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Abatement of SO_2 in a Multistage Counter-Current Gas-Solid Fluidized Bed Reactor

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A multistage counter-current gas-solid fluidized bed reactor operating in three stages has been designed, constructed and operated to investigate the hydrodynamics of the system. Staging of a fluidisation column with horizontal screens reduces the axial mixing of the phases and limits the formation and growth of the bubbles. The gas-solid flow mechanism, pressure drop and the solids holdup have been studied in continuous regime for two phase system over a wide range of stable operating conditions. The result of this study has great industrial importance for scale-up, design and steady operation of a multi-stage fluidized bed reactor for control of gaseous pollutants.

1. Introduction

Sulphur dioxide in flue gas generated as a result of combustion of fossil fuel in, e.g., thermal power plants, etc., is the main cause of global environmental problems such as air pollution and acid rain. Many countries have therefore adopted stringent SO_2 emission standard from industries. But, in India, the thermal power plants emit SO_2 to the atmosphere through high stacks considering dilution as control of pollution. Development of stringent SO_2 emission standard for thermal power plants in India is in progress. The other SO_2 emitting plants such as sulfuric acid plant, oil refineries comply with prescribed emission standard by wet processes resulting in generation of liquid effluent, which create more problems to handle with and dispose of. Many researchers (Paiuk-Bronikowska et al., 1991; Meitzinger, 1992) have worked on wet removal of SO_2 citing its advantages and disadvantages. Since many inherent problems are associated with wet processes, the dry processes are now promoted to control the gaseous pollutants throughout the world. However, all the dry process techniques are mostly used in fixed bed or in single stage fluidized bed reactor at high temperature, which is not suitable for removal of sulfur dioxide from flue gas in the industries. Thus the dry process to control SO_2 at lower temperature is the need of the day and the equipment to be selected for the control of sulfur dioxide must have a very high efficiency of collection. Literatures suggest that the fluidized bed reactor operating at various regimes can be used as possible equipment for removal of sulfur dioxide at high

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temperature (Kato et al., 1994; Chiang et al., 2003). But, at low temperature the efficiency of these reactors is very low besides other limitations. The limitations of a single stage continuous fluidized bed reactor can be avoided by the use of multistage continuous fluidized bed reactor due to its staging effects which, in turn, enhances separation efficiency. Therefore, a counter current multi-stage fluidized bed reactor with downcomer has been developed to investigate the pressure drop characteristics of gas (Air-SO_2) and Solid (Hydrated lime) in the reactor.

2. Methodology

2.1 Experimental set-up and techniques

Figure 1 is the schematic of the multi-stage fluidized bed reactor developed and used in this study. The reactor consisted of a three stage fluidization column having provision of solid feeding from the top and air supplying system from the bottom. Each stage of the column was constructed of perspex cylinder of 0.10 m ID and 0.305 m long. The SS plates of 0.002 m thick each were used as internal baffles between two stages having 8.56% total grid openings (Siegle, 1976). The grid plates were covered with fine wire mesh (100 mesh size) to prevent the solids from the falling through the openings. Each section was provided with a downcomer of perspex cylinder of 0.025m ID and the downcomers were fitted to the gas distributor by special threading arrangement having the provision for adjusting the weir height as desired. The pressure taps at each stage of the reactor and whole column were provided and connected to U-tube manometers

