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A NOVEL MODIFIED MULTI-STAGE BUBBLE COLUMN SCRUBBER FOR SO_2 REMOVAL FROM INDUSTRIAL OFF GASES*

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ABSTRACT

The emission of SO_2 from various chemical industries, always occur in association with particulate and most of the time the concentrations of sulfur dioxide in and around these plants overshoot the danger point. In the present investigation, an attempt has been made for wet flue gas de-sulfurization using water as the absorbing medium in a newly designed scrubber. Prediction of SO_2 removal efficiency is very important for selection of a pollution control equipment. The present paper reports on the detailed experimental investigations on the scrubbing of SO_2 in the modified multi-stage bubble column scrubber (MMSBCS) using water.

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Experimental results show that almost 100% removal efficiency of SO_2, can be achieved in the present system. A correlation has been developed for predicting the percentage removal efficiency of sulfur dioxide. Experimental results are in excellent agreement with the correlation.

Key Words: Pollution; Wet scrubber; SO_2; Processes; Absorption; Environment

INTRODUCTION

The emission of sulfur dioxide from various industrial sources always occur in association with particulate matters (fly-ash), in varying composition and quantities. The effects of sulfur dioxide individually are very severe. However, several toxicological/epidemiological investigations during the last few decades have shown that the presence particulate matters synergistically modify the effects of the physiologically active gases and the combined synergistic effects are much more severe and harmful than the simple additive effects of the individual pollutants. This synergism modified effects of particulate laden gases have motivated the public and private sector industries, government agencies, and environmentalists to work out 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 particulate laden sulfur dioxide to a very high degree and the existing pollution control devices either alone or in combination, are not fully satisfactory and/or cost effective to meet the demands of the pollution control regulations. Consequently, in the recent past various investigations have been undertaken for developing equipment and processes, which can meet the demands of technology and increasing stringent environmental regulations. Furthermore, most of the present day sulfur dioxide and particulate control systems have been evolved in response to a particular set of environmental regulations mandating control of a specific pollutant and these systems are generally inflexible and have mostly become less economical to operate with the increasing stringency of old regulations or promulgation of new regulations. Options are also limited in using process modifications and raw material substitutions as the methods of pollution abatement.

Therefore, the abatement of particulate and gases in one single step, seems to be the only viable alternative to achieve techno-economic-feasibility.

The various wet scrubbers used in practice offer a choice between the liquid dispersed and gas dispersed system. According to film theory of mass transfer, gas absorption in liquid, with or without chemical reactions, depends on the gas and liquid side resistance, either alone or in combination. Whenever the principal resistance to gas absorption is concentrated on gas side, a gas dispersed system, i.e., bubble column or packed column is necessary. In addition, 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 22.65 gm per 0.294 MW, which converts to 0.1634 g/nm^3 for an Indian thermal power plant. Calculations show that at least 76% removal of particulate less than 2 μm in size, is essential to meet the stringent standards prescribed by EPA. The existing emission standards for particulate matter in India are higher (0150 g/nm^3) than the proposed World Bank standards of 0.050 nm^{-3}. Furthermore, the World Bank guidelines propose that the particulate removal efficiency should be at least 99.9% if 50 mg/nm^3 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 demanded under the above context.

Bubble columns, where the gas is dispersed through a deep pool of liquid, are particularly suitable for absorption accompanied by very slow chemical reactions. These are multiphase reaction devices, in which a discontinuous gas phase moves in the form of bubbles relative to a continuous liquid phase. Compared to other multiphase contactors, the BCS 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.

It may further be appreciated that a simple bubble column operates in one stage only and cannot achieve high efficiency except for highly soluble gases in chemically reactive systems. In order to achieve high efficiency of mass transfer bubble columns must be operated in series or in multiple stages. In commercially available bubble columns, multiple stage operation has been achieved by the use of perforated multi-orifice plates or multi screens. Thus in such columns, high efficiency can only be achieved with high-energy dissipation and mechanical complications. The efficiency in a normal bubble column is very limited, due to the limitations of specific interfacial area, a, and the individual film mass transfer coefficient, k_L. In addition, large amount of energy is to be spent for generating small bubbles. Thus the mass transfer efficiency of single-stage bubble column cannot be very high.

Literature survey revealed that very few studies have been reported on the absorption of sulfur dioxide in water, using bubble columns of various configurations. Mehta and Sharma[2] investigated the absorption of sulfur dioxide in sodium hydroxide solutions in spray columns of various heights and using various nozzles for the determination of true and volumetric gas side mass transfer coefficients.

Huckaby and Ray[3] reported studies on the absorption of SO_2 into growing or evaporating droplets of water.

Han and Park[4] reported studies on the absorption of a single bubble of SO_2 into pure water. The rate of absorption of a bubble of SO_2 into water was studied by allowing a single bubble to rise through a column of quiescent water of height 300 cm.

Bronikowska and Rudzinski[5] proposed a model for the absorption of SO_2 based on the film theory of gas absorption and the chemical-equilibrium treatment of chemical reactions. The ability of the method to predict rates of absorption, enhancement factor, and concentration profiles of the reagent was successfully demonstrated using the experimental cases of SO_2 absorption selected from literature.

Schmidt and Stichlmair[6] reported experimental investigations in spray scrubbers of different sizes with co-current flow of gas and liquid. This investigation highlighted the mass transfer units obtainable using SO_2 as one of the systems. The effects of the different operating variables and temperature on the mass transfer units were reported.

Bandyopadhyay and Biswas[7,8] developed a spray-cum-bubble column, which operate in both spray and bubble flow regimes. Their experimental results claimed a very high percentage removal of SO_2 (99–99.5%) by alkaline solution of sodium hydroxide.

Meikap et al.[9] developed a horizontal co-current ejector system for scrubbing of SO_2 by using water and alkaline solution. Their experimental results indicate that, SO_2 can be scrubbed from lean gas mixture by water with a removal efficiency exceeding 98.62%. In addition, they reported that 100% removal of SO_2 could be achieved by alkaline solution from rich gas mixtures, by using alkaline scrubber.

Terasaka, Hieda, and Tsuge[10] proposed a theory for SO_2 bubble formation at an orifice submerged in water. Their experimental results reported on the rate of absorption from pure SO_2 gas bubble to water as well as the bubble shape and growth rate.

