HYDRODYNAMIC CHARACTERISTICS STUDY OF THREE PHASE TRICKLE BED REACTOR

A thesis submitted in partial fulfilment 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 Characteristics Study of Three Phase Trickle Bed Reactor” being submitted by **Sai Abhilash Vemala (110CH0596)** 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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ACKNOWLEDGEMENTS

I take this opportunity to express my deepest gratitude and sincere thanks to my guide Dr Hara Mohan Jena for his constant support and motivation throughout the course of the project.

I also thank prof. Pradeep Rath, HOD, Department of chemical engineering for providing me excellent facilities in successfully completing the project.

Finally, I would like thank Mr. Rahul Omar, Ph.D. student, for his valuable assistance and support and everyone who have directly or indirectly helped me in successfully completing the project.

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ABSTRACT

Trickle bed reactors are the simplest three phase contacting devices employed in wide variety of fields such as fine chemicals, waste water treatment, food processing, petrochemicals, and petroleum industries. Their operation involves passing the gas and liquid phase reactants in downward direction along gravity over a solid packing. Most industrial trickle beds are used for hydro treating, hydrodesulphurization and oxidation operations. With wide range of applications, in depth understanding of working of the trickle bed reactor has become imperative to realize its full potential. The fundamental parameters which are used in the design and operation of trickle bed reactors are the dynamic liquid holdup and pressure drop. The pressure drop indicates the energy required to move the fluid through the column while dynamic liquid saturation indicates the efficiency of contacting between solid-liquid- gas phases. The present study has been carried out to investigate the pressure drop and dynamic liquid holdup of air-water system and air-CMC solution system. Air- CMC system has been selected to understand and quantify the effect of viscosity on pressure drop and dynamic liquid holdup. By varying the liquid and gas flow rates along with viscosity, the pressure drop and dynamic liquid saturation changes were studied. Results from pressure drop plots indicate increase in pressure drop with increase in liquid and gas flow rate, while dynamic liquid saturation decreases with increase in air flow rate. It was also observed that pressure drop and dynamic liquid holdup increased with increasing the viscosity of the liquid solution. The results provide the transition region between trickle and pulse flow regime. This region is very important because most of the trickle bed reactors used in various industries operate in this region.

Keywords: Trickle bed reactor, dynamic liquid saturation, pressure drop, hydro treating, hydrodesulphurization, and hydrodynamics.

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CHAPTER 1: INTRODUCTION AND LITERATURE REVIEW

1.1 Trickle bed reactors

Trickle-bed reactors are the most commonly used three-phase contacting equipment in chemical industry. In a trickle bed reactor the liquid and gas move over bed of solid particles in the downward direction along the direction of gravity. Because of their simple design they are widely used in catalytic and non-catalytic reactions involving solid, liquid and gaseous phases. The word trickle clearly describes the flow pattern in a trickle bed reactor i.e. liquid trickles or moves slowly down the packing. The solid particles inside the reactor can be randomly packed or in definite patterns. Majority of Reactions carried out in a trickle bed reactor like hydro cracking are exothermic in nature. Hence, control of the liberated energy and temperature is key to maintaining the reaction conditions. Typical applications of trickle bed reactors include hydrocracking, hydrodenitrogenation and hydrodesulphurization in petroleum refineries and in treatment of waste water streams (Ranade et al., 2011). Although trickle bed can be operated both co-current and counter current, co-current mode of operation is the most popular mode of operation in petroleum industries and other industries because of low pressure drop and absence of flooding**.** With wide range of applications it is imperative for engineers to understand the important parameters that affect the design and operation of the reactors. The monetary value of reactants processed in trickle bed reactors is around 300 billion dollars per year and is constantly on rise with stringent emission standards all over the world (Sie & Krishna, 1998). Trickle bed reactors are being used on a very large extent in chemical processing industries. Most of the information available on trickle bed reactors concerns treating hydrogen with various petroleum stocks.

Important parameters that affect the overall performance of the trickle bed reactors are:

1. Dimensions of the column
2. Gas and liquid flow rates
3. Reaction kinetics
4. Type of packing
5. Pressure drop across the bed
6. Porosity of catalytic bed
7. Wetting of catalyst particles
8. Dynamic liquid saturation

9. Heat and mass transfer
10. Density of liquid and gas
11. Surface tension
12. Viscosity
13. Particle size

Although the reactor is simple in design, the gas, liquid and solid interactions are very complex to understand mainly because of harsh operating conditions like high pressure and temperature or inaccessibility of the packing used. The packed bed inside the reactor is normally supported by a mesh (Ranade et al., 2011).

1.2 Hydrodynamics of trickle flow:

The performance of a trickle bed reactor is mainly influenced by the hydrodynamics parameters like pressure drop, dynamic liquid holdup. When gas and liquid reactants flow over the packing, different flow regimes are observed. These flow patterns are influenced by various parameters like the packing density, liquid and gas flow rates, density and viscosity of the fluids etc. generally four flow regimes are recognized in a trickle bed reactor. They are

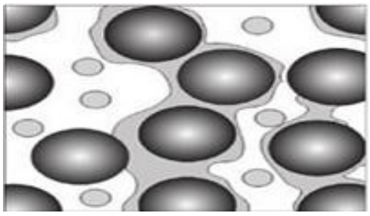
1. Trickle flow
2. Pulse flow
3. Spray flow
4. Bubble flow

Trickle flow is observed at low liquid and moderate gas flow rates. In trickle flow the gas is the continuous phase and liquid occupies the semi continuous phase. Low pressure drop, less catalyst damage and suitability for foaming liquids are some of the principal advantages of trickle flow regime.

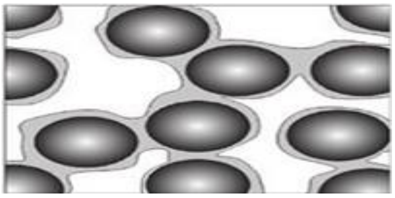
Pulse flow is observed at moderate liquid and moderate gas velocities. The transition from trickle flow regime to pulse flow regime can be observed visually. In pulse flow both gas and liquid are in semi continuous phase. Majority of the trickle bed reactors used in chemical industries are operated in the narrow boundary region between trickle flow and pulse flow regime (Satterfield, 1975). Some of the advantages of pulse flow regime include higher heat and mass transfer rates, effective wetting and usage of catalyst packing.

Spray flow regime is observed at high gas flow rates and low liquid flow rates. In spray flow regime the gas phase is the continuous phase and the liquid phase is the dispersed phase. Some of the advantages of spray flow regime include low liquid holdup and high heat and mass transfer rates.

