Multiwall Carbon Nanotubes (MWNT) Fluid in EOR Using Core Flooding Method Under The Presence of Electromagnetic Waves

by

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Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the

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Approved by,

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TRONOH, PERAK

May 2013

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.

(KAYATHIRI A/P CHANDRAN)

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First and foremost I would like to express my thanks to Almighty God on successful completion of this project and report. This dissertation is a milestone in my academic career. I have been fortunate to learn theories, concepts and apply the engineering knowledge that I have learnt through this project.I hereby, express my sincere and profound gratitute to my Final Year Project supervisor, Professor Dr. Noorhana for her continuous assistance, support, guidance and understanding throughout the successful completion of my FYP. Her trust, patience, guidance and leadership had been a good inspiration and motivation for me and lead to a successful completion of my FYP.

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ABSTRACT

A non-invasive method is proposed by applying nanotechnology in EOR under the presence of electromagnetic waves to increase oil recovery from high pressure and high temperature reservoir. Therefore, a study on potential of Multiwall Carbon Nanotubes (MWNT) fluid in EOR under the presence of electromagnetic waves was carried out. Firstly, MWNT was characterized using Field Emission Scanning Electron Microscopy (FESEM) and High Resolution Transmission Electron Microscope (HRTEM). The characterization result shows that MWNT that is being used in this research are in cylindrical shape and have multiwall. Three phases core flooding experiments were carried out to improve oil recovery using MWNT fluid. The first two phases of the experiment is to study the impact of MWNT fluid concentration and flow rate on permeability under the absence of electromagnetic waves. The results of the first two phases of the experiments shows that 0.01wt% of MWNT fluid being injected into the porous medium at the flow rate of 2ml/min under the absence of electromagnetic wave causes the least reduction in permeability with the ability to recover 36.67% of residual oil in place (ROIP) from the porous medium. Injection of MWNT fluid under the presence of electromagnetic waves yielded a 61.1% of recovery efficiency, which is 24.43% higher than the 36.67% of recovery efficiency when MWNT fluid was injected into the porous medium under the absence of electromagnetic wave. It is investigated that the drastic increment in recovery efficiency is due to adsorption of electromagnetic wave by MWNT which causes the causes the oil viscosity to be reduced and hence, increases oil recovery.

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CHAPTER 1

1. INTRODUCTION

1.1 Background of study

In the coming oil crises, through 2002, it is estimated that the world oil production since late 1800's has totaled up to about 930 billion stock tank barrel (STB) of oil. However, the global oil production of the world is predicted to occur around 2005 until 2020 which is approximately 50% conventional oil reserves. Conventional oil reserves is defined as oil reserves that can be recovered economically using conventional oil (Kjarstad, 2009) recovery methods such as miscible carbon dioxide displacement and chemical injection. A conventional oil reservoir is a high to medium permeability reservoir that can be drilled vertically and produce oil at commercial flow rates and recover oil's economic value (Holditch, 2003). Massive production of conventional oil reserves to fulfill the global demand causes the production of conventional oil reserves to decline and indirectly causes oil price to increase. Moreover, the global demand energy in the world is expected to increase by the next few decades as it is predicted that the energy consumption will increase by 50% for the next 20 years which causes further increment in societies living cost, utility bills, and prices of consumers' goods (Selien De Schryder, 2012). According to the World Economic Outlook (WEO) in 2008, it is observed that the oil productions from existing wells are decreasing and causes the discovery of new conventional oil reserves to decrease as shown in figure 1.1. (Kjell Aleklett, 2010)

Since conventional oil reserves is depleting, this situation urges the oil and gas companies to find for new oil resources by searching unconventional oil reserves. Unconventional oil reservoirs are referred as the reservoir that does not produce at economic volumes of oil and gas without the assistance of stimulation treatment or recovery technologies. (Holditch, 2003) Unconventional oil reserves are also defined based on geographical location of the reservoir and properties of the oil to be recovered. If the reservoir is located 500m below the seafloor, conventional methods that are used to extract oil out from the reservoir such as chemical injection or microbial injection can destroyed due to existence of high temperature and high pressure environment in the reservoir. (Lakatos, 2009)

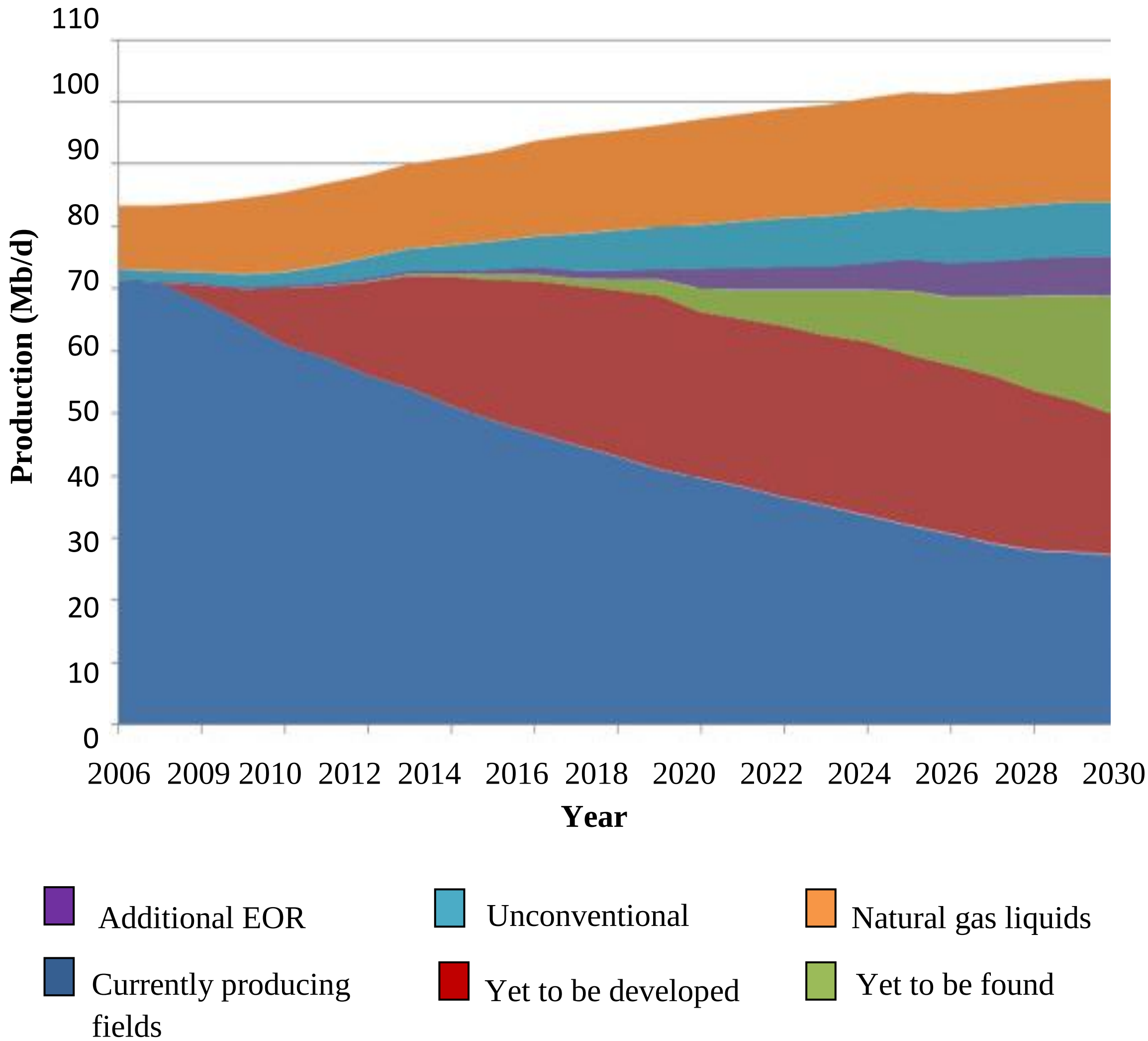


Figure 1: World oil production by source in the Reference Scenario of World Energy Outlook 2008

Conventional recovery methods are common oil recovery methods being used in Enhanced Oil recovery (EOR) or also known as tertiary recovery method. Before EOR is being carried out in the reservoir, primary and secondary recovery methods will be carried out first to extract oil from the reservoir.

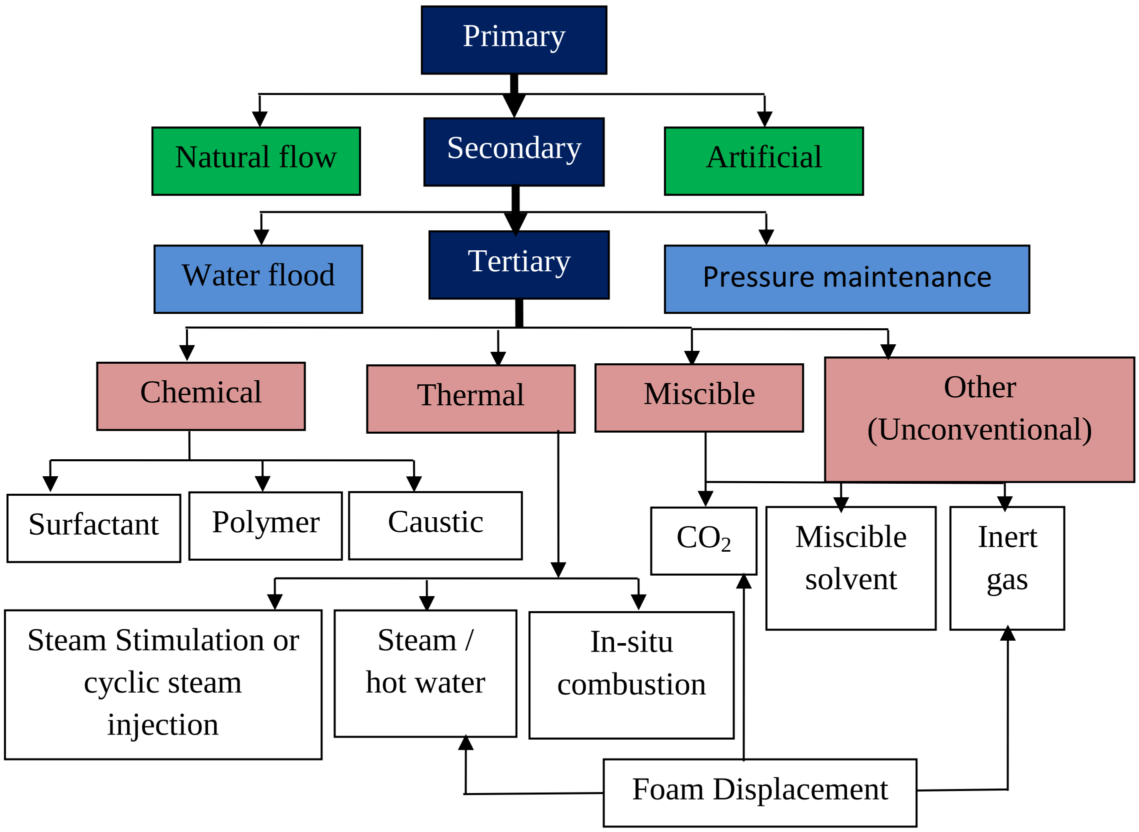


Figure 2 : Various EOR methods

Figure 1.2 shows the flow of three recovery phases and various EOR methods that is being carried out to recover oil from the reservoir. Primary recovery is the first oil that comes out from the reservoir after drilling activity took place. This recovery uses the natural pressure of the reservoir to push the crude oil to the surface. By using this recovery method, usually 5-10% of oil is being recovered from the reservoir. . (Technology, 2007) After primary recovery phase is being carried out, secondary recovery phase will be carried out.

In secondary recovery phase, pressurized gas and water will be injected into the reservoir to drive residual crude oil and remaining gas to the surface wells. The most common methods being used in secondary recovery phase are gas injection and waterflooding. The gas is injected into the gas cap while the water is injected into the production zone to sweep oil from the reservoir. The secondary stage will reach its limit when the injected water or gas is being produced in a considerable amount which is no longer economical. Secondary recovery allows additional 25% to 30% of oil being recovered from the reservoir.

Finally, tertiary oil recovery phase will be carried out. In tertiary recovery phase, different chemical agents and materials will be injected to improve the flow between the oil, gas and rock and to recover remaining crude oil after primary and secondary recovery phase. Tertiary recovery allows additional 20% to 30% of oil to be recovered from the reservoir. Hence oil and gas industry must face the challenges to reach the resources that are impossible to be reached using conventional technology. Tertiary recovery phase is also known as Enhanced Oil Recovery (EOR). According to International Energy Agency, oil and gas industries are able to recover 35% of oil from the reservoir. However, through EOR, around 300 billion of oil recovery can be discovered. There are 4 well known EOR techniques which are chemical, thermal, microbial and gas injection.

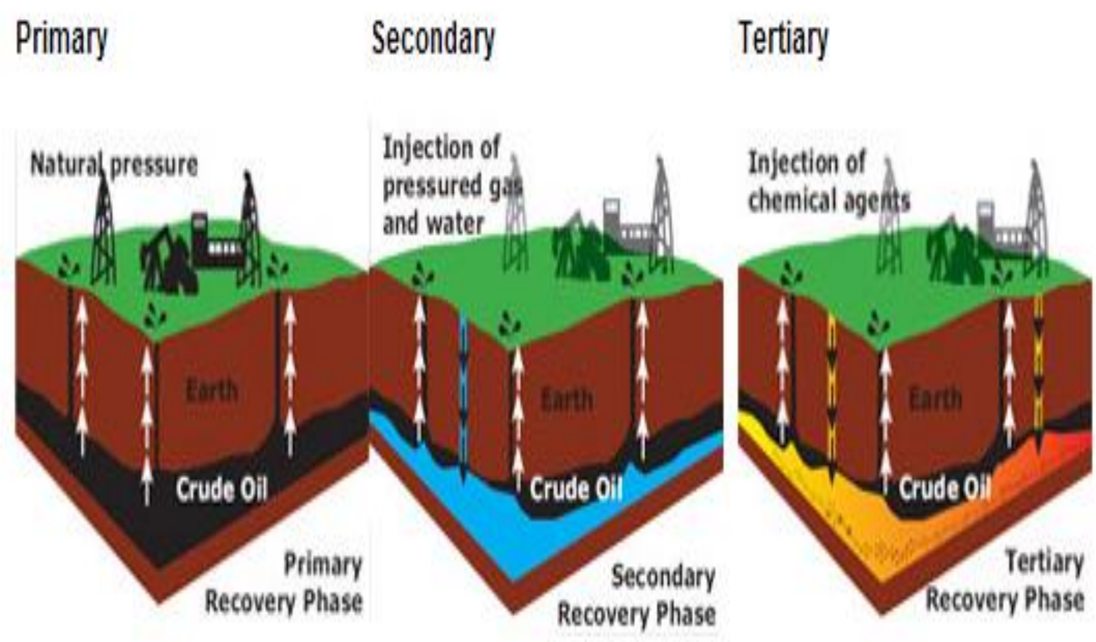


Figure 3 : Three phases of oil recovery in a reservoir

These 4 EOR methods will be further explained in order to know the application of each EOR techniques in oil recovery and the challenges that needs to be overcome to implement these EOR techniques.

a) Thermal Recovery Method

Thermal recovery method as shown in figure recovers oil by raising the temperature of the reservoir through steam injection, steam stimulation, in-situ combustion and SAGD. Thermal method can help to reduce viscosity of high viscous oil and reduce interfacial surface tension between oil and water (Shahab Ayatollahi, 2012. However, the challenges that need to be faced in order to use thermal recovery are

1. high energy cost
2. low thermal conductivity of rock and fluids
3. heat leakage to undesired layers
4. low effective thermal degradation
5. wellbore damage due to initial high temperature
6. heat loss from heat generator to the reservoir

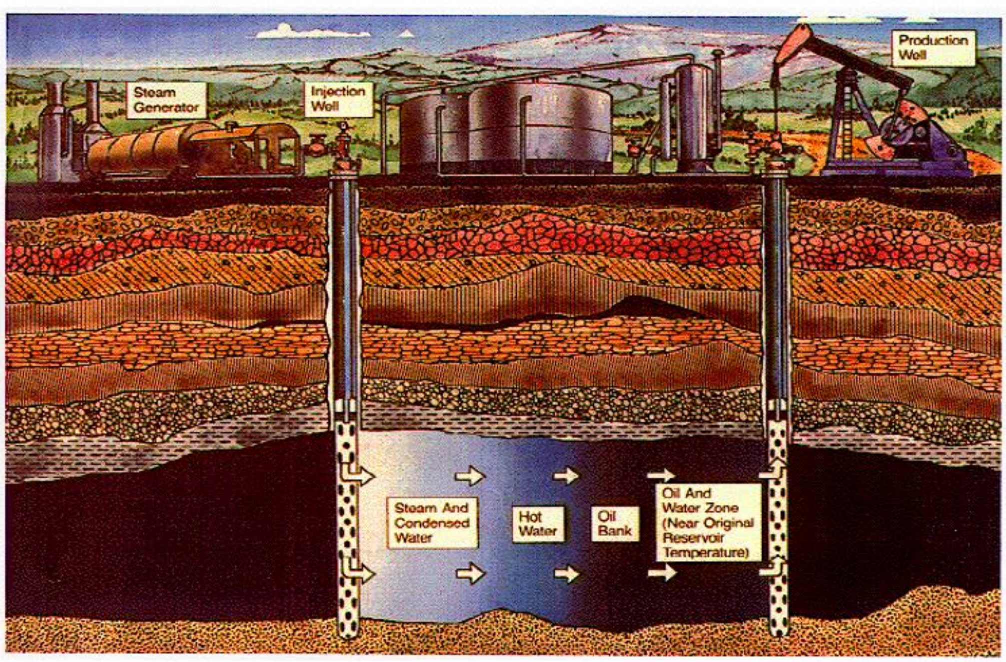


Figure 4 : Thermal recovery method

b) Chemical Recovery Method

Chemical recovery method as shown in figure 4 recovers oil by injecting surfactant and polymer into the reservoir. Polymer is able to increase the effectiveness of water flood in the reservoir. Surfactant helps to lower the surface tension to enable the oil to flow out from the reservoir. (Shahab Ayatollahi, 2012) However, similar to thermal recovery, there are several problems that need to be encountered in order to use chemical recovery method which are

1. high cost because excess amount needed
2. low effectiveness on interfacial tension and viscosity changes due to harsh reservoir conditions
3. unfavourable mobility ratio due to solution viscosity
4. damage due to incompatibility
5. slow diffusion rate in pore structure
6. unknown mechanisms foe wettability alteration

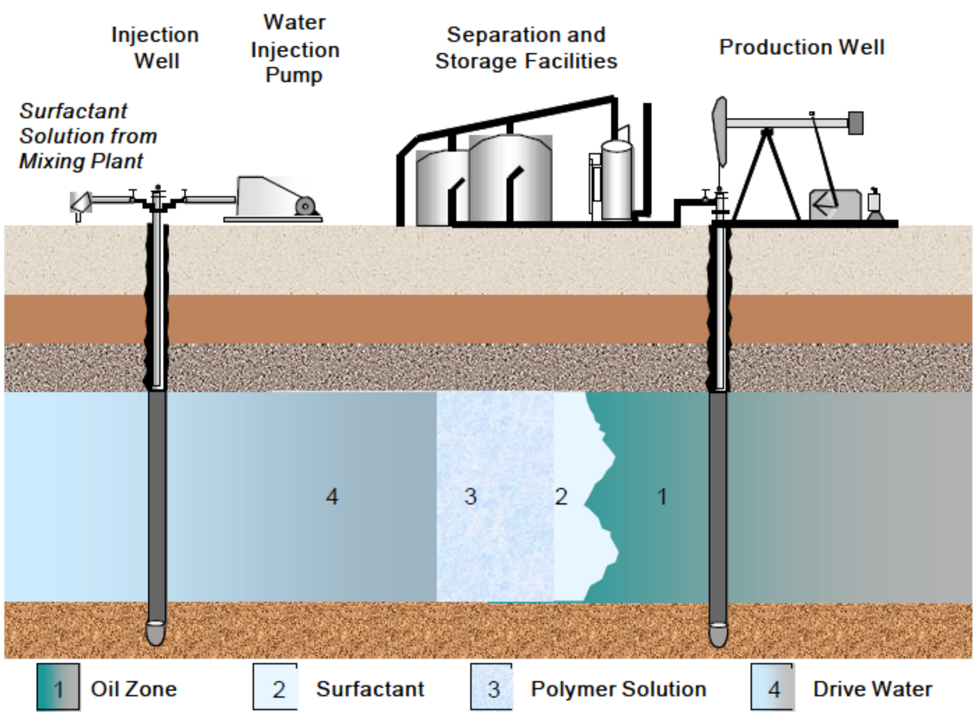


Figure 5 : Chemical recovery technique

c) Gas Injection Recovery Method

Gas Injection recovery which uses gases such as Carbon Dioxide, Nitrogen and natural gas expands in the reservoir in order to push additional oil to the production wellbore. Gas injection also causes the gases to dissolve in the oil to lower its viscosity and improve its flow rate. Gas injection enables the pressure of the reservoir to be maintained, viscosity of the oil to be reduced, and oil expansion to take place. (Shahab Ayatollahi, 2012) There are several disadvantages that should be considered in order to use gas injection method which are

1. gas viscosity leads to early breakthrough
2. corrosive resistance materials are needed when carbon dioxide is injected
3. asphaltene deposition may occur

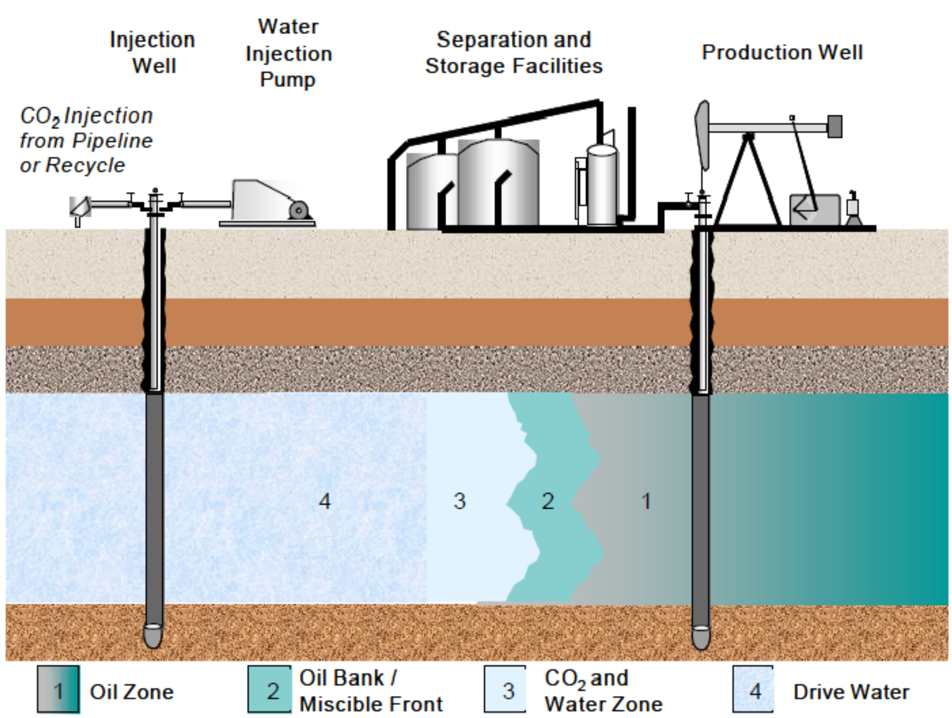


Figure 6 : Gas injection recovery technique

d) Microbial recovery method

Microbial as shown in the figure consists of nutrition injection and bioproducts injection such as biosurfactant and biopolymer flooding. Microbial recovery technique helps to clean the wellbore by removing mud and debris that blocks the channels for oil to flow through. This recovery also helps to improve oil flow from the drainage area into the wellbore. Microbial recovery method is able to reduce the interfacial tension between oil and water in the reservoir and able to alter the wettability of the reservoir rocks. (Shahab Ayatollahi, 2012) Similar to thermal, chemical and gas injection recovery method, microbial recovery method also has its own disadvantages that need to be faced in order to implement this recovery which are

1. causes undesired plugging
2. causes undesired bio reaction
3. this recovery indirectly delivers nutrition to microorganisms
4. this recovery method is a slow biodegration process

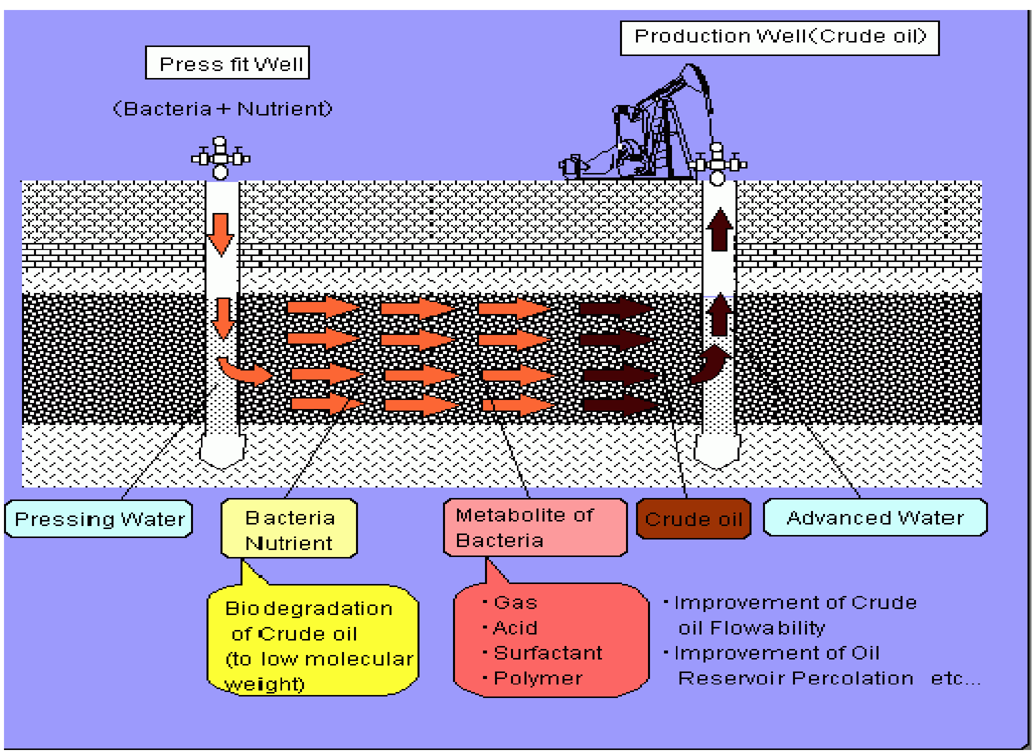


Figure 7 : Microbial Injection technique

These 4 EOR conventional methods can be used to recover conventional oil from the reservoir. Conventional oil is defined as oil that can be recovered easily from the reservoir at a very low cost without implementing advanced technology. However, since conventional oil is being depleted, newly discovered reservoir are recognized for producing unconventional oil such as heavy oil and tar in a very high pressure and high temperature reservoir environment. As the depth of the unconventional oil reservoir increases, the temperature of the reservoir also increases. Due to the existence of extreme high pressure and high temperature environment in the unconventional oil reservoir, EOR conventional methods are not applicable to recover oil from such reservoirs because the chemical properties of these 4 EOR conventional methods can be altered and destroyed under the presence of high temperature and pressure. If EOR conventional methods are still being applied to recovery oil from unconventional reservoirs, it will result in bad recovery efficiency and the oil production will be low.

