

# Abatement of particulate-laden SO<sub>2</sub> in tapered bubble column with internals

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**Abstract** The performance of particulate-laden SO<sub>2</sub> scrubbing in a modified tapered bubble column with internals is reported in this article. The presence of particles improved the particulate-laden SO<sub>2</sub> removal efficiency to about 15% that was elucidated by the facilitated adsorptive mass transport. Experimentation revealed that nearly 100% removal efficiency of particulate-laden SO<sub>2</sub> was achievable without any additives or pretreatment under certain operating condition of the scrubber. An empirical correlation was developed to predict the performance of the modified tapered scrubber. Experimental values fitted excellently well with the predicted values through the correlation (within ±5% deviation). The performance of the modified tapered bubble scrubber with column internals has been found to be better than a tapered bubble column without any internals.

**Keywords** Particulate-laden SO<sub>2</sub> scrubbing · Enhancement of removal efficiency by particulates · Modified tapered bubble column · Wet scrubber · Air pollution control

## Symbols and notation

ACM Actual cubic meter (m<sup>3</sup>)  
C<sub>i</sub> Pollutant concentration at the scrubber inlet (kg/m<sup>3</sup>)  
C<sub>o</sub> Pollutant concentration at the scrubber outlet (kg/m<sup>3</sup>)

C<sub>Si</sub> Particulate concentration at the scrubber inlet (kg/m<sup>3</sup>)  
C<sub>SO<sub>2</sub>i</sub> SO<sub>2</sub> concentration at the scrubber inlet (ppm)  
C<sub>SO<sub>2</sub>o</sub> SO<sub>2</sub> concentration at the scrubber outlet (ppm)  
D Diffusivity of SO<sub>2</sub> in air (m<sup>2</sup>/s)  
D' Diffusivity of SO<sub>2</sub> in water (m<sup>2</sup>/s)  
D'' Diffusivity of NaOH in water (m<sup>2</sup>/s)  
d<sub>B</sub> Average bubble diameter (m)  
D<sub>c</sub> Log mean diameter of the tapered bubble column (m)  
Di Axial dispersion number in the bubble section {D/(u<sub>b</sub>·H<sub>C</sub>)}, dimensionless  
d<sub>p</sub> Particle SMD (m)  
f Functions of variables, dimensionless  
H<sub>c</sub> Height of the tapered bubble column (m)  
H<sub>e</sub> Henry's law coefficient (m<sup>3</sup>·atm/kmol)  
P<sub>L</sub> Liquid property parameter {μ<sub>L</sub>/(ν<sub>L</sub><sup>2</sup>·H<sub>e</sub>)}, dimensionless  
ppm Parts per million (volume fraction), dimensionless  
Q<sub>G</sub> Gas flow rate (m<sup>3</sup>/s)  
Q<sub>L</sub> Liquid flow rate (m<sup>3</sup>/s)  
Re<sub>p</sub> Particle Reynold's number, (d<sub>p</sub>·v<sub>g</sub>·ρ<sub>p</sub>/μ<sub>g</sub>), dimensionless  
Sc Modified Schmidt number {μ<sub>L</sub>/(D'·C<sub>SO<sub>2</sub>i</sub>)}, dimensionless  
SMD Sauter mean diameter (m)  
T Temperature (K)  
u<sub>b</sub> Bubble slip velocity (m/s)  
V Volume of the aerated liquid (m)  
v<sub>g</sub> Superficial gas velocity, m/s  
v<sub>L</sub> Superficial liquid velocity (m/s)  
V<sub>QL</sub> Quiescent liquid volume (m<sup>3</sup>)  
V<sub>o</sub> Volume of the clear liquid without any aeration (m)

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$V_R$  Ratio of static water volume to total column volume, dimensionless

### Greek letters

$\eta$  Percentage removal of pollutant, dimensionless

$\eta_{\text{SO}_2\text{-P-H}_2\text{O}}$  Percentage removal of particulate-laden  $\text{SO}_2$  in water scrubbing, dimensionless

$\eta_{\text{SO}_2\text{-H}_2\text{O}}$  Percentage removal of  $\text{SO}_2$  in water scrubbing in particle free situation, dimensionless

$\phi_{\text{SO}_2\text{-P}}$  Enhancement of removal efficiency of particulate-laden  $\text{SO}_2$  due to presence of fly-ash in water scrubbing, dimensionless

$\mu_g$  Viscosity of gas (kg/ms)

$\mu_L$  viscosity of liquid (kg/ms)

$\rho_g$  Gas density ( $\text{kg/m}^3$ )

$\rho_L$  Liquid density ( $\text{kg/m}^3$ )

$\rho_P$  Fly-ash particle density ( $\text{kg/m}^3$ )

$\varepsilon_g$  Fractional gas holdup, dimensionless

### Introduction

The particulate-laden  $\text{SO}_2$  emissions from different industrial sources can cause considerable deleterious health effects. As a result, curbing such emission is given significant attention even in recent years through the promulgation of stringent emission standards of both particulate matter and  $\text{SO}_2$ . In spite of its shortcomings, the wet scrubber, among various wet and dry systems, is one of the air pollution control devices that can potentially abate the particulate-laden  $\text{SO}_2$  emission when control of both of them are very much desired owing to its unique ability to remove these pollutants, in a single step (Tomany 1975). Given the problems associated with sequential removal of particulates and gases, the simultaneous abatement of particulate and gases in a single-step assumes significant importance. In addition, wet scrubbers offer a very high turn down ratio, smaller onsite plant space, higher service factor, simpler operation, less investment, and lower operating costs than other air emission control devices. Literature survey indicated that a flurry of research in this field was conducted three decades back. A comprehensive literature survey was described by Bandyopadhyay and Biswas (2008). Analysis of the literature detailed therein revealed that a tapered column with circular cross-section was better than the other system.

