ENHANCE OIL RECOVERY BY ULTRASONIC WAVES

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CHEMICAL ENGINEERING
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JULY 2009

Enhance Oil Recovery by Ultrasonic Waves

by

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

July 2009

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CERTIFICATION OF APPROVAL

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Approved by,

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July 2009

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 person.

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(NUR SYAZWANI BINTI KENNY YUSOFF)

ABSTRACT

In oil reservoirs about 60% of the original oil in place remains as residual oil after primary and secondary oil recovery due to geological and physical factors. By means of improved oil recovery (IOR) methods, additional oil can be mobilized. One of the alternatives is the application of waves in the reservoirs to overcome the interfacial tension between oil and water, resulting in reduction of capillary pressure in the pores and therefore, a higher oil recovery can be achieved. It is known that propagation of the sound waves depends on the elasticity, grain size and density of the rock. The development of methods for mobilizing residual oil trapped in porous media after primary and secondary recovery is becoming increasingly important. The lack of mechanistic understanding of the effects of vibration on mobilization of oil ganglia has prevented the method from being applied commercially in the field. The behavior of a non wetting ganglion of residual oil entrapped in a pore constriction and subjected to vibrations of the pore wall can be approximated by the equation of motion of an oscillator moving under the effect of the external pressure gradient, inertial oscillatory force, and restoring capillary force. When there is attenuation of waves, the oil droplets experience forced oscillations which can be liberated from its entrapped configuration if the acceleration of the wall exceeds an unplugging value or threshold value.

ACKNOWLEDGEMENTS

In the name of Allah, the most merciful, the Most Gracious, Praise to Him, who gave an opportunity to the author to complete her Final Year Project. Through Him everything is possible and this project can be completed despite those obstacles and hardship encountered.

The author would like to express her greatest gratitude to her project supervisor, Associate Professor Dr Isa b M Tan for his guidance and supervision. The idea of enhancing oil recovery by using ultrasonic waves is great and brilliant. Thank you for the time that you had spent to guide and supervise the author from the very beginning of the project until the end.

Thousand of thanks to the other colleagues, Mr Ridwan, Mr Shah (technicians), Mr Fikri and Mr Khaled (Post graduate students) from Petroleum and Geosciences Department who have given fullest support and help in finishing the project during experimental work.

Last but not least, the author would like to thank her parents and friends whom had supported and motivated her in many kinds of ways. For always being there to lift up her spirit and provide her all the needs to complete this project.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Oil is extracted from reservoir by primary, secondary and tertiary recovery. After primary and secondary recovery, about 50% of the residual oil remains in the reservoir. The main causes of the poor recovery of the first two production stages are due to the existence of the interfacial tension between oil and water, high oil viscosity, heterogeneities in the reservoir rock and also wettability factor [1]. The remaining oil is the target of tertiary recovery, which is also known as Enhanced Oil Recovery, EOR. Currently there are various promising methods of EOR such as infill drilling, reservoir stimulation by hydraulic fracturing and the uses of polymers for mobility control.

However, efforts are made to develop new technology and techniques with lower application risks and cost. In this project, the potential of mechanical waves for example ultrasonic waves in improving oil recovery will be investigated. This wave stimulation technology has the potential to enhance the oil recovery in depleted fields and lead to increase in oil cut. Recently, wave propagation to mobilize residual oil trapped in porous media becomes more significant. Wave attenuation techniques would replace the need for chemical stimulation which in some cases is not compatible with the reservoir rock or fluids.

1.2 Problem Statement

The remaining residual oil after primary and secondary oil recovery is mainly due to the existence of the interfacial tension between oil and water (capillary forces) and the heterogeneities in the reservoir rock. One of the applications to displace the remaining oil is by the attenuation of waves in the reservoir. Vibrating reservoir contents is thought to facilitate production by changing the capillary forces, adhesion between rocks and fluids and causing oil coalescence. Generating elastic waves/mechanical waves or vibrations in the reservoir can cause an acceleration of gravitational segregation of residual oil.

Even though the understanding of the conditions for oil-ganglia mobilization by waves and vibrations is well studied, a physical theory that could readily be used to calculate the mobilization conditions for given geometric parameters of the channel, frequency, and amplitude of the vibratory field is still missing.

