HYDRODYNAMIC CHARACTERISTIC STUDY OF A THREE PHASE CO-CURRENT TRICKLE-BED SYSTEM

A thesis submitted in partial fulfillment of the requirements for the degree of
Bachelor of Technology

in

Chemical Engineering
by

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CERTIFICATE

This is to certify that the thesis entitled "**Hydrodynamic Characteristic Study of a Three Phase Co-current Trickle-Bed Reactor**" being submitted by **Nitish Kumar Singh (110CH0506)** as an academic project in the Department of Chemical Engineering, National Institute of Technology, Rourkela, is a record of bonafide work carried out by him under my guidance and supervision.

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ABSTRACT

Trickle-bed has been extensively used in chemical process industries mainly in petrochemical and refinery process since it provide flexibility and simplicity of operation as well as high throughputs. The basic parameter which is used in the design, scale-up and operations of a trickle bed reactor are the pressure gradient and liquid saturation. Knowledge of these hydrodynamics parameters and prevailing flow regime is the fundamental parameters for the design and performance evaluation of the reactor. But trickle bed reactor involves complex interaction of gas and liquid phase with packed solid which is very difficult to understand. Many computational models have been developed and extensive computational fluid dynamics study of hydrodynamics parameters has been done in last few decades to understand the behavior of trickle bed reactor.

In the present study experiments have been carried out in a concurrent downflow air water trickle bed reactor to investigate the pressure drop and dynamic liquid saturation in trickle flow and pulse flow regime. In trickle flow regime it is found that dynamic liquid saturation increases with increase in liquid flow rate followed by decrease when transition to pulse flow regime begins. However, in the pulse flow regime a dip in the dynamic liquid saturation curve is found. A sudden rise in pressure drop is observed when transition from trickle to pulse flow regime occurs.

Keywords: Hydrodynamics, Trickle-bed reactor, Dynamic liquid saturation, Pressure Drop

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Chapter 1

INTRODUCTION

1.1 Trickle Bed Reactor:

A trickle bed reactor is commonly known as a packed bed of stationary particle that are subjected to co-current gas and liquid flow at relatively low fluid superficial velocities. It is the simplest reactor for performing catalytic reactions. Trickle bed reactor has various use in petroleum refining, in chemical and process industries, in pollution control and biochemical industries. For chemical engineers the major challenges of trickle bed reactor are the design and scale up of the reactors. The elementary mathematical representation of trickle flow dynamics has not been accomplished. The design and scale-up of trickle bed reactors depend on key hydrodynamic variables such as liquid volume fraction (dynamic liquid saturation), particle wetting and overall gas–liquid distribution. Some of the important aspects for design of Trickle-bed reactor are: (Sie and Krishna, 1998)

1. Pressure Drop
2. Liquid and Gas Holdups
3. Catalyst Contacting
4. Axial and Radial Dispersion of liquid and gas
5. Mass Transfer
6. Heat Transfer
7. Thermal stability

The interactions between these has been poorly understood. Even though many experimental studies have been reported in measurement of these variables, but no coherent and conclusive methodology for doing so has yet been obtained. In order to explain the hydrodynamics of trickle bed reactor many models and approaches has been proposed by the authors.

In trickle bed reactor Hydrodynamics is classified in terms of hydrodynamics parameter like pressure drop, liquid holdup, gas holdup, liquid mal-distribution which are related in some way to the gas-liquid-solid contacting effectiveness and operational efficiency of the reactor column. A phenomenon that greatly complicates the mathematical description of trickle bed reactor is that these hydrodynamic variables are path variable, which depend on the history of the operation.

Factors which affect the performance of a trickle bed reactor are:

- Porosity

- Particle size
- Liquid density
- Liquid viscosity
- Surface tension
- Liquid superficial velocity
- Gas superficial velocity
- Pressure (gas density)

1.2 Hydrodynamics of trickle flow:

The performance of the trickle flow column is mainly depended on the hydrodynamics of trickle flow. We will come across some generally used parameters like holdup of the liquid and pressure drop, the holdup of the gas is a roughly symbolic of the liquid-solid contact efficiency. The overall operating cost will also depended on the pressure drop, sometimes it is an implication of degree of gas-solid interaction. The external liquid-solid mass transfer area is also proportional to the wetting efficiency (Satterfield, 1975).

1.2.1 Flow Regimes

Depending upon the operating conditions and gas and liquid velocities a number of flow regimes can be seen in the trickle bed reactor. Trickle flow regime is mainly determined by superficial velocities of liquid and gas. For downward co-current flow of gas and liquid flowing through the bed of solid particles four types of regime can be distinguished (Sie & Krishna, 1998).

