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Critical flow atomizer in SO_2 spray scrubbing

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Abstract

Owing to its various deleterious effects, abatement of SO_2 from point sources assumes significant importance over the years. Spray towers offer great advantages over other gas cleaning devices. The performance of a counter-current spray tower for SO_2 scrubbing using water and dilute NaOH deploying an energy efficient critical flow atomizer is reported. The atomizer is capable of generating finer drops at very high velocity with high degree of spray uniformity. Preliminary hydrodynamic studies indicated that droplet diameter and velocity were strongly dependent on atomizing air pressure and liquid flow rate. Experimentation revealed that SO_2 removal efficiency increased with the increase in liquid flow rate, liquid-to-gas flow rate ratio, atomizing air pressure, droplet velocity and pH of the scrubbing liquor while it decreased with the increase in droplet diameter and gas flow rate. Inlet SO_2 concentration, however, has no noticeable effect on the removal efficiency. Very encouraging results were obtained for removal efficiency (~100%) and critical design parameters. Results also indicated that the present system is energy wise and efficiency wise much better than the existing systems. Empirical and semi-empirical correlations were developed for predicting the scrubbing performances as a function of pertinent variables studied in water and alkali, respectively. The water scrubbing efficiency and the mass transfer enhancement factor were combined while predicting the performance in alkaline scrubbing. The predicted values fitted excellently well with the experimental values. That the enhancement factor of mass transfer in alkaline scrubbing could never be expected to increase indefinitely with the concentration ratio of alkali to SO_2 at the interface is a striking feature of this study verified by experimentation. This finding does not seem to be detailed in the available literature of gas–liquid mass transfer as well as gas scrubbing. Determination of sizing parameters is also described for the purpose of designing.

Keywords: Spray tower (scrubber); Two-phase critical flow atomizer; Air pollution control; SO_2 scrubbing

1. Introduction

Abatement of SO_2 assumes significant importance due to its deleterious effects on living systems. Legion of SO_2 scrubbing technologies have been evolved from the requirements of a number of industries stemming from their definite process and regulatory mandates. Scrubbing of SO_2 is common in petroleum industry, power generation, incineration, pulp and paper, metallurgical installations so on and forth. Each of these processes has specific scrubbing need. Amongst various wet scrubbers studied so far for SO_2 scrubbing, literature [1] revealed that wet scrubbers with column internals were replaced with spray towers especially due to its ability to treat large volume of gas in addition to its other advantages like offering least pressure drop (compared to any other gas–liquid contacting devices) and no scaling problem.

Information available in the literature in the last decade is sparse on the subject although a flurry of research was undertaken over the past few decades. Some of the studies that were undertaken in the recent past are briefly highlighted here. Schmidt and Stichlmair [2] reported on the modeling of SO_2 absorption in co-current spray scrubbers using NaOH as one of the reagents for studying the effects of the different operating variables on the number of transfer units (NTU) for the purpose of designing. Experimental values were well predicted through the model developed. Brogren and Hans [3] developed a model based on the penetration theory to calculate the dynamic absorption rate of SO_2 into a droplet of limestone slurry. The model includes both instantaneous equilibrium reactions and reactions with finite rates; limestone dissolution, sulfite oxidation, gypsum crystallization and the hydrolysis reaction of CO_2. The model elucidated various facets of reactive mass transfer; importantly,

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Nomenclature

C''	initial NaOH concentration (kg/m^3)
$C_{SO_2,i}$	inlet SO_2 concentration (ppm)
$C_{SO_2,int}$	interfacial SO_2 concentration (kmol/m^3)
$C_{SO_2,o}$	outlet SO_2 concentration (ppm)
d_i	droplet diameter in the i-th group (m)
D	diffusivity of SO_2 in air (m^2/s)
D'	diffusivity of SO_2 in water (m^2/s)
D''	diffusivity of NaOH in water (m^2/s)
D_C	diameter of the spray tower (m)
D_d	droplet Sauter mean diameter (SMD) (m)
D_i	dispersion number $\{D/(v_L H_T)\}$, dimensionless
f	functions of variables, dimensionless
F_i	number of droplets in the i-th group, dimensionless
H_T	height of spray tower (m)
H_α	thermodynamic equilibrium solubility constant (kmol/m^3 s atm)
i	mole ratio of SO_2 to NaOH, dimensionless
N_d	number of droplets generated (homogeneous flow) (s^{-1})
ppm	parts per million (v/v), dimensionless
P_a	atomizing air pressure (absolute) (N/m^2)
P_{SO_2}	partial pressure of SO_2 (atm)
Q_G	gas flow rate (m^3/s)
Q_L	liquid flow rate (m^3/s)
Re_D	modified droplet Reynold's number $(D_d v_d \rho_L/\mu_L)$, dimensionless
S	single droplet surface area (m^2)
S_T	total droplet surface area generated (homogeneous flow) (m^2/s)
Sc	modified Schmidt number $\{\mu_g/(D' C_{SO_2,i})\}$, dimensionless
T	Temperature (K)
v_d	droplet velocity (m/s)
v_g	superficial gas velocity to the spray tower (m/s)
V_{Gi}	inlet gas velocity to the nozzle (m/s)
V_{Li}	inlet liquid velocity to the nozzle (m/s)
v_L	superficial liquid velocity to the spray tower (m/s)
We_D	droplet Weber number $[\rho_g(V_{Gi}-V_{Li})^2 D_d/\sigma_L]$, dimensionless

Greek letters

η	removal efficiency of SO_2, percentage
η_C	removal efficiency of SO_2 in alkaline scrubbing, percentage
η_{SO2}	removal efficiency of SO_2 in water scrubbing, percentage
ϕ	mass transfer enhancement factor dimensionless
μ_g	viscosity of gas (kg/m s)
μ_L	viscosity of liquid (kg/m s)
ρ_g	gas density (kg/m^3)
ρ_L	liquid density (kg/m^3)
σ_L	liquid surface tension (N/m)

it was used to quantify the mass transfer within a spray scrubber and to estimate the impact of the reactions with finite rate of the SO_2 absorption. Pettersson et al. [4] developed a simplified model for a wet flue gas cleaning system that was verified with a SO_2 spray scrubber at I/S Faelles Forbraending's waste incinerator plant in Hobro, Denmark. SO_2 removal efficiency of around 90% was achieved using 2.5–20 kmol/m^3 NaOH as the scrubbing liquor for inlet SO_2 concentration varied from 100 to 500 ppm. Experimentation and theoretical analysis revealed that the initial SO_2 concentration did not influence the removal efficiency. Chen [5,6] theoretically investigated on the unsteady absorption of SO_2 by single atmospheric water droplet in motion and the dynamics of SO_2 absorption in a raindrop falling at terminal velocity. Hay et al. [7] reported on the various operating features on an once through caustic spray scrubber treating the acid plant tail gas containing ∼500 ppm SO_2 of the Port Kembla Copper (PKC) smelter in Australia. A very high removal efficiency of about 95%+ was achieved at a pH of 11. Limestone/gypsum wet flue gas desulfurization (WFGD) process was reported [8] for controlling SO_2 emissions from coal-fired power plants achieving very high removal efficiencies of SO_2, SO_3 and particulate matter. Huang [9] reported a novel theoretical model to determine the SO_2 removal efficiency using fine water spray. The performance of the system was shown to generally improve by reducing the droplet diameter or the initial S(IV) concentration, or by increasing the inlet SO_2 concentration, the droplet pH or the liquid-to-gas flow rate ratio. In one of our previous studies reported [10] on the performance of a spray-cum-bubble column for SO_2 removal using water and dilute NaOH solution indicated very high removal efficiency. The prediction of removal efficiency of SO_2 was made using experimental data as a function of gas–liquid flow rates and other physico-chemical properties of the system. The behavior of a hybrid scrubber dealing with a spray system, as one of the two stages studied, was reported and compared were the stage-wise removal efficiencies. The performance was, however, not reported in detail characterizing the parameters governing the process of atomization.

Critical analysis of the available literature revealed that the spray tower has been used for scrubbing of SO_2 by either water or alkalis but the performance reported so far seldom takes into account the detailed studies on the droplet size and droplet velocity in tandem augmented with the atomizing air pressure as also the liquid flow rate that are essentially desired for the operation of the spray tower. On the other hand, characterization of the spray tower during the prediction of the performance in alkali scrubbing by combining the mass transfer enhancement factor with the performance in water scrubbing does not seem to be detailed in the available literature. An attempt has been made in this article to report on the performance of a counter-current spray tower for SO_2 scrubbing using water and dilute NaOH deploying an energy efficient critical flow atomizer [11] that is capable of producing finer droplets at very high relative velocity without sacrificing the spray uniformity. Attempts have also been made to develop empirical and semi-empirical correlations with the help of the experimental data that would take into account the various hydro-dynamic parameters including the atomizing parameters and the mass transfer enhancement factor for predicting the performance of the spray tower in water and in alkali scrubbing respectively.