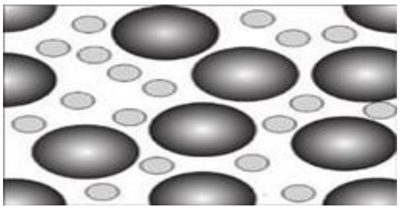
Bubble flow is observed at low gas flow rates and high liquid flow rates. In bubble flow regime the liquid occupies the continuous phase while the gas occupies dispersed phase. High heat and mass transfer rates are achieved in this flow regime.



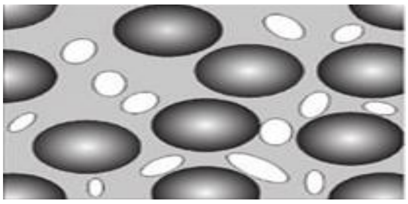
(a) Trickle flow regime, continuous phase: gas, semi continuous phase: liquid (low interaction regime).



(b) Pulse flow regime, semi continuous phase: gas, semi continuous phase: liquid (high interaction regime).



(c) Spray flow regime, continuous phase: gas, dispersed phase: liquid.



(d) Bubble flow regime, continuous phase: liquid, dispersed phase: gas.

Figure 1.1 Schematic showing dispersion of gas and liquid in various flow regimes (Gunjal et al., 2005).

Several flow regime maps were reported giving the transition from one flow regime to another.

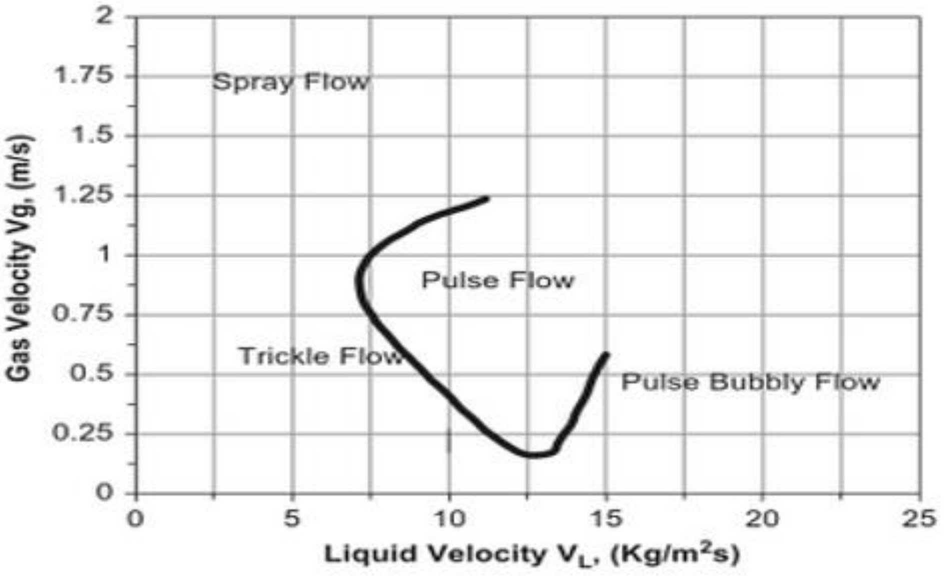


Figure1.2 Schematic showing various flow regimes, Sie & Krishna (1998).

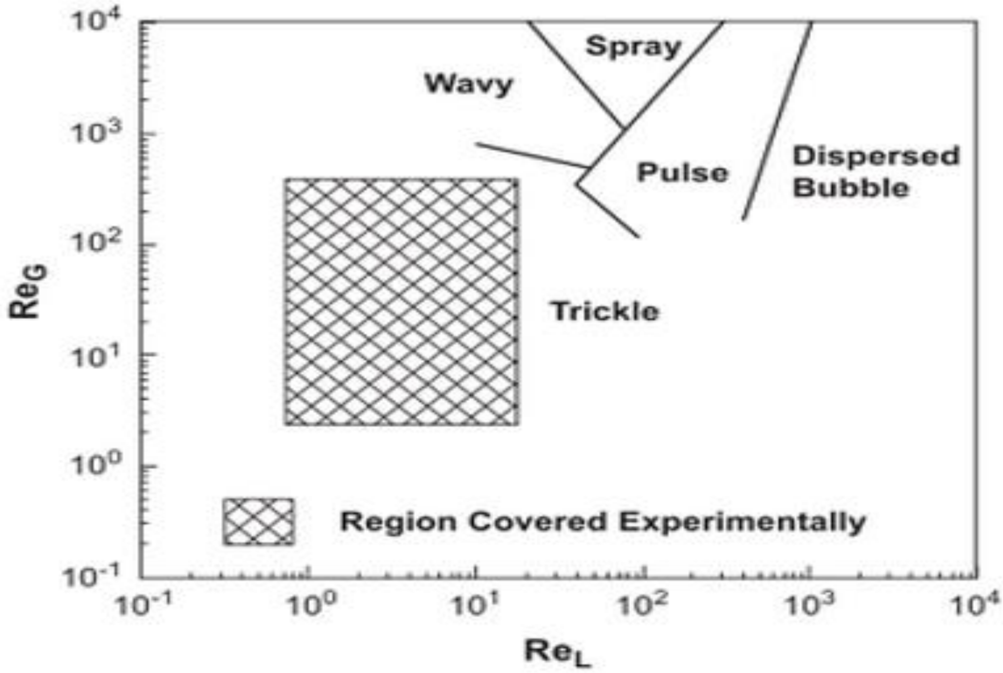


Fig 1.3 Schematic showing various flow regimes, Al-Dahhan & Dudukovic, 1994; Fukushima & Kusaka, 1977b).

1.3 Advantages and disadvantages of trickle bed reactors:

Advantages:

1. The Liquid flow in Trickle bed reactor is almost close to plug flow behaviour, this results in high conversion yields.
2. Less catalyst damage, this offers a significant advantage when expensive catalysts are used.
3. Construction of the Trickle bed reactor is very simple as there are no moving parts.
4. Trickle bed reactors provide the flexibility of operating at extreme conditions of high temperatures and high pressures.
5. Large reactor volume. Hence, large throughput.
6. Cost of setting up the plant and running costs are low.
7. The liquid-solid volume ratio is low. Therefore, there is little possibility of homogenous side reactions.
8. The reactor can be operated at different flow regimes according to requirement.
9. Pressure drop inside the Trickle bed reactor is low, this results in lower pumping costs.
10. Easy operations with rigid adiabatic beds. For exothermic reactions, gas or liquid reactants are often used as coolants to absorb the excess heat, thereby controlling the reaction temperature.