In the light of these findings, attempts have been made in this article to report on the detailed performance of a modified tapered bubble scrubber with internals for simultaneous removal of particulates and  $\text{SO}_2$  in a single-step using water without any additives or pretreatment.

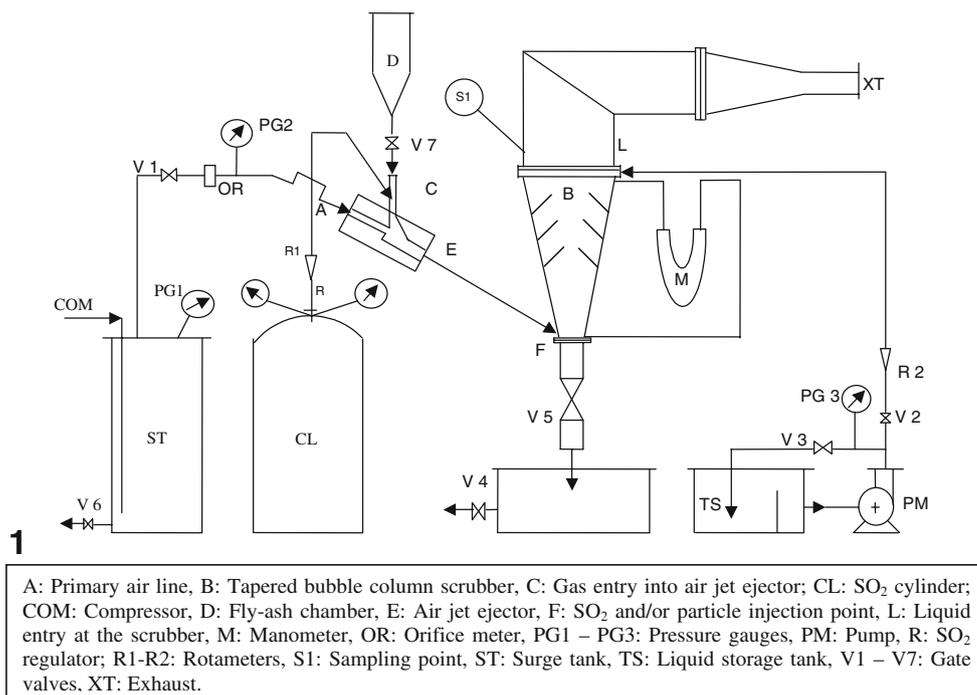
### Experimental programme

The experimental setup is schematically shown in Fig. 1. The column made up of mild steel had a divergence angle of  $7^\circ$  and a height of 0.87 m. Twelve plates, as column internals, having dimension of  $0.015 \text{ m} \times 0.080 \text{ m}$  were fabricated inside the column. Four sets consisting three plates each were fixed radially. Each set is separated by  $90^\circ$ , and plates in each set were fixed at a vertical distance of 53, 63, and 73 cm from the top of the column at an upward inclination of  $60^\circ$ , as shown in Fig. 2. Arrangements were provided in the column by replacing a small portion with Perspex sheet for visualizing the bubbly flow. Liquid was introduced into the column from top of the column. At desired pressure and flow rate, compressed air, as motive fluid, was forced through the air nozzle (A) in the ejector to aspirate particulate and  $\text{SO}_2$  and to mix intensely with air in the mixing throat of the ejector. The simulated mixture was then allowed to feed at the base of the scrubber. The liquid was withdrawn at the bottom in such a way that a constant liquid volume could be maintained within the column.

### Measurement and chemical analysis

The concentrations of  $\text{SO}_2$  at scrubber inlet ( $S_2$ ) were measured from the volumetric flow rates of air and  $\text{SO}_2$ . This method of measurement was adopted since concentrations of  $\text{SO}_2$  measured using volumetric flow rates and by chemical methods under identical situations at the scrubber entry (F) did not produce any noticeable deviation. On the other hand, concentrations of  $\text{SO}_2$  at scrubber outlet ( $S_1$ ) were measured in two distinct steps: (1) at first, samples were drawn through midget type of impingers attached to an aspirator bottle under steady state operating conditions and then (2) the liquid collected in the impinger was analyzed by the iodine method (Jackobs 1949) to determine the concentration of  $\text{SO}_2$ . This method was deployed since this method yielded stable results below 5 ppm, compared with other methods. Furthermore, gaseous sampling was not carried out iso-kinetically, since the sampling efficiency generally remained in unity in such a situation. The concentrations of particulates at scrubber entry were measured in situ by using a pre-calibrated online photoelectric system details of which is described in the literature (Bandyopadhyay and Biswas 2006). On the other hand, the concentrations of particulates at scrubber exit were measured by drawing samples through filter assembly containing glass fiber filter paper mounted on a filter holder attached to an aspirator bottle under steady-state operating conditions. For particulate sampling, it was necessary to maintain iso-kinetic conditions matching with the experi-

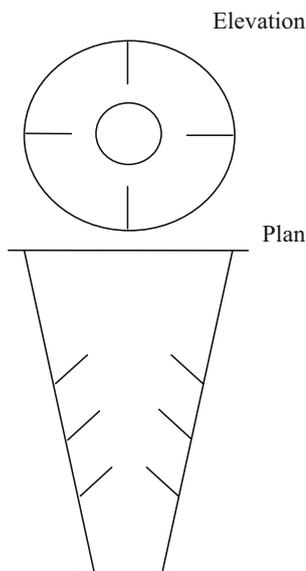
**Fig. 1** Schematic of the experimental setup