2. Development of critical flow atomizer

Central to any spray operation, is the atomization or the disintegration of the liquid stream into droplets or sprays. For spray scrubbing, a good atomizer should produce a fairly uniform spray with drop diameters small enough to generate large interfacial area of contact at the same time large enough to prevent excessive entrainment. Uniformity of spray, small drop size with high velocity and low energy of atomization are the desired criteria for the atomizer. Existing commercial atomizers are requiring very high energies for desired spray hydrodynamics. Therefore, an energy efficient and cost-effective critical flow atomizer [11] satisfying the above desired criteria is used in the present study.

In the present atomizer (Fig. 1) liquid and gas are brought together in a dispersing chamber at relatively low velocity in comparison to the critical velocity of individual phases because the critical velocity of a two-phase mixture is lower than that of the individual critical velocities. This concept exploits the shock mechanism arising in critical flow of any liquid–gas or liquid–liquid mixture. Since both frictional and acceleration pressure losses are strong functions of the phase velocities, the low operating critical velocities practicable in two-phase flow limit the overall system pressure drop. At the end of the atomizer, the two-phase mixture is expanded due to a pressure jump so that critical flow occurs. At the critical flow point, a sudden pressure difference, owing to this pressure jump, at the atomizer exit, between the upstream and downstream creates an instantaneous shock in the fluid stream which results in intense mixing of the phases as well as blasting and the liquid leaves the atomizer in the form of uniformly dispersed fine sprays. The advantages of this design consist in lower frictional acceleration losses compared to the external mixing atomizer. As can be seen in Fig. 1 that the gas–liquid mixing area can be adjusted so that sprays with different droplet sizes and different initial droplet velocities can be generated. It can also be seen from the figure that the gas–liquid mixing volume and mixing area can be adjusted so that either sprays with different droplet Sauter Mean Diameters (SMDs) at a fixed mean droplet velocity, or a fixed droplet SMD with different mean velocities can be generated.

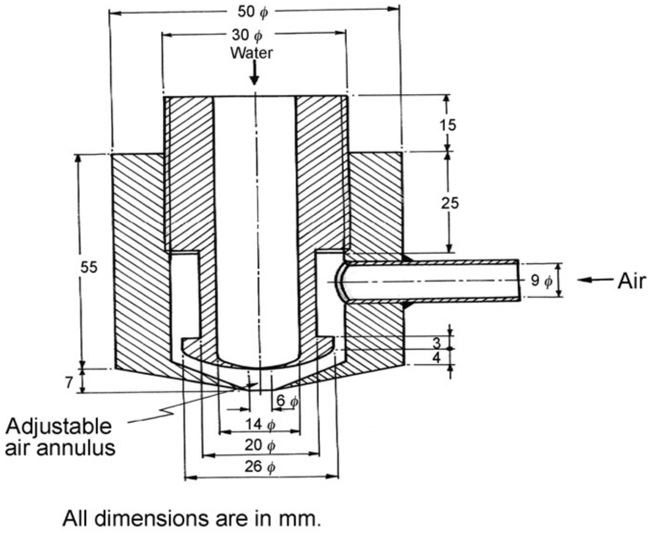


Fig. 1. Schematic diagram of the two-phase critical flow atomizer.

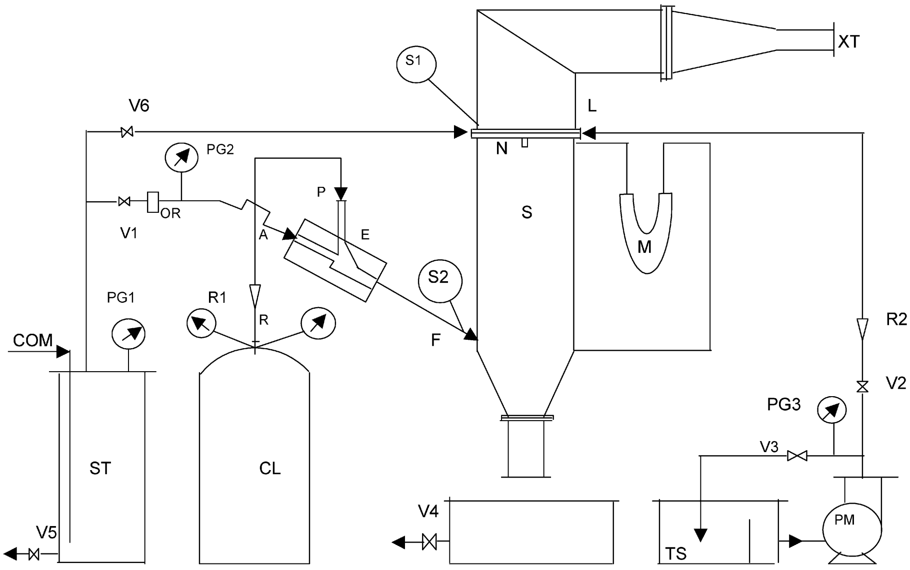
3. Selection of absorbent

The selection of a suitable absorbent or scrubbing liquid poses a very complex problem for removing SO_2 from waste gas stream and is of significant importance for process design as well. Many of the problems experienced at various facilities are the result of the inappropriate selection of a scrubbing process [7]. For instance, a scrubber using limestone slurry that works well on the steady and weak SO_2 generated in a coal-fired boiler will not be suitable for the stronger and fluctuating SO_2 produced by the metallurgical processes. Common commercial scrubbing processes utilized lime/limestone and dual alkali. Lime slurry and limestone scrubbing is suitable for relatively low concentrations of SO_2 [<100–5000 ppm] and moderate collection efficiencies [90–95%]. When concentration of SO_2 absorbed became sufficiently large [<100–150,000 ppm] to make the economics of a simple throwaway process uneconomical, the waste solutions can be regenerated in the dual alkali process by reacting it with lime i.e., $Ca(OH)_2$ outside the scrubber circuit. This approach permits the gas to be contacted with a clear solution of highly soluble scrubbing agent (usually sodium or aluminum based), thereby minimizing scaling, plugging and erosion problems in the absorbent circuit. The removal efficiency that can be offered by the dual alkali process is also very high [99%+]. Furthermore, it has been pointed out that the neutralization capacity of NaOH for SO_2 is extremely high [12]. The reduction of SO_2 concentration below 5 ppm (threshold limit value of SO_2) can best be achieved with appropriate controls on pH, ionic strength and liquid recirculation rate with sodium alkalis.

Considering the foregoing discussion, water has been selected as a scrubbing liquid in our preludial study to characterize the overall performance of the spray tower and later dilute NaOH has been selected as a reagent for attaining very high removal efficiency under the optimum scrubber operating conditions that followed from water scrubbing. Furthermore, such a selection of dilute NaOH will help in determining the critical design parameters: the volumetric gas-side mass transfer coefficient and number of transfer unit [13] for spray tower and investigating into the definite insight of the process. The detailed reaction schemes for SO_2–H_2O and SO_2–NaOH considered in the present article is discussed in the reported literature [10,14].

4. Experimental methods

The experimental column is a vertical cylindrical Perspex column, 0.1905 m in diameter and 2.0 m long. At the top of the cylindrical column the energy efficient two-phase critical flow



A: Primary air line: CL: SO_2 Cylinder; COM: Air from compressor; E: Air jet ejector; F: Air diluted SO_2 entry; L: Liquid entry; M: Manometer; N: Two-phase critical flow atomizer; OR: Orifice meter; P: SO_2 entry into the ejector; PG1 – PG3: Pressure gauges; PM: Pump; R: SO_2 regulator; R1 – R2: Rotameters; S: Spray tower; S1-S2: Sampling points; ST: Surge tank; TS: Scrubbing liquid tank; V1 – V6: Gate valves; XT: Exhaust

Fig. 2. Schematic diagram of the experimental setup.

atomizer was provided for generating sprays. The simulated SO_2 concentration in the range of 500–2000 ppm was generated by mixing air and SO_2 in an air-jet ejector (E) assembly for intense mixing of the components. Compressed air at the desired motive pressure and flow rate was forced through the air nozzle and simultaneously the SO_2 from the SO_2 cylinder (CL), was routed through SO_2 regulator (R), into the ejector at point P. The air and SO_2 mixed intensely in the mixing throat of the ejector and the mixture was allowed to feed into the spray tower at point F. SO_2 concentration was varied by changing the flow rate of SO_2 with the help of rotameter (R_1). The detailed experimental setup is schematically shown in Fig. 2 [15].