Disadvantages:

1. The effectiveness of the catalyst decreases when the size of catalyst particle is large.
2. There is a limitation on the minimum size of the catalyst particle inside the trickle bed reactor i.e. is 1 mm due to pressure drop.
3. Side reactions might result in fouling products that could obstruct the pores of catalyst and also result in higher pressure drop.
4. At low liquid velocities channelling, improper distribution of reactor scale and inefficient wetting of catalyst might occur.
5. Viscous and foaming liquids cause lot of problems during operation.
6. The reactor is very sensitive to thermal effects. This shortcoming can be overcome by using a coolant or by recycling the outlet liquid.
7. Recovery of heat produced during the reaction is very challenging.
8. Dynamic liquid saturation is low in comparison to co-current gas-liquid upward flow.

9. There is a chance of deactivation of catalyst due to formation of scales.
10. The entire reactor has to be dismantled for the replacement of the catalyst.
11. Trickle bed reactors are restricted to considerably fast reactions.
12. Although widely used in petroleum refineries, the reactor offers poor degree of conversion because of poisoning of the catalyst by ammonia and hydrogen sulphide produced during various operations.

1.4 Applications of Trickle-Bed Reactor:

1. Hydrodesulphurization and hydrocracking of heavy residual stocks.
2. Hydro-finishing or hydro treating of lubricating oils.
3. Production of Quinone and hydrogen peroxide.
4. Hydrogenation of benzene (Guo et al.,2008).
5. Hydrodesulphurization, hydro denitrification and hydrodemetallization.
6. Esterification of acetone and butanol.
7. Fischer-tropsch reaction.
8. Catalytic hydro cracking.
9. Oxidative Treatment of waste water.
10. Synthesis of diols

1.5 Literature Review:

Although having wide range of applications, very little is known about the hydrodynamics of the trickle bed reactors. The most important hydrodynamic parameters that influence the design and operation of trickle bed reactors are pressure drop across the bed and dynamic liquid saturation. Pressure drop and dynamic liquid saturation are strongly interrelated. Accurate measurement of pressure drop and dynamic liquid saturation is an indispensable step for accurate design and performance of the trickle bed reactor. A new improved and accurate measurement of the dynamic liquid saturation was presented by Ellman et al., (1989).

Majority studies on Trickle-bed reactor hydrodynamics are limited to pulse flow regime and trickle flow regime. Certain important aspects of reactor hydrodynamics including various flow regimes, wetting efficiency, liquid holdup etc. were thoroughly studied by Satterfield and co-workers (Satterfield, 1975).

Al-Dahhan et al., (1996) have shown that in a diluted bed containing mix of catalyst and fines, the wetting efficiency, dynamic liquid saturation and pressure drop increases as and the improvement of liquid-catalyst contacting efficiency in a diluted bed improves the performance of laboratory reactor. This operation involved filling up of the Voidage of the original dry solid packing with dry fines.

Saroha and Nigam, (1996) studied the liquid distribution in the trickle bed reactors. They concluded that the liquid flow in outer most annulus decreased with the increase in the liquid flow rates. This phenomenon was observed both with and without gas flow rates. They have also demonstrated that the liquid flow in the annulus region decreases with the increase in gas flow rates.

Wammes et al., (1991) studied the impact of the gas density on the liquid holdup, the pressure drop, and the transition between trickle and pulse flow regime has been examined in a trickle-bed reactor at high pressure with N_2 or helium as the gas phase. Carbon monoxide absorption from carbon dioxide/nitrogen gas mixtures into amine solutions were used to determine the interfacial areas for gas liquid interface. The gas-liquid interfacial area was found to be increasing when operating at higher gas densities. This showed that the density of a gas has strong impact on the liquid holdup inside the trickle bed reactor.

Larachi et al., (2003) studied the magneto hydrodynamics of a trickle bed reactor under magnetic-field gradients. They have shown that the ability to influence two-phase flow by the application of an external inhomogeneous magnetic field is of potential use in the operation of trickle-bed reactors from the point of view of catalytic process intensification.

Kundu et al., (2003) studied the Characteristics of catalyst wetting in Trickle-Bed Reactors. Based on 1-D force balance equation involving drag forces in a three phase system, a new model for determining the external catalyst wetting efficiency was developed.

Gladden et al., (2005) studied the Transition from trickle flow to Pulsing Flow in Trickle-Bed Reactors Using magnetic resonance imaging. Ultrafast MRI was used to provide 2-D images of gas-liquid distribution inside the trickle-bed reactors with data acquisition times of 20 and 40 ms. Ultrafast magnetic resonance imaging techniques were used to acquire the two dimensional images of gas and liquid distribution within fixed-bed reactors operating over a range of liquid and gas velocities in two-phase co current down flow. These images make it clear that the macroscopic gas and liquid distribution in a trickle flow is constant.

Houwelingen et al., (2006) studied the distribution of wetting of particles inside the Trickle-Bed Reactors. They used an innovative technique to determine the particle wetting distribution in trickle-bed reactors for different flow rates and prewetting conditions. Two important prewetting methods were studied: (1) Levec prewetting, in Levec prewetting the packed bed of catalyst is fully inundated and then allowed to empty before the commencement of steady state trickle flow regime. (2) Kan prewetting, in Kan prewetting the bed is prewetted by pulsing with the liquid before the flow, after which the liquid flow is progressively set back to the requisite rate. It was shown that this method has a significant impact on the distribution of particle wetting and average wetting efficiency. They have also shown that the modelling of the Levec prewetted catalyst beds for gas and liquid limited systems was greatly influenced by the distribution of the wetting of the particles.

There are numerous uses of trickle bed reactors in the chemical processing industry (Saroha and Nigam, 1996) and petroleum refining industries. Studies regarding hydrodynamics of trickle flow using foaming liquids is still an early stage research topic in comparison to many literature related to the non- foaming systems. Foams play very important role in pharmaceuticals, petroleum and food processing industries. The foams in industries are 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 the two- phase flow of fixed bed reactors using non-Newtonian foaming liquids.

Turpin et al., (1967) worked on the Prediction of Pressure Drop for Two-Phase, Two-Component Concurrent Flow in Packed Beds. Two-phase, gas-liquid concurrent flow in packed beds was investigated with the use of on air-water system and 2-, 4-, and 6-in. diameter columns pocked with tabular alumina particles of 0.025 and 0.027 ft. diameters. Diameter columns packed with tabular alumina particles of 0.025 and 0.027 ft. diameters. Total pressure drop, column operating pressure, and liquid saturation were measured as functions of gas flow rote, fluid temperatures, and flow direction at several constant liquid flaw rates for each column. Correlation of the frictional pressure loss was achieved in terms of a defined two-phase friction factor and a second correlating parameter which is a function of the liquid and gas Reynolds numbers. A viscosity correction factor was required to extend the friction factor correlation to include liquid viscosities widely divergent from that of water. The liquid saturation data for both upward and downward flaw were correlated in terms of the ratio of moss flow rates of the respective phases.