1.3 Objectives and Scope of Study

In this project, the main objective is to investigate the impact and identify how wave attenuation affects oil recovery. This project will focus on the research of the behavior of residual oil in porous media (including the interfacial tension, capillary pressure, molecular interaction and etc.) and the potential and mechanism of waves to dislodge residual oil especially in finding the suitable magnitude of frequency and amplitude of the attenuated waves.

Besides, the water flooding simulation will also be conducted before the ultrasonic wave is applied to the core sample. The water flooding experiment will be conducted using Relative Permeability System until the amount of residual oil is obtained. The core sample that contains the residual oil is then will be placed in ultrasonic bath for further recovery.

The world oil resources are limited and the exploitation of oil fields to a higher degree is desirable. Thus, significant methods are required to improve the recovery rates of oil fields. During the last 10 years, interest in mechanical wave stimulation technology in EOR has increased. Various results have been achieved and continuous research and application testing efforts will be beneficial for oil industry. In fact, this technology has the potential for being a low-cost procedure for enhancing oil recovery in depleted fields.

CHAPTER 2

LITERATURE REVIEW

2.1 An Overview of Waves

A wave is any disturbance that transmits energy through matter or space. Sound is a type of energy that requires waves traveling through matter. The material or substance through which a wave may travel is called the medium. The medium for a wave can be any of the common states of matter: solid, liquid, or gas. Sound waves require a medium. The medium does not move with the energy. Sound waves travel by vibration of particles. If there are no particles, there will be no sound. Waves that require a medium are called mechanical waves. In addition to sound waves, ocean waves and seismic waves require a medium. Therefore ocean waves and seismic waves are mechanical waves.

Waves that do not require a medium are called electromagnetic waves (or E-M waves). Electromagnetic waves can travel through solids, liquids, and gases, but they travel fastest through empty space. Waves are classified based on the direction in which the particles of the medium vibrate compared with the direction in which the waves travel. There are three classifications of waves based on this criterion.

I. **Transverse waves** are waves in which the particles of the medium vibrate with an up and down motion. Particles in a transverse wave move perpendicular to the direction that the wave is traveling. The crest is the highest point of a transverse wave. The trough is the lowest point of a transverse wave. Although electromagnetic waves do not require a medium, they are considered transverse waves. When studying seismic waves associated with earthquakes, these are the S-waves.

II. **Longitudinal waves** are waves in which the particles of the medium vibrate back and forth along the path that the wave travels. A compression is a section of longitudinal wave where the particles are crowded together. A rarefaction is a section of the wave where particles are less crowded than normal. Sound waves are longitudinal waves.

III. **Surface wave.** When waves occur at or near the boundary between two media, a transverse wave and a longitudinal wave can combine to form a surface wave. An example of a surface wave is a type of seismic wave formed as a result of an earthquake.

2.2 Earthquakes Effects on Oil Recovery

Figure 1 shows the aggregate oil and water production, and oil cut at 58 producers in ChevronTexaco's Lost Hill Diatomite Reservoir in California. During September and October 1999, there were earthquakes ranging from 5.2 to 7.1 on the Richter scale with epicentres located about 233 miles away at Hector Mine. There is a clear response to the earthquake in terms of a short increase in oil production. Subsequently, a single slimhole Hydro-Impact Tool was installed and operated for three and a half months from June through November 2000 [12].

This gives a clear comparison between the response of the oil field to earthquake events and artificially induced shock waves, both producing about the same effect on oil production. It is clear that the high energy elastic waves generated by the Applied Seismic Research Corporation Hydro-Impact Tool are similar to the seismic waves created by earthquakes. Once the stimulation stopped the response came back on trend [11]