In the actual experiment, water and dilute NaOH solution (scrubbing liquid-phases studied) were pumped into the column through the atomizer routed through valve (V_2) and rotameter (R_2). Low pressure [1.19×10^5–1.68×10^5 N/m^2 (abs)] air was used to convert the liquid into fine sprays at high velocities. A simulated air borne SO_2 mixture was then introduced into the spray tower as discussed earlier. The scrubbing experiments were carried out without liquid recirculation. The experimental conditions were as follows:

4.1. Spray hydrodynamics and water scrubbing

$T = 306 \pm 1$ K; $Q_L = 0.4 \times 10^{-5}$–4.02×10^{-5} m^3/s; $Q_G = 3.75 \times 10^{-3}$–$6.20 \times 10^{-3}$ m^3/s; $P_a = 1.19 \times 10^5$–1.68×10^5 N/m^2 (abs); $D_d = 33.6 \times 10^{-6}$–$149 \times 10^{-6}$ m; $v_d =$ 21.06–35.33 m/s; $C_{SO_2,i} = 500$–2000 ppm; relative humidity of the ambient air = 98.2% ± 2%. The atomizing air introduced into the scrubber was about 1% of the total gas flow rate. The effects of $C_{SO_2,i}$ as well as various flow and operating variables on the performance of the spray tower were studied at a fixed P_a of 1.19×10^5 N/m^2 (abs), while the effect of D_d on the performance was separately conducted at different P_a ranging between 1.23×10^5 and 1.68×10^5 N/m^2 (abs).

4.2. Alkali scrubbing

Alkaline scrubbing experiments were carried out under optimum hydro dynamical conditions in water scrubbing discussed later. The chemical variables studied were: $C_{SO_2,i} = 500$–2000 ppm; $C'' = 2 \times 10^{-4}$ to 50×10^{-4} kmol/m^3; $T = 306.7 \pm 1$ K; relative humidity of the ambient air = 97.7% ± 2%.

The SO_2 concentrations (at S_1 and S_2) were analyzed using aspirator bottles by the Iodine Method [16] under steady operating conditions as detailed in the literature [10,14]. The SO_2 concentrations were corrected for the dilute atomized air (∼1%) that was introduced into the gas phase. The reproducibility of the measured SO_2 concentration using Iodine Method was 97%. The droplet size was measured with a Phase Doppler Analyzer (PDA). The PDA was programmed to evaluate the droplet Sauter Mean Diameter (SMD) in situ while measuring the size distribution. The SMD or the volume to surface mean diameter is

Table 1
Experimental data on liquid flow rate, droplet SMD and calculated values of number of droplets generated per second, single droplet surface area, total droplet surface area generated per second

Liquid flow rate (m^3/s)	Atomizing air pressure, P_a, (N/m^2)	Droplet SMD $D_d \times 10^6$ (m)	Number of droplets N_d (s^{-1})	Single droplet surface area, S (m^2)	Total droplet surface area generated $S_T = N_d \times S$ (m^2/s)
(a) For SO_2 scrubbing at a constant atomizing air pressure					
5.56E−06	1.19E+05	4.16E−05	1.48E+08	5.44E−09	0.8019
1.11E−05		7.22E−05	5.63E+07	1.64E−08	0.9224
1.83E−05		1.02E−04	3.26E+07	3.29E−08	1.0733
2.50E−05		1.19E−04	2.84E+07	4.44E−08	1.2616
3.11E−05		1.40E−04	2.17E+07	6.14E−08	1.3348
(b) For SO_2 scrubbing at various atomizing air pressures					
4.10E−06	1.23E+05	5.00E−05	6.26E+07	7.85E−09	0.4920
	1.39E+05	3.38E−05	2.03E+08	3.59E−09	0.7278
	1.58E+05	3.57E−05	1.72E+08	4.00E−09	0.6891
	1.68E+05	3.33E−05	2.12E+08	3.48E−09	0.7387
1.04E−05	1.23E+05	7.22E−05	5.28E+07	1.64E−08	0.8643
	1.39E+05	5.06E−05	1.53E+08	8.04E−09	1.2332
	1.58E+05	4.11E−05	2.86E+08	5.31E−09	1.5182
	1.68E+05	3.86E−05	3.45E+08	4.68E−09	1.6166
2.02E−05	1.23E+05	9.43E−05	4.60E+07	2.79E−08	1.2853
	1.39E+05	7.90E−05	7.82E+07	1.96E−08	1.5342
	1.58E+05	5.90E−05	1.88E+08	1.09E−08	2.0542
	1.68E+05	5.35E−05	2.52E+08	8.99E−09	2.2654
3.01E−05	1.23E+05	1.40E−04	2.10E+07	6.14E−08	1.2918
	1.39E+05	1.07E−04	4.69E+07	3.60E−08	1.6879
	1.58E+05	7.93E−05	1.15E+08	1.98E−08	2.2774
	1.68E+05	6.99E−05	1.68E+08	1.53E−08	2.5837
4.02E−05	1.23E+05	1.49E−04	2.32E+07	6.97E−08	1.6188
	1.39E+05	1.27E−04	3.71E+07	5.10E−08	1.8932
	1.58E+05	1.03E−04	7.05E+07	3.33E−08	2.3440
	1.68E+05	8.06E−05	1.47E+08	2.04E−08	2.9926

defined as:

$$\mathrm{SMD} = \sum \frac{F_i \times d_i^3}{F_i \times d_i^2} \qquad (1)$$

where F_i is the number of droplets in the i-th group. SMD averages the diameter (first order of length) yet weighs according to its surface area (second order of length), which contributes to the total surface area of the droplet population. SMD is useful in the present case since gas-droplet mass transfer is influenced by the droplet surface amongst other parameters similar to other gas–liquid mass transfer applications.

The mean velocity and the root mean square (r.m.s.) velocity of the droplets were measured by Laser Doppler Velocimetry (LDV) method. Mean droplet velocities were measured 1 m downstream from the nozzle exit. The measured droplet SMDs along with the atomizing air pressure necessary to generate the droplets are presented in Table 1. The errors in the measured and reported flow rates and droplet sizes were within ±5%.

5. Results and discussion

Experiments on the SO_2 scrubbing have been conducted at various process operating conditions as mentioned earlier. The percentage removal of SO_2 has been calculated in each run by the formula:

$$\eta = \left[\frac{(C_{SO_2,i} - C_{SO_2,o})}{C_{SO_2,i}} \right] \times 100 \qquad (2)$$

The spray hydro dynamics are initially highlighted and then the trends of variation of percentage removal (performance analysis) are discussed in details in the respective sections.

5.1. Spray hydrodynamics

5.1.1. Effect of atomizing air pressure on droplet SMD

The effect of atomizing air pressure (absolute) on droplet SMD at various liquid flow rates is shown in Fig. 3. It can be seen from the figure that the droplet SMD was reduced gradually with the increase in atomizing air pressure at a constant liquid flow rate. Atomizing air at higher pressure enabled the mass of definite amount of liquid to accelerate at a higher rate when the liquid was being disintegrated into smaller droplets. In the process, reduction of droplet SMD was achieved. It can also be seen from the figure that increase in liquid flow rate, in contrast, has an opposite effect on droplet SMD. The droplet SMD increased with the increase in the liquid flow rate at a constant atomizing air pressure. It may be attributed to the fact that increase in the definite mass of liquid at a constant atomizing air pressure retarded the disintegration process and larger droplets

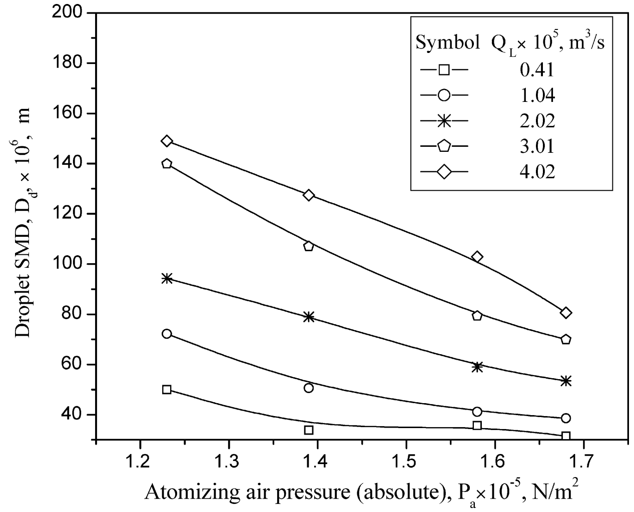


Fig. 3. Effect of atomizing air pressure on the droplet SMD at constant liquid flow rates.