Elgin et al., (1939) examined the liquid holdup and flooding in packed bed towers. The true flooding point of the packed bed tower was defined as the one at which the liquid reactants inundates the packed bed tower to the top most level of the catalyst bed. The effect of liquid and gas flow rates on the pressure drop in the inundated zone is in agreement with earlier studies.

1.6 Scope of the project:

Trickle bed reactors are the simplest three phase reactors used in chemical industries. A complete knowledge of the working of trickle bed reactor is fundamental to the understanding of the design, operation and scale up of the reactor. The understanding of important parameters like dynamic liquid saturation and pressure drop is very important. With stringent emission standards and depleting levels of sweet crude, hydrodesulphurization has become very important industrial process. With rising demand for cleaner fuels all over the world, especially in developed countries like US and EU, the trickle bed reactors have the great potential to contribute a lion’s share of the future demand.

1.7 Objectives of the work:

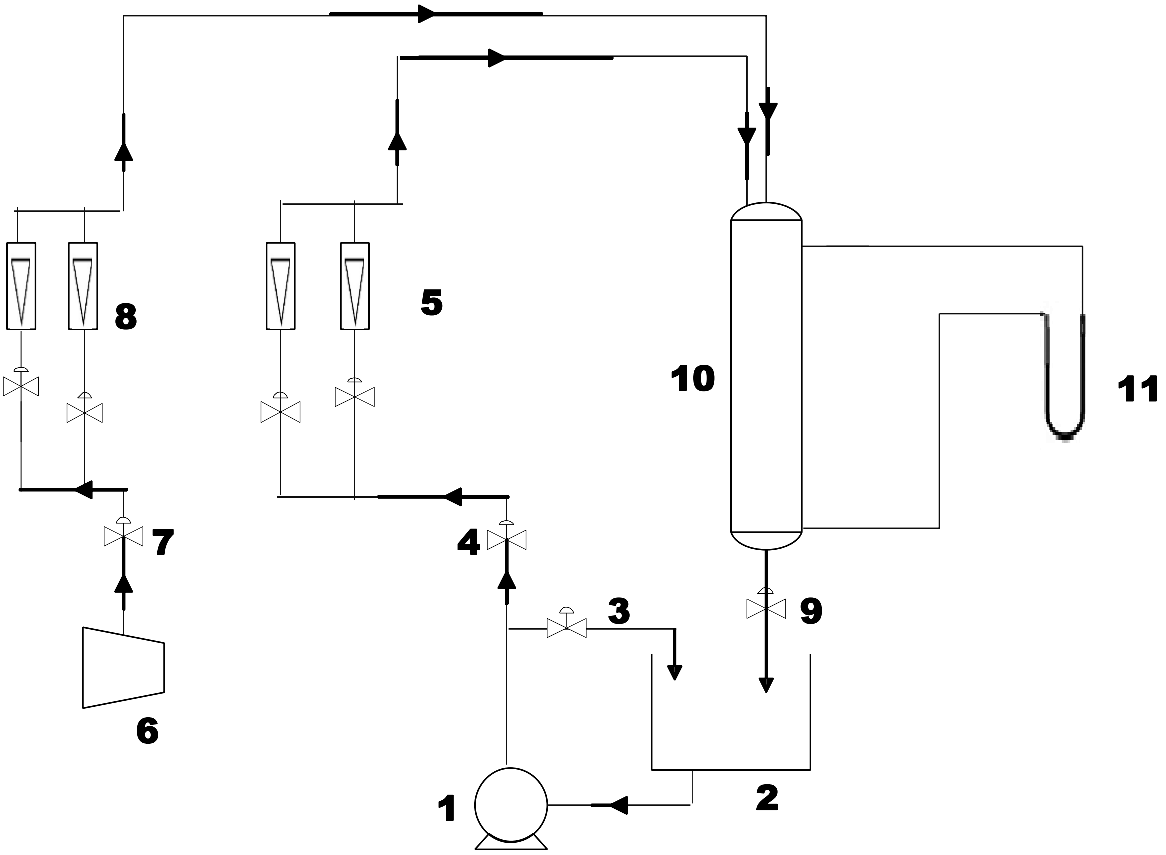
The main objectives of the present work include:

1. Hydrodynamic characteristics study of three phase co-current trickle bed reactor.
2. Determination of pressure drop and dynamic liquid saturation for given gas-liquid mixture.
3. Observing the flow patterns at different gas and liquid flowrates and distinguishing them visually.
4. Examining the impact of liquid and gas velocities on the dynamic liquid saturation and pressure drop.

CHAPTER 2: EXPERIMENTAL SETUP AND TECHNIQUES

2.1 Experimental setup

The experiments were carried out in a Perspex column with internal diameter 91 mm and outer diameter 100mm. The height of the column is 1280 mm. The column was packed with Raschig ring of length 10 mm, inner diameter 6mm and outer diameter 10 mm. The bed porosity was 0.56. The packing inside the column is supported on a wire mesh made of iron. Schematic diagram is shown in the figure below. A distributor plate having 120 holes of 3mm diameter each and 1 mm thickness is placed at the top column. The liquid and gas were fed through the distributor plate. There is an air compressor which provides required air flowrate into the column through air flow rota meter. There is a centrifugal pump connected to the storage tank that supplies liquid at required flow rate through liquid flow rota meter.



1. Centrifugal pump 2. Storage tank 3. Liquid Control valve 4. Liquid control valve
5. Liquid flow rota meter 6. Air compressor 7. Air control valve 8. Gas flow rota meter
9. Outlet valve 10. Column 11. U-Tube manometer

Fig 2.1 Schematic representation of experimental setup.

The top and bottom of the trickle bed reactor are joined via rubber pipes to a U-Tube manometer that uses water as the manometric fluid to indicate the pressure drop across the column. A measuring cylinder was employed to collect and measure the liquid drained from the trickle bed reactor. While several techniques exist for measuring liquid holdup, drainage method was used in the experiment to calculate the dynamic liquid holdup.

Figure 2.2 Photographic view of the experimental setup.

