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Experimental Hydrodynamic Study of a Three-phase Semi-Fluidized Bed

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A semi-fluidized bed is characterized by a fluidized bed (acts as CSTR) and a packed bed (acts as a tubular flow reactor) in series within a single contacting vessel. The possible alteration of the internal structure allows the device to be utilized for a wide range of physical, chemical and biochemical applications. Little information is available on semi-fluidization in the gas-liquid-solid three phase systems, which can best be used as immobilized cell bioreactor. In the present study hydrodynamic characteristics viz. the pressure drop, minimum and maximum semi-fluidization velocity, and rate of top packed bed formation 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 has been conducted in a 100 mm ID, 2m-height vertical Plexiglas column using air, water and glass beads 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 and static bed height. The minimum liquid semi-fluidization velocity (U_{lmsf}) increases with particle size but is a weak function of static bed height. U_{lmsf} decreases with gas velocity. The height of top packed bed increases with liquid and gas velocities, but decreases with particle size and static bed height.

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

INTRODUCTION

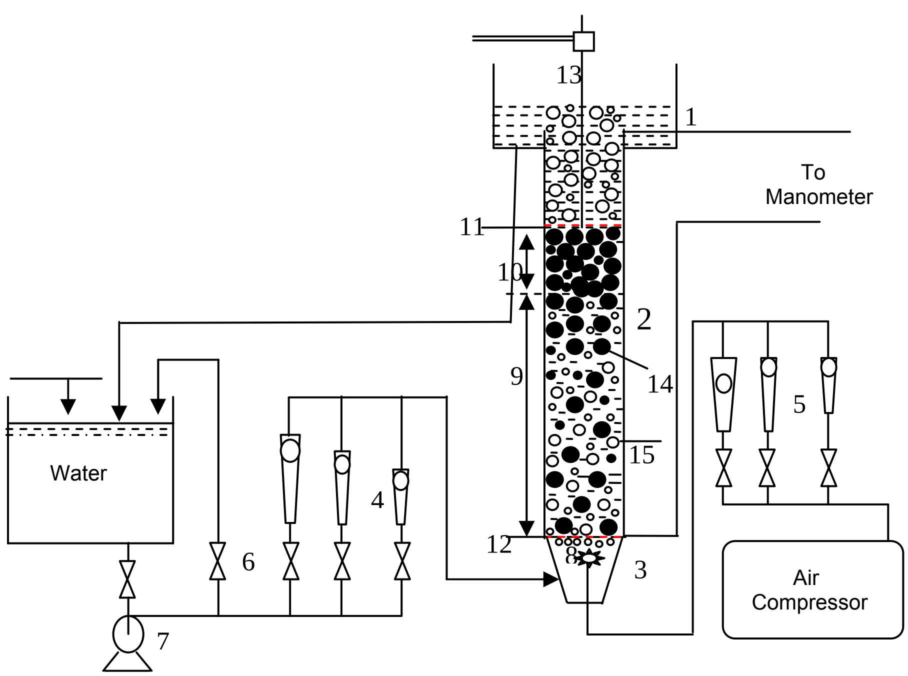
Semi-fluidization is a novel fluid solid contacting technique. The increasing popularity of semi-fluidized bed, as it overcomes some inherent disadvantages of both fluidized and fixed beds has forced to learn it more (Murthy and Roy, 1986). The phenomenon of semi-fluidization was first reported, which was related to mass transfer in a liquid solid system (Fan et al., 1959). 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 at the top. The internal structure of a semi-fluidized bed can easily altered to create an optimal operating configuration. This unique feature of semi-fluidized bed allows it to be utilized for a wide range of physical, chemical and biochemical applications (Chern et al., 1984) .The application of semi-fluidized beds has been broadly stressed by Fan and Hsu. According to them semi-fluidized beds find wide applications as reactors for exothermic and bioreactors, in ion exchange and in filtration operation for the removal of suspended particles from gases or liquid (Fan and Hsu, 1978). Studies of semi-fluidization have been mainly limited to the gas-solid or liquid-solid systems (Fan and Wen, 1961, Babu Rao and Doriaswamy, 1970, Murthy and Roy, 1986).A little information however is available on semi-fluidization in the gas-liquid-solid systems (Chern et al, 1984). Hydrodynamic study on cocurrent gas-liquid solid semi-fluidization with liquid as the continuous phase was carried out by Chern et al., separate investigation was 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 developed to predict the pressure drop and compared with the experimental values (Chern et al., 1984). Singh et al. were investigated the pressure drop of semi-fluidization with irregular solid particles in a single experiment and developed a correlation from dimensional analysis (Singh et al., 2005).

