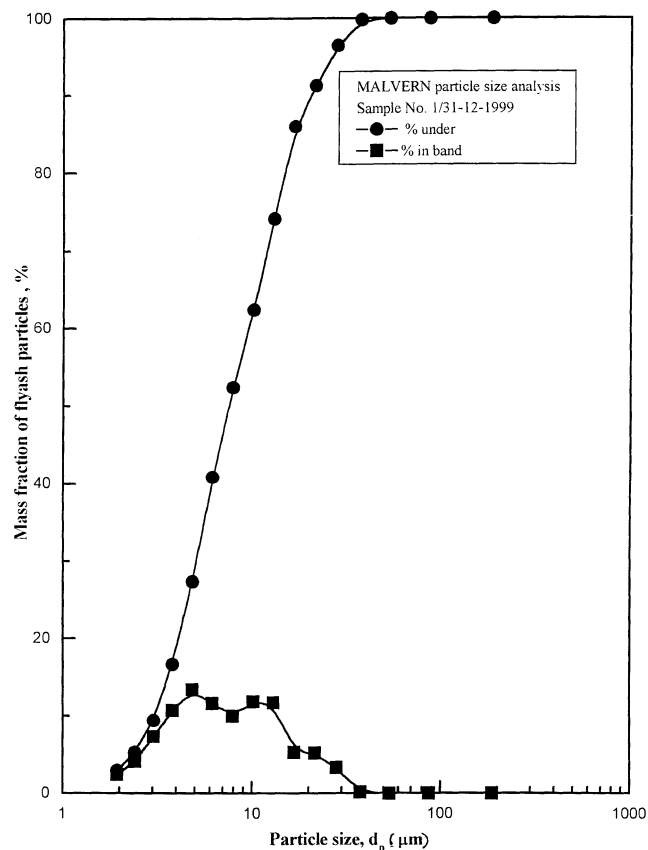


Figure 3. Particle-size distribution of fly ash.

Courtesy: Kolaghat Thermal Power Station.

- (a) The catalytic activity of the fly-ash particle or
- (b) The increased pH of the scrubbing liquor in the presence of fly-ash particles, or
- (c) The adhesion of the gas-adsorbing fly-ash particles to the gas bubbles (Vinke et al., 1992).

Since SO_2 -water absorption is controlled by physical gas-liquid absorptive mass transfer, the increase in the overall mass transfer, that is, the increase in the percentage removal of SO_2 , by catalytic activity can be ruled out. Furthermore, the fly-ash in aqueous medium does not alter the pH appreciably, so that the experimentally observed enhancement is

Table 2. Experimental Conditions for SO_2 -Air-Fly-Ash-Water System

Liquid flow rate	4.48×10^{-6} , 68.95×10^{-6} , 103.44×10^{-6} , 137.9×10^{-6} , 172.4×10^{-6} and $206.9 \times 10^{-6} \text{ m}^3/\text{s}$.
Gas flow rate	3.031×10^{-3} , 3.640×10^{-3} , 4.248×10^{-3} , 4.856×10^{-3} , 5.462×10^{-3} and $6.062 \times 10^{-3} \text{ N} \cdot \text{m}^3/\text{s}$
SO_2 loading	600, 800, 1,000, 1,200, and 1,500 ppm
Fly-ash loading	13.65×10^{-3} , 17.29×10^{-3} , 20.93×10^{-3} , 24.57×10^{-3} , and $28.21 \times 10^{-3} \text{ kg}/\text{N} \cdot \text{m}^3$
Bubble size (SMD)	3–5 mm (by visual observation)