Critical analysis of the literature revealed that very few studies on the absorption of SO_2 in bubble column have been reported. Even though different wet scrubbers in various types and configurations have been suggested for the absorption of sulfur dioxide by either water or sodium alkalis, their widespread commercial deployment have been few and far between. From a purely theoretical stand point it is expected that bubble breakup and regeneration of the dispersed medium would provide a large surface area in the form of discrete bubbles and that such a surface traveling through the liquid would be ideal for the absorption of soluble gases. In practice, however, simple bubble column have not met with the favor that the existing theory would apparently justify. However, more recently bubble columns are finding increasing favor for air pollution abatement systems for handling both particulate and gases in one single step. In the recent industrial applications the trend appears to be away from complex contactors with mechanical agitation or complex internal components, which may offer high pressure drop and sites for the deposition of solids, in the form of scale, unused reactants, and uncollected fly-ash.

Measurements by laboratory units, mostly made using single bubble of known size, have verified the existence of high absorption rate, under certain operating conditions. The unpredictability of bubble column operation may, therefore, be attributed to the inadequacy of the existing theories in predicting bubble column performance. In addition, most laboratory investigations on absorption of SO_2 in water, have chosen to neglect liquid side resistance while determining the mass transfer coefficient. This is a serious inadequacy, since SO_2 water systems are known to have controlling resistances in both the gas and the liquid sides.[11] On the other hand, the reports from commercial units mainly deal with empirical correlations for predicting SO_2 removal efficiency, without attempting to develop any understanding of the fundamental process of bubble absorption.

In the present investigation, therefore, an attempt has been made to develop a generalized theoretical model, for predicting the performance of a bubble column scrubber with a view to attain definite insight into the process of absorption of SO_2 in water. The proposed model takes into consideration, the concentration distribution of SO_2 and the mixing dynamics of bubble movement. It attempts to predict the removal efficiencies of SO_2 as a function of bubble size and velocities, gas and liquid flow rates, and tower height. In "Development of newly design modified multi-stage bubble column scrubber," an attempt has been made to generate experimental data on the scrubbing of SO_2 in the modified multi-stage bubble column and to develop an empirical overall correlation for predicting its performance.

DEVELOPMENT OF NEWLY DESIGNED MODIFIED MMSBCs

In the present investigation a bubble column, operating in three stages have been designed. The staging effect being achieved through hydro-dynamically induced continuous bubble generation and break-up through bubble rupture and regeneration. The experimental 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, wherein bubbles are generated at relatively high velocities. At the end of the first stage, bubbles have been ruptured and coalesced by imposing a flow disturbance using a single orifice in the form of a hollow disk with a central axial opening. The gas-in-liquid dispersion passing through the orifice is subjected to dynamic instabilities in the form flow expansion followed by flow contraction. The flow expansion after stage 1, has been achieved by positioning a relatively large diameter hollow disk above the first orifice and contraction of the two-phase dispersion has been achieved by using a hollow disk with a smaller sized central axial opening, positioned above this expansion disk. The column section consisting of a horizontal disk with relatively large central axial opening (expansion disks) positioned between two horizontal disks of relatively smaller diameter central axial opening (contraction disks) comprises of one stage. At the end of each stage, bubbles loose their individual identities and new bubbles are generated at the beginning of each stage.

Thus in stage 1 of the column, bubbles were generated in the size range of 3–6 mm, using an unique multi-orifice antenna type of sparger. The sparger design was tailored to give identical velocities through individual orifices, to insure uniform generation of relatively large bubbles. At the end of this stage, the bubbles are forced to deform and collapse in response to a sudden flow disturbance imposed on the flow field, by constricting the flow cross-sectional area by using a hollow disk, which has a central axial opening of about 25% of the original column diameter. Because of the high nozzle velocity maintained at the sparger orifices in stage 1, the bubbles rise almost vertically up to the lower surface of the disk. The sparger distributed the bubbles uniformly over the entire cross section of the column. Because of the construction of the sparger and due to the high gas velocities maintained at the sparger orifices, the bubbles rise almost vertically in this section without bubble pairing or bubble coalescence, then tend to move radically towards the central axial opening. Migration of the bubbles towards this opening leads to bubble crowding, direct impaction, impingement, and bubble coalescence. As the constricted passage gets choked with bubbles trying to move upwards, all the bubbles collapse into a few large bubbles at the lower surface of the disk. Vigorous bubble collapse creates very turbulent churning action at the disk opening. However, on passing through this disk opening the superficial gas velocity increases to sixteen times the original empty column superficial velocity—a velocity which leads to the breakup of the larger bubbles through fluid shear. In addition, in this stage a flow expansion disk (guide disk) of relatively large diameter (50% of the column diameter) is positioned above the small diameter disk, to prevent bubble migration to the wall of the column and to insure axial movement of the bubble swarms. Further, this increase in flow area reduces the forward velocity of the bubbles and this leads to stretching of the bubble surface without coalescence. As the dispersion moves upward through the guide disks, the bubbles surface is subjected to contraction in response to the reduction in flow area due to the presence of the small diameter rupture disk, positioned above and equidistant from the guide disc. Flow through this disk again creates bubble crowding, coalescence, and bubble regeneration as described earlier. The diameter and other proportions of the column viz. position of the rupture and guide disks, the distance between them, etc., were arrived at through carefully controlled initial experiments.

EXPERIMENTAL SETUP AND TECHNIQUES

Figure 1 shows the schematic diagram of the experimental setup. Provision was made to feed the air–SO_2 mixture at the base of the cylindrical vertical column (0.1905 m ID) so that the effect of the flow pattern changes due to the contraction and expansion disks can be studied. The vertical cylindrical column was fitted with a total of five hollow disks of different openings.

The air–SO_2 mixture, in composition similar to that existing in the exhaust of a coal fired thermal power plant using coal with 0.5% sulfur content, was generated by mixing air and SO_2 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 SO_2 from the SO_2 gas cylinder [GC]. The ejector was mounted with a downward slope of 30° with the air nozzle perfectly aligned along the axis of the ejector throat to ensure an axially symmetrical jet. 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, which was 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 and regulated by a valve (V_4). Simultaneously the SO_2 was routed at a controlled rate through SO_2 gas regulator and into the ejector. The air and SO_2 gas mixed intensely in the mixing throat of the ejector and the mixture was fed into the sparger fitted at the bottom of the vertical column.

