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Hydrodynamics of a Three-phase Semi-fluidized Bed with Irregular Particles

H. M. Jena*[a], G. K. Roy[a] and B. C. Meikap[b]

Department of Chemical Engineering
[a]National Institute of Technology, Rourkela-769008, INDIA
[b]Indian Institute of Technology, Kharagpur-721 302, INDIA
*E. Mail: **hara_jena@rediffmail.com**, gkroy@nitrkl.ac.in, bcmeikap@iitkgp.ac.in*
** Tel.: 91-661-2462264(O) / 2463264(R), fax: +91-661-2462999*

In the present study hydrodynamic characteristics of a co-current gas-liquid-solid three-phase semi-fluidized bed has been studied using liquid as the continuous phase and gas as the discontinuous phase Experiments have been conducted in a 100 mm ID, 2m-height vertical Plexiglas column using air, water and dolomite in order to develop a good understanding of each flow regime in gas-liquid-solid semi-fluidization. It is found that pressure drop increases with increase in particle size, gas velocity and bed expansion ratio. The minimum liquid semi-fluidization velocity increases with particle size, bed expansion ratio, but decreases with gas velocity. The height of the top packed bed increases with liquid and gas velocities, but decreases with particle size and bed expansion ratio.

Keywords: three-phase semi-fluidization, pressure drop, minimum and maximum semi-fluidization velocity, top packed bed.

1. INTRODUCTION

Due to increasing popularity of semi-fluidized bed, as it overcomes some inherent disadvantages of both fluidized and fixed beds, more investigations are carried out to get acquainted with the bed behaviour. The phenomenon of semi-fluidization was first reported, which was related to mass transfer in a liquid solid system [1]. A semi-fluidized bed which is characterized by a fluidized bed and a fixed bed in series within a single contacting vessel is formed when a mass of fluidized particles is compressed by fluids with a porous retaining grid fixed at the top. The internal structure of a semi-fluidized bed can easily altered to create an optimal operating configuration. This unique feature of a semi-fluidized bed allows it to be utilized for a wide range of physical, chemical and biochemical applications [2].The semi-fluidized beds find wide applications as reactors for exothermic reactions and bioreactors, in ion exchange and in filtration operation for the removal of suspended particles from gases or liquid. Studies of semi-fluidization have been mainly limited to the gas-solid or liquid-solid systems [3]. However, limited information however is available on semi-fluidization in the gas-liquid-solid systems [4]. Hydrodynamic study on cocurrent gas-liquid solid semi-fluidization with liquid as the continuous phase has carried out by Chern et al. [2], Separate investigations were performed on a packed bed and a fluidized bed under gas-liquid flow conditions. Parameters like pressure drop, gas holdup, onset liquid velocity for semi-fluidization, and the height of the packed bed and fluidized bed sections were studied by them. A mathematical model was also developed to predict the pressure drop and compared with the experimental values [2]. Singh et al. have investigated the pressure drop of a semi-fluidized bed with irregular solid particles in a single experiment and have developed a correlation for pressure drop from dimensional analysis [3].

In view of the limited study on semi-fluidization in a three-phase system, the present study have been conducted to predict the hydrodynamic behaviour such as pressure drop, minimum semi-fluidization velocity, rate of top packed bed formation, ratio of packed bed to fluidized bed etc. in which co-current flow of a gas and a liquid takes place in a bed of dolomite particles of various size.

2. EXPERIMENTAL

A schematic representation of the experimental setup is shown in Figure-1. The vertical Plexiglas fluidizer column is of 100 mm ID with a maximum height of 2m. The column consists of three sections, v.i.z., the gas-liquid disengagement section, test section, and gas-liquid distributor section. The gas-liquid distributor is located at the bottom of the test section and is designed in such a manner that uniform distribution of the liquid and gas can be maintained in the column. The distributor section made of Perspex is fructo-conical of 0.31 m in height, has a divergence angle of 4.5^0 with one end of 0.0508 m in internal diameter and the other end of 0.1 m in internal diameter. In between distributor section and test section there is a perforated distributor plate made of G.I. sheet of 0.001 m thick, 0.12 m diameter having open area 20 % of the column area. There is an antenna-type air sparger just below the distributor plate containing 50 numbers of 0.001 m holes, for generating uniform bubbles. In this section the gas and liquid streams are merged and passed through the perforated grid. The mixing section and the grid ensured that the gas and liquid are well mixed and evenly distributed into the bed. The gas-liquid disengagement section at the top of the column is a cylindrical section of 0.026 m internal diameter and 0.034 m height, assembled to the test section with 0.08 m of the test section inside it, which allows gas to escape and liquid to be circulated through the outlet of 0.0254 m internal diameter at the bottom of this section. A movable top grid is provided in the test section to achieve semi-fluidization. Bed pressure drop has been measured using U-tube mercury manometers.