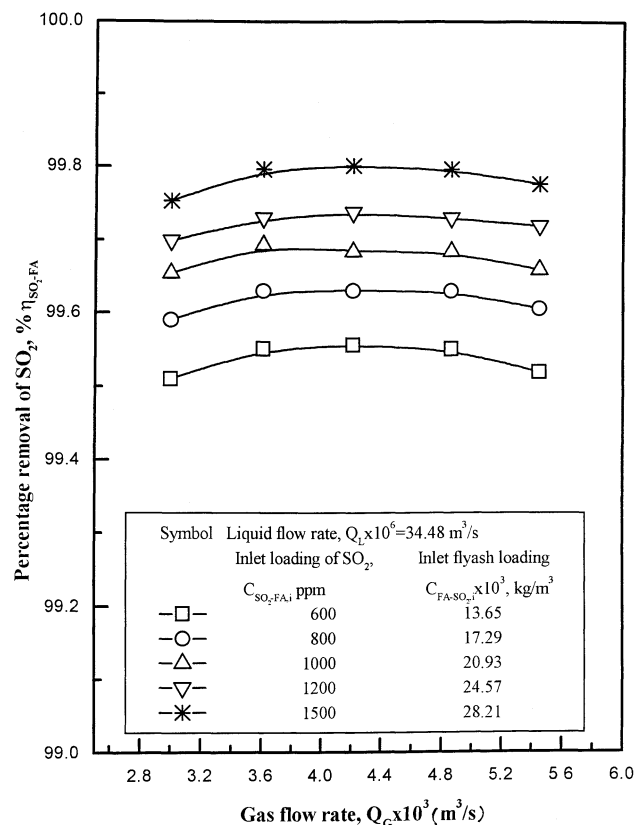


Figure 4. Effect of gas-flow rate on % removal of SO_2 for fly-ash- SO_2 -air-water system at various inlet SO_2 loading and at a constant liquid flow rate $Q_L = 34.48 \times 10^{-6} \text{ m}^3/\text{s}$.

also not due to the change in pH. Therefore, the increase in percentage removal of SO_2 in the presence of fly-ash particles can be explained by the adsorption of SO_2 by the gas-adsorbing fly-ash particles, which adhere to the gas bubbles. Thus, adsorption, in addition to the absorption of SO_2 by water, enhances SO_2 removal, which supports the observation reported by Vinke et al. (1992), Bandyopadhyay and Biswas (1995, 1998), and Meikap et al. (1999).

Effect of liquid flow rate and SO_2 loading on percentage removal of SO_2

The effect of liquid flow rate Q_L on the percentage removal of SO_2 , $\eta_{\text{SO}_2-\text{FA}}$, is presented in Figure 6 at various inlet SO_2 loading, and for constant gas-flow rates. It can be seen from the figure that $\eta_{\text{SO}_2-\text{FA}}$ increases as the liquid flow rate is increased. In the present investigation, as the liquid flow rate is increased, the bubble-water interfacial contact area increases. As a result, the percentage removal increases with the increase in liquid flow rate. In addition, the faster removal of materials from the bubble surface by the downward flowing liquid might have also enhanced the SO_2 removal. It is also revealed from Figure 6 that, at a liquid flow rate of $170 \times 10^{-6} \text{ m}^3/\text{s}$, the percentage removal almost

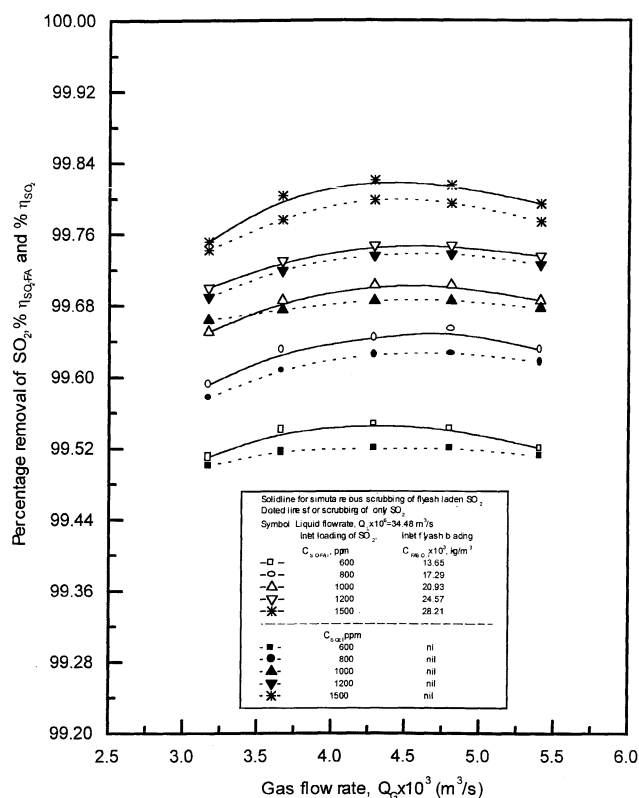


Figure 5. Effect of gas-flow rate on % removal of SO₂ for the SO₂-fly-ash-air-water and SO₂-water systems at various inlet SO₂ loading.

reaches 99.9% at a gas-flow rate of $5.462 \times 10^{-3} \text{ Nm}^3/\text{s}$ and at the inlet SO₂ loading of 1,500 ppm. Furthermore, the higher the inlet SO₂ loading is, the higher the efficiency is. The reasons for this observation have been explained earlier.