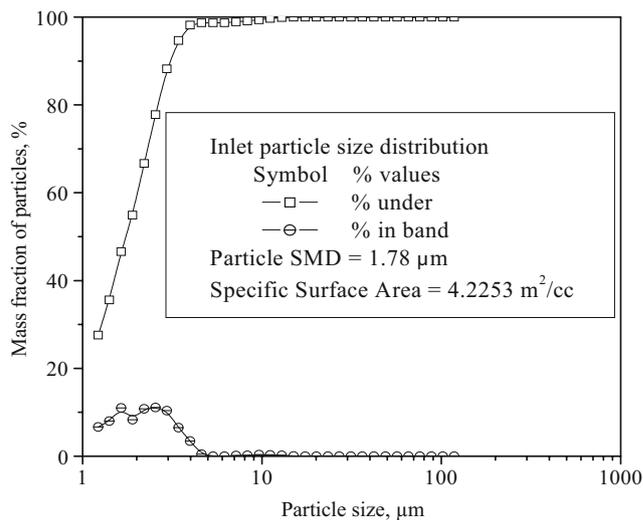
mental gas flow rates, and in doing so, samples at scrubber exit were drawn at a rate ranging from  $1.67 \times 10^{-5}$  to  $2.50 \times 10^{-5}$  m<sup>3</sup>/s. The difference in weight of the filter paper containing particles and the filter paper previously weighed alone gave the total mass of particles collected. The particle concentration was measured thereafter by dividing the total mass of particles collected by the total volume of gas drawn through the glass fiber filter paper (Indian Standards 1973). The particle size distributions and the specific surface area

of the particles were measured using Malvern sizer (Fig. 3). The dust was collected from a local industry. The industry used a thermic fluid heater for steam generation by burning hog fuel. The flue gas was passed thereafter through a particulate collection device, viz., bag house filter. Particulates collected in the bag house filter were used in this present study.

The range of experimental parameters studied were the following: temperature (*T*),  $306.4 \pm 1$  K; liquid flow rate (*Q<sub>L</sub>*),  $1.11 \times 10^{-5}$ ,  $1.83 \times 10^{-5}$ ,  $2.50 \times 10^{-5}$ , and  $3.11 \times 10^{-5}$  m<sup>3</sup>/s;



**Fig. 2** Schematic of the plan and elevation of the modified tapered bubble column showing the column internals



**Fig. 3** Typical particle size distribution at the inlet of the modified tapered bubble column scrubber

gas flow rate ( $Q_G$ ),  $3.75 \times 10^{-3}$ ,  $4.60 \times 10^{-3}$ ,  $5.45 \times 10^{-3}$ , and  $6.20 \times 10^{-3}$  m<sup>3</sup>/s; inlet SO<sub>2</sub> concentration ( $C_{SO_2,i}$ ), 700, 1,000, 1,300, 1,600, and 2,000 ppm; inlet particle concentration ( $C_{Si}$ ),  $11.0 \times 10^{-3}$ ,  $16.7 \times 10^{-3}$ ,  $22.5 \times 10^{-3}$ , and  $30.4 \times 10^{-3}$  kg/m<sup>3</sup>; average bubble diameter, 4–7 mm (visual observation); quiescent liquid (water) volume ( $V_{QL}$ ),  $2.7 \times 10^{-3}$ ,  $3.4 \times 10^{-3}$ ,  $4.2 \times 10^{-3}$ ,  $5.0 \times 10^{-3}$ , and  $5.9 \times 10^{-3}$  m<sup>3</sup>.

The fractional gas holdup ( $\varepsilon_g$ ) was determined by measuring the volume of the aerated liquid ( $V$ ) and that of the clear liquid without any aeration ( $V_o$ ). Such measurement was unaffected by the cross-section of the column. The holdup remained unaltered whether it was measured either in quiescent liquid or downward flowing liquid probably due to the extremely lower liquid velocity ( $v_L$  ranging between  $4.41 \times 10^{-4}$  and  $2.55 \times 10^{-3}$  m/s) compared to that of the superficial gas velocity ( $v_g$  ranging between 0.307 and 0.492 m/s) at  $V_{QL} = 2.7 \times 10^{-3}$  m<sup>3</sup>. The relative difference between gas and liquid velocities would remain almost similar for other values of  $V_{QL}$ . The superficial gas velocity ( $v_g$ ) and liquid velocity ( $v_L$ ) were calculated using logarithmic mean cross-sectional areas of the top and bottom of the dispersion. The holdup was, therefore, represented by the following expression:

$$\varepsilon_g = (V - V_o)/V \quad \dots \quad (1)$$

Stable bubbles with uniformity were also observed though bubble bursting and regeneration took place. Furthermore, the gas holdup and volume to surface mean bubble diameter (Sauter mean diameter) are related to the interfacial area of contact as

$$a = \frac{6 \varepsilon_g}{d_{b,SMD}} \quad \dots \quad (2)$$

Subsequent measurement of fractional holdup and interfacial area of contact in this column had shown that the average bubble size was between 4 and 7 mm using Eq. 2. Although the average bubble size was not measured directly by the conventional techniques (like photographic method, electrical conductivity probe method, etc.), the visual observation was made in this work since the average bubble sizes measured by measuring the interfacial area of contact and fractional gas holdup were comparable with the values determined from visual observation.