1. Trickle flow (gas continuous)
2. Pulse flow (unstable regime with partly gas continuous and partly liquid continuous)
3. Dispersed bubble flow
4. Spray flow (gas continuous, highly dispersed liquid)

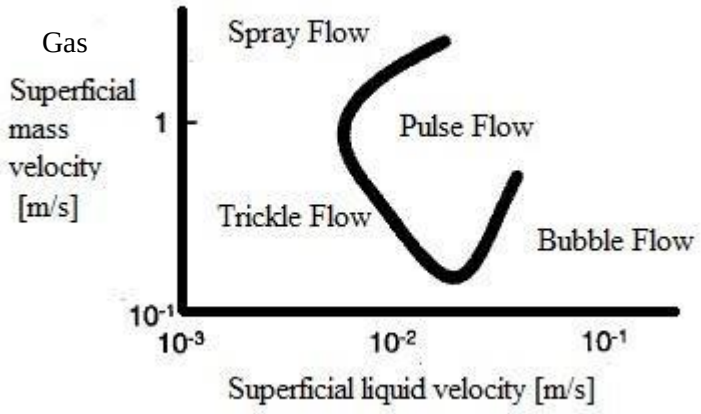

Figure 1.1 Co-current down flow regime in a trickle bed reactor

The increase of operating pressure plays an important role in the shifting flow regime between the trickle-flow and pulse-flow regime (Wammes et al, 1990). The region of stable trickle flow also extends to higher velocity as the pressure increases. The catalyst particle tends to be covered by a film of liquid of varying thickness, in trickle flow whereas gas tends to flow through interstitial space which is not occupied by the liquid. In the figure 1.2 it is clearly shown.

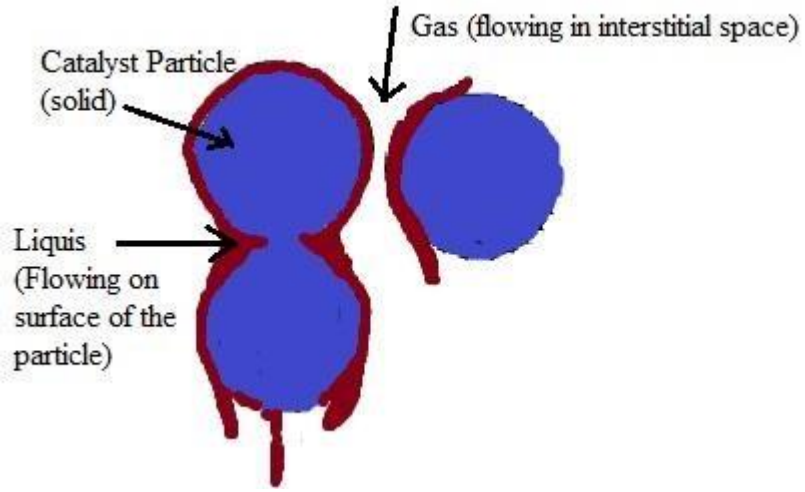

Figure 1.2. Gas and liquid flow pattern in a Trickle-Flow

1.3 Advantages and Dis-advantages of Trickle-Bed Reactor:

The main advantages of trickle-bed reactors are as follows:

- Inside a trickle-bed reactor the flow is closed to plug flow of liquid phase and gas phase.

- There is no problem of flooding as occurs in counter-current flow Because of co-current flow of gas and liquid.
- The Trickle bed construction is simple and easy to operate with fixed beds. If the reaction is exothermic in this case, there will be an excessive rise in temperature it can be limited by gas or liquid recycle.

The main Dis-advantages of trickle-bed reactors are as follows:

- Mal-distribution, channeling and incomplete catalyst wetting occurs at low liquid velocities.
- For high gas-liquid interaction counter-current operation is a preferred mode of operation, but usually not possible at practical velocities due to flooding.
- The radial dispersion of heat and mass is a problem in the case of trickle-bed. For highly endothermic or exothermic reactions multi-tubular or internally cooled fixed beds are necessary.

1.4 Application of Trickle-Bed Reactor:

Trickle bed reactors have been commonly used in the petroleum industry for many years and are now gaining wild use in several other fields from electrochemical and bio chemical industries to the repetition of surface and underground water resources, being also recognized for its applications in advanced wastewaters treatments (Rodrigo et al, 2009). In a large number of processes in a refineries for operations such as fine chemicals and biochemical operations the packed bed reactors with multiphase flow have been preferred. The effective scale up of packed bed reactors in the development of new processes and scale down of the commercial units in the improvement of existing processes have become major tasks in the research and development section of many companies (Sie& Krishna, 1998). Various processes using trickle bed reactor are:

- Hydro-desulfurization of gas-oil, vacuum gas-oil and residues.
- Hydro-de-nitrogenation of gas-oil and Vacuum gas-oil.
- Hydro cracking of cat-cracked gas-oil and vacuum gas-oil.
- FCC feed Hydro-treating.
- Hydro-metallization of residual oil.
- Hydro-cracking of residual oil.
- Hydro-cracking/Hydro-fining of lubeoils
- Hydro-processing of shale oils Paraffin Synthesis by Fischer-Tropsch.
- Oxidative Treatment of Waste water.
- Synthesis of diols.

- ## 1.5 Literature Review

Most of the experimental studies on Trickle-bed hydrodynamics were restricted to trickle and pulse flow regimes. Several aspects of hydrodynamics including flow pattern, gas and liquid holdup, wetting efficiency etc. were thoroughly studied by Satterfield and co-workers. (Satterfield, 1975). The effect of boundary on trickle bed reactor hydrodynamics is studied by Sundaresan. They examined the effect of boundaries and effect on the hysteresis by taking four different beds with different packing. He studied the effect of superficial liquid and gas velocities on the pressure drop of the column (Sundaresan et al 1991).

The influence of the gas density on the liquid holdup, the pressure drop, and the transition between trickle and pulse flow has been investigated in a trickle-bed reactor at high pressure with nitrogen or helium as the gas phase was investigated by Wammes,(Wammes et al 1991).CO absorption from $C0_2/N_2$ gas mixtures into amine solutions are used to determine the gas-liquid interfacial areas. The gas-liquid interfacial area increases when operating at higher gas densities. They showed that the gas density has a strong influence on the liquid holdup.