Effect of inlet SO₂ loading on the percentage removal of SO₂

The effect of inlet SO₂ loading on the percentage removal of sulfur dioxide in the presence of fly-ash for a constant liquid flow rate at various gas-flow rates and a constant bubble volume is shown in Figure 7. It appears from the figure that the increase in SO₂ loading increases the $\eta_{\text{SO}_2-\text{FA}}$. The increase in $\eta_{\text{SO}_2-\text{FA}}$ with the increase in gas-flow rate indicates that increased turbulence in the gas phase increases the probability of inter-SO₂ molecule and SO₂ molecule-water film collision in the bubble column, which leads to increases in the collection at high gas-flow rates. However, higher gas-flow rates may also result in bubble coalescence, thereby resulting in a decrease in collection efficiency at a higher gas-flow rate. Also, the SO₂ with increased gas-flow rate gets absorbed by the water through bubble bursting, formation, regeneration, and enhanced turbulence. However, beyond a gas-flow rate of approximately $4.25 \times 10^{-3} \text{ Nm}^3/\text{s}$, bubble coalescence predominates, which reduces the removal efficiency. Increased SO₂ loading increases molecule-molecule interactions, which contribute positively to the removal of SO₂. In addition, at a high inlet loading of SO₂, the impact

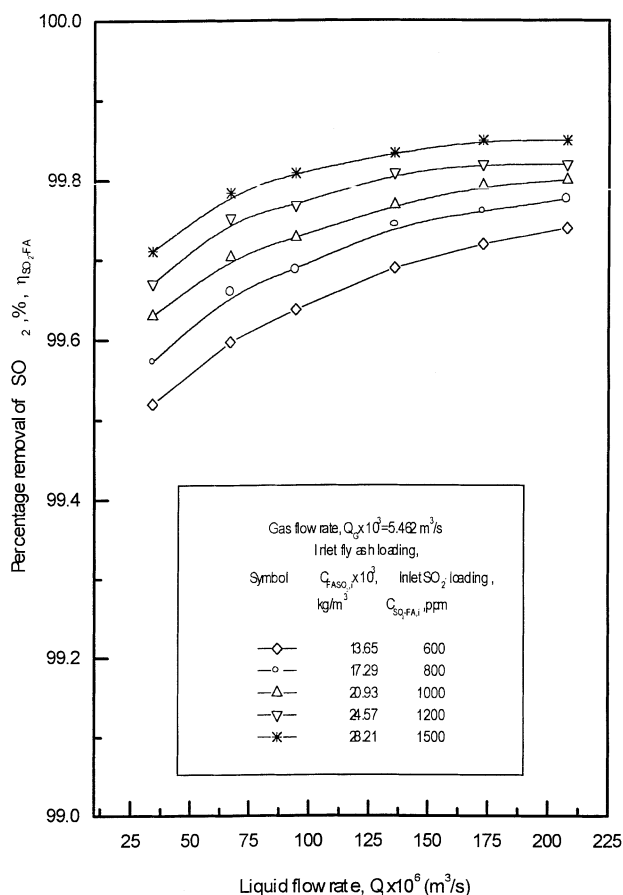


Figure 6. Effect of liquid flow rate on % removal of SO₂ for simultaneous scrubbing of fly-ash and SO₂ at various inlet SO₂ and fly-ash loading at a constant gas flow, $Q_G = 5.462 \times 10^{-3} \text{ m}^3/\text{s}$.

of SO₂ inside the bubble increases and, during bubble breakup and formation mechanism, SO₂ molecules immediately get absorbed by the water molecule, thereby increasing the efficiency of collection. The enhancement of SO₂ absorption due to the presence of fly-ash is also shown in Figure 8. Adsorption of SO₂ by the fly-ash particles, as explained earlier, leads to a somewhat higher percentage removal of SO₂, at all heights.

