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Prediction of Pressure Drop and Top Packed Bed Height in Three-Phase Semi-fluidized Bed with Cylindrical Particles

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ABSTRACT

The phenomenon of semi-fluidization can be visualized as a combination of fluidized bed at the bottom and a fixed bed at the top. Such a reactor bed can be used in the bio-oxidation process for wastewater treatment in which various low-moderate density solid particles of different shape and size can be used as cell support. Ceramic raschig ring possess moderate density and high surface area due to its hollow cylindrical structure, thus can be used as solid support for microorganisms, where higher mass transfer rate can be achieved. In this study the hydrodynamic characteristics viz. the pressure drop, formation of top packed bed and phase hold up of a co-current gas-liquid-solid three-phase semi-fluidized bed are studied using liquid as the continuous phase and gas as the discontinuous phase. These have been done in order to develop a good understanding of each flow regime in gas-liquid and liquid-solid semi-fluidization. Air, water and ceramic raschig rings are used as the gas, liquid and solid phases respectively. The experiments were carried out in a 100 mm ID, 2m-height vertical Plexiglas column. The column consists of three sections, viz., the gas-liquid disengagement section, test section and gas-liquid distributor section. Bed pressure measurements have been made to predict the minimum liquid semi-fluidization velocity and variation of pressure drop with the top packed bed. By keeping gas velocity at a fixed value, the liquid velocity is varied and its effect on minimum liquid fluidization velocity, pressure drop and the expansion ratio is studied for different particle size and static bed height, expansion ratio and gas velocities.

Keywords: three phase semi-fluidization, pressure drop, minimum semi-fluidization velocity, bed expansion, phase holdup

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 in the subject which was concerned with the mass transfer in the semi-fluidized bed in the 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. 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). Investigation on the hydrodynamic behavior of the inverse gas-liquid-solid semi-fluidized bed where the liquid is continuous phase was done by Chern et al. A mathematical model was proposed to account for the pressure drop in the inverse gas-liquid-solid semi-fluidized bed (Chern et al., 1984). Hydrodynamic study on cocurrent gas-liquid solid semi-fluidization with liquid as the continuous phase was done by Fan et al. a separate investigation was performed on a packed bed and a fluidized bed under gas-liquid flow conditions similar to that of the fluidized bed. Parameters like pressure drop, gas holdup, onset liquid velocity for semi-fluidization, and the height of the packed bed section and fluidized bed section were studied by them. A mathematical model was developed to predict the pressure drop and compared with the experiments Chern et al., 1984). Singh et al. were investigated the pressure drop in a single experiment for semi-fluidization with irregular solid particles 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 semi-fluidized bed can be best used as an immobilized biochemical reactor where the top packed bed will act as a polishing section. Particles of the shape of raschig rings can provide high surface area for microbial growth and mass transfer hence can be best utilized as the solid support in such reactors. 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 semi-fluidized bed.

In this study, experiments are done 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 hollow cylindrical particles with moderate density.

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, one end 5.08 cm in diameter and the other end of 10 cm diameter having liquid inlets one of 24 cm ID with a perforated plate (Figure-2) made of G.I. sheet of I 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 a gas distributor consists of 50 numbers of 1mm pores placed randomly. In this section the gas and liquid streams merged 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. For pressure drop measurement the pressure ports are being fitted to the U-tube manometers of 1m & 0.5m long filled with mercury and carbon tetrachloride.

The three phases (solid, liquid and gas) present in the column were raschig rings L=OD= 6.6mm, ID= 3.3mm and L=OD= 11.2mm, ID= 5.6mm, tap water and the oil free compressed air. The properties of the bed material, the fluidizing medium and the manometric fluid are shown in Table-1. The air-water flow are co-current and upwards. Accurately weighed amount of material was fed into the column and adjusted for a specified initial static bed height. Four initial static bed heights Hs=15.4 cm, Hs=21.4 cm, Hs=26.4 cm and Hs=31.4 cm are used in this experiment. 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. Similarly keeping the liquid flow rate constant at desired values, the air flow rate varied and above experiments repeated. The bed pressure drop and bed expansion is noted and used to predict the minimum semi-fluidization velocity. The maximum fluidization velocity is predicted from the extrapolation of the plot of H/Hs.

