ASIA-PACIFIC JOURNAL OF CHEMICAL ENGINEERING
Asia-Pac. J. Chem. Eng. 2008; **3**: 544–549
Published online 16 September 2008 in Wiley InterScience
(www.interscience.wiley.com) DOI:10.1002/apj.177

Curtin University of Technology

Research Article

Hydrodynamics characterization of a counter-current spray column for particulate scrubbing from flue gases

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Received 7 May 2008; Revised 11 June 2008; Accepted 19 June 2008

ABSTRACT: Growing environmental concern and tightening of the regulations for particulate emission from various sources force us to think of an alternative technology for their control, which is cost effective and of high performance. A spray column using a wet process to control the particulates offers design simplicity, and has various other advantages over other conventional equipment used in industry. This work presents the hydrodynamic study of the spray column for the removal of particulates from gaseous wastes. Experiments were carried out to quantify pressure drop (ΔP), for varied gas and liquid rates ranging from 3.084×10^{-3} to 5.584×10^{-3} Nm^3/s and 8.35×10^{-6} to 33.34×10^{-6} m^3/s, respectively with Q_L/Q_G ratio ranging from 1.59 to 10.81 m^3 per 1000 ACM (actual cubic meter). The maximum pressure drop incurred in the column is 327 N/m^3, which is at a gas rate of 5.584×10^{-3} Nm^3/s, liquid rate of 33.34×10^{-6} m^3/s, and an inlet solid loading range of 0–2.5 kg/m^3. This is quite low compared to other wet process-based equipment, thus making it a low power loss scrubber. These results have further demonstrated the impact of solid dust (particulates) on the pressuredrop-hydrodynamics. A correlation was put forward for prediction of the overall pressure drop in the column. The experimental values agreed well with the predicted values, with minimum percentage error and standard deviation. © 2008 Curtin University of Technology and John Wiley & Sons, Ltd.

KEYWORDS: particulate matter (fly-ash); scrubbing; turbulence; hydrodynamics; spray column; empirical correlation

INTRODUCTION

The presence of particulate matter in the atmosphere has created many undesirable changes in the lives of plants, animals, and human beings and has even caused a considerable damage to the nonliving things on the earth during the last few decades. A significant increase in the volume of particulate matter has been found entering and influencing the atmosphere through gaseous emissions. The cleaning of the gaseous wastes containing particulates requires their control at the source itself and presents special challenges because of the large volumes of gases and the submicron sizes of the pollutants to be treated.

Recently, wet scrubbers with newer designs, which are modified versions of the conventional ones, are used as particulate control devices. The spray columns and the bubble columns, owing to their intrinsic pressure drop and flow characteristics, are the most widely preferred devices. However, the literature reveals that in the conventional bubble column the pressure drop is unacceptablyquite high, and moreover, there are frequent cleaning problems due to particulate accumulations when employed with a sparer disk.[1]

Although it has been reported[2] that, in multistage operation of the bubble column, a very high efficiency has been achieved, the mechanical complications in multistage operation of the bubble column cannot be overlooked. The simplest, least expensive, and lowest energy scrubber among the wet scrubbers is the simple counter-current spray scrubber. In this counter-current spray column, drops of liquid are introduced through spray nozzles and are allowed to fall down through a rising stream of dirty gas.[3]

The spray column, apart from its design simplicity and requirement of less horizontal spacing, can handle very fine submicron sizes of the particulate matter. They produce low pressure drop and so less energy dissipation, apart from being economical.

Although the pressure drop in the spray column is quite low, it should not be ignored. Pressure drop has become one of the most important design criteria for the scrubbers, giving an indirect estimation of the liquid phase holdup and droplet residence time through

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the column as reported by Sanchez *et al*.[4] It gives the quantification of the dissipated power and is a decisive factor for the estimation of the efficiency of the column based on the energy criteria. Hence the correct estimation of the overall pressure drop in a spray column is very important. An attempt has, therefore been made to carry out the hydrodynamic studies and quantify the overall pressure drop within the column at varied gas–liquid rates and for different inlet solid loading conditions for understanding the influence of solid dust on the pressure drop hydrodynamics. Finally, the experimental data were compared with an empirical model developed for the system.