Effect of column height on the outlet SO₂ loading at constant liquid and gas-flow rate

Figure 9 shows the outlet loading of SO₂ vs. height of the bubble column at a constant liquid and gas-flow rate at different inlet SO₂ loading. It is seen in this figure that the outlet loading of SO₂ decreases with the height of the bubble column. Initially, the rate of decrease is very fast and dependent on the inlet fly-ash loading. However, at the top of the column, the change is very slow and remains almost constant for all the inlet concentrations. This trend shows that the removal of SO₂ is almost complete within the column height of 120 cm, just below the last contraction disk.

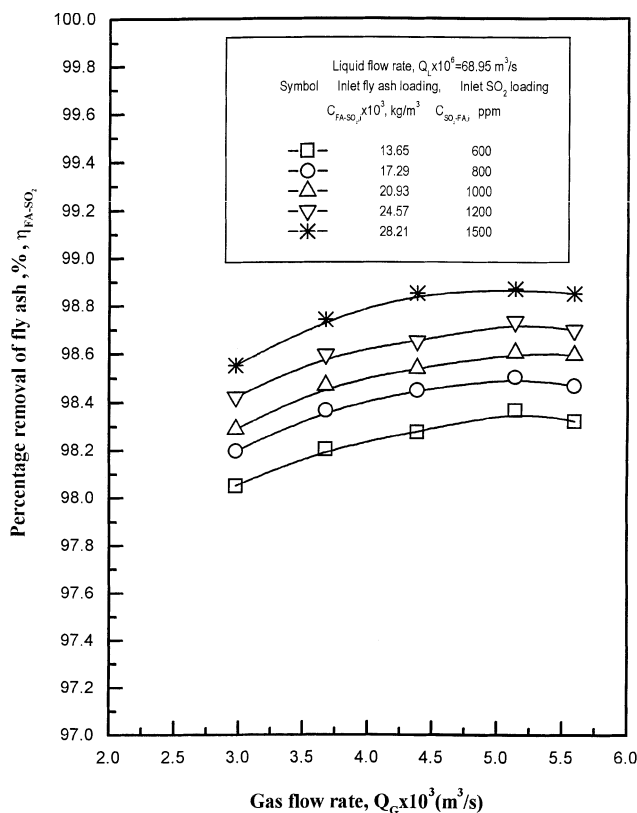
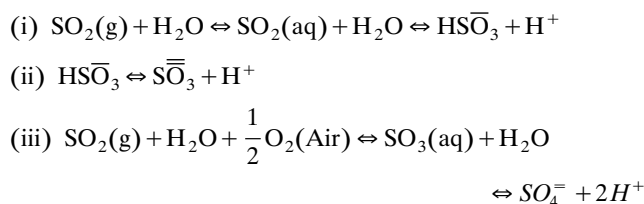


Figure 7. Effect of gas-flow rate on % removal of SO_2 for simultaneous scrubbing of fly-ash and SO_2 at various inlet fly-ash and SO_2 loading at a constant liquid flow rate $Q_L = 68.95 \times 10^{-6} \text{ m}^3/\text{s}$.

Effect of time on slurry pH for simultaneous scrubbing of fly-ash laden SO_2

It may be expected that absorption of SO_2 in water shall result in the production of sulfurous and sulfuric acid as per the following reaction scheme:



Thus, for a batch of liquid, the pH of the solution should change with time. Figure 10 shows the effluent pH vs. time for the simultaneous scrubbing of fly-ash laden SO_2 at constant bubble volume. From this figure, it is seen that the pH of the effluent slurry decreases gradually with the increase in time. Within about 20 min, the pH reaches the level 2.0, which is equivalent to 0.01 N sulfurous/sulfuric acid.