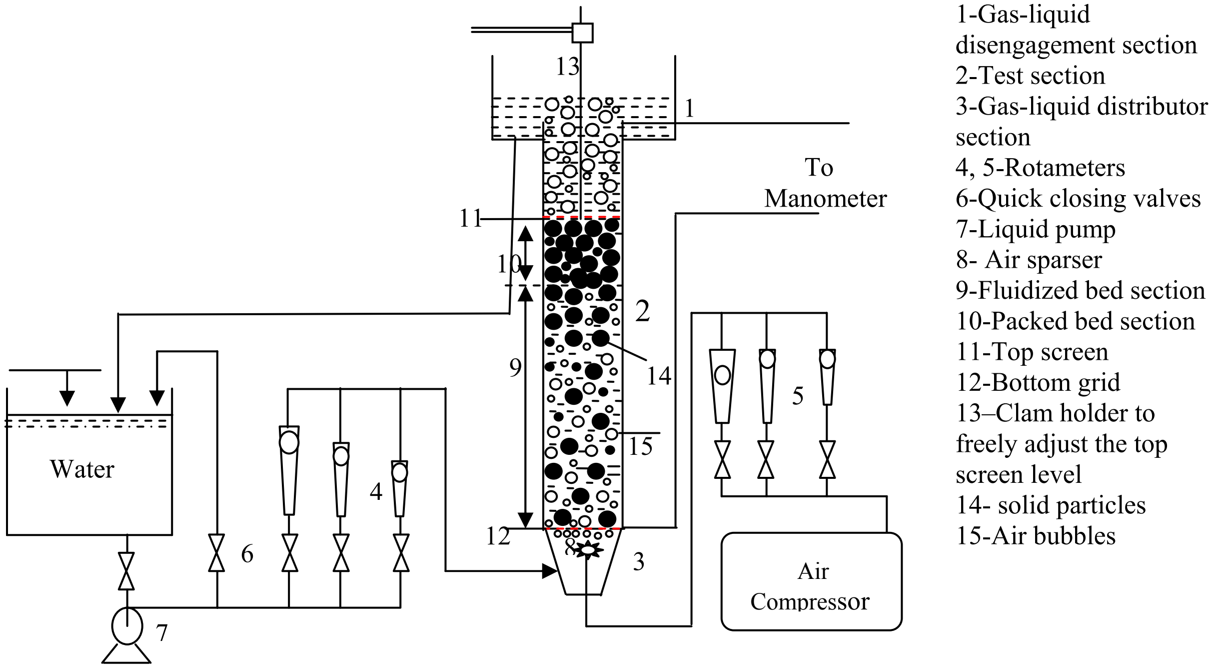

Figure 1: Schematic diagram of a three-phase semi-fluidized bed

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 against pressure drop gives a break which corresponds to the minimum liquid semi-fluidization velocity (Ulosf).

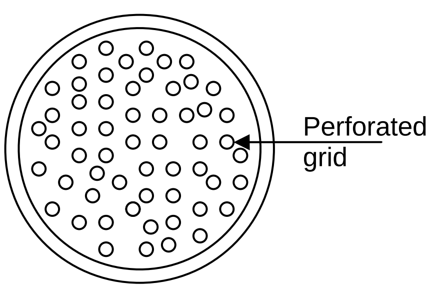

Figure 2: Schematic diagram of the gas and liquid distributor.