To determine the flow regime in a trickle bed reactor latifi used micro-electrode in a non-conducting wall and analyzed the wall wetting by Probability Density Function. He also identified the trickling-pulsing, trickling-dispersed and dispersed-pulsing regime transition (Latifi et al 1992).

To examine the influence of various parameters on pressure drop hysteresis Wang conducted experimental work with three different gas-liquid systems and three kinds of pickings. (Wang et al 1995).The most important factors that influence the behavior of hysteresis in the packed reactor, and liquid flow rate are the gas and liquid flow rates, physical properties of liquid and operation modes. They found that the hysteresis is not so pronounced for columns packed with large particles and it disappears in the pulsing flow regime and the mechanism responsible for hysteretic behavior resides in the variable uniformity of gas-liquid flow in the packed section. A parallel zone model for pressure drop in the trickling flow regime was established on the basis of experimental facts and analysis of flow structure.

Extensive experimental work on hysteresis in a concurrent gas–liquid up flow packed bed was carried out with three kinds of packing and the air–water system done by Mao,(Mao et al 2001). Two more liquids with different liquid properties were employed to further examine the influence of parameters on pressure drop hysteresis.

(Kundu et al 2001) studied the radial distribution in a trickle bed reactor with five different size of catalytic packing with uniformly distributed liquid inlet.

(Trivizadakis et al 2004) worked on two types of catalytic particle packing i. e. spherical and cylindrical extrudes to study co-current down flow in steady state trickling and induced liquid-pulsing mode operation and predicted the mechanical characteristics of trickle bed reactor.

Experimental and theoretical study of forced unsteady-state operation of trickle-bed reactors in comparison to the steady-state operation is done by Lange. In their study a forced periodic operation of a trickle-bed reactor an unsteady-state technique was used in which the catalyst bed was contacted periodically with different liquid flow rates.(Lange et al 2004) The unsteady-state operation was considered as square-waves cycling liquid flow rate at the reactor inlet. They demonstrated that the liquid flow variation has a strong influence on the liquid hold-up oscillation and on the catalyst wetting efficiency.

(Gunjal et al 2005) used wall pressure fluctuation measurements to identify prevailing flow regime in trickle beds. Experiments were carried out on two scales of columns (of diameter 10 cm and 20 cm) with two sets of particles (3 mm and 6 mm diameter spherical particles). Effects of pre-wetted and un-wetted bed conditions on pressure drop and liquid holdup were reported for a range of operating conditions.

(Maiti et al 2006) made a concise review of the hysteresis in co-current down-flow trickle bed reactors (TBRs). The effects of several factors on the hysteresis, such as the type of particles (porous/nonporous), the size of the particles, the operating flow ranges, and the start-up conditions (wet/dry) were studied. Also effects of other factors, such as addition of wetting agents (surfactants) and inlet liquid distribution, are also determined. Empirical and theoretical models were developed to predict hysteresis. An attempt was made to understand the comprehensive hysteretic behavior of both porous and nonporous particles with the conceptual framework of hysteresis.

(Saroha & Nandi 2008) performed experiment to study the effect of liquid and gas velocity, liquid surface tension, liquid viscosity and particle diameter of the packing in two phase pressure drop hysteresis. An understanding of the hydrodynamics of trickle bed reactors (TBR) is essential for their design and prediction of their performance was made by The Flow variables, packing characteristics, physical properties of fluids and operation modes influence the behavior of the trickle bed reactors.

The existence of multiple hydrodynamic states or hysteresis (pressure drop, liquid holdup, catalyst wetting gas--liquid mass transfer) due to the different flow structures in the packed bed was studied, (Saroha et al 2008). Experiments were performed to study the effect of liquid and gas velocity, liquid surface tension, liquid viscosity and the particle diameter of

the packing on two-phase pressure drop hysteresis. He developed the parallel zone model for pressure drop hysteresis in the trickling flow was for analysis of experimental data and flow structure.

Trickle bed has been found useful in production of H_2O_2 in E- Fenton process (Yangming et. al.). To avoid electrolyte leakage and gas bubbles in the E- Fenton reactors, trickle bed cathode is used by coating a layer composed of C- PTFE onto graphite chips instead of carbon cloth.

There are many uses of trickle bed reactors in the petroleum industry, as well as in the chemical process industry (Saroha and Nigam, 1996). Studies about the hydrodynamics of trickle flow using foaming liquids is still an orphan research topic in comparison to many literature related to the non- foaming systems. Foams play important role in petroleum, pharmaceuticals and food industries (Bartelmus and janecki, 2004). The foams in industries is used to lower the surface tension. There are a lot of literatures available on foaming liquids but literature are very less regarding the hydrodynamics of two- phase flow fixed bed reactors using (non-)Newtonian foaming fluids. Thus far few experimental studies on foaming fluids have been published (Larkins et al. 1961; Weekman and Myers, 1964; Sai, 1997). These author recognize that the value of liquid holdup for foaming liquids are much lower than those in non-foaming systems.

