Pinning in Radial Flow Moving Bed Reactor

By

Mohd Khairul Azhar Bin Abd Aziz
10764

Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
(Chemical Engineering)

SEPT 2011

Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

Pinning in Radial Flow Moving Bed Reactor

By

Mohd Khairul Azhar Bin Abd Aziz
10764

A project dissertation submitted to the
Chemical Engineering Programme
Universiti Teknologi PETRONAS
In partial fulfillment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(CHEMICAL ENGINEERING)

Approved by,

(Prof. Dr Duvvuri Subbarao)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
January 2006

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

(_________________________________)

MOHD KHAIRUL AZHAR BIN ABD AZIZ

ACKNOWLEDGEMENT

Bissmillahirrahmanirrahim,

Alhamdulillah. Thanks to Allah SWT, whom with His willing giving me the opportunity to complete this Final Year Project which is title **Pinning in Radial Flow Moving Bed Reactor**. This final year project report was prepared for Chemical Engineering Department, University Teknologi PETRONAS (UTP), basically for student in final year to complete the undergraduate program that leads to the degree of Bachelor of Chemical Engineering. This report is based on the methods given by the university.

Firstly, I would like to express my deepest thanks to, Prof. Dr Duvvuri Subbarao, a lecturer at Chemical Engineering Department UTP and also assign, as my supervisor who had guided be a lot of task during two semesters session MAY & SEPT 2011. I also want to thanks the lecturers and staffs of Chemical Engineering Department UTP for their cooperation during my final year project. They had given valuable information, suggestions and guidance in the compilation and preparation this final year project report.

Deepest thanks and appreciation to my parents, family, my friends and others for their cooperation, encouragement, constructive suggestion and full of support for the report completion, from the beginning till the end. Also thanks to all of my friends and everyone, those have been contributed by supporting my work and help myself during the final year project progress till it is fully completed.

Thank you

TABLE OF CONTENTS

LIST OF FIGURE

LIST OF TABLE

ABSTRACT

For certain types of chemical reactors where the catalyst decays rapidly but reversibly, continuous operation is possible by use of a Radial Flow Moving Bed Reactor (RFMBR). A Continuous Catalyst Regeneration (CCR) reformer unit is one of the industrial units using the RFMBR. RFMBR can be simply described as a reactor where the catalyst flows downward by gravity and the feed gas flow radially across the reactor and leaves through a center pipe.

In this type of reactor there is an upper limit on the gas flowrate imposed by a mechanical phenomenon called "pinning". "Pinning" is when the catalyst particles are pinned against the center pipe due to high gas velocity. Understanding the pinning and the factors influencing it is required for the CCR reformer process engineers before doing any plant optimization. By conducting the experiment we can study the effect the flowrate of gas to the maximum pinned film thickness.

CHAPTER 1
INTRODUCTION

INTRODUCTION

1.1 BACKGROUND

For certain types of chemical reactor whose catalyst decays rapidly but reversibly, continuous operation with a lower pressure drop is possible by use of a moving-bed radial flow reactor. In this type of reactor there is an upper limit on the gas flowrate imposed by the mechanical phenomenon of 'pinning', or the formation of a cavity. A theoretical model is developed using the theories of particulate media mechanics to predict the dimensionless pressure drop for the initiation of the cavity. The theoretical results agree very well with experimental data. The shape of the interface between the cavity and the particle bed has also been measured.

The pinning phenomenon was investigated respectively of two-dimensional rectangular moving beds, their cross-flow sections of the gas flow. In this case show that the bed pressure drop produced by the gas flow increases with the increase of gas velocity, and when the pressure drop is increased to a value high enough-the *critical pressure drop causing pinning*, some particles close to the downstream face of the gas flow would stick together on the face and stop moving downwards, then the pinning occurs. Due to this phenomenon, pinning can be avoid when operate the reactor in optimum velocity which means the maximum velocity of the gas without pinning occur in the reactor. So, the spoil catalyst can move down and replaced by another new catalyst without any pressure push the catalyst that make pinning occur.

1.1.1 MOVING BED REACTOR

A radial flow moving bed reactor (RFMBR) is one in which the solid, usually the catalyst, flows downwards under the influence of gravity, and the gas reactants flow radially through the solid bed, reacts before being collected as the product. RFMBRs are used in many applications, the most common of which are the Continuous Catalyst Regeneration (CCR) reforming units.

The reforming process combines catalyst, hardware, and process technology to produce optimal results. Currently, several processes are being used in the refining industry. These processes are generally classified into three types: semi-regenerative, cyclic or moving bed. All three types mainly differ in the configuration of the reactor system.

These classifications are based on the methods and the frequency of the reforming catalyst regeneration. The reforming catalyst, similar to any catalytic process, becomes less active with time due to coke accumulation on the catalyst surface.

A moving bed unit, as the name implies, permits the catalyst to be moved continuously through the reactors system, to be regenerated and sent back to the reactors system as fresh catalyst. There are two types of moving bed units. One is licensed by UOP and the other is licensed by Institut Francais du Petrole (IFP) (Little, 1985)

The coked catalyst is withdrawn from the last reactor and sent to the regeneration section by a lifting gas. The regenerated catalyst is then sent back to the first reactor also by a lifting gas. The UOP CCR unit uses three or four reactors.

In the IFP CCR design, the reactors are placed separately as in a semi-regenerative unit (Little, 1985). The catalyst moves slowly by gravity through each reactor. It is transferred by a lifting gas from the bottom of one reactor to the top of the next reactor. The coked catalyst is withdrawn from the last reactor and sent to a regeneration section. The regenerated catalyst is then sent back to the first reactor. The IFP CCR unit also uses three or four reactors.

This continuous catalyst circulation prevents excessive coke buildup on the catalyst and maintains the catalyst at high activity. Catalyst circulation rates have been designed from as low as 200 lb/h to as high as 6000 lb/h, depending on the capacity and operating conditions of the reforming unit (Meyers, 1997) [6]. A CCR unit can be operated at a very low pressure compared to the semi-regenerative and cyclic units, since the coke buildup on the catalyst is controlled by the continuous catalyst circulation. Operating at low pressure increases reformate and hydrogen yields. The operating pressure of this unit can be as low as 50 psig. The reformate octane number is in the 95-108 range.

In addition to the high reformate yield and high octane number a CCR unit has the advantages of eliminating the downtime for catalyst regeneration and maintaining a steady operation. Due to these advantages, CCR reactors design is applied to most of the new reforming process. Also some of the fixed bed reforming units were revamped to CCR units.

A CCR unit involves complex design, operation control and multiphase flow of gas and solid catalyst. This research will focus on the multiphase flow inside the moving bed reactor. The study will be linked with the reforming reactor design, catalyst circulation system, and CCR unit process variables that are discussed in the next section

1.1.2 REACTOR DESIGN

Any catalytic reactor must be designed to provide good flow distribution through the catalyst bed. Non-uniform flow inside the reactor may play a role more important than that of the kinetic or diffusion factors and impact the conversion, the temperature distribution in the reactor, the product yields and the normal operation of the reactor (Song *et al.,* 1993). Reactors used in reforming units are classified as either axial flow or radial flow. Figure 1 illustrates these types of reactors. In an axial flow reactor, feed enters at the top and flows downward through the catalyst bed. The product exits at the bottom. In a radial flow reactor, the feed enters at the top and product exits at the bottom, however the feed flows across an annular catalyst bed to a center pipe. The radial flow reactors provide larger mean cross-sectional area and reduce distance of travel for flow compared to axial flow reactors. The main advantages of radial flow in comparison to axial flow reactors are the low pressure drop and the high flow capacity