were produced. The dependence of the droplet SMD on atomizing air pressure (abs) and liquid flow rate in the present system is found to be of the following form (correlation coefficient of 0.97527)

$$D_\mathrm{d} = 3.78934 \times 10^7 (P_\mathrm{a})^{-1.82414} (Q_\mathrm{L})^{0.48657} \tag{3}$$

5.1.2. *Effect of atomizing air pressure on droplet velocity*

The effect of atomizing air pressure on the droplet velocity at various liquid flow rates is shown in Fig. 4. It can be seen from the figure that the droplet velocity was increased sharply with the increase in the atomizing air pressure for all the liquid flow rates and finally reached almost a constant value of 1.68×10^5 N/m^2 (abs). Beyond this atomizing pressure no significant change in droplet velocity was observed perhaps due to attaining the critical velocity of the two-phase mixture at about 35 m/s. It can also be seen from the figure that the increase in the liquid flow rate, reduced the droplet velocity for a fixed atomizing air pressure, the reason for such variation is discussed earlier. The dependence of the droplet velocity on atomizing air pressure (abs) and liquid flow rate in the present system is found to be of the following form (correlation coefficient of 0.96689)

$$v_\mathrm{d} = 6.73225 \times 10^{-6} (P_\mathrm{a})^{1.2608} (Q_\mathrm{L})^{-0.02754} \tag{4}$$

On combining Eq. (3) and (4) the relationship of D_d and v_d with P_a and Q_L can be comprehensively represented as:

$$[D_\mathrm{d} \times v_\mathrm{d}] = 2.55 \times 10^2 (P_\mathrm{a})^{-0.56334} (Q_\mathrm{L})^{0.45903} \tag{5}$$

Eq. (5) will be useful for selecting the droplet SMD and droplet velocity based on the flow regime available for a system.

5.1.3. *Effect of atomizing air pressure and water flow rate on fineness of droplet generation*

The operating limits of the 6 mm atomizer for generating sprays of various finenesses is shown in Fig. 5 as a function of water flow rates and atomizing air pressure. In these sets of experiments the air entry area was adjusted such that the velocity of air at the entry corresponded to the velocity of sound in the two-phase mixture or was within 80% of it. It is seen from the figure that the maximum operating mass flow rate of water should be below 7.5 kg/h for generating sprays with droplet of SMD of 10 μm, whereas the water capacity as high as 32.5 kg/h may be required for generating sprays with droplet of SMD of 40 μm. These maximum rates corresponded to the critical mass flux as discussed earlier. Experiments with 4, 6, 8 and 10 mm atomizer have shown that the liquid capacities of the 4 and 6 mm atomizers were very low. However, for smaller atomizers, somewhat finer atomization was produced with identical flow conditions. On the other hand, it was observed necessary to use atomizers with larger diameters for generating finer droplets with higher liquid flow rates.

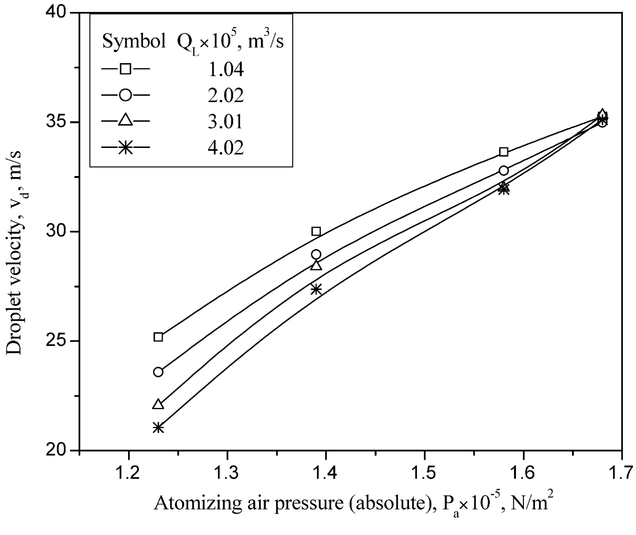


Fig. 4. Effect of atomizing air pressure on the droplet velocity at constant liquid flow rate.

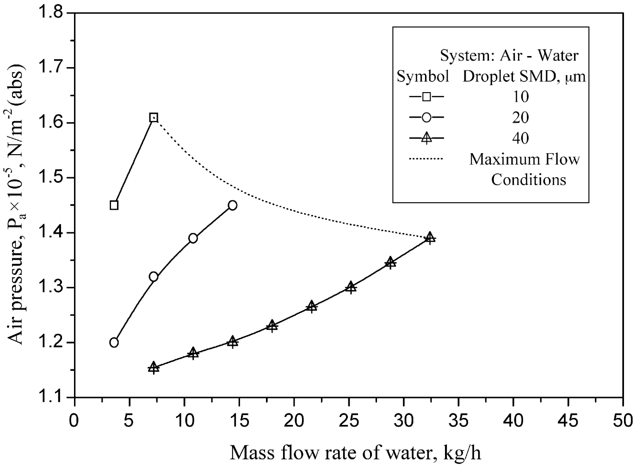


Fig. 5. Spray characteristics relating to atomizer operating conditions for 6 mm atomizer.

5.2. *Water scrubbing of SO_2*

5.2.1. *Effect of inlet concentration of SO_2*

The experimentation revealed that the variation of inlet SO_2 concentration in the range of 500–2000 ppm had insignificant effect on the percentage removal. In fact, the amount of SO_2 removed was increased with the increase in initial concentration of SO_2 since the concentration driving force was also increased in such a situation.

Furthermore, the removal efficiency is the ratio of the amount absorbed to the initial concentration and with the rise in the initial concentration of SO_2 both the numerator and the denominator were increased almost to the same extent in the present case that resulted in the removal efficiency almost unaffected with the increase in initial concentration of SO_2. However, the removal efficiency could have increased with the rise in initial concentration of SO_2 if the amount absorbed at (a) lower initial concentration of SO_2 would have relatively lower than at the higher initial concentration of SO_2 and (b) higher initial concentration of SO_2 would have relatively higher than that absorbed actually. These could not happened perhaps due to the fact that the tower was charged with very high velocity droplets that were capable of momentarily absorbing the gas and the droplet surface was reaching the equilibrium concentration of SO_2 very fast.

That the inlet SO_2 concentration did not have any influence on the percentage removal was theoretically investigated and validated with experiments by Pettersson et al. [4]. Huang [9] theoretically investigated that the percentage removal of SO_2 increased very sharply with the inlet concentration of SO_2 up to 10^{-2} ppb beyond which the percentage removal reached a constant value. Therefore, the observed effect of inlet concentration of SO_2 on the percentage removal of SO_2 in the present study agreed excellently well with the findings reported in the literature [4,9]. The maximum removal efficiency achieved in water scrubbing was 73.53%.

5.2.2. *Effect of liquid flow rate, gas flow rate and liquid-to-gas flow rate ratio*

From the economic point of view, the liquid-to-gas flow rate ratio in terms of $m^3/1000$ ACM (Actual Cubic Meter) has been found to be one of the most important criteria for reporting the scrubbing performance. In the light of this observation, the effect of Q_L/Q_G ratio on the percentage removal of SO_2 is shown in Fig. 6 for different gas flow rates at a constant inlet SO_2 loading of 2000 ppm. It can be seen from the figure that the percentage removal of SO_2 increased initially very sharply with the increase in Q_L/Q_G ratio and thereafter reaches almost a constant value beyond a Q_L/Q_G ratio of $3.0\,m^3/1000$ ACM [10]. The reason for such observation may be explained as follows. With the increase in Q_L/Q_G ratio the hydraulic loading, i.e., Q_L was increased in the scrubber. As the liquid flow rate was increased, the drop diameter and the total droplet surface area were also increased (Table 1(a)). This phenomena coupled with enhanced droplet oscillation at higher liquid flow rate might have caused the droplet-gas collision more effective and hence the percentage removal was increased with the increase in Q_L as well as Q_L/Q_G ratio. It can also be seen from the figure that the increase in Q_G reduced the percentage removal. It might be due to the reduction in gas–liquid contact time i.e., the reduction in the overall mass transfer. Also the SO_2 accumulated at the surface of the droplet phase did not get enough time to diffuse into the bulk liquid phase and this phenomenon hindered the absorption rate of SO_2 at higher gas flow rate, which resulted in the reduction in the percentage removal. On the other hand, at higher gas flow rate with relatively lower liquid flow rate, the rate of flow of SO_2 molecules into the scrubber was also higher and there might have been an over-crowding of SO_2 molecules in the bulk liquid phase causing a hindrance to the overall diffusion of SO_2 which resulted in reduction in the percentage removal at higher gas flow rate. That the percentage removal remained almost unaltered beyond a Q_L/Q_G ratio of $3.0\,m^3/1000$ ACM, might be due to the fact that SO_2 concentration in the liquid was reaching its equilibrium value in the gas phase. It could also be due to the result of increased rate of coalescence of the droplets, whereby both the number and the total droplet surface area might decrease, and the percentage removal might level off. This trend of variation of the performance of the spray tower also supports the observation made by Huang [9].