The three phases (solid, liquid and gas) present in the column are dolomite, tap water and the oil free compressed air. The scope of the experiment is shown in Table-1. The flow of air and water is co-current and upward. Accurately weighed amount of material was fed into the column and adjusted for a specified reproducible initial static bed height. Keeping gas flow rate constant at different values, the liquid flow rate is varied using the control valves and bypass adjustment. The bed pressure drop is measured from manometer reading and packed bed formation noted down visually for different particle size, bed expansion ratio and static bed heights. The bed pressure drop and bed expansion is noted and used to predict the minimum semi-fluidization velocity. The maximum semi-fluidization velocity is predicted from the extrapolation of the plot of Hpa/Hs vs. superficial liquid velocity.

3. RESULTS AND DISCUSSION

3.1 Pressure Drop and Minimum Semi-fluidization Velocity

The Minimum semi-fluidization velocity or onset velocity of semi-fluidization is defined as the fluid velocity at which the first particle at the top of the fluidized bed just touches the top restraint. The plot of the superficial liquid velocity (above the minimum fluidization condition) against pressure drop gives a break which corresponds to the minimum liquid semi-fluidization velocity (U_{lmsf}). The minimum liquid semi-fluidization velocity (U_{lmsf}) in this study has been obtained from the relationship between pressure drop and superficial liquid velocity. Fig. 2 shows the variation of pressure drop with superficial liquid velocity for gas-liquid-solid system at various superficial gas velocities. From this it is observed that the minimum liquid semi-fluidization velocity decreases with increase in gas velocity. It shows steady decrease in minimum liquid semi-fluidization velocity with gas velocity. The values of U_{lmsf} at different superficial gas velocities are listed in Table-2.

Fig. 3 shows the variation of pressure drop with superficial liquid velocity at constant gas velocity, particle size and static bed height for different bed expansion ratios. The expansion ratio in the semi-fluidized bed is defined as the ratio of the height of top grid to the initial static bed height of the solid particles. The pressure drop is more for low expansion ratio for the same liquid velocity due to higher packed bed formation. The minimum liquid semi-fluidization velocity increases with expansion ratio.

A correlation has been developed for the minimum liquid semi-fluidization velocity. The results have been fitted to a power-law equation passing through origin which is as under,

$$U_{lmsf} = 0.3832(dp)^{0.4373}(R)^{0.3982}(Ug)^{-0.2354} \quad (1)$$

(with a standard deviation of 0.00785 and a correlation factor of 0.9821).

The correlation is found to agree well with experimentally determined minimum liquid semi-fluidization velocities and is shown in Fig. 5. It is clear from the plot that the correlation perfectly fits other experimental values obtained by varying the parameters like U_g, R, and d_p.

3.2 Height of Top Packed Bed and Maximum Liquid Semi-fluidization Velocity

Due to arrest of the free expansion of the fluidized bed by the top retaining grid a packed bed is formed at the top. The extent of packed bed formation is expressed as the ratio of packed bed height to the initial static bed height. The liquid velocity at which all the solid particles are supported by fluid in top packed bed at a constant gas velocity is called the maximum liquid semi-fluidization velocity. The maximum semi-fluidization velocity can be obtained by plotting porosity of fluidized bed against the superficial fluid velocity or the extrapolation of the plot of H_{pa}/H_s to the value of 1.