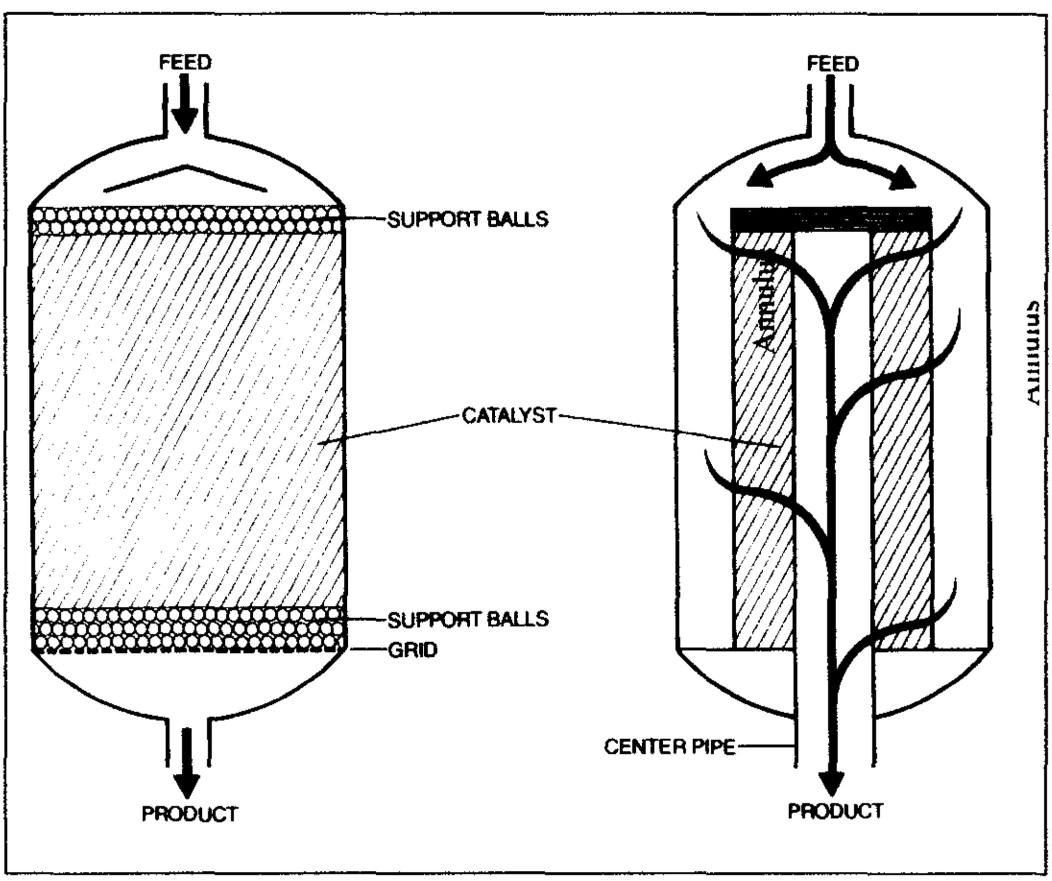


Figure 1: Illustrate these Types of Reactor

1.2 PROBLEM STATEMENT

Pinning in radial flow moving bed reactor

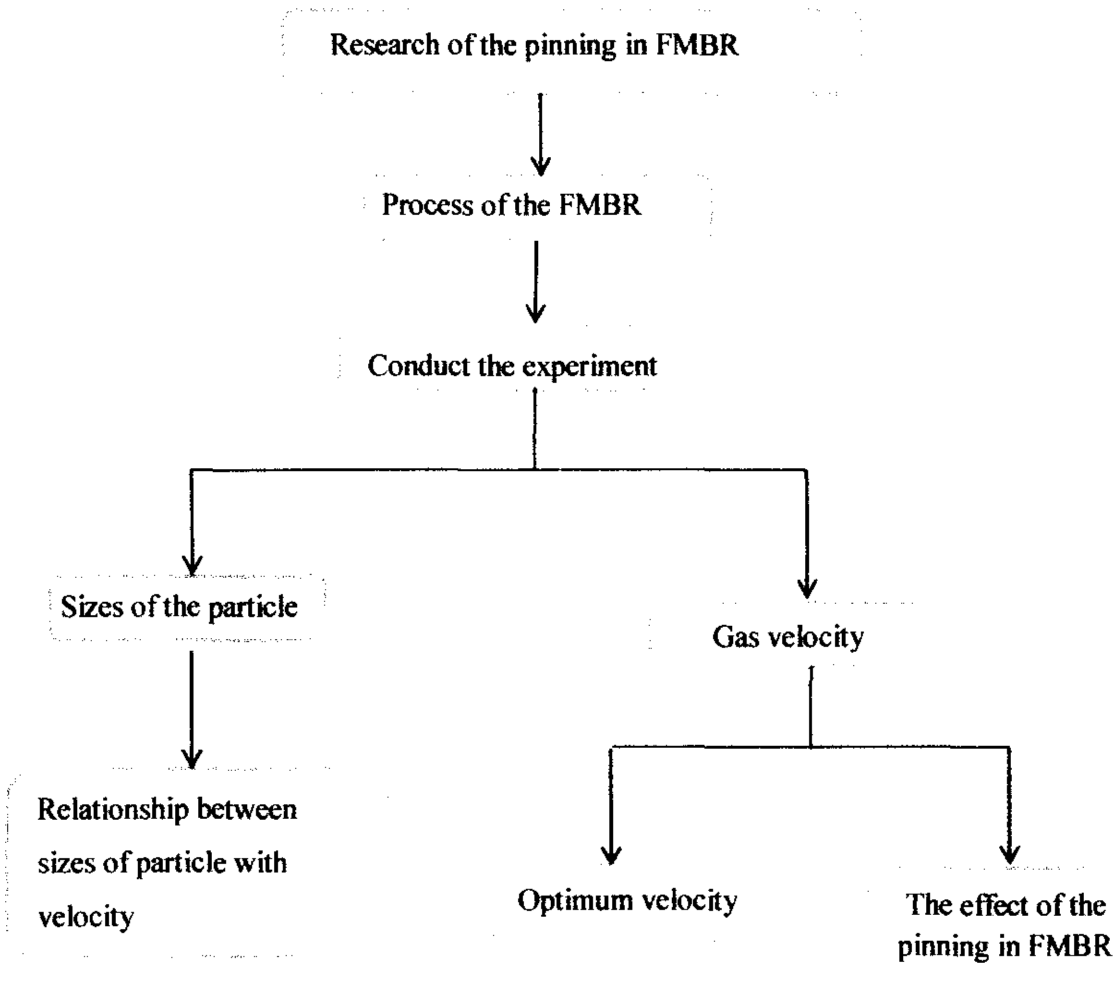
Many vapor phase catalytic processes are designed with radial flow reactors. The main advantage of a radial flow reactor is that it has a lower bed pressure drop in comparison with an axial flow reactor. That means the bed pressure drop increase as the velocity of gas increase. Although the radial flow gives the low pressure drop, it can create the problem of 'pinning' which can hinder the flows of solid in the downward direction. Pinning occurs when the pressure drop increases to a critical value where some particles close to the downstream face of the gas flow would be pressed to the downstream face and stop moving downward. Besides, the catalyst in the pinned zone will forms a dead zone and the reactor will get deactivated soon. This phenomena can reduces the efficiency of reactor and conversion

1.3 OBJECTIVE

The objectives of this project which is pinning in radial flow moving bed reactor are:

- To study the relationship between gas flow velocity and thickness of the pinned zone as a function of the particle properties in a 2-D radial (gas phase) flow moving bed.
- To study the relationship between height differences with the maximum pinned film thickness.
- To study the relationship between the pressure differences with the maximum distance pinned.

1.4 SCOPE OF STUDY



The scope of study will be revolving around pinning in radial flow moving bed reactor (FMBR). First, find the information by doing some research about the pinning in FMBR. The study will then proceed by understanding the process in flow moving bed reactor. After understand about the pinning in radial flow moving bed reactor (FMBR) and how the reactor is operated. The study will then proceed by conducting the experiment about the pinning. The experiment is conducted by two parts which are based on between the sizes of the particle and also regarding gas velocity.

CHAPTER 2

LITERATURE REVIEW

2.1 LITERATURE REVIEW

2.1.1 RADIAL FLOW REACTOR

There are two types of radial flow reactors depending on whether the catalyst bed is fixed or moving inside the reactor. They are the radial flow fixed bed reactor (RFBR) and the radial flow moving bed reactor (RFMBR). Both types can be found in the catalytic reformer processes. An RFMBR is a reactor in which the solids moves at a low velocity that around 1 mm/s under the influence of gravity. Due to this low velocity, the moving bed void fraction is considered to be constant and therefore, the hydrodynamics of an RFBR and an RFMBR are similar. Due to this similarity, this work is applicable to both types.