EXPERIMENTAL SET UP AND TECHNIQUE

A schematic diagram of the experimental setup is shown in Fig. 1. It is constructed of transparent, vertical Perspex column of 2400-mm long and 125-mm (i.d.) diameter, fitted with a fructo-conical top outlet. At 565 mm from the bottom of the column was fitted the experimental hot-air inlet duct coming from a blower (2.2 kW) and a heater (4.5 kW). A digital display control panel was provided to control and monitor the temperature in the air heater. The solids are kept in a steel hopper (400 mm × 250 mm), having an electric vibratory-feeder to feed the solids at a controlled and calibrated rate to the venturi-ejector and introduce to the column just 350 mm above the hot-air inlet point. There, they are allowed to mix with the up-flowing experimental hot air and the mixture ascends upwards (like the flue-gas of the industrial standard). The water used for scrubbing is pumped from the water tank through a 0.5 kW high pressure (HP) pump and atomized at the top of the tower using a twin fluid air-assist atomizer. The droplet sizes are measured as Sauter mean diameter (SMD) using Rizkalla and Lefebvre (1975)[5] dimensionless correlation given in Eqn (1).

$$\mathrm{SMD} = 10^{-3}\left[\frac{\sqrt{\sigma\rho_L}}{\rho_G v_G}\right]\left(1+\frac{1}{\mathrm{AWR}}\right)^{0.5} + 6\times10^{-5}\left[\frac{\mu_L{}^2}{\sigma\rho_G}\right]\left(1+\frac{1}{\mathrm{AWR}}\right)^{0.5}\ \mu\mathrm{m} \qquad (1)$$

The SMD values of the droplets for various air to water ratios (AWR) in the atomizer are presented in Table 1. Dry and moisture-free fly ash has been used as the particulate matter (solids) in the hot-air medium. The fly ash brought from a thermal power plant is dried and demoisturized in an oven and kept in a desiccator. The particle size-distributions of inlet fly ash were measured using a Malvern Master Size 2000 Ver.5.22. The pressure drop studies were conducted to estimate the sectional pressure drop as well as the overall pressure drop in the column. Pressure taps Pi