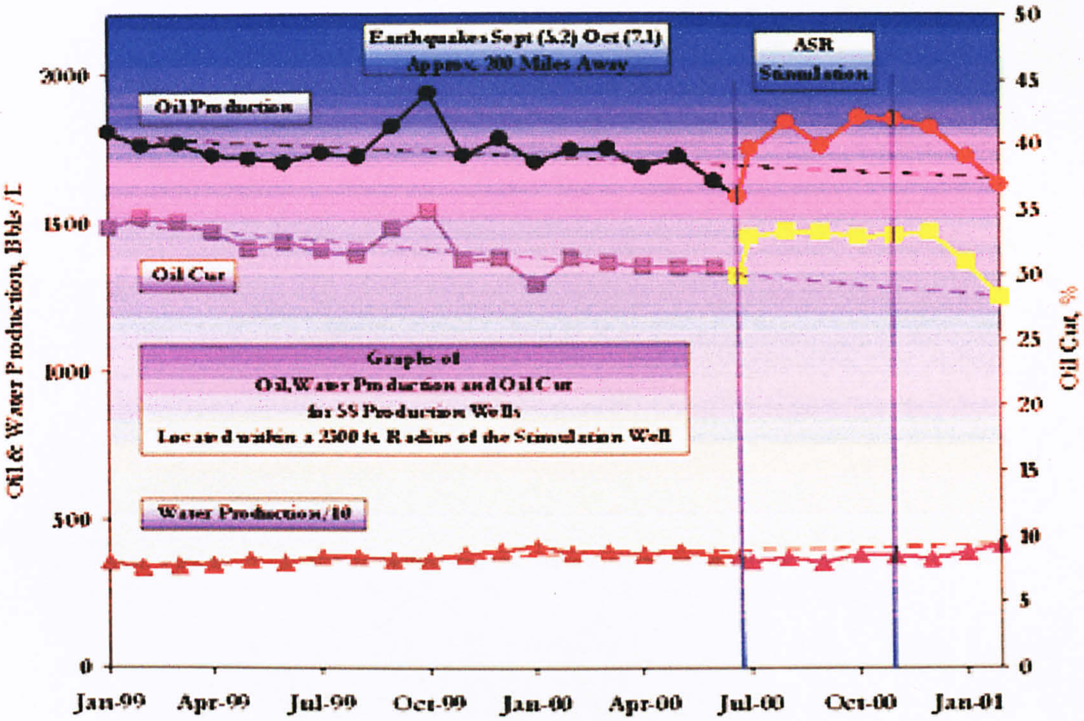

Figure 1 : Effect of Earthquakes and Seismic Stimulation at ChevronTexaco's Lost Hills Reservoir [11]

It is postulated that as the elastic waves migrate through the porous media they cause deformation of the grain structure. Once the waves have passed the grains relax back into their normal structure and in so doing cause a vibrational frequency. This high frequency waves form causes oil droplets, otherwise too small to move, to coalesce into larger, mobile droplets. Similarly oil films are transformed into mobile droplets.

2.3 Ultrasonic Wave and Ultrasonic Cavitation

Ultrasound is cyclic sound pressure with a frequency greater than the upper limit of human hearing. Ultrasonic waves generate and evenly distribute cavitation implosions in a liquid medium. The released energies reach and penetrate deep into crevices, blind holes and areas that are inaccessible to other cleaning methods. The removal of contaminants is consistent and uniform, regardless of the complexity and the geometry of the substrates.

Ultrasonic waves are mechanical pressure waves formed by actuating the ultrasonic transducers with high frequency, high voltage current generated by electronic oscillators. A typical industrial high power generator produces ultrasonic frequencies ranging from 20 - 120 kHz. The generated ultrasonic waves propagate perpendicularly to the resonating surface. The waves interact with liquid media to generate cavitation implosions. High intensity ultrasonic waves create micro vapor/vacuum bubbles in the liquid medium, which grow to maximum sizes proportional to the applied ultrasonic frequency and then implode, releasing their energies. Higher frequency will lead to smaller cavitations' size.

The implosion also produces dynamic pressure waves which carry the fragments away from the surface. The implosion is also accompanied by high speed micro streaming currents of the liquid molecules. The cumulative effect of millions of continuous tiny implosions in a liquid medium is what provides the necessary mechanical energy to break physically bonded contaminants, speed up the hydrolysis of chemically bonded ones and enhance the solubilization of ionic contaminants. The chemical composition of the medium is an important factor in speeding the removal rate of various contaminants.

Several factors have great influence on the cavitations' intensity and abundance in a given medium. Among these factors are the ultrasonic wave form, its frequency and the power amplitude. Other determining factors are the colligative properties of the liquid medium, including viscosity, surface tension, density and vapor pressure; the medium temperature and the liquid flow, whether static or dynamic or laminar; and dissolved gases.