In the actual experiment, water was continuously fed at the top of the column and withdrawn at the bottom at such a rate that, a particular liquid height and bubble volume can be maintained in the column. In order to collect representative samples, SO_2 gas samples were withdrawn at an approximately iso-kinetic rate. Samples at points S_1 and S_2 were drawn at the rate of $1–2 \times 10^{-3}\,nm^3$/min to match the experimental gas flow rate and the conditions of iso-kinetic sampling. The SO_2 absorption experiments were conducted at gas flow rates of $1.20–5.46 \times 10^{-3}\,nm^3$/sec and a liquid flow rate of $34.48–175 \times 10^{-6}\,m^3$/sec. Under steady state operating conditions the SO_2 gas samples were collected at source points S_1 and S_2 with the help of midget impingers (IB) and aspirator bottles. The gas samples were analyzed for sulfur dioxide by the "Tetrachloro Mercurate Method" (IS: 5182 (Part-VI)[12]). The method consisted

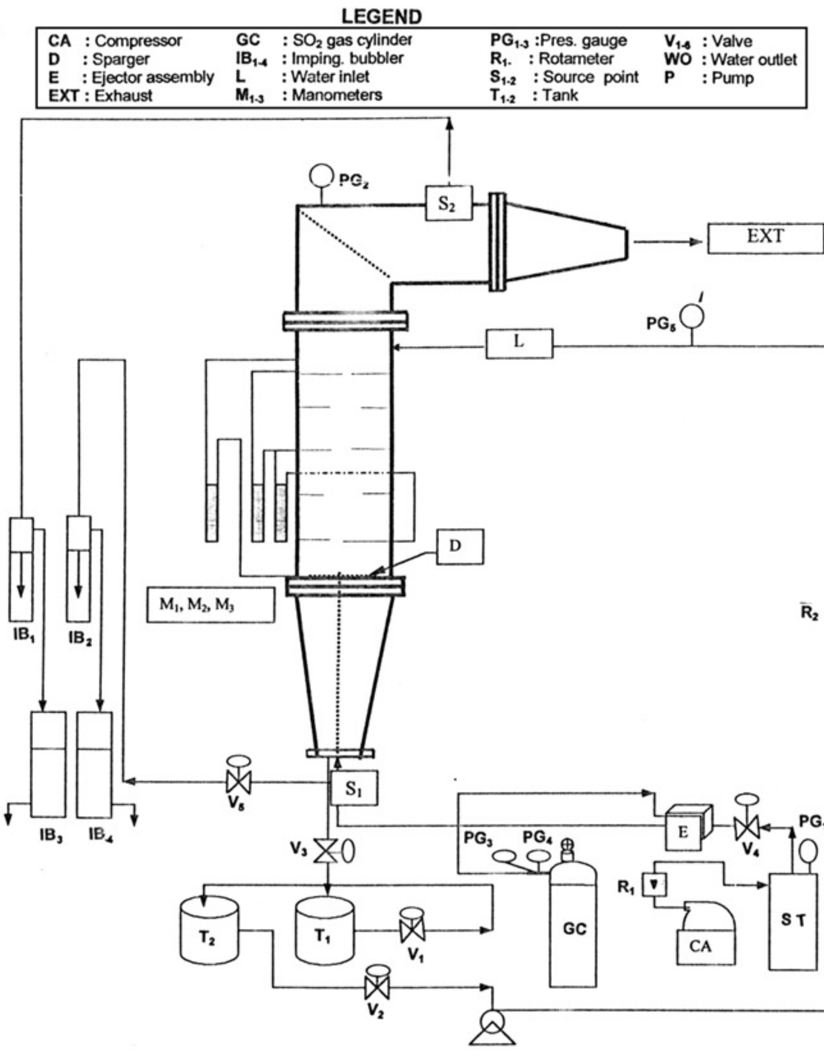

Figure 1. Schematic diagram of the experimental set-up for the scrubbing of SO_2 in water in a MMSBCS.

of passing a portion of the air sampled, through a solution of absorbing medium (sodium tetra-chloro mercurate) and analyzing the resulting solution spectrophotometrically (UV-visible recording spectrophotometer, Model No. UV-2100, Shimadzu, Japan).

When SO_2 from the air stream was absorbed in a sodium tetra-chloro-mercurate solution, it formed a stable di-chloro-sulphito-mercurate complex. The amount of SO_2 was then estimated by the color produced when *p*-rosaniline hydrochloride was added to the solution. The color was estimated by using a spectrophotometer for which a calibration curve (Fig. 2) was already prepared. The amount of sulfur dioxide in air sample was obtained from the differences in spectrophotometric values of the blank and test samples and reported in ppm, using the calibration curve. The measurement has been reported to the nearest 0.005 ppm at concentration below 0.15 ppm and to the nearest 0.01 ppm for concentrations above 0.15 ppm.

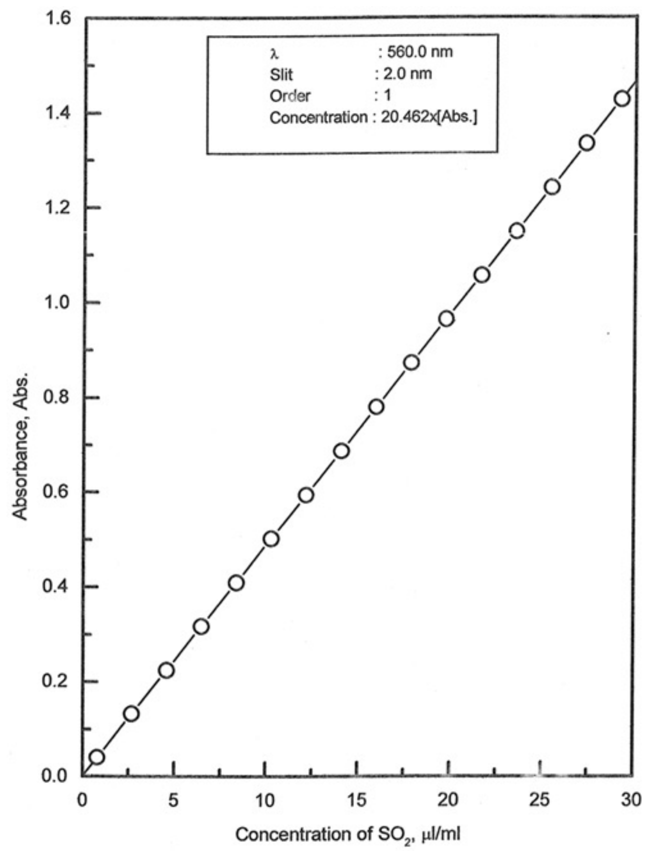

Figure 2. Calibration curve for SO_2 of UV spectrophotometer at slit = 2.0 nm, $\lambda =$ 560.0 nm.