Correlation for the Prediction of the Percentage Removal of SO_2 in the Presence of Fly-ash

In order to predict the SO_2 collection efficiencies, in the MMBCS from the directly measurable parameters in the

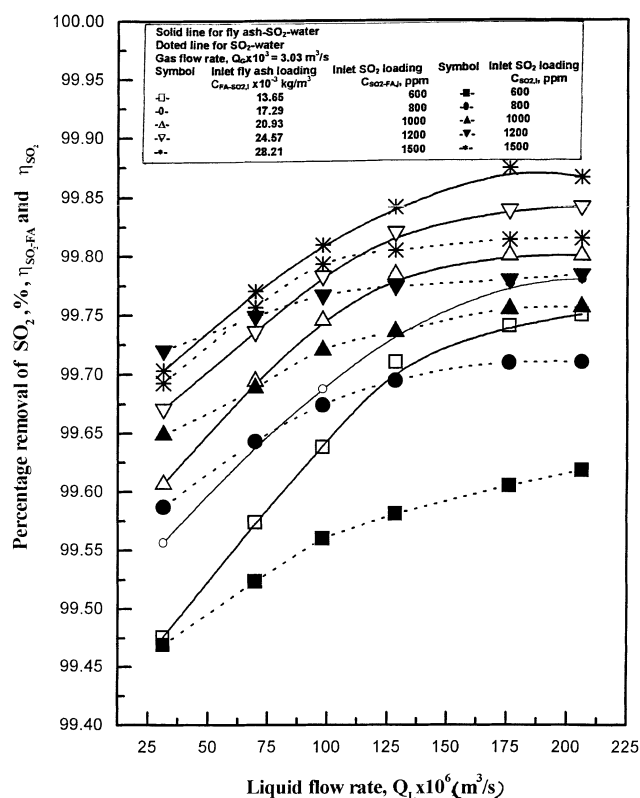


Figure 8. Effect of liquid flow rate and inlet loading of SO_2 , on % removal of SO_2 for the SO_2 -air-fly-ash-water and SO_2 -water system.

presence of fly-ash, an attempt has been made to develop an empirical correlation, by the method of multiple linear regression analysis.

The parameters, which could possibly affect the collection efficiency η_{SO_2-FA} are:

(a) geometrical parameters, namely, bubble sauter mean diameter (d_o), particle sauter mean diameter (d_p); diameter of the column (D_c), height of the column H , diameters of contraction and expansion disks = $f(D_c)$;

(b) flow parameters, namely gas velocity (V_G), liquid velocity (V_L); and

(c) physical properties, namely, particle density (ρ_p), gas density (ρ_G), liquid density (ρ_L), gas viscosity (μ_G), inlet particle loading ($C_{FA-SO_2,i}$), inlet SO_2 loading ($C_{SO_2-FA,i}$), gravitational acceleration (g), surface tension of the liquid (σ_L) and diffusivity (D_L).

The dimensionless analysis may be simplified to

$$\eta_{\text{SO}_2-FA} = f[L_{P''}]^a [Re_G]^b [Sc']^c [H \setminus D_c]^d \quad (2)$$

In order to establish the functional relationship between percentage removal of SO_2 from a mixture of fly-ash-air- SO_2 , η_{SO_2-FA} , and the various dimensionless groups in Eq. 2, multiple linear regression analysis has been used to evaluate the constant and coefficients of the equation.

It can be seen that the following equation, which yields the minimum percentage error and the minimum standard deviation

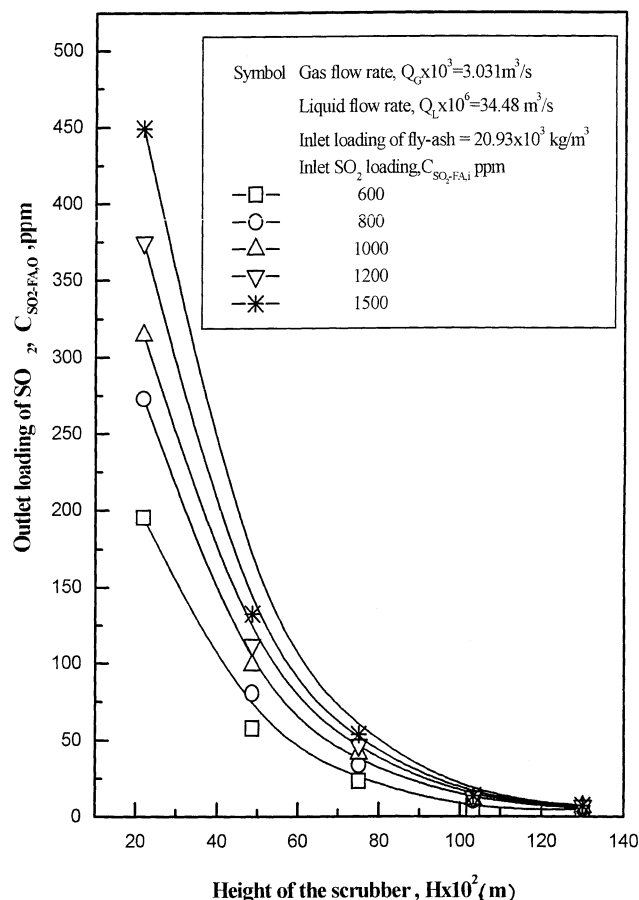


Figure 9. Effect of scrubber height on the outlet concentration of SO_2 at various inlet SO_2 loading.