For successful design and operation of such reactor the knowledge of pressure drop, minimum semi-fluidization velocity, top packed formation etc. are required. The prediction of pressure drop is still not very accurate due to non-availability of a suitable method for the correct determination of porosity in the packed section of the semi fluidized bed. The study of semi fluidized bed has been broadly classified as prediction of minimum and maximum semi-fluidization velocities, prediction of top packed bed height, and prediction of pressure drop across a semi-fluidized bed.

In this study, experiments have been conducted to predict the hydrodynamic behaviour such as pressure drop across the semi-fluidized bed, 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 glass beads of various sizes.

EXPERIMENTAL

A schematic diagram 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 (Figure-3) is a conical frustum of 12 cm in height, with diameter of 5.08 cm and 10 cm at the two ends and having liquid inlets. A perforated plate (Figure-2) of 24 cm ID 1 mm thick, 120 mm diameter, of about 278 numbers of 2, 2.5 and 3mm pores in placed at the top of this section. There is an air sparger consists of 50 numbers of 1mm pores, well distributed. In this section the gas and liquid streams get mixed and passed through the perforated grid. The mixing section and grid ensure that the gas and liquid are well mixed and evenly distributed into the bed. Gas-Liquid disengagement section is at the top of the column, which allows gas to escape and liquid to be circulated. 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.



1-Gas-liquid disengagement section
2-Test section
3-Gas-liquid distributor section
4, 5-Rotameters
6-Quick closing valves
7-Liquid pump
8- Air sparser
9-Fluidized bed section
10-Packed bed section
11-Top screen
12-Bottom grid
13–Clam holder to freely adjust the top screen level
14- solid particles
15-Air bubbles

Figure 1: Schematic Diagram of a Three-Phase Semi-Fluidized Bed

The three phases (solid, liquid and gas) present in the column are glass beads, 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.

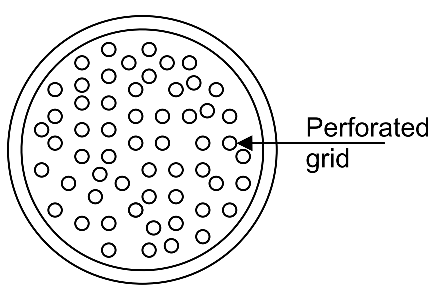


Figure 2: Schematic Diagram of The Gas And Liquid Distributor.

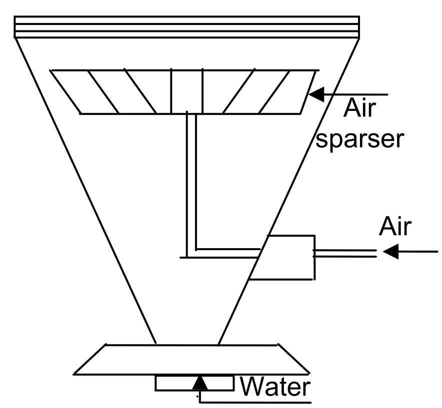


Figure 3: Schematic Diagram of Conical Calming Section.

