THE EFFECT OF USING COMPOSITE CORE ON WATER ALTERNATING GAS EXPERIMENTS

by

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14831

Dissertation submitted in partial fulfilment of
the requirement for the
Bachelor of Engineering (Hons)
(Petroleum Engineering)

JAN 2015

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CERTIFICATION OF APPROVAL

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Approved by,

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TRONOH, PERAK
JAN 2015

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 acknowledgement, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

……………………………

MUHAMMAD AZWAN BIN ANUAR

ABSTRACT

Since the discovery of oil in the Sarawak in 1910, oil and gas industry in Malaysia has been expanding rapidly. The volume of oil in Malaysian's field is reduce yearly as we continuously extract the black gold. Therefore to meet the ever increasing demand, the current recovery technique especially lab experiments must be updated and improved to get a better understanding of the reservoirs condition. The recovery technique that will be discuss in this report is Water Alternating Gas method. In this report, brine of 24000ppm and Nitrogen gas will be used as WAG fluids. The size of the composite core in the current WAG lab experiments has a significant impact on the laboratory experiments itself. Horizontal stacking procedure is widely used to overcome the capillary end effect during core flooding experiments. The effect of the discontinuity between the composite cores is neglected. In this study, the core that being used are 3 inch cores and the composite core comprises two 1.5 inch cores arranged end to end and the effect of discontinuity has been determined. When the core is cut, there is a significance changes happen to the grain volume, pore volume, and permeability. The result of permeability value for the composite core give out a lower reading compare with a single whole core and the differential pressure for the flow rate to stabilize is also relatively higher on composite core compare to a single whole core. Besides that, composite core also produce a lower brine recovery compare to single core during gas injection process.

ACKNOWLEDGEMENT

In the name of Allah, the most Gracious and the most Merciful

Alhamdulillah, author has finally completed the final year project and able to come up with this report. Author thank Allah for allowing all of these to happen. Without His permission, author might probably not able to complete this project. Author like to extend upmost gratitude to Dr Mohammed Idrees Ali Al-Mossawy for all his guidance, help, and suggestions on author’s activity during completion of the project. Also to all technicians who has been patiently teaching and helping author throughout the project especially Mr Saiful, Mr Shahrul and Mdm Helmayeni. Not to forget, author’s appreciation to friends who has been supported author throughout the two semester project.

Last but not least, author most appreciation goes to author’s family for their encouragement and support which helped author to give the best to complete the project.

Thank you. May Allah repay for all your kindness.

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ABREVIATIONS AND NOMENCLATURES

Bpd	Barrels per day
EOR	Enhanced oil recovery
K_{or}	Relative permeability to oil
K_{rw}	Relative permeability to water
OOIP	Oil originally in place
S_{wi}	Irreducible water saturation
S_{or}	Residual oil saturation
WAG	Water Alternating Ga

CHAPTER 1

INTRODUCTION

1.1 PROJECT BACKGROUND

Since the first discovery of oil in Sarawak in 1910, oil and gas industry has provided the crucial support for the development of Malaysia. The industry had opened up opportunities for big foreign oil and gas operators to invest in Malaysia; in upstream and downstream sectors. The company offered employment to Malaysian and indirectly changed the economic sectors. As of last year, Malaysia's daily production stood at 630 000 barrels per day which was around 25% below the peak of production in 2004 that produced staggering 860 000 barrels per day [1]. Therefore to meet the ever increasing demand from various sector in Malaysia, the current recovery technique must be updated and improved to collect the black gold from the reservoirs.

One of the enhanced oil recovery technique that PETRONAS and other major oil operators used in order to extract the oil from the depleted reservoir is **Water Alternating Gas Injection**. This enhanced oil recovery technique is the updated and improved version of the current water injection and gas injection recovery processes. Water injection is a secondary recovery program which used water; mostly produced water, to increase the production of the reservoir. The water that re-injected back into the formation will replace the formation water that had been produced thus continuously maintain the reservoir pressure. On the other hand, gas injection is secondary recovery process that re-inject produced gas from nearby field or the field itself. The concept is to use the gas as a sweeping agent to sweep the remaining residual oil that trapped in the reservoir.

The Water Alternating Gas Injection is an enhanced oil recovery technique that inject water and gas alternately for a specified period of time in order to provide both microscopic and macroscopic sweep efficiencies and reduce gas override effect [3]. There are two types of WAG injection processes which are miscible and immiscible process. Miscible process define when the gas injection routine happened above the minimum miscibility pressure (MMP) whereas immiscible process happened below the MMP. Apart from that, the gases used for the gas injection also have two types which are hydrocarbon and non-hydrocarbon gases. The hydrocarbon gases are the paraffins of lower molecular weight (e.g. propane, methane, butane, and ethane) and the non-hydrocarbon gases are like Carbon Dioxide and Nitrogen [4]. Due to the factor that this recovery technique is quite new in the industry, numerous modelling, numerical simulation, and laboratory experiments done on WAG recovery method to better understanding the process.

1.2 PROBLEM STATEMENT

There are two types of coring operations which are full diameter coring and side wall coring. From these two operations, the maximum length of the core that can be used in laboratory as a core plugs is around 2 to 3 inch. The length of the core is short due to the way that the core is extracted. The size of the core does has a significant impact on the laboratory experiments itself. The implication of the short core is that the capillary pressure has a significance impact on the calculation of the relative permeability. In order to overcome capillary pressure during laboratory experiments, the flow rate is increased or the core is stacked horizontally inside the core flooding equipment to increase the experimental core length.

This horizontal stacking procedure is widely used to overcome the capillary end effect during core flooding experiments. The effect of the discontinuity between the cores is neglected. In the interpretation of result, the core is treated as a whole core length rather than a horizontally stacked 3 inch cores.

In this study, a 3 inch core will be used as the equipment that will be utilize has a limitation on the length of the core.

1.3 OBJECTIVE

The main objectives that have been identified for this study is to determine whether the effect of the discontinuity of the core's length has a significance impact on WAG experimentation.

1.4 SCOPE OF STUDIES

There are several scope of studies that will be focused in this project:

1) The parameters of WAG that will be evaluate are pressure difference, flow rate, permeability and recovery of brine.
2) In the WAG experiments, brine and Nitrogen gas will be used as the main WAG fluids.
3) The WAG experiments will be done in standard room temperature and the pressure limited to equipment capacity.

CHAPTER 2

LITERATURE REVIEW

2.1 WATER ALTERNATING GAS

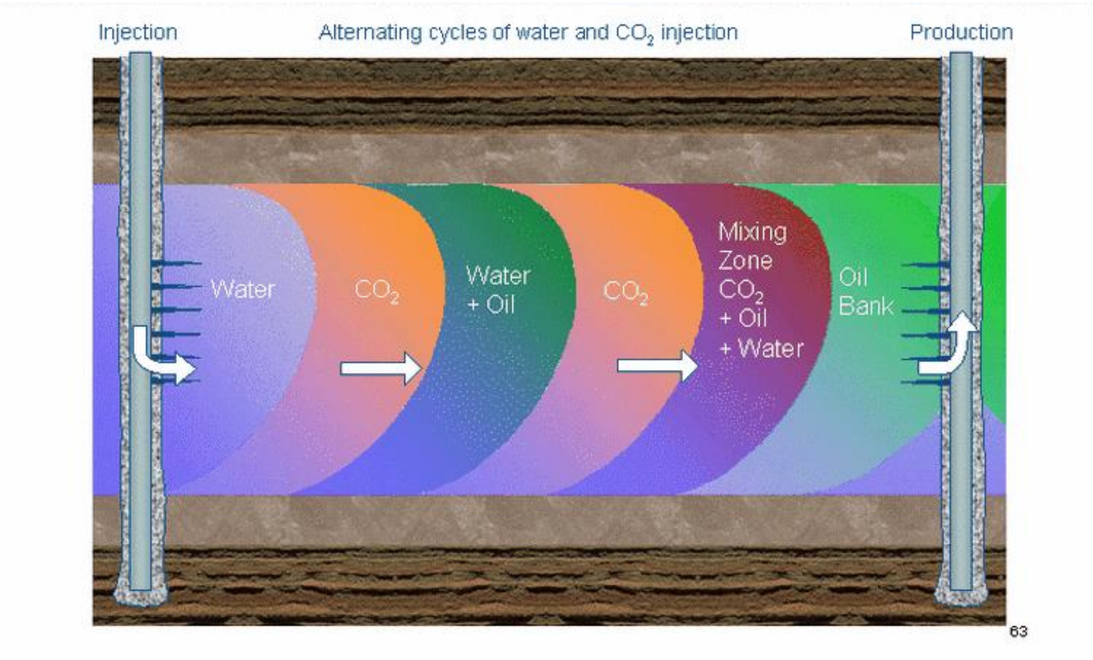

Figure 2.1: WAG process in reservoir [15]

Water alternating gas is one of the technique in tertiary recovery process. Under the Enhanced Oil Recovery scheme, WAG process is widely used due the fact that this method could improve the oil recovery by 5% - 10% [6]. In the process, water and gas are injected from the injection well into the reservoir within a certain period of time. The water and gas are injected alternately in a cycle form; one complete cycle is define as the water is re-injected back after gas injection process that had been done after water injection process. From figure 2.1**,** the reservoir undergone both the drainage and imbibition routine during the WAG injection process. The type of water and gas used during the WAG process vary from field to another field. Due to the high mobility and low densities of gas, the type of gas used in the experiment does play an important role [5].

Based on definition by Tarek A. (2006), heterogeneity is defined as ‘a variation in reservoir properties as a function of space’. The communication between each of formation layer did determine the effectiveness of the displacement of oil that will be recovered from the reservoir [4]. Barriers for the fluid to flow such as laterals, faults, variation of facies, and unconformities will distort an effective connection between the layers [4]. One the key reasons that had been assess for the failure of EOR project is due to the reservoir heterogeneity [8]. Consequently, conducting interference tests and pressure history analysis test is essential so the information about the reservoir size, shape and heterogeneity could be fully understand before any EOR project is carried out [8].

Heterogeneity occurs in most reservoirs. The reservoir consist of different value of permeability level dependent on its formation layers separated by thin deposits of shale. The heterogeneity in permeability may occur in vertical direction or horizontal direction and horizontal permeability may be preferable compare to vertical permeability [4]. The advancement of the displacement front does not follow a regular pattern due to the layers exhibit different value of permeability [4]. Based on Donaldson et al., (1989), the thin shale deposits that separate the formation layers prevent the injecting fluid from crossed over to the most permeable layers thus increasing the sweep efficiency and the overall recovery efficiency [4].