It has been observed that for a fixed liquid superficial velocity, H_{pa}/H_s increases with increase in gas velocity (Fig. 6). There is almost linear increase in the packed bed height with increase in gas velocity. The plot of H_{pa}/H_s vs liquid superficial velocity for different gas velocities almost approaches parallel nature with increase in liquid superficial velocity. The curves of variation of H_{pa}/H_s with superficial liquid velocity has been extrapolated to H_{pa}/H_s=1 to get the values of maximum liquid semi-fluidization velocities for different superficial gas velocities. It has been observed that maximum liquid semi-fluidization velocity decreases with increase in superficial gas velocity.

4. CONCLUSIONS

The results and discussion relating to bed pressure drop, minimum and maximum liquid semi-fluidization velocity, and top packed bed height provide an insight to the dynamics of co-current gas-liquid-solid three phase semi-fluidized systems, which is a prerequisite for consideration of potential application of such systems to waste water treatment and mass transfer. The developed correlation for minimum and maximum semi-fluidization velocity can be used as the limit of the operating conditions. The study will help in successful design and operation of a three-phase semi-fluidized bed reactor.

NOMENCLATURE

d_p	Particle diameter, [m]
H_{pa}	Top packed bed height, [m]
H_s	Static bed height, [m]
R	Bed expansion ratio
U_l	Superficial liquid velocity, [m/s]

U_g	Superficial gas velocity, [m/s]
U_{lmsf}	Onset liquid velocity or minimum liquid velocity for semi-fluidization, [m/s]
U_{lMsf}	Maximum liquid semi-fluidization velocity, [m/s]

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Fig. captions

Fig. 1. Schematic representation of a Three-Phase Semi-Fluidized Bed

Fig. 2. Variation of bed pressure drop with liquid velocity for different gas velocities at [d_p=0.00405 m, R=2, hs=0.171m].

Fig. 3. Variation of bed pressure drop with liquid velocity for different bed expansion ratios at [d_p=0.00405 m U_g=0.0764 m/s, hs=0.171m].

Fig. 4. Variation of bed pressure drop with liquid velocity for different particle sizes at [R=2 , U_g=0.0764 m/s, hs=0.171m].

Fig. 5. Comparison of minimum liquid semi-fluidization velocity experimental and calculated from Eq. (1).

Fig. 6. Variation of H_{pa}/H_s with liquid velocity for different superficial gas velocities at [d_p=0.00405 m, R=2, hs=0.171m].

Table 1: Scope of the Experiment

Particle size, m and particle density , kg.m^{-3}	Static bed height, m	Expansion ratio	Fluidizing medium	
			Liquid	Gas
0.00155, 2652 0.00218, 2652 0.00307, 2652 0.00405, 2652	0.176 0.216 0.256 0.296	2.0 2.5 3.0 3.5	Water at 30 ± 5^{0}C of density 997.4 kg.m^{-3} and viscosity 0.095 Pa	Air at 30 ± 5^{0}C of density 1.168 kg.m^{-3} and viscosity 0.00187 Pa

Table 2: Values of minimum semi-fluidization velocities

For d_p=0.00405 m, R=2, hs=0.171m		For d_p=0.00405 m U_g=0.0764 m/s, hs=0.171m		For R=2 , U_g=0.0764 m/s, hs=0.171m	
Ug (m/s)	**U_{lmsf} (m/s)**	**R**	**U_{lmsf} (m/s)**	**d_p (m)**	**U_{lmsf} (m/s)**
0.0000	0.1312	2.0	0.0827	0.00155	0.0546
0.0255	0.1078	2.5	0.0896	0.00218	0.0628
0.0509	0.0918	3.0	0.0965	0.00307	0.0726
0.0764	0.0841	3.5	0.1034	0.00405	0.0833
0.1019	0.0774				

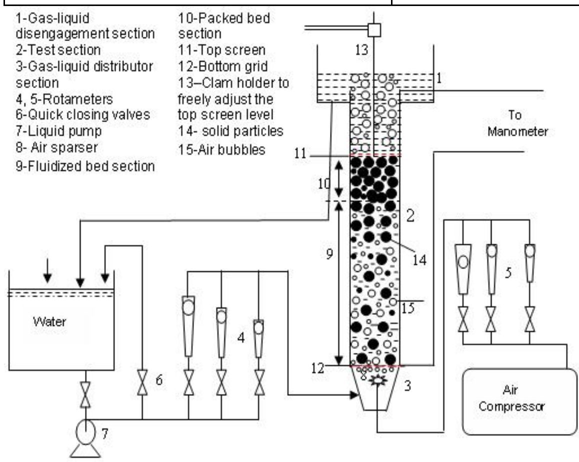


Fig. 1.