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
0.00218, 2253	0.171	2.0	Water at 30 ± 5^{0}C	Air at 30 ± 5^{0}C of

0.00258, 2253	0.213	2.5	of density 999.4 $kg.m^{-3}$ and viscosity 0.095 Pa	density 1.168 $kg.m^{-3}$ and viscosity 0.00187 Pa
0.003075, 2253	0.256	3.0		
0.00405, 2253	0.301	3.5		

RESULTS AND DISCUSSION

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 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. Figure-4 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. The variation of minimum liquid semi-fluidization velocity with superficial gas velocity is shown in Figure-5. 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.

Table 2: U_{lmsf} in m/sec at Different U_g in m/sec for Hs=0.171m, d_p=0.00218m and R=2.

Ug = 0	Ug = 0.02123	Ug = 0.04246	Ug = 0.06369	Ug = 0.08493
0.0997	0.08934	0.0807	0.0743	0.06685

Figure-6 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.

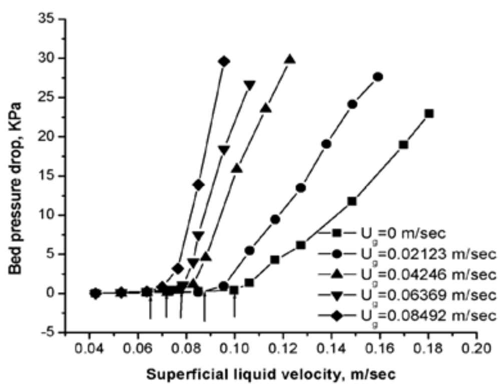


Figure 4: Variation of Bed Pressure Drop with Superficial Liquid Velocity at Different Superficial Gas Velocities for 0.00218 m Glass Beads at R=2 and Hs=0.171m.

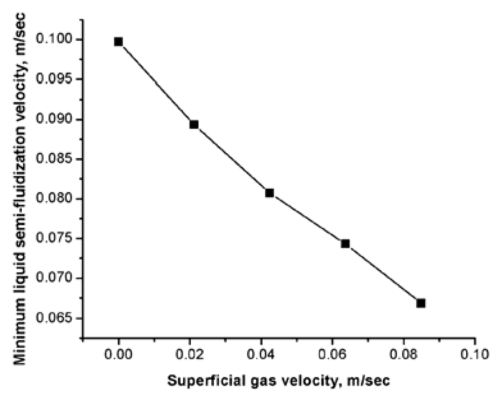
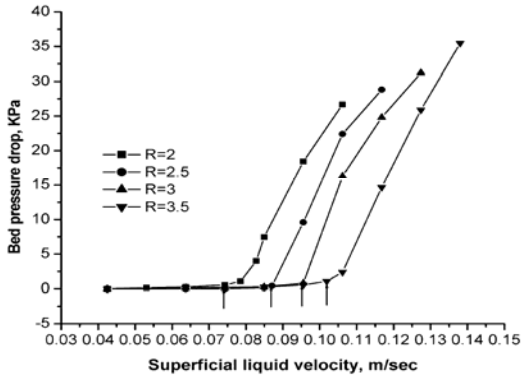


Figure 5: Variation of Minimum Liquid Semi-Fluidization Velocity with Superficial Gas Velocity for 0.00218 m Glass Beads at R=2 and Hs=0.171 m.

Figure-7 shows variation of the minimum liquid semi-fluidization velocity with bed expansion ratio. The plot shows the monotonic increase of U_{lmsf} with bed expansion ratio.



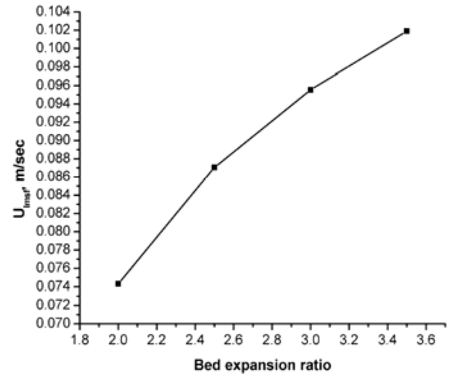


Figure 6: Variation of Bed Pressure Drop with Superficial Liquid Velocity at Different Bed Expansion Ratios for 0.00218 m glass beads at Hs=0.214 m and Ug=0.06369 m/sec.