Core length and flow rate play an important role in WAG experiment that will be carried out. Some researcher have found that the amount of oil bypassed is sensitive to flow rate and core length [11]. Based on research by Rogers J. & Grigg R. (2001), the experimental observations of flow rate and core length can give some indication of the comparative importance of each type of bypassing. Increasing recovery with flow rate identified that capillary pressure effect dominate, while a decrease indicates that dispersive bypassing is prevailing [11]. Recovery does not governed by core length shows that either capillarity or dispersive bypassing dictates [11]. While capillarity bypassing is much weaker function of oil viscosity, viscous fingering and dispersive bypassing increase with oil viscosity [11].

2.2 PETROPHYSICAL PROPERTIES

Porosity, permeability, saturation and wettability are some of the petrophysical properties that effect the enhancement of oil recovery process.

A. Porosity

Porosity is defined as ratio of pore volume to the bulk volume [4]. Porosity also can be defined as the ability of the rock formation to hold liquid or gas within its porous space. The higher the value of porosity of the rock, the higher the ability of the rock to store the oil [4]. Porosity formulation is expressed as:

$$\phi = \frac{V_b - V_{gr}}{V_b} = \frac{V_p}{V_b}$$

Where:

ϕ = porosity, [-]

V_b = bulk volume of reservoir rock [cm^3]

V_{gr} = grain volume [cm^3]

V_p = pore volume [cm^3]

There are two types of porosity which namely as effective porosity and absolute porosity. Absolute porosity define as ratio of the total pore volume to the bulk volume whereas effective porosity define as ratio of interconnected pores to the bulk volume [4]. Our concern as a petroleum engineer is the effective porosity value. The porosity value of the formation sediments are controlled by degree of cementation, degree of compaction during and after deposition, homogeneousness of grain size, and the way of the grain packed itself [8].

B. Permeability

Permeability definition is the ability of a medium to transport fluids. In the petroleum engineering, it refers as the ability of rock formation to transmit fluids (oil, gas & water) [4]. This permeability ability somehow have a connection with porosity which is in term of connected pores. The factors that influence permeability are rock shape, grain size, size distribution and the grain arrangement apart from the extent of compaction [4].

The mathematical formulation for permeability is called Darcy's Law. It is define as:

$$k = \frac{q\mu L}{A\Delta P}$$

q = flowrate (cm^3/s)

μ = viscosity (cP)

L = length (cm)

A = area (cm^2)

ΔP = pressure difference (atm)

Permeability is vital because it is one of the main rock properties that govern the hydrocarbon recovery rate [4]. In any enhanced oil recovery process, the effectiveness of the program greatly depend on the permeability of the formation. The primary recovery from highly permeable reservoirs is usually very high and such reservoir are less viable option for EOR due the fact that most of the oil would have been produced via primary recovery [4].

From research by Rogers J. & Grigg R. (2001), core material dissolution could be a serious problem during CO_2 flooding under reservoir condition on North Sea. A relative small change in the pore arrangement and structure due to dissolution could significantly impact the total permeability [11].

C. Saturation

Saturation is fraction or percentage of the pore volume occupied by a particular fluid (water, oil & gas) [7]. The expression as below:

$$Fluid\ Saturation = \frac{Total\ volume\ of\ fluid}{Pore\ volume}$$

The equation below express the saturation in term of each respective reservoir fluids:

$$S_o = \frac{Volume\ of\ oil}{Pore\ volume}$$

$$S_G = \frac{Volume\ of\ gas}{Pore\ volume}$$

$$S_W = \frac{Volume\ of\ water}{Pore\ volume}$$

Where

S_O = Saturation of oil

S_G = Saturation of gas

S_W = Saturation of water

As expressed above, all saturation values are based on pore volume. The saturation of each phase ranges between 0 to 100 %. Therefore $\boldsymbol{S_O + S_W + S_G = 1.0}$

D. Wettability

Definition of wettability is the tendency of a fluid to spread or adhere to a solid surface in the presence of other immiscible fluids [4]. The way fluids distributed in the reservoir rocks is an important information need to be highlighted as the fluids distribution governed by wettability. Oil recovery are depending on the wettability of the reservoir, hence an evaluation has to be done to determine either the reservoir water-wet or oil-wet reservoir. In the case of oil-wet reservoir, the recovering of the oil would be difficult [8]. The reason is because the oil will adhere to the small pores inside the rocks, resulting higher production of water compare to oil (hydrocarbon). Based on the research by Rogers J. & Griggs R. (2001), they has showed in a controlled synthetic and properly clean sandstone core flood experiments that wettability can change with the pH of the brine. A synthetic cores will more towards water-wet conditions when using a high pH brine whereas lower pH brine have a tendency to alter the core and surfaces towards less water-wet settings. So, the pH of the brine that being used in this experiments is a constant value to ensure an optimum result will be obtained. Apart from that, the cores used in our experiment are used cores. Hence after cleaning process from previous experiment, the core should be in water-wet consition.

2.3 FLUIDS PROPERTIES

The most important fluids properties in any EOR projects and in the WAG experiments itself is viscosity. The definition of viscosity is the resistance of the fluids to flow [7]. When the viscosity value reduce, the tendencies of the fluids to flow would be higher and vice versa. The viscosity of hydrocarbon especially oil is reliant on pressure, temperature, oil gravity, and gas solubility [4].

2.4 CAPILLARY END EFFECT

Capillary effect exist from the discontinuity of capillarity in the wetting phase at the outlet end of the core sample [2]. The effect frequently appear in situation of oil displacing water in water-wet core, and gas-displacing-oil case [2]. In the dynamic displacement test, data often obtained using simplified non-capillary Buckley-Leverett theory. This theory neglect the effect of capillary and thus may produce a distorted data [9]. From Huang D. & Honarpour M. (1998), the study has shown that the correction for oil relative permeability is highly significance when the capillary force is the same order of magnitude as the viscous force.

2.5 KLINKENBERG GAS SLIPPAGE EFFECT

Permeability depends on the characteristic of the rock core and do not depend on the property of the fluid used to measure it. However in 1941, Klinkenberg found that when using gases as the fluid, the permeability measurement on the core sample were not constant. The permeability result were varied according the gas used in that particular experiment.

When liquid flows through cylindrical container, the velocity is maximum at the center of the container and zero at the container wall due to viscous forces. When gas flowing at low pressures, this effect does not happening. The gas molecules are in constant motion traveling back and forth a distance called the "mean free path". When there is a low pressure, the mean free path distance is big enough so that no gas molecules will hit the walls during some short periods of time. This effect reduces the friction loss at the wall. This same effect occurs in the pore space of core and as the result, permeability calculation is higher than the true permeability. As pressure is increase, the mean free path of the gas molecules becomes reduced and more molecules will collide with the wall. It will increasing the friction losses and the measured permeability tends to absolute permeability. Klinkenberg effect is only important at laboratory conditions where permeability is generally measure at low pressures.

2.6 Composite Core

Composite core is widely used in current water flooding or gas flooding experiments. During the experimentation, a few cores which have relatively the same permeability will be arrange side by side to make it a composite core. The core is assumed to have a capillary continuity, which mean the capillary pressure is continuous across the interface. This will often cause a discontinuity in the saturation [13]. Huppler (1969) suggested that in order to reduce the importance of capillary end effect, the use of composite cores for waterflooding experiment is suggested. Apart from that, by choosing the proper ordering of individual section in arranging a composite core, it is possible to obtain relative permeability that are more representative of the selected reservoir.

3.0 METHODOLOGY

3.1 RESEARCH METHODOLOGY

Figure 3.1: Steps in carrying out the project

3.2 EXPERIMENTAL PROCEDURE

The lab experiment that have been conducted is determination of porosity and permeability by gas, saturation of the cores by brine, and permeability determination by liquid.

For determination of porosity and permeability by gas, PoroPerm equipment is used.

Figure 3.2 *PoroPerm* equipment

The PoroPerm instrument is a permeameter and porosimeter used to determine properties of plug sized core samples at ambient confining pressure using Helium gas. The equipment is designed to determine the porosity of the core by the method Boyle's law Single Cell Method for direct void volume measurement. The direct measurements that the instrument could give up are gas permeability (md), pore volume, core length, and diameter. The instrument equip with the PoroPerm software. There is basically 3 key steps to determine the core's porosity and permeability:

1) Setup

- In the ‘Setup” panel, a suitable class is selected. The reference volume that being used is standard and the sample series is 3 inch.

2) Define

- Define allows the operator defined the working report file with a particular name.
- After specific name has been designated, the core ID, core diameter, length, and the dry weight of the core is put into the input panel interface.
- The matrix cup is opened and the core sample is loaded.

3) Measure

- The measure is start after clicking the button “measurement”.
- The result for porosity and permeability are determine after the pressure inside the core holder went to 0 psi.

For the saturation process, a saturation cell and a vacuum pump was used.