Radial flow reactors can be classified into a z-flow type or a Π- flow type depending on the axial directions of the flow in the annular channel and the center pipe. If the axial flow directions in the annular and in the center pipe are the same, it is classified as the z-flow type, and if they opposite it is classified as the Π- flow type. Moreover,, radial flow reactors can be also classified into centripetal (CP) or centrifugal (CF) flow types depending on the reactor radial flow direction. In the CP-flow type, the gas is fed to the annular channel and travels radially inward from the annular channel to the center pipe. In the CF- flow configuration, the gas is fed to the center pipe and travels radially outward from the center pipe to the annular channel. Therefore, four flow configurations are possible for a radial flow reactor. They are classified as CP-z, CP-Π CF-z and CF-Π configuration as shown in figure 2. All four configurations can be applied to an RFBR and RFMBR.

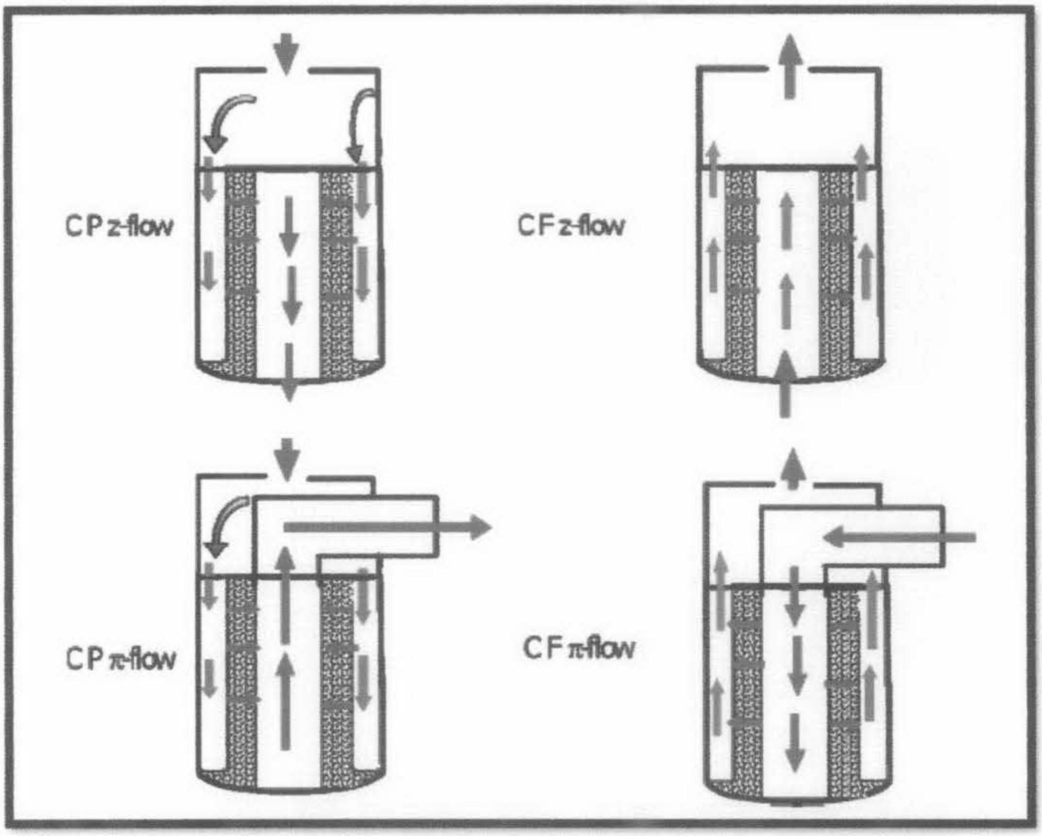


Figure 2: Four possible flow configurations for a radial flow reactor

A RADIAL FLOW MOVING BED REACTOR (RFMBR)

In a process where the catalyst is deactivated rapidly due to coke formation, a RFMBR can be used to allow regenerating the catalyst and returning it back to the reactor without shutting down the process as in a fixed bed reactor process. A RFMBR can be used for catalytic cracking, adsorption, and granular filtration processes (Marb and Vortmeyer, 1988; Tsubaki and Tien, 1987). The well-known processes using RFMBR are the IFP and the UOP CCR reformer.

In a RFMBR CCR reformer, catalyst moves down vertically through the reactor by gravity, while the reacting gas flows horizontally across the bed toward the center pipe. The catalyst flow rate in a moving bed reactor is very low compared to a fluidized reactor. The catalyst flow in a fluidized catalytic cracking FCC unit is measured in tons per hour, while in CCR reforming it is measured in a few hundred or a few thousand pounds per hour (Little, 1985). A moving bed reactor can be a downflow radial reactor with a wire screen or scallops or an upflow radial reactor with a wire screen or scallops. Figure 3 illustrates a RFMBR. Despite its major advantage in maintaining a continuous operation, RFMBR suffers from a major defect which is known as the pinning phenomenon.

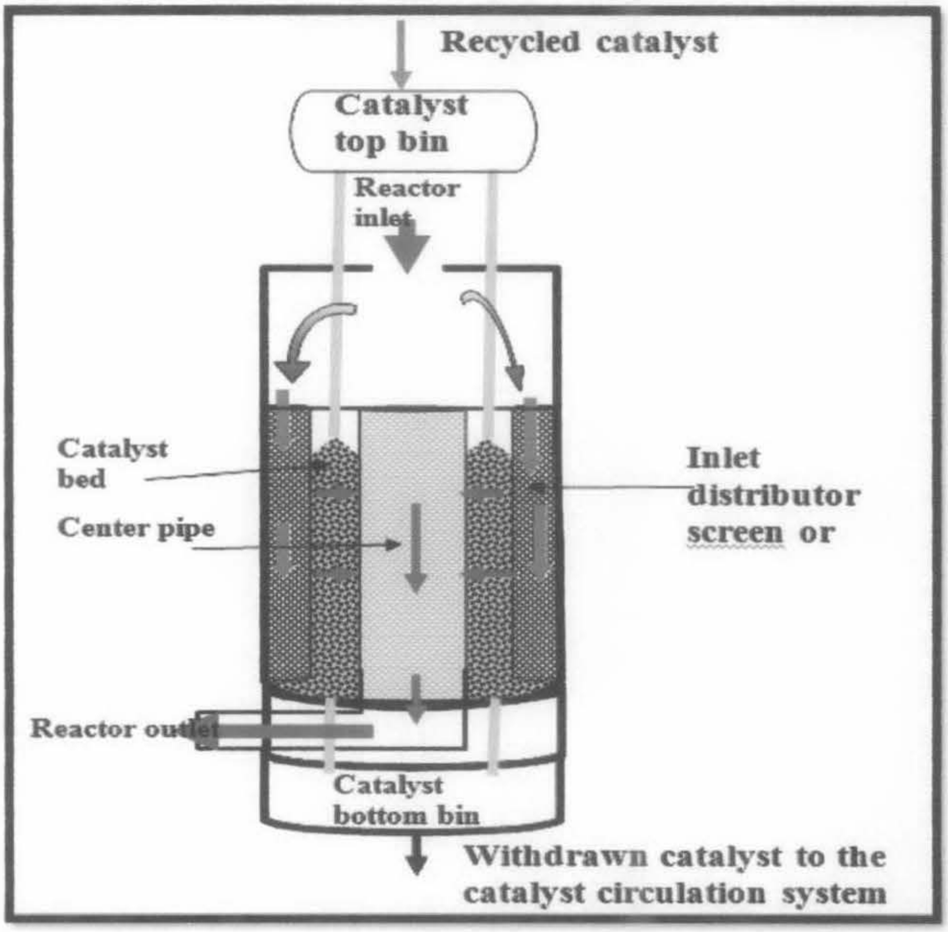


Figure 3: A down flow moving bed radial reactor.

In a radial flow moving bed reactor (RFMBR), the catalysts move down by gravity. The gas stream flow perpendicular to the catalyst movement. It exerts a drag force on the catalyst particles. This drag force is a function of the gas radial velocity. The gas radial velocity can be increased by increasing the gas flow rate or by a flow maldistribution in the reactor. Under normal condition, catalyst particles move down with normal friction at the upstream and downstream perforated wall. The gas enters and leaves the bed through the upstream and downstream perforated walls, respectively. If the drag force on the catalyst particles increases, the normal stress between the particles and the upstream wall will be decreased. When the normal stress is reduced to zero, the bed particles start to lose contact with the upstream wall. Under this condition, a thin cavity will open between the catalyst bed and the upstream wall. Under very high drag condition, the size of cavity adjacent to the upstream face might be increased until it ultimately spans the full width of the catalyst bed. At this point, the bed may not move down at all and bed is said to be completely pinned.