Figure 7: Variation of Minimum Liquid Semi-fluidization Velocity with Bed Expansion Ratio for 0.00218 m glass beads at Hs=0.214 m and Ug=0.06369 m/sec.

Similarly the bed pressure drop values are plotted against the superficial liquid velocities for different static bed height and particles size with other parameters maintained at constant level. It is found that the minimum liquid semi-fluidization velocity is not a strong function of initial static bed height. There is small increase in minimum liquid semi-fluidization velocity with increase in initial static bed height, while the minimum liquid semi-fluidization velocity is a strong function of the particle size. As particle size increases minimum liquid semi-fluidization velocity increases. A correlation has been developed for the minimum liquid semi-fluidization velocity as

$$U_{lmsf} = 0.1514(U_g)^{-0.2443}(R)^{0.5207}(H_s)^{0.1796}(d_p)^{0.2304}.$$

The correlation is found to agree well with experimentally determined minimum liquid semi-fluidization velocities and is shown in Figure-8. It is clear from the plot that the correlation perfectly fits other experimental values obtained by varying the parameters like U_g, R, H_s and d_p.

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. In two-phase system there exists a clear zone in between top packed bed and bottom fluidized bed which is almost devoid of particles. This phenomenon is not observed in three-phase fluidization, but the concentration of the particles remains low in this region. This is due to discontinuous motion of the gas bubbles in the bed.

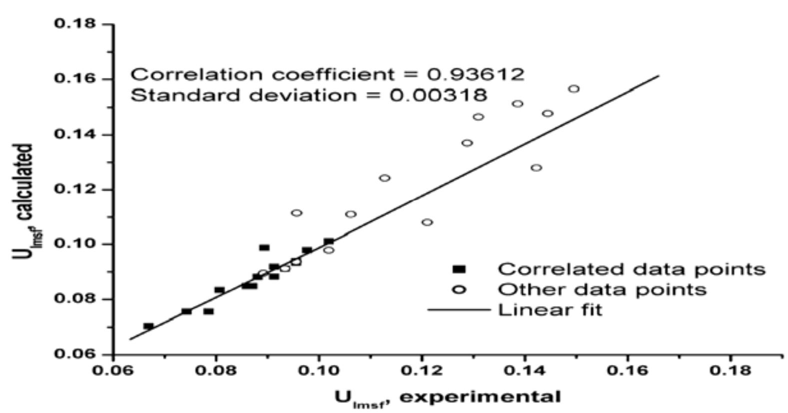


Figure 8: Plot of Calculated Value of U_{lmsf} from Correlation vs. Experimental Values of U_{lmsf}

The rate of formation of packed bed is expressed as the ratio of packed bed height (H_{pa}) to the initial static bed height (H_s). 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 (U_{lMsf}) 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.

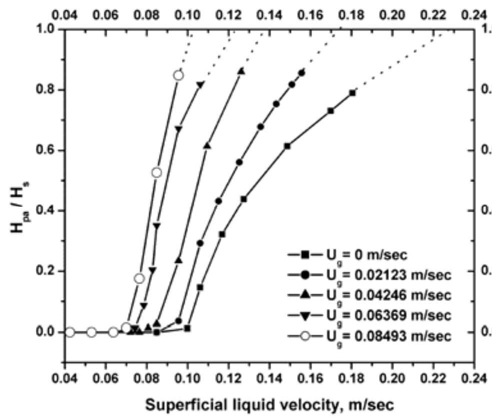


Figure 9: Variation of H_{pa}/H_s with Superficial Liquid Velocity at Different Superficial Gas Velocities for 0.00218 m Glass Beads at R=2 and H_s=0.171 m.