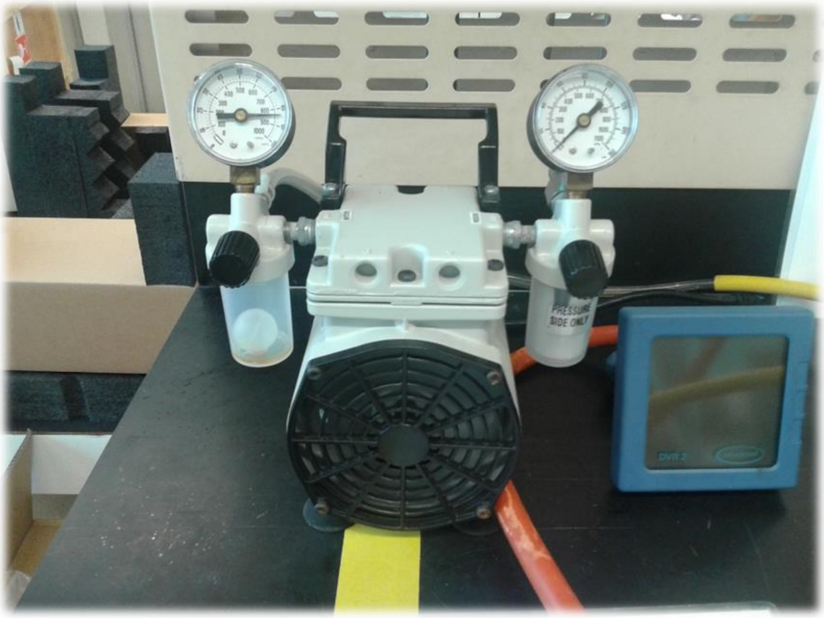

Figure 3.3 Vacuum pump

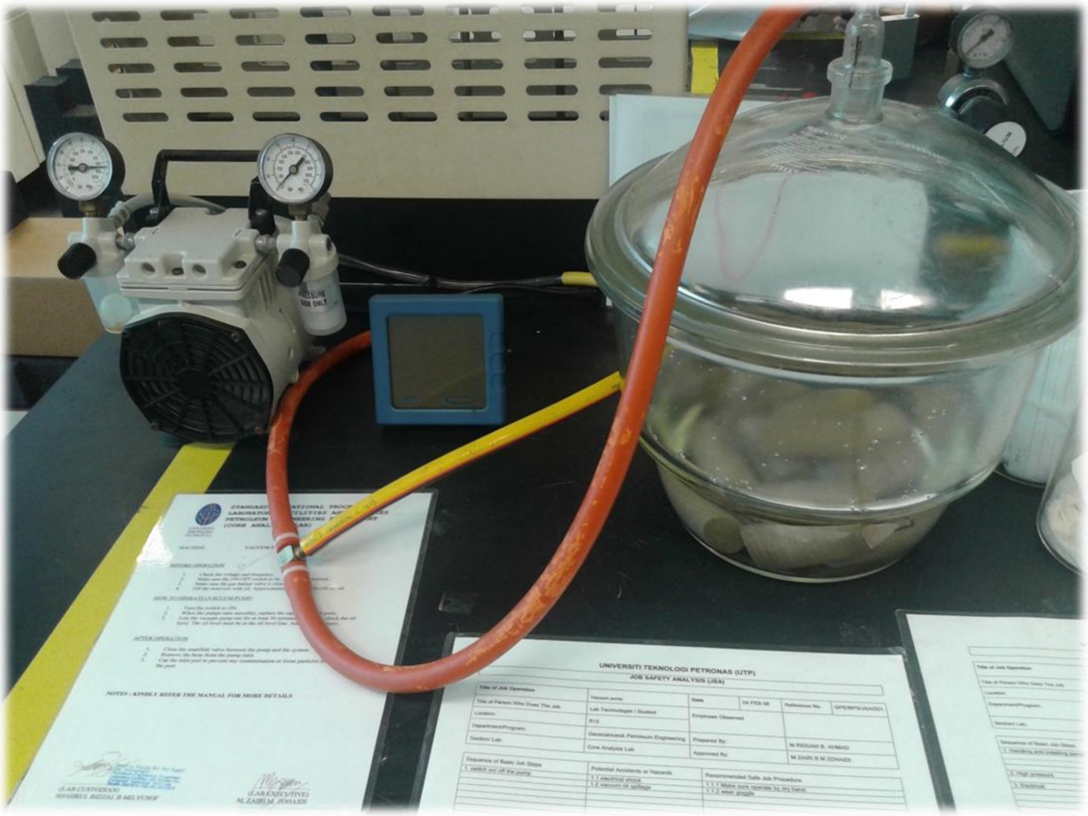

Figure 3.4 Saturation setup

In the saturation process, a few steps are carried out to ensure a successful saturation process. The steps are:

1. Preparation of 24000ppm brine water
2. Saturation cell was filled with brine water
3. Immersed all cores into the brine water
4. On the vacuum pump
5. Open the valve on top of the saturation cell
6. Let the air inside the cell to be vacuum out
7. Closed the valve on top of the saturation cell
8. Lastly, the pump is closed.

The process of vacuum out the air inside the saturation cell take about 6 hours. After all the air is vacuum out, the cores are still immersed in the brine water to prevent the brine inside the cores to evaporate to surrounding.

In the Water Alternating Gas experiment, Benchtop Permeability System BPS-850 is used to simulate one WAG cycle. One WAG cycle consist of the injection of brine with the flow rate of 2.5cm^3/min followed by injecting gas at 22.63cm^3/min and finally end with injection of brine with flow rate of 2.5cm^3/min. The flow rate of the gas is determine based on the displacement experiment by Al-Mossawy & Demiral (2011). During the experiment, the outlet flow rate of brine will be collected by placing a beaker and a digital mass balance. The reading for outlet flow rate is measure to calculate the recovery of the brine during brine injection and gas injection.

Figure 3.5 Benchtop Permeability System BPS-805

In order to form a composite core, the single core need to be cut into two 1.5 inch sections. The equipment that being used to form the composite core is a geological cutter, GeoCut.

Figure 3.6 GeoCut machine

After the cores have been cut, the edge need to be trimmed using a core trimmer machine.

Figure 3.7 Trimming process

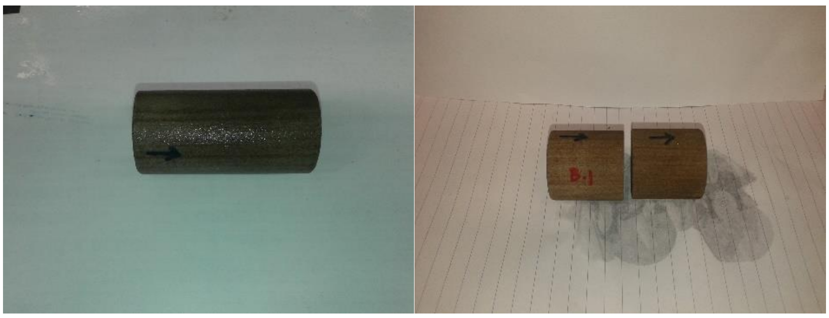

Figure 3.8 Selected core before and after cutting process

3.3 KEY MILESTONE

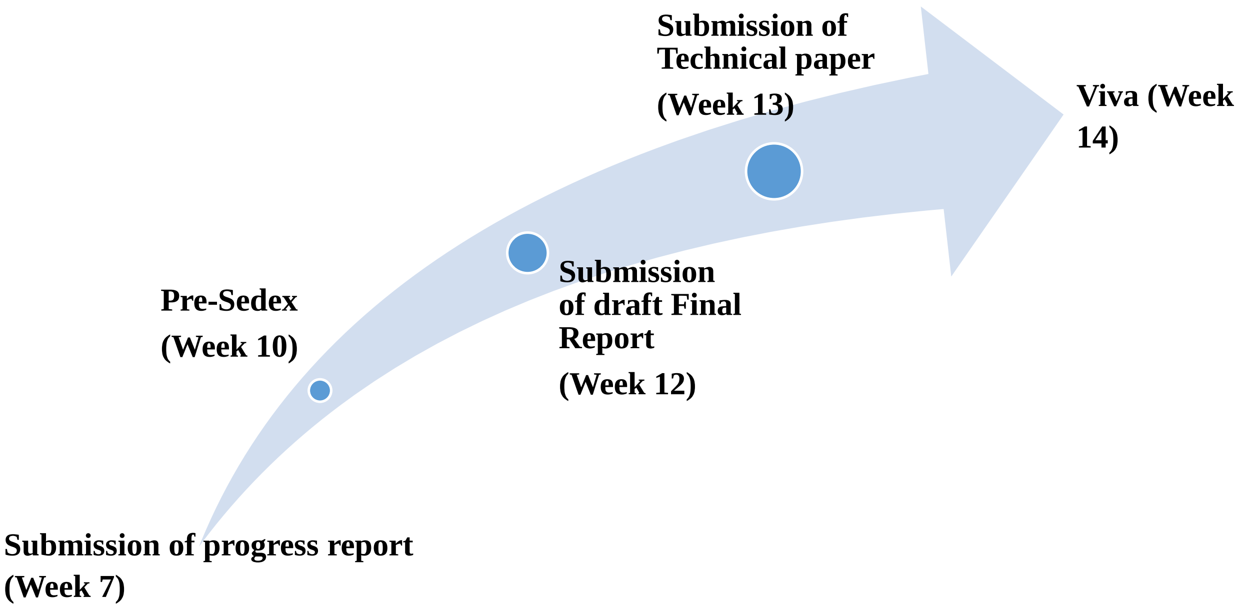

Figure 3.9 The key milestone in FYP 2

3.4 TOOLS, SOFTWARE, APPARATUS & MATERIALS REQUIRED

Tools/Apparatus	Functions
Benchtop Permeability System	To determine permeability & carry out WAG experiments.
Beaker	To carry out saturation of core
Digital Balance	To weigh the core sample
Software	**Functions**
Microsoft Office	The software is used to record all data regarding the project as well as for documentation.
Microsoft Power Point	The software used for presentation along the duration of the project.
Materials	
1. Core samples 2. Brine water 3. Nitrogen Gas	

Table 3.1 List of tools, software, apparatus and materials needed to complete the project

3.5 GANTT CHART

Timeline for FYP 1

No.	Detail/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Selection of project topics	■	■												
2	Preliminary research work		■	■	■	■									
3	Submission of extended proposal						●								
4	Proposal defence								■	■					
5	Project work continous										■	■	■		
6	Submission of Interim Draft Report													●	
7	Submission of Interim Report														●

Timeline FYP 2

No.	Detail/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Project work continous	■	■	■	■	■	■	■								
2	Submission of progress report							●								
3	Project work continues								■	■	■	■	■			
	Permeability determination															
	WAG experiment										●					
4	Pre-Sedex											●				
5	Submission of Draft Final Report												●			
6	Submission of Dissertation(soft bound)												●			
7	Submission of Technical paper													●		
8	Viva															●
	Submission of Project Dissertation															

●	suggested milestone
■	process

CHAPTER 4

RESULT AND DISCUSSION

4.1 Quality check of the cores

The result presented in this part is the result to determine the characteristic of the cores. This result is important for the next stage of the project as this result formed a basic value for the core such as the porosity, permeability, pore volume, and grain volume. Initially, six cores is provided to be used in this experiment. But due to the condition of used core, we need to do a quality check for all the cores before a core is selected to be used in the WAG experiment. Moreover, due to the time constraints, only one core is selected based on experiment requirement. Table 4.1.1 shows the basic core properties that has been measured.

Table 4.1 Core properties

Sample Name	Length(mm)	Diameter(mm)	Dry Weight(g)
L3	75.05	38.24	186.648
B1	75.18	36.85	174.109
M2	72.79	37.70	173.000
ONG	72.71	36.88	169.724
R5	76.90	37.39	169.446
ONG2	67.65	36.91	158.744

The result in Table 4.1 has been arrange according to its dry weight; the heaviest on top and the lightest on the bottom. The length and diameter of the core is measured using a mechanical caliper while the dry weight is measured using a digital weight balance. This measurement is important as we need to key in this data into the PoroPerm software. L3 is the heaviest core with 186.65g while the lightest is ONG2 with only 158.74g. The weight of the core compare to its size can be an early indicator of the volume of porous space inside the core. Hence, the lighter the core, the higher the volume of porous space inside it. This hypothesis can be verify by the PoroPerm experiment.

4.1.1 PoroPerm Experiment

In this experiment, Poroperm equipment is used to determine the core's permeability, porosity, pore volume, grain volume and bulk volume.