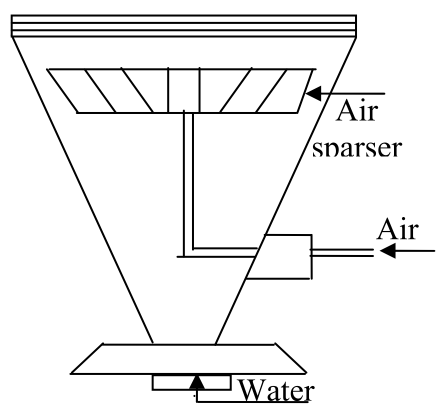

Figure 3: Schematic diagram of conical calming section.

Table 1: Properties of Bed Materials (A), Fluidizing Medium (B), Manometric Fluid (C)

A. Properties of Bed Materials

Particle Notation.	Materials	L = OD, mm	ID, mm	ρ_p (kg.m^{-3})
P1	Ceramic raschig ring	11.2	5.6	1670

P2	Ceramic raschig ring	6.6	3.3	1670

B.Properties of Fluidizing Medium

Fluidizing Medium	ρ (kg.m^{-3})	μ (Ns/m^2)
Air at 30^{0}C	1.168	0.00187
Water at 30^{0}C	999.4	0.095

C.Proprties of Manometric Fluid

Manometric Fluid	ρ (kg.m^{-3})	μ (Ns/m^2)
Mercury	13600	0.15
Carbon Tetra-Chloride (CCl_4)	1600	0.09

The minimum liquid semi-fluidization velocity (Ulosf) in this study is 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 initial sharp decrease in minimum liquid semi-fluidization velocity with gas velocity but then the rate of decrease is slow. This indicates the bubble supported fluidization in presence of gas i.e. the enhancement of the bed expansion with gas bubbles. The values of Ulosf are listed in Table-2a.

Table 2a: Ulosf in m/sec for different particle sizes, gas velocities for Hs=21.4 cm.

Dp, mm	Ug = 0 m/sec	Ug = 0.02123 m/sec	Ug = 0.04246 m/sec	Ug = 0.06369 m/sec	Ug = 0.08492 m/sec
6.6	0.138	0.104	0.0976	0.0891	0.0764

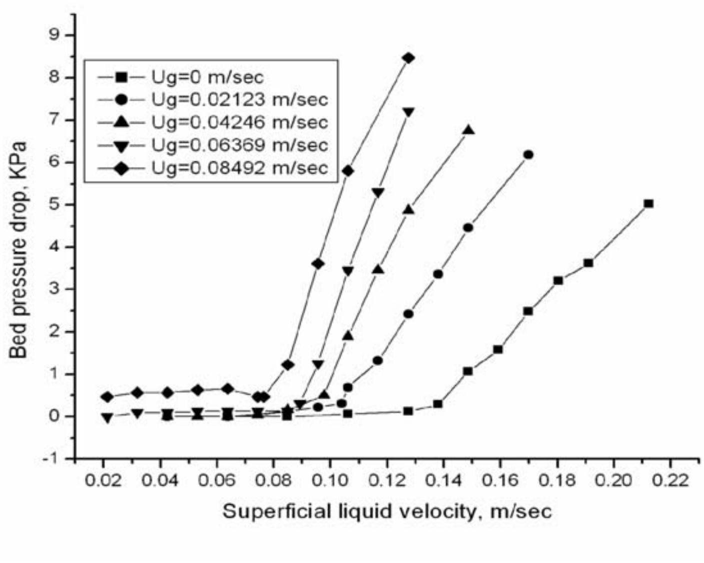

Figure 4: Variation of bed pressure drop with superficial liquid velocity at R=2 and Hs=15.4 cm for different superficial gas velocities for 6.6 mm raschig rings.