Therefore, a non-invasive method which can withstand high pressure and high temperature should be developed to recover oil from unconventional reservoir. Electromagnetic wave (EM) EOR is observed to be a good potential candidate to recover oil from high temperature and high pressure reservoir, based on fact that transmitter should be located far apart from the target zone using suitable frequency. The electrical energy that is produced from EM wave is able to reduce the oil viscosity and results in the increment of oil mobility. In order to maximize the oil production from the reservoir, dielectric nanoparticles suspension will be injected into the reservoir to be adsorbed at oil-water interface and activated by the alternating electric field. Among different types of nanomaterials that are being used in nanotechnology field, Carbon Nanotubes or also known as CNT is a very good dielectric nanomaterial since it has lead applications from large scales until small scales of electronics. (Bandaru, 2007) Moreover, CNT is well known for its extremely small size, lightweight and most importantly, resistant to temperature changes. This special property of CNT indicates that CNT is able to function well in high temperature and high pressure reservoir (Vaughn, 2011). However, since the shape of CNT is in the form of cylindrical, there is a high possibility that CNT can block the porous medium in the reservoir and causes reduction in permeability. In this research, the impact of CNT nanofluid concentration and flow rate on permeability to recover residual oil in place in an oil reservoir under the absence and presence of EM wave is studied. So therefore, in this project, core flooding experiments were carried out to compare the EOR efficiency that can be produced by using CNT with and without the presence of EM wave.

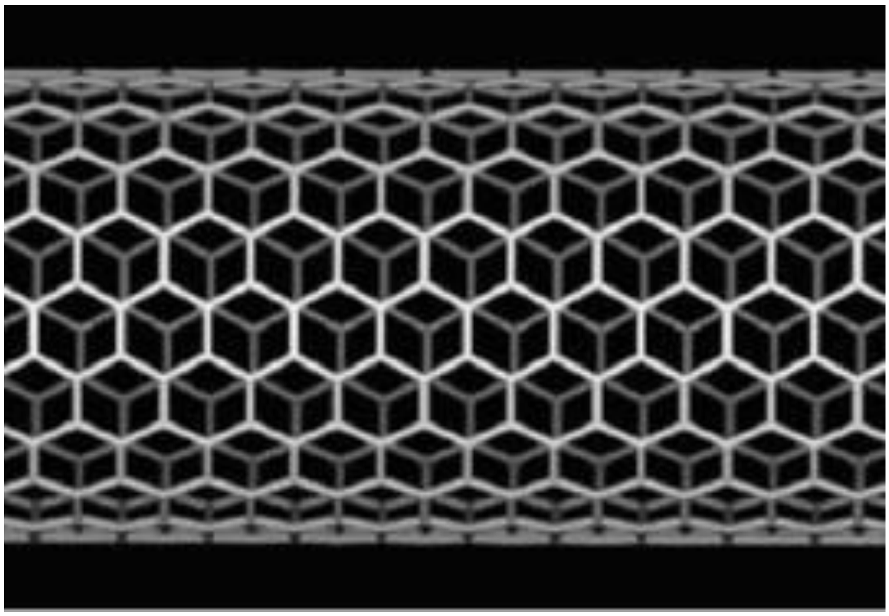


Figure 8 : Structure of Carbon Nanotubes (CNT)

1.2 Problem statement

Formation damage is an undesirable problem that occurs while carrying out various phases of oil and gas recovery from subsurface reservoirs, including drilling, production, hydraulic fracturing and workover operations. Formation damage can occur due to various unfavorable processes including physical, biological, chemical and thermal interactions of formation and fluids. The indicators that will indicate formation damamge occurs in a reservoir are permeability impairment, skin damage, and deformation of formation under stress and fluid shear. Once particles in nanometer size are being injected into the porous medium, the particles retention in porous medium can damage formation properties and one of the leading issues regarding nanoparticle transport. Particle retention in porous medium has been main concern for many industries since the transport of particles is limited to the degree to which particles are retained by the porous medium. So therefore, nanofluid can cause reduction in reservoir rocks permeability.

1.2.1 Significant of the project

The aim of this project is to study the potential of CNT nanofluid in increasing oil recovery from the reservoir by carrying out core flooding experiment under the presence of electromagnetic waves.

1.3 Objectives

There are several objectives that need to be achieved in order to complete this project. The objectives of this project are

(a) To characterize CNT sample using Field Emission Electron Microscopy (FESEM) and High Resolution Transmission Electron Microscopy (HRTEM).

(b) To study the role of CNT nanofluid on EOR by observing the impact of concentration and flow rate on permeability under the absence and presence of electromagnetic wave.

(c) To evaluate and carry out quantitative comparison of recovery efficiency and do justification of the results under the absence and presence of electromagnetic waves.

1.3.1 Scope of study

The scope of study of this project is divided into three parts which is to characterization of CNT sample, to setup core flooding experiment, and to study the impact of CNT nanofluid concentration and flow rate on permeability to recover residual oil in place (ROIP) from the porous medium under the absence and presence of electromagnetic wave.

1.4 Relevancy of the project

The project will focus on the impact of CNT nanofluid concentration and flow rate on permeability which is used to recover Residual Oil In Place (ROIP) from the porous medium. After finding out the best CNT nanofluid concentration and flow rate, EOR experiment will be carried out under the presence of electromagnetic wave by injecting in the best CNT nanofluid concentration at the best flow rate. Finally, a quantitative comparison of recovery efficiency will be carried out between the best concentration and flow rate of CNT nanofluid under the absence and presence of electromagnetic and justified. The knowledge that is required to carry out this project is related to Reservoir Rocks and Fluid Properties, Principles of Reservoir Engineering and Enhanced Oil Recovery (EOR) courses.

1.5 Feasibility of project within scope and time frame

This project is feasible to be done within 7 months which comprises of Final Year Project 1 and Final Year project 2 from January until August 2013. This project has been divided into three scopes of studies in order to achieve the objective and complete this project. The first two scope of study of this project which is to characterize CNT sample and to setup core flooding experiment was carried out in Final Year Project 1 which is from January until April 2013. The third scope of study of this project which to study the impact of CNT nanofluid concentration and flow rate on permeability while recovering residual oil in place from the porous medium under the absence and presence of electromagnetic wave was carried out in Final Year Project 2 from May until August 2013.

CHAPTER 2

2. LITERATURE REVIEW

2.1 Enhanced Oil Recovery

Enhanced oil recovery (EOR) or sometimes referred as tertiary recovery is a common term being used for methods to increase amount of crude oil that can be extracted out from an oil field. EOR is carried out to restore the formation pressure and also to improve oil displacement in the reservoir. The optimal application of each oil recovery methods to extract oil from the reservoir depends on the reservoir temperature, permeability, net pay, depth, porosity, water saturations and fluid properties. (Schlumberger, 2013) Traditional oil recovery methods consist by understanding the main three forces that exist in the reservoir which are capillary pressure, viscosity and gravity. (A.J.P. Fletcher, 2010)

Table 1 : 4 main forces that exist in the reservoir (A.J.P. Fletcher, 2010)

Force	Phenomena of force
Coulombic	It is regarded as intermolecular force. This force is made of van der Waals which consists of induced dipole (London), dipole-dipole and hydrogen bonding forces. The presence of polar molecules and ions will induce the existence of ion dipole an ionic bonding forces.
Capillary	This force is formed from the curvature of fluid interfaces. The curvature of fluid interfaces leads to pressure difference between the different fluid stages.
Viscous	This force is related to viscosity difference

	of the fluids and controls the displacement efficiency of one fluid by another.
Gravity	This force controls the oil/water separation due to buoyancy effects and differences in density.

EOR recovery methods can be divided into four groups which are thermal, chemical, gas and microbial methods. Thermal recovery method is carried out by introducing heat into the reservoir through steam injection method. This causes the viscosity of heavy oil to be reduced and able to improve the mobility of the oil out from the reservoir. For gas injection method, natural gases such as Carbon Dioxide, Nitrogen will be injected to into the reservoir so that these natural gases can expand in the reservoir to push additional oil to the production wellbore. Chemical injection involves the use of long chained molecules of polymers to increase the efficiency of waterfloods and the use of surfactant to reduce the surface tension to enable oil droplets to move out from the reservoir. So therefore, chemical flooding functions by reducing the interfacial tension between water and oil, changing the wettability of the rock and increases the sweep efficiency. Detail explanation on each mechanism on how oil is being recovered and extracted out from the reservoir will be discussed in the following subsection.

2.1.1 Reduction in oil-water interfacial tension

Interfacial tension is referred as the boundary tension between two immiscible liquids. There are several properties that need to be considered which influences the interfacial tension between two liquids phases which are viscosity, thermal conductivity, freezing and boiling points. (Y.Dandekar, 2006). The dependence on the rock properties can be summarized as shown below

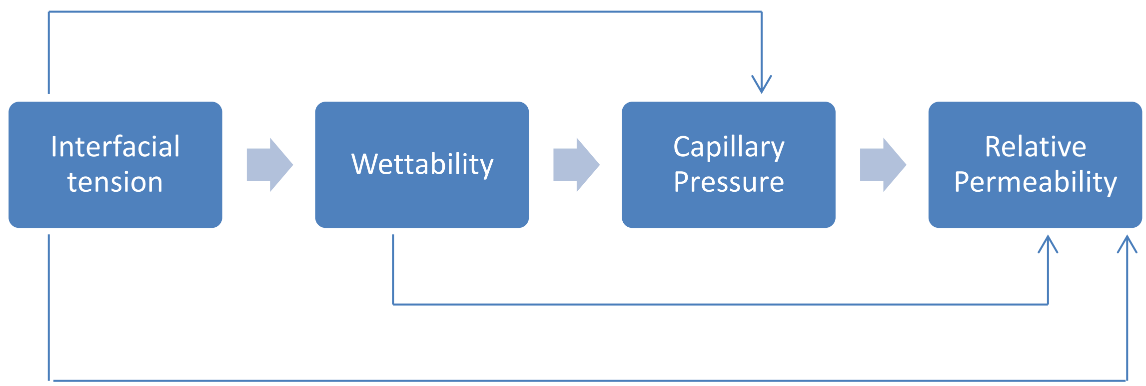


Figure 9 : Properites that influences rock wettabilies (Y.Dandekar, 2006)

Reduction in oil-water interfacial tension can help to increase oil production using EOR method. One of the techniques that is being used to lower the interfacial tension is through chemical injection into the oil reservoir. Dong et al. had carried out a study to prove that there is a reaction between alkali and acidic components in the crude oil. It was found out that the interfacial tension between the oil and water is reduced when alkaline solution which is sodium hydroxide is injected into the porous medium. (M. Dong, 2010)

2.1.2 Alteration of surface wettability

Wettability is defined as the ability of a fluid to adhere a solid surface in the presence of other immiscible fluid. Wettability term is also used to describe the relative adhesion of two solids to a solid surface. There are five types of wettability that exist in the reservoir which are water wet, oil wet, intermediate wet, fractional wettability and mixed wettability. In water wet wettability state, the rock surface prefers water phase more compared to hydrocarbon phase while in oil wet wettability state, the rock surface prefers hydrocarbon phase more compared to water phase. Intermediate wettability state has preference to both hydrocarbon and water phase while fractional wettability occurs when the surface of rocks which is composed of minerals which comprised of different kind of chemical properties leads to variation in wettability throughout the internal surface of the pores. Mixed wettability is associated with smaller pores filled with water and are water wet while interconnected pores are filled with oil. Figure 2.2 below shows the contact angle between oil or air and water to show the nature of hydrophobic and hydrophilic (Y.Dandekar, 2006).

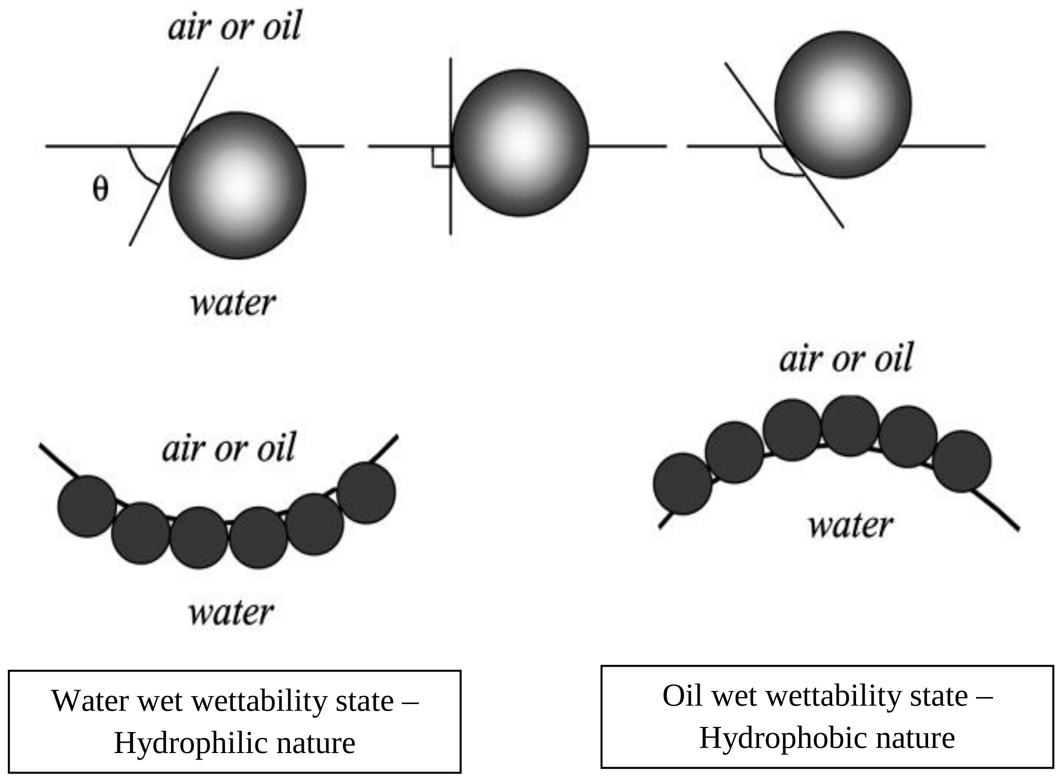


Figure 10 : Types of rock wettabilites (Binks, 2002)

The alteration of reservoir rocks surface wettability can cause additional production from unconventional or depleted reservoir. Roosta et al conducted a research to test wettability alteration in reservoir. In this research, it is mentioned that wettability alteration can work in two ways which are by

a) Changing the wettability state of a surface from oil wet to water wet, which indirectly contributes to higher oil production by preventing re-imbibition of oil back into the pore spaces.
b) Changing the wettability state of surface from strongly oil wet to neutral wettability, which increases oil production in non-fractured reservoirs. (Roosta, 2009)

EOR conventional methods such as thermal and chemical recovery methods are able to alter the wettability of reservoir rocks. Surfactant injected into the reservoir can alter the reservoir rock wettability by forming ionic pairs which can help to smoothen the adsorption of surfactant molecules into the crude oil which is adsorbed on the reservoir rocks. M. Dong et al carried out a study to check the feasibility of thermal recovery method to change the wettability state of reservoir rocks. Based on M. Dong et al research, it was reported that surface active components such as asphaltenes has desorbed from the surface of the reservoir rock and making it water wet and displaced the oil out from the reservoir. (M. Dong, 2010)

2.1.3 Improvement of sweep efficiency and displacement

Sweep efficiency measurement is dependent on the how effective an EOR process. The effectiveness of EOR process depends on the volume of reservoir contacted by injected fluid. The sweep efficiency is dependent on various factors which are permeability, flow rate densities differences between displaced and displacement fluid and mobility ratio. Mobility ratio is defined as the ratio between displacing fluid to the displaced fluid. The mobility of oil is known as displaced fluid and the mobility of the injectant is known as displacement fluid. High mobility ratio between the oil and the displacement fluid causes the injected fluid will finger through the reservoir and leave a huge amount of reserves in the reservoir and results in low recovery. Below is the equation used to compute mobility ratio. (Glossary, 2013)

$$M = \frac{k_{rw}}{k_{ro}} \frac{\mu_w}{\mu_o} \quad [1]$$

where k_{rw} is the relative permeability of water, k_{ro} is the relative permeability of oil, μ_w is the viscosity of water and μ_o is the viscosity of oil. Chang et al mentioned that increment in viscosity of aqueous phase and reduction in mobility ratio is able to lead a better mobility control. (Chang, 2011) J.Wang et al carried out a research by changing viscosity from 1cp to 4pcp of the brine solution in the application of partially hydrolyzed polyacramides in enhanced oil recovery using core flooding method. The change in brine viscosity causes the 14% of ROIP is being recovered. (J. Wang, 2007) Samanta et al mentioned that another factor that should be considered is that after water flooding, there will be a large viscous force that is perpendicular to the oil-wet interface to push the residual oil. . (A. Samanta, 2011)

2.2 Application of nanotechnology in EOR

There are many producing regions in the world that have reached to a critical stage where the total rate of production is reaching the declining stage. Besides that, abandoned of older and larger field have more than 50% original oil in place (OOIP) is remained unrecovered. This situation creates a challenge for oil and gas industry to find way on how to extract oil economically and to delay abandonment. (A.J.P. Fletcher, 2010) So therefore, oil and gas industry decided to implement nanotechnology in EOR in order to recover more unconventional oil from the reservoir.

Nanotechnology is defined as a field of applied science and technology which controls the matter of atomic and molecular scale, usually 100 nanometers or smaller. Xiang ling et al mentioned that this field has changed our perspective in scientific aspects by leading development of enhanced enabling tools, devices and materials which has features that cannot be compared to conventional technologies (Xiangling Kong, 2010) Tippee et al mentioned in his research that an extensive application of nanotechnology in oil and gas is expected because research on nanotechnology is being carried out extensively in oil and gas industry. It is expected that application of nanotechnology in EOR may increase the global recovery factor of oil and gas by 10%. (Tippee, 2009)

N.A Ogolo carried out a research on how nanoparticles oxide can affect the oil recovery. Research was carried out by conducting EOR experiment under surface conditions using several types of nanoparticles. From this research, it was found out that Aluminium Oxide and Silicon Oxide is good for oil recovery as Aluminium Oxide is able to reduce oil viscosity and Silicon Oxide is able to alter the rock wettability. Morever, since Silicon oxide is dispersed in ethanol, the interfacial tension between oil and water is reduced because ethanol acts as a surfactant. The reduction in oil viscosity due to nanofluid will directly increase the oil recovery because the viscosity of the nanofluid (displacing fluid) in the reservoir will be higher than the viscosity of the oil (displaced fluid). As viscosity is defined as the resistance of the fluid to flow, displacing fluid having less viscosity is easily displace by displaced fluid which has higher viscosity. The alteration of the displaced fluid and displacing fluid viscosity can improve the mobility ratio which indirectly can enhance the sweep efficiency of the displacing fluid. (N.A Ogolo, 2012) According to a laboratory test, the viscosity of CO_2 is increased by adding 1 % of CuO nanoparticles only. This causes the viscosity of CO_2 is 140 times higher than conventional CO_2 (Shah, 2009) A favorable mobility and sweep efficiency can be achieved when nanoparticles are being dispersed in CO_2 fluids which lead to higher oil recovery. The surface to volume ratio of nanoparticles is 1000 times higher than the microparticles. (Burgard,2011) Nanoparticles tend to coalescent to each other in order to become stabilize due to unsaturated daggling bonds. This causes their specific surface area, surface coalesce energy and surface energy increases immediately which provokes the nanoparticles to exhibit high chemical activity and strong ability of absorption. It was reported that nanoparticles injection into the oil reservoir can change the rheology, mobility, wettability and other properties of the fluid (El-Amin 2013). Nanoparticles are able to increase the properties of base fluid such as viscosity, thermal conductivity, density and specific heat.(Zhang, 2010) Nanofluid is formed by dispersing nanoparticles into fluid to strengthen the properties of the dispersing medium. Nanoparticles that is used to form nanofluid is preferably to be inorganic to avoid any dissolution and aggregation of nanoparticles mechanism to take place in the liquid environment. Nanofluids are designed to be environmentally friendly and compatible to reservoir fluids.(Xiangling 2010) Table 2 shows how nanofluid is able to fulfill oil and gas industrial needs to recover more oil from the reservoir.

Table 2 : Benefits of nanofluid injection into the reservoir.(Xiangling ,2010)

	Benefits of nanofluid injection into the reservoir
Nanofluid	It is an environmentally friendly solution
	It is able to improve production rates
	It is usable and reversible
	It is able to enhance oil recovery by increasing the fluid viscosity
	It can reverse and control the making or breaking of emulsion in the reservoir.