## Results and discussion

The effects of various operating variable on the percentage removal of particulate-laden SO<sub>2</sub> are described for different concentrations of SO<sub>2</sub> and particulate

matter. The percentage removal of particulate-laden SO<sub>2</sub> were calculated in each run by the following conventional expression,

$$\eta = [(C_i - C_o)/C_i] \times 100 \quad \dots \quad (3)$$

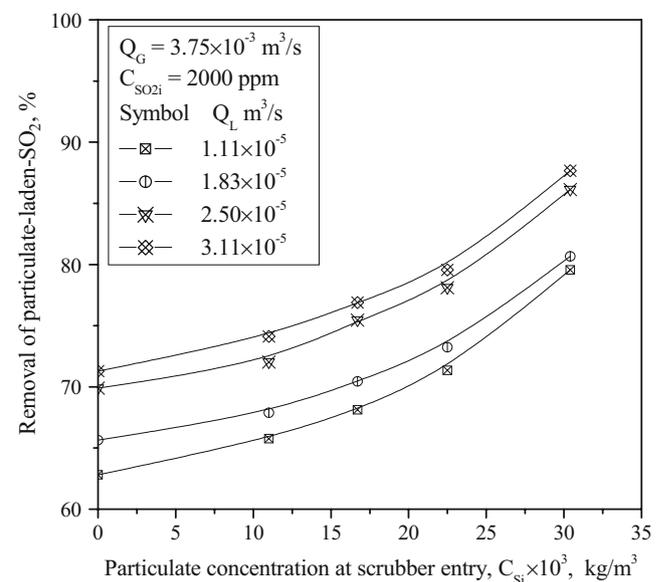
### Effect of initial concentration of SO<sub>2</sub>

Experimentation revealed that the percentage removal of particulate-laden SO<sub>2</sub> was independent of the initial concentration of SO<sub>2</sub>. It might be attributed due to the fact that the absorption of SO<sub>2</sub> in water was governed by the physical mechanism even in presence of particles.

### Effect of inlet particle concentration and liquid flow rate

The effect of inlet particle concentration and liquid flow rate on the percentage removal of particulate-laden SO<sub>2</sub> at a constant gas flow rate of  $3.75 \times 10^{-3}$  m<sup>3</sup>/s and at constant inlet SO<sub>2</sub> loading of 2,000 ppm is shown in Fig. 4. It can be seen from the figure that the presence of particles enhanced the percentage removal of SO<sub>2</sub> significantly. The enhancement was attributed due to the facilitated adsorptive mass transport that is discussed as follows.

The enhancement observed could not be due to the catalytic activity of the particles and the increased pH of the scrubbing liquid in the presence of particles, since absorption of SO<sub>2</sub> in water was governed by the physical gas–liquid absorptive mass transport phenomena, and the



**Fig. 4** Effect of inlet particle concentration on the percentage removal of particulate-laden SO<sub>2</sub> for various liquid flow rates at constant gas flow rate and inlet SO<sub>2</sub> concentration

study particles in aqueous medium did not alter the pH appreciably as was revealed from relevant experimentation. This enhancement was, however, similar to the enhancement of absorption observed in CO<sub>2</sub> in Na<sub>2</sub>CO<sub>3</sub>+NaHCO<sub>3</sub> system in a stirred cell with fine activated carbon particles (size ~5 mm and concentration ranging from 0.1 to 38 kg/m<sup>3</sup> of liquid; Alper et al. 1980). They elucidated this enhancement through a simple transport mechanism that resulted in the facilitated adsorptive transfer of gas. Similar kind of facilitated transport in a bubble column with same gas–liquid system using activated carbon particles (with 73.5% falling in the size range of 0 to 6 mm; concentration, 2 and 9 kg/m<sup>3</sup> of liquid) was described by Quicker et al. (1987). Vinke et al. (1992) also illustrated similar observation using fine carbon particles of size ~6 mm and concentration ranging from 2 to 3 kg/m<sup>3</sup> of liquid in an agitated slurry reactor in which no chemical reaction was occurring.

Adsorption of SO<sub>2</sub> on study dust particles was not carried out in the present investigation, since there was evidence in support of such phenomenon in the existing literature (Liberti et al. 1978). Therefore, the increase in the percentage removal of SO<sub>2</sub> in the presence of study particles was due to the adsorption of SO<sub>2</sub> by the gas-adsorbing particles adhering to the uprising bubbles that was available for dissolution in the bubble regime, which supports the observation made by earlier workers (Alper et al. 1980; Quicker et al. 1987; Vinke et al. 1992). The enhancement was observed to be about 15% (Fig. 4). The maximum percentage removal of particulate-laden SO<sub>2</sub> was about 87.5% within the range of variables specified in Fig. 4.

It can be also seen from the figure that the percentage removal was increased with the increase in the liquid flow rate. It might be due to the quicker removal of the absorbed material from the scrubber. It might also be due to the fact that the removal efficiency of particulates and the driving force for mass transfer were increased resulting in the increased percentage removal of SO<sub>2</sub>.

Effect of gas flow rate

The effect of gas flow rate on the percentage removal of particulate-laden SO<sub>2</sub> is shown in Fig. 5 at various liquid flow rates at constant C<sub>SO<sub>2</sub>i</sub> and at two values of C<sub>si</sub>. It can be seen from the figure that the percentage removal was decreased with the increase in gas flow rate. It might be