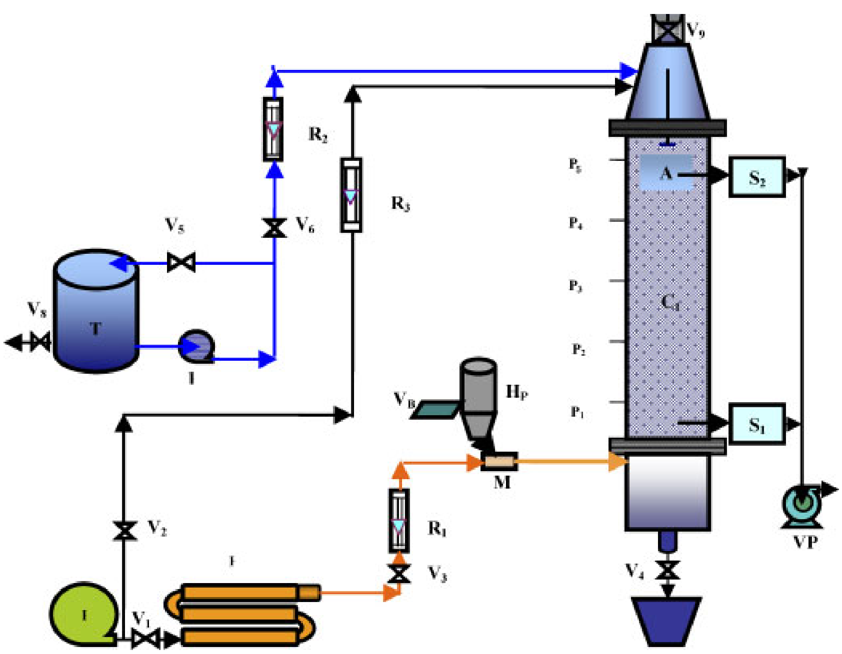

Figure 1. Schematic diagram of the experimental setup. A–Airblast atomizer, B–Blower, C_1–Spray Column, H–Heater, H_P–Hopper, M–Venturi Mixer, P–Pump, P_1 to P_5–Ports for pressure tappings and thermometers insertion, R_1–R_3 Air and Water Rotameters, T–Water Tank, S_1 and S_2–Sample ports V_1 to V_9–Valves, V_B–Vibrator, VP–Vacuum Pump. This figure is available in colour online at www.apjChemEng.com.

(i = 1, 2, 3, 4, 5) are situated along the length of the column and linked to manometers in order to measure the pressure drops. The pressure difference for each set of liquid–gas flow rates inside the column is measured by the difference between the heads of the CCl_4 column in the U-tube manometer. The operating variables along with their ranges are presented in Table 2.

Hydrodynamic study

Within the stability range of the spray column, a hydrodynamic study was conducted, for different gas–liquid rates and constant inlet solid loading. The gas and liquid flow rates are selected such that the liquid to gas Q_L/Q_G ratio ranges from 1.59 to 10.81 m^3 per 1000 ACM (actual cubic meter). The pressure taps are fixed along the length of the column at definite intervals and linked to U-tube manometers in order to measure the pressure drops. The pressure difference (ΔP) for each set of liquid–gas rates inside the column is measured by the difference between the heads (Δh) of the CCl_4 column in the U-tube manometers connected to the taps. The operating variables of the spray column and the ranges are given in Table 1.

Thus,

$$\Delta P = \Delta h\ (\rho_L - \rho_G)\ g \tag{2}$$

Table 1. Sauter mean diameter of the liquid droplets predicted using Rizkalla and Lefebvre.

Gas flow rate to the nozzle $Q_G \times 10^4$, (m^3/s)	Liquid flow rate to the nozzle $Q_L \times 10^6$, (m^3/s)	SMD (μm)	Number of droplets produced per second (approximate)
3.15	8.34	117.6	9 798 637
3.15	16.67	119.1	18 854 799
3.15	25.00	120.6	27 234 517
3.15	33.34	122.0	35 083 887
3.50	8.34	97.8	17 036 135
3.50	16.67	98.9	32 928 225
3.50	25.00	100.0	47 770 700
3.50	33.34	101.1	61 650 092
3.93	8.34	83.0	27 871 053
3.93	16.67	83.9	53 935 079
3.93	25.00	84.7	78 616 079
3.93	33.34	85.6	101 570 106
4.72	8.34	62.4	65 589 434
4.72	16.67	62.9	127 998 614
4.72	25.00	63.5	186 569 409
4.72	33.34	64.0	243 022 943

Table 2. Operating variables and their ranges in the spray column.

Parameters	Values
Ambient temperature	305 ± 1 K
Inlet temperature of the experimental hot air	70–80 °C
Fly-ash particle-size range	2–200 μm
Liquid spray droplet-size range	80–200 μm
Gas flow rates	3.084×10^{-3} to 5.584×10^{-3} Nm^3/s
Liquid flow rates	8.35×10^{-6} to 33.34×10^{-6} m^3/s
Inlet fly-ash loading	$0–10.0 \times 10^{-3}$ kg/m^3

RESULTS AND DISCUSSIONS

Effect of inlet fly-ash loading

The Fig. 2 represents hydrodynamics of the column; when conducted with changing inlet solid loading it shows that that there is a rise in pressure drop with higher inlet solid loading, but the rise is negligible. Almost similar view has been reported by Reddy *et al*.[6] that the average drag coefficient due to variation