1.6 scope

Trickle-bed reactors (TBR) are one of the most extensively used three-phase reactors. A fundamental understanding of the hydrodynamics of trickle-bed reactors can not be forgotten in their design scale-up and performance. In each flow regime the hydrodynamics of the trickle bed are affected differently in the three-phase reactors (Gas-Liquid-Solid) and gaseous phases have various applications, especially in the petroleum industry for hydro-processing of oils (e.g. hydro-treating, hydro cracking). With the prospects of developing more efficient TBR units in the future, for meeting strict environmental and profitability targets, it is crucial that we know about the flow patterns in beds to match the demands made by the kinetics of these reaction processes. One of the problem industries encounter in the efficient use of TBRs is the understanding and prediction of liquid mal-distribution. With current interest in technologies of "deep" processing, such as Deep hydrodesulphurization, the need to be able to predict liquid misdistribution accurately is even more important, since small variations in liquid distribution can cause significant loss in activity in trickle-bed reactors.

1.7 Objective of the work

The aim of the present work includes:

- The hydrodynamic study of three phase co-current Trickle bed.
- The determination of dynamic liquid and phase holdup in a gas-liquid-solid Trickle bed.
- Analysis of the liquid holdup behavior and various parameters that affect the holdup.
- Examining the effect of superficial gas and liquid velocity on the individual liquid holdup.

The present work is concentrated on understanding the liquid holdup and pressure drop behaviors in a three phase co-current Trickle bed. Trickle bed of height 128 cm with diameter of 0.1 m has been fabricated. Raschig ring of diameter 6.2 mm are used as the solid packing. Gas (Air) is taken as the continuous phase. Liquid (water) and Gas (air) has been injected at the top with different superficial velocities. In all the cases the Solid (raschig ring) volume fraction is taken to be 0.63 with the superficial velocity of gas varying from 0.0128-0.05125 m/s and that of liquid ranging from 0.00128-0.0153 m/s.

Chapter 3

Experimental setup and Technique

Experiments were carried out on a glass column whose internal diameter is 91 mm and outer diameter is 100 mm. the height of the column is 128 cm. Glass column was packed with raschig ring having length 11.5 mm and diameter is 6.2 mm. Schematic diagram is shown in figure. Entry for air and water is provided at the top of the column. The packing in the column is supported on a thick wire mesh. The whole setup was supported on the slaughtered angle. A distributor is placed on the top of the column with 120 holes having 3 mm diameter. There is a compressor which provides necessary air flow rate into the column through air flow rotameter. There is a motor connected to the tank that supplies necessary water to the column via water flow rotameter. At several points in the column, a monometer is connected to measure the pressure drop.