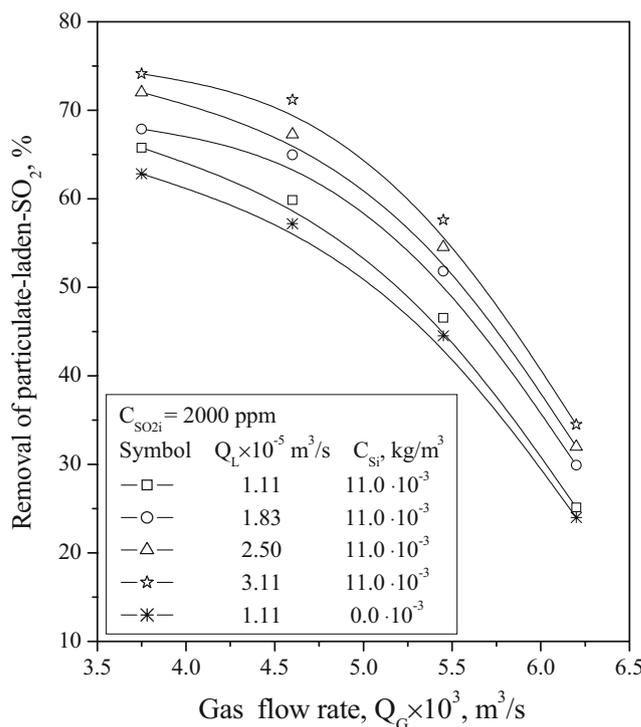


Fig. 5 Effect of gas flow rate on the percentage removal of particulate-laden SO<sub>2</sub> for various liquid flow rates at fixed inlet SO<sub>2</sub> concentration

perhaps due to the fact that the gas phase residence time was decreased with the increase in gas flow rate, and as a result, the percentage removal was decreased. The extent of enhancement of removal efficiency of SO<sub>2</sub> is also clearly seen from the figure when the percentage removals are compared with those under particle free situation. The percentage removal was also increased with the increase in the liquid flow rate. The reasons for increase in the percentage removal with the liquid flow rate and with the initial particle concentration are discussed earlier. The quantification of enhancement can be elucidated as follows.

The three-phase holdup notably differs from the two-phase holdup for solid concentration more than 10% volume as reported by Sauer and Hempel (1987). The maximum solid concentration that was attained in this study was of 5.00% volume (approximate). Hence, these findings justify the use of two-phase holdup in the present case. The enhancement of particulate-laden SO<sub>2</sub> removal in water scrubbing in such a situation can be expressed by the following equation:

$$\phi_{SO_2-P} = \frac{\text{removal efficiency of particulate – laden SO}_2 \text{ in water scrubbing}}{\text{removal efficiency of SO}_2 \text{ in particle free situation in water scrubbing}} = \frac{\eta_{SO_2-P-H_2O}}{\eta_{SO_2-H_2O}} \dots \quad (4)$$

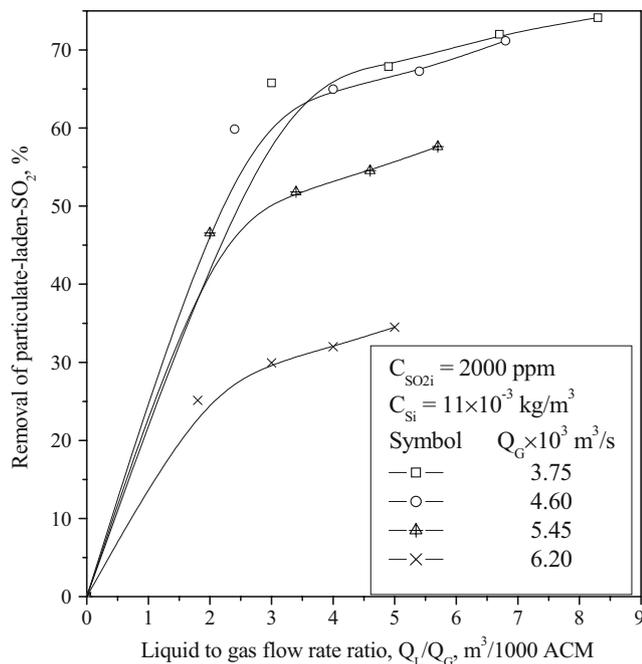
Equation 4 can be further analyzed considering the absorption of SO<sub>2</sub> in H<sub>2</sub>O from particulate-laden SO<sub>2</sub> from airborne SO<sub>2</sub> streams under identical inlet loading of SO<sub>2</sub>. Equation 6 under this circumstance takes the following form:

$$\begin{aligned} \phi_{\text{SO}_2\text{-P}} &= \frac{\eta_{\text{SO}_2\text{-P-H}_2\text{O}}}{\eta_{\text{SO}_2\text{-H}_2\text{O}}} = \left[ \frac{C_{\text{SO}_2\text{i}} - C_{\text{SO}_2\text{o}}}{C_{\text{SO}_2\text{i}}} \right]_{\text{P}} \times \left[ \frac{C_{\text{SO}_2\text{i}}}{C_{\text{SO}_2\text{i}} - C_{\text{SO}_2\text{o}}} \right]_{\text{without P}} \\ &= \frac{[C_{\text{SO}_2\text{i}} - C_{\text{SO}_2\text{o}}]_{\text{P}}}{[C_{\text{SO}_2\text{i}} - C_{\text{SO}_2\text{o}}]_{\text{without P}}} \dots \end{aligned} \tag{5}$$

For increased fractional gas flow rate, the collection efficiency of particulate would be higher as revealed from preliminary experimentation; consequently, the number of particles captured within the scrubber would be relatively higher. As a result, the driving force for mass transfer of SO<sub>2</sub> in such a situation was increased, due primarily to facilitated adsorptive mass transport, than what it would be in particle free situation. Therefore, with increased gas flow rate

$$[C_{\text{SO}_2\text{i}} - C_{\text{SO}_2\text{o}}]_{\text{P}} > [C_{\text{SO}_2\text{i}} - C_{\text{SO}_2\text{o}}]_{\text{without P}} \dots \tag{6}$$

which in turn caused  $\phi_{\text{SO}_2\text{-P}}$  to increase as per Eq. 5. This finding is important and is very useful for modeling of the scrubber.