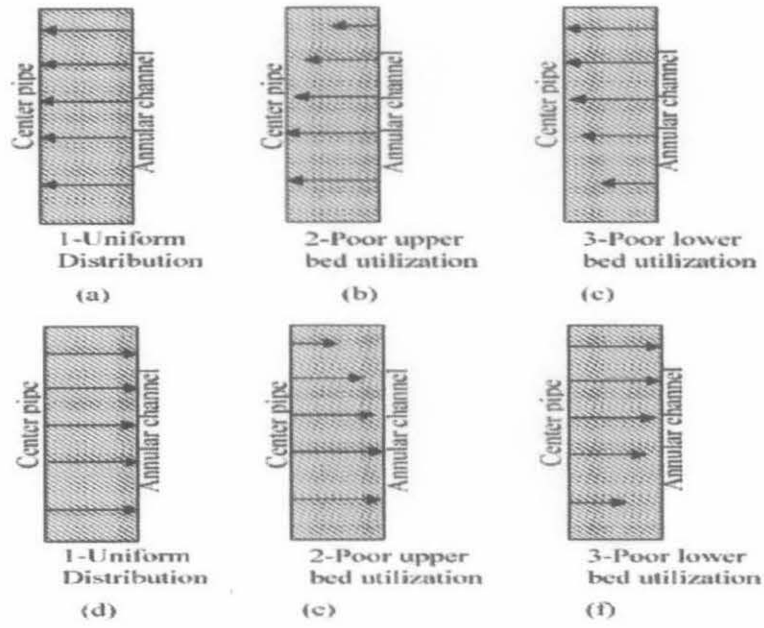


Figure 4: Typical flow distributions over the bed length in radial flow reactor at the same feed flow rate for CP configuration (a-c) and for CF (d-f). The arrow length is represent the mass flow magnitude

PINNING IN RADIAL FLOW MOVNING BED REACTOR

Gravity is the driving force for the solid particles movement through the RFMBR. Pressure is the driving force for the gas flow from the distributor header to the center pipe. When the pressure gradient along the gas flow direction is sufficiently large, it will cause a holdup of solid particles against the center pipe. At this stage the drag force exerted by the gas stream is greater than the gravitational force on the solid and hence the action of gravity is not enough to cause the solid particle to move down. A portion of or the whole solid bed can be pinned depending on the magnitude of the pressure drop across the reactor (Pilcher and Bridgwater, 1990). Figure 5 illustrates some forms of the catalyst bed inside a RFMBR.

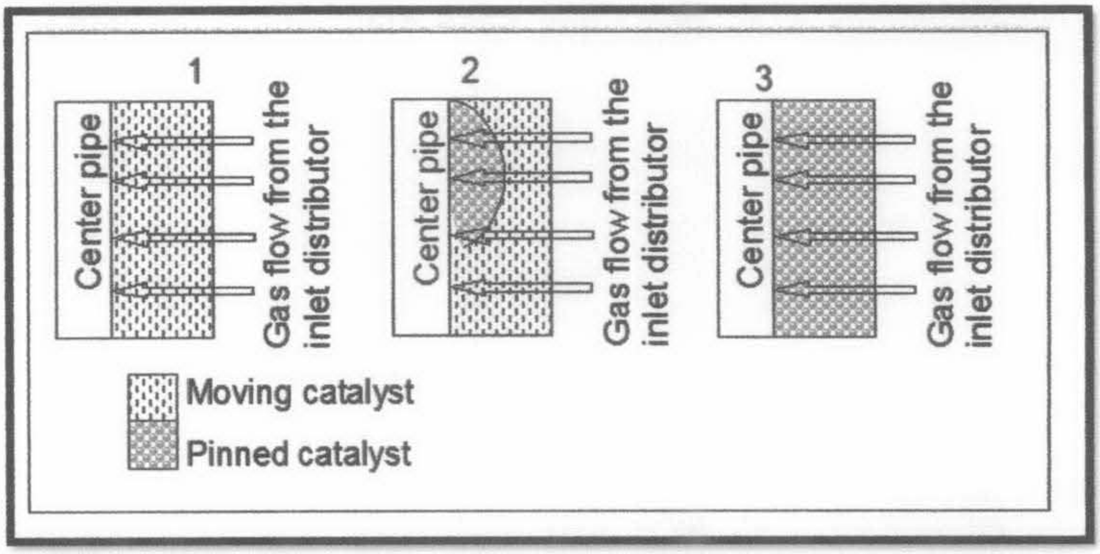
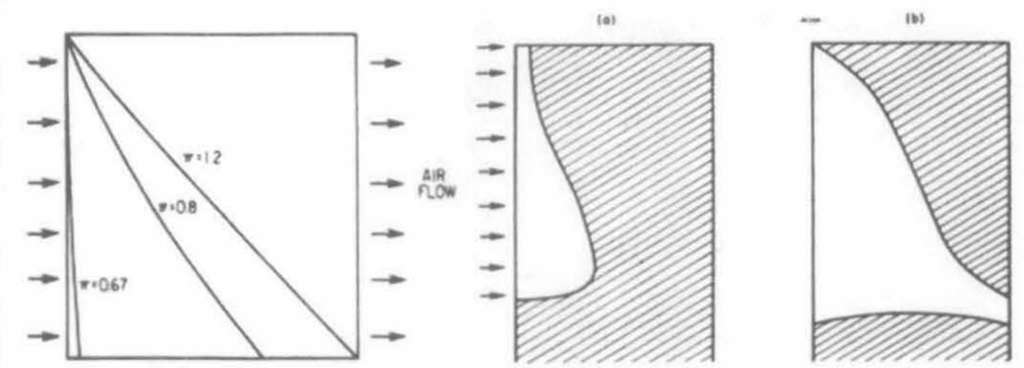


Figure 5: (1) Total moving bed, (2) Partially pinned bed, (3) Totally pinned bed.

The main cause of pinning is the high gas flow rate to the reactor. If pinning occurs, it will cause maldistribution inside the reactor which will lead to low reactor performance. In any CCR process, pinning is a major concern, because the pinned catalyst can become highly coked and may then flow to the regeneration system. The highly coked catalyst may contain coke higher than the design limitation for the regeneration system. If the highly coked catalyst burns in the regeneration system it will cause equipment damage. Due to that pinning is the first limitation to be evaluated before increasing the feed rate above the design value for the CCR process.

Ginestra and Jackson (1985) conducted an experimental study for the same rectangular geometry to validate the theoretical analysis. The cavity growth process was qualitatively similar to that predicted theoretically. Figure 6 shows the theoretical and the experimental cavity growth process. In the experimental study cavity growth process was observed by photographing through a transparent wall of the bed. They observed good agreement between the theoretical and experimental cavity wall profiles at complete pinning.



Theoretical cavity growth
π=0.67 cavity initiation at Δp_0
π=0.8 cavity wall between Δp_0 and Δp_1
π=0.8 cavity wall at Δp_1 complete pinning

Experimental cavity growth
(a) Cavity wall between Δp_0 and Δp_1
(b) Cavity wall at Δp_1 complete pinning

Figure 6: Theoretical and experimental cavity wall profiles.

Doyle *et al.* (1986) generalized the cavity growth theory by Ginestra and Jackson (1985) [3] to theoretically describe the pinning phenomena in a simple RFMBR configuration which is shown in Figure 3.4. The reactor is z-flow type. They applied the theoretical analysis to CP and CF z-flow configurations. It was found that the CP flow type is preferable, since a large gas flow can be achieved before pinning. They performed an experimental study for the same geometry and the results were in good qualitatively agreement. Doyle *et al.* (1986) [2] concluded that the CP flow type can sustain more pressure drop before pinning than the CF flow type.