2.2 Experimental Procedure

1. The column was initially filled with liquid alone to achieve complete wetting of solid packing.

2. The liquid was then drained completely.

3. Air and liquid were supplied at set flow rates by adjusting their respective rota meters. Air flowrate was set initially at 0.0256 m/s and liquid flowrate was varied from 0.00256 m/s – 0.0234 m/s.

4. Column is left alone for twenty minutes in order to achieve steady state.

5. The liquid flow pattern was observed and readings of the manometer were noted down.

6. After attaining steady state, the column was isolated by shutting down air and liquid supply and the valve at the bottom of the column.

7. After allowing the liquid to settle for five minutes, the liquid was drained and collected in a measuring cylinder and the reading of the measuring cylinder was noted.

8. The same procedure was repeated for different gas and liquid flowrates, with air flowrates ranging from 0.0256 m/s to 0.128 m/s and liquid flowrates ranging from 0.00256 m/s to 0.0234 m/s.

9. The pressure drop across the bed and dynamic liquid saturation were calculated using given formulas.

Table 2.1 Equipment specifications:

Column Specification	
Material of construction	PMMA(Perspex)
Height of the column	128 cm
Column outer diameter	10 cm
Column inner diameter	9.1 cm
Volume of the empty column	8.32 litre
Distributor	
Material used	Mild steel
Thickness of the distributor	1 mm
Hole diameter	3 mm
Number of holes	120
Pipe Specification	

Pipe used	PVC pipe
Pipe diameter	½ inch
Packing material	
Packing shape	Hollow cylinder
Material used	Raschig ring
outer diameter of the cylinder	10 mm
Inner diameter of the cylinder	6 mm
Height of the cylinder	10 mm
Manometer used	U-tube manometer
Valve used	Gate valve
Operating conditions	
Air superficial velocity	0.0256 – 0.128 m/s
liquid superficial velocity	0.0256– 0.02304 m/s

CHAPTER 3: RESULTS AND DISCUSSION

3.1 Pressure drop:

Pressure drop is an indicator of energy dissipation in the trickle bed reactor. Energy dissipation is caused mainly by opposing friction forces operating at the interfaces of solid-gas, liquid-gas and solid-liquid systems. Inertial forces caused due to fluctuating velocities of the fluids across the packed bed and turbulence also contribute to pressure drop. The relative significance of these forces is dependent on the flow conditions inside the column. At higher fluid velocities the pressure drop is mainly due to inertial forces while at low fluid velocities it is mainly due to shear forces and capillary forces. Thus in trickle flow regime observed at moderate gas and low liquid velocities the pressure drop is mainly due to shear capillary forces and shear forces. Figure 3.1 shows the relationship between pressure drop across the bed and liquid velocity at various gas flow rates. It is observed that with the increase in liquid velocity at constant air flow rate pressure drop in the bed increases. This is observed because as the liquid velocity is increased the friction at the wall increases. The flow regimes operated were trickle flow and pulse flow. The distinction between the two flow regimes can be observed visually and from the plot of pressure drop vs liquid velocity. At any given air flow rate it is observed that there is a sudden increase in the slope of the curve. This sudden change in gradient indicates the transition from trickle flow to pulse flow regime. The transition can be visually observed by the formation of small bubbles inside the column. With further increase in liquid velocity the bubbles increase in size and transition to bubble flow regime takes place. It is also observed that the transition from trickle flow to pulse flow takes place at low liquid velocities. Identifying the transition region from trickle flow to pulse flow is very important because most industrial trickle bed reactors are operated in that region to take advantage of the benefits offered by both the flow regimes. From figure 3.1 it can be observed that the transition region from trickle flow to pulse flow lies between liquid velocities 0.01 m/s and 0.015 m/s. At high gas and liquid flow rates it is observed that the pressure drop increases rapidly. Although the pressure drop increases rapidly from trickle flow to pulse flow regime, the pressure drop increases more rapidly in bubble flow regime because of formation, breakage and reformation of bubbles on a very large scale.

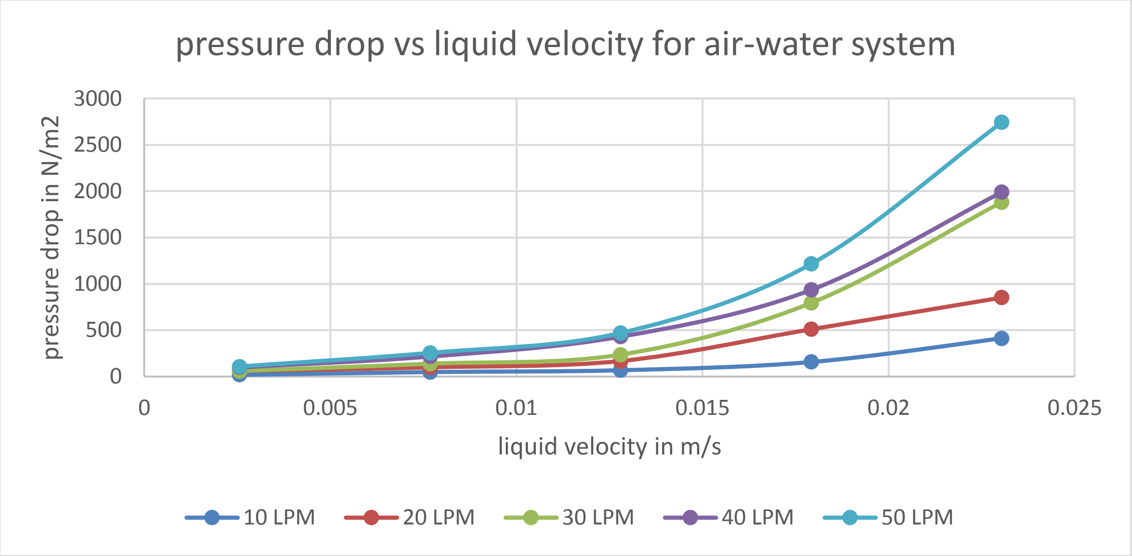


Fig 3.1 plot of pressure drop vs liquid velocity for air-water system at different air flow rates.