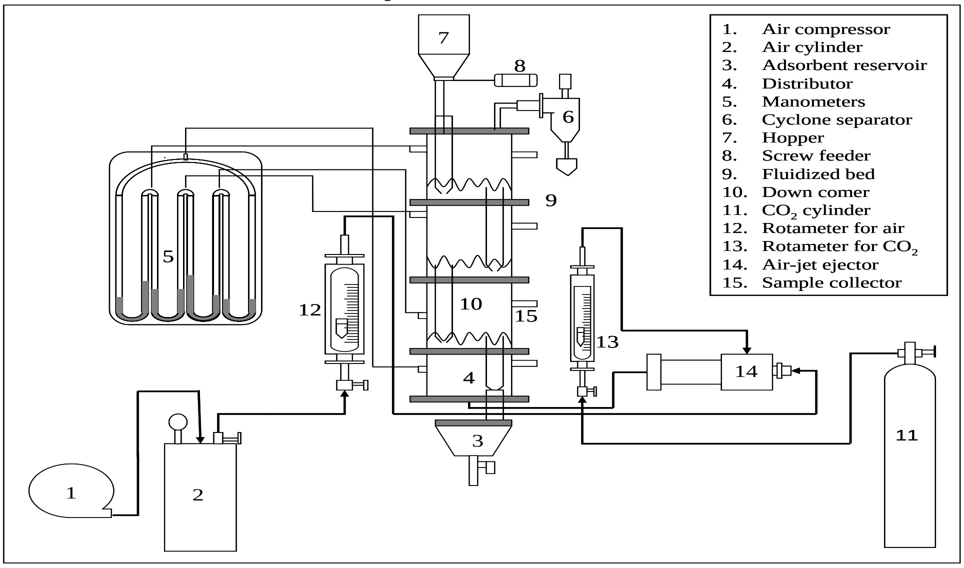


Figure 1: Schematic diagram of the experimental set-up of a three-stage counter-current fluidized bed reactor

to measure the differential pressure at each stage and total pressure drop across the entire column. The air-SO_2 mixture was generated by mixing air and SO_2 in an air-jet ejector assembly for uniform gas composition. Compressed air from the compressor was used as the motive fluid in the ejector to aspirate and thoroughly mix air with SO_2

from the SO_2 gas cylinder. The air-SO_2 gas mixture was fed into chamber fitted at the bottom of the column. Pre-calibrated rotameters were used to measure the gas flow rate. The gas leaving the column from the top stage was passed through a standard cyclone and then into the exhaust system. The solids from the screw feeder were fed to the first stage downcomer of the reactor. The system was operated in bubbling regime within stable operating range for two phase system and all the stages had sufficient bed material.

2.2 Operating range of experimental conditions

The flow properties of hydrated lime such as particle size, density, porosity, sphericity and minimum fluidization velocity were determined using standard established procedures. Table 1 shows the flow properties of bed materials.

Table 1 Properties of bed materials

Material	Density ($\rho_{S)}$, Kg/m^3	Particle size (d_p), μm	Minimum bed porosity, ε_{mf}	Sphericity $Ø_s$	Minimum fluidization velocity (m/s)
Lime	2040	426	0.48	0.7	0.112

Experiments were conducted at gas flow rate (G_a) in the range from 31.27 x 10^{-2} to 56.4 x 10^{-2} $kg/m^2 \cdot s$ corresponding to solid flow rate (G_s) varying from 35.4 x 10^{-3} to 141.5 x 10^{-3} $kg/m^2 \cdot s$. The weir heights (h_W) of the downcomer were kept at 3 x 10^{-2} m and 7 x 10^{-2} m. The study was carried out at room temperature and pressure 1 *atm*.