Recent investigations have confirmed that higher frequencies are more effective for the removal of certain contaminants. Reports on particle removal efficiency have shown that the removal efficiency of one micron and submicron particles in deionized water has increased with the higher frequency. At 65 kHz, the removal efficiency of a one micron particle is 95 percent, versus 88 percent at 40 kHz [10].

2.4 Vibrational Stimulation of Reservoir

Petroleum is initially produced due to the original reservoir pressure being higher than the complex forces of adherence to the porous media. As pressure decreases during production, a point of equilibrium is reached when the adhesion force are higher than the remaining pressure in place, leaving most part of the petroleum still in reservoir. Oil phase cannot move by its own pressure gradient due to the existence of threshold pressure value. The residual oil can be removed by other "pressure field".

Below are the summary of the effects of mechanical waves on the formation of residual oil in the porous medium:

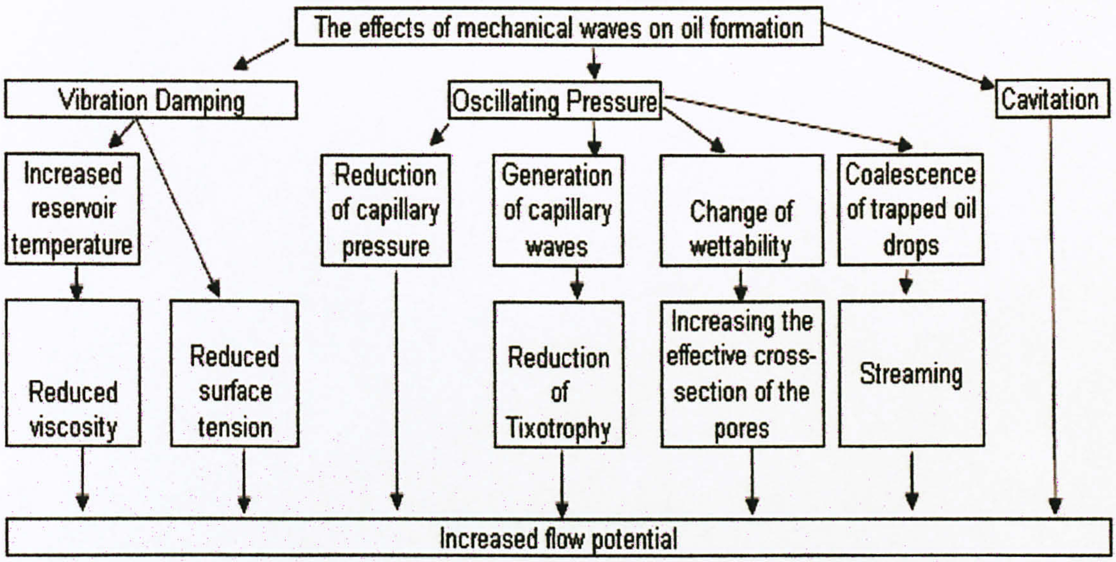

Figure 2 : Effects of mechanical waves

2.4.1 Reduction of capillary pressure

The equilibrium saturation in a petroleum reservoir prior to initiating its production is controlled by rock geometry and by fluid characteristics. Since water and hydrocarbons are immiscible fluids, a pressure differential exists. The capillary pressure, Pc is the pressure between the two fluid phases due to the attractive forces between the molecules in the different fluids.

The cohesive forces between molecules down into a liquid are shared with all neighboring molecules. Those on the surface have no neighboring molecules above, and therefore exhibit stronger attractive forces upon their nearest neighbors on the surface. This enhancement of the intermolecular attractive forces at the surface is called surface tension. Since capillary pressure may oppose to oil recovery, particularly in the case of small pores, it must be overcome by another pressure differential in order to displace the oil phase.

2.4.2 Capillary waves

Restoring Force is the force which attempts to bring the surface back to its original undisturbed state. There are waves/fluctuations generated at the interface of two fluids. In addition, capillary wave affects tixotrophy. Tixotrophy is a property of high molecular weight substances that can decrease their viscosity if subjected to a mechanical stress (without thermal stress). Tixotrophy behavior is due to the internal structure modifications of the fluid. Component molecules at rest in the liquid offer resistance to break-up, but there after take the flow direction and reduce their viscosity.