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

RESULTS AND DISCUSSIONS

Experiments have been conducted by setting the sparger to a condition to generate 2–5 mm range of bubble SMDs (by visual observation), with liquid flow rate of 34.48×10^{-6}, 68.95×10^{-6}, 103.44×10^{-6}, 137.9×10^{-6}, 172.4×10^{-6}, and $206.9 \times 10^{-6}\,m^3$/sec. Corresponding to each liquid flow rate, gas flow rates of 3.031×10^{-3}, 3.640×10^{-3}, 4.248×10^{-3}, 4.856×10^{-3}, 5.462×10^{-3}, and $6.062 \times 10^{-3}\,nm^3$/sec have been used. For each liquid flow rate the inlet SO_2 loadings were varied from 600 to 1500 ppm in five stages, e.g., 600, 800, 1000, 1200, and 1500 ppm.

Percentage removal of SO_2 have been calculated for each experimental run by the formula,

$$\eta_{SO_2} = \frac{C_{SO_2,i} - C_{SO_2,o}}{C_{SO_2,i}} \times 100 \tag{1}$$

The trend of the variation of percentage removal have been plotted in Figs. 3–7 for the various inlet loading of SO_2, and for the various operating and flow variables of the bubble column scrubber. The trend of variation of SO_2 removal have also been plotted in the figure along the height of the scrubber.

Effect of Gas Flow Rate and SO_2 Loading on the Percentage Removal of SO_2

The percentage removal efficiency of SO_2 (η_{SO_2}) at different inlet SO_2 loading and for a constant height of the bubble column scrubber, have been plotted against gas flow rates in Fig. 3. It can be seen from the figure that the percentage removal of SO_2 in the MMSBCS is very high, due to the continuous bursting, reformation, and regeneration of bubbles along the vertical height of the column. Very high values of fractional gas holdup, specific interfacial are, etc., as reported by Meikap,[13] supports these high values. The percentage removal also increases very slightly with the increase in the gas flow rate, for constant liquid flow rates. The increase in the percentage removal of SO_2, with the increase in gas flow rate results from the increased turbulence in the gas phase and higher relative velocity of the gas–liquid interface. It is also interesting to note that