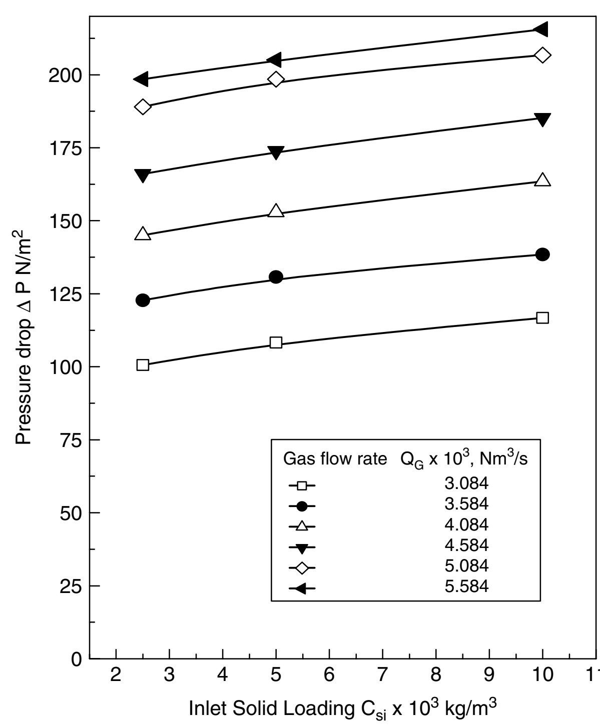

Figure 2. Effect of inlet solid loading on overall pressure drop of the spray column at different gas rates and constant liquid rate of 8.35×10^{-6} m^3/s.

of solid loading rates is negligible. This rise in the pressure drop is primarily arising from the increased particle–wall, particle–particle, particle–droplet, and particle–gas interactions, collectively called 'solid frictional losses'. The particle–wall and particle–gas interactions are very small, as the particles' concentration in the gas is very less. But the frictional drag is also small when interparticle spacing is more than ten times the particle diameter. With increase in the inlet solid loading rate, particle–particle spacing decreases; as a result the frictional pressure drop increases, which is observed to be minimal. Thus the pressure drop is not much influenced by the presence of solids and the process hydrodynamics is only slightly modified by the change in inlet solid loading that gains less importance from the application point of view.

Effect of the gas flow rate

In the Fig. 3, the overall pressure drop is found to increase as the gas flow rate increases. The increase in the pressure drop is due to the fact that at a higher gas velocity the relative velocity increases and a greater inertial impaction and interception of gas–solid–droplet interactions occur. This leads to the development of strong aerodynamic, hydrodynamic and other turbulent or disruptive forces within the gas–liquid system at the expense of gas motive pressure in the form of pressure losses or pressure drop.[7,8] The pressure drop is found to increase for higher gas rates right from 3.084×10^{-3} Nm^3/s almost steeply. Above 5.084×10^{-3} Nm^3/s gas rate, a considerable amount of liquid droplets is found to get entrained, and hence a slight decrease in the rate of pressure drop with respect to the gas flow rate is observed. This is only due to the fact that at the higher gas velocity the relative velocity increases. In addition, greater inertial impaction and interception of gas–solid–droplet interactions may lead to the higher-pressure drop. Further, the pressure drop tends to reach a constant value for the operated range of gas–liquid flowrates.

Effect of the liquid flow rate

It is evident from the Fig. 4 that the pressure drop increases with liquid flow rate. At higher liquid rates, the greater volume of liquid not only increases the gas–liquid velocity, but also assists in producing a