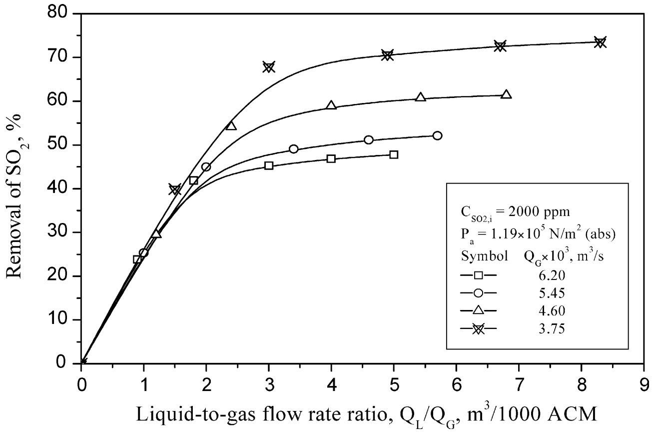


Fig. 6. Effect of liquid-to-gas flow rate ratio on the percentage removal of SO_2.

5.2.3. *Effect of droplet SMD, atomizing air pressure and droplet velocity*

In the previous discussion, the effect of droplet SMD could not be studied since the liquid flow rate was varied at a fixed atomizing air pressure and in the process the droplet SMD was also changed with the liquid flow rate. In fact, the performance of the spray tower was shown as a function of Q_L/Q_G ratio in Fig. 6. To study the effect of the droplet SMD either at constant Q_L or at fixed P_a on the performance of the spray tower a few experiments was conducted as discussed earlier. The effect of droplet SMD on the percentage removal of SO_2 under these circumstances is shown in Fig. 7. In general, it can be seen from the figure that the percentage removal of SO_2 was sharply increased with the increase in the atomizing air pressure while slowly decreased with the increase in droplet SMD for all liquid flow rates. This behavior can be explained with the variation of the droplet SMD based on the hydrodynamic parameters that

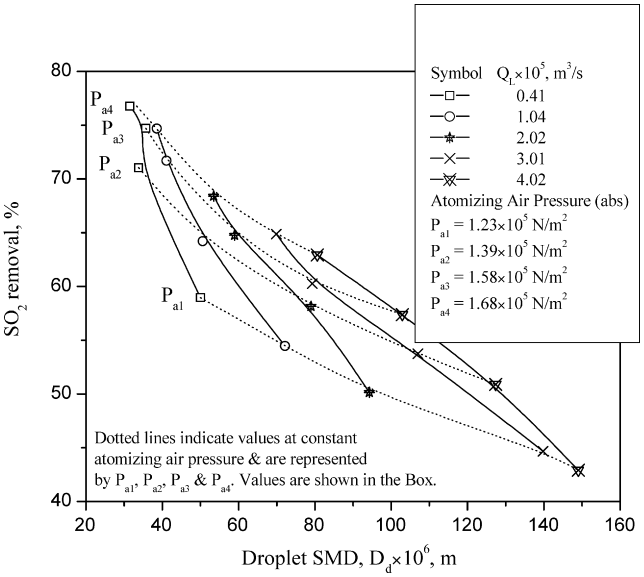


Fig. 7. Effect of droplet SMD and atomizing air pressure on the percentage removal of SO_2.

are affecting the atomization process. On increasing P_a at constant Q_L, the droplet SMD was generally observed to decrease and the droplet loading introduced into the scrubber was enormously increased (Table 1(b)) and thereby the interfacial area of contact was also increased which resulted in the sharp increase in the percentage removal of SO_2. This phenomenon expectedly resulted in the higher SO_2 removal for smaller droplets than larger ones at a constant Q_L. Furthermore, on decreasing Q_L at a constant P_a the droplet SMD was reduced and the number of droplets was increased slowly effecting the total droplet surface available for mass transfer increased (Table 1(b)). This resulted in the increase in the percentage removal of SO_2 slowly with the increase in the Q_L.

The effect of droplet velocity on the percentage removal of SO_2 is shown in Fig. 8 for different liquid flow rates. It can be seen from the figure that the percentage removal of SO_2 was increased sharply with the increase in droplet velocity. This can be explained as follows. The droplet velocity, a manifestation of the atomizing air pressure (P_a), was increased with the increase in P_a (Eq. (3)) and hence the percentage removal of SO_2 was increased as discussed earlier. Thus for an assigned droplet SMD or v_d, achieving a desired removal will require selecting Q_L and P_a. These findings are very useful for scrubber modeling as also for its design.

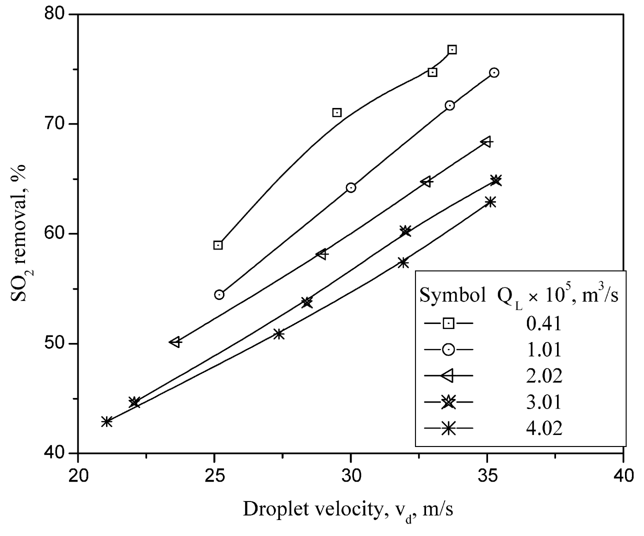


Fig. 8. Effect of droplet velocity on the percentage removal of SO_2.

The comparison of energy efficiencies of the present atomizer with the commercially available Caldyn nozzle revealed that the present atomizer required energy of 2.5 kJ/kg – H_2O/h at a liquid loading of 20 kg/h to generate droplets with an SMD of 40 μm, compared with 15 kJ/kg – H_2O/h for Caldyn nozzle under similar hydro dynamical conditions [11]. Thus the performance of the present atomizer, i.e., the operation of the spray tower, indicates that it is energetically better than the existing systems.

5.2.4. *Predicting SO_2 scrubbing efficiency with the help of empirical correlation*

The performance of the present system takes into account of a wide range of variables of the system in addition to the physico-chemical properties of the gas–liquid system. These variables were $C_{SO_2,i}$, C'', Q_L, Q_G, D_d, v_d, P_a, V_{Gi}, V_{Li}, D_C and H_T. Therefore, the performance can be presented as a function of these variables and the physico-chemical properties of the gas–liquid system. Variables considered in the available literature require analysis for the purpose of comparing the performances of the present system with the system reported. Therefore, relevant investigations are discussed here. Pettersson et al. [4] reported on $C_{SO_2,i}$ (100–500 ppm), NaOH concentration (2.5–20 kmol/m^3), scrubber bleed pH (3.75–5.5) for validating their model and obtained maximum removal efficiency of around 90%. Chen [5,6] developed theoretical models for SO_2 absorption using single water droplets in atmospheric process falling under terminal settling velocities. Hay et al. [7] investigated on the experimental removal of SO_2 (95%+) using the variables: NaOH concentration (∼5.0 kmol/m^3), $C_{SO_2,i}$ (∼500 ppm), scrubber exit SO_2 concentration (∼50 ppm), Q_G (130,000 Nm^3/h) and T (80 °C). None of these investigations reported on the complete set of variables comparable to the present study especially on the parameters that govern the process of atomization, one of our prime objectives in the present case for the purpose of design and analysis of the spraying devices used commercially. Huang [9] developed a theoretical model for predicting SO_2 removal efficiencies in water scrubbing and validated the model considering D_d (30–150 μm), droplet pH (6–9), droplet phase S(IV) concentration (0.10–10 M), $C_{SO_2,i}$ (10^{-5}–10^2 ppb) and Q_L/Q_G ratio (0.025–0.00575 m^3/1000ACM). Removal efficiency of ∼100% was reported theoretically. Though this investigation resembles to our study, its use is limited here due to the use of very low values of $C_{SO_2,i}$ and absence of parameters governing the process atomization. Critical appraisal of the available literature, therefore, indicates that an exact comparison of the performance achieved in the present study with the available data in the literature is not possible.