Nanofluid can influence the interfacial tension between crude oil and fluid in the reservoir. Interfacial tension is defined as interfacial forces between two liquid phases. Nanofluid is able to increase oil recovery by reducing the interfacial tension between oil and brine/nanofluids. The higher concentration of nanofluid also could contribute to higher disjoining pressure which causes more oil to be produced from the reservoir. When the interfacial tension decreases, the curve of oil-water relative permeability system will be more straight lines. So therefore, it will be easier for the oil to move out since the friction force between water-phase and oil-phase also reduced. . (Luky Hendraningrat, 2012)

The disjoining pressure theory is the ability of the fluid to spread along the surface of a substrate. The spreading occurs due to the imbalance of the forces between the surface, oil phase and aqueous phase. The nanoparticles that present in these three phase contact region tend to form a wedge-like structure and push themselves between the discontinuous phase and substrate. Particles that are present in the nanofluid exert pressure forcing the particle in the confined region forward, conveying the disjoining pressure force. The energy that drive this mechanism are Brownian motion and electrostatic repulsion between particles. The electric repulsion between those particles will be larger when the nanoparticle size is smaller. When the concentration of nanoparticles increases, the forces will increase as well. (Luky Hendraningrat, 2012)

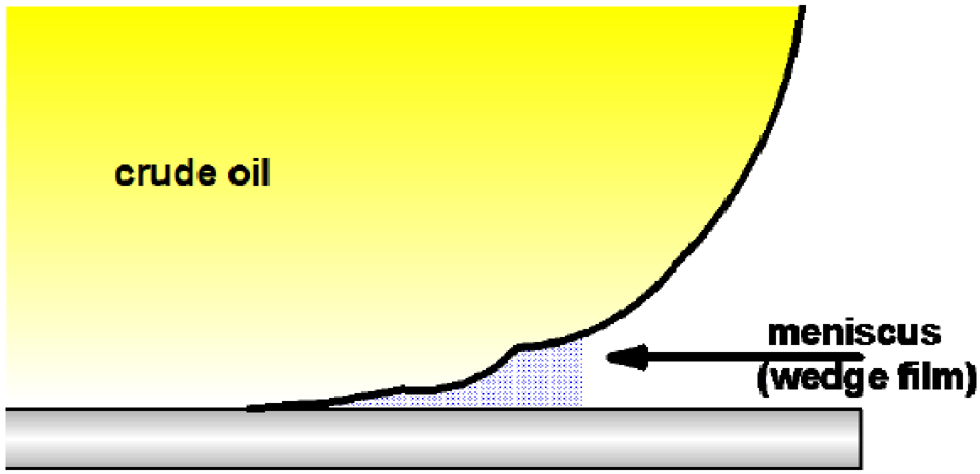


Figure 11 : Oil drop placed on a solid surface (Luky Hendraningrat, 2012)

Nanoparticles with surfactants enable a nanofluid to act as wetting agents and surface tension reducers at the very smallest contact angles which greatly enhances the removal of oil from the substrate water wet. (Paul McElfresh, 2012)

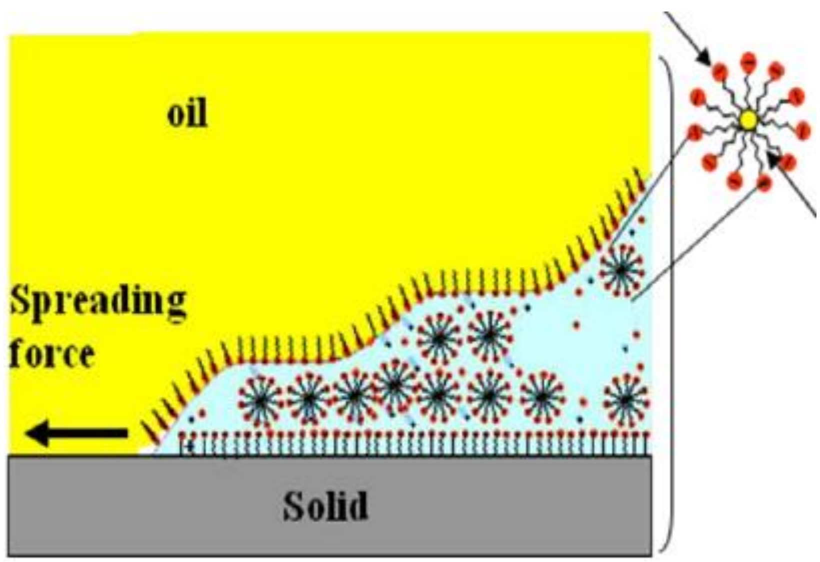


Figure 12 : Nanoparticles structuring in the wedge-like film, resulting in structural disjoining pressure at the wedge vertex (Paul McElfresh, 2012)

Many researchers have carried out research and experiment using nanofluid to prove that application of nanofluid in EOR is able to further increase oil recovery by extracting out the residual oil in place from an oil reservoir. Shah et al conducted a core flooding experiment to recover heavy oil by injecting in Carbon Dioxide nanofluid. The experimental result shows that injection of CO2 nanofluid into the porous medium allows 71.30% of heavy oil to be recovered which is 13.3% higher than the conventional CO_2 core flooding result. (Shah, 2009)

Researches also tend to manipulate several physical and chemical properties of nanoparticles in order to test the efficiency of nanoparticles itself so that it can be transported the best in the porous medium to recover oil from the oil reservoir in the form of nanofluid. Several factors that should be considered in order to choose suitable nanoparticles to be injected into the reservoir are nanoparticle size, surface charge of nanoparticles, and the shape of the nanoparticles itself. Mohammed Alaskar et al carried out a study to investigate the effect of particle size, shape and surface charge on their transport through porous medium. The effect of nanoparticle shapes on recovery was explored through the injection of silver nanowires into the porous medium while surface charge was studied by injecting uncoated and PVP coated hematite nanorice into the porous medium. The effect of nanoparticle size on recovery is also tested by injecting tin-bismuth alloy nanoparticles into the porous medium in various sizes. Below is the outcome of the three experiments being carried out to test the effect of nanoparticle size, shape and surface charge on oil recovery. (Mohammed Alaskar, 2011)

Table 3 : The effect of shape, surface charge and particle size on permeability

(Mohammed Alaskar, 2011)

Nanoparticle properties	Outcome of the experiments
Shape	Silver nanowires which are a rod-like type of nanoparticles were trapped in the porous medium and could not flow out from the porous medium and causes reduction in permeability by 45%. The spherical shape of silver nanoparticles able to flow out with a recovery of 25%. It is concluded that spherical shaped nanoparticles have contributes to better recovery compared to rod-like nanoparticles.
Surface charge	Hematite Nanorice were trapped in the porous medium due to incompatibility of surface charge nanoparticles itself with the porous medium while 23% of injected nanorice were recovered when Hematite Nanorice coated with surfactant being injected into the porous medium. It is concluded that the affinity of the nanoparticle in the porous medium is dependent on the surface charge of the nanoparticle itself.
Particle Size	It was found out that there is reduction in permeability by 56% compared to original value because larger Tin Bismuth nanoparticles causes direct plugging of the pore space while high concentration of smaller nanoparticles causes bridging and plugging across the pore throat. This study shows there is an optimum size of nanoparticles that should be injected into the porous medium.

Injection of nanofluid into the reservoir which consists of rod-like nanoparticles and nanoparticle size which is way smaller or larger than the pore throat of the reservoir can cause nanoparticle retention mechanism to occur in the reservoir. This mechanism can directly cause reduction in permeability in the reservoir. Table 4 shows three types of mechanism that occurs in the reservoir which directly leads to nanoparticle retention.

Table 4 : Three mechanism that causes permeability reduction

Type of mechanism	Explanation of the mechanism	Reference
Adsorption of nanoparticles on rock surface	This mechanism occurs due to Brownian motion and electrostatic interaction between the transported particles and solid surface of the pores.	(Gao, 2007)
Mechanical entrapment / straining	This mechanism leads to blocking of narrow pore throats by larger size nanoparticles.	(Skauge,2010)
Log jamming	This mechanism is similar to mechanical entrapment but the difference is that nanoparticles can block the pore throats which are larger than the nanoparticle size itself. This mechanism occurs due to the density difference between the carrier fluid and the migrating particles in reservoir will form sediments and settle down in the pore throat due to gravity.	(S. Bolantaba, 2009)

The blockage that occurs in the porous medium due to these three types of mechanism can damage the reservoir and causes in permeability reduction. The flow rate of the nanofluid will increase when the pore throat decreases. This causes the water molecules of the nanofluid to flow faster than the nanoparticles in the nanofluid which causes the accumulation of nanoparticles to occur in the porous medium. The main factors of nanofluid that have great influence on permeability reduction are nanoparticle concentration, flow rate of nanofluid, nanofluid viscosity and pH value of nanofluid. Some researchers carried out experiment to prove that nanofluid can cause permeability reduction in the porous medium. A research was carried out to study the transport behavior of nanoparticles in the porous medium. After injecting silica nanoparticles into a dolomite porous medium, it was found out that the porous medium were plugged and blocked by the silica nanoparticle itself. This causes the pressure of the porous medium to increase and the permeability of the core to be low. It was reported that Magnesium Oxide (MgO) and Zinc Oxide ZnO nanoparticles can cause reduction in permeability by blocking the pore spaces in the porous medium when an extensive study on the effect of nanoparticles oxides on oil recovery was being carried out. It was observed in this study that ZnO agglomerates to form larger particles when zinc oxide nanofluid is being injected into the porous medium. The EOR produced due to MgO nanofluid injection into the porous medium is very low which is only 1.7% of recovery oil in place (ROIP) that is being extracted out from the porous medium.

Nanoparticles can stabilize emulsion that occurs in the reservoir. Emulsion that is stabilized by solid stabilizers such as colloidal particles is known as Pickering emulsions. Pickering emulsion is defined as the coalescence of the droplets is suppressed when solid particle adsorbed at oil-water interface. Bragg et al reported that oil can be recovered from the reservoir by injecting undissolved solid particles to form Pickering emulsion in the reservoir. (Bragg, 2010) This is because partially stabilized emulsion can be used as a driving force to extract the oil out from the porous medium. Colloidal particles are not suitable to be used to recover oil from the reservoir because colloidal particles are in size of micron can easily be trapped in the pore throats of the reservoir. So therefore, nanoparticles are used to recover more oil from the reservoir through emulsion because they are in the solid form and their magnitude is smaller than colloidal particles. Nanoparticle stabilized emulsion is able to travel through small pore throats, and flow through the reservoir rocks without any retention and ensures the stabilized emulsion to withstand harsh condition. (Kokal,2009)

Nanoparticle stabilizes the emulsion by being attach irreversibly to the oil-water interface and form a rigid nanoparticle monolayer of the droplet layer. The formation of rigid nanoparticle monolayer on the droplet induces highly stabilized emulsion. Bink et al mentioned that nanoparticles with different wettabilities may stabilize different types of emulsions. Nanoparticles that hydrophilic is able to stabilize oil in water (o/w) emulsion while hydrophobic nanoparticles are able to stabilize water in oil (w/o) emulsion. (Min Sheng ,2009)

The presence of nanoagents in the reservoir formation is able to alter the wettability of reservoir rocks into ideal state which can improve recovery. There are three kinds of nanoparticles that can be used to alter the wettability of reservoir rocks which are hydrophilic, hydrophobic and neutral. Hydrophilic nanoparticles is able to alter the wettability of water wet rock to oil wet rock or make an already oil wet rock to strongly oil wet rock. Hydrophobic nanoparticles is able to alter the wettability of oil wet rock to water wet rock or water wet rock to strongly water wet rock. Neutral nanoparticles can alter the wettability of a reservoir rock into an intermediate state. For optimal distribution of nanoparticles in the reservoir, concentration and particle size are important factor that need to be considered.

Vafaei et al carried out a research about nanoparticles wettability by observing the effect of nanoparticles on sessile droplet contact angle. The result of this research shows that size of nanoparticle and concentration plays important role in the variation of the droplet contact angle.

Table 5 shows the application of nanoparticles in enhanced oil recovery.

Table 5 : Application of nanoparticles in EOR

Nanoparticles type and carrier	Mechanism	Results	Reference
Hydrophilic Silica Nanoparticles, called HNP-A and HNP- B being dispersed in synthetic brine	Reducing interfacial tension	Higher concentration of nanofluids gives lower IFT which indicates potential candidates for EOR	(Luky Hendraningrat, 2012)
Lipophobic and hydrophilic nanoparticle (LHP) being dispersed in Synthethic brine and deionized water	Reducing interfacial tension	When the concentration of nanofluid increases, the lower the IFT	(Luky Hendraningrat, 2012) (Caetano Rodrigues Miranda, 2012)
Three different polysilicon nanoparticles a) Lipophobic and hydrophilic PSNP (LHPN) b) Hydrophobic and Lipophilic PSNP (HLPN) c) Neutrally wet PSNP (NWPN) NWPN and LHPN was dispersed in ethanol and LHPN in deionized water	Changing rock wettability to an ideal state that can improve recovery Reduction of interfacial tension	LHPN is not a good agent for EOR in a water wet rock. The complimentary effects of NWPN and HLPN with Ethanol which acts as a good surfactant, reduces IFT between oil and water and improves oil recovery efficiency. Hence NWPN and HLPN should be used for EOR purpose in water wet formation and LHPN should be used only in oil wet formations. 38.8% of more oil are recovered.	(Mike O. Onyekonwu, 2010)
Nanosilica dispersed in 5000 ppm with 2% NaCI	To study transport behavior of nanosilica particles in three	Sandstone : nanoparticles can easily pass through without changing the core permeability Limestone : Small adsorption	(Jianjia Yu, 2012)

	different porous media which are sandstone, limestone and dolomite	occurs when nanoparticles flooded the limestone Dolomite : Highest particle recovery was obtained.	
Silica Nanoparticles dispersed in brine	Stability and mobility of the nanoparticles at high temperature and high salt concentration	The mobility of nanoparticles will increase as the salinity increases.	(Caetano Rodrigues Miranda, 2012)
Hydrophobic and Lipophilic Polysilicon (HLPN) dispersed in ethanol	Reduction in interfacial tension Wettability alteration	HLP able to alter the rock wettability from strongly water wet rock to less water wet rock and reduces interfacial tension between oil and water. HLP able to increase oil recovery	(Abbas Shahrabdi, 2012)
Zinc Oxide (ZnO) Aluminium Oxide (Al2 O3)	Improvement id sweep efficiency by increase in viscosity	Al_2O_3 gives the highest recovery of 50% ROIP with EM irradiation	(Rasyada, 2012)
Cobalt Ferrite ($CoFe_2O_4$)	Reduction in oil viscosity by absorption of EM wave using nanoparticles	Cobalt Ferrite gives the highest recovery of 31.58% ROIP under presence of EM wave compared to 8.70% when it was used as nanofluid alone	(Noorhana,2012)

2.3 Carbon Nanotubes

Carbon Nanotubes or also known as CNT is a graphitic sheet which consists of carbon atoms which are covalently bonded in a hexagonal type arrangement. The sheet rolled up into a cylindrical form with its end closed by hemispherical graphitic domes. CNT is well known for its extraordinary structural, electrical, and mechanical properties which are derived from their unique 1 D structure.(Yacobson,1997) CNT is being viewed as a remarkable material by the physicists because it allows the exploration and application of quantum effects. The mechanical (stiffness, strength, and toughness (S.K. Srivastava, 2008), thermal (heat dissipation) (S. Xie, 2000) and electrical (conductor and semi-conductor) (J.J. Taber, 1997) properties of CNT enable various potential applications from batteries and fuel cells, fibers and cables to pharmaceuticals and bio-medical materials. In terms of electric, the electron flow through CNT is 10 times faster than the function in CPUs silicon circuit. CNT are suitable to be used as electron field emitters due to their perfection in structure, high electric conductivity CNT consists of multi-walled nanotubes (MWNT) and single walled nanotube (SWNT). (Ganesh, 2013) They differ from each other in terms of their grapheme cylindrical arrangement. SWNT have only one layer of graphical cylinder layer while MWNT have multiple layers.

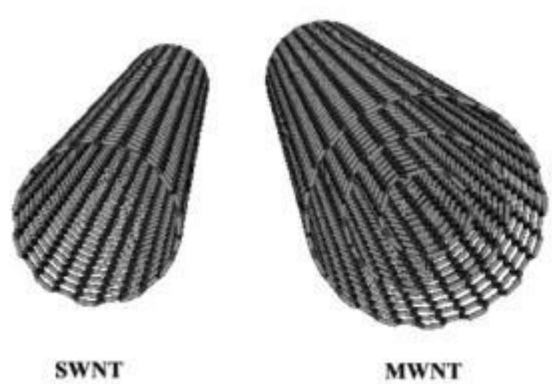


Figure 13 : Example of single wall and multiwall Carbon nanotubes

Due to its remarkable properties, CNT are proposed to be potentially used in oil and gas industry for EOR purposes. Below are the examples of CNT image under X-Ray Diffraction, FESEM and HRTEM.

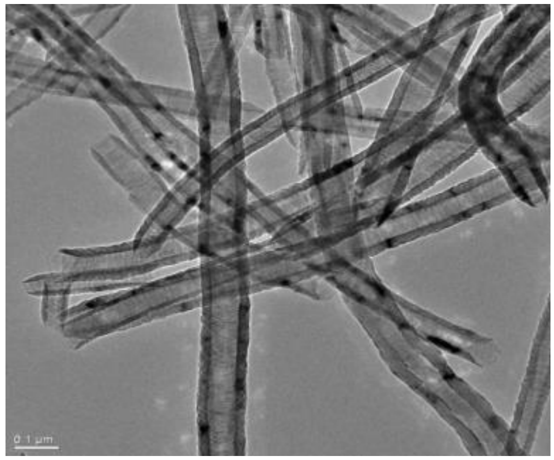


Figure 14 :Image of CNT using FESEM

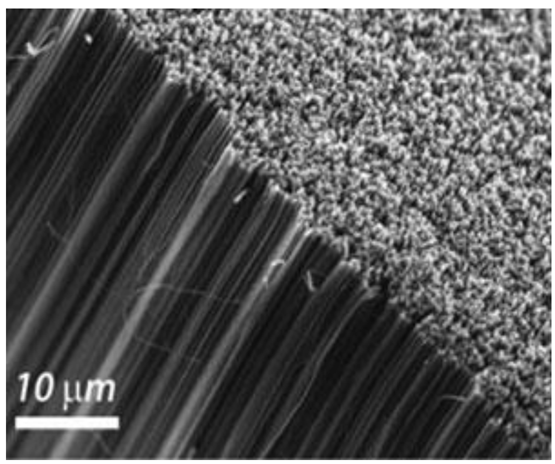


Figure 15 : Image of CNT using TEM

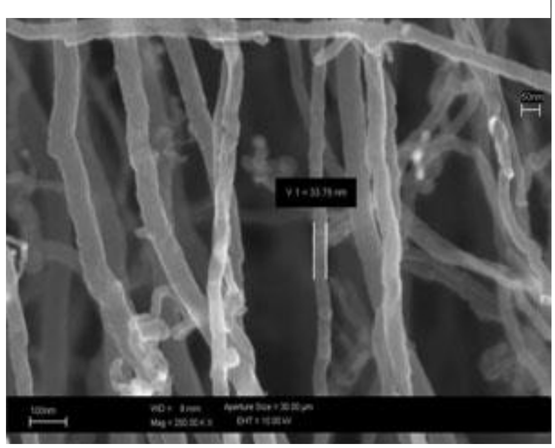


Figure 16 : Image of CNT using XRD

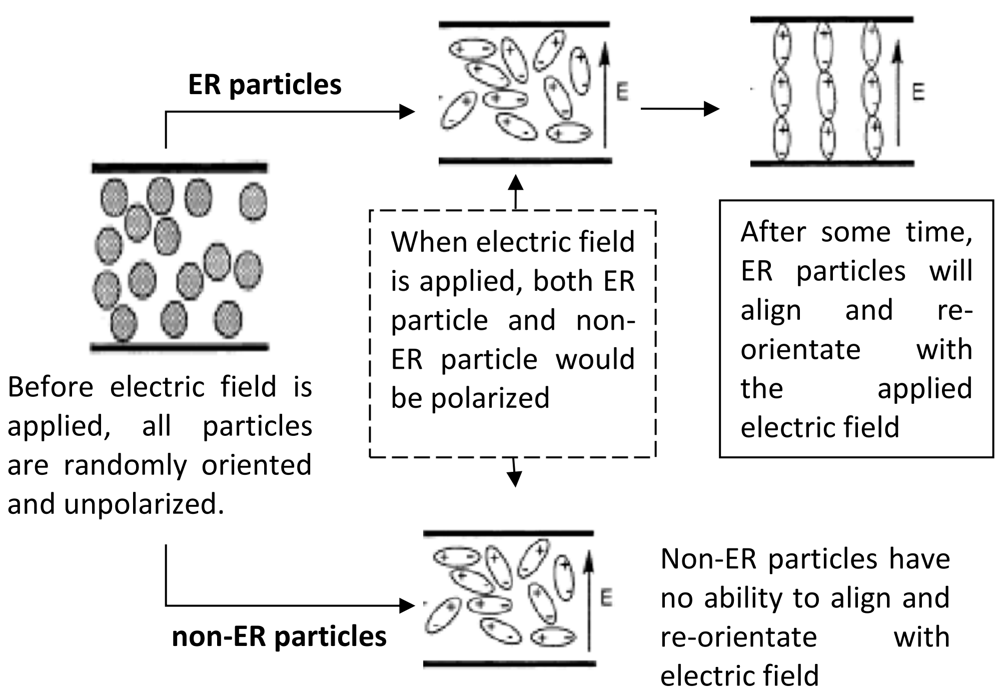
2.4 Use of Electromagnetic Wave in EOR

Electromagnetic wave is defined as wavy disturbances that repeat itself over a distance which is known as wavelength. Many researches have been carried out theoretically and experimentally to study the use of electromagnetic wave in enhanced oil recovery. Bridges et al. had carried an experiment by developing a model for electromagnetic heating of single well (J.E. Bridges, 1985). In this model, when electromagnetic source was considered as constant variable with time, it was reported that there is an increment in oil production rate by 25% compared to initial production. As for the involvement of electromagnetic wave frequency in recovering oil form reservoir, Stretsy et al carried out an experiment by applying radio frequency electromagnetic wave in both laboratory and field for bitumen recovery from tar and sand deposits. The outcome of the experimental work shows that 80% of bitumen recovered. This process was shows to be economical and energy efficient. (G.C.Stretsy, 1986) Chakma et al developed a model using the combination of electromagnetic wave and gas injection to recover oil from thin pay zones. It was observed from the experiment that minimum heat loss occurred when electromagnetic wave was confined in oil bearing zone. This experiment shows that salinity, temperature, pressure, oil viscosity and frequency does influence oil recovery. Hence it was concluded from this experiment that 45% of oil recovery was obtained when electromagnetic wave with gas injection was applied at the model. (A. Chakma, 2010).

Electromagnetic wave can be used to recover oil from the reservoir using two techniques which are high frequency and low frequency electromagnetic wave emission. High frequency is known as radio and microwave while low frequency is known as resistive heating. The oil mobility in the reservoir can be increased when electrical energy from the electromagnetic wave is transferred through dielectric and resistive materials in the form of heat. Material properties play an important as it can influence the amount of heat being absorbed by the material when being placed under high frequency. Electromagnetic wave can cause change in dipole alignment of the molecules. This phenomenon can cause heat to be produced which can heat the surrounding environment.