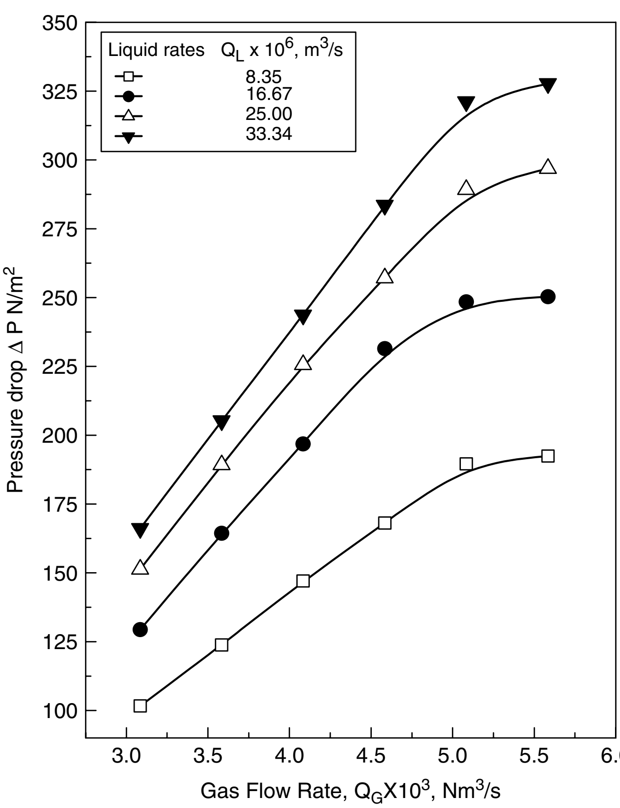

Figure 3. Effect of gas rate on the overall pressure drop of the spray column at constant liquid rate and inlet solid concentration.

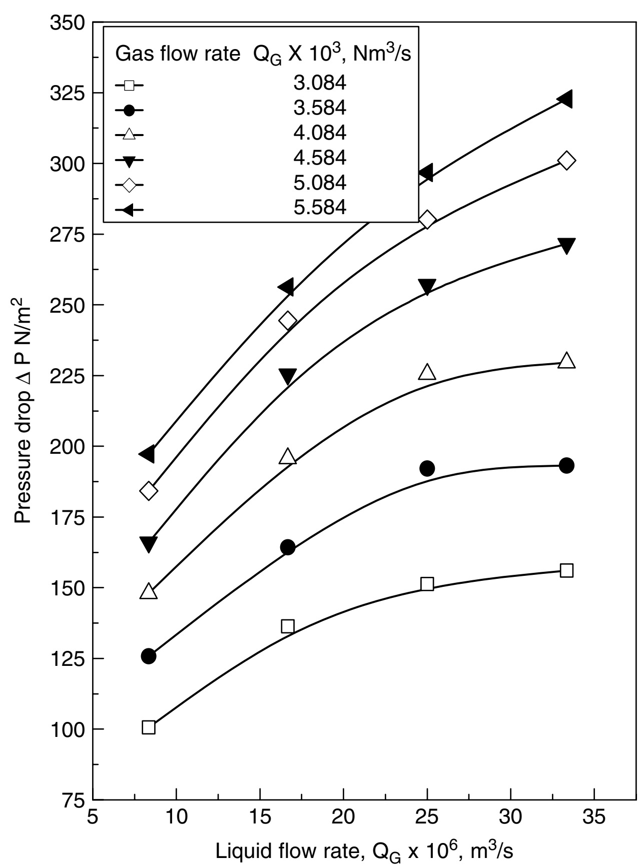

Figure 4. Effect of liquid rate on the overall pressure drop of the spray column at constant gas rate with inlet solid concentration of 2.5×10^{-3} kg/m^3.

DOI: 10.1002/apj

comparatively larger number of drops (Schuer *et al*., 1951).[9,10,11] The quality of impaction and interception, is improved due to increase in number of droplets and hence it leads to higher losses of pressure. The maximum energy lost in the form of pressure drop within the spray column is around 327 N/m^2 for the liquid rate of 33.34×10^{-6} m^3/s, the gas rate of 5.584×10^{-3} Nm^3/s and the inlet solid loading of 2.5 kg/m^3 of the gas. This is quite a low value compared to other scrubbers and conventional devices available in industrial market today.