An attempt has therefore, been made to develop a correlation by dimensional analysis in order to predict the SO_2 removal efficiency from the directly measurable parameters of the system. The pertinent variables that could possibly influence the performance i.e., the removal efficiency, η_{SO_2}, of the spray tower are as:

(a) physical parameters: inlet SO_2 concentration ($C_{SO_2,i}$), gas density (ρ_g), liquid density (ρ_L), gas viscosity (μ_g), liquid viscosity (μ_L), liquid surface tension (σ_L), diffusivity of SO_2 in air (D), diffusivity of SO_2 in water (D').
(b) geometrical parameters: droplet SMD (D_d), column height (H_T), column diameter (D_C);
(c) flow parameters: droplet velocity (v_d), superficial gas velocity (v_g), air velocity at atomizer entry (V_{Gi}), superficial liquid velocity (v_L), liquid velocity at atomizer entry (V_{Li});

Dimensional analysis was carried out with the formation of relevant dimensionless groups leading to the following equation:

$$\eta_{SO_2} = f\left[\frac{D_d v_d \rho_L}{\mu_L}\right]^{a} \times \left[\frac{\rho_g (V_{Gi} - V_{Li})^2 D_d}{\sigma_L}\right]^{b} \times \left[\frac{\mu_g}{(D' C_{SO_2,i})}\right]^{c} \times \left[\frac{D}{(v_L H_T)}\right]^{d} \qquad (6)$$

$$= f[Re_D]^{a} \times [We_D]^{b} \times [Sc]^{c} \times [D_i]^{d} \qquad (7)$$

The inlet concentration of SO_2 is expressed in kg/m^3 for the purpose of the dimensional analysis. In order to establish the functional relationship between the percentage removal of SO_2 from a mixture of air–SO_2, and the various dimensionless groups in Eq. (7), 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 (0.907%) and the minimum standard deviation of percentage error (0.971%), presents the best possible correlation with a correlation coefficient of 0.9979

$$\eta_{SO_2} = 1 - 0.74557\,[(Re_D)^{-0.1636} \times (We_D)^{-1.34853} \times (Sc)^{-0.349} \times (D_i)^{-0.77869}] \qquad (8)$$

Eq. (8) describes the percentage removal of SO_2 from an air borne SO_2 stream in the spray tower, which is an important parameter for assessing the performance of the spray tower from the standpoint of air pollution control. The above equation is obtained for the modified droplet Reynold's number in the range 1160–3420, droplet Weber number in the range of 0.061–0.199, modified Schmidt number in the range of 2.7×10^6 to 11.5×10^6 and dispersion number in the range of 5.96×10^{-3} to 33.3×10^{-3}. The values of percentage removal of SO_2 (η_{SO_2}) predicted by Eq. (8) have been plotted against the experimental values of percentage removal of SO_2 in Fig. 9. It can be seen from the figure that the predicted values fitted excellently well with the experimental values (well within ±10% deviation). Furthermore, to test the acceptability of the correlation, various statistical tests (t-test and F-test) have been carried out and determined at 99.1% confidence level, which reveals that the correlation is highly functional. In our previous study [10] discussed earlier, the correlation was developed without considering the dimensionless droplet Weber number, We_D, and was unable to take in to account the intrinsic parameters that governed the atomization process for the purpose of predicting the performance of the critical flow atomizer in SO_2 spray scrubbing.

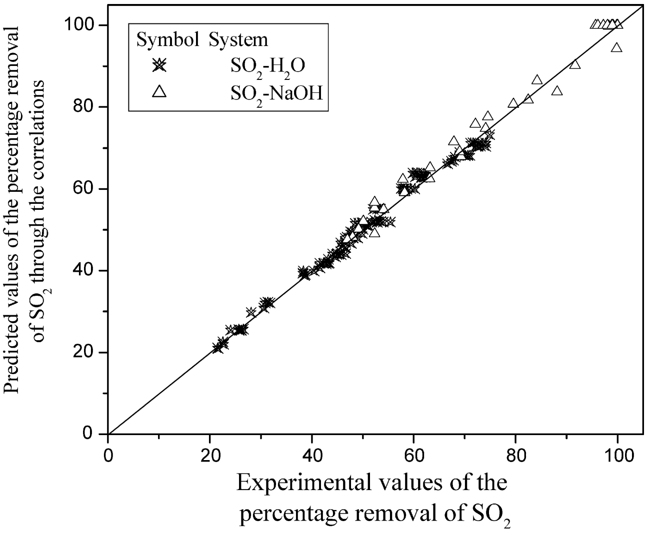


Fig. 9. Comparison of predicted and experimental percentage removal of SO_2 in water and alkali scrubbing.

5.3. Alkaline scrubbing of SO_2

In general, the overall rate of mass transfer influences the removal efficiency of a pollutant gas during its scrubbing using a liquid. In such a situation, the two-film model [17] can be used for studying the gas–liquid mass transfer operation having gas-side as well as liquid-side resistances [18]. Furthermore, the mass transfer in alkaline scrubbing is characterized by the enhancement factor, which is defined as follows:

$$\text{mass transfer enhancement factor, } \phi = \frac{\text{rate of mass transfer due to chemical reaction}}{\text{rate of mass transfer due to physical absorption}} \qquad (9)$$

while the enhancement factor following the two-film model for SO_2–NaOH system can be given by [19]:

$$\phi = \left(1 + i\frac{D''}{D'}\frac{C''}{C_{SO_2,\text{int}}}\right) \qquad (10)$$

The interfacial concentration of SO_2 was obtained from the following relationship:

$$C_{SO_2,\text{int}} = H_\infty P_{SO_2} \qquad (11)$$

where $H_\propto$ is the thermodynamic equilibrium-distribution constant given by [20]:

$$H_\infty = \exp\left[\left(\frac{32,143.3}{T}\right) + 198.14 \ln T - 0.3384T - 1135.62\right] \qquad (12)$$

The removal efficiency in alkaline scrubbing can, therefore, be determined from the enhancement factor and the water scrubbing efficiency considering the fact that the ratio of mass transfer rates of SO_2 with and without chemical reaction occurring inside a drop is proportional to the ratio of the overall spray tower removal efficiencies of SO_2 with and without chemical reaction [15]. Thus the removal efficiency of SO_2 in alkaline scrubbing in aqueous NaOH solution can be given by the following generalized equation:

alkaline removal efficiency of SO_2

= (removal efficiency of SO_2 in water scrubbing)

(mass transfer enhancement factor)

or, $\eta_C = \eta_{SO_2}\phi$ (13)

Eq. (13) can be applicable to any gas–liquid absorption process in reactive systems based on the assumptions and conditions specified by the physico-chemical hydrodynamics. It is evident from Eq. (13) that the alkaline removal efficiency of any pollutant gas (for instance, SO_2) is strongly dependent on the initial gas phase and the initial reagent concentrations. It can also be seen from Eq. (13) that the removal efficiency would decrease with the increase in the initial gas phase concentration while it would increase with the increase in the initial reagent concentration. The removal efficiency using Eq. (13) may sometimes yield values greater than 100% and in that case it should be considered 100%, since such a situation does not practically possible [10,14].

The behavior of the spraying device in alkaline scrubbing using dilute aqueous NaOH solution has been studied by carrying out a few experiments choosing the combinations of flow variables (Q_L and Q_G) based on the following consideration [10]:

(a) Intermediate Q_L, amongst the range of liquid flow rates studied, which was 1.83×10^{-5} m^3/s.
(b) Optimum Q_L/Q_G ratio, above which the variation of percentage removal of the scrubber in water scrubbing was insignificant, which was 3.0 m^3/1000 ACM.
(c) Q_G arrived, at using $Q_L = 1.83 \times 10^{-5}$ m^3/s and Q_L/Q_G ratio = 3.0 m^3/1000 ACM, was 6.20×10^{-3} m^3/s.