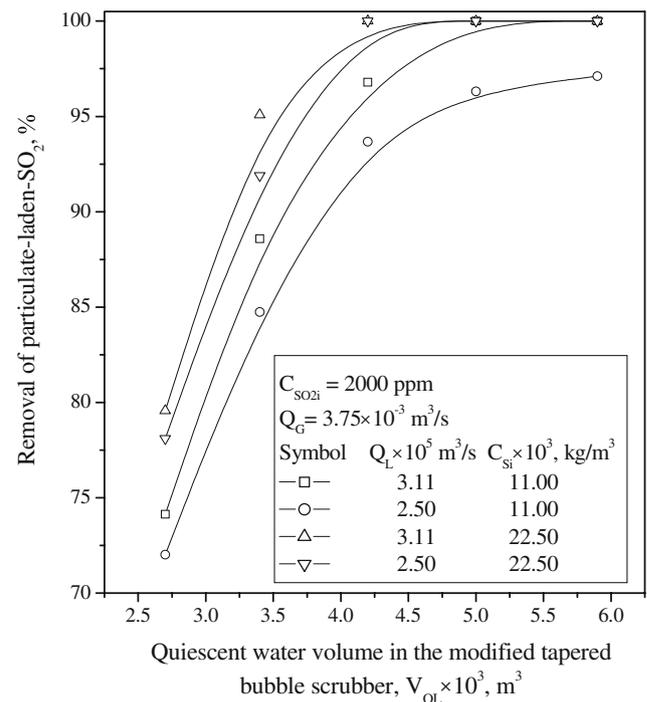
**Fig. 6** Effect of liquid to gas flow rate ratio on the percentage removal of particulate-laden SO<sub>2</sub> for various gas flow rates at fixed inlet SO<sub>2</sub> and particle concentrations

Effect of liquid to gas flow rate ratio

The effect of liquid to gas flow rate ratio on the percentage removal of particulate-laden SO<sub>2</sub> is shown in Fig. 6 at various gas flow rates and at constant initial SO<sub>2</sub> concentration as well as particle concentration. It can be seen from the figure that the percentage removal was increased with the increase in liquid to gas flow rate ratio. The percentage removal increased initially very sharply, and it reached almost a constant value beyond  $Q_L/Q_G$  of about 2.5 m<sup>3</sup>/1,000 ACM. Beyond this value, there might not be effective mass transfer of gas into the liquid perhaps due to liquid phase reaching equilibrium.

Effect of quiescent liquid volume in the bubble column

The effect of quiescent liquid volume in the modified tapered bubble column,  $V_{QL}$ , on the percentage removal of particulate-laden SO<sub>2</sub> is shown in Fig. 7 at various liquid flow rates and initial particle concentrations at constant gas flow rate and inlet SO<sub>2</sub> concentration. It can be seen from the figure that the percentage removal was increased very sharply initially with the increase in the values of  $V_{QL}$ . At higher values of  $V_{QL}$ , the percentage removal of particulate-laden SO<sub>2</sub> was increased perhaps due to increased



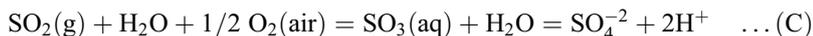
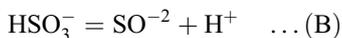
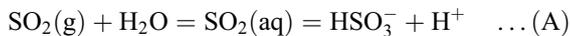
**Fig. 7** Effect of quiescent liquid volume in the bubble column on the percentage removal of particulate-laden SO<sub>2</sub> for various liquid flow rates and initial particle concentrations at fixed gas flow rate and inlet SO<sub>2</sub> concentration

absorption capacity. However, the percentage removal reached almost a constant value beyond  $V_{QL} \approx 4.2 \times 10^{-3} \text{ m}^3$ . It might be perhaps due to the fact that the solute gas concentration might reach its equilibrium value in the liquid phase beyond  $V_{QL} \approx 4.2 \times 10^{-3} \text{ m}^3$  resulting in constancy of percentage removal. Maximum percentage removal was attained about 100% at higher  $Q_L$  and  $C_{Si}$  values. This clearly demonstrates that the scrubber could be operated at

a removal efficiency of ~100% by manipulating the operating variables.

### Scrubber purge stream pH

The absorption of  $\text{SO}_2$  in water may result in the production of sulfurous and sulfuric acid per the following reaction scheme:



Thus, there would be a temporal variation of pH of the scrubbing liquor for a specific batch of liquid. The effect of scrubbing time on the scrubber purge stream pH is shown in Fig. 8. It is seen from the figure that the pH of the scrubber exit slurry was decreased with the increase in scrubbing time as was expected. It is also seen from the figure that the pH was initially decreased very sharply between 10 and 15 min of scrubbing time; thereafter, pH was reached almost a constant value. It was perhaps due to the fact that the liquid was loaded with  $\text{SO}_2$  as the process of scrubbing progressed and simultaneously  $\text{H}^+$  ions were formed as per reactions (A) to (C). Formation of  $\text{H}^+$  ions within this scrubbing period might have been very rapid, and as a result, pH of the slurry was decreased initially very rapidly. However, beyond a pH of about 2.5 as can be seen from Fig. 8, there might have been an overcrowding of  $\text{H}^+$  ions in the interfacial region of liquid and gas phases that

hindered further  $\text{SO}_2$  absorption. This has resulted in a slower rate of decrease in pH with the increase in scrubbing time. Clearly, this observation indicated that the absorption of  $\text{SO}_2$  might be limited to a certain pH at which the  $\text{SO}_2$  reached its equilibrium concentration in the liquid phase, and in this case, it could be around pH 2.5 within other specified range of variables studied. Finally, the pH reached a constant value of 2.0, which is equivalent to  $\approx 0.01 \text{ N}$  sulfurous/sulfuric acid. All the experimental runs were taken after the pH of the exit slurry was stabilized.