Although the geometries used by Ginestra and Jackson (1985) and Doyle *et al.* (1986) are simple, they give a good idea of the pinning mechanics. Both works are based on the cavity growth which initiates first at the upstream porous and then propagates to the downstream porous face as the pressure drop increases. The cavity growth theory that was used by Ginestra and Jackson (1985) and Doyle *et al.* (1986) [2] may be applicable for a bed with small thickness and uniform flow distribution. However for large bed and not completely uniform flow the situation will be different. The cavity may initiate within the bed particles depending on the location of the highest drag force exerted by the gas. Therefore it may better to solve the flow profile inside a RFMBR simultaneously with a pinning model.

Tsubaki and Tien (1987) performed analytical study for solid movement in cross flow moving bed filters similar to the configuration in Figure 3.2. The analysis was done by obtaining the stress distribution throughout the solid phase. It was found that the solid velocity profile depends on the gas pressure drop and the frictional stress between the particles and between the particle and the surface of the filters. The results were found to agree reasonably well with available experimental data.

Pilcher and Bridwater (1990) experimentally studied the pinning in a rectangular moving bed reactor similar to the configuration. They investigated the effects of the shape and the size of the solid particles and the distance separating the upstream and downstream porous faces. They observed the same cavity growth process that was observed by Ginestra and Jackson (1985) and Doyle *et al.* (1986). Pilcher and Bridwater (1990) [7] experimental setup was more advanced than that of Ginestra and Jackson (1985) and Doyle *et al.* (1986) [2]. This allowed them to record the cavity initiation and the partial pinning, where the cavity encompasses a part of the bed width and not all of it.

It was concluded from this study that the pressure drop required for the cavity initiation is independent of the equipment size. This conclusion contradicts Ginestra *et al.* (1985) and Doyle *et al.* (1986) theoretical analysis. Also it was concluded that the cavity initiation, cavity wall profile and complete pinning depend on the shape and the size of the solid particles.

Song *et al.* (1993) performed experimental study for the effects of the gas flow rate on RFMBR. They found that at high gas flow rate, the drag force exerted on the particles enhances friction between the particles and the downstream wall which is sufficient to prevent bed motion.

Kareeri Zughbi and Al- Ali studied effects of radial flow maldistribution and flow direction of gas flow due to non-uniformity on radial flow reactor performance. To have a uniform flow distribution, the gas mass flow should be equally divided to produce an even carbon concentration over the catalyst bed height. If the mass flow not equally divided, some parts of the bed will be under-utilized and non-uniform carbon concentration over the catalyst bed height.

CHAPTER 3

METHODOLOGY

3. METHODOLOGY

3.1 PROJECT WORK

Title Selection

Preliminary Research/ Literature Review

Experimental Setup

Experimental Work

Analysis of Result

Discussion of Analysis

Report Writing

Figure 7: Flow chart of the research methodology

Title selection:

An appropriate title is chosen for the final project

Preliminary research:

This would be reading related research journal papers to better understanding the theory and concept of the project which is pinning in radial flow moving bed reactor

Experimental setup:

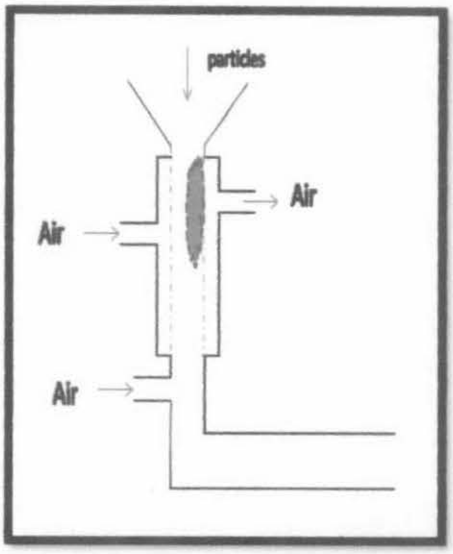
The pinning in radial flow moving bed reactor will be performed the experiment with using apparatus which is vacuum, box and soil with difference sizes. This experiment will be conduct with different velocity of vacuum (velocity of gas). The vacuum hose will be tied up with cloth and start the vacuum with different velocity. Then, the particles that stick at the cloth will be weighted.

EXPERIMENT: PINNING IN RADIAL FLOW MOVING BED REACTOR.

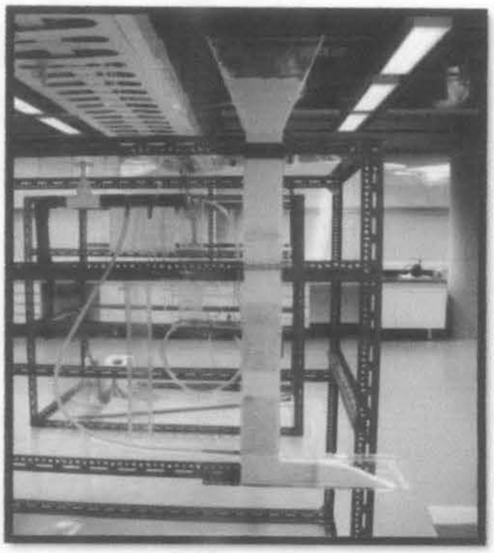
Apparatus: L-valve, hose, particles, compressor air.

Procedure:

1) The experiment was conducted as shown below in figure 8.
2) The particles were put in the hopper.
3) A hose from the pipe was connected between compressor air and standpipe.
4) Compressor was started. The air flow is then started and is increased in discrete steps until the initiation of the cavity is observed.
5) Air flow is then increased further until a full cavity, pinning, is formed which results in stopping the solids above the perforated section from flowing.
6) The result will be recorded in the 10 minutes. Maximum pinned film thickness measured.
7) The experiment was repeated with the different velocity of gas in standpipe
8) Plot the result collected between the maximum pinned film thickness versus volume metric flowrate and also between maximum pinned film thickness versus pressure differences.



(a)



(b)

Figure 8: (a) Experiment setup and (b) actual experiment of pinning in radial flow.

Experimental work:

The experiment will be conducted to collect the result based on the amount of the soil with the variables velocity. The result will record in the table 1.

Discussion of analysis:

The expected analysis from the experiment would be to find relationship between velocities of the gas with the amount soils collected. Besides that, it may know the effect of the velocity to the pinning. In this experiment that investigated the the relationship between gas flow velocity and thickness of the pinned zone. As shown below in figure 9 when X equal to L the flow moving in the reactor in good condition. When X equal to zero the flow moving in the reactor in bad condition. Besides, different between X and L is callaed pinned area.

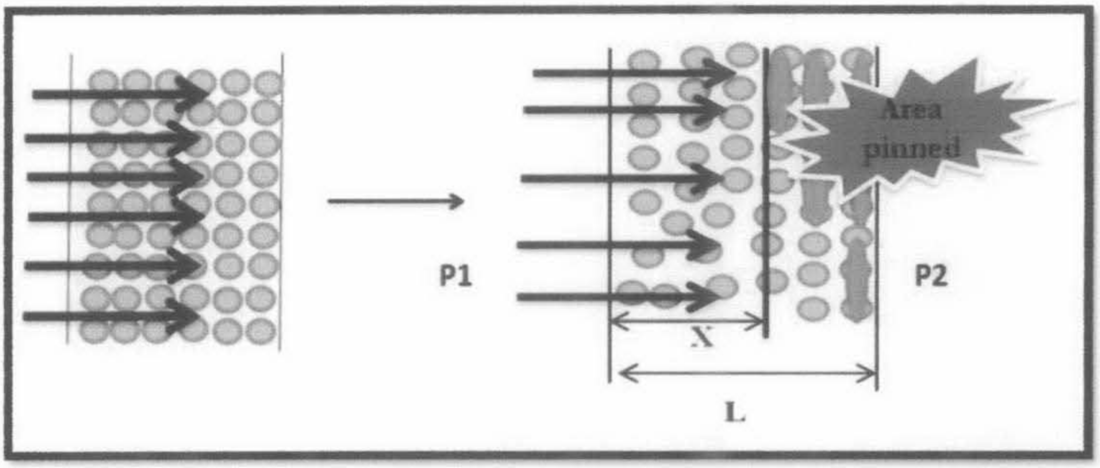


Figure 9: Pinned area in radial flow moving bed

The expected result for this experiment is shown in the figure 10. We can see that when the velocity of gas increases the area of pinned will be increase. Besides, when size of the particles increase the area of pinned will be decrease. That mean velocity of gas is proportional with the area pinned and the size of the particles is not proportional with the area pinned. So, the phenomena of the pinning can be reducing by using low velocity of gas and large size of the particles.