Development of correlation and pressure drop prediction

To estimate the overall pressure drop of the spray column, an empirical model has been developed by dimensional analysis and the pressure drop from the measurable parameters was predicted. From the experimental data obtained, it is clear that for the operating range of inlet solid loading rates, a very small or insignificant effect on the pressure drop was observed and so it was deliberately excluded from further analysis of the pressure drop studies. From the experimental results it was seen that the overall pressure drop within the spray column might be influenced by the following parameters: geometrical parameters namely, (1) droplet SMD, d_O, (2) particle SMD, d_p, flow conditions namely, (3) droplet slip velocity, V_L, (4) superficial gas velocity V_G, design aspects namely, (5) spray-column diameter, D_C, (6) spray-column height H_C, physical parameters namely, (7) droplet density, ρ_L, (8) gas density ρ_G, (9) gas viscosity, μ_G, (10) droplet viscosity, μ_L and finally (11) acceleration due to gravity, g.

The pressure drop thus becomes a function of 11 sensitive parameters, each of them trying to exert its influences:

$$\Delta P = f\ (V_L, V_G, D_C, H_C, \rho_G, \rho_L, \mu_G, \mu_L, d_O, d_P, g) \tag{3}$$

The dimensionless analysis, using the Buckingham π-Theorem yields the following Eqn (4):

$$\Delta P = k_0[Fr_L]^a[Re_G]^b[Re_L]^c\left[\frac{d_O}{D_C}\right]^d \tag{4}$$

On the basis of the experimental data, the correlation obtained by multiple linear regressions analysis is given as Eqn (5) which is the most closely related correlation on the statistical analysis, giving the minimum percentage of error and standard deviations.

$$\Delta P = 1.78141 \times 10^{-4}[Fr_L]^{-1/8}[Re_G]^{1/4} [Re_L]^{5/8}\left[\frac{d_O}{D_C}\right]^{-5/8} \quad N/m^2 \tag{5}$$

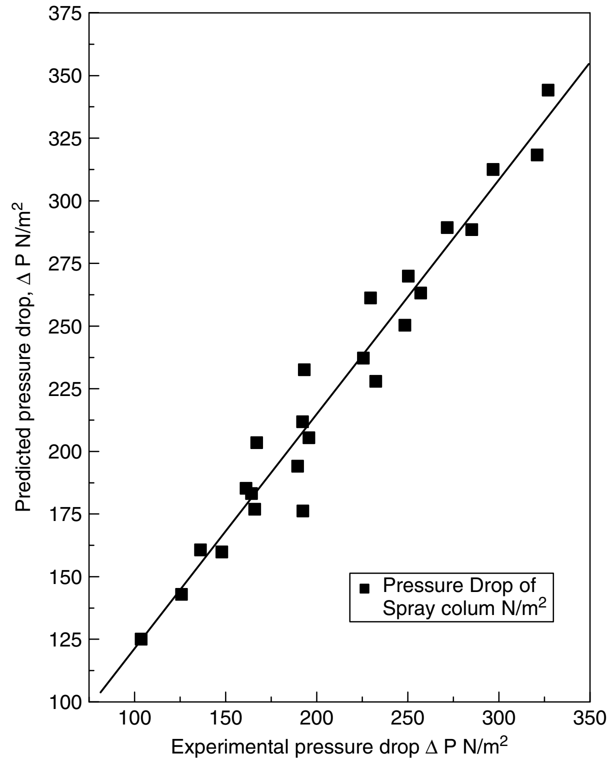

Figure 5. Comparison of the experimental and predicted values of pressure drop of the fly ash scrubbing in the spray column.

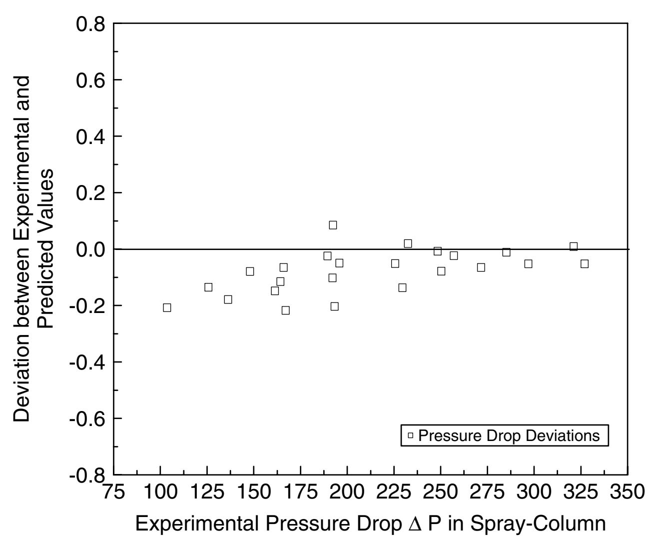

Figure 6. Deviation between the experimental and predicted values of pressure drop.