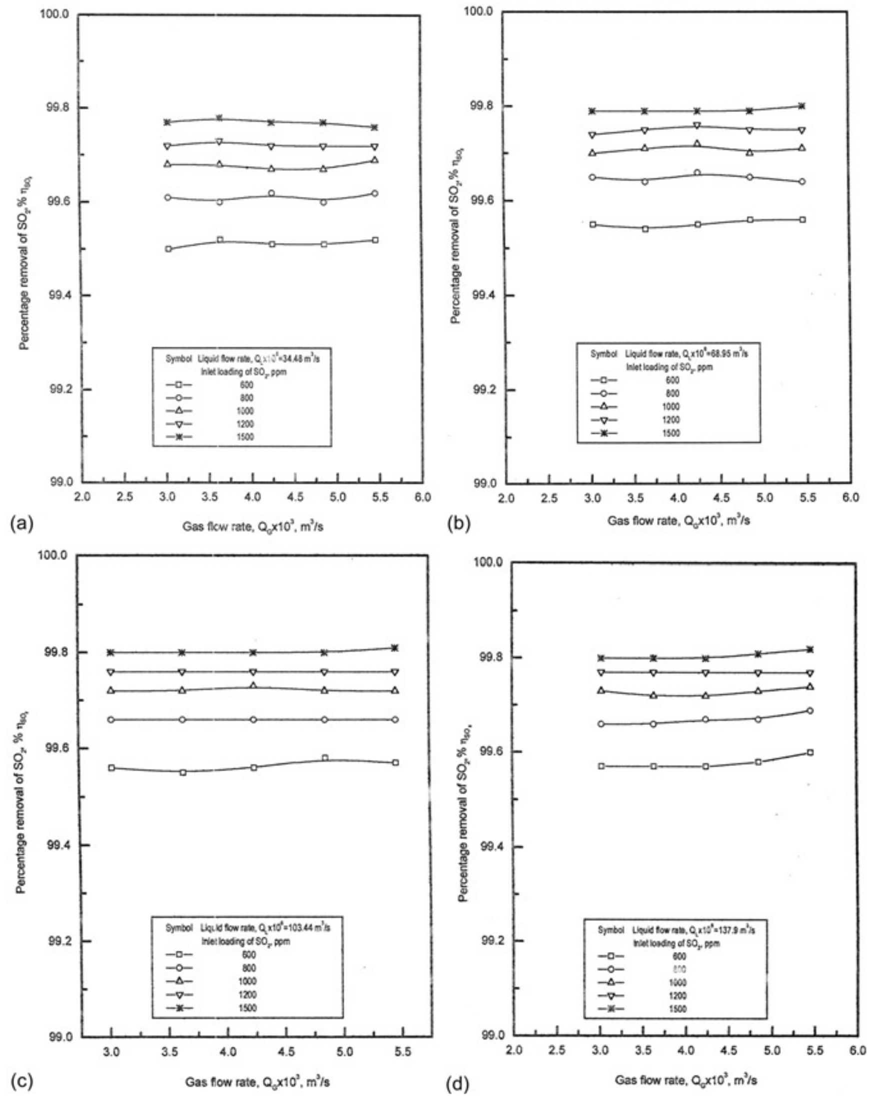

Figure 3. (a) Effect of gas flow rate on the percentage removal of SO_2 for SO_2 scrubbing at various inlet SO_2 loading, $C_{SO_2,i} = 600$, 800, 1000, 1200, 1500 ppm, and liquid flow rate, $Q_L = 34.48 \times 10^{-6}\ m^3/sec$. (b) Effect of gas flow rate on the percentage removal of SO_2 for SO_2 scrubbing at various inlet SO_2 loading, $C_{SO_2,i} = 600$, 800, 1000, 1200, 1500 ppm, and liquid flow rate, $Q_L = 103.44 \times 10^{-6}\ m^3/sec$. (c) Effect of gas flow rate on the percentage removal of SO_2 for SO_2 scrubbing at various inlet SO_2 loading, $C_{SO_2,i} = 600$, 800, 1000, 1200, 1500 ppm, and liquid flow rate, $Q_L = 137.9 \times 10^{-6}\ m^3/sec$. (d) Effect of gas flow rate on the percentage removal of SO_2 for SO_2 scrubbing at various inlet SO_2 loading, $C_{SO_2,i} =$ 600, 800, 1000, 1200, 1500 ppm, and liquid flow rate, $Q_L = 206.9 \times 10^{-6}\ m^3/sec$.

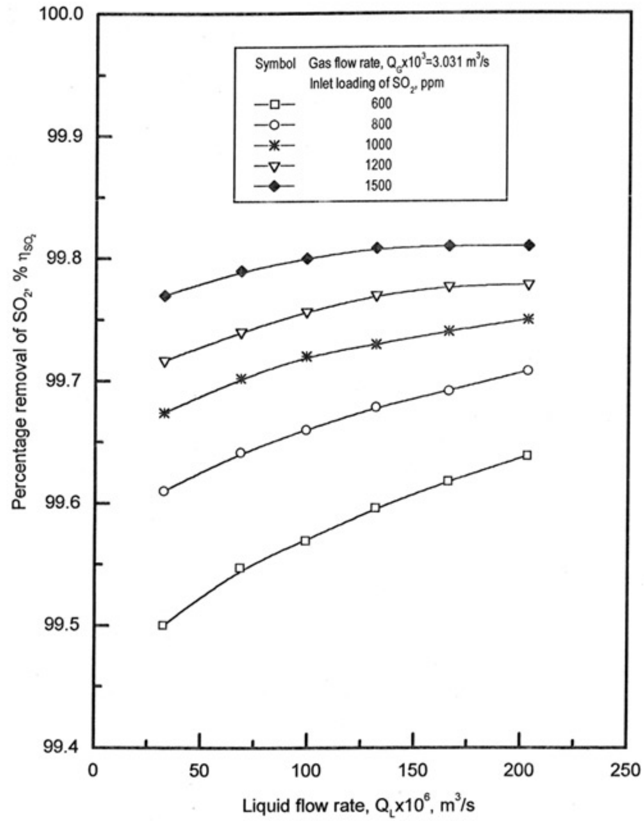

Figure 4. Effect of liquid flow rate on percentage removal of SO_2 at constant gas flow rate, $Q_G = 3.031 \times 10^{-3}\ m^3/sec$, and for various inlet SO_2 loading. $C_{SO_2-FA,i} = 600, 800, 1000, 1200, 1500$ ppm.

beyond a certain value of gas flow rate, e.g., $Q_G = 4.25 \times 10^{-3}\ nm^3/sec$, the percentage removal of SO_2, remains almost constant (Fig. 2(d)).

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, η_{SO_2}, has been presented in a typical plot (Fig. 4) at various inlet SO_2 concentrations, and for constant gas flow rates. It can be seen from the figures that percentage removal of SO_2, η_{SO_2}, increases as the liquid flow rate is increased. In the present