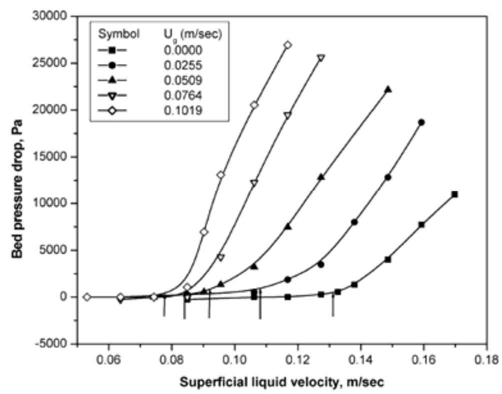


Fig. 2.

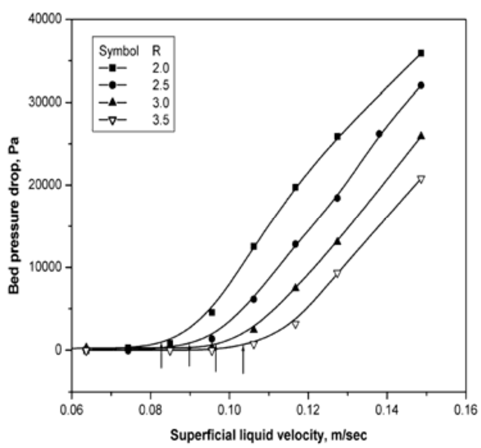


Fig. 3.

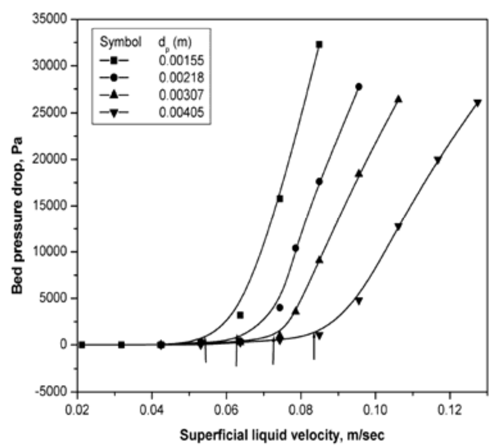
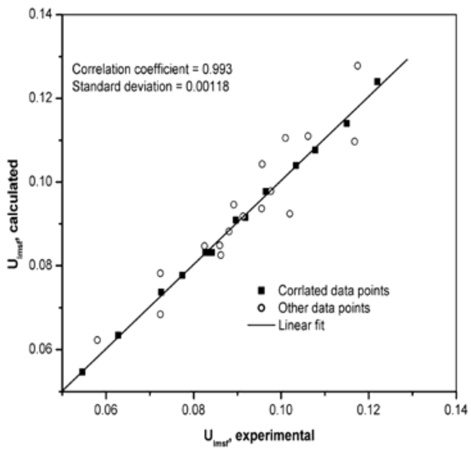


Fig. 4.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Standard deviation = 0.00118
Corrlated data points
Other data points
Linear fit
U_lmsf, calculated
U_lmsf, experimental

Fig. 5.

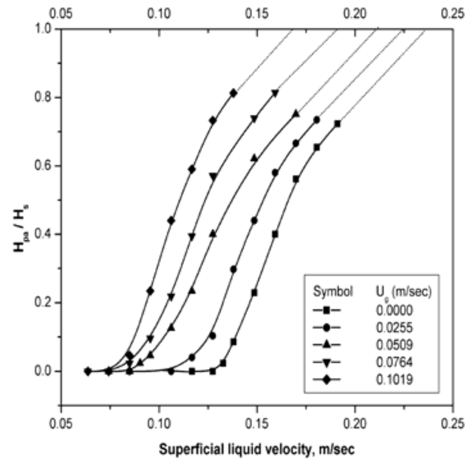
Symbol
U_s (m/sec)
0.0000
0.0255
0.0509
0.0764
0.1019
H_pa / H_s
Superficial liquid velocity, m/sec

Fig. 6.