3.2 Effect of viscosity on pressure drop:

The major applications of the trickle bed reactors is in petroleum industries. Important operations like hydro treating, hydrodesulphurization (HDS) and hydrodenitization (HDN) use trickle bed reactor. The feed stock that is used in these operations is highly viscous and foaming. Highly viscous liquid result in higher energy losses there by increasing the cost of pumping. Therefore understanding the hydrodynamic characteristics of viscous liquid is imperative for efficient and economic operation of the reactor. Carboxy methyl cellulose solution of 2%, 2.5% and 3.5% concentrations were used in the experiment for hydrodynamic studies as carboxy methyl cellulose solution is highly viscous. The viscosity of the carboxy methyl cellulose solution increases with increase in concentration of CMC. The hydrodynamic characteristics of these solution were studied and it is observed that pressure drop was significantly higher than water-air system. Figure 3.2 gives the plot of pressure drop vs liquid velocity for different liquid and air flow rates. It is observed that the plot shifts upward with the increase in the concentration of the CMC solution. This can be explained by the fact that as the viscosity of the CMC solution increases the frictional resistance offered by the packing material, reactor wall, and the gas-liquid interface increases along increasing bubble formation causing more energy dissipation. In such situations the viscous forces play dominant role in the contribution to pressure drop. The plot of pressure drop vs liquid velocity for air-CMC solution is almost same as that of water-air system with transition from trickle to pulse regime occurring at even lower liquid velocity than air-water system. The transition region for air-3.5% CMC solution is present between liquid velocities between 0.005 m/s – 0.01 m/s.

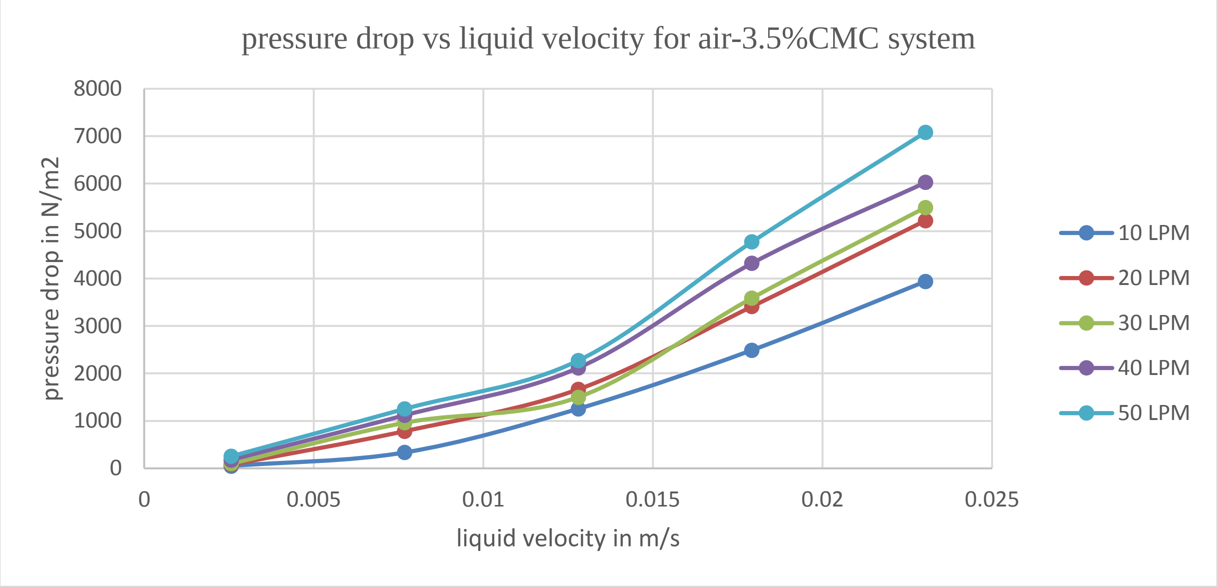


Figure 3.2 Plot of pressure drop vs liquid velocity of air-3.5% CMC system at different at different air flow rates.

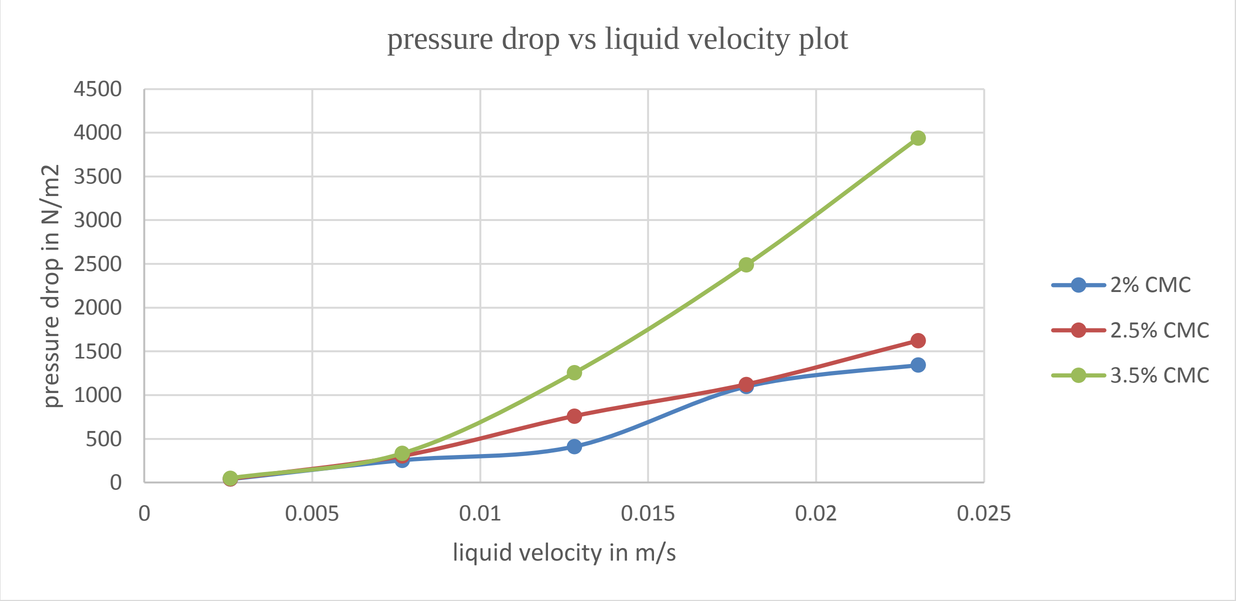


Figure 3.3 Plot of pressure drop vs superficial liquid velocity air-CMC solution of different concentrations at 0.0256 m/s liquid velocity.

3.3 Dynamic liquid saturation:

Dynamic liquid saturation is an important parameter that influences the efficiency of working of the trickle bed reactor. It is the measure of the fraction of liquid present in the column at the given time. During operation, the total volume of the reactor is the sum of the volume occupied by the packing, gas and liquid. While the volume of column occupied by the packing is constant, the volume of column occupied by the liquid and gas varies according to gas and liquid velocities. The dynamic liquid saturation is a function of bed porosity, gas flow rate and liquid velocity. Figure 3.4 gives the plot of dynamic liquid saturation vs superficial liquid velocity for air-water system at different air flow rates. It is observed that with the dynamic liquid saturation increases with increase in liquid velocity at a constant air flow rate. It is also observed that dynamic liquid holdup decreases with increase in air flow rate at constant liquid velocity. This can be explained by the fact that at higher air flow rates more and more air occupies the voids in the column pushing liquid out. Unlike pressure drop, the plot of dynamic saturation vs liquid velocity is almost linear.