The impacts of different parameters studied on the performance of the spraying device are presented in this section within the framework of the present investigation.

5.3.1. Effect of scrubbing liquid pH and inlet concentration of SO_2

The effect of scrubbing liquid pH at the scrubber entry and inlet concentration of SO_2 on the percentage removal is shown in Fig. 10. Expectedly, the figure indicates that the percentage removal increased with the increase in pH of the scrubbing liquid. It can also be seen from the figure that higher removal efficiency was obtained at lower initial concentration of SO_2, while it was necessary to increase the pH of the scrubbing liquid to achieve higher removal efficiency at higher inlet SO_2 concentration and this observation is in good agreement with Eq. (13) discussed earlier. Almost 100% removal of SO_2 was achieved at a pH of 11.0 for inlet SO_2 concentration of 500 ppm and at a pH of 11.7 for all initial concentrations of SO_2. In general, the spray tower performed well beyond pH of about 11.3. Hay et al. [7] reported removal efficiency of about 95%+ at a pH of 11.0 for inlet SO_2 concentration of 500 ppm. On comparison of the present findings with the result reported by Hay et al. [7] indicates that the present system is efficiency wise much better than the existing system. Thus for a desired performance in alkali scrubbing, pH of the scrubbing liquid should be selected based on the initial SO_2 concentration besides knowing the effects of other pertinent variables on water scrubbing.

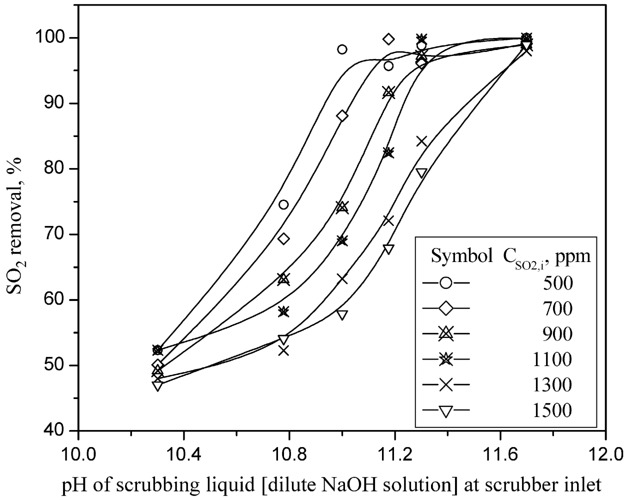


Fig. 10. Effect of scrubbing liquid pH at scrubber inlet on the percentage removal of SO_2.

5.3.2. Effect of ratio of initial concentration of NaOH to interfacial concentration of SO_2 on enhancement factor of mass transfer and percentage removal of SO_2

The effect of concentration ratio on the experimental enhancement factor at $Q_L = 1.83 \times 10^{-5}$ m^3/s, $Q_G = 6.20 \times 10^{-3}$ m^3/s and Q_L/Q_G ratio = 3.0 m^3/1000 ACM is compared with theoretical values as shown in Fig. 11. The experimental values of the removal efficiencies are also shown in the same figure (see right vertical axis). It can be seen from the figure that the theoretical enhancement factor increased linearly and sharply with the increase in concentration ratio as expected from the linear nature of Eq. (9). The experimental values were also increased sharply with the concentration ratio up to a value of 2.0 kmol/kmol. In this range, the predicted values are found to be in excellent agreement with the experimental values. Beyond a concentration ratio of 2.0 kmol/kmol, a very striking feature was, however, observed from the figure. The enhancement factor theoretically increased with the concentration ratio linearly and indefinitely but the experimentally determined values did not follow the trend in the same manner. In the present case for SO_2–NaOH system, the enhancement factor after reaching a maximum value of 2.10 at a concentration

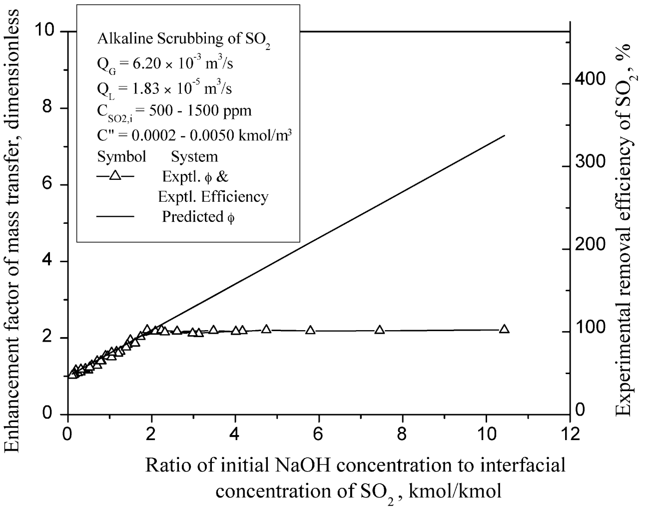


Fig. 11. Effect of concentration ratio on the mass transfer enhancement factor and on the percentage removal of SO_2 in alkaline scrubbing at a Q_L/Q_G ratio of 3.0 m^3/1000 ACM.

ratio of about 2.0 kmol/kmol, saturates and moves along the concentration ratio axis. It is attributed to the fact that the maximum enhancement could only be achieved at maximum removal efficiency of ∼100% as can be seen from the right vertical axis and beyond which there was no scope of any mass transfer and hence no scope of any enhancement of mass transfer further, which resulted in such behavior of the enhancement factor in alkaline scrubbing. Clearly, it demonstrates that the enhancement factor of mass transfer in alkaline scrubbing can never be expected to increase indefinitely with the increase in concentration ratio. This feature does not seem to be detailed in the available literature of gas–liquid mass transfer as well as gas scrubbing and is an extremely important finding for designing the scrubber operation. The application of enhancement factor reported in the present article may also be extended to other available gas–liquid mass transfer models.

It can also be seen from the figure that the percentage removal was increased with the increase in the concentration ratio. The maximum removal of SO_2 obtained was almost 100% at a concentration ratio of 2.0 kmol/kmol in the studied spraying device within the framework of the investigation. Available literature [1] on the other hand, indicated that the removal efficiency of SO_2 over 95% was readily attainable in a double alkali scrubbing process at a Q_L/Q_G ratio of 4.35 m^3/1000 ACM [3.35 m^3/1000 ACM in the venturi (Stage-I) and 1.0 m^3/1000 ACM in the tray/spray tower (Stage-II)]. SO_2 removal efficiency of around 90% was achieved by Pettersson et al. [4] using 2.5–20 kmol/m^3 of NaOH solution and 95%+ by Hay et al. [7] using ∼2.5 kmol/m^3 of NaOH solution. But in the present study maximum concentration of NaOH used was 5×10^{-3} kmol/m^3. Clearly, the comparison of the performance of the present spraying device with the systems reported in the literature indicates that the present system had performed efficiently at significantly lower values of Q_L/Q_G ratio and NaOH concentration than the existing systems. Furthermore, the atomizer generated droplets at lower energy than the existing systems. Thus the system developed is efficiency wise and energy wise much better than the existing systems. Here is the novelty of the system developed.

5.3.3. *Prediction of removal efficiency of SO_2 in alkaline scrubbing*

The percentage removal of SO_2 in alkaline scrubbing can be predicted for the spraying device with the help of Eqs. (8), (10) and (13). The final form can be given as:

$$\eta_C = \eta_{SO_2}\phi = [1 - 0.74557[(Re_D)^{-0.1636} \times (We_D)^{-1.34853} \times (Sc)^{-0.349} \times (D_i)^{-0.77869}] \times \left(1 + i\frac{D''}{D'}\frac{C''}{C_{SO_2,\mathrm{int}}}\right) \quad (14)$$

Diffusivities of SO_2 in water and NaOH were taken from previous workers [21,22] for the purpose of calculating the percentage removal. It can be seen from Eq. (14) that the percentage removal of SO_2 would increase with the decrease in droplet SMD and with the increase in droplet velocity as discussed earlier. Thus either reducing the droplet SMD or increasing the droplet velocity would reduce the consumption of the reagent for SO_2 scrubbing. The predicted values have been plotted against the experimental values of percentage removal of SO_2 in Fig. 9. It can be seen from the figure that the predicted values fitted excellently well with the experimental values (well within ±10% deviation).