### Predicting removal efficiency of particulate-laden $\text{SO}_2$ scrubbing by correlation

The present article deals with the particulate-laden  $\text{SO}_2$  scrubbing in a modified tapered bubble column scrubber. An attempt was made to develop an empirical correlation in order to predict the percentage removal of particulate-laden  $\text{SO}_2$  from the directly measurable as well as derived parameters. The parameters, which could possibly affect the percentage removal efficiency of particulate-laden  $\text{SO}_2$ ,  $\eta_{\text{SO}_2-\text{P}-\text{H}_2\text{O}}$ , are furnished in Table 1. The inlet  $\text{SO}_2$  concentration was expressed in kilogram per cubic meter for the purpose of the dimensional analysis. The dimensional analysis may be simplified to

$$\eta_{\text{SO}_2-\text{P}-\text{H}_2\text{O}} = f \left\{ (\text{Re}_p)^a \times (\text{Sc})^b \times (D_i)^c \times \left( C_{\text{Si}} / \rho_g \right)^d \times (P_L)^e \times (\varepsilon_g)^f \times (V_R)^g \right\} \quad \dots (7)$$

In order to establish the functionality between the percentage removals of particulate-laden  $\text{SO}_2$  and the various dimensionless groups in Eq. 7, as also to evaluate the constants and coefficients of the equation, multiple linear regression analysis was carried out. The data obtained on statistical analysis are also given in Table 1. With this analysis, the best correlation (significant at 99.1%

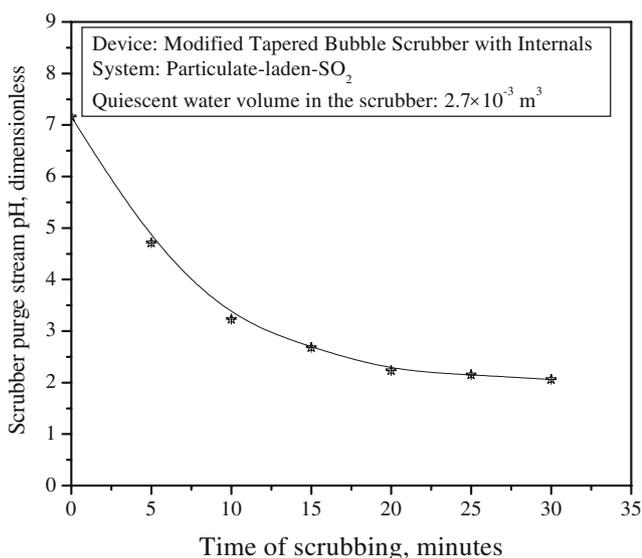


Fig. 8 Effect of scrubbing time on the scrubber purge stream pH for the simultaneous scrubbing of particle and  $\text{SO}_2$

**Table 1** Development of empirical correlation and results of dimensional analysis

Items	Variables and details of analysis
Geometrical parameters	$d_p, d_b, D_c, H_c, V_R$
Flow parameters	$u_b, v_g, v_L, \varepsilon_g$
Physical parameters	$\rho_p, \rho_g, \rho_L, \mu_g, \mu_L, C_{Si}, C_{SO_2i}, D, D', H_c$
Results of statistical analysis	Minimum percentage error=0.77% Minimum standard deviation of percentage error=0.89% Correlation coefficient=0.9925 $t$ test and $F$ test indicate that the correlation (Eq. 8) is significant at 99.1% confidence level
Range of dimensionless variables	$Re_p=58.8$ to $92.4$ , $Sc=1.07 \times 10^8$ to $3.05 \times 10^8$ $D_i=3.21 \times 10^{-5}$ to $4.97 \times 10^{-5}$ $C_{Si}/\rho_g=39.5$ to $109$ $P_L=3.01 \times 10^{-5}$ to $25.24 \times 10^{-5}$ $V_R=0.18$ to $0.39$ $\varepsilon_g=0.4921$ to $0.5631$

confidence level) for predicting the percentage removal of particulate-laden SO<sub>2</sub> is given below:

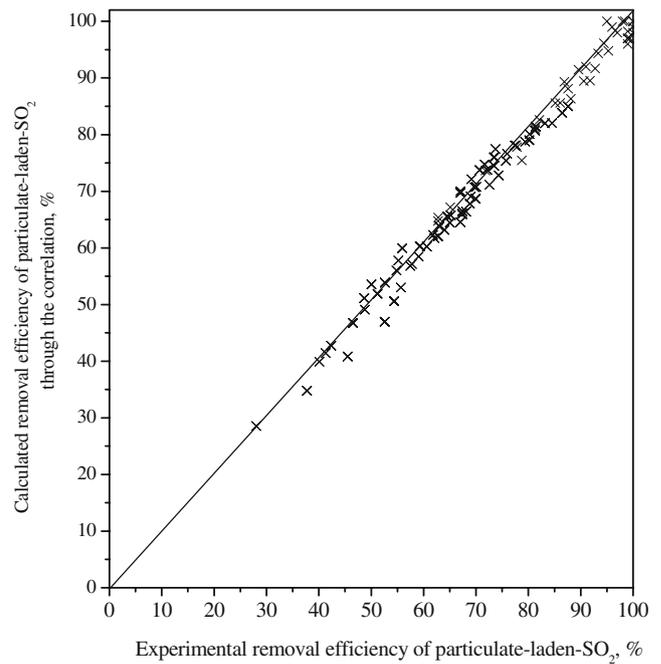
$$\eta_{SO_2-P-H_2O} = 100 - 1.0105 \times 10^{-7} \times \left\{ (Re_p)^{2.031} \times (Sc)^{-0.00068} \times (D_i)^{-0.1301} \times \left( C_{Si}/\rho_g \right)^{-0.6003} \times (P_L)^{0.0796} \times \varepsilon_g^{-4.9432} \times (V_R)^{0.0946} \right\} \dots \quad (8)$$