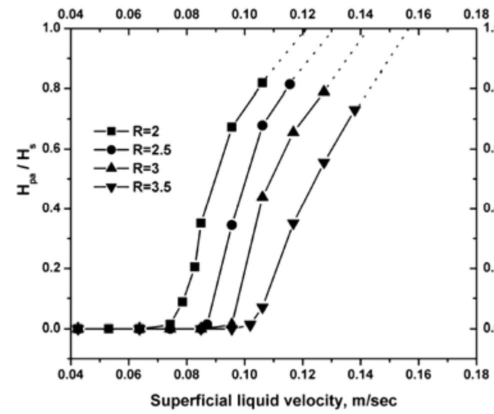


Figure 10: Variation of H_{pa}/H_s with Superficial Liquid Velocity at Different Expansion Ratio for 0.00218 m Glass Beads at U_g= 0.06369 m/sec and H_s=0.171 m.

Figure-9 shows the variation of the ratio of packed bed to initial static bed with superficial liquid velocity at different superficial gas velocities. It can be seen from the graph that for a fixed liquid superficial velocity, H_{pa}/H_s increases with increase in gas velocity. There is almost linear increase in the packed bed height with increase in gas velocity. It can be stated that the buoyancing action due to gas flow plays an important role in packed bed formation in three phase semi-fluidization. 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 are extrapolated to H_{pa}/H_s=1 to get the values of maximum liquid semi-fluidization velocities for different superficial gas velocities, as shown in the figure. It is seen from the plot that maximum liquid semi-fluidization velocity decreases with increase in superficial gas velocity. The values of U_{lMsf} at different superficial gas velocities are listed in Table-3.

Table 3: U_{lMsf} in m/sec at Different U_g in m/sec for Hs=0.171m, d_p=0.00218m and R=2.

Ug = 0	Ug = 0.02123	Ug = 0.04246	Ug = 0.06369	Ug = 0.08493
0.2275	0.1738	0.1374	0.1234	0.1027

Figure-10 shows the variation of H_{pa}/H_s with superficial liquid velocity at different expansion ratios. It can be seen from the graph that for a fixed liquid superficial velocity, the packed bed height decreases with increase in expansion ratio. It is seen that for fixed R, H_{pa}/H_s increases monotonically with increase in liquid superficial velocity. Figure-10 shows the steep increase in H_{pa}/H_s values for lower bed expansion ratios compared to beds with higher bed expansion ratios indicating higher packed bed formation in beds with lower expansion ratios. It is seen from the plot that maximum liquid semi-fluidization velocity increases with bed expansion ratio. From similar plots of H_{pa}/H_s with U_l for different static bed heights and particle size, it has been observed that H_{pa}/H_s decreases with satic bed height and particle size. The plot of Hp/Hs vs liquid superficial velocity almost approaches parallel nature with increase in liquid superficial velocity. It is seen from the plot that maximum liquid semi-fluidization velocity increases with initial static bed height and particle size.

CONCLUSIONS

The hydrodynamic study of the three-phase semi-fluidized bed with spherical particles reveals that the minimum liquid semi-fluidization velocity (U_{lmsf}) is a strong function of gas superficial velocity, particle size, bed expansion ratio but not of the initial static bed height. The pressure drop is found to increase with gas superficial velocity, particle size and decrease with bed expansion ratio for a fixed liquid superficial velocity. H_{pa}/H_s increases with gas superficial velocity, but decreases with bed expansion ratio, particle size and initial static bed height. The maximum semi-fluidization velocity decreases with gas superficial velocity and increases with particle size, initial static bed height and bed expansion ratio. The developed correlation agrees well with experimental results. 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]
ΔP	Pressure drop, [kpa]
U_l	Superficial liquid velocity, [m/sec]
U_g	Superficial gas velocity, [m/sec]
U_{lmsf}	Onset liquid velocity or minimum liquid velocity for semi-fluidization, [m/sec]
U_{lMsf}	Maximum liquid semi-fluidization velocity, [m/sec]
ρ	Phase density,[kgm^{-3}]

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