The variance (σ^2) of estimates $S^2(Y)$ and regression correlation coeffecients of the above equations are 1.0742×10^2 and 0.97651 respectively for a value of 1.711 at 0.05 probability and 95% confidence range.

Figure 5 shows a comparative study between the predicted model and the experimental data obtained.

DOI: 10.1002/apj

It reflects quite a good agreement with minimum percentage error. While Fig. 6 shows the variations of the deviations of the model and experimental values, the maximum deviation is within 20%.

CONCLUSION

The aim of this study was to characterize the hydrodynamics in the spray column. Pressure drops were measured for varied gas rates and for four different liquid rates, and the values found to match excellently with those predicted from the empirical equation. However, it may be noted that a maximum difference of 20% was observed between the experimental and predicted values for lower ranges of gas–liquid rates. This may be due to the fact that, in the droplet–gas interactions, main emphasis was on inertial impaction and interception as reported by Pulley and Waters.[12] But the effect of the vapor pressure and temperature gradient between the water droplet and dust laden gas cannot be overlooked while dealing with submicron dust particles scrubbing in operations at elevated temperatures.[13] They have their respective share of influences in the development of the overall column pressure drop. Moreover, the particle size has been defined by the average particle-size distribution, which is far from being uniform in reality. Finally, employing the Rizkalla and Lefebvre empirical expression for the prediction of droplet size for the whole range of operating conditions may incorporate small errors as this equation has its own limitations. But these high deviations were observed only for few cases, and rest of the data showed a very fine agreement. A high regression coefficient value of 0.97651 with a minimum percentage of error (standard deviation) has been achieved for the experimented spray-system. However, to improve the validity of the present correlation it needs to be tested for some higher ranges of gas–liquid flowrates. The maximum energy lost in form of pressure drop under the operating conditions of the column is around 327 N/m^2. Moreover, there was not much change in pressure drop due to the variations of solid loading. The simple counter-current spray column is, therefore, hydrodynamically and energetically very efficient. However,[14] it is reported that for different types of dust which can be treated in a droplet column, an adequate liquid flow rate must be experimentally defined to allow efficient treatment without wasting energy.

NOMENCLATURE

AWR	Air to water ratio
C_{Si}	Inlet solid loading rate
D_{C}	Diameter of the column (m)
d_{O}	Liquid droplet sauter mean diameter (μm)
d_{p}	Particle sauter mean diameter (μm)
Fr_{L}	Liquid Froude number
g	Acceleration due to gravity (m/s^2)
H_{C}	Height of the column (m)
Q_{G}	Gas flow rate (Nm^3/s)
Q_{L}	Liquid flow rate (m^3/s)
Re_{G}	Gas Reynolds number
Re_{L}	Liquid Reynolds number
V_{G}	Gas velocity (m/s)
V_{L}	Liquid droplet velocity (m/s)
Δh	Head in the manometer (m)
ΔP	Pressure drop in the column (N/m^2)
ρ_{G}	Density of the gas (kg/m^3)
ρ_{L}	Density of the liquid (kg/m^3)
σ_{L}	Surface tension of liquid (N)
μ_{G}	Viscosity of the gas (kg/ms)
μ_{L}	Viscosity of the liquid (kg/ms)

Symbols

a, b, c, d	Coefficients of the correlation
k_0	Constants of the correlation
f	function
σ^2	Variance of correlation
$S^2(Y)$	Estimate of variance

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DOI: 10.1002/apj