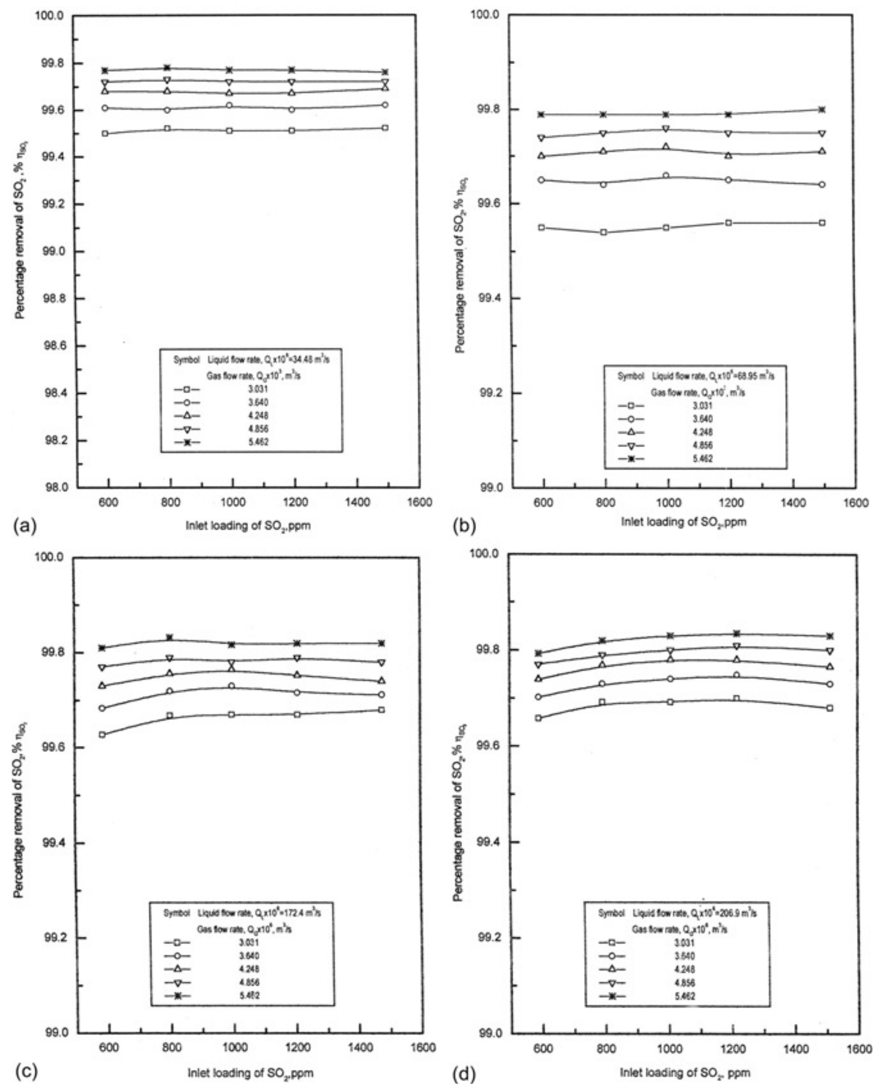

Figure 5. (a) Effect of gas flow rate on percentage removal of SO_2, at constant liquid flow rate, $Q_L = 34.48 \times 10^{-6} m^3/sec$, and for various inlet SO_2 loading. (b) Effect of gas flow rate on percentage removal of SO_2, at constant liquid flow rate, $Q_L = 103.44 \times 10^{-6}\, m^3/sec$, and for various inlet SO_2 loading. (c) Effect of gas flow rate on percentage removal of SO_2, at constant liquid flow rate, $Q_L = 172.4 \times 10^{-6}\, m^3/sec$, and for various inlet SO_2 loading. (d) Effect of gas flow rate on percentage removal of SO_2, at constant liquid flow rate, $Q_L = 206.9 \times 10^{-6}\, m^3/sec$, and for various inlet SO_2 loading.

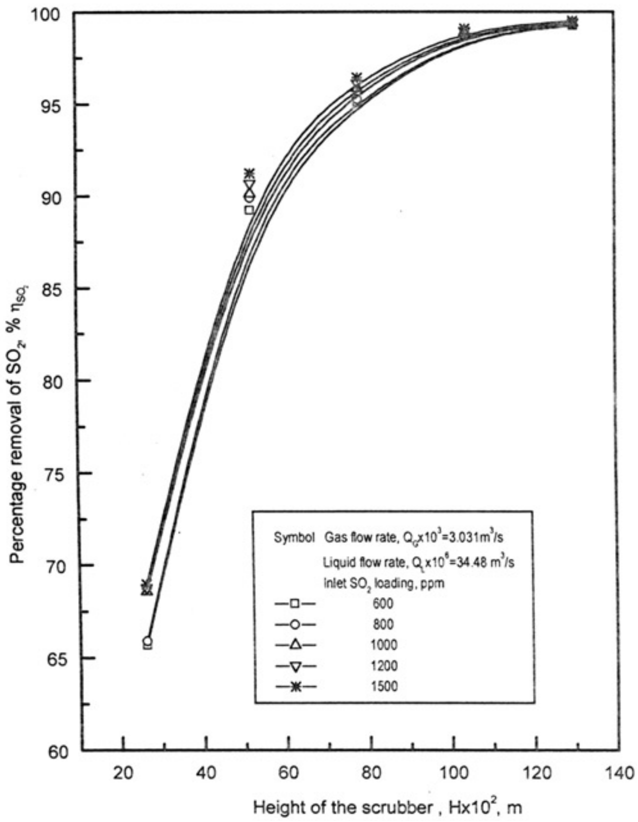

Figure 6. Effect of scrubber height on the percentage removal SO_2 loading at various inlet SO_2 loading for SO_2−water system.

investigation, as the liquid flow rate is increased the bubble-water interfacial contact area increases.[13] As a result of this, the percentage removal increases with increase in liquid flow rate. In addition, the faster removal of materials from the bubble surface by the downward flowing liquid also helps in the enhancement of SO_2 removal. Thus, increasing liquid flow rate may not increase the total number of bubbles but affect positively the efficiency of individual bubbles, as long sufficient 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/sec the percentage removal almost reaches 99.8% at a gas flow rate of 3.031×10^{-3} nm^3/sec and at inlet SO_2 loading of 1500 ppm. Furthermore, the higher the inlet SO_2 loading the higher is the efficiency (Fig. 5). This may be attributed to the fact that low inlet loading

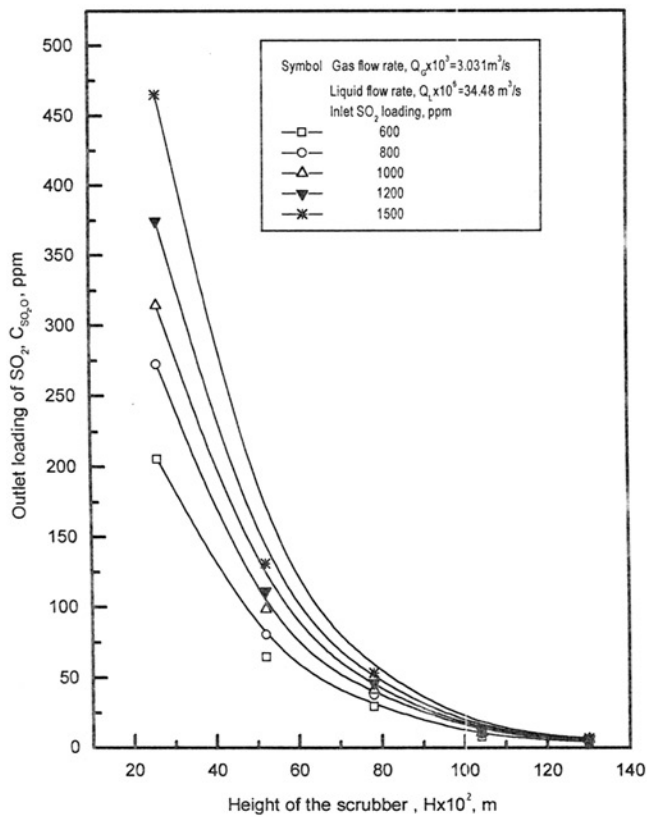

Figure 7. Effect of scrubber height on the outlet concentration of SO_2 at various inlet SO_2 loading.

hinders SO_2 collection in bubble column due to lower molecule–molecule interaction (kinetic theory of gas). Increased loading increases SO_2 molecule–molecule interactions which contribute positively to the removal of SO_2.