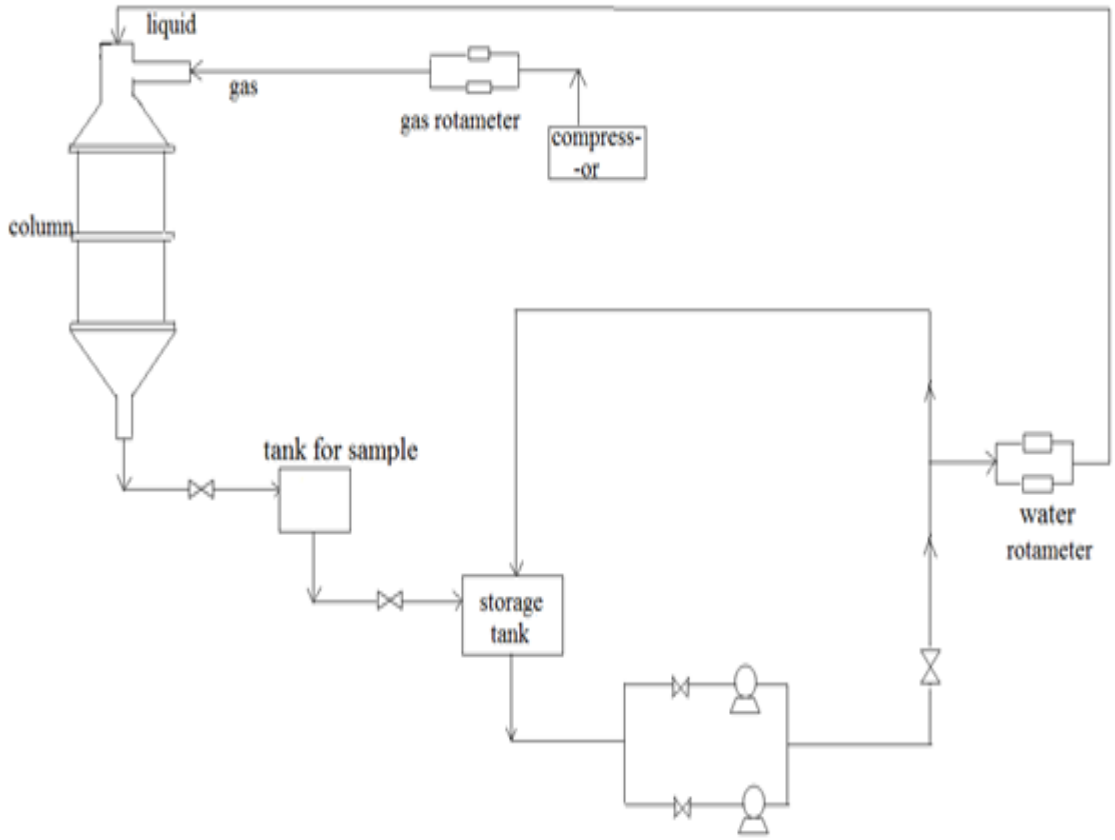

Figure 3.1 Schematic representation of the experimental setup

Figure 3.2 Photographic view of the experimental setup

Experimental Procedure

- The column is initially flooded with water alone to completely wet the packing.
- Then it is drained and again liquid is flown into the column at 0.00128 m/s.
- Air velocity is set at 0.0128 m/s.
- Column is left for 30 minutes for uniform wetting and to attain the steady state.
- We observe the liquid flow pattern and write down the readings of manometer.
- Then gas and liquid flow rate is stopped and outlet and inlet valves of the reactor are shut off. The column is again left for 30 minutes to attain the steady state. After 30 minute outlet valve is opened and water is allowed to drain. That water is collected in the flask and measured.
- Keeping the air velocity constant at 0.0128 m/s liquid velocity is increased to 0.00256 m/s.
- Repeat the same process for 0.0256 m/s and readings of manometer and volume of water collected in the flask after the drainage is taken.
- Now change the air velocity to 0.0384 m/s and then 0.05145 m/s and at different liquid velocity manometer readings and volume of water collected is taken.
-

Equipment Characteristics

Column Specification	
Height of the column	128 cm
Column inner diameter	9.1 cm
Column outer diameter	10 cm
Area of the column	65.038 cm^2
Volume of the empty column	8.2 liter
Distributor	
Material used	Mild steel
Thickness of the distributor	1 mm
No. of holes	120
Hole diameter	3 mm
Pipe Specification	
Pipe used	PVC pipe
Pipe diameter	½ inch
Packing material	
Material used	Raschig ring
Raschig ring outer diameter	6.25 mm
Voidage	0.63
Manometer used	U-tube manometer
Valve used	Gate valve
Operating conditions	
Air superficial velocity	0.0128-0.05125 m/s
liquid superficial velocity	0.00128-0.0153 m/s

Chapter 4
Observations and readings

4.1 At 0.0128 m/s air velocity

Liquid velocity (m/s)	Manometer reading In (cm)	Pressure drop (N/m^2)
0.00128	0.2	31.39
0.00256	0.3	47.04
0.00384	0.7	125.56
0.005125	1.4	219.74
0.00768	4.6	722.01
0.0102	5.4	847.58
0.0128	6.4	1004.54
0.0153	8.2	1287.08

4.1 At 0.0128 m/s air velocity

Liquid velocity (m/s)	Volume of water collected in ml	Dynamic liquid saturation
0.00128	390	0.093
0.00256	504	0.12
0.00384	630	0.15
0.005125	710	0.17
0.00641	840	0.201
0.00768	960	0.24
0.0102	660	0.157
0.0128	780	0.186
0.0153	850	0.202

4.2 At 0.0128 m/s air velocity

Distance from the Top of the column (cm)	Pressure drop at 0.0153(m/s)	Pressure drop at 0.0102(m/s)	Pressure drop at 0.00768(m/s)	Pressure drop at 0.00384(m/s)	Pressure drop at 0.00128(m/s)
0	1208.59	1051.63	737.12	706.32	486.576
12	2150.35	1789.34	1538.20	1318.46	1130.112
38	1648.08	1444.03	1161.50	1004.54	800.49
79	392.40	323.79	376.71	282.52	266.83
105	345.31	219.74	204.05	172.65	78.48
128	172.66	78.48	31.39	28.25	15.696

4.3 At 0.0256 m/s air velocity

Liquid velocity (m/s)	Manometer reading In (cm)	Pressure drop (N/m^2)
0.00128	0.2	39.42
0.00256	0.4	64.35
0.00384	0.9	149.112
0.005125	1.9	298.2
0.00641	4.8	753.41
0.00768	6.8	1067.32
0.0102	8.1	1271.376
0.0128	10.2	1600.992
0.0153	12.6	1977.69

4.4 At 0.0256 m/s air velocity

Liquid velocity(m/s)	Volume of water collected in ml	Dynamic liquid saturation
0.00128	340	0.08
0.00256	420	0.1
0.00384	600	0.145
0.005125	680	0.164
0.00641	780	0.185
0.00768	640	0.153
0.0102	610	0.145
0.0128	720	0.171
0.0153	810	0.192

4.5 At 0.0256 m/s air velocity

Distance from the Top of the column (cm)	Pressure drop at 0.0153(m/s)	Pressure drop at 0.0102(m/s)	Pressure drop at 0.00768(m/s)	Pressure drop at 0.00384(m/s)	Pressure drop at 0.00128(m/s)
0	1130.112	1287.072	565.056	172.656	78.48
12	2432.88	1968.278	1587.493	1139.53	831.88
38	596.448	549.36	439.488	376.704	329.616
79	109.872	62.784	54.936	47.088	32.9616
105	94.176	78.48	47.088	32.9616	21.9744
128	47.088	40.809	31.392	25.1136	15.696

4.6 At 0.0384 m/s air velocity

Liquid velocity (m/s)	Manometer reading In (cm)	Pressure drop (N/m^2)
0.00128	0.4	62.70
0.00256	1.2	188.352
0.00384	2.1	329.616
0.005125	5.8	910.36
0.00641	8.2	1287.07
0.00768	10.5	1657.49
0.0102	11.8	1852.12
0.0128	12.6	1977.69
0.0153	14.2	2228.832