tion of percentage error, presents the best possible correlation

$$\eta_{\text{SO}_2 - \text{FA}} = 1.08 \text{ EXP}$$

$$\left[-[L_{P''}]^{-0.20} [Re_G]^{-0.45} [Sc']^{0.45} [H_R]^{-4.23} \right] \quad (3)$$

Equation 3 describes the percentage removal of from a mixture of fly-ash-air- SO_2 (fly-ash laden SO_2) in the MMS-BCS, which is an important parameter for assessing the performance of the bubble column from the standpoint of air-pollution control.

The form of equation can be rearranged to ,

$$q = 1 - \eta_{\text{SO}_2 - \text{FA}} = 1 - 1.0 \text{ EXP}$$

$$\left[-[L_{P''}]^{-0.20} [Re_G]^{-0.45} [Sc']^{0.45} [H_R]^{-4.23} \right] \quad (4)$$

Equation 4 actually describes the penetration q in the fly-ash-laden SO_2 emission through the bubble column, which is an important parameter for assessing the performance of the bubble column from the standpoint of air-pollution control. The values of percentage removal of fly-ash laden SO_2 , $\eta_{\text{SO}_2 - \text{FA}}$ predicted by Eq. 4 have been plotted against the

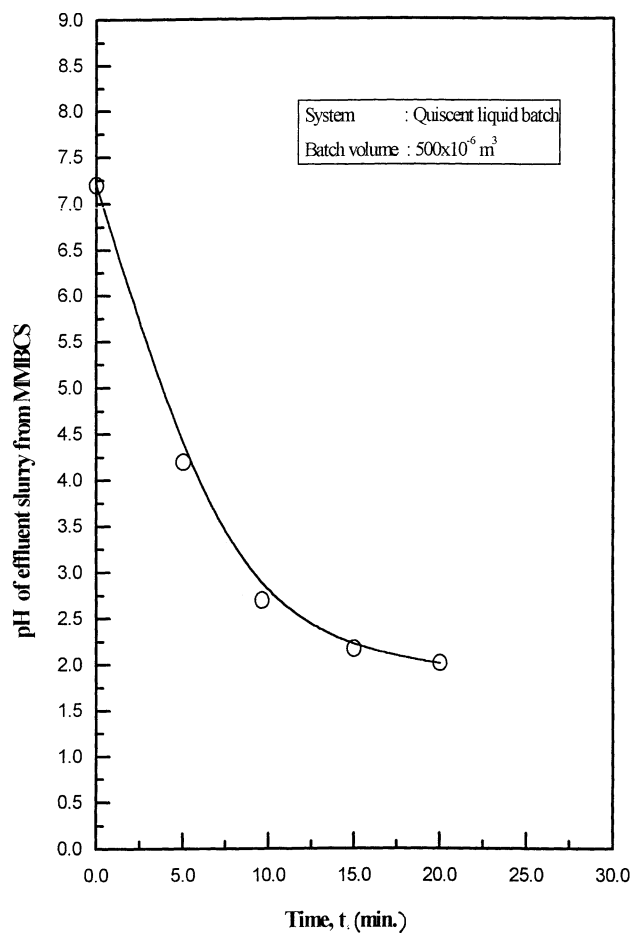


Figure 10. Effect of contact time on the slurry pH for the simultaneous scrubbing of fly-ash and SO_2 .

experimental values of percentage removal of fly-ash laden SO_2 , $\eta_{\text{SO}_2 - \text{FA}}$ in Figure 11. The percentage deviation between the experimental data and those predicted by Eq. 4 has been plotted in Figure 12. It is seen from this figure that the percentage deviation is quite low. Furthermore, to test the acceptability of the correlation, various statistical tests have been carried out and determined a 99.1% confidence level.