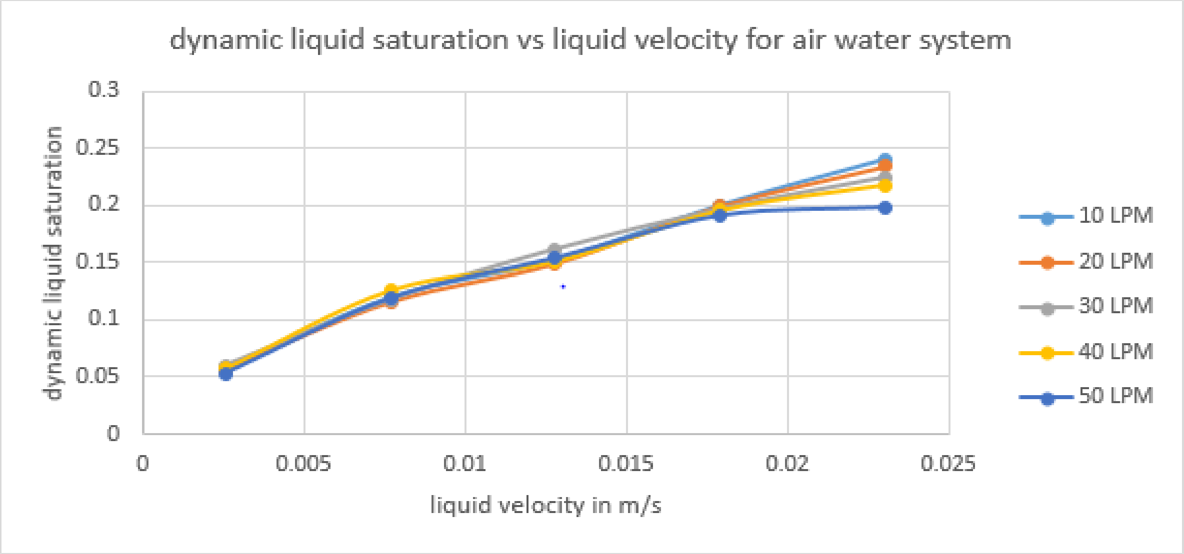


Figure 3.4 Plot of dynamic liquid saturation vs liquid velocity for air-water system at different air flow rates.

3.4 Effect of viscosity on dynamic liquid saturation:

As viscosity is a measure of flow resistance, higher the viscosity, higher is the resistance experienced by the fluid. It means under similar conditions, high viscosity liquid will take more time to flow through the bed than a low viscosity liquid. Hence, the residence time of high viscosity fluid is higher in comparison to the low viscosity fluid. Therefore, a highly viscous liquid will have more liquid retention. The observations shown in figure 3.5 validate the last statement. Dynamic liquid saturation of air- 3.5% CMC solution was plotted in figure 3.5. Figure 3.6 gives the plot of dynamic liquid saturation vs superficial liquid velocity for air- CMC system at different concentrations of CMC solution.

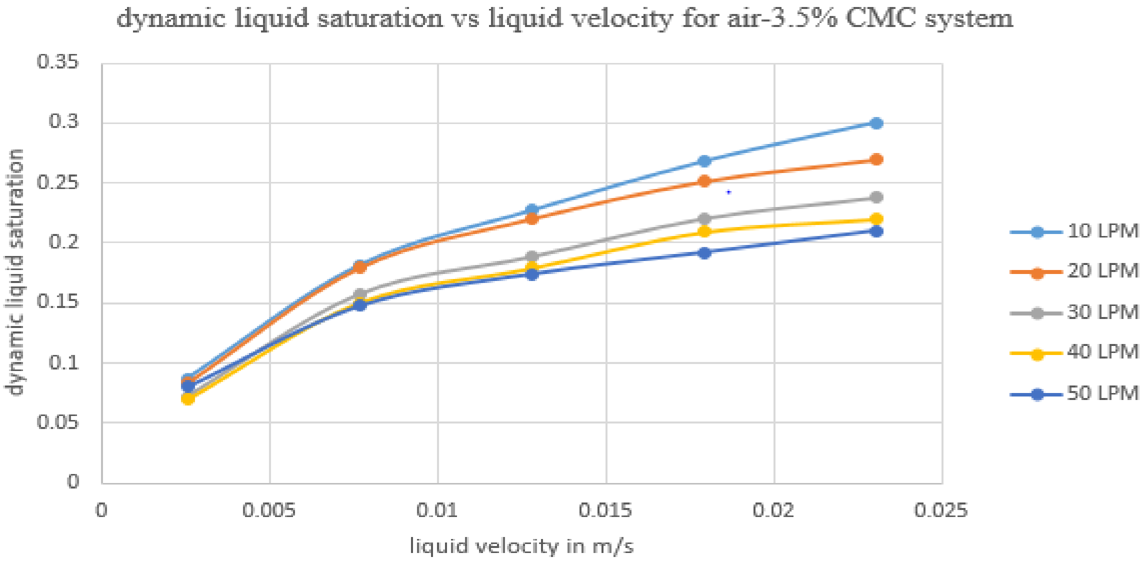


Figure 3.5 Plot of dynamic liquid saturation vs liquid velocity for air-3.5% CMC system at different air flow rates.