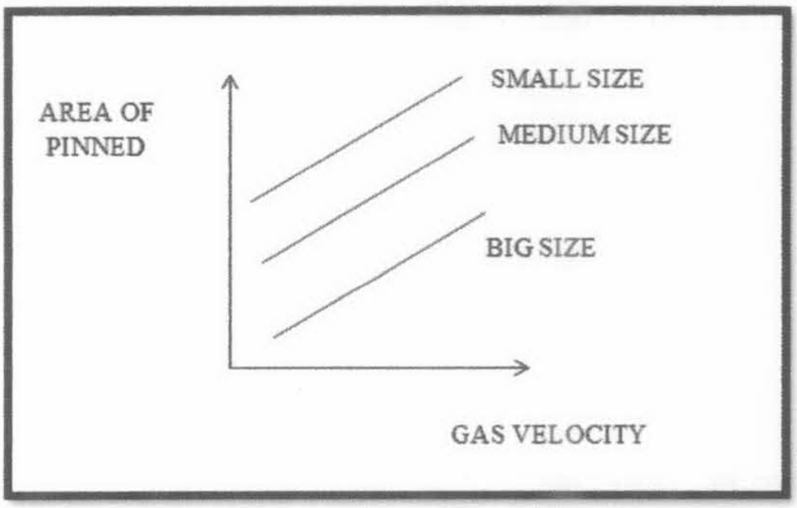


Figure 10: Expected result for pinning experiment

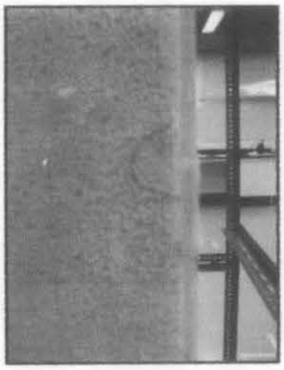
CHAPTER 4

RESULT AND DISCUSSION

Based on the experiment of pinning in radial flow moving beds reactor that conducted which result as:

Table 1: Data for Maximum Distance Pinned

Δh (m)	Maximum Distance Pinned (m)			
	SET 1	SET 2	SET 3	Average
0.145	0.011	0.012	0.01	0.033
0.255	0.019	0.018	0.019	0.056
0.315	0.023	0.022	0.024	0.069
0.465	0.027	0.026	0.029	0.082



Δh = 0.145m

Δh = 0.255m

Δh = 0.315m

Δh = 0.465m

Table 2: Data of Maximum Pinned Thickness (L-X)

Δh (m) orifice meter	Maximum Pinned thickness, L-X (m)				Bed Length L (m)
	SET 1	SET 2	SET 3	Average	
0.145	0.011	0.012	0.01	0.011	0.087
0.255	0.019	0.018	0.019	0.01867	0.087
0.315	0.023	0.022	0.024	0.023	0.087
0.465	0.027	0.026	0.029	0.02733	0.087

Table 3: Data of Non-maximum Thickness and (L-X)/X

Non-pinned thickness, X (m)				(L-X)/X (m)			
SET 1	SET 2	SET 3	Average	SET 1	SET 2	SET 3	Average
0.076	0.075	0.077	0.228	0.14473	0.16	0.1298701	0.43460
0.068	0.069	0.068	0.205	0.27941	0.26086956	0.2794117	0.81969
0.064	0.065	0.063	0.192	0.35937	0.33846153	0.3809523	1.07878
0.06	0.061	0.058	0.179	0.45	0.426229508	0.5	1.37623

<u>Orifice Meter</u>

The orifice meter consists of a primary element and secondary element(s). The primary element includes a section of straight run pipe with a constrictive device, most commonly and orifice plate, which causes change in energy's. The energy changes in the form of a loss in static pressure and increased velocity through the orifice. The secondary element senses the change in pressure, or differential pressure. This differential pressure combined with correction factors for the primary device and physical characteristics of the fluid being measured allows computation of rate of flow. Proven flow factors and established procedures convert the differential pressure into flow rate. These factors and / or coefficients are based on measurable dimensions of the primary device, such as the pipe inside diameter and the orifice bore diameter, along with the physical properties of the fluid being measured, such as specific gravity, density, and viscosity

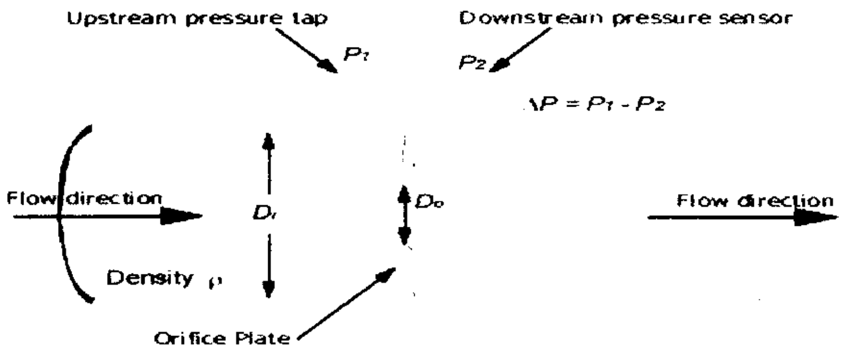


Figure 11: Orifice meter

As long as the fluid speed is sufficiently subsonic, the incompressible Bernoulli's equation describes the flow reasonably well. Applying this equation to a streamline traveling down the axis of the horizontal tubes gives,

$$\Delta p = p1 - p2 = \frac{1}{2}\,\rho V_2^2 - \frac{1}{2}\,\rho V_1^2$$

Where location 1 is upstream of the orifice and location 2 is slightly behind the orifice. It is recommended that location 1 be positioned one pipe diameter upstream of the orifice, and location 2 be positioned one –half pipe diameter downstream of the orifice. Since the pressure at 1 will be higher than the pressure at 2 which is for flow moving from 1 to 2), the pressure difference as defined will be a positive quantity.

From continuity, the velocities can be replaced by cross-sectional areas of the flow and the volumetric flowrate Q,

$$\Delta p = \frac{1}{2}\,\rho Q^2\,\frac{1}{A_2^2}\left[1-\left(\frac{A_2}{A_1}\right)^2\right]$$

By continuity equation:

$$Q = A_1 V_1 = A_2 V_2 \quad or$$

$$V_1 = \frac{Q}{A_1} \text{ and } V_2 = \frac{Q}{A_2}$$

Solving for air flow rate, Q:

$$P_1 - P_2 = \frac{1}{2}\rho\left(\frac{Q}{A_2}\right)^2 - \frac{1}{2}\rho\left(\frac{Q}{A_1}\right)^2$$

$$Q = C_0 A_2 \sqrt{\frac{2(P_1 - P_2)/\rho}{1 - (A_2/A_1)^2}}$$

$$Q = C_0 A_2 \sqrt{\frac{1}{1 - (d_2/d_1)^4}} \sqrt{2(P_1 - P_2)/\rho}$$

For the pressure difference in pivot tube,

$$P_1 - P_2 = \Delta P = \rho g \Delta h$$

So,

$\Delta P = (1000\ kg/m^3) \times (9.81\ m/s^2) \times (0.145 m)$

$= 1422.45\ kg/ms^2$

The results for pressure difference (ΔP) are shown as below:

Table 4: Data of Pressure Difference

ΔP (kg/ms^2)	Diameter 1 (m)	Diameter 2 (m)	D2/D1	(D2/D1)^4
1422.45	0.026	0.006	0.230769231	0.002836035
2501.55	0.026	0.006	0.230769231	0.002836035
3090.15	0.026	0.006	0.230769231	0.002836035
4561.65	0.026	0.006	0.230769231	0.002836035

Based on the value of pressure difference, we can find the volume metric flowrate, Q.