Conclusions

Experimental results show that almost zero penetration ($\sim 100\%$ removal) of fly-ash laden SO_2 can be achieved at a liquid to gas-flow rate ratio of $5.5 \text{ m}^3/1,000 \text{ ACM}$ of gas-flow rate in the present system. Removal efficiency for both SO_2 and fly-ash for fly-ash-laden- SO_2 has been found to be a function of inlet fly-ash and SO_2 loading. Stage efficiencies in the range of 70–71% were obtained in the bubble stage (stage-1) and 82–89% in Stage 2 and 3, respectively, which indicates the efficacy of the contraction-expansion disks. Higher inlet fly-ash and SO_2 loading leads to a higher efficiency of the collection at a low scrubber height. Results also indicate that a higher gas-flow rate results in higher SO_2 collection efficiency for the particulate-laden fly-ash. Further-

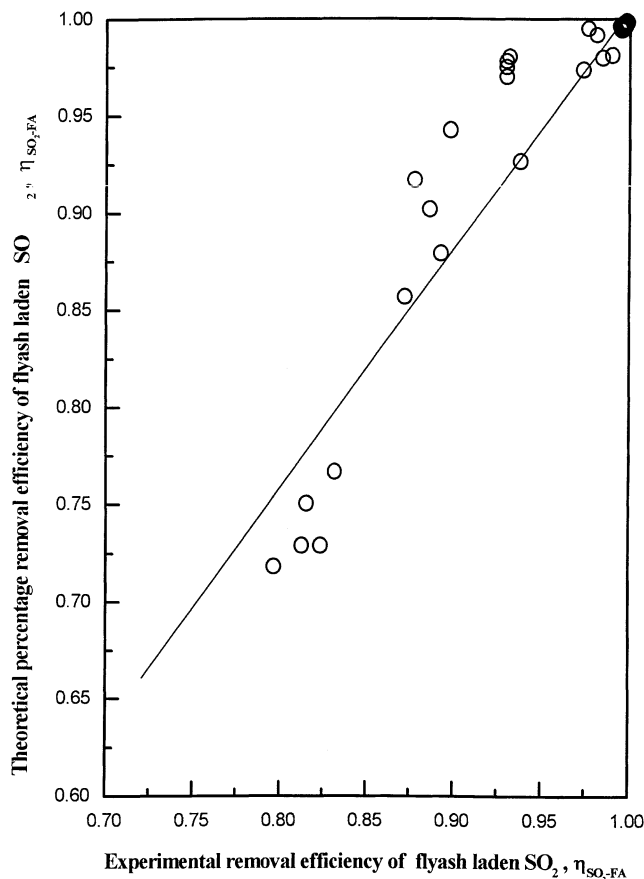


Figure 11. Experimental vs. predicted (through the correlation) values of % removal SO_2 for the fly-ash- SO_2 -air-water system.

more, a correlation has been developed for predicting the percentage collection efficiency of sulfur dioxide in the presence of fly-ash. Experimental results are in excellent agreement with the correlation. Enhancement of the SO_2 collection due to the presence of fly-ash has also been quantified.

As the particulate collection efficiency of the present scrubber is more than 99.5% and since the fly-ash particles used in the present system contains less than 10% of the total particles of diameter of less than 2.0 micron, which is much below the standards prescribed by EPA.

Acknowledgment

A patent is pending for the modified multistage bubble column scrubber.

Notation

BCS = bubble column scrubber
 $C_{FA,i}$ = inlet concentration of fly-ash $\text{kg}/\text{N} \cdot \text{m}^3$
 $C_{FA,o}$ = outlet concentration of fly-ash $\text{kg}/\text{N} \cdot \text{m}^3$
 $C_{\text{SO}_2,i}$ = inlet concentration of sulfur dioxide, ppm
 $C_{\text{SO}_2,o}$ = outlet concentration of sulfur dioxide, ppm
 d_o = orifice diameter, m
 d_p = diameter of fly-ash particle, m
 D_c = diameter of bubble column, m
 D_H = diameter of expansion, contraction disks, m