Figure 4.1 PoroPerm equipment in used

Three different confining pressure is used in this experiment which are 400psig, 375psig and 350psig. The maximum confining pressure that the equipment can provide is 400psig while the minimum confining pressure is 350psig. The maximum pressure is set at 400psig due to the equipment maximum capacity while the minimum pressure is set due to safety reason that the core may not be fully confined to the core holder sleeve. The impact of poorly confined core is that the core might detach from the equipment and can posed danger to operator of the equipment. Apart from that, approximately 150psig of pressure difference between confining pressure and injection pressure is set to ensure that the data collected is valid and not corrupted due the gas seepage through the core sleeve holder that confined the core.

Table 4.2 shows the result for confining pressure of 400psig and the injection pressure of 250psig. The temperature during the experiment is ambient temperature, approximately 23°c. The result afterward only shows for three selected cores. These cores are selected based on its permeability value which has a large range between each other. The wide range of data is needed to see the any variations happens along the wide set of value.

Table 4.2 400psig confining pressure, 250psig injection pressure

Sample Name	K air	K ∞ (mD)	Porosity (%)	Pore Volume(cc)	Grain volume(cc)	Bulk volume(cc)
R5	247.866	229.2	22.264	18.799	65.637	84.436
ONG2	96.612	96.184	14.421	10.439	61.946	72.385
B1	48.425	47.543	19.066	15.287	64.893	80.18

The result of permeability is refer to the K∞ which has been included the effect of Klinkenberg gas slippage effect. The result in table 4.2 has been arrange according to permeability value. The highest permeability at the top while low permeability at the bottom. R5 core has exhibit the highest permeability with 229.2mD. R5 also has the highest pore volume followed by B1 and ONG2. If refer back to Table 4.1**,** R5 is the second lightest core. So the hypothesis that ‘the lighter the core, the higher the porous volume inside it’ is valid. R5 high permeability value is the highest may due to the connectivity of the pore space inside the core.

Table 4.3 psig confining pressure, 150psig injection pressure

Sample Name	K air(mD)	K ∞ (mD)	Porosity (%)	Pore Volume(cc)	Grain volume(cc)	Bulk volume(cc)
R5	238.199	224.8	21.502	18.155	66.281	84.436
ONG2	95.625	93.662	16.551	11.98	60.404	71.385
B1	37.286	33.205	17.83	14.296	65.884	80.18

Table 4.3 show the result of cores when the confining pressure is set at 375psig and the injection pressure is set at 150psig. R5 still exhibit the highest permeability value and B1 is the lowest permeability value.

Table 4.4 350psig confining pressure, 150psig injection pressure

Sample Name	K air(mD)	K ∞ (mD)	Porosity (%)	Pore Volume(cc)	Grain volume(cc)	Bulk volume(cc)
R5	236.43	222.3	22.224	18.765	65.671	84.436
ONG2	94.665	92.377	16.061	11.626	60.759	71.385
B1	36.678	31.744	17.094	13.706	66.474	80.18

Table 4.4 shows the result of cores which has been arrange according to permeability value. The third experiment is using the confining pressure of 350psig and the injection pressure of 150psig. R5 is exhibits the highest permeability value followed by ONG2 and B1.

The porosity value for each core varies from each experiment to another due to different confining pressure apply on the cores. The sleeve that hold the core or the confining pressure will compress the core to ensure that no injection gas are bleed into the surrounding of the core. The compression of the core may have an impact on the size of the porous space. Based on Farquhar, R. A., & Tompkins, D. E. (1990), caution should be employed when core analysis data generated under different stress conditions, particularly at low values of stress are compared. Thus, the effect of this variation need to be address because in the next step of the project, the Benchtop Permeability System equipment will apply confining pressure around 1000psig onto the core.

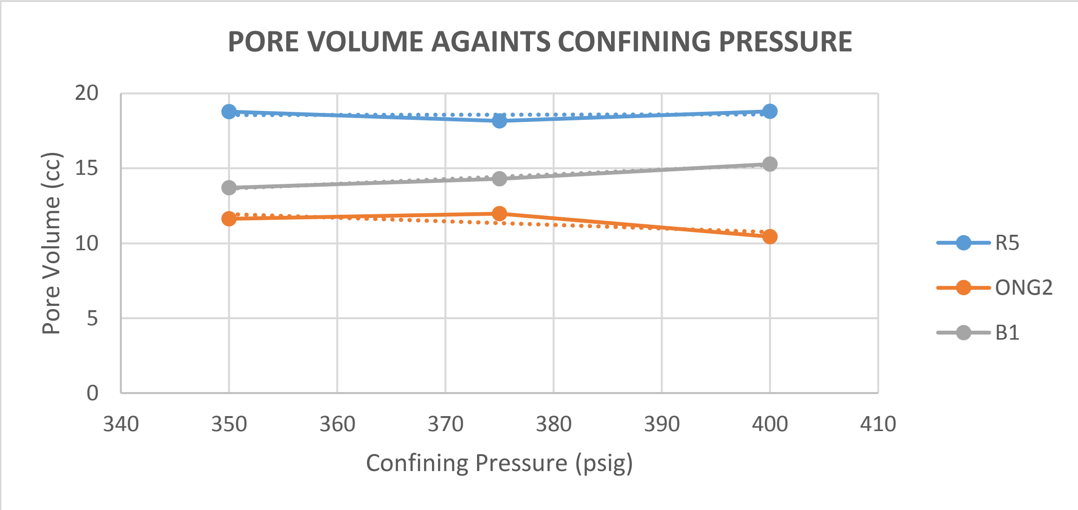

Figure 4.2 Graph of Pore volume against Confining pressure

Figure 4.2 shows the graph of pore volume against the confining pressure. From the graph, it is proven that there are variation in the porous space of the core when difference confining pressure are applied. Although there are changes that happen to the core's pore space, the changes are considered small and can be neglected. If the variation is huge, a correlation need to be made to ensure the calculation for the Benchtop Permeability equipment are correct. The small changes in volume of porous space of core also may due to the small range of data collected. The equipment can only provide the minimum confining pressure of 350psig and the maximum confining pressure of 400psig. This is categorized as equipment limitation. The stress that act upon the core are biaxial stress state. Biaxial stress state is where stresses are applied equally in two directions only by confining the core in a rubber sleeve. This could be considered to represent the stress at the well bore where stress relaxation in a lateral direction exist.

4.1.2 Saturation

Saturation process is done after the Poroperm experiment is completed. Once the cores are soaked in brine, no Poroperm experiment can be done unless the cores are properly dry again.

Below is the formula to calculate the volume of brine in the porous space.

$$\text{Volume of brine in porous space (cc)} = \frac{\text{Net weight of core (g)}}{\rho \text{ of brine (g/cc)}}$$

- Net weight of core refer to = wet weight of core(g) – dry weight of core(g)
- Density of brine = 1.01534g/cc*

* value reference based on *Al-Mossawy & Demiral (2011).*

The formula to calculate the saturation are as follow:

$$\text{Saturation(\%)} = \frac{\text{Volume of brine in porous space (cc)}}{\text{Pore volume (cc)}} \times 100\%$$

- Pore volume value we get from the data that provided by Poroperm software.

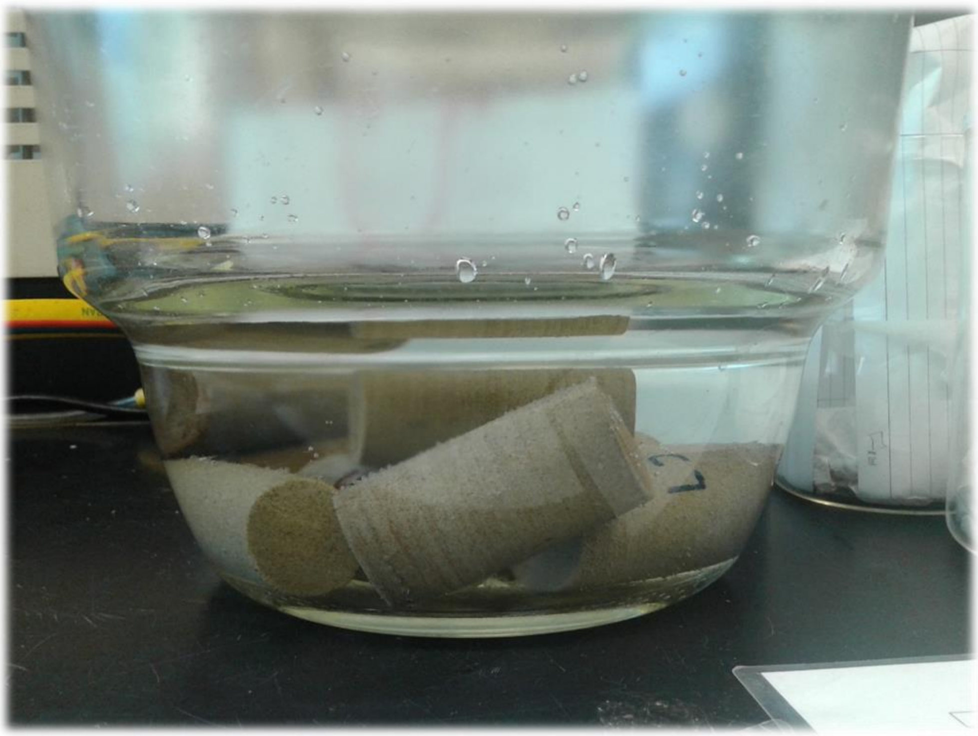

Figure 4.3 Cores inside saturation cell during saturation process

Figure 4.3 show the process of saturation done in the lab. Note there are air bubbles come out from the cores. The bubble produced are an indication that the brine solution is replacing the air inside the core porous space. Vacuum pump was used to create vacuum condition inside the saturation cell hence minimize the time taken to saturated the cores. This vacuum process take approximately 6 hours and the cores are let inside the saturation cell for three days under vacuum condition to ensure the cores are fully saturated with brine.

Table 4.5 show the saturation result that are done for all the cores. The wet weight are obtain after the cores has been saturated with brine in vacuum condition for 6 hours.

Table 4.5 Saturation result

Sample Name	Length(mm)	Diameter (mm)	Dry Weight(g)	Wet Weight(g)	Pore Volume(cc)	Net weight (g)	Saturation	Saturation (%)
R5	76.90	37.39	169.446	188.018	18.765	18.572	0.975	97.5
ONG2	67.65	36.91	158.744	169.500	10.819	10.756	0.980	98.0
B1	75.18	36.85	174.109	187.858	13.706	13.749	0.990	99.0

Based on Table 4.5 result, all the cores are saturated more than 95%. All the cores need to be saturated at least more than 95% to ensure most of the porous space is filled with brine. A fully saturated cores with brine will simulate the condition in the reservoir which the targeted area for Water Alternating Gas process is filled with water.