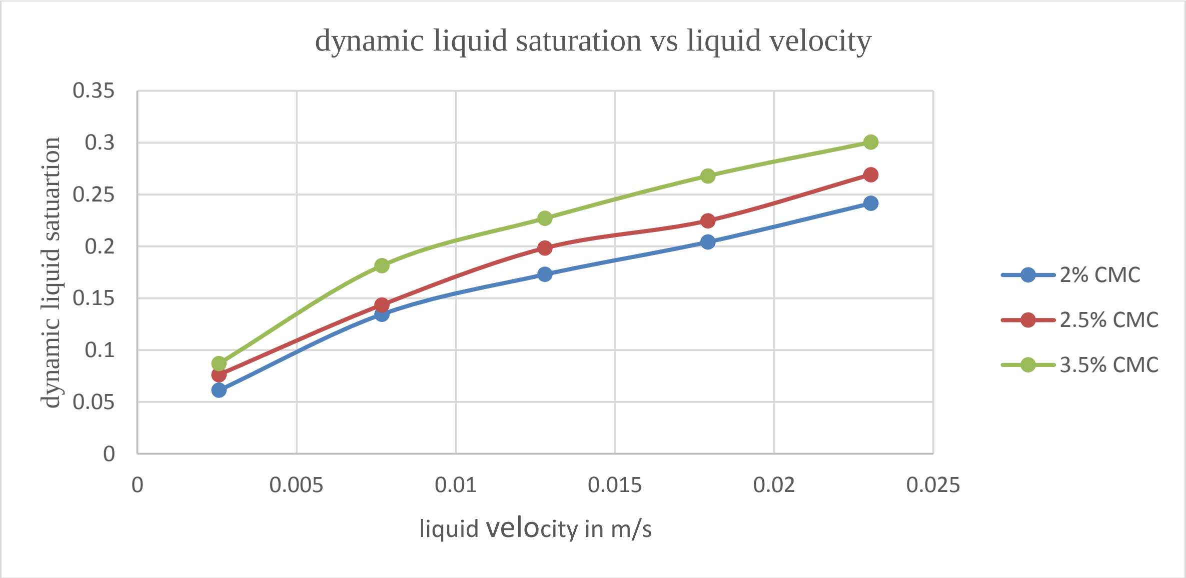


Figure 3.6 Plot of dynamic liquid saturation vs liquid velocity for air- CMC solution system for 2%, 2.5% and 3.5% CMC solutions.

CHAPTER 4: CONCLUSIONS AND FUTURE SCOPE OF THE WORK

Based on the obtained results the following conclusions can be drawn.

1. The pressure drop inside the bed increases with increase in liquid and air flow rates.
2. The transition from trickle flow to pulse flow is generally observed at low liquid velocities.
3. There is a sudden increase in pressure drop across the bed after transition from trickle flow to pulse flow regime. There is additional pressure drop across the bed because loss in energy due to bubble formation, breakage and reformation. This explains why majority of industrial trickle bed reactors are operated at the transition region between trickle flow and pulse flow regime to take advantage of the benefits offered by both the flow regimes.
4. Trickle flow regime was observed for low liquid and moderate gas velocities.
5. Dynamic liquid saturation of the bed increases with increase in liquid flow rates at constant gas flow rates.
6. Dynamic liquid saturation of the bed decreases with increase in gas flow rate for a constant liquid flow rate. This is observed because at high gas velocities more gas occupies the void space and pushes the liquid out reducing the dynamic liquid saturation.
7. For viscous liquids the pressure drop across the bed is significantly higher. Knowledge of optimum operating conditions can be obtained from the plot of pressure drop vs liquid velocity for viscous liquids to have minimum pumping costs.
8. The pressure drop across the different points of bed decreases as we move downward. I.e. the pressure drop is maximum at the top and minimum at the bottom.

The future work on the project includes:

1. Study of dynamic liquid saturation and pressure drop for various foaming and non-foaming liquids.
2. Independently identifying various flow regimes and verify the results with existing literature.
3. Study of hydrodynamic parameters and percentage conversions for reactive systems.
4. Study of mass transfer and heat transfer effects for different gas-solid-liquid systems.
5. Study of pressure drop and dynamic liquid saturation for a given gas- liquid system using different packing.

REFERENCESs

1. Sie, S.T and Krishna R (1998). Process development and scale up: III. Scale up and scale down of trickle bed process. Rev. Chem. Eng. 149(3), 203-252.

2. Ellman.M.J, Midoux.N, Wild.G, Laurent.A and Charpentier.J.C (1990). A new improved liquid holdup-up correlation for trickle-bed reactors. Chemical engineering science, 45(7), 1677-1684.

3. Satterfield, C.N. (1975). Trickle bed reactors, AIChE journal, 21, 209.

4. Muthanna H. Al-Dahhan and Milorad P. Dudukovic (1996). Catalyst Wetting Bed Dilution for Improving Catalyst in Laboratory Trickle-Bed Reactors. AIChE Journal, 42(9), 2594.

5. Iliuta, I. and Larachi.F (2003). Theory of Trickle-Bed Magneto hydrodynamics under Magnetic-Field Gradients. AIChE Journal, 49(6), 1524.

6. Kundu,A and K. D. P. Nigam (2003). Catalyst Wetting Characteristics in Trickle-Bed Reactors. AIChE Journal, 49(9), 2253.

7. Sederman.A.J and Gladden.L.F (2005). Transition to Pulsing Flow in Trickle-Bed Reactors Studied Using MRI. AIChE Journal, 51,(2), 615.

8. Houwelingen.A.J, Sandrock.C, and Nicol.W (2006). Particle wetting distribution in Trickle-bed reactors. AIChE Journal, 52(10), 3532.

9. Turpin.J.L and Huntington.R.L (1967). Prediction of Pressure Drop for Two-Phase, Two-Component Concurrent Flow in Packed Beds. AIChE journal, 13(6), 1196.

10. Elgin.J.C and Weiss.F.B (1939). Liquid holdup and flooding in packed towers, Industrial and engineering chemistry.31(4), 435.

11. Saroha, A. K., and K. D. R. Nigam (1996). Trickle Bed Reactor. *Rev.Chem. Eng.*, **12**, 207.

12. Saroha, A.K and K. D. P. Nigam (1998). Liquid Distribution in Trickle-Bed Reactors. AIChE Journal, 44(9), 2044.

13. Wammes W. J. A., Michaelson S. J., and Westerterf. K. R (1990). The transition between trickle flow and pulse flow in a co-current gas- liquid trickle bed reactor at elevated pressures. Chemical Engineering Science, 45, 3149-3158.

14. Ranade V.V, Chaudhari.R.V, and Gunjal.P.R (2011). Trickle Bed Reactors: Reactor engineering and applications.

15. Gunjal, P.R., Kashid, M. N., Ranade, V.V., and Chaudhuri, R.V. (2005). Hydrodynamics of trickle bed reactors: experiments and CFD modelling. Industrial and engineering chemistry research. 44, 6278-6294.

16. Al-Dahhan, M.H., and Dudukovic, M.P. (1995). Pressure drop and liquid holdup in high pressure trickle-bed reactors. Chemical engineering Science, 49, 5681-5698.

17. Fukushima, S., and Kusaka, K. (1977). Liquid-phase volumetric and mass transfer coefficient, and boundary of hydrodynamic flow region in packed column with co-current downward flow. Journal of Chemical engineering of Japan, 10, 468.

18. Guo, J., Jiang, Y., and Al-Dahan, M.H. (2008). Modeling of trickle bed reactors with exothermic reactions using cell network approach. Chemical engineering science, 59, 2023.