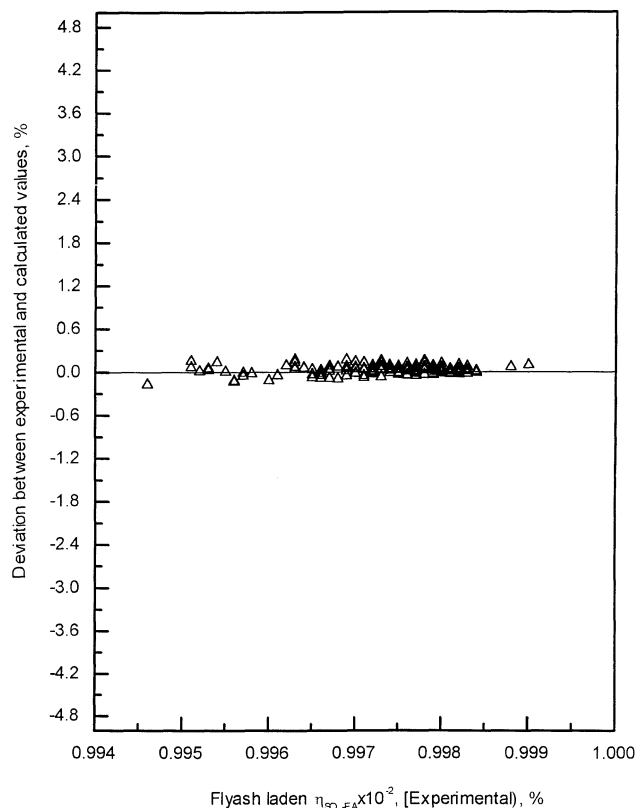


Figure 12. Deviation between calculated and experimental values for water-scrubbing fly-ash laden SO_2 .

D_L = dispersion coefficient, liquid phase, m^2/s
 f = functions of variables
 g = acceleration due to gravity, m/s^2
 H = height of the bubble column, m
 H_e = Henry's law constant ($\text{cm}^3 \cdot \text{atm}/\text{gmol}$)
 H_R = height to diameter ratio of the bubble column, dimensionless
 $L_{p''}$ = liquid property group [$C_{FA-\text{SO}_2,i} V_L^2/\text{He}$], dimensionless
MMBCS = modified multistage bubble column scrubber
 P = pressure, N/m^2
 q = penetration of fly-ash and SO_2 weight fraction
 Q_G = volumetric flow rate of gas, Nm^3/s
 Q_L = volumetric flow rate of liquid, m^3/s
 R = gas constant, $\text{N} \cdot \text{m}/\text{kmol} \cdot \text{K}$
 Re_G = superficial gas Reynold's number ($Re_G = D_c V_G \rho_G / \mu_G$), dimensionless
 Re_L = superficial liquid Reynold's number ($Re_L = D_c V_L \rho_L / \mu_L$), dimensionless
 Sc' = Schmidt number based on fly-ash laden SO_2 concentration, ($Sc' = DC_{\text{SO}_2-FA,i} / \mu_L$), dimensionless
 t = time, min.
 V = operating scrubber volume, m^3
 V_G = gas velocity, m/s
 V_L = liquid velocity, m/s
 V_T = total system volume, m^3
 q = which penetrates into the exhaust, ($q = 1 - \eta_T$), dimensionless

Greek letters

η_{FA} = removal efficiency of fly-ash, from fly-ash-air mixture
 $\eta_{FA-\text{SO}_2}$ = removal efficiency of fly-ash, from fly-ash- SO_2 -air mixture

ρ_G = gas density, kg/m³
 μ_G = gas viscosity, kg/m/s
 ρ_L = liquid density, kg/m³
 μ_L = liquid viscosity, kg/m/s
 η_{SO_2} = removal efficiency of sulfur dioxide, from SO₂-air mixture
 η_{SO_2-FA} = removal efficiency sulfur dioxide, from a mixture of fly-ash-SO₂-air

Subscripts

– = anion
 + = cation
 cal = calculated
 exp = experimental
 FA_i = inlet concentration of fly-ash
 FA_o = outlet concentration of fly-ash
 FA = fly-ash
 $FA - SO_2$ = fly-ash in fly-ash-SO₂-air mixture
 SO_2 = sulfur dioxide
 $SO_{2,i}$ = inlet concentration of SO₂
 $SO_{2,o}$ = outlet concentration of SO₂
 $SO_2 - FA$ = sulfur dioxide in SO₂-fly-ash-air mixture

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