When electrical is in low frequency, electromagnetic wave causes resistive heating to take place and power dissipation becomes P=I2R. (Noorhana Yahya, 2012)

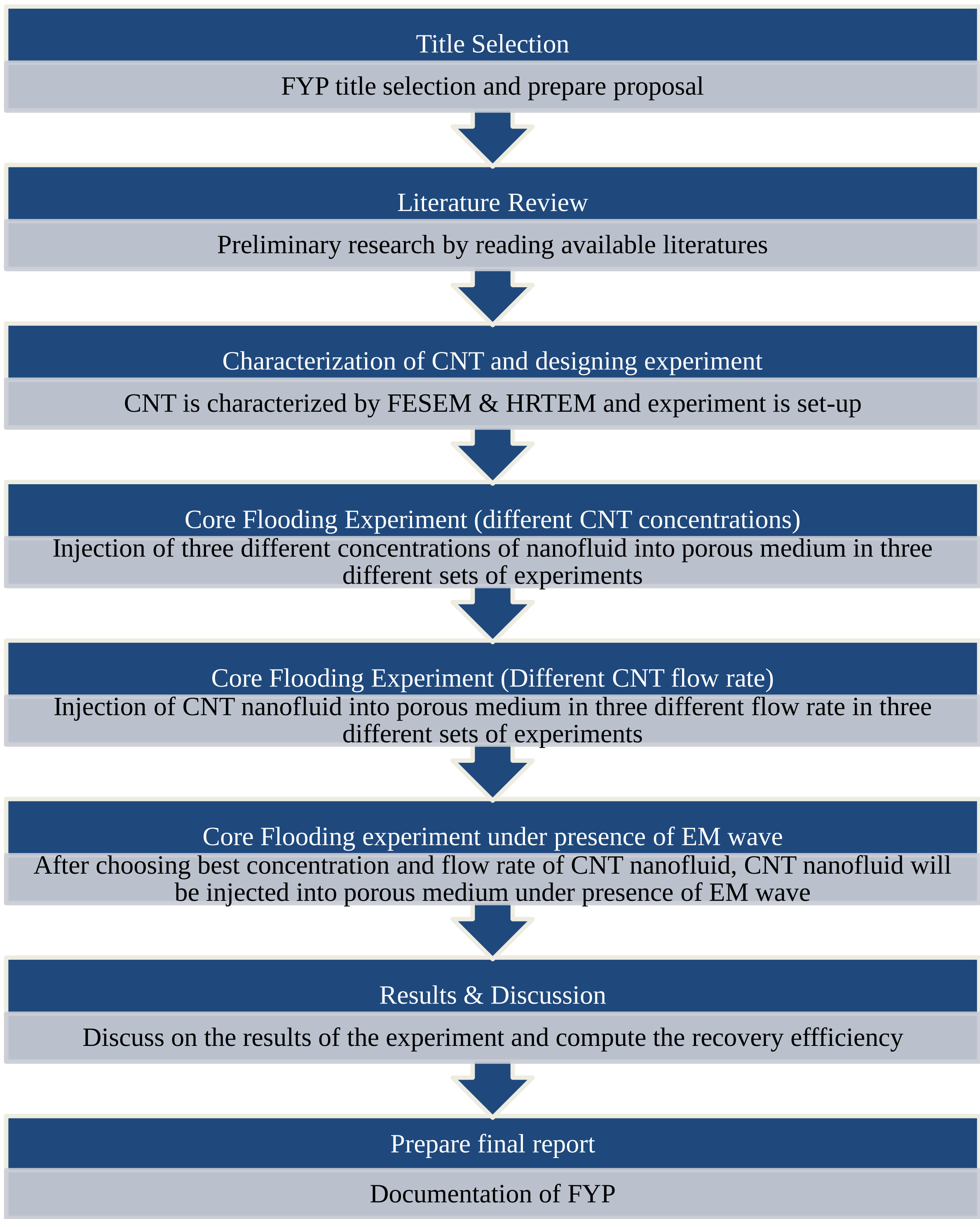
An experiment was carried out by using Cobalt Ferrite nanofluid to improve oil recovery. From the experiment, the injection of Cobalt Ferrite nanolfuid into the porous medium under the presence of electromagnetic wave is able to yield higher recovery of ROIP which is 31.85% as compared to 8.70% by using nanofluid alone. It was investigated that due to the absorption of electromagnetic waves by Cobalt Ferrite nanoparticles, the oil viscosity reduces and induces the increment in oil recovery from the porous medium. (Noorhana Yahya, 2012) R On the other side, Rasyada et al had carried put an experiment by using Aluminium Oxide nanofluid to improve oil recovery. The injection of Aluminium Oxide nanofluid into the porous medium under the presence of electromagnetic wave causes 54.2% of ROIP is being recovered from the porous medium. The injection of Aluminium Oxide under the presence of electromagnetic wave increases the amount oil recovered from the porous medium by 5.12% more as compared to Aluminium Oxide nanofluid alone which is only 32.88%. It was investigated that there is change in viscosity of dielectric nanofluids when nanofluids is injected into the reservoir under the presence of electromagnetic wave. Besides that the sweep efficiency was also improved and results in higher oil recovery. (Rasyada, 2012)



CHAPTER 3

3. METHODOLOGY

3.1 Research Methodology



3.1.1 Characterization of Carbon Nanotubes

The microstructural of CNT is being analyzed by using analytical equipment that is available in UTP. Carbon Nanotubes is characterized using Field Emission Electron Scanning Microscopy (FESEM) and High Resolution Transmission Microscopic (HRTEM) to identify the surface morphology and crystallographic of the CNT sample.

3.1.1.1 Characterization of CNT using FESEM

When CNT is being characterized using FESEM, the electron beam will interact with CNT sample and generates important information about the CNT sample such as composition, size features, morphology, crystalline structure and texture. FESEM is conducted by using equipment called Supra 55VP Variable Pressure Field Emission Scanning Electrons Microcope. This equipment works by using electrons instead of protons. This equipment operation is depends on low sum energy is produced by secondary electron. Secondary electrons are produced at the primary electrons' impact point of the beam. This beam is intercepted by weak electrical field that is emitted at the surface of the sample. Later, the electrons will be accelerated by the electrostatic lens field. These electrons will be focused to high energy using the annular in-lens detector which is located inside the beam booster, above the objective lens. Electron microscope comprises of many advantages compared to light microscope in terms of resolution and magnification. For example, electron microscope can resolve nanometer scale measurement of objects while for light microscope, the magnification range is about 1000 and its resolution is about 200nm.

Figure 17: Supra 55VP Zeiss Variable Pressure Field Emission Scanning

3.1.1.2 Characterization of CNT using HRTEM

Characterization of CNT using High Resolution Transmission Electron Microscope helps to generate information on nanostructure and micro-texture of electron-transparent specimens. High quality and detailed image is obtained when electrons are required to move fast which will create shorter wavelength. The movement of the electrons can be increased by increasing the speed of electron during transmission stage to correlate with electron wavelength. When the number of electrons that pass through the specimen is less, the formation of the image will appear darker at that particular area, while brighter areas shows the less dense areas of the specimen. Different information on the physical properties of the specimen can be extracted using this equipment depending on the brightness of the specimen such as shape, structure, and texture. The CNT sample needs to be sliced in a thin layer so that it will allow electrons to pass through the sample to obtain TEM analysis which is electron transparency. There are several procedures need to be done in order to produce a thin layer of the sample. First, a few miligrams of nanoparticles need to be dispersed in 2-Propanol and then sonicated for about an hour. Later, the mixture will be allowed to settle for an hour under room temperature. After settling down, the formation of two layers which consists of sediments and clear solution can be observed. A few drops of clear solution need to be dropped on Carbon-coated Copper grid surface. This copper grid will then be transferred to the chamber of TEM. As shown in the figure below. TEM that is used in this research is Zeiss Libra 200FE model which can be used to analyse at 200kV and its magnification range is from 8X to 1,000,000X.

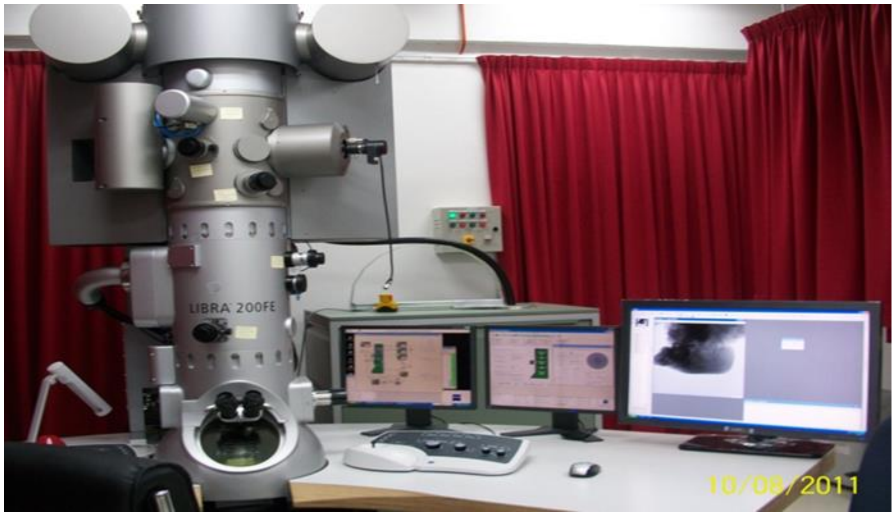


Figure 18 : Libra 200FE Zeiss Transmission Electron Microscope

3.1.2 Carbon Nanotube nanofluid preparation

Carbon Nanotubes was dispersed in distilled water which acts as the base fluid and will magnetically stirred for an hour to form a homogenous dispersion. Then, Carbon Nanotubes nanofluid undergoes ultrasonic agitation in order to break any nanotubes agglomeration and produce highly uniform dispersion. The next step of the experiment will be carrying out core flooding experiment. During core flooding experiment, firstly the impact of CNT nanofluid concentration and flow rate on permeability under the absence and presence of electromagnetic wave is studied. Then, the total recovery efficiency with and without EM wave will be calculated and compared.

3.1.3 Parameters considered in core flooding experiment

In this core flooding experiment, there are four important parameters that need to be considered.

3.1.3.1 Reservoir rock characteristics

The composition of petroleum rocks varies in many materials which are from very loose and unconsolidated sand to very hard and dense limestone, dolomite and sandstone. The grains in petroleum rocks are cemented or bonded together due to chemical properties of several materials such as silica, clay and calcite. In order to evaluate the performance of a reservoir, it is very important to understand the interaction between petroleum and reservoir formation and the knowledge of reservoir rocks and fluid properties itself. For research purpose, rock properties are analyzed using a core sample which is extracted from the reservoir. The core is extracted from the reservoir formation where its environment has subsequent changes in bulk volume, wettability of the formation and reservoir fluid saturations. These effects can cause changes of reservoir rock properties which can range from negligible to substantial in testing program. Basically, there are three classifications of the core analysis test that are performed on core sample which are porosity, permeability and fluid saturation. These three rock properties are important for reservoir engineering calculation because these rock properties directly influence the quantity and distribution of petroleum.

3.1.3.2 Permeability

Permeability is being referred as the ability of the fluid to be transmitted through a formation. K, which is rock permeability, is the most important rock property that should be considered as this property controls the direction and flow rate of reservoir fluids in the formation. An equation was developed by Henry Darcy in 1856 to define permeability in terms of measurable quantities in order to express rock characterization which is being known as Darcy law. This fluid flow equation had contributed massively and became on standard mathematical tool for Petroleum Engineers. In order to apply Darcy law equation, there are several assumptions that need to be considered which are

- Core Plug should be 100% saturated with flowing fluid
- The fluid flow should be incompressible
- The fluid flow should be horizontal, steady state and under laminar regime

The equation of Darcy law is as shown below.

$$q = \frac{kA(p_1 - p_2)}{\mu L} \qquad [2]$$

Where q is the flow rate through the porous medium, cm^3/s; A is the cross-sectional area across which flow occurs, cm^2; k is the proportionality constant, or permeability, Darcy; μ is the viscosity of the flowing fluid, cp; $(p_1\text{-}p_2)$ is the differential pressure, atm and L is the length, cm. In this research, unconsolidated cores will be made of packed silica beads to be used as a porous medium, to replicate the reservoir material. A 12 cm acrylic tube, with radius 1.688 cm will be used as a column to contain glass beads mixtures. Glass beads will be filled in a PVC tube.

3.1.3.3 Porosity

Porosity is referred at the measure of storage capacity of a reservoir rock to store fluids. Porosity is also defined as the ratio of the pore volume in a reservoir to the total volume (bulk volume) and is expressed as percentage. There are three types of porosity which are absolute porosity, effective porosity and ineffective porosity. Absolute porosity is the ratio of the total void space in the reservoir rock to the bulk volume of the rock. Effective porosity is defined as the ratio of the volume of the interconnected pores to the bulk volume. Ineffective porosity is defined as the ratio of the volume of isolated disconnected pores to the bulk volume.

Effective porosity will be the focus in this experiment because, if the porosity of a rock is determined by saturating the rock sample in 100% of fluid with known density and there is increment in weight of the rock sample after being weighed, this would yield the saturating fluid could only enter the interconnected pore spaces of the rock sample. The equation of effective porosity is as shown below.

$$\varphi = \frac{\text{Interconnected Pore Volume}}{\text{Bulk Volume}} \qquad [3]$$

Where φ is the effective porosity usually expressed in term of ratio or percentage. Effective porosity value is used extensively in all reservoir engineering calculations as it represents the interconnected pore space that contains recoverable hydrocarbon fluids.

3.1.3.4 Fluid Saturation

Saturation is defined as ratio of the volume of a fluid phase in a reservoir rock to the pore volume (gas, oil, water) of the sample. This property is expressed mathematically as shown below

$$\text{Fluid Saturation} = \frac{\text{Total volume of the fluid}}{\text{Pore volume}} \qquad [4]$$

Applying the above mathematical concept of saturation to each reservoir consists of gas, oil and water only gives,

$$S_g = \frac{\text{Volume of oil}}{\text{Pore Volume}} \qquad [5]$$

$$S_o = \frac{\text{Volume of oil}}{\text{Pore Volume}} \qquad [6]$$

$$S_w = \frac{\text{Volume of water}}{\text{Pore Volume}} \qquad [7]$$

where $S_{g,}$, S_{θ} and S_w are the saturation value of the oil and water, respectively. The saturation of each individual phase ranges between zeros to 100%. By definition, the sum of the saturations is 100%, therefore,

$$S_g + S_o + S_w = 1.0 \qquad [8]$$

The fluids in most of reservoirs will become separate according to their density after reaching state of equilibrium. For example, oil will be overlain by gas and underlain by water. At the edge or bottom of the water, connate water will be distributed throughout the gas and oil zones. Connate water or also known as irreducible water saturation is defined as minimum water saturation that is present in a porous medium. The water in this zone will be reduced into some irreducible minimum. The force that retains the water existence in oil and gas zone is known as capillary force. Connate water saturation S_{wc} is important to lessen the space between oil and gas. The connate water saturation is generally not uniformly distributed in reservoir as it varies according to lithology and permeability. There is another phase saturation of interest that should be taken into consideration which is called the critical saturation. Critical saturation is associated with each fluid in the reservoir. The definition and importance of the critical saturation of each phase are mentioned below.

a) Critical oil saturation, S_{oc}

Saturation of oil should exceed some value called critical oil saturation in order to ensure oil phase to flow. At critical oil saturation S_{oc}, the oil will remain in the pores and will not flow for all practical purposes.

b) Residual oil saturation, S_{or}

When crude oil is displaced from the porous medium by water, there will be some oil remaining left in the porous medium. This remaining oil is quantitatively characterized by saturation value which is called as residual oil saturation S_{or} is larger than critical oil saturation. Residual saturation is a term that is usually related to non-wetting phase when it being displaced by a wetting phase.

c) Critical water saturation, S_{wc}

The maximum water saturation at which the water phase will remain immobile is defined as the critical water saturation, connate water saturation, and irreducible water saturation are extensively used interchangeably.

3.1.4 Core Flooding experiment

The core flooding experiment will be carried out a 60˚C in ambient pressure. The reservoir material will be prepared by saturating glass beads by continuous injection of brine at the concentration of 30 ppm at a rate of 1 ml/min to achieve base permeability which creates a condition where the differential pressure between the inlet and outlet becomes stable. After that, Arabian heavy crude oil with the dynamic viscosity of 16.5cp will be injected into the glass beads that is saturated with glass beads at 60˚C to flush out the brine from the porous medium until oil flows out from the outlet and collected as effluent. This step is carried out to ensure that the pore spaces are saturated with oil and brine of known initial saturation.

Once the initial amount of oil that saturates the porous medium can be determined and critical water saturation, S_{wc}, is achieved, brine will be injected continuously into the porous medium with the same concentration at the flow rate of 1ml/min to carry out the secondary recovery stage. This is called as water flooding process. During secondary recovery stage is being carried out, it is estimated that 40% of initial oil in place will be displaced out during this sage before reaching residual oil saturation, S_{or}, and leaving remaining oil to be recovered in the next stage.

During the tertiary stage or also known as enhanced oil recovery (EOR) stage, 2 pore volume of CNT nanofluid will be injected into the porous medium at a rate of 1ml/min. In core flooding experiment, there were three major stages which were carried out using CNT nanofluid. These three stages of core flooding test was carried out to study the impact of CNT nanofluid concentration and flow rate on permeability under the absence and presence of electromagnetic waves and to improve oil recovery. The three stages of the core flooding experiment carried out are described as following in detailed.

a) Injection of 0.01wt% of CNT nanofluid in to the porous medium under the absence of electromagnetic wave to study the impact of concentration on permeability in porous medium and to recovery more oil from the porous medium. The experiment is repeated by injecting 0.05wt% and 0.1wt% of CNT nanofluid into the porous medium. After all three core flooding experiment is carried out, the best concentration will be chosen by observing which concentration results in the least reduction of permeability in the porous medium and contributes to higher oil recovery.

b) After choosing the best concentration of nanofluid, CNT nanofluid will be injected into the porous medium at the flow rate of 0.5ml/min under the absence of electromagnetic wave. The experiment is repeated by injecting CNT nanofluid into the porous medium at the flow rate of 1 ml/min and 2 ml/min. After all three, core flooding experiment is carried out under different flow rate, the best flow rate will be selected by observing which flow rate results in the least reduction of permeability in the porous medium and contributes to highest oil recovery.

c) After the best concentration and flow rate of CNT nanofluid is selected, CNT nanofluid will be injected into the porous medium again under the presence of electromagnetic wave at the frequency range of 13.60 Mhz square. The CNT nanofluid injection into the porous medium is stopped when critical oil saturation, S_{oc} is reached. The recovery efficiency, Er will be computed by using the ratio of volume of oil recovered in EOR stage to the oil that still trapped in the porous medium after water flooding process, (ROIP). The equation used to compute recovery efficiency as shown below.

$$E_R\ (\%ROIP) = \left(\frac{\text{Volume of oil recovered in EOR fluid injection}}{\text{Volume of Remaining Oil in Place (ROIP)}} \right) \times 100 \quad [8]$$

The gantt chart of this project is attached as attachment B.