2.4.3 Change of wettability

Wettability of the reservoir measures the affinity which the rock exhibits to oil or water. It depends on the ability of adsorption and desorption of polar compounds and/or deposits of organic matter present in the crude oil The polar extremities of those molecules may be adsorbed onto the rock surface, forming a thin organic film which makes the surface oil wet.

2.4.4 Coalescing trapped oil drops

Acoustic stimulation can generate continuous streams of oil just allowing oil drops to be merged into "streams". Coalescence of oil drops is induced by "Bjerknes Force". Bjerknes Force is attractive forces acting between oscillating drops of one liquid in another that induces the coalescence of oil drops, enabling continuous streams of oil to flow.

Theoretically, this force caused the bubbles to either attract or repel each other depends upon whether the bubble pulsation are in phase or out of phase, respectively. In particular, when the frequency of an applied acoustic field was greater than or less the natural oscillation frequencies of both bubbles, then the bubbles were found to pulsate in phase and attract, where as if the driving frequency was in between the two natural frequencies, the bubbles would oscillate out of phase and repel each other.

CHAPTER 3

METHODOLOGY

3.1 Introduction

To validate the effectives and behavior of waves in mobilizing residual oil trapped in porous media, a few sets of experiments will be carried out. Basically, for water flooding experiment, the equipment used is Relative Permeability System and for further oil recovery, ultrasonic bath is used and the experiments will be based on the theory of ultrasonic cavitation. In this study, core samples analysis will be conducted with the following objectives:

This chapter outlines the experimental research work to be done in order to achieve the objectives of this study. Materials used, design of the experimental equipment, set up and experimental procedure are all described in the following sections.

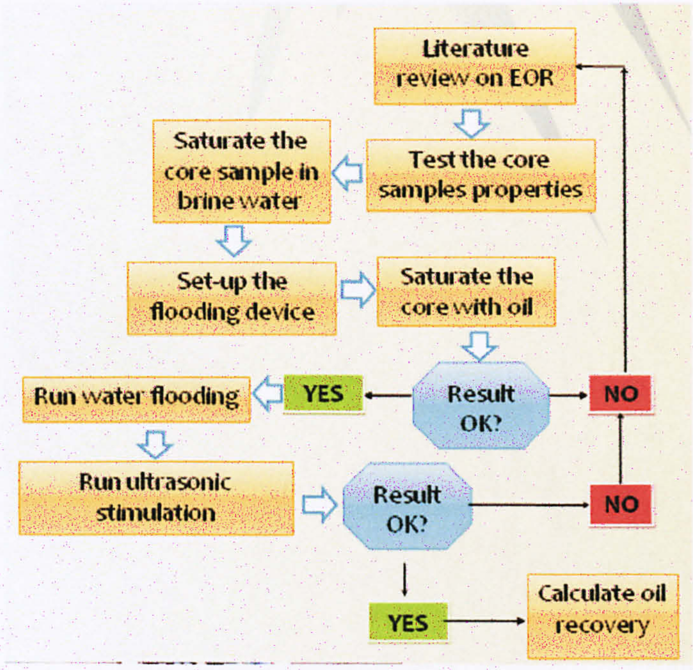

Figure 3 : Flow Chart of experiment

3.2 Materials Used

The materials used in this study were:

3.2.1 Crude Oil

The type of crude oil used is Angsi 163. Below are the properties of Angsi reservoir and Angsi crude oil.

Parameters	Quantity	Units
Carbonate Contents	7	ppm
Formation Thickness	31	meters
Average Porosity	22	%
Permeability	200	mD
Oil viscosity	3	cp
Oil density at 20°C	0.827	g/cm^3
Formation Temperature	119	°C
Clay contents	4-29	%
Salinity of brine	20,000	ppm
Saturation pressure	2514.95	psi
Current pressure	2199.93	psi
Reservoir depth	1730 - 1761	meters
Initial Oil in Place	26757600	m^3
Lithology	sandstone	-

Table 1 : Angsi Crude Oil Properties

3.2.2 Pore Medium

In all flooding experiments, sandstone cores from Malaysia with the range of ~ 3 inch in length and diameter of ~1.5 inch with average porosity of 26% were used. No oil was present in the cores. The physical properties of all core samples used in this study are presented in result and discussion part.