3. Results and Discussion

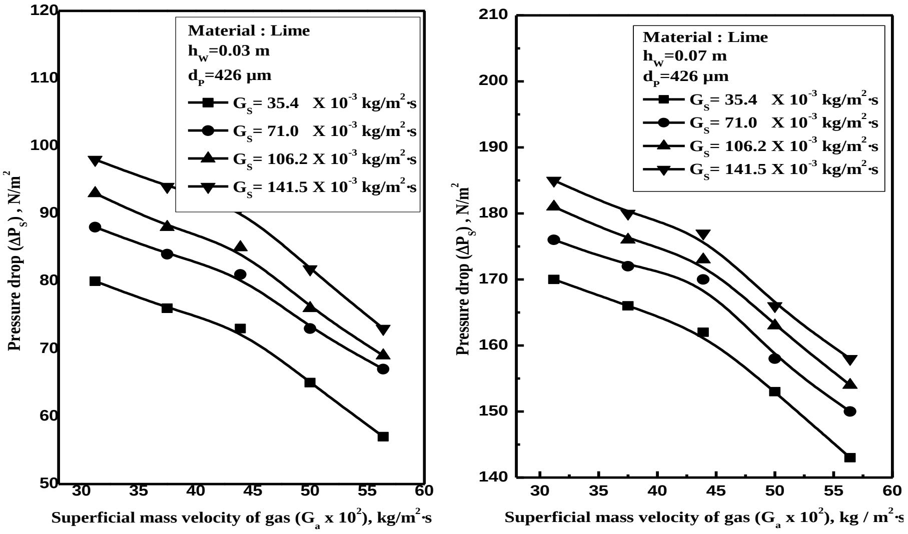
3.1 Gas solid flow mechanism

When the solids are introduced into top most stage by downcomer, the solids get discharged into fluidized bed. The discharge of solids from downcomer is complicated due to presence of other solids and also changes in direction of flow of solids. Once in the bed, the solids move across the tray towards the overflow line. The solid movement across the tray is expected to be governed by the number of inter particle collisions and the air cushion provided by the up moving gas. At the overflow, the solids tend to move down to the stage below. The process is repeated on each stage till the solids are discharged from the column. The solid flow is downward in the downcomer, while it is cross flow on the grid and may be up flow before its entry into the overflow weir. Thus the behavior of a multistage column was observed to be governed by (i) Feeding mechanism and solids flow in the downcomers (ii) Flow of solids across the tray (iii) Flow of solids through overflow weir in to the downcomers. Since the solids flow in the downcomers is affected due to the presence of gas, it is considered as slowest transfer rate which ultimately detect the overall rate of flow of solids in the column. In the entire column as a whole, solids flow is counter current to the gas flow.

3.2 Pressure drop variation

The gas pressure drop corresponding to perforated plate in absence of solids was measured at different mass velocity of gas. While operating the system with solids, the system was considered to be stable when all the stages of the reactor were identical in their operation as well as performance. The pressure drops across each stage and across the entire column were recorded. No discernible difference in the pressure drop across the stage was noticed from stage to stage. In view of identical performance, the pressure drop due to solids was obtained from the difference between the total column pressure drop with and without solids. Dividing it by the number of the stages gives ΔPs, the pressure drop due to solids per stage of the multistage fluidization column.

3.2.1 Effect of superficial mass velocity of gas on pressure drop



a) b)

Figure 2: Effect of superficial mass velocity of gas (G_a) on pressure drop (ΔP_s) for lime particles at a) h_W = 0.03 m b) h_W = 0.07 m.

Figure 2 describes the effect of mass velocity of gas on pressure-drop due to lime particles (ΔP_S) across each stage at different mass velocity of solids and weir heights. It may be seen from the figures that the pressure drop due to solids, ΔPs, decreased with increase in the mass velocity of gas. This was mainly due to the fact that at higher mass velocity of gas, the movement of the particles increases in bed leading to outflow resulting in decrease in solids concentration in bed. The decrease in solids concentration decreases the frictional and impact forces between gas-solid resulting in decrease in pressure drop. It was observed that the minimum pressure drop occurred at minimum mass velocity of solids corresponding to maximum mass velocity of gas and the maximum pressure drop occurred at minimum mass velocity of gas corresponding to maximum mass velocity of solids. The minimum pressure drops occurred in the column at high mass velocity of gas (56.4 x 10^{-2} kg/m^2·s) corresponding to minimum mass velocity of solids (35.4 x 10^{-3} kg/m^2 ·s) is 57.0 and 143.1 N/m^2 at 0.03 and 0.07 m weir height respectively. The maximum pressure drops occurred in the column at low mass velocity of gas (31.2 x 10^{-2} kg/m^2·s) corresponding to maximum mass velocity of solids (141.5 x 10^{-3} kg/m^2·s) are 98.4 and 185.1 N/m^2 at 0.03 and 0.07 m weir height respectively. At a particular mass velocity of solids and gas, increasing the weir height increases the bed volume resulting in increase in solids concentration and thus, pressure drop. The total column pressure drop was found to be in the range of 170 to 555 Pa for the given operating condition

3.2.2 Empirical correlation for friction factor

The theoretical equation, which gives the friction factor, is as follows;