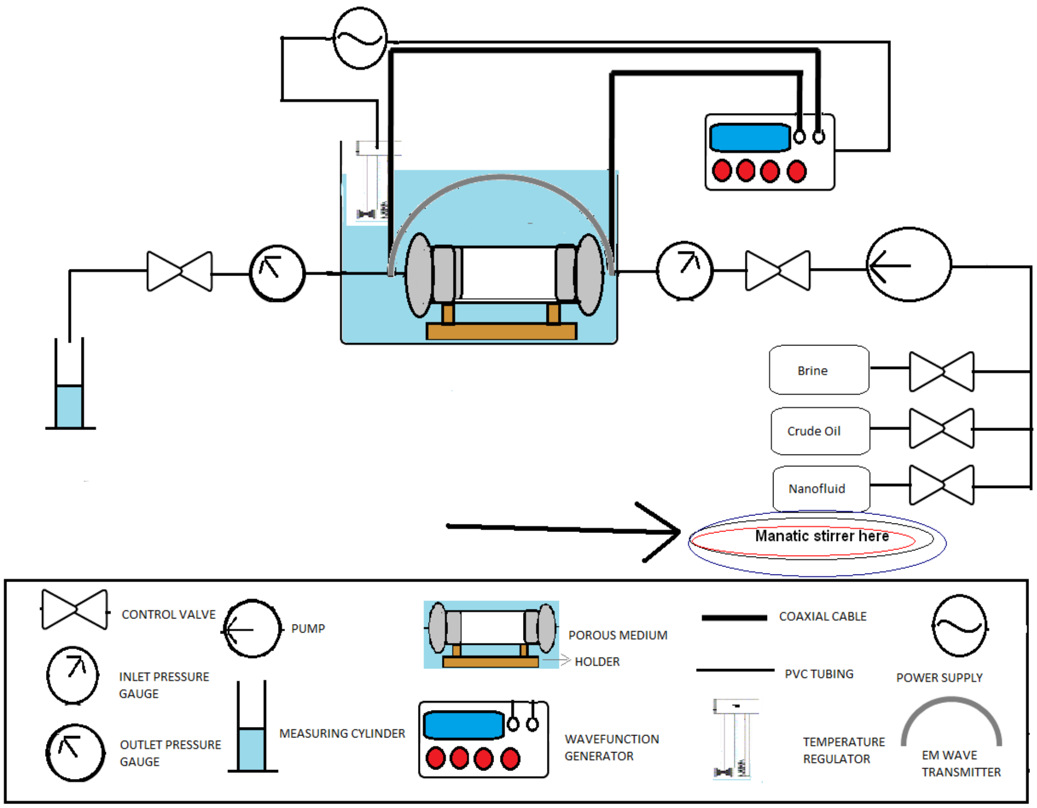


Figure 19 : Schematic diagram of core flooding experiment set up

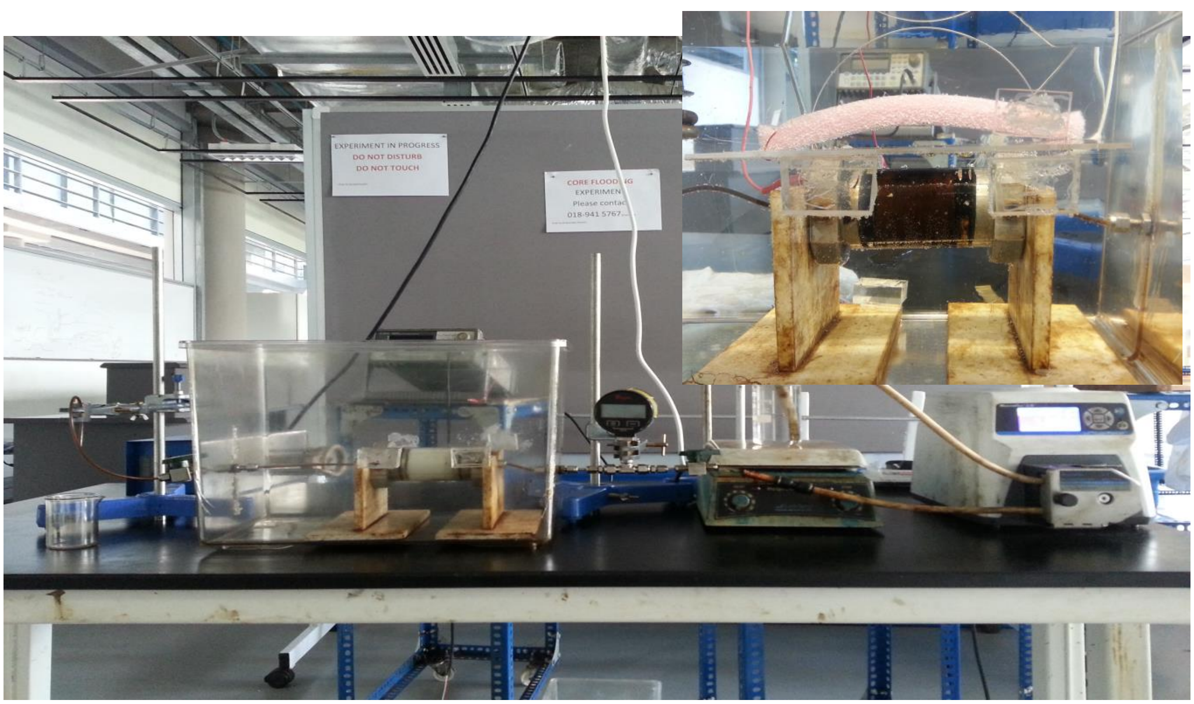


Figure 20 : Core Flooding experiment set up

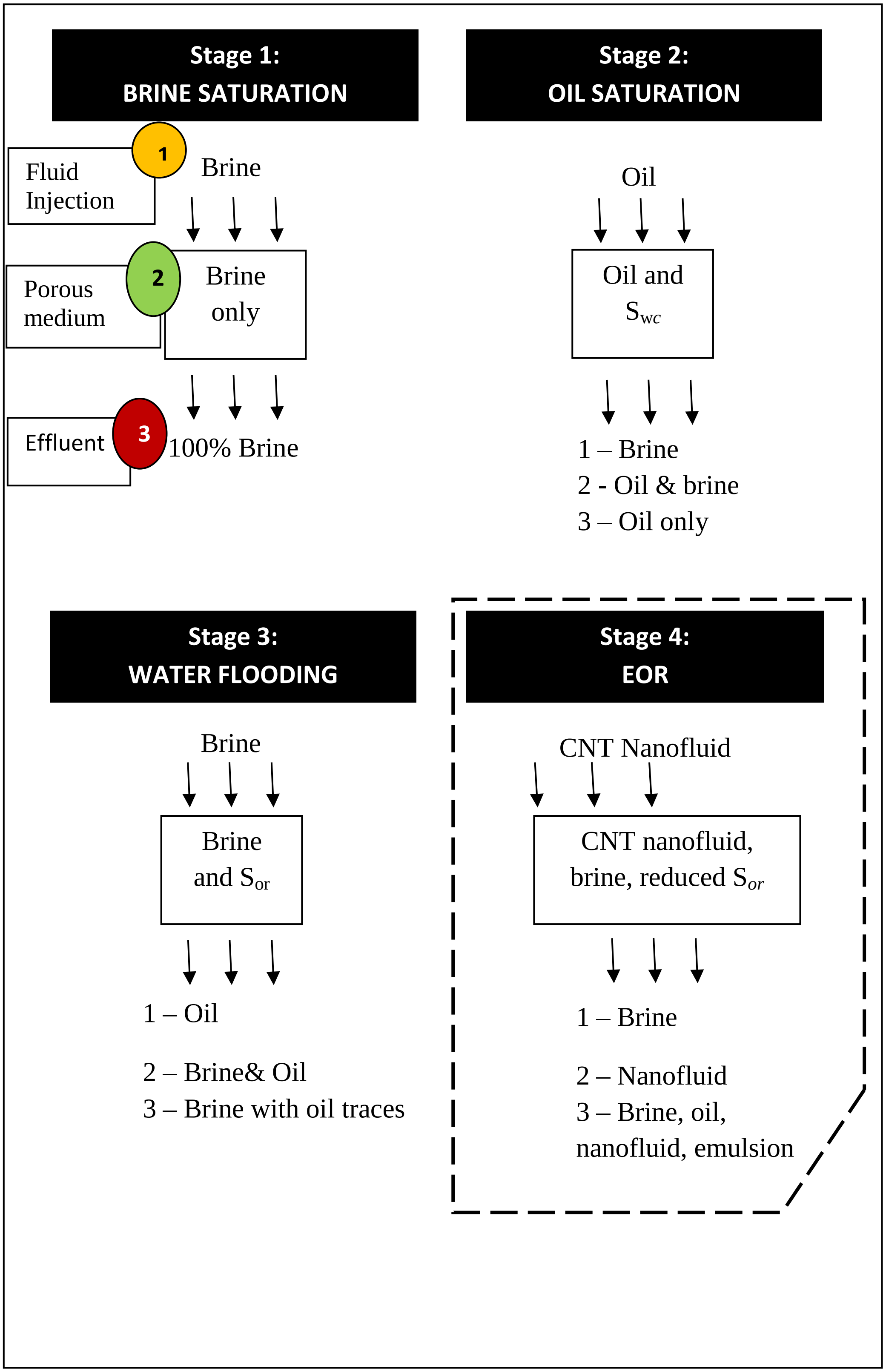
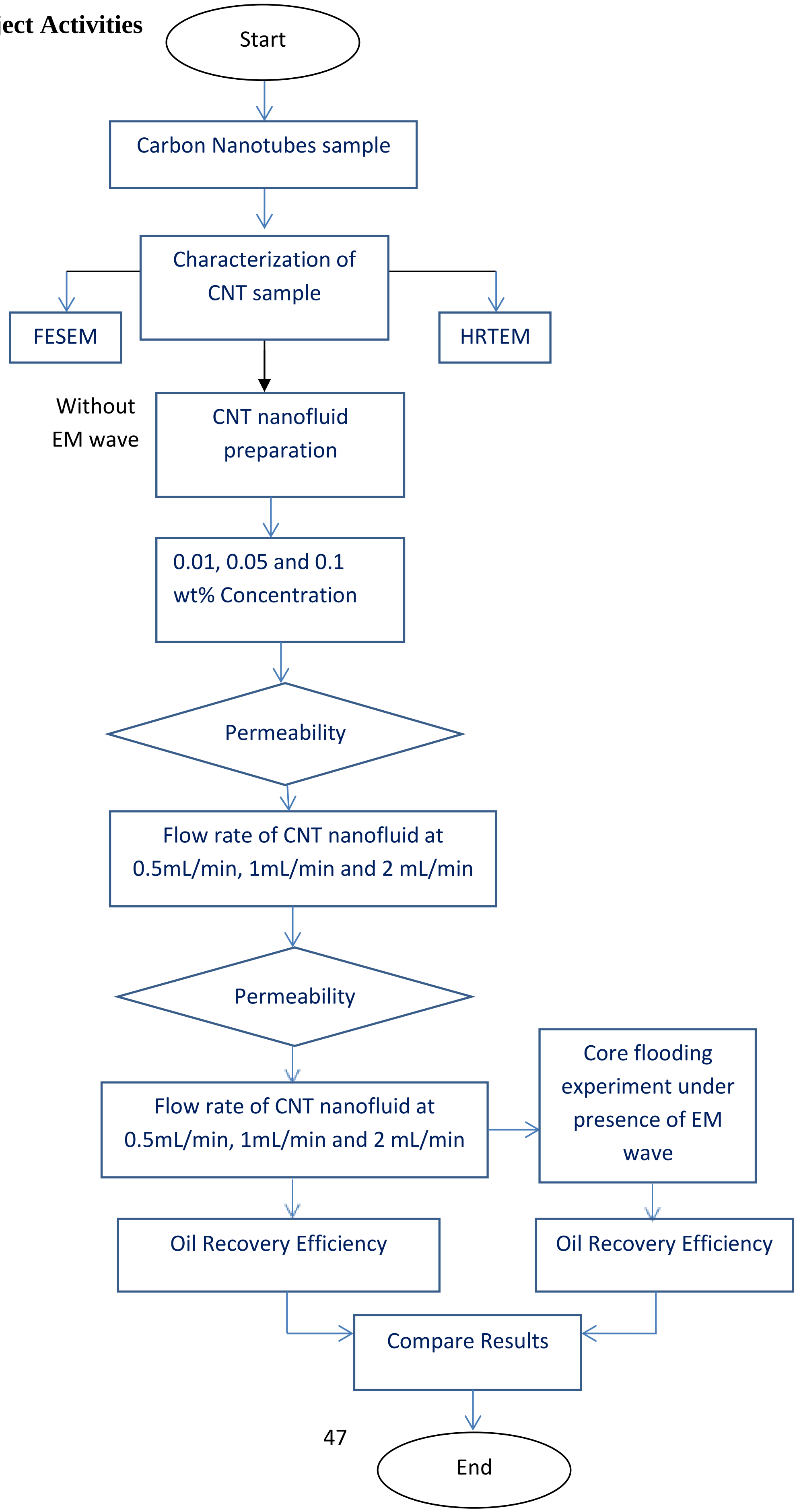


Figure 21 : Stages of core flooding carried out for each EOR fluid

3.2 Project Activities



CHAPTER 4

4. RESULTS & DISCUSSION

4.1 Characterization of Carbon Nanotubes (CNT)

Carbon Nanotubes is characterized using Field Emission Electron Microscopy (FESEM) and High Resolution Transmission Electron Microscopy (HRTEM).

4.1.1 Characterization of Carbon Nanotubes (CNT) using FESEM

CNT is characterized using FESEM to check the morphology of the CNT sample. The result of the FESEM shows that morphology of CNT is in the form of cylindrical shape. The figure below shows the images of CNT taken under FESEM.

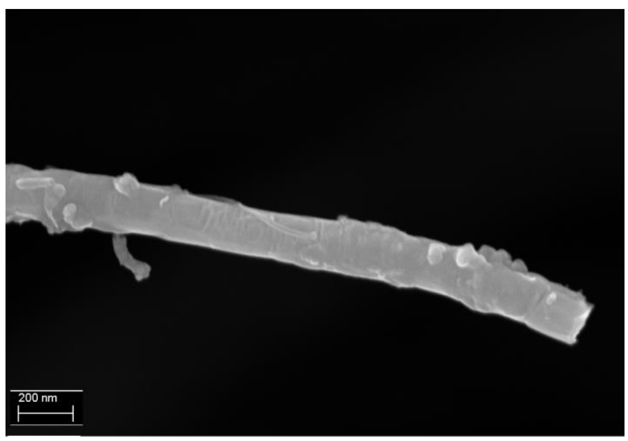


Figure 22 : Image of multiwall CNT in cylindrical form in near view

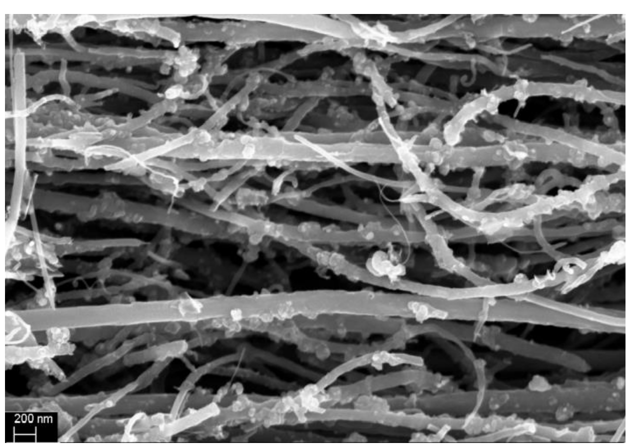


Figure 23 :Image of multiwall CNT in cylindrical form in far view

4.1.2 Characterization of CNT using HRTEM

CNT is characterized using HRTEM to check the structure or texture of the CNT sample. The result of HRTEM shows that the structure of the CNT sample that is being used in this research is multiwall CNT (MWNT).

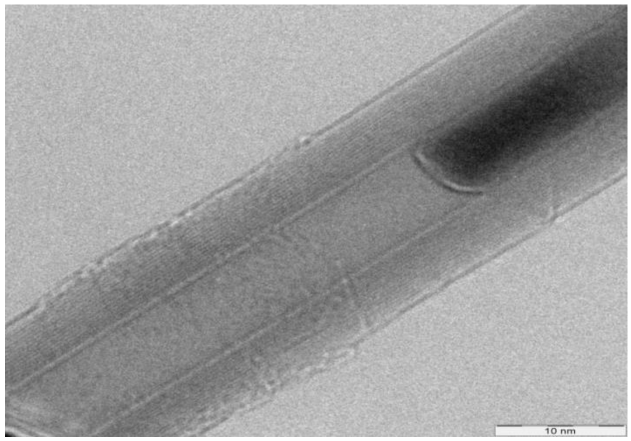


Figure 24: Image 1 of multiwall CNT

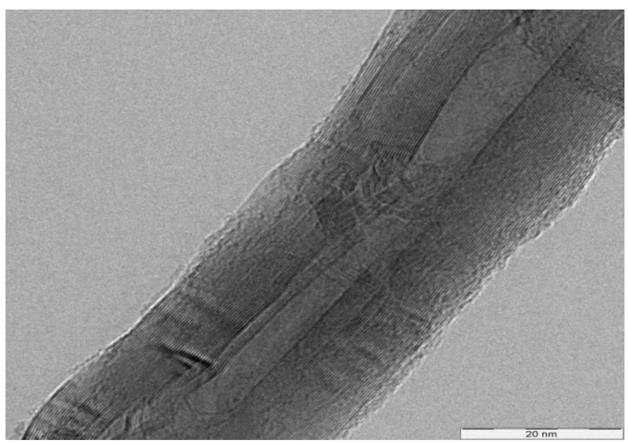


Figure 25 : Image 2 of multiwall CNT

4.2 Impact of Carbon Nanotubes (CNT) nanofluid concentration on permeability.

4.2.1 Impact of 0.01wt% of CNT nanofluid concentration on permeability

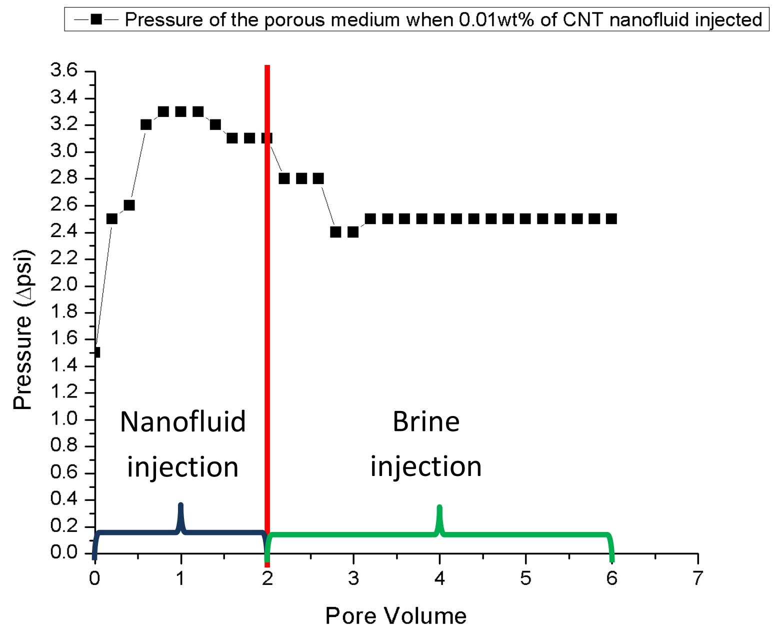


Figure 26 : Differential pressure of porous medium when 0.01wt% of MWNT nanofluid being injected

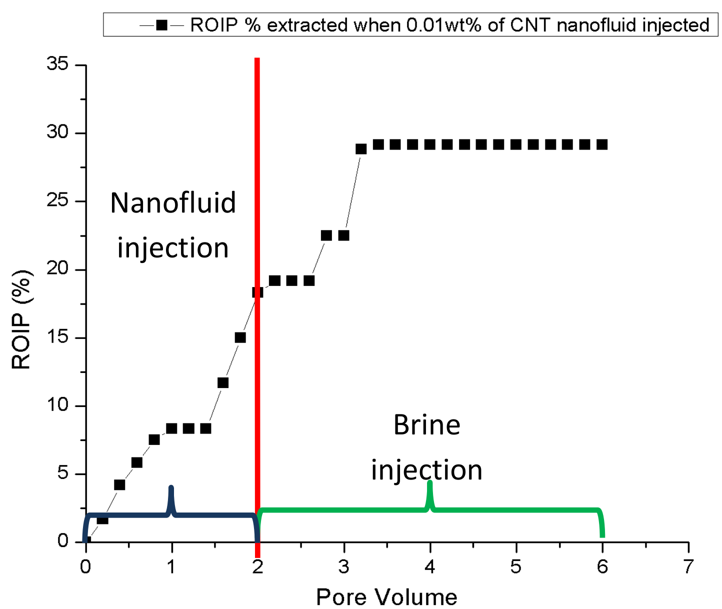


Figure 27 : ROIP extracted when 0.01wt% of CNT is being injected

Figure 26 and Figure 27 display the results of differential pressure and amount of residual oil in place is recovered when 0.01 wt % of MWNT nanofluid is being injected into the porous medium. The experimental data gathered and ROIP% calculation when 0.01wt% of MWNT is being injected into the porous medium is attached as Appendix A.1.1. The figures are divided into two regions to show when MWNT nanofluid and brine is injected into the porous medium. During core flooding experiment, MWNT is injected into the porous medium until 2 pore volume (PV). Then, brine will be injected into the porous medium until there is no more oil is being extracted out from the porous medium. The mechanism that took place in both regions when MWNT nanofluid and brine injected into the porous medium will be explained in detail to justify the reasoning of pressure changes in the porous medium and its effects on the oil recovery from the porous medium.

<u>0.01wt% of MWNT nanofluid injection into the porous medium from 0PV to 2PV</u>

From Figure 26, it is observed that the differential pressure recorded after secondary recovery was carried out is 1.5 psi. When MWNT nanofluid is being injected into the porous medium from 0PV until 0.8PV, it is observed that the pressure increases immediately to 3.3psi. The reason why the pressure increased drastically is there are possibilities that some of the channels in the porous medium are blocked by MWNT and reduces the permeability. Hence the MWNT nanofluid that is being injected continuously into the porous medium could not flow through channels starts to accumulate at the inlet and causes pressure to build up. Then the pressure remains constant at 3.3psi until 1.4 PV of MWNT nanofluid being injected into the porous medium. It is also observed in Figure 27, that there is no oil recovery from 1.2PV until 1.4PV This indicates that the blocked channels are being cleared by the MWNT nanofluid since the high pressure build up is able to break the blockage the occurs in the channel of the porous medium. However, there is no oil found after the blocked channels are cleared. Later, it is observed that the pressure drops to 3.1psi from 1.4PV until 1.6PV and pressure remains constant at 3.1 psi from 1.6PV until 2PV. This indicates that the blocked channels are cleared by the MWNT nanofluid which causes the nanofluid are able to flow through the channels to extract oil from the porous medium. Hence, this mechanism causes the pressure to decrease. The constant pressure at 3.1psi indicates that some blocked channels which contain oil is being cleared by the MWNT nanofluid and extracts more oil from the porous medium as it is observed in figure 27 that there are oil being recovered from the porous medium from 1.6PV until 2PV although pressure remains constant at 3.1psi.

Brine injection into the porous medium after 0.01wt%MWNT nanofluid injection

When brine was injected into the porous medium from 2PV, it is observed that the pressure decreased to 2.8 psi at 2.2PV and remains constant until 2.6PV. The decrement in pressure shows that the brine manages to clear some blocked channels in the porous medium to allow CNT nanofluid to flow through the channels to extract oil out porous medium. However, as it is observed in Figure 27 that there is no oil being recovered from 2.4 PV until 2.6PV. This indicates there was no oil in the channels when the blocked channels were cleared out. Then, it is observed in Figure 26 that the pressure decreases again slightly and indicates that some blocked channels are cleared and oil was extracted out from the blocked channels. Later, the pressure increases to 2.5 psi at 3.2PV and remains constant at 2.5 psi until 6PV. It is observed that there is no more oil recovered from the porous medium from 3.6PV until 6PV. This indicates that the channels of the porous medium are completely blocked by MWNT and reduces the permeability. Hence this causes remaining oil could not be extracted out more and still being trapped in the porous medium. So therefore, overall, the residual oil in place (ROIP) that is being extracted from the porous medium when 0.01wt% of MWNT nanofluid is being injected into the porous medium is 29.17%.

4.2.2 Impact of 0.05% of CNT nanofluid concentration on permeability

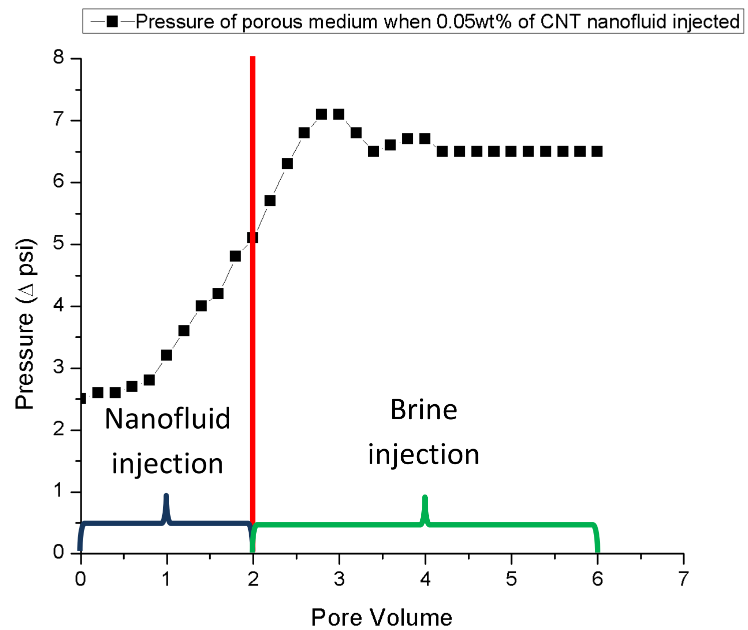


Figure 28 : Differential Pressure of the porous medium when 0.05wt% of MWNT nanofluid injected

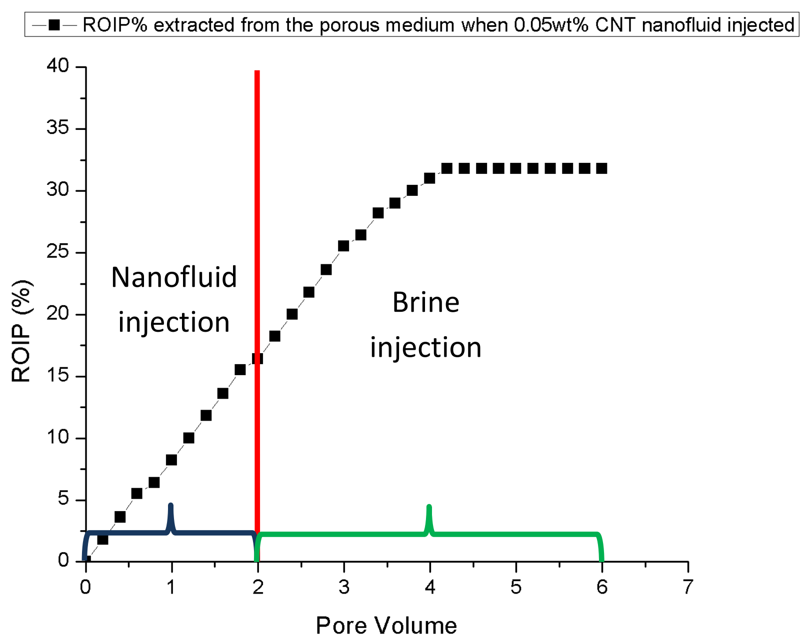


Figure 29 : ROIP extracted from the porous medium when 0.05wt% of CNT nanofluid injected

Figure 28 and Figure 29 displays the results of differential pressure and amount of residual oil in place are recovered when 0.05 wt % of MWNT nanofluid is being injected into the porous medium. The experimental data gathered and ROIP% calculation when 0.05wt% of MWNT is being injected into the porous medium is attached as Appendix A.1.2.

<u>0.05wt% of MWNT nanofluid injected into the porous medium from 0PV to 2PV</u>

From Figure 28, it can be observed that the differential pressure recorded after secondary recovery 2.5psi. Then, it is observed that the differential pressure increases continuously 2.5 psi until 5.1 psi from 0PV to 2PV when 0.05wt% of MWNT nanofluid is being injected into the porous medium. The continuous increment of differential pressure indicates that the channels of the porous medium are being blocked by MWNT which causes reduction in permeability. The continual MWNT nanofluid injection into the porous medium causes it to accumulate at the inlet of the porous medium since it could not flow through the blocked channels in the porous medium and causes pressure to build up. However, it is observed that although the differential pressure increases, which indicates blockage occurs in the porous medium, however, there are some oil being recovered from the porous medium. This shows that there is possibility water-oil emulsion mechanism might occur in the porous medium. Since the viscosity of the emulsion is higher than viscosity of water and viscosity of oil itself, this causes the differential pressure to build up to push the emulsion out from the porous medium.

<u>Brine injection into the porous medium after 0.05wt% of CNT nanofluid injection</u>

When brine is being injected into the porous medium from 2PV, it is observed in Figure 28 that the differential pressure continues to increase from 5.1psi to 7.1psi at 2.8PV. This indicates that still more channels in the porous medium is being blocked by MWNT and causes brine to accumulate at the inlet of the porous medium and causes pressure to build up. There is possibility that emulsion mechanism might occurs in some channels of the porous medium since it is observed in Figure 29 there are some oil being recovered from the porous medium from 2.2PV until 2.8PV although the differential pressure increases up to 7.1psi. Later it is observed in Figure 28 that pressure remains constant at 7.1psi until 3PV and decreases to 6.5 psi at 3.4PV. This indicates that the brine is able to breakthrough some walls of blocked channels and allows MWNT nanofluid to recover oil out from the channel of the porous medium. Then, it is observed that the pressure slowly builds up to 6.7psi at 4PV and remains constant at 6.7psi until 6PV. Figure 29 shows that there is no more oil being recovered out from the porous medium 4.4PV until 6PV. This indicates that the channels of the porous medium is completely blocked by MWNT and causes reduction in permeability. This causes the remaining oil could not be extracted from the porous medium. Overall, the residual oil in place (ROIP) that is being extracted from the porous medium when 0.05wt% of MWNT nanofluid is being injected into the porous medium is 31.1%.