Figure 4.4 Cores that have been saturated

Figure 4.4 shows the core that have been saturated with brine. The cores need to be kept inside a beaker and immersed under the brine water. This method of keeping the cores are essentials to ensure brine water inside the porous space of the core does not evaporate to surrounding environment thus reducing the saturation value.

Based on the result of porosity and permeability by PoroPerm equipment also supported by the saturation result, it has been decided that the core that will be selected for the WAG experiment is core B1.

4.2 Permeability Experiment Using BPS-850 before WAG

After the quality check of the cores and saturation process, next step will be the determination of the permeability by liquid for the chosen core which is B1.

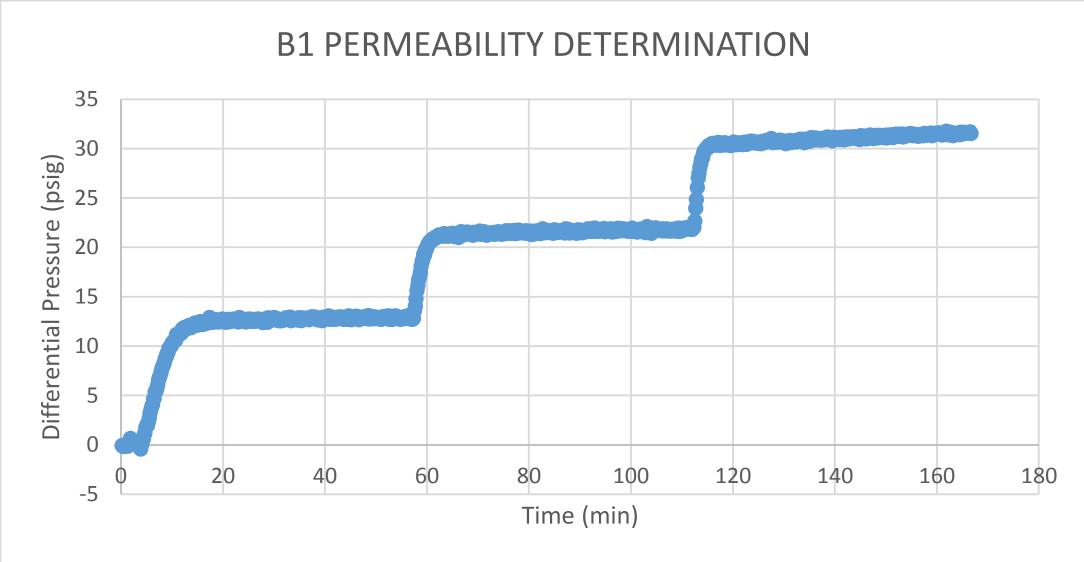

Figure 4.5 Graph of differential pressure against time

In Figure 4.5, the flow rate that has been used for determination of the permeability by liquid are 1.5cc/min, 2.5cc/min, and 3.5cc/min.

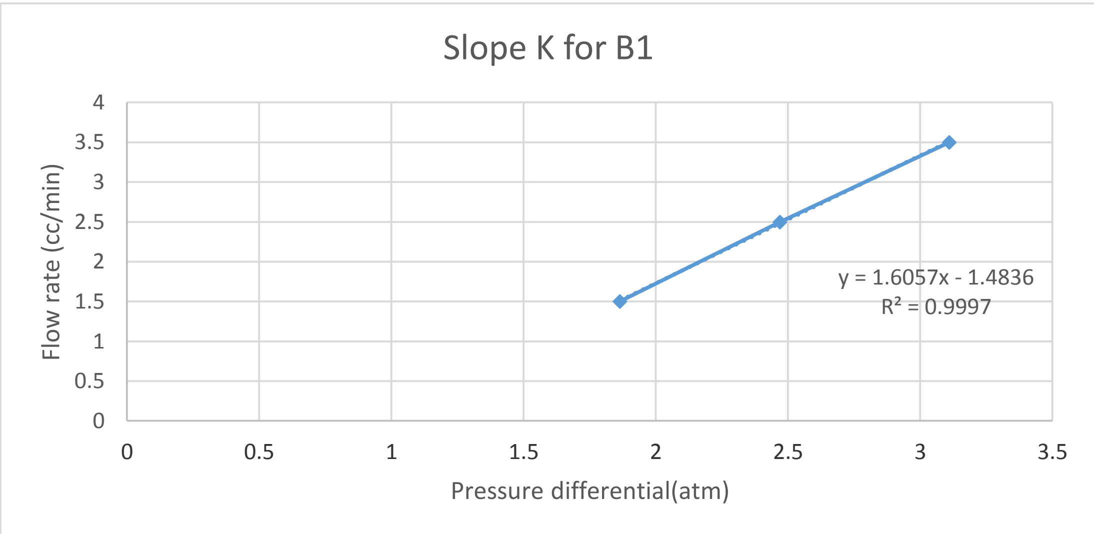

Figure 4.6 Slope determination for permeability calculation.

Based on Figure 4.6, it has been determined that the permeability by liquid value for B1 core is 21.9 mD. R^2 value that on the graph show 0.99997. The R^2 value should be approximately 1.0 to ensure the straight line is a good fit line.

4.3 Water Alternating Gas Experiment: Single Core

In this WAG experiment using a single core, the first phase of this experiment is the injection of brine (24000 ppm) at 2.5cm^3/min. The differential pressure and brine water recovery is recorded as a function of time.

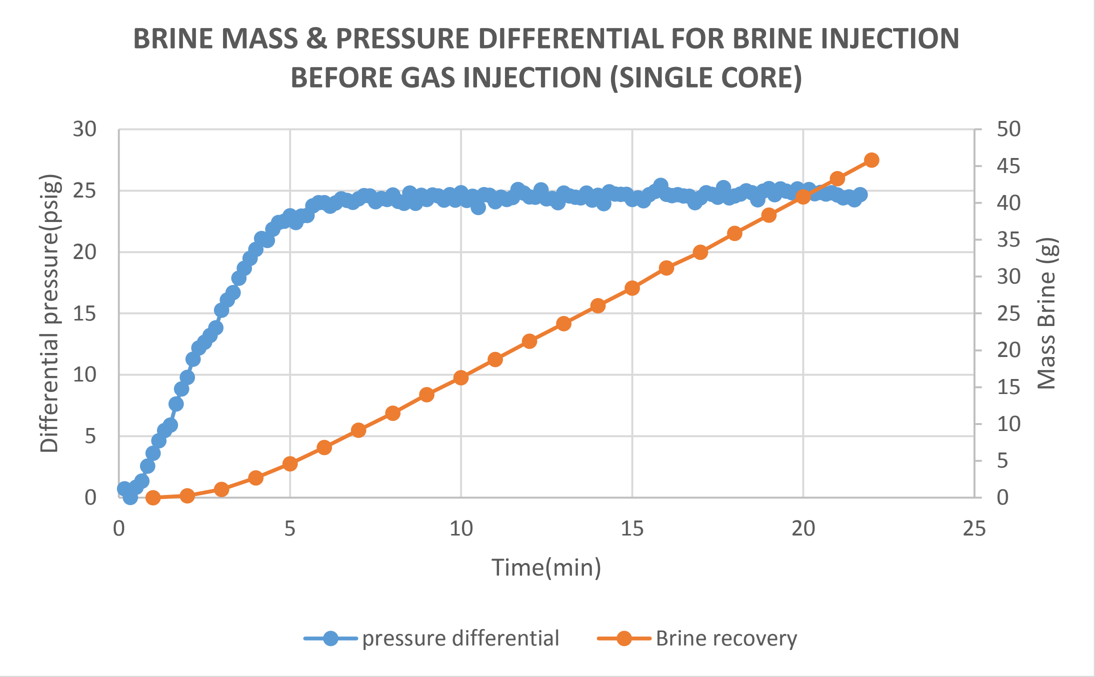

Figure 4.7 Graph of brine mass and differential pressure against time for brine injection before gas injection (single core)

The figure 4.7 show the graph of brine mass and pressure differential against time for brine injection before gas injection. The unit for differential pressure is pound per square inch gauge (psig) while time in minutes. Due to the equipment settings, the time taken for each pressure differential point is on the per 10 seconds basis. The figure 4.7 show that the differential pressure is stabilize at approximately 25 psig.

The figure 4.7 also integrated the graph of mass of brine against time. From the figure 4.7, it can be seen that the core has been saturated with the brine because the breakthrough for the first drop of brine from the outlet is in the early minutes. Apart from that, the graph in figure 4.7 also show that the outlet flow rate is constant along the total time taken for the differential pressure to be stabilized which is around 25psig.

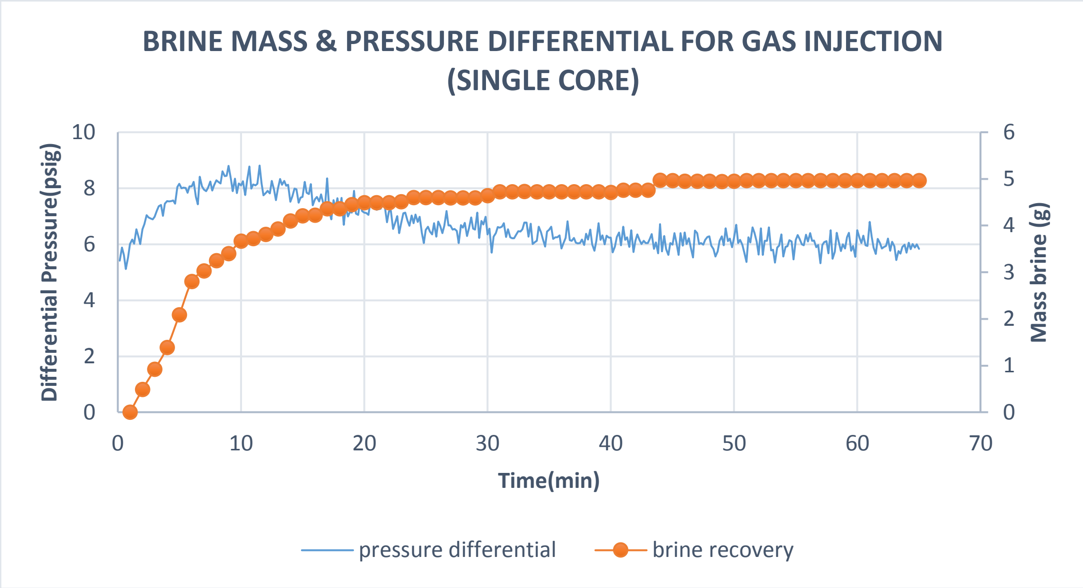

Figure 4.8 Graph of brine mass and differential pressure for gas injection(single core)

The figure 4.8 show the graph of differential pressure against time for gas injection. The flow rate of Nitrogen gas used in this experiment is 22.63cm^3/min. From the figure 4.8, we could observe that the differential pressure reading is high around the early minutes of experiment but gradually stabilized at approximately 6 psig. The figure 4.8 also show the graph of mass of brine against time. From the figure 4.8, we can observes that the core is saturated with the brine because the breakthrough for the first drop of brine from the outlet is also in the early minutes. The graph in figure 4.8 also show that the outlet flow rate is gradually decreasing at approximately 5 gram of brine. It can be derived that the process of drainage has happened which defined as wetting phase decreases.