4.7 At 0.0384 m/s air velocity

Liquid velocity (m/s)	Volume of water collected in ml	Dynamic liquid saturation
0.00128	310	0.074
0.00256	340	0.08
0.00384	550	0.131
0.005125	640	0.152
0.00641	530	0.126
0.00768	550	0.132
0.0102	570	0.13
0.0128	630	0.15
0.0153	670	0.16

4.8 At 0.0384 m/s air v3elocity

Distance from the Top of the column (cm)	Pressure drop at 0.0153(m/s)	Pressure drop at 0.0102(m/s)	Pressure drop at 0.00768(m/s)	Pressure drop at 0.00384(m/s)	Pressure drop at 0.00128(m/s)
0	3233.376	1805.04	910.368	125.568	109.872
12	4112.352	2448.576	1600.992	1145.808	1067.328
38	690.624	580.752	643.536	533.664	439.488
79	520.272	439.488	235.44	219.744	141.264
105	219.744	204.048	188.352	172.656	125.568
128	67.784	54.936	47.088	40.8096	23.544

4.10 At 0.05125 m/s air velocity

Liquid velocity (m/s)	Manometer reading In (cm)	Pressure drop (N/m^2)
0.00128	0.5	81.62
0.00256	1.8	282.52
0.00384	5.3	831.88
0.005125	7.9	1250.81
0.00641	9.8	1553.25
0.00768	11.8	1866.25
0.0102	13.2	2071.18
0.0128	14.6	2291.61
0.0153	15.5	2684.02

4.11 At 0.05125 m/s air velocity

Liquid velocity(m/s)	Volume of water collected in ml	Dynamic liquid saturation
.00128	210	0.05
0.00256	250	0.06
0.00384	530	0.126
0.005125	450	0.107
0.00641	430	0.102
0.00768	380	0.09
0.0102	460	0.11
0.0128	500	0.12
0.0153	550	0.132

4.12 At 0.05125 m/s air velocity

Distance from the Top of the column (cm)	Pressure drop at 0.0153(m/s)	Pressure drop at 0.0102(m/s)	Pressure drop at 0.00768(m/s)	Pressure drop at 0.00384(m/s)	Pressure drop at 0.00128(m/s)
0	2417.184	1224.288	847.584	753.408	486.576
12	4269.312	1946.304	1192.896	988.848	910.368
38	2919.456	1585.296	973.152	800.496	655.232
79	816.192	722.016	596.448	376.704	266.832
105	188.352	94.176	81.6192	62.784	31.392
128	50.227	43.948	31.392	28.2528	15.696

Chapter 5
Results and discussion
5.1 Pressure Drop:

Figure shows the relationship between pressure drop in the bed and the liquid velocity at a various gas flow rate. It has been observed that as we increase the flow rate of the liquid in the column keeping the air flow rate constant the pressure drop in the bed increases. But at a particular liquid flow rate a steep rise in the pressure drop is noticed and that is the onset of transition region from the trickle flow to pulse flow.