4.2.3 Impact of 0.1wt% of CNT nanofluid concentration on permeability

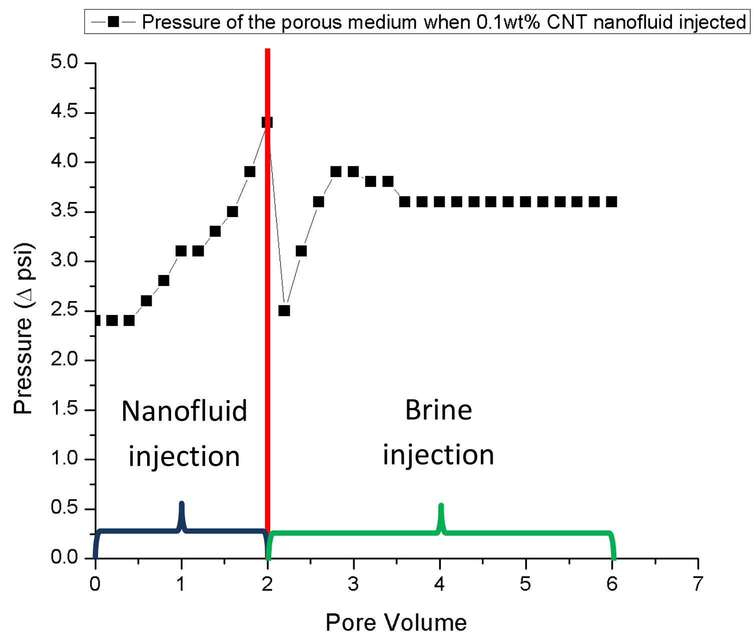


Figure 30 : Pressure of the porous medium when 0.1wt% of CNT nanofluid injected

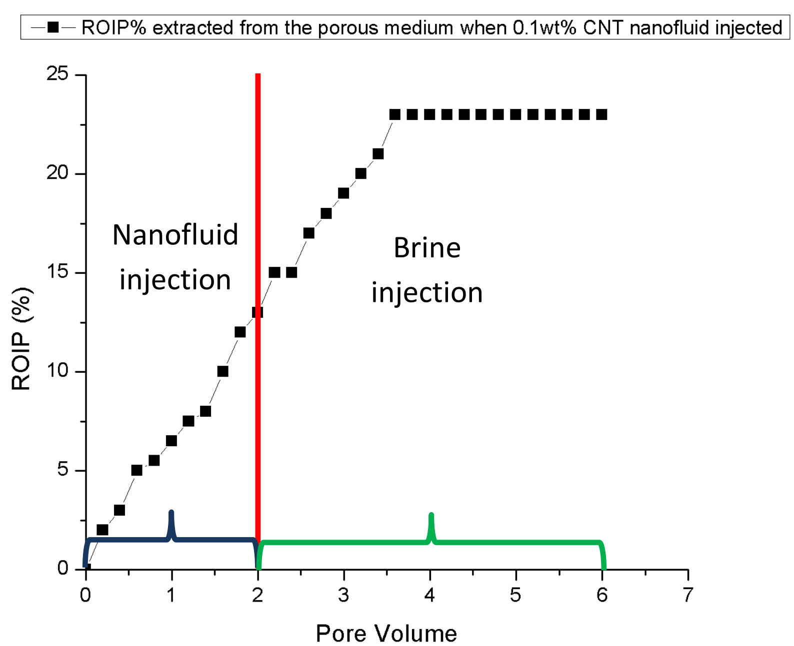


Figure 31 : ROIP% extracted from the porous medium when 0.1wt% of CNT nanofluid injected

Figure 30 and Figure 31 displays the results of differential pressure and amount of residual oil in place are recovered when 0.1 wt % of MWNT nanofluid is being injected into the porous medium. The experimental data gathered and ROIP% calculation when 0.1wt% of MWNT is being injected into the porous medium is attached as Appendix A.1.3.

<u>0.1wt% of MWNT nanofluid injected into the porous medium from 0PV to 2PV</u>

From Figure 31, it can be observed that the differential pressure of the porous medium recorded after secondary recovery is 2.4 psi. Then, it is observed that the differential pressure remains at 2.4psi until 0.4PV and increases until 3.1psi at 1PV. This shows that the channels of the porous medium are slowly being blocked by MWNT and causes the pressure to build up slowly and causes reduction in permeability. As it is observed the amount of oil recovered in the porous medium from 0PV until 1PV is very low and not consistent which indicates that not much oil is being extracted out from the porous medium. The pressure remains constant at 3.1psi from 1PV to 1.2PV indicates that MWNT nanofluid is trying to clear some blocked channels in the porous medium. It is observed in Figure 30 that the pressure continuously increases from 3.1 to 4.4 psi at 2PV. The incremental in pressure is caused by channels in the porous medium is blocked due to MWNT.

<u>Brine injected into the porous medium after 0.1wt% of MWNT nanofluid injection</u>

When brine is injected into the porous medium, it is observed in Figure 32 that the differential pressure decreases immediately from 4.4psi to 2.5 psi and then increases until 3.9psi at 2.8PV. This indicates that the differential pressure build manage to breakthrough some blocked channels walls and allows MWNT to flow through the channel to extract oil out from the channel. The blocked channels breakthrough causes the differential pressure to reduce as the wall breakthrough allows the pressure to be released. Later, it is observed that pressure seems to be constant at 3.9psi from 2.8PV until 3PV. Then, the pressure reduces to 3.8psi and become constant from 1.2psi until 1.4psi. This indicates that some blocked channels are being cleared which allows MWNT to extract oil out from the porous medium. It is observed in Figure 31 that the pressure decreases from 3.8 psi to 3.6 psi at 3.6PV and remains constant until 6PV. It is observed in Figure 32 that there is no more oil being extracted out from the porous medium after 3.6PV until 6PV. This indicates that the channels of the porous medium is completely blocked with MWNT and causes reduction in permeability. Therefore, the residual oil in place (ROIP) that is being extracted from the porous medium when 0.1wt% of MWNT nanofluid is being injected into the porous medium is 23%. In summary, the Residual Oil In Place (ROIP) being extracted from the porous medium using different concentration of MWNT fluid is given in Table 6.

Table 6 : ROIP (%) extracted using different concentration of MWNT fluid

Concentration of MWNT nanofluid (wt%)	Permeability (mD)	Recovery Efficiency (%)
0.01	1	29.17
0.05	0.2	31.8
1	0.833	23

4.2.4 Choosing the best CNT nanofluid concentration

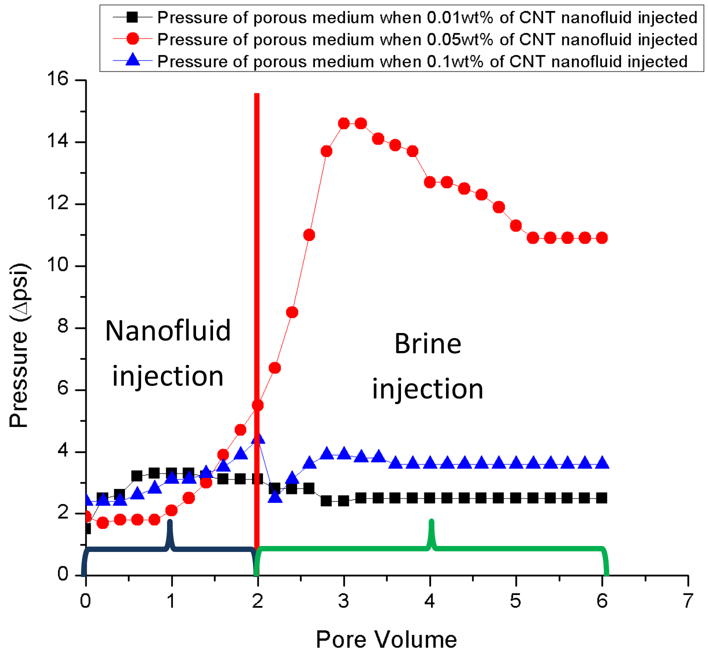


Figure 32 : Comparison of differential pressure of the porous medium for different CNT nanofluid concentration

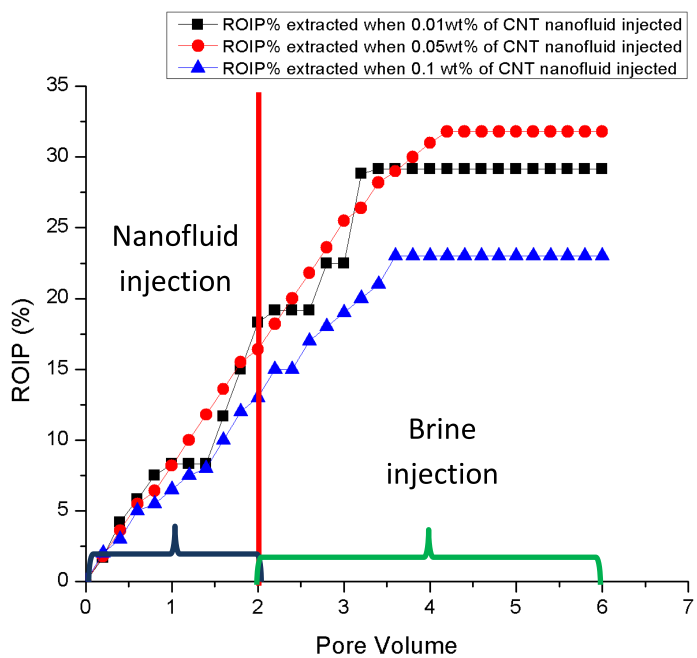


Figure 33 : Comparison of ROIP % extracted from the porous medium when different MWNT nanofluid concentration being injected

Based on the three results of core flooding experiment using 0.01wt%, 0.05wt% and 0.1wt% concentration of MWNT nanofluid, it is observed that MWNT nanofluid does causes reduction in permeability when it is being injected into the porous medium because MWNT tend to block the channels of the porous medium. MWNT tends to block the porous medium due to its morphology shape which is in the form of cylindrical and the texture of MWNT shows that it is a multiwall carbon nanotube. There are several phenomena that might occur in the porous medium when MWNT nanofluid is being injected into the porous medium which leads to permeability reduction. The phenomena that might took place in the porous medium are adsorption, desorption, blocking and transportation. This explains on why the differential pressure increases when MWNT is being injected into the porous medium. This indicates that the MWNT are reducing the ability of water to flow through the porous medium. After applying Darcy's formula to calculate the permeability, it was found out that 0.01wt% of MWNT nanofluid concentration causes the least permeability reduction compared to 0.05wt% and 0.1wt% of MWNT nanofluid concentration. Based on the three results shown on the impact of MWNT nanofluid concentration on permeability, it shows that a higher concentration results in a higher permeability reduction. So therefore, 0.01wt% of MWNT nanofluid concentration is chosen to carry out the next core flooding experiment to study the impact of CNT nanofluid flow rate on permeability.

4.3 Impact of Carbon Nanotubes (CNT) nanofluid flow rates on permeability

4.3.1 Impact of CNT nanofluid injected at 0.5 ml/min of flow rate on permeability

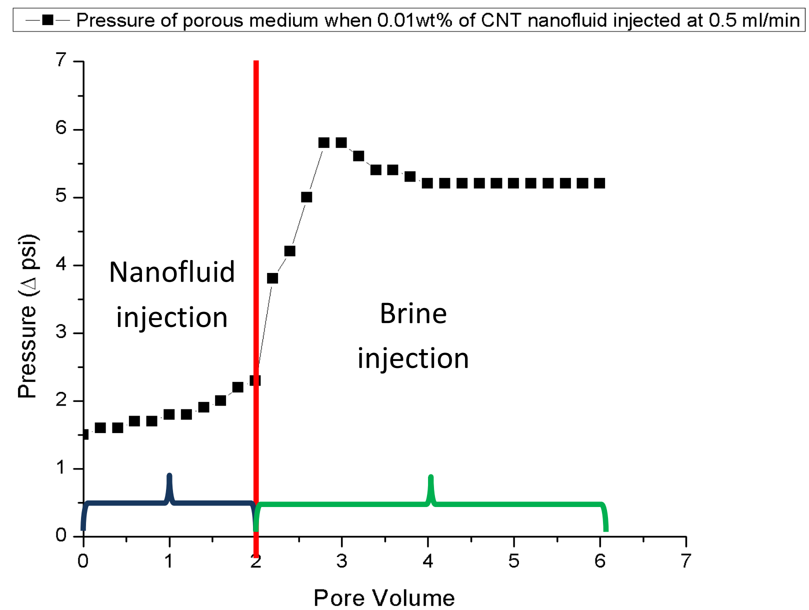


Figure 34 : Differential pressure of the porous medium when MWNT nanofluid injected at the flow rate of 0.5ml/min

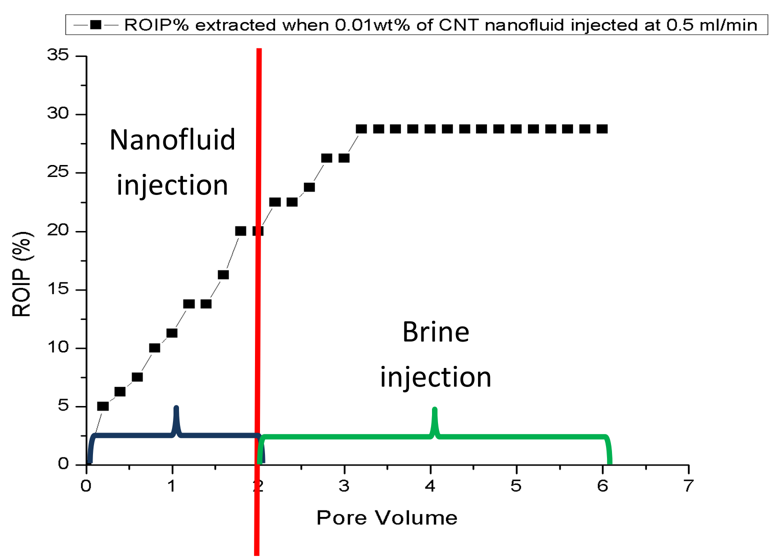


Figure 35 : ROIP% extracted when MWNT nanofluid injected at the flow rate of 0.5ml/min

Figure 34 and Figure 35 displays the results of differential pressure and amount of residual oil in place are recovered when 0.01 wt % of MWNT nanofluid is being injected into the porous medium at the flow rate of 0.5ml/min. The experimental data gathered and ROIP% calculation when 0.01wt% of MWNT is being injected into the porous medium at the flow rate of 0.5ml/min is attached as Appendix A.1.4.

<u>MWNT nanofluid injected into the porous medium at flow rate of 0.5ml/min</u>

From Figure 34, it is observed that the differential pressure of the porous medium recorded after secondary recovery process is 1.5psi. When MWNT nanofluid is being injected into the porous medium, it is observed that the pressure still remains at 1.5 psi from 0PV until 0.4PV. The constant in pressure indicates that most probably the MWNT is slowly settling down at the channels of the porous medium before blocking the channels of the porous medium completely. As it is observed in the graph that the pressure increases from 1.5psi to 2.3psi at 2PV, this indicates that the MWNT is slowly blocking the porous channel by settling down due to gravity in the channels of the porous medium and causes log-jamming effect since the flow rate of the MWNT nanofluid being injected into the porous medium is very low. It is observed in Figure 35, that there is some oil being recovered from the porous medium when the high differential pressure indicates that emulsion mechanism might occur in the porous medium. Since emulsion has higher viscosity compared to viscosity water and viscosity of oil, the differential pressure builds up in order to push the emulsion out from the porous medium.

<u>Brine injected into the porous medium at flow rate of 0.5ml/min</u>

When brine is being injected into the porous medium, it is observed in figure 34, that the differential pressure continues to increase from 2.3psi at 2PV until 5.8psi at 2.8PV. It is observed in Figure 35, that the oil being recovered from 2PV until 2.8PV is very low. This indicates that MWNT blocks the channel of the porous medium and causes brine injection to accumulate at the inlet of the porous medium and causes the differential pressure to build up. Later, it is observed in figure 34, that the differential pressure decreases from 5.8psi to 5.2 psi at 4PV and remains constant at 5.2psi until 6PV. It is also observed in figure 10 that there is no more oil being recovered from the porous medium from 3.6PV until 6PV. This indicates that MWNT has completely blocked the channels of the porous medium and causes reduction in permeability. Therefore, the residual oil in place (ROIP) that is being extracted from the porous medium when 0.01wt% of MWNT nanofluid is being injected at the flow rate of 0.5ml/min into the porous medium is 28.75%.

4.3.2 Impact of CNT nanofluid injected at 1 ml/min of flow rate on permeability

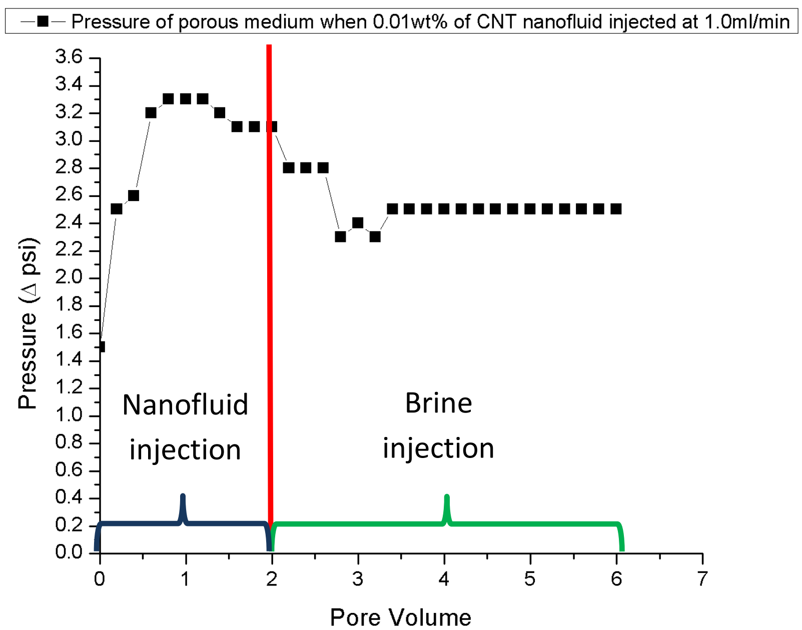


Figure 36: Differential pressure of porous medium when MWNT nanofluid injected at 1.0ml/min

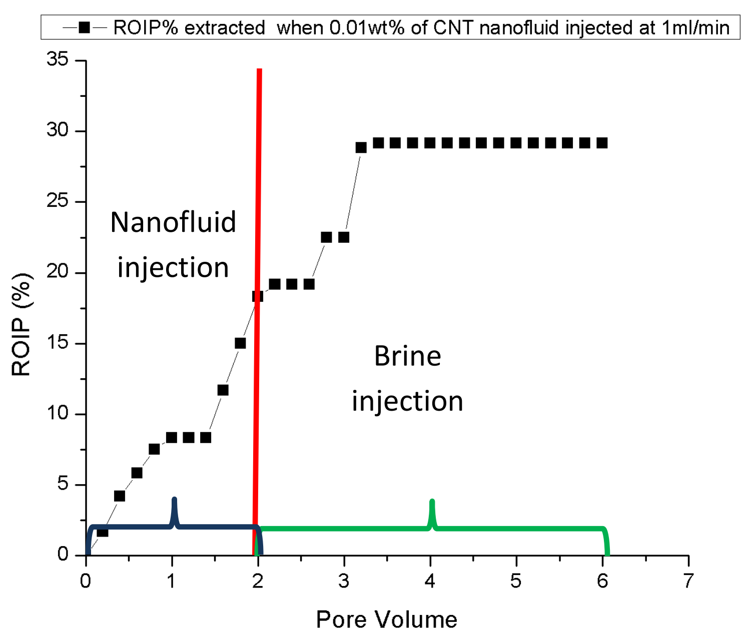


Figure 37: ROIP% extracted when MWNT nanofluid injected at 1.0ml/min

Figure 36 and Figure 37 displays the results of differential pressure and amount of residual oil in place are recovered when 0.01 wt % of MWNT nanofluid is being injected into the porous medium at the flow rate of 1ml/min. The experimental data gathered and ROIP% calculation when 0.01wt% of MWNT is being injected into the porous medium is attached as Appendix A.1.5. The mechanism that took place in both regions when MWNT nanofluid and brine injected into the porous medium will be explained in detail to justify the reasoning of pressure changes in the porous medium and its effects on the oil recovery from the porous medium.

<u>MWNT nanofluid injected into the porous medium at flow rate of 1ml/min</u>

From Figure 36, it is observed that the differential pressure recorded after secondary recovery was carried out is 1.5 psi. When MWNT nanofluid is being injected into the porous medium from 0PV until 0.8PV, it is observed that the pressure increases immediately to 3.3psi. The reason why the pressure increased drastically is there are possibilities that some of the channels in the porous medium are blocked by MWNT and reduces the permeability. Hence the MWNT nanofluid that is being injected continuously into the porous medium could not flow through channels starts to accumulate at the inlet and causes pressure to build up. Then the pressure remains constant at 3.3psi until 1.4 PV of MWNT nanofluid being injected into the porous medium. It is also observed in Figure 37, that there is no oil recovery from 1.2PV until 1.4PV This indicates that the blocked channels are being cleared by the MWNT nanofluid since the high pressure build up is able to break the blockage the occurs in the channel of the porous medium. However, there is no oil found after the blocked channels are cleared. Later, it is observed that the pressure drops to 3.1psi from 1.4PV until 1.6PV and pressure remains constant at 3.1 psi from 1.6PV until 2PV. This indicates that the blocked channels are cleared by the MWNT nanofluid which causes the nanofluid are able to flow through the channels to extract oil from the porous medium. Hence, this mechanism causes the pressure to decrease. The constant pressure at 3.1psi indicates that some blocked channels which contain oil is being cleared by the MWNT nanofluid and extracts more oil from the porous medium as it is observed in Figure 37 that there are oil being recovered from the porous medium from 1.6PV until 2PV although pressure remains constant at 3.1psi.

Brine injection into the porous medium at flow rate of 1ml/min

When brine was injected into the porous medium from 2PV, it is observed that the pressure decreased to 2.8 psi at 2.2PV and remains constant until 2.6PV. The decrement in pressure shows that the brine manages to clear some blocked channels in the porous medium to allow MWNT nanofluid to flow through the channels to extract oil out porous medium. However, as it is observed in Figure 37 that there is no oil being recovered from 2.4 PV until 2.6PV. This indicates there was no oil in the channels when the blocked channels were cleared out. Then, it is observed in Figure 36 that the pressure decreases again slightly and indicates that some blocked channels are cleared and oil was extracted out from the blocked channels. Later, the pressure increases to 2.5 psi at 3.2PV and remains constant at 2.5 psi until 6PV. It is observed that there is no more oil recovered from the porous medium from 3.6PV until 6PV. This indicates that the channels of the porous medium are completely blocked by MWNT and reduces the permeability. Hence this causes remaining oil could not be extracted out more and still being trapped in the porous medium. So therefore, overall, the residual oil in place (ROIP) that is being extracted from the porous medium when 0.01wt% of MWNT nanofluid is being injected into the porous medium is 29.17%.