6. Scrubber design

In view of a large volume of dilute gas to be scrubbed in industrial gas cleaning processes, equipment which reduces energy consumption to a reasonable magnitude are preferable, as in the long run this leads to a substantial savings in the operating cost. The present system developed is a kind of device that can satisfy this condition. In this section the aspects of design is presented. The critical process design parameters for a gas–liquid mass transfer device are true volumetric gas side mass transfer coefficient and number of transfer unit. In order to compare the performances of the present spraying device with the existing devices, reporting on these two parameters are necessary.

The true volumetric gas side mass transfer coefficient was found to vary between 3×10^{-3} and 40×10^{-3} kmol/m s atm [10] as compared to 0.0754×10^{-3} and 0.2557×10^{-3} kmol/m s atm reported by Mehta and Sharma [23,24] under similar flow regimes. The maximum value of number of transfer unit of 9 obtained [10] was very high than that reported by Schmidt and Stichlmair [2] ranging between 0.2 and 2.0 for tower height of 0.2–4.2 m, tower diameter of 0.025–0.390 m and liquid-to-gas flow rate ratio of 1.0–5.0 m^3/1000 ACM. Thus the system is better than the existing systems from the standpoint of intrinsic parameters of process design.

The sizing analysis as a part of the process design has been shown in a flow chart (Fig. 12) that takes into account the empirical and semi-empirical correlations. The desired performance level coupled with the available physico-chemical properties is the feed data into this flow chart. The desired performance can

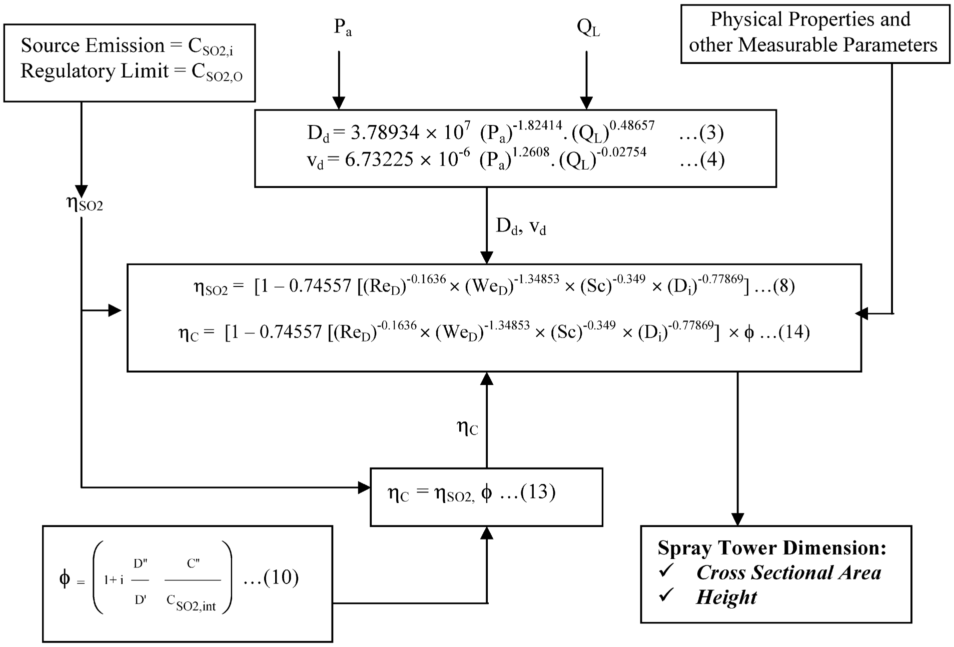


Fig. 12. Spray tower sizing analysis.

be obtained from the source emission and regulatory limit in tandem. Eq. (8) shall be rearranged as follows to generate data for the sizing of the spray tower for water scrubbing.

$$\begin{aligned}\eta_{SO_2} &= [1 - 0.74557[(Re_D)^{-0.1636} \times (We_D)^{-1.34853} \\ &\quad \times (Sc)^{-0.349}(D_i)^{-0.77869}] \\ &= 1 - 0.74557[(D_d v_d \rho_L/\mu_L)^{-0.1636} \\ &\quad \times \{\rho_g (V_{Gi} - V_{Li})^2 D_d/\sigma_L\}^{-1.34853}\{\mu_g/D' C_{SO_2,i})^{-0.349} \\ &\quad \times \{D/v_L H_T\}^{-0.77869}] = f\{(D_d, v_d, C_{SO_2,i}, \rho_L, \rho_g, \mu_L, \\ &\quad \mu_g, \sigma_L, D', D, V_{Gi}, V_{Li}, Q_L)(D_T, H_T)\} \\ &\quad [\text{substituting } v_L = 4 \times Q_L/(\pi D_T^2)] = f\{K, (D_T, H_T\} \\ &\quad \times [\text{where, } K = D_d, v_d, C_{SO_2,i}, \rho_L, \rho_g, \mu_L, \mu_g, \sigma_L, D', \\ &\quad D, V_{Gi}, V_{Li}, Q_L)]\end{aligned}$$

K contains the pertinent parameters of the systems that are available. Therefore, knowing the desired performance level, cross-sectional area of the tower (hence the diameter) and the height of the tower can be determined using the correlation developed by a trial-error between the height and the diameter of the tower considering the fact that the ratio of height to diameter of the tower is ranging between 8.0 and 10.0 for gas scrubbing operations [2]. Similarly, Eq. (14) shall be rearranged to generate data for sizing the spray tower for alkaline scrubbing.

7. Conclusions

Abatement of SO_2 assumes significant importance due to its deleterious effects on living systems. Legion of SO_2 scrubbing technologies have evolved from the requirements of a number of industries stemming from their definite process and regulatory mandates. The performance of an energy efficient critical flow atomizer deploying in a counter-current spray tower for SO_2 scrubbing using water and dilute NaOH was reported. The atomizer is capable of producing finer droplets at very high relative velocity without sacrificing the spray uniformity. Followings were the major findings of the present investigation:

7.1. Hydrodynamics of the spray tower

Preliminary hydrodynamic studies revealed that the droplet SMD was reduced with the increase in atomizing air pressure (absolute) and decrease in the liquid flow rate while the droplet velocity was increased with the increase in atomizing air pressure (absolute) and decrease in the liquid flow rate.

7.2. Performance in water and in alkaline scrubbing

Experimentation revealed that the SO_2 removal efficiency increased with the increase in liquid flow rate, liquid-to-gas flow rate ratio, atomizing air pressure and droplet velocity while it decreased with the increase in droplet SMD and gas flow rate. Inlet SO_2 concentration, however, did not have any significant effect on the SO_2 removal efficiency. Results also indicated that the percentage removal of SO_2 had almost reached a maximum value for a Q_L/Q_G ratio of $3.0\,\text{m}^3/1000$ ACM and was considered as optimum for the scrubber operation. Results showed almost 100% removal efficiency at a Q_L/Q_G ratio of $3.0\,\text{m}^3/1000$ ACM and at a scrubbing liquor pH of 11.7. Results also indicated that the present system is energy wise and efficiency wise much better than the existing systems.

7.3. Prediction of the performance

Critical appraisal of the available literature revealed that an exact comparison of the performance achieved in the present study with the available reported data is not possible. Therefore, empirical and semi-empirical correlations were developed for predicting the removal efficiencies of SO_2 in water and alkaline scrubbing respectively and the predicted values fitted excellently well with the experimental values. The water scrubbing efficiency and the mass transfer enhancement factor were combined while predicting the performance in alkaline scrubbing. It was further pointed out that the removal efficiency for any gas would inversely varied with initial gas phase concentration while directly varied with initial reagent concentration. It should be considered 100% in case it exceeds 100%. Experimentation coupled with theoretical analysis further revealed that the enhancement factor of mass transfer in alkaline scrubbing could never be expected to increase indefinitely with the increase in ratio of initial concentration of NaOH to the interfacial concentration of SO_2. This feature does not seem to be detailed in the available literature of gas–liquid mass transfer as well as gas scrubbing and is an extremely important finding for designing the scrubber operation. The application of enhancement factor reported in the present article may also be extended to other available gas–liquid mass transfer models. Furthermore, the semi-empirical correlation developed for characterizing the performance of alkaline scrubbing of SO_2 revealed that either reducing the droplet SMD or increasing the droplet velocity would reduce the consumption of the reagent.

7.4. Process design and sizing analysis

Reportedly the values of true volumetric gas side mass transfer coefficient were very high and were better than the existing system. Knowing the desired performance level and physical properties pertinent to the system studied should be fed to the rearranged empirical and semi-empirical correlations developed so as to evaluate the tower sizing parameters, for instance, the tower cross-section (hence the tower diameter) and the tower height, in water and alkaline scrubbing respectively.

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