3.2.3 Brines

Synthetic model brines at salt concentration of 25 000 ppm were applied in flooding test. It also consists of 83% sodium chloride (NaCl) and 17% calcium chloride ($CaCl_2$).

3.3 Experiment Set-up

A schematic diagram and photograph of the experimental set-up used in this study were shown below. It comprised:

3.3.1 Memmert Universal Oven

Before each run, the core sample was dried overnight in a temperature controlled oven at 100^0C as shown in below:

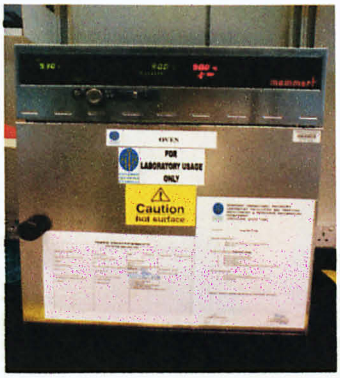

Figure 4 : Universal Oven

3.3.2 Soxhlet Extractor

Before each run, the core sample was cleaned for 48 hours by toluene in Soxhlet Extractor. It consists of cellulose timber, flask and extractor

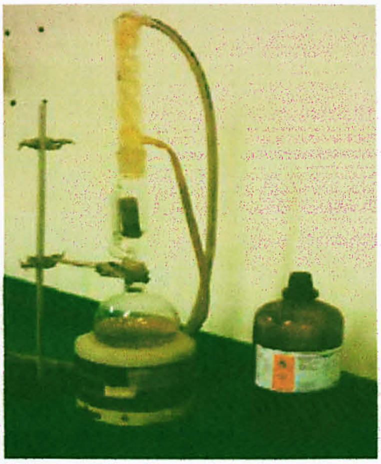

Figure 5 : Soxhlet Extractor

3.3.3 HePorosimeter Production Series

The system which is manufactured by VINCI Technologies FRANCE allows for automatic Grain Volume and Pore Volume determination on rock samples including unconsolidated or irregular shape samples.

Figure 6: HePorosimeter Production Series

3.3.4 Bench Top Permeability System

Bench Top Permeability System is used to measure the permeability of the saturated core. In this project, the permeability of the core will be measured before and after the core being saturated with the sample solution.

3.3.5 Manual Saturator

This Model SSC-2 Saturation System for cores is manufactured by TEMCO, Inc., USA. It is designed for saturating core samples with liquid. A hand pump draws the desired liquid from a reservoir and injects it into the saturation cell where the core sits. The pump and cell are mounted on a base plate.

Figure 7: Manual Saturator

3.3.6 Relative Permeability System

The TEMCO RPS-800-10000 HTHP Relative Permeability Test System is designed for Permeability and Relative Permeability flow testing of core samples, at in-situ conditions of pressure and temperature. Tests that can be performed with the system include initial oil saturation, secondary water flooding, tertiary water flooding, permeability, and relative permeability. Brine, oil, or other fluids can be injected into and through the core sample.

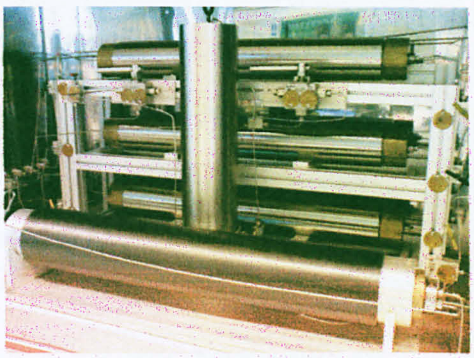

Figure 8: Relative Permeability System

3.3.7 Transsonic Ultrasonic Cleaning Units

The ELMA ultrasonic cleaning bath has ultrasonic transducers which is mounted under the tank floor turns electric energy into mechanic vibrations. The cleaning liquid (in this experiment we consider brine as the cleaning liquid) in the stainless-steel tank starts vibrating too.

During this process, tiny vacuum bubbles that produced are imploded. This is called cavitation. The cavitation will remove dirt (in this experiment we consider residual oil as the target) from every spot that the cleaning liquid reaches. The operation mode can be selected between the operation modes sweep, standard and degas by means of knob.