4.3.3 Impact of CNT nanofluid injected at 2ml/min of flow rate on permeability

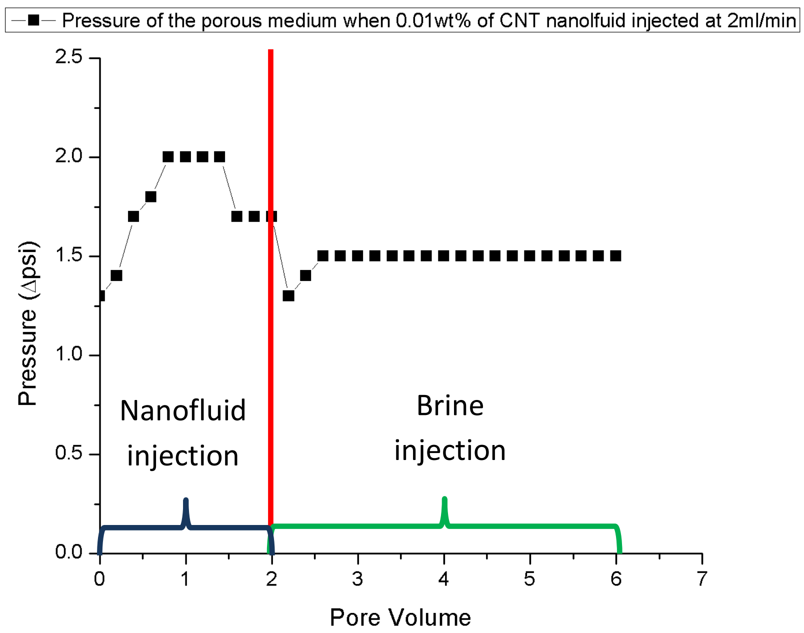


Figure 38 : Differential pressure of porous medium when MWNT nanofluid being injected at 2ml/min

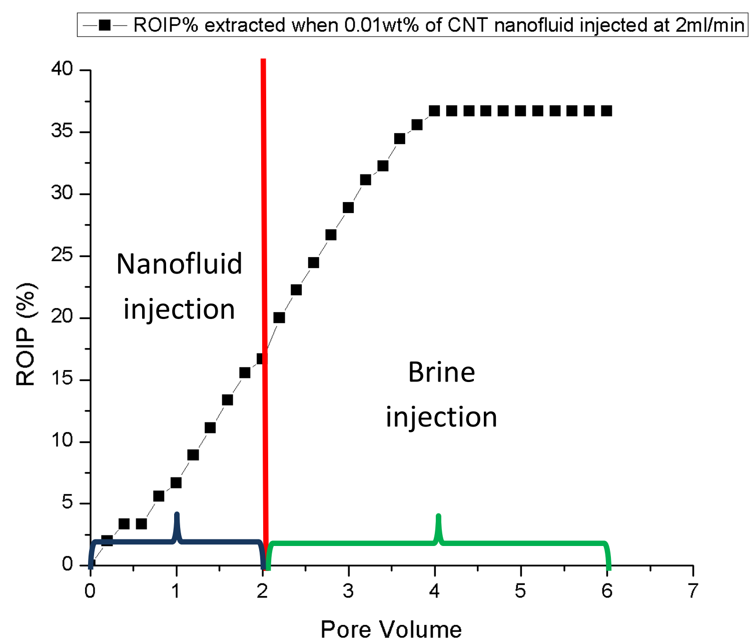


Figure 39 : ROIP% extracted when MWNT nanofluid injected being injected at 2ml/min

Figure 38 and Figure 39 displays the results of differential pressure and amount of residual oil in place are recovered when 0.01 wt % of MWNT nanofluid is being injected into the porous medium at the flow rate of 2 ml/min. The experimental data gathered and ROIP% calculation when 0.01wt% of MWNT is being injected into the porous medium is attached as Appendix A.1.6. The mechanism that took place in both regions when MWNT nanofluid and brine injected into the porous medium will be explained in detail to justify the reasoning of pressure changes in the porous medium and its effects on the oil recovery from the porous medium.

<u>MWNT nanofluid injected into the porous medium at flow rate of 2ml/min</u>

From Figure 38, it is observed that the differential pressure of the porous medium recorded after secondary recovery is 1.3psi. When MWNT nanofluid is being injected into the porous medium, it is observed that the pressure increases up to 2 psi from 0PV until 0.8PV. Then the pressure remains constant at 2psi from 0.8 PV until 1.4PV. The increment in differential pressure from 1.3 psi until 2 psi indicates that some channels in the porous medium are blocked with MWNT and causes permeability reduction. It is observed in Figure 39 that during the oil recovery from 0.2PV until 0.8PV is very low which indicates that very less oil is being extracted out from the porous medium due to the blockage of channels in the porous medium. The pressure remains constant at 2psi from 0.8 PV until 1.4PV indicates that MWNT nanofluid is trying to clear some blocked channels in the porous medium so that MWNT nanofluid can flow through the clear channels to extract oil out from the porous medium. Later it is observed in figure 38, that the pressure decreases to 1.7 psi at 1.6PV and remains constant at 1.7psi until 2PV. This indicates that MWNT nanofluid manage to break through the walls of he blocked channels in the porous medium and causes the pressure to decrease as the MWNT nanofluid is now able to flow to the channels to extract oil out from the porous medium.

<u>Brine injection into the porous medium at flow rate of 2ml/min</u>

When brine is injected into the porous medium, it is observed that the pressure decreased immediately to 1.3psi at 2.2PV and then increases back to 1.5psi at 2.6PV. The pressure remains at 1.5 psi from 2.6PV until 6PV. The immediate decrement in pressure from 1.7psi to 1.3psi shows that the brine manage to clear some blocked channels in the porous medium which allows MWNT nanofluid to flow through the channels to extract oil out from the reservoir. Then when the differential pressure increases to 1.5 psi and remains constant at 1.5psi from 2.6PV until 6PV, it indicates that the channels in the porous medium are completely blocked with MWNT and causes reduction in permeability. It is observed in Figure 39 that there is no more oil recovered from the porous medium 4PV until 6PV. This indicates that remaining oil is still trapped in the porous medium to the blocked channels in the porous medium. Therefore, overall, the residual oil in place (ROIP) that is being extracted from the porous medium when 0.01wt% of MWNT nanofluid is being injected into the porous medium at flow rate of 2ml/min is 36.67%. In summary, the Residual Oil In Place (ROIP) being extracted from the porous medium is given in Table 7.

Table 7 : ROIP (%) extracted when MWNT fluid injected at different flow rate

Flow rate of 0.01MWNT nanofluid being injected (ml/min)	Permeability (mD)	Recovery Efficiency (%)
0.5	0.27	28.75
1	1	29.17
2	5	36.67

4.3.4 Choosing the best CNT nanofluid flow rate

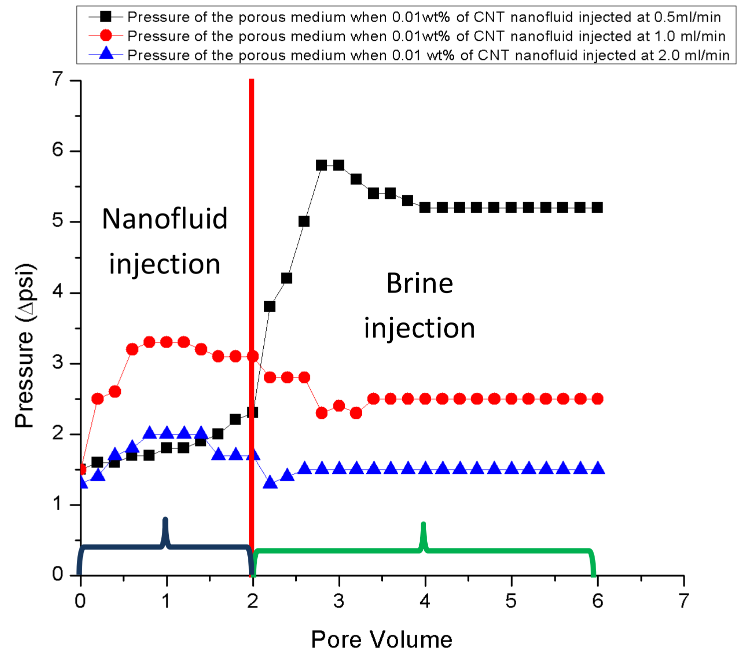


Figure 40 : Comparison of differential pressure when MWNT nanofluid being injected under different flow rate

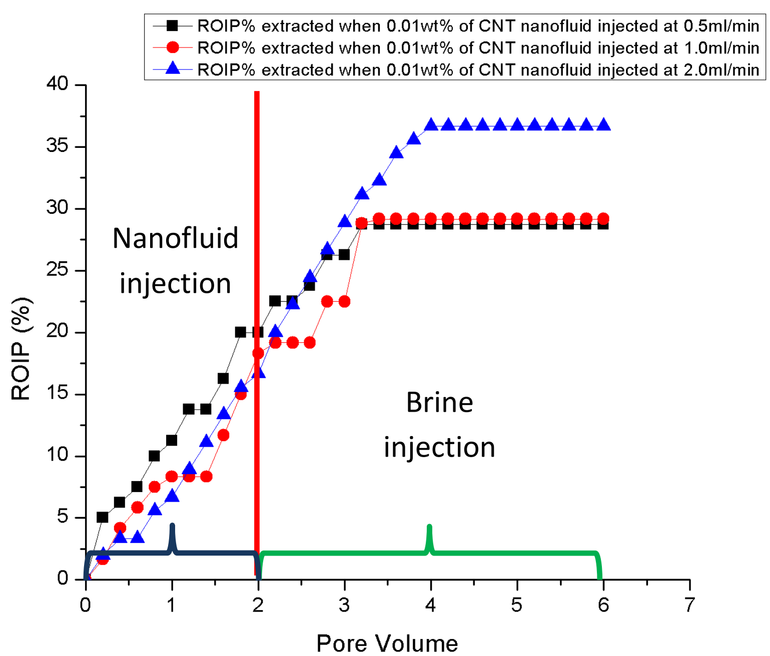


Figure 41 : ROIP% extracted when MWNT nanofluid being injected using different flow rates

Based on the three results using 0.01wt% of MWNT nanofluid concentration being injected at the flow rate of 0.5ml/min, 1.0ml/min, and 2ml/min, it is observed that the higher the flow rate, the lower the permeability reduction. This is because when MWNT is being injected into the porous medium at higher velocity, MWNT will not have enough time to settle down due to continual fast injection flow rate and able to breakthrough any walls of blockage that is being formed in the channels immediately to extract oil out from the porous medium. When MWNT nanofluid is being injected into the porous medium at a very low flow rate, it causes MWNT to settle down at the channels of the porous medium due to gravity and can cause permeability reduction in the porous medium. The permeability is calculated for each experiment by using Darcy's Law formula as shown below After applying Darcy's formula to calculate the permeability, it was found out that 0.01wt% MWNT nanofluid concentration being injected into the porous medium at 2ml/mim flow rate causes the least permeability reduction compared to flow rate of 1.0ml/min and 2ml/min. So therefore, 0.01wt% of MWNT nanofluid with the flow rate of 2ml/min will be used to carry out the next core flooding experiment under the presence of electromagnetic wave. This experiment is carried out to compare the recovery efficiency of MWNT nanofluid under the absence and presence of electromagnetic wave.

4.4 Impact of Carbon Nanotubes (CNT) nanofluid on permeability under electromagnetic wave

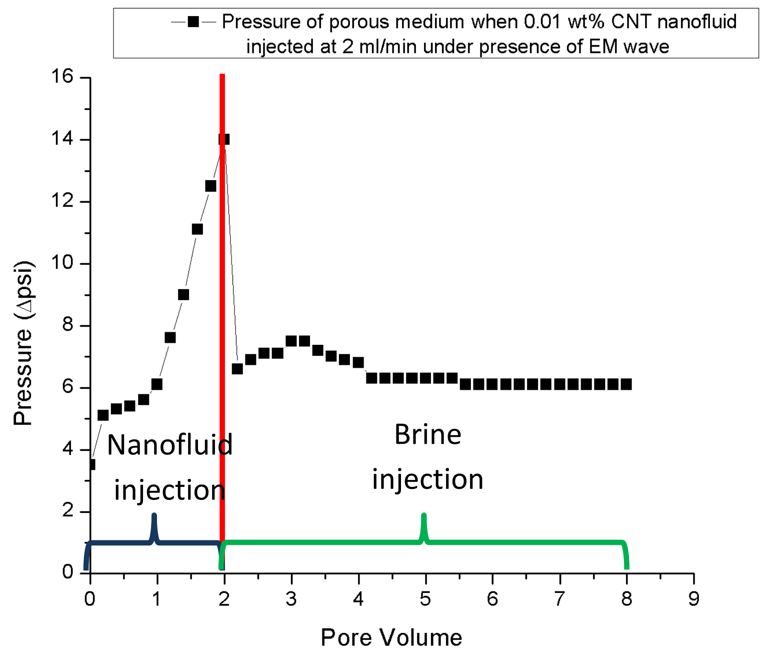


Figure 42 : Differential pressure of porous medium when MWNT nanofluid being injected under presence of EM wave

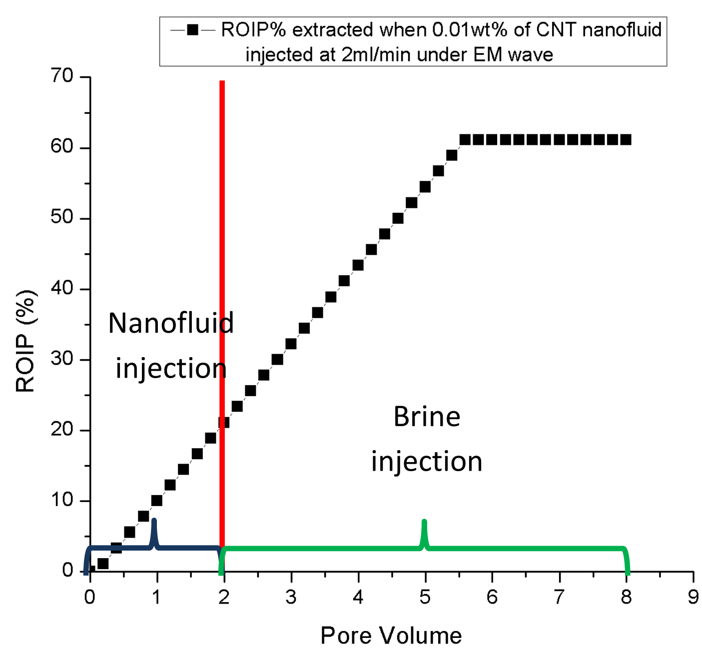


Figure 43 : ROIP% extracted when MWNT nanofluid being injected under presence of EM wave

Figure 42 and Figure 43 displays the results of differential pressure and amount of residual oil in place are recovered when 0.01 wt % of MWNT nanofluid is being injected into the porous medium at the flow rate of 2 ml/min under the presence of electromagnetic wave. The experimental data gathered and ROIP% calculation when 0.01wt% of MWNT is being injected into the porous medium at the flow rate of 2ml/min under the presence of electromagnetic wave is attached as Appendix A.1.7. The mechanism that took place in both regions when MWNT nanofluid and brine injected into the porous medium will be explained in detail to justify the reasoning of pressure changes in the porous medium and its effects on the oil recovery from the porous medium.

Injection of MWNT nanofluid into the porous medium under presence of electromagnetic wave

From Figure 42, it is observed that the differential pressure of the porous medium after secondary recovery is 3.5psi. Later, it is observed that the pressure increases immediately to 14 psi at 2PV when 0.01wt% MWNT nanofluid is being injected into the porous medium at the flow rate of 2ml/min under the presence of electromagnetic wave. It is also observed in Figure 43 that the oil recovery from 0.2PV until 2PV is highly consistent. This indicates that electromagnetic wave that is being emitted during the core flooding experiment had triggered the MWNT particles in the porous medium to vibrate in a same frequency and provides better stabilization to emulsion mechanism that occurs in the porous medium. The occurrence of emulsion mechanism in the porous medium explains on why the differential pressure of the porous medium increases until 2PV. This is because viscosity of the emulsion is higher than the viscosity of water and viscosity of oil. Hence higher differential pressure is created in order to expel the emulsion from the porous medium.

Brine injection into the porous medium under presence of electromagnetic wave

It is observed that the differential pressure decreases immediately 6.6 psi at 2.2PV when brine is being injected into the porous medium. This is because the injected brine helps to clear channels that are blocked with MWNT in the porous medium in order to allow

MWNT nanofluid to flow through the channels to extract oil out from the porous medium. Later it is observed in Figure 44 that the pressure increases from 6.6psi to 7.5psi at 3PV. This indicates that some channels in the porous medium are being blocked by MWNT and causes reduction in permeability. Somehow, it is observed that there is oil being recovered from the porous medium from 2.2PV until 3PV. This shows that there is possibility that emulsion mechanism occurs in the porous medium. Then, it is observed in Figure 42, that the pressure decreases to 6.3 psi at 4.2PV and remains constant at 6.3psi until 5.4PV. The differential pressure later drops to 6.1psi at 5.6PV and remains constant at 6.1psi until 8 PV. It is also observed in Figure 43 that there is no more oil being recovered from the porous medium from 5.8PV until 8PV. This indicates that the channel of the porous medium is completely blocked by MWNT and causes permeability reduction. The permeability reduction in the porous medium causes no more oil being recovered from the porous medium starting from 5.8PV. Therefore, overall, the residual oil in place (ROIP) that is being extracted from the porous medium when 0.01wt% of MWNT nanofluid is being injected into the porous medium at flow rate of 2ml/min under the presence of the electromagnetic wave is 61.1%.

4.5 Comparison of EOR results due to CNT nanofluid into the porous medium under the absence and presence of electromagnetic wave and it's justification

The recovery efficiency obtained when is MWNT nanofluid is being injected into the porous medium under the presence of electromagnetic wave is higher which is 61.1% compared to the recovery efficiency obtained when MWNT nanofluid is being injected into the porous medium under the absence of ellectromagentic wave which is 36.67%. Based on this result it is concluded that MWNT nanofluid that is being injected into porous medium under the presence of electromagnetic wave is able to recover more oil compared to injection of MWNT nanofluid alone into the porous medium. This is because This is because electromagnetic wave triggered the MWNT particles in the porous medium to vibrate in a same frequency and provides better stabilization to emulsion mechanism that occurs in the porous medium. At the same time, the electrical energy that is being generated from the electromagnetic waves transfers to the MWNT material in the form of heat and reduces the oil viscosity, which as a result causes increment in oil mobility and recovery.

CHAPTER 5

5. CONCLUSION & RECOMMENDATION

In conclusion, MWNT nanofluid is able to recover 36.67% of ROIP from the porous medium. This proves that MWNT nanofluid is a very good nanoagent in increasing oil recovery from the reservoir during EOR. MWNT nanofluid that is being injected into the porous medium under the presence of EM wave has a yielded a recovery efficiency of 61.1% which is 24.43% higher than the recovery efficiency of MWNT nanofluid alone which is 36.67%. efficiency of MWNT nanofluid alone which is 36.67%. So therefore, this research is able to prove that MWNT nanofluid assisted by EM wave is able to recover more oil from the reservoir compared to MWNT nanofluid alone.

The objectives of this project are achieved because the characterization of MWNT sample was carried out, the role of MWNT nanofluid on EOR by observing the concentration and flow rate impact of MWNT nanofluid on permeability has been studied and quantittave comparison has been carried out between recovery efficiency and the results are justified under the absence and presence of EM wave.

As for recommendation for this research, it is recommended to study the impact of MWNT nanofluid on wettability, viscosity and interfacial tension. It is also recommended to study the impact of MWNT nanofluid on emulsion mechanism.

CHAPTER 6

6. REFERENCES

1. A.J.P. Fletcher, J.P.Davis 2010 "How EOR can be transformed by nanotechnology", University of Bristol, SPE 129531, p. 5.

2. Y.Dandekar 2006, "Petroleum Reservoir Rock and Fluid Properties," Published by Taylor & Francis Group.

3. M. Dong, H. Zhang and S. Zhao. 2010, "Which one is more important in chemcial flooding for enhanced oil recovery,lowering interfacial tension or reducing oil permeability," Energy Fuels, pp. 1829-1836.

4. A. Bahrain and Roosta 2009, "Investigating the mechanism of thermally induced wettability alteration" SPE Middle East Oil and Gas Show and Conference.

5. H. S. Al-Hadhrami, M.J Blunt 2001, "Thermally Induced Wettability Alteration To Improve Oil Recovery in Fractured Reservoirs". SPE Reservoir Evaluation & Engineering, pp. 179-186.

6. Chang, H.G. 2011 "Advances of polymer oil in heavy oil recovery", SPE Heavy Oil Conference and Exhibition, Kuwait City, Kuwait .

7. . Wang, M. Dong. J. 2007 "A Laboratory Study of Polymer Flooding for Improving Heavy Oil Recovery," Canadian International Petroleum Conferences Calgary, Alberta .

8. A. Samanta, K. Ojha, A. Sarkar, A. Mandal 2011 "Surfactant and surfactant polymer flooding for enhanced oil recovery", Advances in Peroleum Exploration and Development, pp. 13-18.

9. . Xiangling Kong and Micheal M. Ohadi 2010 , "*Applications of Micro and Nano Technologies in Oil and Gas Industry-An Overview of the Recent*

Progress" China University of Petroleum (Beijing), The Petroleum Institute (UAE)..

10. Tippee, Bob 2009, "Nanotechnology Seen Boosting Recovery Factors", Oil & Gas journal .

11. Mohammed F El-Amin, Syuyu Sun, Amgad Salama 2013, "Enhanced Oil Recovery by Nanoparticles Inejction: Modelling and Simulation" King Abdullah University of Science and Technology (KAUST).

12. N.A Ogolo, O.A. Olafuyi, M.O. Onyekonwu 2012, "Enhanced Oil Recovery Using Nanoparticles". Petroleum Technology Development Fund Research Group, Institute of Rivers State, Nigeria.

13. Shah, Rusheet, D 2009, "Application of Nanoparticle Saturated Injectant Gases for EOR of Heavy Gases". University of Alaska Fairbanks, SPE 129539, p. 11.

14. Gao, C. 2007, "Factors Affecting Paricle Retenion In Porous Media," Emirates Hournal for Engineering Research, pp. 21,22,23.

15. Mike O. Onyekonwu, Naomi A.Ogolo 2010, "Investigating the Use of Nanoparticles In Enhancing Oil Recovery," Depatment of Petroleum and Gas Engineering, University of Port Harcourt, RIvers State, Nigeria. 2010, SPE 140744.

16. Luky Hendraningrat, Li Shidong, Suwarno, Ole Torsaeter 2012, "A Glass micromodel Experimenal Study of Hydrophilic Nanoparticles Retention for EOR Project" SPE, Norwegian University of Science and Technology (NTNU). SPE 159161.

17. Paul McElfresh, David Holcomb, Daniel Ector 2012, "Application of Nanofluid Technology To Improve Recovery in Oil an Gas Wells,". SPE 154827.

18. Mohammed Alaskar, SPE, Morgan Ames, Steve Connor, Chong Liu, Yi Cui, Kewen Li,SPE, Roland Horne 2011 "Nanoparticle and Microparticle Flow in Porous and Fractures Media: An Experimental study," Dpeartment of Energy

Resources Engineering, Department of Material Science and Engineering, Standford University, SPE 146752, pp. 1-19.

19. T. Skauge, K. Spildo, A. Skauge. Al-Khobar, Saudi Arabia 2010 “Nano-sized Particles for EOR,” SPE Saudi Arabia Section Technical Symposium and Exhibition. p. 18.

20. S. Bolantaba, A. Skauge, E.Mackay 2009 “Pore Scale Modelling of Linked Polymer Solution (LPS)- A new EOR Process,” European Symposium on Improved Recovery ,Paris.p. 22.

21. Jianjia Yu, Cheng An, Di Mo, Ning Liu, Robert Lee 2012, “Study of adsorption and transportation behaviour of nanoparticles in three different porous media” SPE Petroleum Recovery and Research Center, SPE 153337.

22. Min Shen, Daniel E. Resasco 2009, “Emulsions Stabilized by Carbon Nanotubes-Silica Nanohybrids”, Langmuir Article.

23. Bragg, James R. 1999, “Oil Recovery Method Using Emulsion”., United States Patent 5,855,243.

24. Caetano Rodrigues Miranda, Lucos Stori de Lara, Bruno Costa Tonetto 2012, “Stability and mobility of functionalized silica nanoparticles for enhanced oil recovery applications”. SPE 157033.

25. Abbas Shahrabdi, Hadi Bagherzadi, Abbas Roustaei, Hassan Golghanddashti 2012, “Experimental Investigation of HLP Nanofluid Potential to Enhanced Oil Recovery : A Mechanistic Approach”. SPE 156642.

26. Rasyada, Noor 2012, “Application of electromagnetic waves and zinc oxide and aluminum oxide as dielectric nanoparticles in enhanced oil recovery”.