Although drainage process has occur, the volume of the brine which collected does not represent the pore volume measured earlier in quality check of the cores which is around 13cm^3. It can be conclude that due to the connate water saturation of the core (Berea Sandstones), equal volume of brine collected and the total pore volume is not possible.

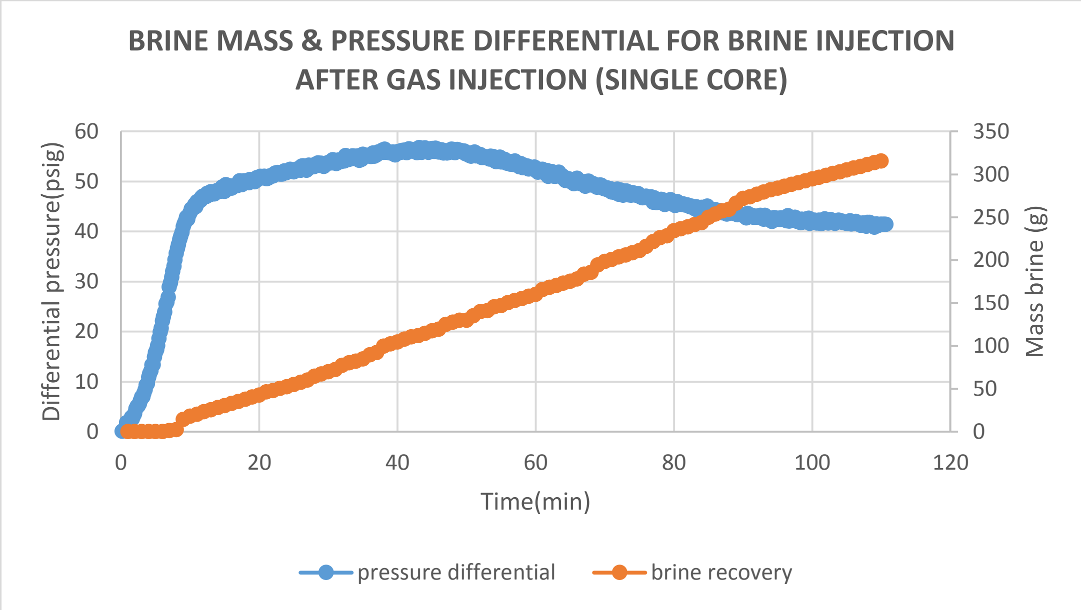

Figure 4.9 Graph of brine mass and differential pressure for brine injection after gas injection

To complete a one whole cycle of WAG experiment, brine injection will take place after gas injection. Figure 4.9 show the graph of differential pressure against time for brine injection after gas injection. The graph 4.9 show unsteady differential pressure reading along the time taken for the pressure to stabilize. We can observe that the differential pressure is stabilize at roughly 40 psig. The figure 4.9 also show the graph of the mass of brine collected against time. The injection of brine after the gas injection is said to be an imbibition process because the wetting phase is increased. From the figure 4.9, we can observe that the time taken for the first brine water drop is around 5 minutes. The time taken for the first brine water drop is longer compare to time taken for the first brine water drop in figure 4.7.

From the flow rate of 2.5cm^3/min and the time taken for the first brine water drop is around 5 minutes, calculation has been made and the volume of brine injected into the core before the first brine water drop is approximately 12.5cm^3. It can be concluded that the moment of brine water breakthrough is longer due to the pore spaces inside the core is being filled by brine until the core is saturated before the first brine water drop is produced at the outlet.

4.4 Water Alternating Gas Experiment : Composite Core

After the core is cut into two 1.5inch sections, the core is stacked in the same manner as before cut when inserted into the equipment confining chamber. In this WAG experiment of using a composite core, the first phase of this experiment is the injection of brine (24000 ppm) at 2.5cm^3/min.

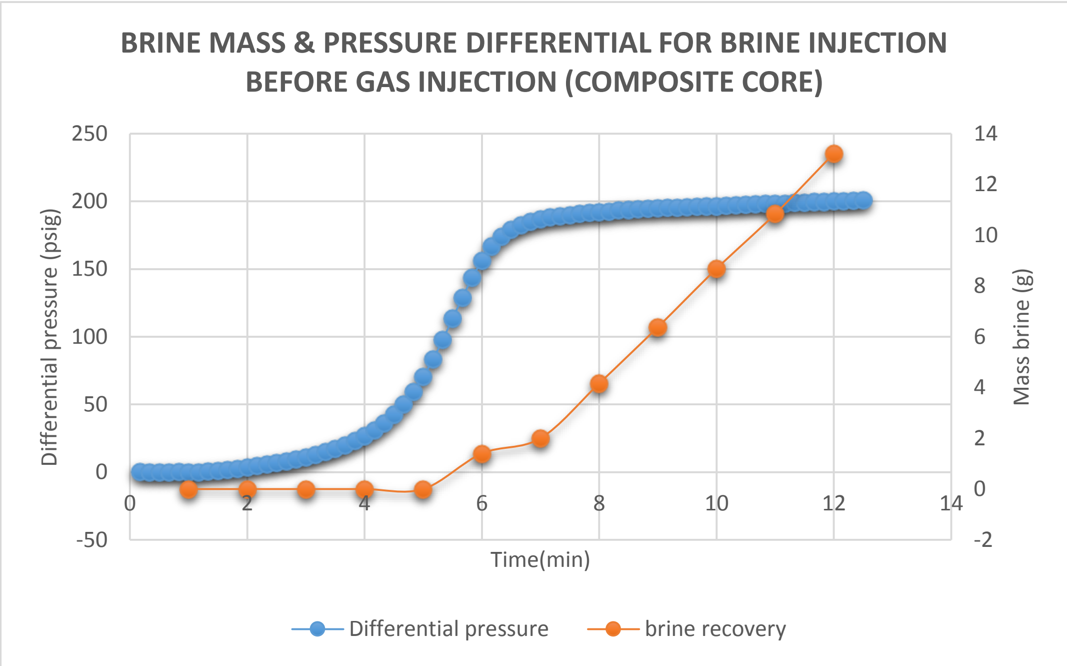

Figure 4.10 Graph of brine mass and differential pressure for brine injection before gas injection (composite core)

The figure 4.10 is the graph of differential pressure against time for brine injection before gas injection of using composite core. From the figure 4.10 show that the differential pressure is stabilize at approximately 200psig. The figure 4.10 also show the graph of mass of brine recovery during brine injection when using a composite core.

From the graph of figure 4.10, we can observe that the time taken for the first drop of brine is longer compare to graph in figure 4.7. A longer moment of breakthrough is needed by the brine to fully saturate the core and then flow to the outlet flow. After the eighth minutes, the outlet reading show a steady outflow of brine. From the figure 4.10, we can assessed that during the core cutting procedure, there must a loss in saturation value of the core. So in order for the first drop of brine exit into the outlet flow, the core's pore space need to be filled by brine until it is fully saturate.

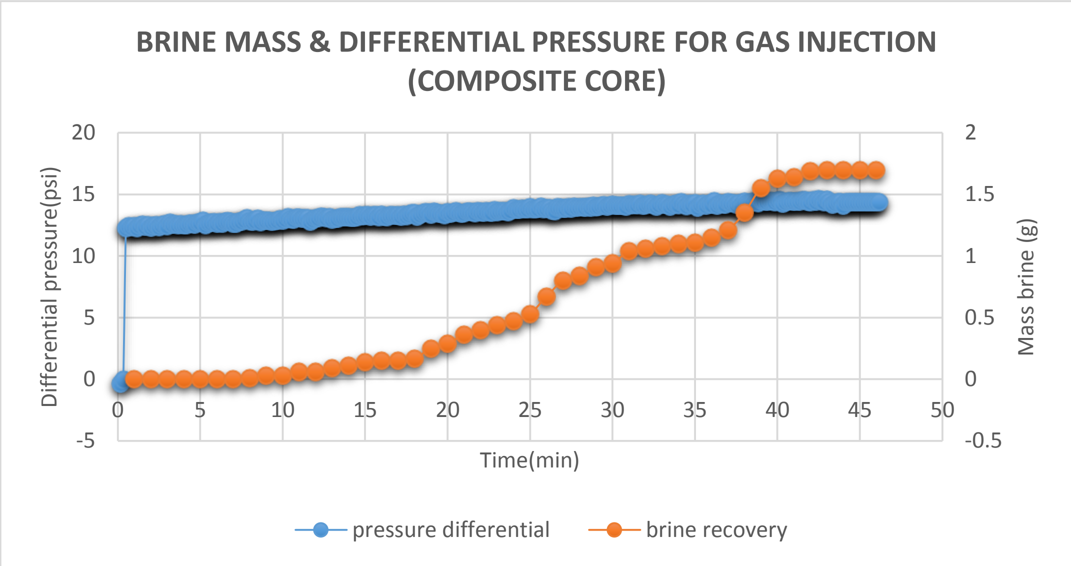

Figure 4.11 Graph of brine mass and differential pressure for gas injection (composite core)

The figure 4.11 show the graph of differential pressure against time for gas injection into the composite core. From the figure 4.11, we can observes that the differential pressure is increasing sharply in the early minutes but progressively stabilizes at around 14 psig. The figure 4.11 also show the graph of mass of brine collected during gas injection for composite core. Initially, the flow rate at the outlet measurement show a fast increase since the water saturation in the core is still at a high value. But later on, the mass of brine started to decrease as the saturation inside the core reduces due to the drainage process. The fluctuation the flow rate of the outlet flow maybe due to the gas compressibility effect.