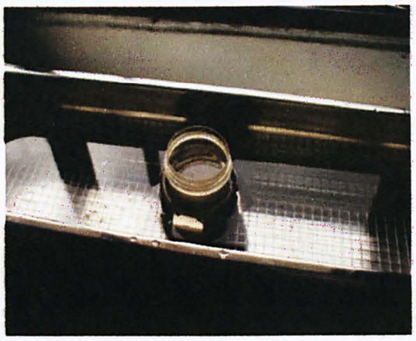

Figure 9: Ultrasonic Cleaning Unit

3.3.8 PASCO Temperature Sensor

This temperature sensor is used to automatically record the temperature profile of the ultrasonic stimulation system.

Figure 10 : PASCO Temperature Sensor

3.4 Experiment Procedure

In this project, the laboratory studies on oil recovery are basically divided into two major parts which are water flooding and ultrasonic cavitation. Overall, the experiments procedures are summarized as follows:

3.4.1 Porosity Measurement

Equipment of porosity measurement in this study was shown in Figure 9. The procedures of core porosity measurement are as follows:

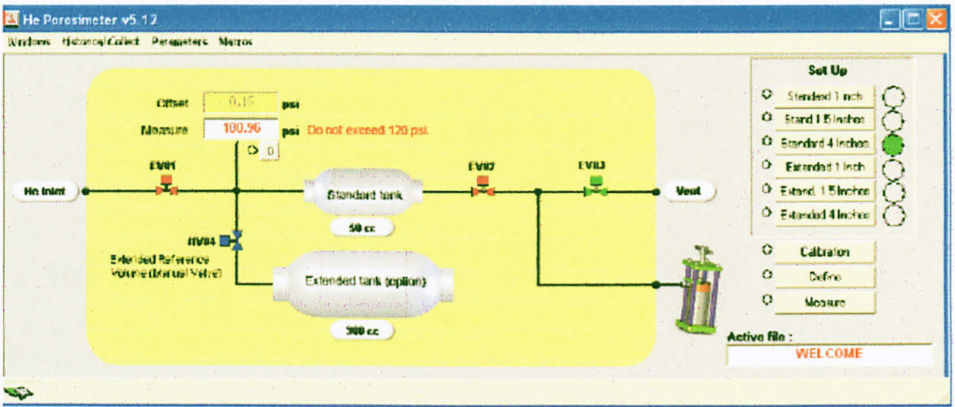

Figure 11: Computer Interface of Porosimeter

1. Before each run, the core sample was cleaned in Soxhlet Extractor for 48 hours and then dried in a Universal Oven at 100^0C for overnight. The core sample was then prepared for installation in the porosimeter
2. The computer interface was set as above. Initially, the EV01, EV02 and EV03 and HV04 valves are closed
3. In this experiment, the standard tank is used instead of extended tank. Thus, the HV04 is maintained closed during the experiment
4. Filled the standard tank with Helium gas.
   Set : (EV01-OPEN; EV02, EV03 and HV04-CLOSE)
5. Porosity measurement is started when standard tank is fully filled.
   Set : (EV02-OPEN; EV01, EV03 and HV04-CLOSE)

3.4.2 Permeability Measurement

1. The confining isolate and the confining bleed valves located on the front panel of the BPS-805 are closed.
2. The confining isolate valve on the panel is opened.
3. The confining fluid from the pump is pump slowly to the core holder until confining pressure reached to 1000psi.
4. The confining isolate valve on the panel is closed.
5. The saturated core sample is inserted in the downstream end of the holder.
6. The computer interface is set and start the experiment

3.4.3 Core Saturation

This equipment is used for manual saturation of brine in core sample. After the cell is filled with brine, the core samples are placed inside the cell. Pressurize the cell by setting the pressure of 1000 psi for at least 24 hours.

3.4.4 Flooding Experiment

The procedures of flooding experiment are shown below:

1. Core sample is installed in the core holder
2. The volume of tubing is measured
3. Overburden pressure is set to ~1400 psi
4. The system is heated to 60^{0}C (Viscosity of brine is 0.81 cp @ 60^{0}C and viscosity of crude oil is 2.48 cp @ 60^{0}C)
5. Floating piston accumulators are filled with fluid.(Accumulator A - Distilled Water, Accumulator B - Brine and Accumulator C - Crude Oil)
6. The inlet pressure is set to 800 psi. After that, the back pressure regulator is set to control the gas booster outlet pressure
7. For each core sample, the brine is injected first to obtain the initial permeability. Then continued by oil injection and finally water flooding
8. Oil is injected with flow rate of 1cc/min until there is no brine is displaced by oil. The value of displaced brine is recorded. This value indicates the amount of oil in place.