So, when $\Delta P = 1422.45\ kg/ms^2$

$$Q = (0.6)\,X\,2.82743E-05\sqrt{\frac{1}{1-(0.002836035)^4}}\sqrt{2(1422.45)/1.275}$$

$Q = 0.00800212\ m^3/s$

The data for volume metric flowrate, Q when ΔP at 2501.5545 kg/ms^2 3090.1545 kg/ms^2 4561.6545 kg/ms^2 are shown in the table below:

Table 5: Data of Volume Metric Flowrate, Q

Area 1(m^2)	Area 2(m^2)	(2(ΔP)/density air)^0.5	Volumemetric flowrate, Q (m^3/s)
0.000530929	2.82743E-05	47.23657606	0.000800212
0.000530929	2.82743E-05	62.64183905	0.001061185
0.000530929	2.82743E-05	69.62251157	0.001179441
0.000530929	2.82743E-05	84.5903624	0.001433004

Let say that a thickness of "X" while the rest (L-X) is pinned. By using the Ergun's equation, the stress acting on the particles downstream of plane X due to flow of gas from the perforated wall can be estimated as:

$$P_1 - P_x = X\left(\frac{180(1-\varepsilon)^2}{\varepsilon^3}\frac{\mu u_o}{d_p^2} + \frac{1.80(1-\varepsilon)}{\varepsilon^3}\frac{\rho u_o^2}{d_p}\right)$$

This stress acts on the particles downstream to pin particles between the plane X and downstream perforated wall by developing frictional resistances to counter the movement due to the weight of particles per unit area.

$$(P_1 - P_x)f = (L-X)(\rho_p - \rho_g)(1-\varepsilon)g$$

The two equations can be combined to obtain

$$\frac{(L-X)}{X} = \frac{L\left(\left(\frac{180(1-\mathcal{E})^2}{\mathcal{E}^3}\frac{\mu u_o}{d_p^2} + \frac{1.80(1-\mathcal{E})}{\mathcal{E}^3}\frac{\rho u_o^2}{d_p}\right)f\right.}{L(\rho_p - \rho_g)(1-\mathcal{E})g}$$

$$\frac{(L-X)}{X} = \frac{(P_1 - P_2)f}{L(\rho_p - \rho_g)(1-\mathcal{E})g}$$

$$\frac{(L-X)}{X} = \frac{Pinned\ thickness}{Non-pinned\ thicknes}$$

So,

$$(L-X) = \frac{(P_1 - P_2)fL}{L(\rho_p - \rho_g)(1-\mathcal{E})g + (P_1 - P_2)f}$$

Table 6: Data of Ergun Equation

Standard Gravity, g (m/s^2)	9.81
Density of Air,ρ (kg/m^3)	1.275
Density of Particle, ρ (kg/m^3)	1100
Viscosity, μ	1.8 x 10^{-5}
Porosity ,Ɛ (kg/m.s)`	0.5

Based on the data above, we can calculate the maximum pinned thickness by using the Ergun equation.

At volume metric flowrate, Q =0.000800212 m^3/s

$$(L-X) = \frac{(12562.74)\ (0.0055)(0.087)}{0.087(1098.725)(1-0.5)9.81 + (12562.74)0.0055}$$

$$(L-X) = 0.012134299$$

The data for maximum pinned thickness (L-X) when Q at 0.001061m^3/s, 0.0011794m^3/s, 0.0021433m^3/s are shown in the table below:

Table 7: Maximum Pinned Thickness with Difference Flowrate

Volumemetric flowrate, Q (m3/s)	Velocity (m/s)	P1-P2	Calculated L-X (Pinned)	Estimated f	Experiment L-X (Pinned)
0.000800212	2.857899368	4809.017	0.011719348	0.0138	0.011
0.001061185	3.789945995	8147.542	0.0181572	0.0138	0.019
0.001179441	4.212289468	9946.995	0.021190612	0.0138	0.023
0.001433004	5.117871858	14407.98	0.027671387	0.0138	0.027

To conduct an experimental run the particle flow was first adjusted so that the particles moved downward steadily. The cross flow of air was increase progressively until pinning occurred. The sequence of events in the aerated section was meanwhile obseved, both through the transparent side wall of the column and using the transparent graph tu measure the area of pinning ocurred. Since this face is the primary seat of pinning, the latter obeservation was valuable for determining when particles in contact with the face to come rest.

The particles used are sago with diameter in the range 1.25-1.75mm. These are large enough to be held in the column by the perforated walls of the aerated section but small enough in relation to the column dimensions. The bulk density of the bed is about 1100 kg/ m^3, larger than that of a bed of refprmeing catalyst pellets in the range 900-1000 kg/m^3, so relatively large air flows are needed for pinning. However, the cleaness and resisitance to attrition of the sago are conducive to achieving reproducible result in experimental runs.

The radial drag on particles can push the particles to the downstream perforated wall and the friction between the bed and the downstream perforated wall can hold the particles unless the gravitational force is larger. The gas flow (air) in perpendicular direction will drags the particles to hold against the downstream perforated wall and the weight of particles will rise up the pressing drag due to gas flow and friction at the downstream wall. As the graph shown below when the volume metric flowrate increase the pinned film thickness will be increase. That means the pinned thickness is proportional with the volume metric flowrate.

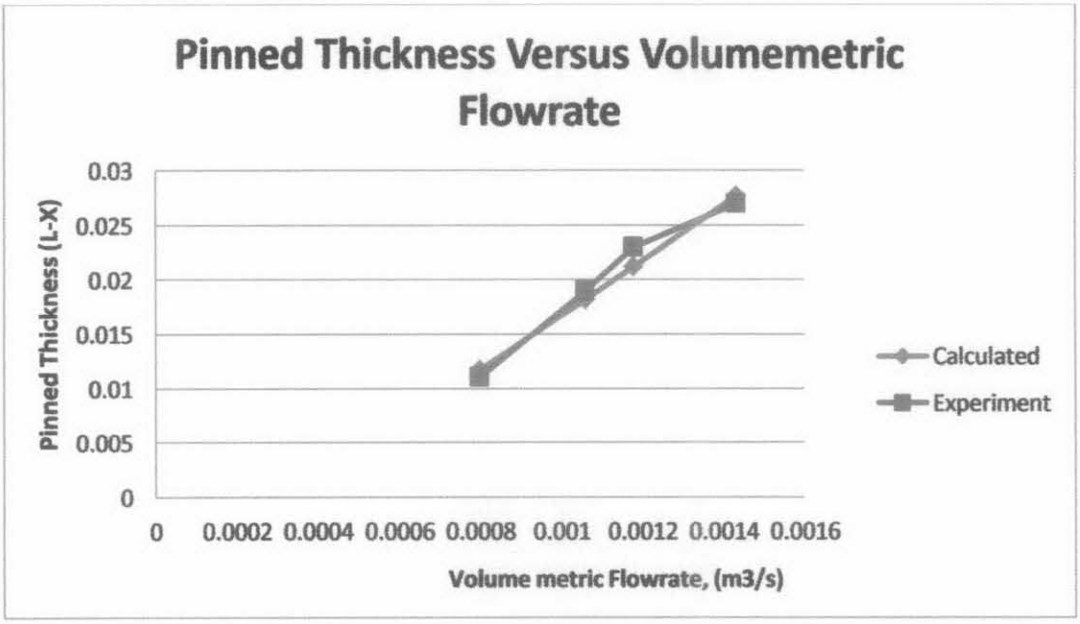


Figure 12: Pinned Thickness versus Volumemetric Flowrate

Based on the graph below, we can say that the maximum pinned thickness is proportional with the pressure difference. If the pressure difference increases, the maximum pinned will be increases. Radial flow in the packed bed, the particles experience drag force in the radial direction while they are trying to move downward by gravitational force. If the drag force on particles increases, the normal stress between the particles and the upstream wall will be decreased. The bed particles start to lose contact with the normal stress is reduced to zero. The pinned could occur between the catalysts bed and the upstream wall. When the pressure increase the pinned thickness will be increase.