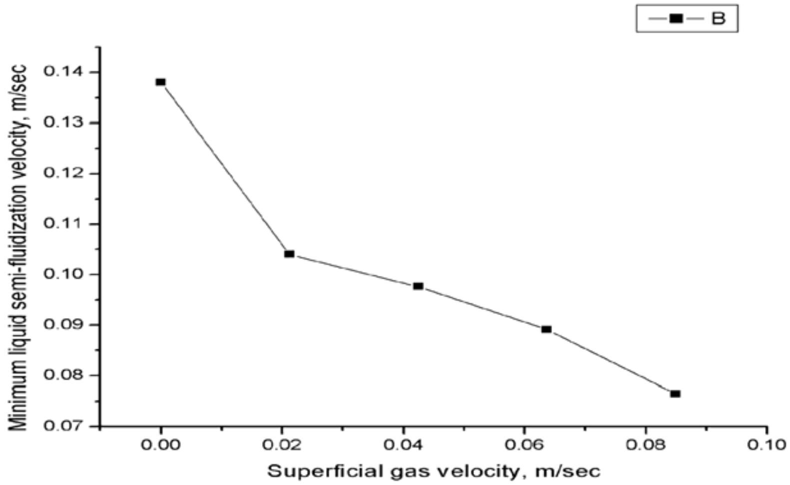

Figure 5: Variation of minimum liquid semi-fluidization velocity with superficial gas velocity at R=2 and Hs=15.4 cm for 6.6 mm raschig rings.

Figure-6 shows the variation of pressure drop with superficial liquid velocity at constant gas velocity and static bed height for different expansion ratios. The expansion ratio in the semi-fluidized bed defined as the ratio of the height of top grid to the 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-7 shows variation of the minimum liquid semi-fluidization velocity with bed expansion ratio. The plot shows the linear variation of the former with the latter. The values of Ulosf are shown in Table-2b.

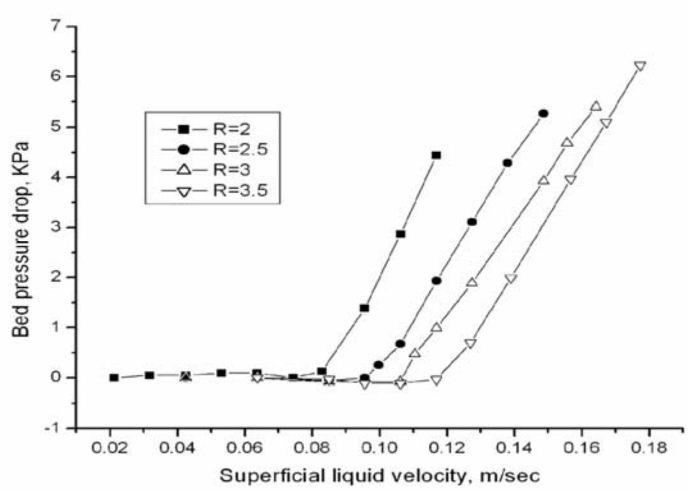

Figure 6: Variation of bed pressure drop with superficial liquid velocity for different bed expansion ratios at Hs=21.4 cm and Ug=0.08492 m/sec for 6.6mm raschig ring.

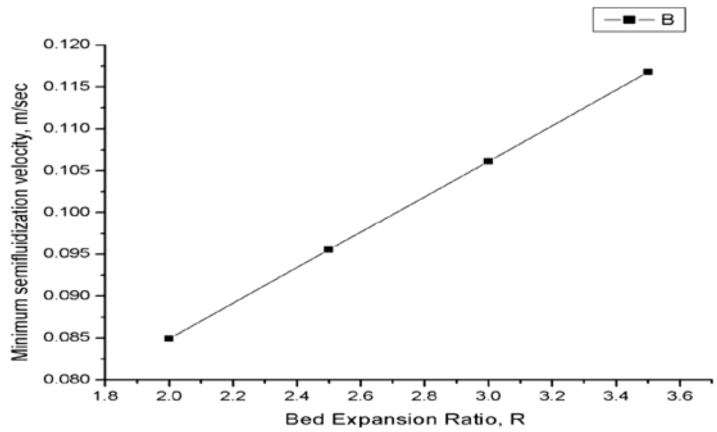

Figure 7: Variation of minimum liquid semi-fluidization velocity with bed expansion ratio at Hs=21.4 cm and Ug=0.08492 m/sec for 6.6mm raschig ring.