27. Yakobson, J.C. 1997, “Modelling and Simulations of solids”, pp. 706-715.

28. S.K. Srivastava, Vankar, Kumar. 2008 Nanoscale., pp. 25-30.

29. S. Xie, W. Li, Z. Pan, B. Chang, L. Sun. 2000, Phys.Chem Solids.61. pp. 1153-1158.

30. J.J. Taber, F.D. Martin, R.S. Seright 1997, "EOR Screening Criteria revisitied-Part 1 : Introduction to screening crieria and Enhanced Recovery Field projects."

31. Ganesh, E. N. 2013, "Single Walled and Multi Walled Carbon Nanotubes Structure, Sytnthesis and Application," International Journal of Innovative Technology and Exploring Engineering.

32. J.E. Bridges, G.C Stretsy, H.L. Spencer, R. A. Wattenbarger 1985, "Electromagnetic Stimulation of Heavy-Oil Wells," Third International Conference on Heavy Crude and Tar Sands. Long Beach, California, USA.

33. M.Y. Soliman, J. 1997, 18(1997)93-100. Pet. Science Engineering, Science Engineering.

34. G.C.Stretsy, H. Dev, R.H. Snow, and J.E Bridges 1986, " Recovery of bitumen from tar san eposits with the raio frequency process SPE 10229". SPE Annual Technical COnference an Exhibition San Antonio, TX, USA .

35. A. Chakma, and K.N. Jha 2010 "Heavy Oil Recovery from thin pay zones by electromagnetic heatin" 67th Annual Technical Conference an Exhibition, USA.

36. Noorhana Yahya, Muhammad Kashif, Naeem Nasir, Majid Niaz Akhtar, Noorasikin Moh Yusof 2012, "Cobaly Ferrite Nanoparticles : An Innovative Approach for Enhanced Oil Recovery Application"., Journal of Nano Research , pp. 115-126.

37. Yakobson, J.C. 1997, "Modelling and Simulations of solids". pp. 706-715.

38. Min Shen, Daniel E. Resasco 2009, "Emulsion stabilized by Carbon-Nanoubes and Silica Hydrobrids". Langmuir.

39. Kokal, Sunil 2005, "Crude-Oil Emulsion : A state of the art review".

40. Min Shien, Daniel E. Rosasco 2009, “Emulsion Stabilized by Carbon Nanotubes,” Langmuir Article.

APPENDIX A

RESULTS AND CALCULATION

A.1 Data collected and ROIP computation of core flooding experiment to study the impact of CNT nanofluid concentrations on permeability which are

A.1.1 0.01 wt% of CNT nanofluid

Dry Weight of porous medium (gram)	747.62
Wet Weight of porous medium (gram)	772.62
Difference in porous weight (∆gram)	24.95
Density of brine saturated the core (g/cm3)	1.006
Pore Volume of core (ml)	24.8
Pressure of porous medium after brine saturation (∆psi)	1.2
Pressure of porous medium after oil saturation (∆psi)	3.6
Pressure of porous medium after 2nd recovery using brine (∆psi)	1.5
Original oil in place (OOIP) (ml)	24
Amount of oil recovered during 2nd recovery (ml)	21
Residual oil in place (ROIP) (ml)	3

Type of fluid injected into porous medium	**Flow rate (ml/min)**
Brine saturation	1.0
Oil saturation	0.8
Brine 2nd recovery	1.0
CNT nanofluid	1.0
Brine 3rd recovery	1.0

2PV of CNT nanofluid being injected into the porous medium	2 X PV of porous medium = 2 X 24.8 = 49.6 ml

Differential pressure of porous medium taken during tertiary recovery when CNT nanofluid is injected

Data collected when 49.6 ml of CNT nanofluid is injected into the porous medium

Pore Volume	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
∆ P	2.5	2.6	3.2	3.3	3.3	3.3	3.2	3.1	3.1	3.1
ROIP	0.05	0.075	0.05	0.05	0.025	0	0	0.1	0.1	0.1
∑ ROIP	0.05	0.125	0.175	0.225	0.25	0.25	0.25	0.35	0.45	0.55
ROIP%	1.67	4.167	5.83	7.5	8.33	8.33	8.33	11.67	15	18.33

Data collected when brine is injected into the porous medium after CNT nanofluid injection

Pore Volume	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
Δ P	2.8	2.8	2.8	2.4	2.4	2.5	2.5	2.5	2.5	2.5
ROIP	0.025	0	0	0.1	0	0.1	0.1	0	0	0
∑ ROIP	0.575	0.575	0.575	0.675	0.675	0.775	0.875	0.875	0.875	0.875
ROIP%	19.17	19.17	19.17	22.5	22.5	25.83	29.17	29.17	29.17	29.17

Pore Volume	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
Δ P	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
ROIP	0	0	0	0	0	0	0	0	0	0
∑ ROIP	0.875	0.875	0.875	0.875	0.875	0.875	0.875	0.875	0.875	0.875
ROIP%	29.17	29.17	29.17	29.17	29.17	29.17	29.17	29.17	29.17	29.17

Reduction in permeability calculation using Darcy's law equation

$$q = \frac{kA(p_1 - p_2)}{\mu L}$$

In this experiment, flow rate, area of porous medium, fluid viscosity and length of the medium is made constant; hence the permeability will be calculated as

$$k = \frac{1}{(P_1 - P_2)}$$

So therefore, the permeability that occurs in the porous medium when 0.01wt% of MWNT nanofluid being injected into the porous medium is 1mD.

$$k = \frac{1}{(2.5 - 1.5)}$$

$$k = 1mD$$

A.1.2 0.05 wt% of CNT nanofluid

Dry Weight of porous medium (gram)	744.72
Wet Weight of porous medium (gram)	770
Difference in porous weight (Δgram)	25.58
Density of brine saturated the core (g/cm3)	1.006
Pore Volume of core (ml)	25.13
Pressure of porous medium after brine saturation (Δpsi)	1.1
Pressure of porous medium after oil saturation (Δpsi)	4
Pressure of porous medium after 2nd recovery using brine (Δpsi)	2.5
Original oil in place (OOIP) (ml)	24
Amount of oil recovered during 2nd recovery (ml)	18.5
Residual oil in place (ROIP) (ml)	5.5

Type of fluid injected into porous medium	**Flow rate (ml/min)**
Brine saturation	1.0
Oil saturation	0.8
Brine 2nd recovery	1.0
CNT nanofluid	1.0
Brine 3rd recovery	1.0

2PV of CNT nanofluid being injected into the porous medium	2 X PV of porous medium = 2 X 25.13 = 50.26 ml

Differential pressure of porous medium taken during tertiary recovery when CNT nanofluid is injected

Data collected when 50.26 ml of CNT nanofluid is injected into the porous medium

Pore Volume	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
Δ P	2.6	2.6	2.7	2.8	3.2	3.6	4	4.2	4.8	5.1
ROIP	0.1	0.1	0.1	0.05	0.1	0.1	0.1	0.1	0.1	0.05
∑ ROIP	0.1	0.2	0.3	0.35	0.45	0.55	0.65	0.75	0.85	0.9
ROIP%	1.8	3.6	5.5	6.4	8.2	10	11.8	13.6	15.5	16.4

Data collected when brine is injected into the porous medium after CNT nanofluid injection

Pore Volume	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
Δ P	5.7	6.3	6.8	7.1	7.1	6.8	6.5	6.6	6.7	6.7
ROIP	0.1	0.1	0.1	0.1	0.1	0.05	0.1	0.05	0.05	0.05
∑ ROIP	1	1.1	1.2	1.3	1.4	1.45	1.55	1.6	1.65	1.7
ROIP%	18.2	20	21.8	23.6	25.5	26.4	28.2	29	30	31

Pore Volume	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
Δ P	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
ROIP	0.05	0	0	0	0	0	0	0	0	0
∑ ROIP	1.75	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
ROIP%	31.8	31.8	31.8	31.8	31.8	31.8	31.8	31.8	31.8	31.8

Reduction in permeability calculation using Darcy's law equation

$$q = \frac{kA(p_1 - p_2)}{\mu L}$$

In this experiment, flow rate, area of porous medium, fluid viscosity and length of the medium is made constant; hence the permeability will be calculated as

$$k = \frac{1}{(P_1 - P_2)}$$

So therefore, the permeability that occurs in the porous medium when 0.05wt% of MWNT nanofluid being injected into the porous medium is 0.2mD.

$$k = \frac{1}{(6.5 - 1.5)}$$

$$k = 0.2mD$$

A.1.3 0.1wt% of CNT nanofluid

Dry Weight of porous medium (gram)	745.2
Wet Weight of porous medium (gram)	772.49
Difference in porous weight (Δgram)	27.29
Density of brine saturated the core (g/cm3)	1.006
Pore Volume of core (ml)	27.13
Pressure of porous medium after brine saturation (Δpsi)	0.7
Pressure of porous medium after oil saturation (Δpsi)	1.7
Pressure of porous medium after 2nd recovery using brine (Δpsi)	2.4
Original oil in place (OOIP) (ml)	26
Amount of oil recovered during 2nd recovery (ml)	21
Residual oil in place (ROIP) (ml)	5

Type of fluid injected into porous medium	**Flow rate (ml/min)**
Brine saturation	1.0
Oil saturation	0.8
Brine 2nd recovery	1.0
CNT nanofluid	1.0
Brine 3rd recovery	1.0

2PV of CNT nanofluid being injected into the porous medium	2 X PV of porous medium = 2 X 27.13 = 54.26 ml

Differential pressure of porous medium taken during tertiary recovery when CNT nanofluid is injected

Data collected when 54.26ml of CNT nanofluid is injected into the porous medium

Pore Volume	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
Δ P	2.4	2.4	2.6	2.8	3.1	3.1	3.3	3.5	3.9	4.4
ROIP	0.1	0.05	0.1	0.025	0.05	0.05	0.025	0.1	0.1	0.05
∑ ROIP	0.1	0.15	0.25	0.275	0.325	0.375	0.4	0.5	0.6	0.65
ROIP%	2	3	5	5.5	6.5	7.5	8	10	12	13

Data collected when brine is injected into the porous medium after CNT nanofluid injection

Pore Volume	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
Δ P	2.5	3.1	3.6	3.9	3.9	3.8	3.8	3.6	3.6	3.6
ROIP	0.1	0	0.1	0.05	0.05	0.05	0.05	0.1	0	0
∑ ROIP	0.75	0.75	0.85	0.9	0.95	1	1.05	1.15	1.15	1.15
ROIP%	15	15	17	18	19	20	21	23	23	23

Pore Volume	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
Δ P	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6
ROIP	0	0	0	0	0	0	0	0	0	0
∑ ROIP	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15
ROIP%	23	23	23	23	23	23	23	23	23	23

Reduction in permeability calculation using Darcy's law equation

$$q = \frac{kA(p_1 - p_2)}{\mu L}$$

In this experiment, flow rate, area of porous medium, fluid viscosity and length of the medium is made constant; hence the permeability will be calculated as

$$k = \frac{1}{(P_1 - P_2)}$$

So therefore, the permeability that occurs in the porous medium when 0.1wt% of MWNT nanofluid being injected into the porous medium is 0.833mD.

$$k = \frac{1}{(3.6 - 2.4)}$$

$$k = 0.833mD$$

A.2 Data collected and ROIP computation of core flooding experiment to study the impact of CNT nanofluid flow rates on permeability which are

A.2.1 CNT nanofluid injected at 0.5ml/min of flow rate

Dry Weight of porous medium (gram)	745.44
Wet Weight of porous medium (gram)	770.95
Difference in porous weight (Δgram)	25.51
Density of brine saturated the core (g/cm3)	1.006
Pore Volume of core (ml)	25.36
Pressure of porous medium after brine saturation (Δpsi)	1.1
Pressure of porous medium after oil saturation (Δpsi)	2.5
Pressure of porous medium after 2nd recovery using brine (Δpsi)	1.5
Original oil in place (OOIP) (ml)	24
Amount of oil recovered during 2nd recovery (ml)	20
Residual oil in place (ROIP) (ml)	4

Type of fluid injected into porous medium	**Flow rate (ml/min)**
Brine saturation	1.0
Oil saturation	0.8
Brine 2nd recovery	1.0
CNT nanofluid	0.5
Brine 3rd recovery	1.0

2PV of CNT nanofluid being injected into the porous medium	2 X PV of porous medium = 2 X 25.36 = 50.72 ml

Differential pressure of porous medium taken during tertiary recovery when CNT nanofluid is injected

Data collected when 50.72 ml CNT nanofluid is injected into the porous medium

Pore Volume	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
Δ P	1.5	1.5	1.7	1.7	1.8	1.8	1.9	2	2.2	2.3
ROIP	0.2	0.05	0.05	0.1	0.05	0.1	0	0.1	0.15	0
∑ ROIP	0.2	0.25	0.3	0.4	0.45	0.55	0.55	0.65	0.8	0.8
ROIP%	5	6.25	7.5	10	11.25	13.75	13.75	16.25	20	20

Data collected when brine is injected into the porous medium after CNT nanofluid injection

Pore Volume	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
Δ P	3.8	4.2	5	5.8	5.8	5.6	5.4	5.4	5.3	5.2
ROIP	0.1	0	0.05	0.1	0	0.1	0	0	0	0
∑ ROIP	0.9	0.9	0.95	1.05	1.05	1.15	1.15	1.15	1.15	1.15
ROIP%	22.5	22.5	23.75	26.25	26.25	28.75	28.75	28.75	28.75	28.75

Pore Volume	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
Δ P	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2
ROIP	0	0	0	0	0	0	0	0	0	0
∑ ROIP	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15
ROIP%	28.75	287.75	28.75	28.75	28.75	28.75	28.75	28.75	28.75	28.75

Reduction in permeability calculation using Darcy's law equation

$$q = \frac{kA(p_1 - p_2)}{\mu L}$$

In this experiment, flow rate, area of porous medium, fluid viscosity and length of the medium is made constant; hence the permeability will be calculated as

$$k = \frac{1}{(P_1 - P_2)}$$

So therefore, the permeability that occurs in the porous medium when 0.01wt% of MWNT nanofluid being injected into the porous medium at the flow rate of 0.5ml/min is

$$k = \frac{1}{(5.2 - 1.5)}$$

$$k = 0.27mD$$

A.2.2 CNT nanofluid injected at 1ml/min of flow rate

Dry Weight of porous medium (gram)	747.62
Wet Weight of porous medium (gram)	772.62
Difference in porous weight (Δgram)	24.95
Density of brine saturated the core (g/cm3)	1.006
Pore Volume of core (ml)	24.8
Pressure of porous medium after brine saturation (Δpsi)	1.2
Pressure of porous medium after oil saturation (Δpsi)	3.6
Pressure of porous medium after 2nd recovery using brine (Δpsi)	1.5
Original oil in place (OOIP) (ml)	24
Amount of oil recovered during 2nd recovery (ml)	21
Residual oil in place (ROIP) (ml)	3

Type of fluid injected into porous medium	Flow rate (ml/min)
Brine saturation	1.0
Oil saturation	0.8
Brine 2nd recovery	1.0
CNT nanofluid	1.0
Brine 3rd recovery	1.0

2PV of CNT nanofluid being injected into the porous medium	2 X PV of porous medium = 2 X 24 = 49.6 ml

Differential pressure of porous medium taken during tertiary recovery when CNT nanofluid is injected

Data collected when 49.6ml CNT nanofluid is injected into the porous medium

Pore Volume	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
Δ P	2.5	2.6	3.2	3.3	3.3	3.3	3.2	3.1	3.1	3.1
ROIP	0.05	0.075	0.05	0.05	0.025	0	0	0.1	0.1	0.1
∑ ROIP	0.05	0.125	0.175	0.225	0.25	0.25	0.25	0.35	0.45	0.55
ROIP%	1.67	4.167	5.83	7.5	8.33	8.33	8.33	11.67	15	18.33

Data collected when brine is injected into the porous medium after CNT nanofluid injection

Pore Volume	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
Δ P	2.8	2.8	2.8	2.4	2.4	2.5	2.5	2.5	2.5	2.5
ROIP	0.025	0	0	0.1	0	0.1	0.1	0	0	0
∑ ROIP	0.575	0.575	0.575	0.675	0.675	0.775	0.875	0.875	0.875	0.875
ROIP%	19.17	19.17	19.17	22.5	22.5	25.83	29.17	29.17	29.17	29.17

Pore Volume	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
Δ P	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
ROIP	0	0	0	0	0	0	0	0	0	0
∑ ROIP	0.875	0.875	0.875	0.875	0.875	0.875	0.875	0.875	0.875	0.875
ROIP%	29.17	29.17	29.17	29.17	29.17	29.17	29.17	29.17	29.17	29.17

Reduction in permeability calculation using Darcy's law equation

$$q = \frac{kA(p_1 - p_2)}{\mu L}$$

In this experiment, flow rate, area of porous medium, fluid viscosity and length of the medium is made constant; hence the permeability will be calculated as

$$k = \frac{1}{(P_1 - P_2)}$$

So therefore, the permeability that occurs in the porous medium when 0.01wt% of MWNT nanofluid being injected into the porous medium at the flow rate of 1ml/min is

$$k = \frac{1}{(2.5 - 1.5)}$$

$$k = 1mD$$

A.2.3 CNT nanofluid injected at 2 ml/min of flow rate

Dry Weight of porous medium (gram)	770.82
Wet Weight of porous medium (gram)	745.89
Difference in porous weight (Δgram)	24.93
Density of brine saturated the core (g/cm3)	1.006
Pore Volume of core (ml)	24.78
Pressure of porous medium after brine saturation (Δpsi)	0.8
Pressure of porous medium after oil saturation (Δpsi)	2.2
Pressure of porous medium after 2nd recovery using brine (Δpsi)	1.3
Original oil in place (OOIP) (ml)	24
Amount of oil recovered during 2nd recovery (ml)	19.5
Residual oil in place (ROIP) (ml)	4.5

Type of fluid injected into porous medium	**Flow rate (ml/min)**
Brine saturation	1.0
Oil saturation	0.8
Brine 2nd recovery	1.0
CNT nanofluid	2.0
Brine 3rd recovery	1.0

2PV of CNT nanofluid being injected into the porous medium	2 X PV of porous medium = 2 X 24.78 = 49.56 ml

Differential pressure of porous medium taken during tertiary recovery when CNT nanofluid is injected

Data collected when 49.56 ml of CNT nanofluid is injected into the porous medium

Pore Volume	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
Δ P	1.4	1.7	1.8	2	2	2	2	1.7	1.7	1.7
ROIP	0.1	0.05	0	0.1	0.05	0.1	0.1	0.1	0.1	0.05
∑ ROIP	0.1	0.15	0.15	0.25	0.3	0.4	0.5	0.6	0.7	0.75
ROIP%	2.22	3.33	3.33	5.56	6.67	8.89	11.11	13.33	15.56	16.67

Data collected when brine is injected into the porous medium after CNT nanofluid injection

Pore Volume	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
Δ P	1.3	1.4	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
ROIP	0.15	0.1	0.1	0.1	0.1	0.1	0.05	0.1	0.05	0.05
∑ ROIP	0.9	1	1.1	1.2	1.3	1.4	1.45	1.55	1.6	1.65
ROIP%	20	22.22	24.44	26.67	28.89	31.11	32.22	34.44	35.56	36.67

Pore Volume	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
Δ P	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
ROIP	0	0	0	0	0	0	0	0	0	0
$\sum$ ROIP	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65
ROIP%	36.67	36.67	36.67	36.67	36.67	36.67	36.67	36.67	36.67	36.67

Reduction in permeability calculation using Darcy's law equation

$$q = \frac{kA(p_1 - p_2)}{\mu L}$$

In this experiment, flow rate, area of porous medium, fluid viscosity and length of the medium is made constant; hence the permeability will be calculated as

$$k = \frac{1}{(P_1 - P_2)}$$

So therefore, the permeability that occurs in the porous medium when 0.01wt% of MWNT nanofluid being injected into the porous medium at the flow rate of 2ml/min is

$$k = \frac{1}{(1.5 - 1.3)}$$

$$k = 5mD$$

A.3 Data collected and ROIP computation of core flooding experiment to study the impact of CNT nanofluid under the presence of electromagnetic wave

Dry Weight of porous medium (gram)	747.33
Wet Weight of porous medium (gram)	772.6
Difference in porous weight (Δgram)	25.27
Density of brine saturated the core (g/cm3)	1.006
Pore Volume of core (ml)	25.12
Pressure of porous medium after brine saturation (Δpsi)	1.1
Pressure of porous medium after oil saturation (Δpsi)	6
Pressure of porous medium after 2nd recovery using brine (Δpsi)	3.5
Original oil in place (OOIP) (ml)	24.5
Amount of oil recovered during 2nd recovery (ml)	20
Residual oil in place (ROIP) (ml)	4.5

Type of fluid injected into porous medium	**Flow rate (ml/min)**
Brine saturation	1.0
Oil saturation	0.8
Brine 2nd recovery	1.0
CNT nanofluid	2.0
Brine 3rd recovery	1.0

2PV of CNT nanofluid being injected into the porous medium	2 X PV of porous medium = 2 X 25.12 = 50.24 ml

Differential pressure of porous medium taken during tertiary recovery when CNT nanofluid is injected

Data collected when 50.24 ml CNT nanofluid is injected into the porous medium

Pore Volume	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
Δ P	5.1	5.3	5.4	5.6	6.1	7.6	9	11.1	12.5	14
ROIP	0.05	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
∑ ROIP	0.05	0.15	0.25	0.35	0.45	0.55	0.65	0.75	0.85	0.95
ROIP%	1.11	3.33	5.56	7.78	9.99	12.22	14.44	16.67	18.89	21.11

Data collected when brine is injected into the porous medium after CNT nanofluid injection

Pore Volume	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
Δ P	6.6	6.9	7.1	7.1	7.5	7.5	7.2	7	6.9	6.8
ROIP	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
∑ ROIP	1.05	1.15	1.25	1.35	1.45	1.55	1.65	1.75	1.85	1.95
ROIP%	23.33	25.56	27.78	29.99	32.22	34.44	36.67	38.89	41.11	43.33

Pore Volume	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
Δ P	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.1	6.1	6.1
ROIP	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0	0
∑ROIP	2.05	2.15	2.25	2.35	2.45	2.55	2.65	2.75	2.75	2.75
ROIP%	45.55	47.78	49.99	52.22	54.44	56.67	58.89	61.1	61.1	61.1

Pore Volume	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
Δ P	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1
ROIP	0	0	0	0	0	0	0	0	0	0
∑ ROIP	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75
ROIP%	61.1	61.1	61.1	61.1	61.1	61.1	61.1	61.1	61.1	61.1

Reduction in permeability calculation using Darcy's law equation

$$q = \frac{kA(p_1 - p_2)}{\mu L}$$

In this experiment, flow rate, area of porous medium, fluid viscosity and length of the medium is made constant; hence the permeability will be calculated as

$$k = \frac{1}{(P_1 - P_2)}$$

So therefore, the permeability that occurs in the porous medium when 0.01wt% of MWNT nanofluid being injected into the porous medium at the flow rate of 2 ml/min under the presence of electromagnetic wave is

$$k = \frac{1}{(6.1 - 3.5)}$$

$$k = 0.38mD$$

APPENDIX B

Final Year Project 1

No	Description	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Selection of project topic	■	■	■	■			Mid-semester break							
2	Preliminary research study to understand about topic			■	■	■	■								
3	Submission of extended proposal						★								
4	Proposal defence presentation									★					
5	Further literature review study on application of nanoparticle in EOR in presence of EM wave								■	■	■	■	★		
6	Design flow of project activities using core-flooding experiment								■	■	■	★			
7	Core-flooding experiment set-up										■	■	■	■	■
8	Interim report preparation											■	■	■	
9	Submission of interim draft report													★	
10	Submission of interim report														★

Final Year Project 2

No	Description	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Characterization of CNT nanomaterial	■	■					Mid-Semester break							
2	Preparation of CNT nanofluid	■	■												
3	Carry out core flooding experiment			■	■	■	■		■	■					
4	Submission of progress report						★								
5	Results and discussion					■	■		■	■	■	■			
6	Reports preparation								■	■	■	■	■		
7	Pre-Sedex Presentation											★			
8	Sedex Presentation												★		
9	Submission of draft reports											★			
10	Submission of dissertation (softbound)												★		
11	Submission of technical report												★		
12	Oral presentation													★	
13	Submission of dissertation (hardbound)														★

■ Activities

★ Key Milestones