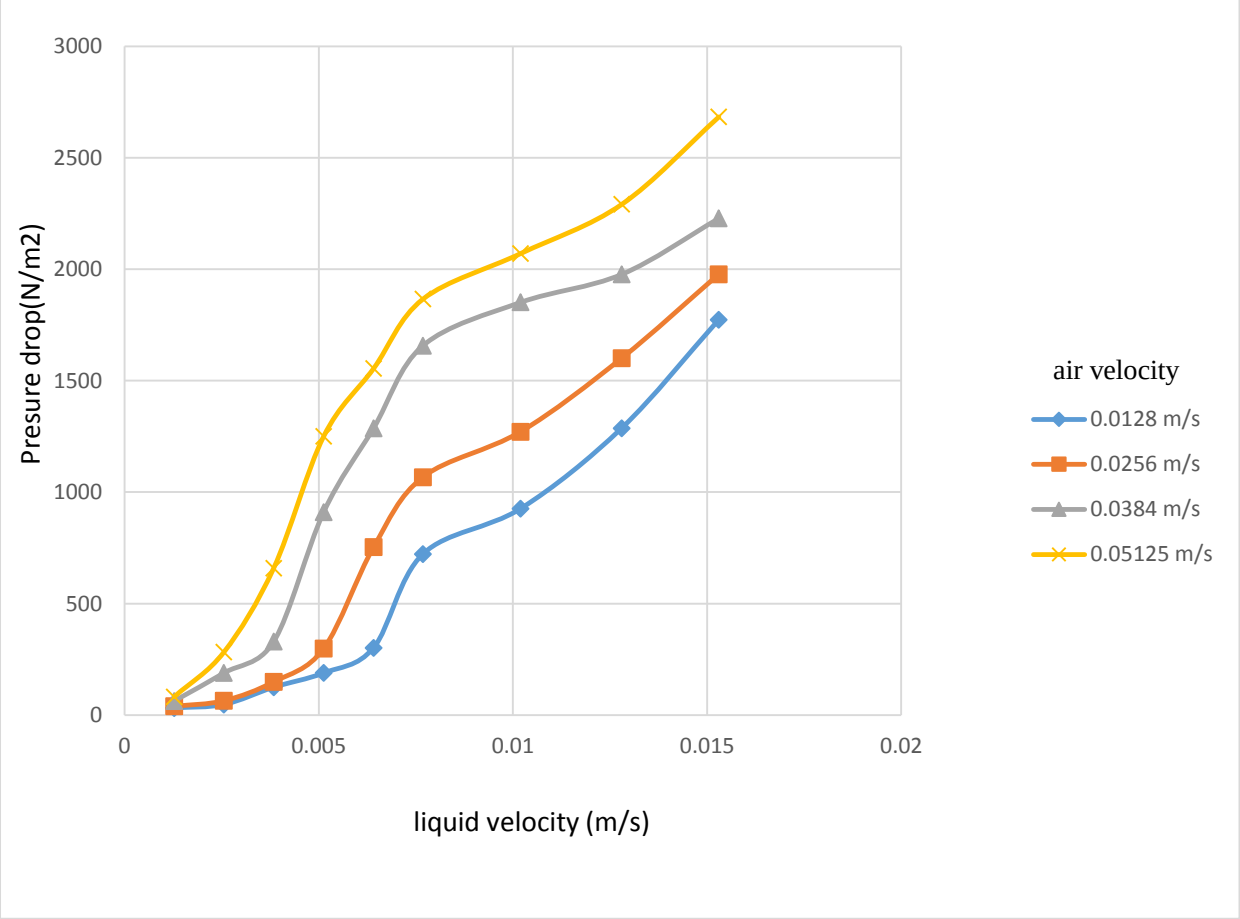

Figure 5.1 Plot of pressure drop vs. liquid velocity at different air velocity

When we increase the air velocity, we observe that the transition from trickle flow to pulse flow occurs at a lower liquid flow rate. At higher air flow rate, transition starts early and there is a much increment in pressure drops.

5.2 Dynamic Liquid Saturation:

Figure 6 shows the plot of dynamic liquid saturation vs. liquid flow rate at various gas flow rates.

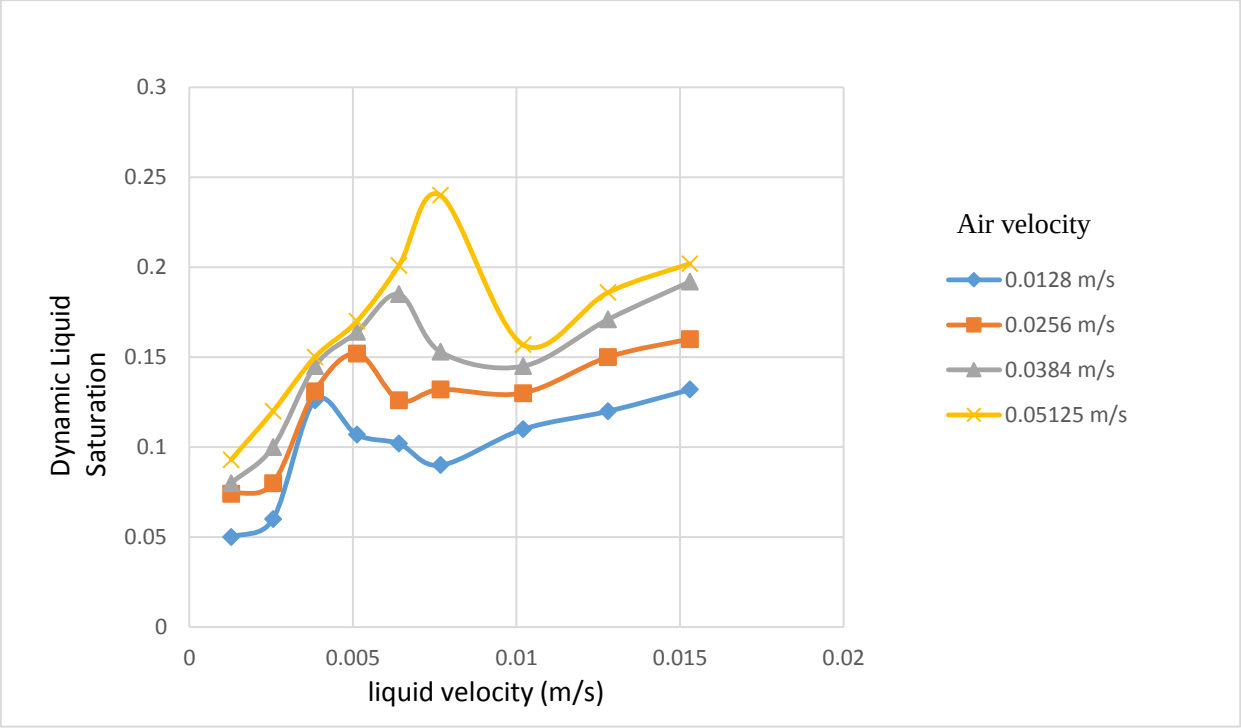

Figure 5.2 Plot of Dynamic liquid saturation vs. liquid velocity

5.2.1 Effects of liquid flow rate:

In the trickle flow regime the dynamic liquid saturation increases with increase in liquid flow rate at constant air flow rate. On increasing the liquid flow rate a point will reach where some small bubbles will begin to form in the bed and here starts the transition from trickle flow to pulse flow. In transition reason dynamic liquid saturation decreases with increase in liquid velocity. Further increase in liquid flow rate causes the bed to be filled with bubbles and it results in the lowest dynamic liquid saturation. The reason for this is that during the bubble formation space is occupied by the bubbles which is otherwise occupied by the liquid in trickle regime. After this point increase in the liquid flow rate causes dynamic liquid saturation to increase.