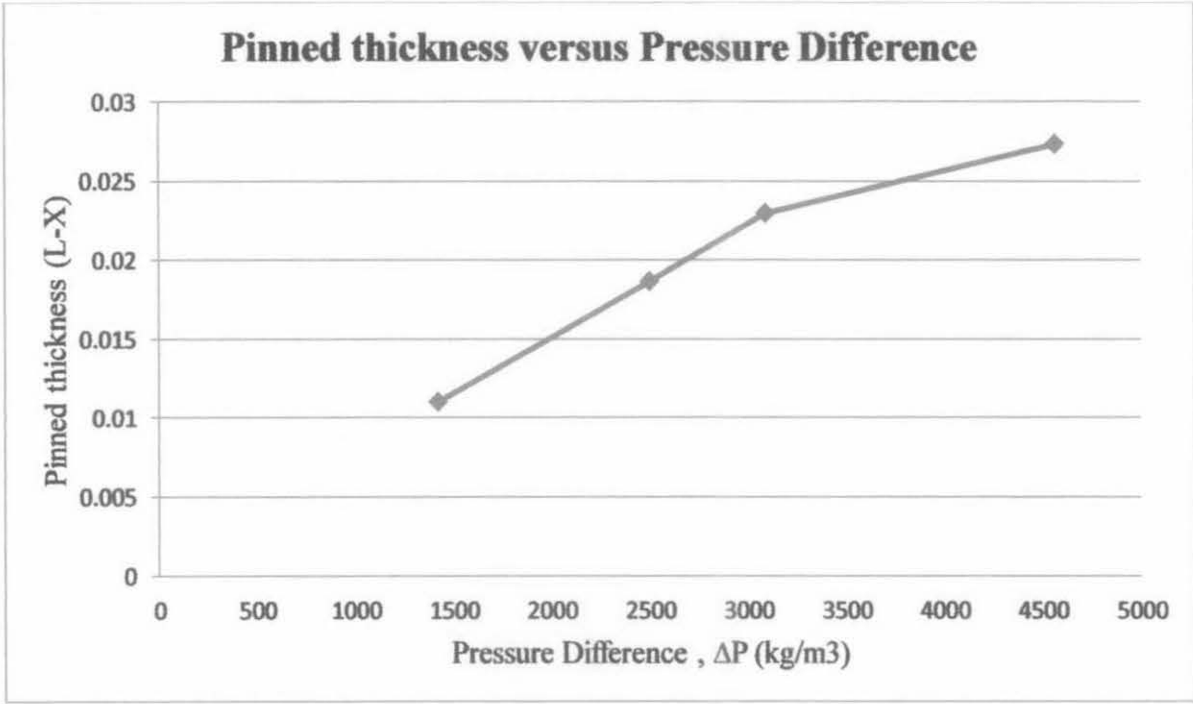


Figure 13: Pinned Thickness versus Pressure Difference

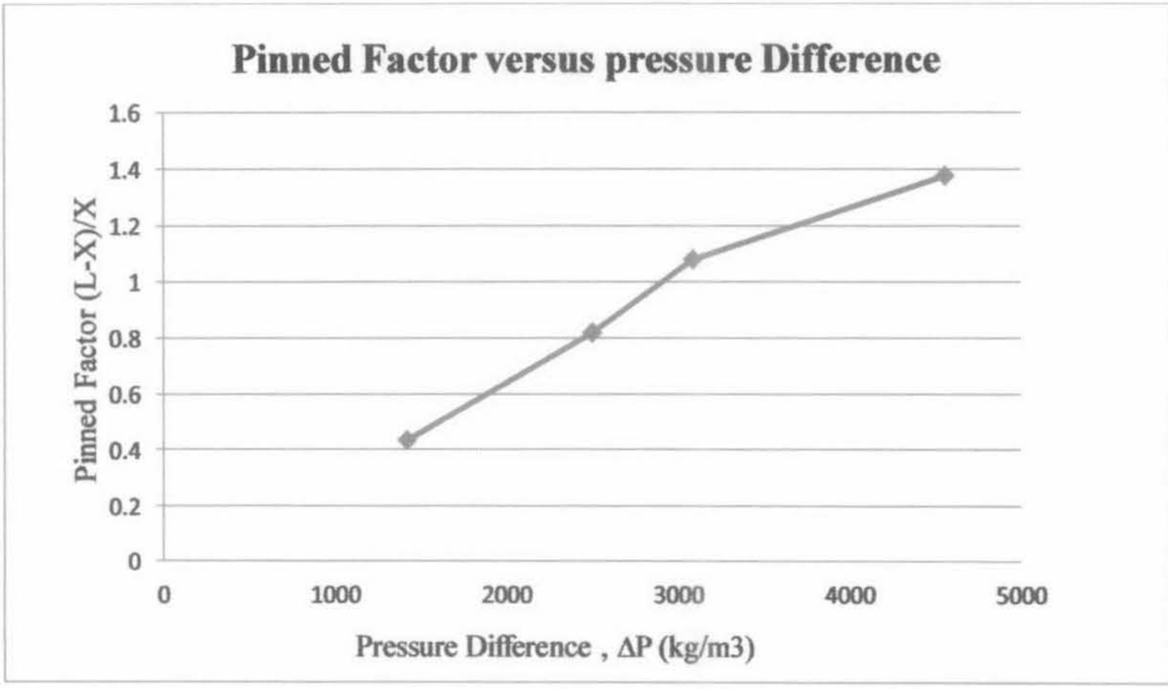


Figure 14: Pinned Factor versus Pressure Difference

As the graph shown below, increasing the height difference will be effect the maximum pinned thickness. By using Bernoulli equation which is:

$$\Delta P = \rho g \Delta h$$

Based on the equation when the height difference (Δh) increase the pressure difference will be increase (ΔP). So, increasing the pressure difference will affected the maximum pinned thickness.

CHAPTER 5

CONCLUSION & RECOMMENDATIONS

CONCLUSION

In our industry the radial flow moving bed reactor is has many useful application. For example certain catalyst of chemical reactor, whose catalyst decays reversibly and rather quickly, continuous operation, is possible by use of a moving bed of catalyst which slide down through the reactor under the gravity, while the reaction mixture is passed horizontally through the bed. There is then an upper limit of the flow rate of reactants, imposed by the mechanical phenomena of 'Pinning', in which the drag force exerted on the particles by the flowing reaction mixture pressed the bed against the wall of the reactor so hard that friction at this wall prevents the bed from sliding downward. So, the phenomena of pinning can be reducing the efficiency of radial flow moving bed reactors.

By using Ergun's equation we can calculate the maximum pinned film thickness. From this equation, it can be seen that pinning film thickness increase with volume metric flowrate, and the bed can get pinned for small particles, low particles densities and at high gas velocities. Hence, pinning can be reduced by using larger and high density particles and minimizing the wall friction at the downstream perforated wall.

RECOMMENDATIONS

The topic of pinning in radial flow moving bed reactors received very little attention in academic circles though they are widely used in the industry. Present work explored in flow moving bed reactors and also other reactor such as radial flow fixed bed reactor, fluid bed, packed bed and others need to be evaluated. Very little is known about the flow distribution in radial flow reactor and pinning of bed of particles in reactor. These need to be explored in greater detail.

For the further study I would recommend this project also can conduct by using the differences aspect or parameters which are:

- Using difference sizes of particles
- Using low and high particle densities
- Using the difference length of beds

REFERENCES

Doyle F. J., Jackson R. and Ginestra J. C. (1986). The phenomenon of pinning in annular moving bed reactor with cross flow of gas, *Chem. Eng. Sci.*, 41 (6), pp. 1485-1495

Ginestra J. C. and Jackson R. (1985). Pinning of a bed particles in a vertical channel by a cross flow of gas, *Ind.Eng.Chem. Fund.*, pp. 121-124

Kareeri A.A, Zughbi H.D. and Al Ali H.H. (2006). Simulation of flow distribution in radial flow reactors,*Ind.Eng. Chem, Res.* Pp.2862-2874

Little, D. M., Catalytic Reforming, PennWell, Tulsa, OK (1985)

Marb, C. M., and Vortmeyer, D., "Multiple states of A Cross-Flow Moving Bed Reactor Theory and Experiment", *Chem. Eng. Sci.*, **43** (4), 811-819, (1988)

Meyers, R. A., Handbook of Petroleum Refining Processes, McGraw Hill, New York (1996)

Pilcher K. A. and Bridgewater J. (1990). Pinning in a rectangular moving bed reactor with gas cross-flow, *Chem.Eng.Sci.* pp. 2535-2542.

Song, X., Wang, Z., Jin, Y., and Gong, M., "Investigations on Hydrodynamics of Radial Flow Moving Bed Reactors", *Chem. Eng. Technol.*, **16**, 383-388, (1993)

Tsubaki, J., and Tien, C., "Solid Velocity in Crossflow Moving Beds", *Powder Technology*, **53**, 105-112, (1987)