$$f = \frac{\Delta P_s}{0.5 \rho_g u_g^2} \cdot \frac{d_p}{h_w} \qquad (1)$$

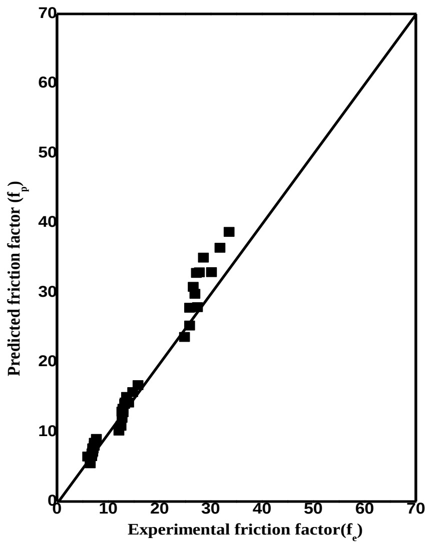


Figure 3: Comparison of the experimental and predicted friction factor

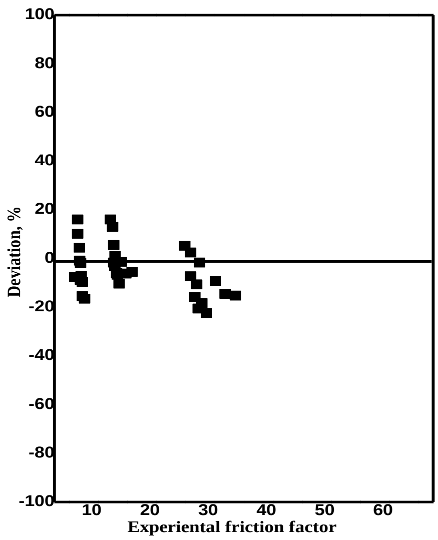


Figure 4: Deviation between experimental and theoretical friction factor

An attempt has been made to correlate the friction factor with variables of the system. The most closely related correlation on the statistical analysis which yields the minimum percentage error, presents the best possible correlation as follows:

$$f = \left[\frac{u_s}{u_g}\right] \left[\frac{g d_p}{u_g^2}\right] \left[\frac{d_p}{h_w}\right] \left[\frac{\rho_s - \rho_g}{\rho_s}\right] \qquad (2)$$

The correlation coefficient and the standard deviation of the experimental data from regression analysis are found to be 0.8738 and 4.43 respectively. The predicted values of friction factor (f_p) from Eq. (2) have been plotted against the experimental values (f_e) in Figure 3. The comparison between the experimental friction factor and that of predicted from the model indicates that there is an excellent agreement with minimum percentage error. The deviation of the model from the experimental values is found to be within 25 % and it is presented in Figure 4.

3.3 Variation in solids hold-up

The expression 'solid hold-up' is used to mean the amount of solids retained on each plate when the fluidized bed column is in operation. Once the system was allowed to reach equilibrium, the gas and the solids flow was then cutoff simultaneously and the solids were weighed. Theoretically, the relation between pressure drop and solids hold-up may be written as;

$\Delta P_S = K\,(W/A)$ (3)

For ideal condition, K=1.0. A comparison of ΔP_s with total weight of the solids on the plate computed from the holdup shows

$$\Delta P_s = 0.94\frac{W}{A} \quad (4)$$

Equation 4 indicates that more than 94% of the material in the stage at any instant is in fluidized state. Since the solids holdup is directly proportional to the pressure drop, the variation in solids holdup follow the trend in the way the pressure drop varies.

4. Conclusions

The maximum pressure drop occurred in the column at low gas flow rate corresponding to maximum solid flow rate. The empirical correlations were developed to estimate the pressure drop of the bed on the stage during the continuous operation of the multistage fluidized bed column. Experimental results are in excellent agreement with the correlations. The maximum solids hold-up occurred at each stage of the column at low gas flow rate corresponding to maximum solid flow rate. This justified the present multistage system, where the solids hold-up achieved is three times higher than the single-stage system for the same superficial gas and solid velocities. The hydrodynamic data presented in this study assume significance from the perspective of design and stable operation of staged fluidized bed reactors.

Nomenclature

A	cross-sectional area of column (m^2)
*d*p	diameter of the particle (m)
f	friction factor
g	acceleration due to gravity (m/s^2)
*G*a	mass velocity of air (kg/ ($m^2 \cdot$ s)
*G*s	mass velocity of solids (kg/ ($m^2 \cdot$ s)
*h*w	weir height (m)
ΔP_S	pressure drop due to solids
*u*g	superficial velocity of air (m/s)
*u*s	flow rate of solids (m/s)
W	weight of solids in bed (kg)

Greek symbols

ρg	density of air (kg/m^3)
ρ_s	bulk density of solid materials (kg/m^3)

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