Table 2b: Ulosf in m/sec for different R at Ug=0.08492 m/sec, Hs=21.4cm & Dp=6.6mm.

R=2	R=2.5	R=3	R=3.5
0.08492	0.09554	0.1061	0.11677

Figure-8 and Figure-9 shows the bed pressure drop with superficial liquid velocity for different static bed height and particles size. It is found from Figure-8 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.

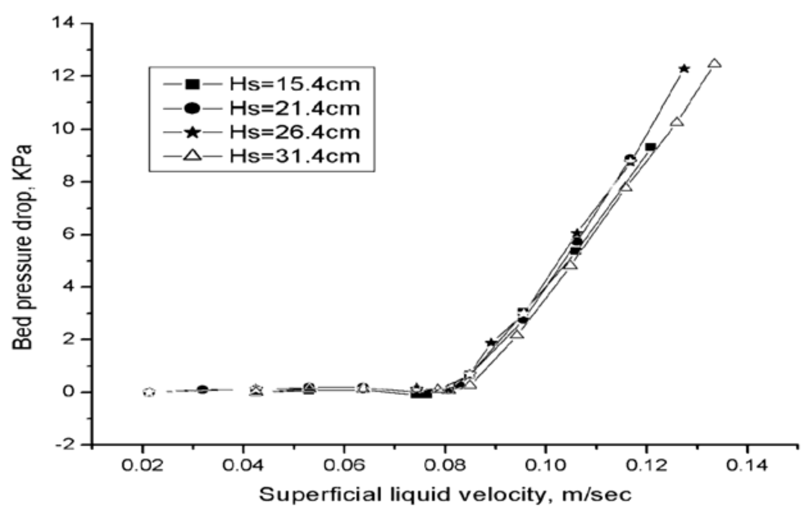

Figure 8: Variation of bed pressure drop with superficial liquid velocity for different static bed heights at R=2 and Ug =0.08492 m/sec for 6.6mm raschig rings.

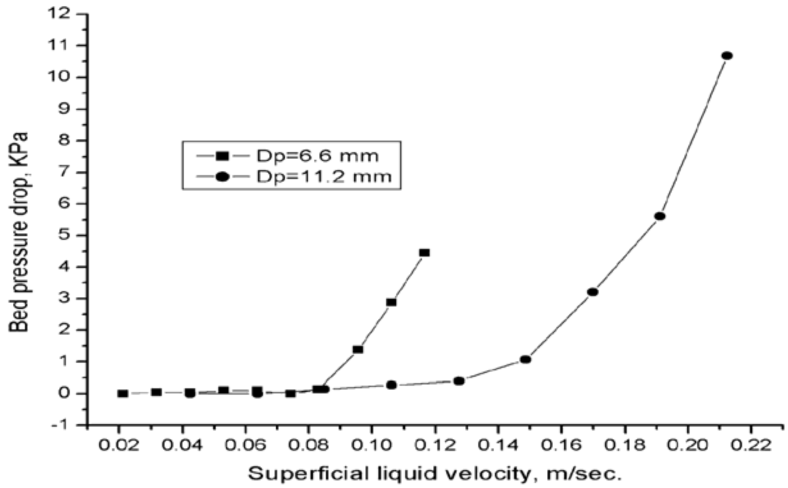

Figure 9: Variation of bed pressure drop with superficial liquid velocity for different particle sizes at R=2 and Ug =0.08492 m/sec and Hs=21.4 cm.

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. Which is negligible 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. The formation of packed are expressed here as the ratio of packed bed height (Hp) to the initial static bed height (Hs). The liquid velocity at which all the solid particles are supported by fluid in top packed bed at a constant gas velocity is called maximum liquid semi-fluidization velocity (Ulmsf). The maximum semi-fluidization velocity can be obtained by plotting porosity of fluidized bed v/s fluid mass velocity or the extrapolation of the plot of Hp/Hs to the value of 1. The maximum liquid semi-fluidization is obtained from the plot of Hp/Hs.