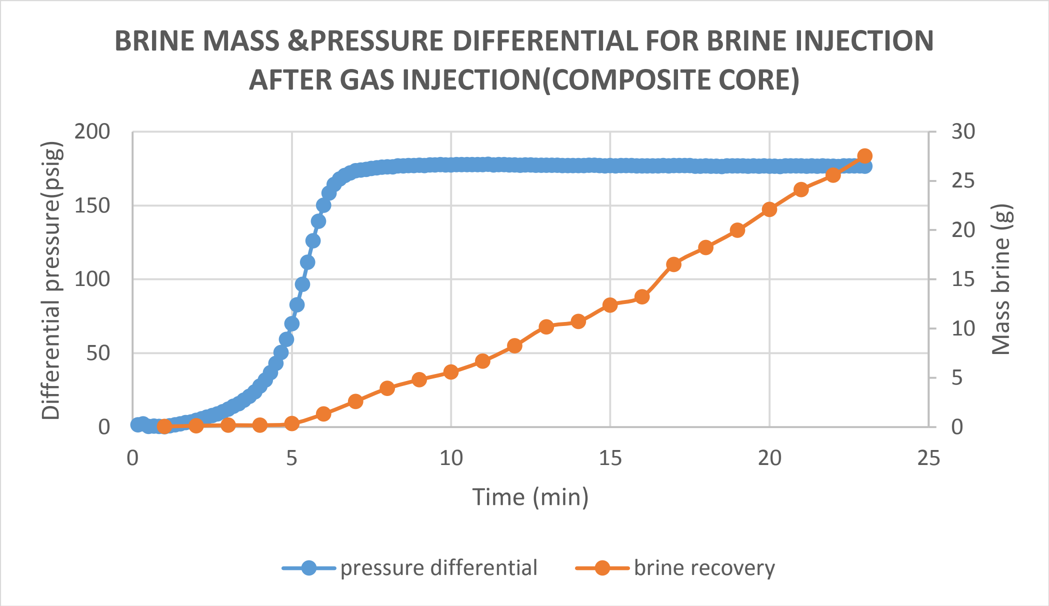

Figure 4.12 Graph of brine mass after gas injection for composite core

The figure 4.12 show the graph of differential pressure against time during brine injection for composite core. The figure 4.12 show that the differential pressure is stabilize at approximately 180psig. The figure also 4.12 combined the graph of the mass of brine collected against time for composite core. The injection of brine after the gas injection is said to be an imbibition process because the wetting phase is increased. From the figure 4.12, we can observe that the time taken for the first brine water drop is around 5 minutes.

The time taken for the first brine water drop is relatively the same compare to time taken for the first brine water drop in figure 4.10. It can be concluded that the moment of brine water breakthrough is longer due to the pore spaces inside the core is being filled by brine until the core is saturated before the first brine water drop is produced at the outlet.

4.5 Permeability Experiment Using BPS-850 After WAG

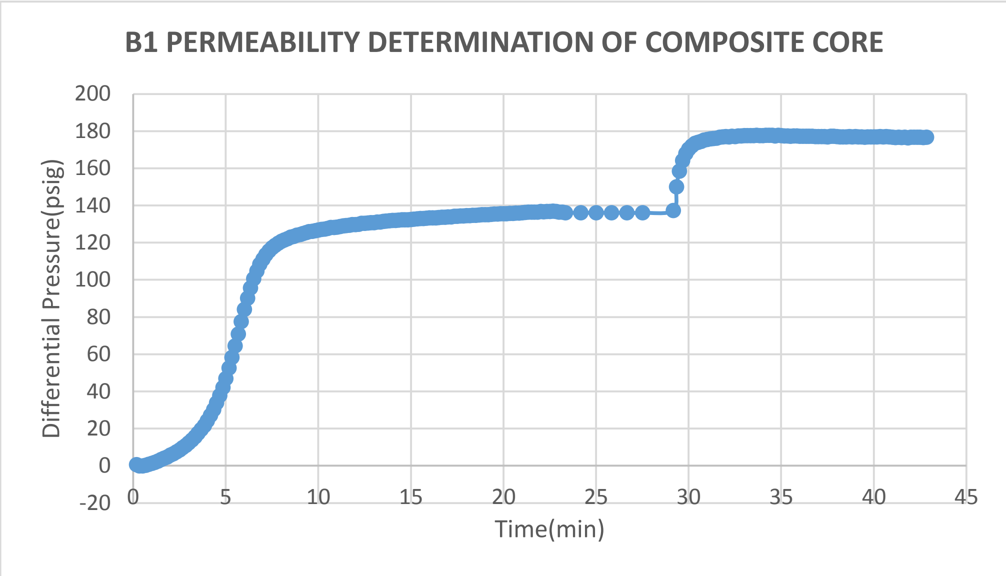

Figure 4.13 Graph of permeability after WAG cycle using composite core

In Figure 4.13, the flow rate that has been used for determination of the permeability by liquid are 1.5cm^3/min and 2.5cm^3/min. The pressure transducer of the equipment is limited to 200psig. A higher flow rate might cause the differential pressure to exceed 200psig. So due the equipment limitation, only two flow rate is determined.

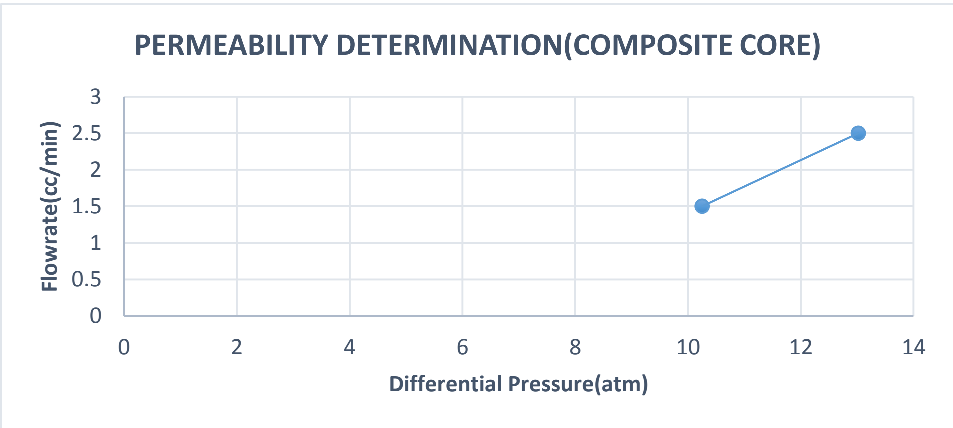

Figure 4.14 Slope determination for calculation of permeability

Based on Figure 4.14, it has been determined that the permeability by liquid value for B1 composite core after WAG experiment is 1.93md. R^2 value that on the graph show 1. The R^2 value should be approximately 1.0 to ensure the straight line is a good fit line.

4.6 Discussion

During the experiment, the test on B1 core only run once. Repeated test on the core is not attempted due to the limited time and equipment availability. Also due to no oil is used in this experiment, brine collected at the outlet flow rate is used as an indicator for recovery.

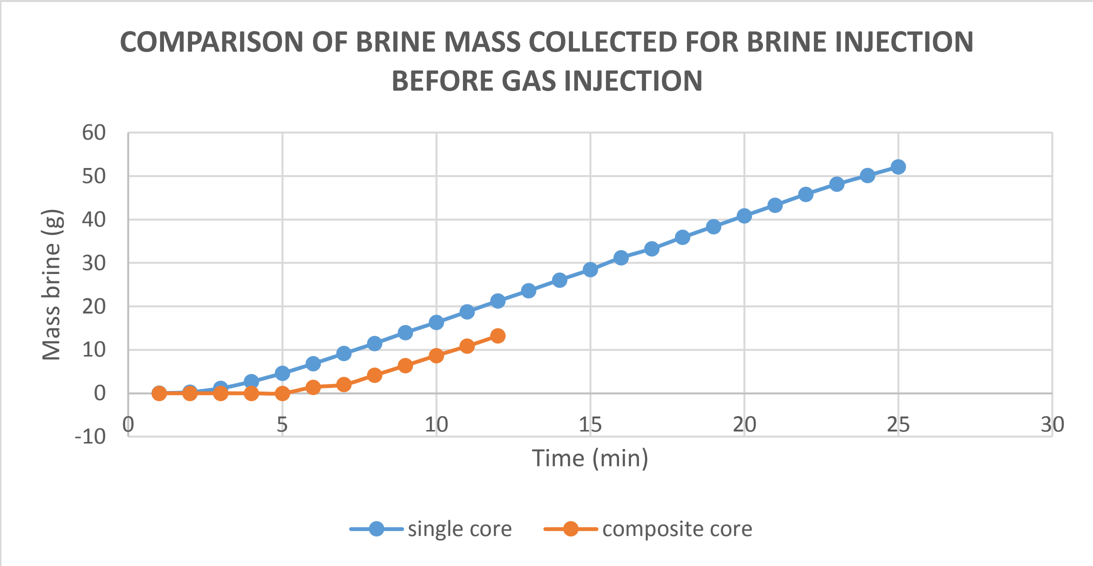

Figure 4.15 Comparison of brine mass for brine injection before gas injection

Figure 4.15 show the comparison of brine mass between single core and composite core brine mass for brine injection before gas injection. From the figure 4.15, we can observe that for the composite core, the recovery flow rate of brine is slower compare to the single core. But both produce the same increasing mass of brine after 5 minutes.

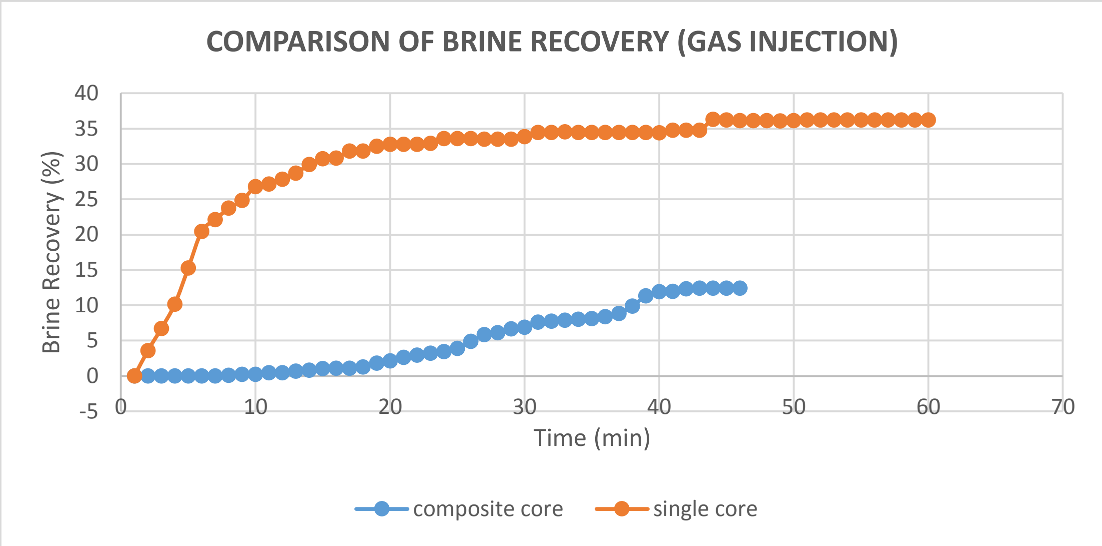

Figure 4.16 Comparison between brine recoveries during gas injection

Based on figure 4.16, we could observe that the recovery for composite core yield a lower mass compare to single core. For the first 10 minutes, the single core shows a faster increment in brine mass compare to composite core. The composite core fast rate increment in mass comes after more than 15 minutes. The brine recovery for composite core is 13.1% while for the single core the brine recovery is 36.5%. The pore volume have reduce slightly when the core is cut. When the core is cut, there is a significant gap between the cores. The brine from the area near the inlet flow might have trap between the gaps thus the reduction in the brine recovery for composite core.