Effect of Scrubber Height on Percentage Removal of SO_2

Figure 6 is a typical plot of percentage removal of SO_2 η_{SO_2} vs. height of the scrubber for a constant gas and liquid flow rate. It may be seen from this figure that for a constant inlet loading of SO_2, the percentage removal of SO_2, η_{SO_2}, increases exponentially with the increase in height of the scrubber. In the present case, bubble breakup, reformation, and re-generation takes place along the height of the reactor due to the presence of the contraction and expansion disks. The initial increase in η_{SO_2}, with the increase in height of the scrubber, is due to the continuous breakup of bubbles and regeneration of the bubble surface area in the different sections of the bubble column. However, once the SO_2 concentration reduces to near equilibrium values, further creation of new surface area does not lead to any further increase in the percentage removal.

Similar plots were obtained at different inlet loading of SO_2 and it may be seen from these figures that at a constant height of the scrubber, the percentage removal of SO_2, η_{SO_2}, increases with the increase in the inlet SO_2 loading (Fig. 5). As discussed earlier this may be attributed to the fact that low inlet loading hinders SO_2 molecule–molecule interaction while increased SO_2 loading increases molecule–molecule interactions which contribute positively to the removal of SO_2.

Figure 7 is a typical plot of the outlet loading of SO_2 vs. the height of the scrubber, at constant liquid and gas flow rates, for the different inlet SO_2 loading. It is seen from this figure that the outlet loading of SO_2 decreases exponentially as the height of the scrubber increases. It has also been seen that the outlet SO_2 loading becomes constant after an expanded scrubber height of 1.30 m. Furthermore, similar plots were obtained at different inlet SO_2 loading and it may be seen from these figure that higher values of outlet loading of SO_2 are obtained with higher values of inlet SO_2 loading at constant height of scrubber.

COMPARISON OF PERFORMANCE OF PRESENT SYSTEM WITH COMMERCIAL SCRUBBERS

The detailed hydrodynamic studies for interfacial area of contact, mass transfer coefficient, energy dissipation, etc., have been carried out and reported elsewhere.[13,14] The performance of the present system to that of commercial scrubbers is presented in Table 1. The number of mass transfer unit (N_{OG}) for wet scrubbers is an important parameter. The N_{OG} has been calculated[15] for the present system and found to be varied from 7 to 9 transfer unit in comparison to commercial limestone scrubber which lie between 4 and 8 unit.

EMPIRICAL CORRELATION FOR THE PREDICTION OF THE PERCENTAGE REMOVAL OF SO_2

In the light of the inadequacy of the existing literature and complex characteristics of the MMSBCS, an attempt has been made to develop a correlation, by dimensional analysis, in order to predict the SO_2 collection efficiencies from the directly measurable parameters.

Table 1. Comparison of Interfacial Area of Contact for Various Gas–Liquid Contacting Equipment with Present System

Contacting Equipment	Gas Velocity V_g (m/sec)	Specific Surface Area, a (m^2/m^3)	Mass Transfer Coefficient k_La (sec^{-1})	Power Consumption E (W/m^3 of Gas–Liquid Mixture)
Plate column	0.60	100–400	0.01–0.05	1300
Packed column	0.90	200	0.005–0.02	—
Wetted wall column	2.10	50	—	—
Gas bubble column	0.02	70	0.005–0.01	400
Stirred bubble absorber	0.06	200	0.02–0.2	2600
Spray column	—	10–100	0.007–0.015	—
Jet(loop)	—	1000–7000	0.01–2.2	10–700
Modified multi-stage bubble column	0.11–0.2	250–600	0.13–0.24	200–450

The conceivable variables on which could possibly affect the collection efficiency of SO_2, η_{SO_2} are as follows.

(i) Flow properties—gas velocity (V_g), liquid velocity (V_L).
(ii) Geometrical properties—column diameter (D_C), height of the scrubber (H), hole diameters of the contraction and expansion disks ($D_H = f(D_C)$), diameters of the sparger orifice (d_O).
(iii) Physical properties—namely the liquid density (ρ_l), gas density (ρ_g), gas viscosity (μ_g), liquid viscosity (μ_l), inlet SO_2 loading (C_{SO_2},i), gravitational acceleration (g), surface tension (σ_l), and dispersion coefficient (D_L).

Therefore, if a theoretical relation exists between the collection efficiency of SO_2, η_{SO_2}, and the characteristic physical, geometrical, and flow variables of the system, then η_{SO_2} may be written in the following form:

$$\eta_{SO_2} = f(d_O, D_C, V_g, V_L, \rho_g, \rho_l, \mu_g, \mu_l, \sigma_l, D_L, D_H, D_C, H, C_{SO_2,i}) \quad (2)$$

In the present experiments due to the presence of the contraction and expansion disks, the percentage sulfur dioxide removal, η_{SO_2}, became a function of height, H and sparger orifice diameter, d_o remains constant.

The variables in Eq. (2) can be grouped into dimensionless numbers by employing Buckingham's theorem and the percentage SO_2 removal may be simplified to

$$\eta_{SO_2} = f[L_P]^a[Re_G]^b[Sc]^c[H\ D_c]^d \tag{3}$$

In order to establish the functional relationship between percentage removal of SO_2, η_{SO_2}, and the various dimensionless groups in Eq. (3), multiple linear regression analysis has been used to evaluate the constant and coefficients of the equation.

It can be seen that the following Eq. (4), which yield the minimum percentage error and minimum standard deviation of percentage error, present the best possible correlation among the family of equations mentioned in Table 1.

$$\eta_{SO_2} = \mathrm{Exp}[L_P]^{0.16}[Re_G]^{0.095}[Sc]^{0.77}[H_R]^{-3.36} \tag{4}$$