Figure-10 shows the variation of ratio of packed bed to initial static bed with superficial liquid velocity at constant gas velocity for different expansion ratio. It can be seen from the graph that for a fixed liquid superficial velocity, the packed bed height decreases with increase in R. It is seen that for fixed R the ratio of packed bed to initial static bed height increases almost linearly with increase in liquid superficial velocity. The graph in Fig. 10 shows the steep increase in Hp/Hs 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 (the value corresponding to Hp/Hs=1) increases with bed expansion ratio.

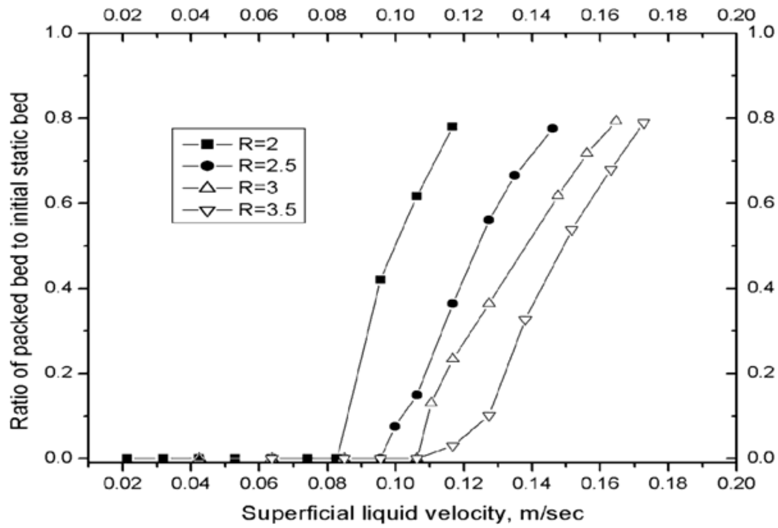

Figure 10: Variation of Hp/Hs with superficial liquid velocity for different expansion ratio at constant gas velocity 0.10191 m/sec, Hs=21.4 cm for 6.6mm raschig rings.

The Variation of Hp/Hs with superficial liquid velocity at constant expansion ratio (R=2) for different superficial gas velocities is shown in Fig.11. It can be seen from the graph that for a fixed liquid superficial velocity, the ratio of Hp/Hs 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 determination of packed bed height in three phase semi-fluidization. The distinct change in the behavior of Hp/Hs vs liquid flow for gas velocity change from 0 to 0.02123 can be seen. It shows the increase in packed bed height as the gas velocity is changed from 0 to .02123 is much as compared to further increase in gas velocity. This is due to enhancement of the bed expansion by discontinuous phase of gas bubbles. The plot of Hp/Hs vs liquid superficial velocity for different gas velocities almost approaches parallel nature with increase in liquid superficial velocity. It is seen from the plot that maximum liquid semi-fluidization velocity (the value corresponding to Hp/Hs=1) decreases with superficial gas velocity.