5.2.2 Effect of Air flow rate:

From the above figure it is clear that with increase in the air flow rate dynamic liquid saturation decreases and the lowest dynamic saturation point shifts toward lower liquid flow rate. At higher air flow rate more and more spaces will be occupied by the air and thus dynamic liquid saturation decreases. The lowest dynamic saturation point suggests that at higher air flow rate the transition starts at lower liquid flow rate.

5.3 Comparison of literatures with present dynamic liquid saturation Data

References	Dynamic liquid saturation for packed bed with raschig ring
Larkins et al.(1961)	0.668
Hochman and Effron(1969)	0.476
Otake and okada(1953)	0.722
Fu et al.(1996)	0.245
Present work	0.241

It was observed that the present dynamic liquid saturation is found to be close to the result obtained by the Fu et al. at 0.0128 m/s air velocity and 0.00128 m/s liquid velocity. The reason of variations from the other authors may be the different conditions and experimental errors.

5.4 Pressure drops at different points in the bed:

It is observed that at constant air flow rate the pressure drop decreases as we move down along the bed. But at higher liquid velocity theses pressure drops are higher than that at lower liquid velocities. At the top of the column pressure drop is low because that point is just below the distributor and there is fluctuation in pressure drop. Otherwise at the second point i.e. at 12 cm from the top the pressure is high and it decreases as we go down.

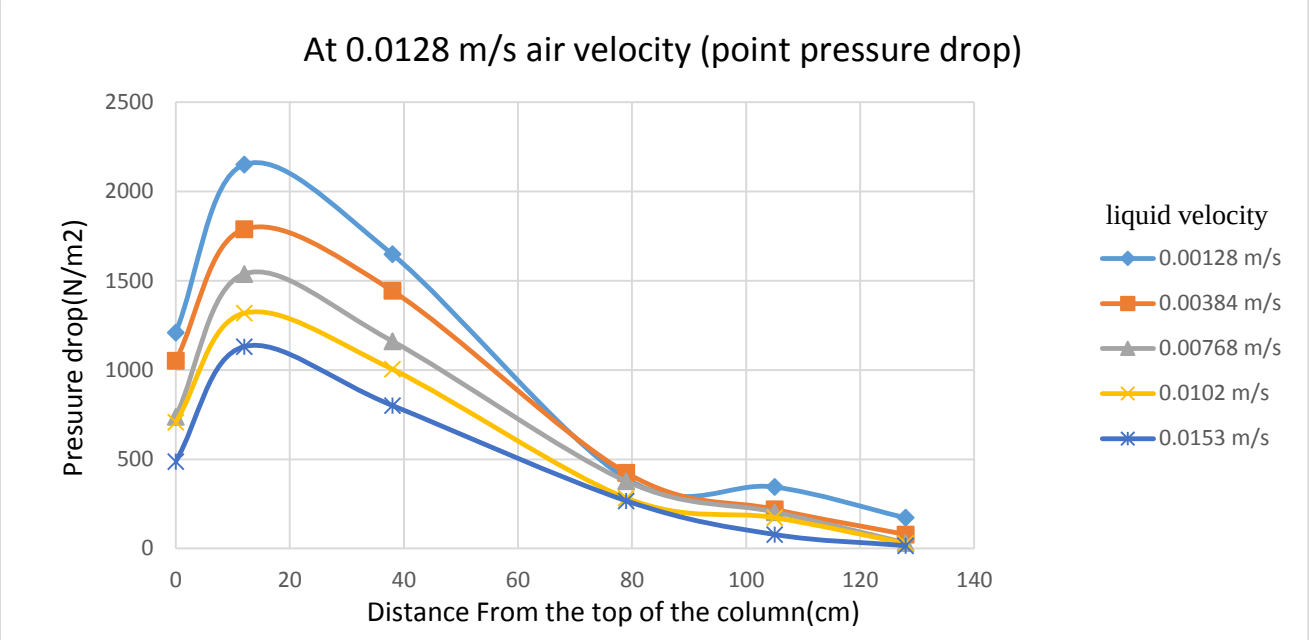

Figure 5.3 Pressure drop at different points in the bed

Chapter 6

Conclusions:

Based on the above results and discussion we can draw following conclusions.

1. The pressure drop in the column increases as we increase the liquid or air flow rate.
2. When Transition from trickle to pulse flow occurs then there is a sudden increase in the pressure drop.
3. At higher air flow rate these transitions occur at lower liquid flow rate.
4. The dynamic liquid saturation increases with increase in liquid flow rate but from transition point it begins to decrease till pulse flow regime and due to that there is a dip in the dynamic liquid saturation curve.
5. At higher air flow rate the dynamic liquid saturation curve is lower than that at lower air flow rate and the peak of the curve also occurs at lower liquid flow rate.
6. The pressure drop at different point in the bed decreases as we move down along the bed.

Future scope of the project

The future work of this project includes

1. The comparison of pressure drops and dynamic liquid saturation for different types of foaming and non-foaming liquids to study the effect of viscosity.
2. In petroleum industries there are many foaming liquids used in the column for separation or for catalytic reactions. There could be a study of mass transfer, heat transfer effect in the bed for the trickle flow regime.
3. The wetting efficiency of the particle and different particle size how affect the pressure drop is a major topic in this field.

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