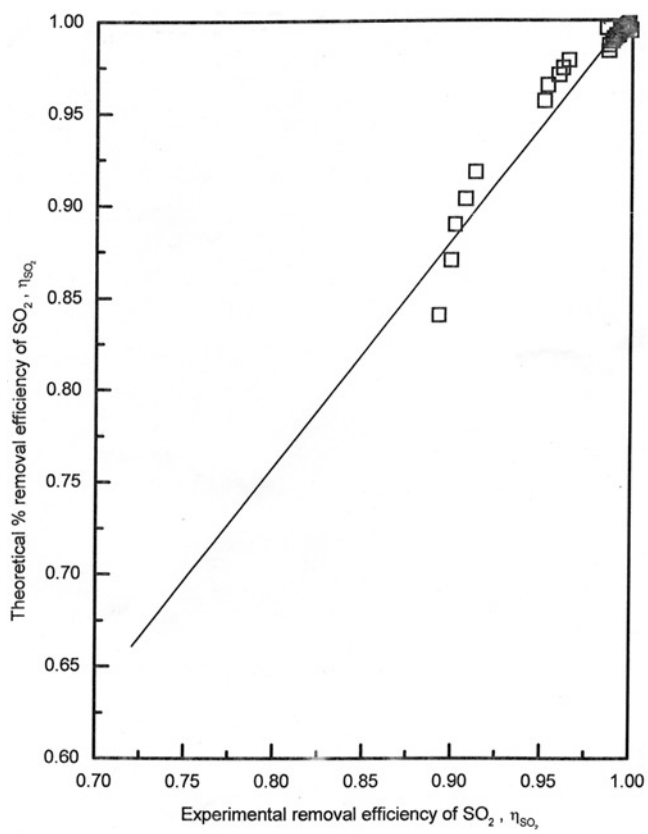

Figure 8. Comparison of experimental percentage removal efficiency of SO_2 with correlated values.

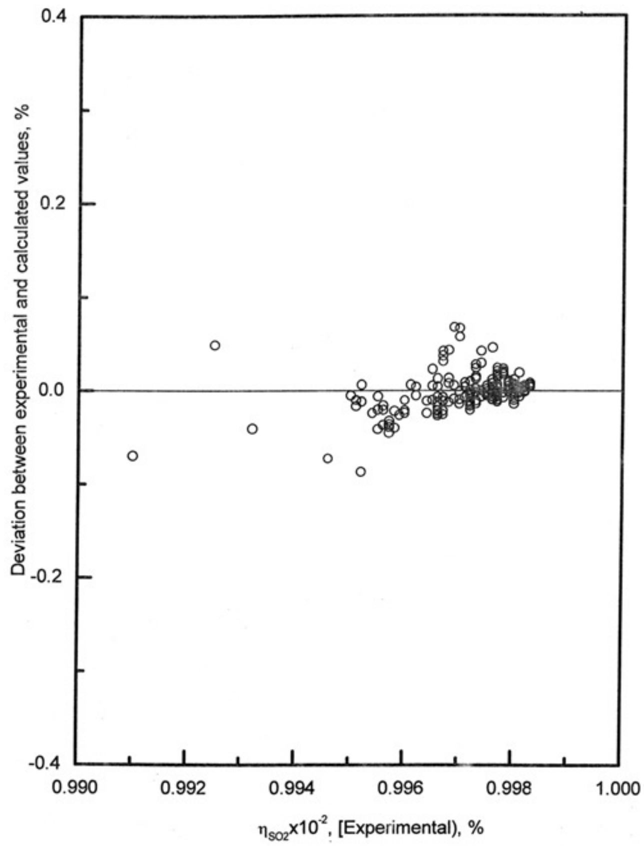

Figure 9. Deviation between calculated and experimental values for water scrubbing of SO_2.

Equation (4) describes the percentage removal of SO_2 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 yield the penetration of SO_2, as

$$q = 1 - \eta_{SO_2} = 1 - \mathrm{Exp}[L_P]^{0.16}[\mathrm{Re_G}]^{0.095}[\mathrm{Sc}]^{0.77}[H_R]^{-3.36} \quad (5)$$

Equation (5) actually describes the SO_2 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 SO_2, η_{SO_2}, predicted by Eq. (4) are plotted against the experimental values of percentage removal of SO_2, η_{SO_2} in Fig. 8. The percentage deviation between the experimental data and those predicted by Eq. (4) are plotted in Fig. 9. 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, which shows the correlation is highly significant at 99.6% confidence level.

CONCLUSIONS

This article dealt with the detailed studies on the scrubbing of SO_2 in water. Experimental investigation shows that, a very high percentage removal of SO_2 can be achieved from air–SO_2 mixture in the modified multi-stage bubble column. These high efficiencies can be predicted by the theoretical equation. For modified multi-stage bubble column, the experimental results show clearly the staging effect, which leads to almost 100% removal efficiency. Individual stage efficiencies determined by assuming multi-stage operation ranges between 80 and 85% in the modified multi-stage bubble column.

Furthermore, a correlation has been developed for predicting the percentage collection efficiency of sulfur dioxide in the modified multi-stage bubble column. Experimental results are in excellent agreement with the correlation, which is found to be statistically sound.

NOMENCLATURE

BCS	bubble column scrubber
$C_{SO_2,i}$	inlet concentration of sulfur dioxide (ppm)
$C_{SO_2,o}$	outlet concentration of sulfur dioxide (ppm)
D_C	diameter of bubble column (m)
D_H	diameter of expansion, contraction disks (m)
D_L	dispersion coefficient, liquid phase (m^2/sec)
d_o	orifice diameter (m)
f	functions of variables
g	acceleration due to gravity (m/sec^2)
H	height of the bubble column (m)
H_e	Henry's law constant (cm^3 atm/gmole)
H_R	height to diameter ratio of the bubble column, dimensionless
L_P	liquid property group $[\pi g D_C \rho_l \mathrm{He} \sigma_l]/[4 Q_L \mu_l]$, dimensionless
MMBCS	modified multi-stage bubble column scrubber

P	pressure (N/m^2)
q	penetration of SO_2 weight fraction
Q_G	volumetric flow rate of gas (nm^3/sec)
Q_L	volumetric flow rate of liquid (m^3/sec)
R	gas constant (N m/Kmol 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	Schimdt number based on SO_2 concentration, ($Sc = DC_{SO_2},i/\mu_l$), dimensionless
V	operating scrubber volume (m^3)
V_g	gas velocity (m/sec)
V_L	liquid velocity (m/sec)
V_T	total system volume (m^3)
q	which penetrates into the exhaust, ($q = 1 - \eta_T$), dimensionless

Greek Letters

ρ_g	gas density (Kg/m^3)
μ_g	gas viscosity (Kg/m/sec)
ρ_l	liquid density (Kg/m^3)
μ_l	liquid viscosity (Kg/m/sec)
η_{SO_2}	removal efficiency of sulfur dioxide, from SO_2–air mixture

Subscripts

$-$	anion
$+$	cation
cal	calculated
exp	experimental
SO_2	sulfur dioxide
$SO_{2,i}$	inlet concentration of SO_2
$SO_{2,o}$	outlet concentration of SO_2

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