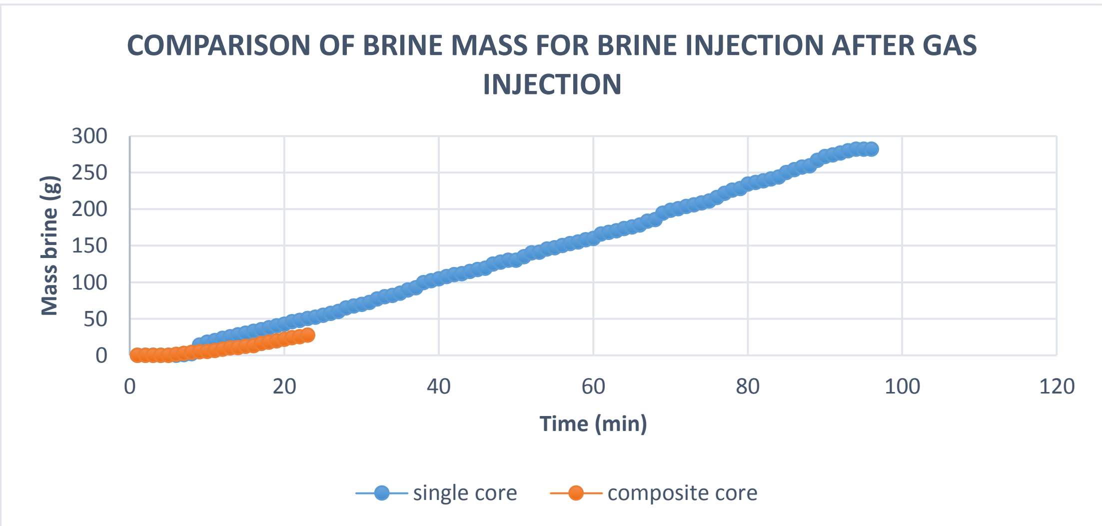

Figure 4.17 Comparison of brine mass for brine injection after gas injection

Figure 4.17 show the comparison of brine recovery between single core and composite core brine recovery for brine injection after gas injection. From the figure 4.17, we can note that for the composite core, the recovery flow rate of brine is slower compare to the single core. The slow rate of recovery in composite core is also the same case as in figure 4.15. In this case, both produce a steady increasing mass of brine after 10 minutes.

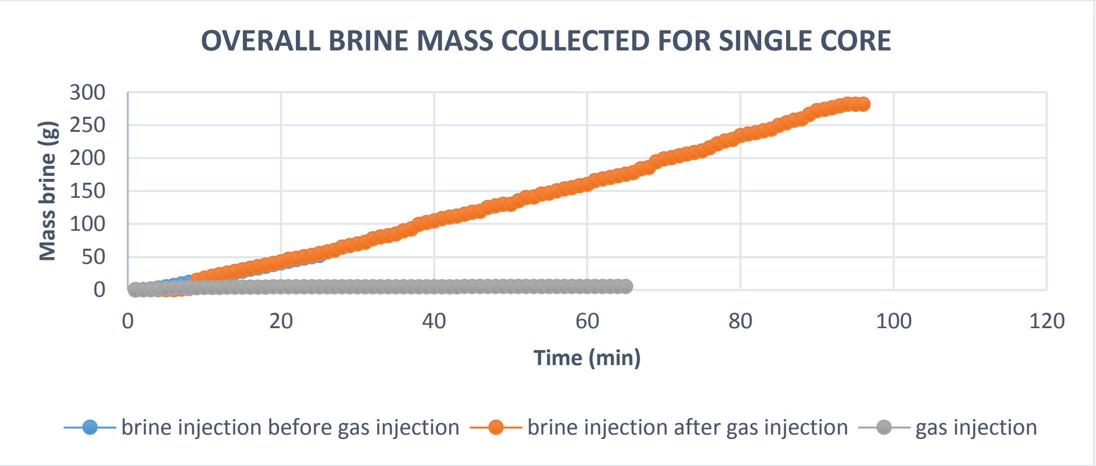

Figure 4.18 Brine mass collected for a whole WAG cycle using single core

The figure 4.18 show the overall performance of the single core in term of brine recovery. From the figure 4.18, we can observe that there is a common steady rate of brine recovery for brine injection before and after gas injection. Meanwhile, the recovery for brine is lower during gas injection compare to both brine injection. The time taken for the brine injection after gas injection to be stabilize also longer compare to brine injection before gas injection where brine injection after gas injection took about 90 minutes while brine injection before gas injection is about 25 minutes.

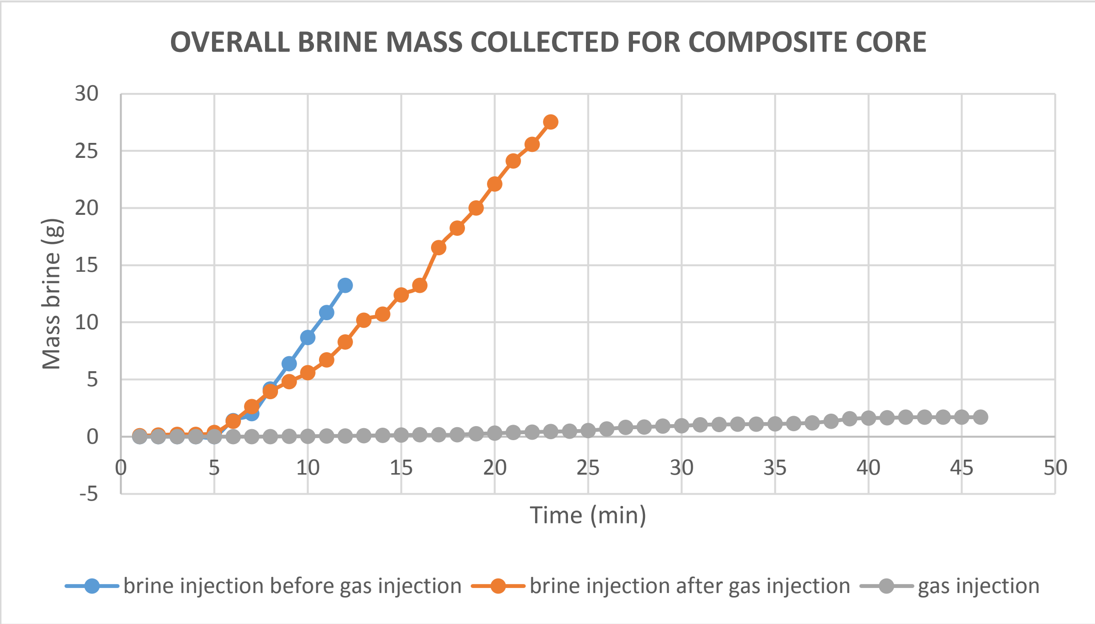

Figure 4.19 Brine mass collected for whole WAG cycle using composite core

Figure 4.19 show the overall performance of composite core for the whole WAG cycle in term of brine recovery. Comparing to figure 4.18, the brine recovery rate in the figure 4.19 yield a less steady recovery rate. The brine injection before gas injection mass recovery rate is much faster compare to brine injection after gas injection. From the time taken for the brine injection, both has a relatively shorter time taken. It can be relate back to the time taken for the differential pressure to be stabilize. Although using the same inlet flow rate with single core, brine injection in composite core take a shorter time for the differential pressure to be stabilized.

Table 4.6 Results of permeability

Type of core	-	Permeability
Single Core	Before WAG	21.9 mD
	After WAG	10.58 mD
Composite Core	Before WAG	2.16 mD
	After WAG	1.93 mD

Table 4.6 show the result of permeability before and after WAG for single core and composite core. For the single core, we could see that the permeability value before WAG experiment is 21.9 mD and after WAG experiment is 10.58 mD. There is almost 50% reduction in permeability. The permeability reduction is quite high and need to be addressed.

While for the composite core, the permeability value before WAG experiment is 2.16 md and after WAG experiment is 1.93md. For the composite core, the permeability value reduce around 10%. Furthermore, there is a differences is value of permeability of single core and the composite core. The permeability value for composite core has reduced almost 79% compare to the single core.

After the WAG experiment for single core, author should weight the core. The objective to weight the core is to ensure the saturation of the core after WAG experiment is the same with the saturation of the core before WAG experiment.

There are few reasons the permeability reduction had occur. One of it is due to the interconnected cores space might have been plugged by fines migration. The experiment has been using the same used core with the same flow direction repeatedly. Hence the fines may have migrate thus clogged the flow of fluid. Another reason for the permeability reduction is due to trapped gas inside the pore space of the core. When the core is not fully saturated with brine, the permeability value that being calculated is the effective permeability instead of absolute permeability.

Thus, it may become the reason the permeability difference is too high is because the permeability value of the core before WAG is absolute permeability while the permeability value after WAG experiment is effective permeability.

Author had missed to weight the core after WAG experiment to eliminate the reason of fines migrate and unable to confirm the saturation value before the composite core WAG experiment to be done. Consequently, the result for the permeability reduction might been too high and un-representatives for permeability reduction result.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

In conclusion, there is a significance value change in the parameters that have been studied in this report.

- There is brine recovery reduction for single core and composite core during gas injection process.
- The outlet flow rate is relatively more stable in single core compare to outlet flow rate of composite core.
- The outlet flow rate for composite core is slower in the early minutes of each run compare to the single core.
- When the core is cut, there is a significance changes in the grain volume, pore volume, and permeability.

The difference in value has been determined and presented. There is an impact of discontinuity of the core length that influence on WAG parameters. Although the effect is significance, this study only report on the early findings of the differences. More study need to be done to ensure the differences in value can be modeled and practice in the field. The project only focus on a limited parameters which are permeability, flow rate, pressure difference and brine recovery. It is recommended for future works to study other parameters that might have an impact to the WAG experiment. Thus the project with the title of '*The Effect of Using Composite Core in WAG Experiments'* is recommended to proceed due to its importance contribution in oil and gas industries.

CHAPTER 6

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