The ranges of dimensionless groups expressed in Eq. 8 are presented in Table 1. Equation 8 describes the percentage removal of particulate-laden SO<sub>2</sub> in the modified tapered scrubber, which is an important parameter for

$$q = 100 - \eta_{SO_2-P-H_2O} = 1.0105 \times 10^{-7} \times \left\{ (Re_p)^{2.031} \times (Sc)^{-0.00068} \times (D_i)^{-0.1301} \times \left( C_{Si}/\rho_g \right)^{-0.6003} \times (P_L)^{0.0796} \times \varepsilon_g^{-4.9432} \times (V_R)^{0.0946} \right\} \dots \quad (9)$$

The penetration expressed in Eq. 9 is also an important parameter for evaluating the scrubber performance as an air pollution control device.

The values of percentage removal of particulate-laden SO<sub>2</sub> predicted by Eq. 9 are plotted against the experimental values of percentage removal of particulate-laden SO<sub>2</sub> in Fig. 9. It can be seen from the figure that the experimental values fitted excellently well with the values predicted by the correlation well within ±5% deviation.



**Fig. 9** Comparison of experimental values of percentage removal of particulate-laden SO<sub>2</sub> with the values predicted through correlations

assessing the performance of the scrubber as an air pollution control device. Equation 8 can be rearranged to describe the SO<sub>2</sub> penetration through the tapered bubble scrubber as

**Practical applications**

The system presented in this article is under trial in few industrial operations, like plywood manufacturing industry that uses hog fuel, induction furnace operation manufacturing steel ingots, small coal-fired down draft kilns, and ferro-alloys manufacturing industries. Since the system is a tapered one and is gaining pressure, the flue generated from such industrial operations is compatible with the system deployed. These industrial operations use very small

operating furnaces. Small entrepreneurs are engaged in operating such furnaces. As such, the existing dust control devices are very cost intensive to these operators, and as a result, facilities suiting their requirements to meet the emission standards are very much necessary. Studies are being also conducted for application of the present system where the inlet dust concentration remains very high.

## Conclusions

The performance of particulate-laden SO<sub>2</sub> scrubbing in a modified tapered bubble column with internals was reported in this article. Experimental results revealed that the presence of particles improved the SO<sub>2</sub> removal efficiency by about 15% that was elucidated by the facilitated adsorptive mass transport. Results further indicated that almost 100% SO<sub>2</sub> removal efficiency could be achieved using water as scrubbing liquid without any additive under certain hydrodynamic conditions. Experimentation further revealed that the inlet SO<sub>2</sub> concentration did not influence the collection efficiency of particles. On the other hand, experimentations conducted on particulate-laden SO<sub>2</sub> scrubbing revealed that SO<sub>2</sub> removal efficiency was (1) directly varied with the inlet particle concentration and was significantly enhanced due to the presence of particles, (2) independent of the initial concentration of SO<sub>2</sub>, (3) inversely varied with the gas flow rate, and (4) directly varied with liquid flow rate and liquid to gas flow rate ratio. The enhancement of the removal efficiency due to the presence of particles was elucidated by the facilitated adsorptive mass transport. Operating domain of maximum removal efficiency (~100%) of particulate-laden SO<sub>2</sub> was determined from experimental results. Empirical correlation was developed for predicting the scrubbing performance of the modified tapered column in water. Experimental values

fitted excellently well with the values predicted through the correlation (within ±5% deviation).

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## References

- Alper E, Wichtendahl B, Deckwer WD (1980) Gas absorption mechanism in catalytic slurry reactors. *Chem Eng Sci* 35:217–222. doi:10.1016/0009-2509(80)80090-X
- Bandyopadhyay A, Biswas MN (2006) Fly-ash scrubbing in a tapered bubble column scrubber. *Trans IChemE Part B* 84(B1):54–62
- Bandyopadhyay A, Biswas MN (2008) Particulate-laden-SO<sub>2</sub> scrubbing in a tapered bubble column. *Environ Prog.* doi:10.1002/ep.10307
- Indian Standard (1973) Methods for measurement of air pollution, suspended particulates, IS: 5182 (part-IV). Bureau of Indian Standards, New Delhi, India, pp 3–7
- Jackobs MB (1949) The analytical chemistry of industrial poisons, hazards and solvents, vol. I, 2nd edn. Interscience, New York
- Liberti A, Brocco D, Possanzini M (1978) Adsorption and oxidation of SO<sub>2</sub> on particles. *Atmos Environ* 12:255–261. doi:10.1016/0004-6981(78)90205-6
- Quicker G, Alper E, Deckwer WD (1987) Effect of fine activated carbon particles on the rate of CO<sub>2</sub> absorption. *AIChE J* 33:871–875. doi:10.1002/aic.690330523
- Sauer T, Hempel DC (1987) Fluid dynamics and mass transfer in a bubble column with suspended particles. *Chem Eng Technol* 10:180–189. doi:10.1002/ceat.270100123
- Tomany JP (1975) Air pollution: the emissions, the regulations and the standards. American Elsevier, New York
- Vinke H, Hamersma P, Fortuin JMH (1992) The enhancement of the gas-adsorption rate in agitated slurry reactors due to the adhesion of the gas-adsorbing particles to gas bubbles. *Chem Eng Sci* 47:3589–3596. doi:10.1016/0009-2509(92)85074-L