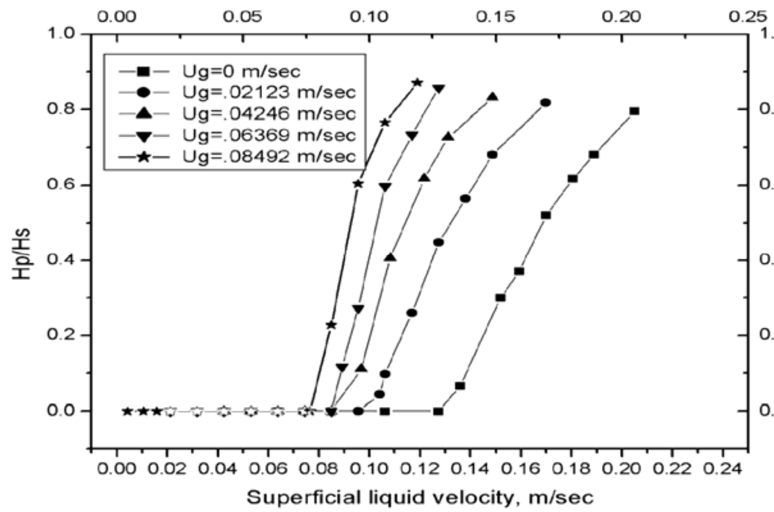

Figure 11: Variation of Hp/Hs with superficial liquid velocity for different superficial gas velocities at constant expansion ratio R=2, Hs=21.4 cm for 6.6mm raschig rings.

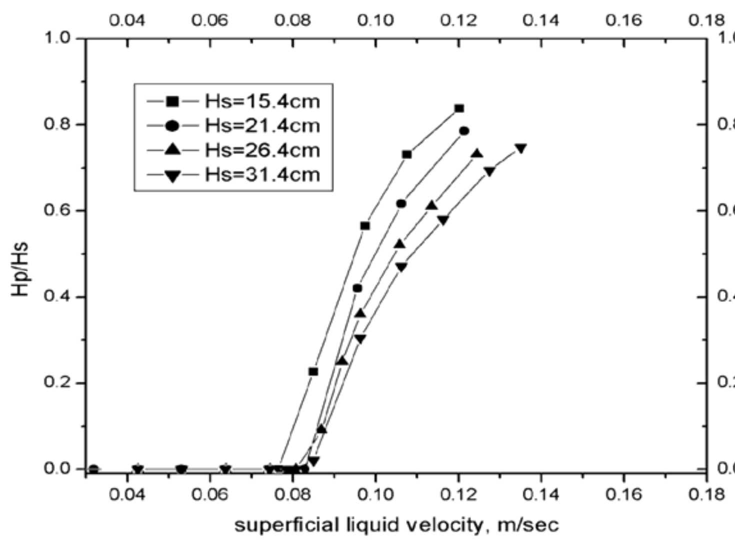

Figure 12: Variation of Hp/Hs with superficial liquid velocity for different static bed height at R=2 and Ug = 0.08492 m/sec for 6.6mm raschig rings

Figure 12 shows the variation of Hp/Hs with superficial liquid velocity for different static bed height. It is observed that for a fixed liquid superficial velocity the packed bed height decreases with increase in initial static bed height. For a fixed initial static bed height the packed bed height increases with increase in liquid superficial velocity. It can be observed that the initially the variation in packed bed height with increase in initial static bed height for a fixed liquid superficial velocity is not much. The plot of Hp/Hs vs liquid superficial velocity almost approaches parallel nature with further increase in liquid superficial velocity. It is seen from the plot that maximum liquid semi-fluidization velocity (the value corresponding to Hp/Hs=1) increases with initial static bed height.

CONCLUSIONS

The hydrodynamic study of the three-phase semi-fluidized bed with cylindrical particles reveals that the minimum liquid semi-fluidization velocity (Ulosf) 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 be increase with gas superficial velocity, particle size and decrease with bed expansion ratio for a fixed liquid superficial velocity. The packed bed height increases with gas superficial velocity and decreases with bed expansion ratio, 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.

NOMENCLATURE

Dp	Particle diameter, [mm], the outer diameter (OD) of particle
Hp	Top packed bed height, [cm]
Hs	Static bed height, [cm]
ΔP	Pressure drop, [KPa]
Ul	Superficial liquid velocity, [m/sec]
Ug	Superficial gas velocity, [m/sec]
Ulosf	Onset liquid velocity or minimum liquid velocity for semi-fluidization, [m/sec]
Ulmsf	Maximum liquid semi-fluidization velocity, [m/sec]
ρ	Phase density,[kgm^{-3}]
s	Solid phase
l	Liquid phase
g	Gas phase

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