9. Run water injection with flow rate of 1cc/min until there is no oil is displaced by water. The value of displaced oil is recorded.
10. The amount of remaining oil after water injection is calculated. This value indicates the amount of residual oil in the core sample
11. Repeat the same steps for the next core samples

3.4.5 Ultrasonic Wave Experiment

For further recovery of oil after water flooding, the concept of ultrasonic cavitation is used. The summarized procedure as follows:

1. The bath is filled with 25 000 ppm brine
2. The weight of core sample is measured
3. Put the core sample in a container
4. Placed the core sample inside the ultrasonic bath
5. Temperature sensor is placed at the core sample surface
6. The ultrasonic unit is switched on and let the liquid degas
7. Any findings are recorded for every 40 minutes

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Initial Porosity and Permeability Measurement

By using Porosimeter, the porosity measurement is based on Boyle-Mariotte's law theory. The Boyle-Mariotte's Law is used to determine grain and pore volume from the expansion of a known mass of helium into a matrix cup.

$$\frac{P_{ref} * V_{ref}}{T_{ref}} = \frac{P_{exp} * V_{exp}}{T_{exp}}$$

Where,

P_{ref} = Reference Pressure (initial pressure)

V_{ref} = Reference Volume (initial volume)

T_{ref} = Reference Absolute Tempeature (initial temperature)

P_{exp} = Expanded Pressure (final pressure)

V_{exp} = Expanded Volume (final Volume)

T_{exp} = Expanded Absolute Temperature (final Temperature)

Based on definitions and theory, the values of grain and pore volumes are as follows and the data below shows the characteristics of each core samples:

- Porosity = Pore volume / bulk volume
- Pore volume = Bulk volume – grain volume
- Porosity = (Bulk volume – grain volume) / Bulk volume

Core	Length (cm)	Diameter (cm)	Bulk Volume (ml)	Pore volume (ml)	Porosity (%)	Area (cm^2)	Weight (g)	Permeability (md)
1	4.746	3.791	53.57	14.77	27.57	56.531	104.924	118.75
2	6.183	3.673	65.51	15.65	23.89	71.355	133.131	209.73
3	5.063	3.804	57.51	13.77	23.94	60.477	117.483	135.36

Table 2: Initial Characteristics of Core Samples

4.2 Oil Saturation and Water Flooding Process

The water flooding simulation is conducted using the Relative Permeability System, RPS. The user parameters are shown below:

Parameters	Values	Units
Viscosity of Oil	2.48	cp
Viscosity of Brine	0.81	cp
Inlet Pressure	800	psi
Overburden (Confining) Pressure	1500	psi
Temperature of Core Holder	60	^0C
Thermal Expansion Factor of Fluid	1.00	ml/ml
Formation Volume Factor of Fluid	1.00	ml/ml
Tubing line volume	2.2	ml

Table 3: User Parameters for RPS

The main objective of using the Relative permeability system is to get the amount of residual oil remains in the core sample after flooding. The results of the water flooding of each core samples are shown below.

The tubing volume must be taken into consideration for obtaining the exact value of oil in-placed in the core samples. In this experiment, the measured tubing volume is 2.2 cc. Thus, the volume of oil in-placed is calculated as follows:

Volume of oil in-placed = Amount of brine collected - Tubing volume

Volume of oil displaced oil = Volume of oil in-placed - Amount of oil collected

Residual oil = Displaced oil - Oil in-place

Core	Water Injection Flow rate (ml/min)	Absolute Permeabilty (md)	Oil Relative Permeability (md)	Water Injection Relative Permeability (md)
1	3.81	12.861	40.525	12.902
2	3.81	18.535	56.805	2.468
3	3.81	31.058	14.877	15.717

Core	Oil in-Place (ml)	Displaced Oil (ml)	Residual Oil (ml)
1	11.7	4.2	7.5
2	11.6	5.0	6.6
3	12.3	5.2	7.1

Table 4: Water Flooding Result

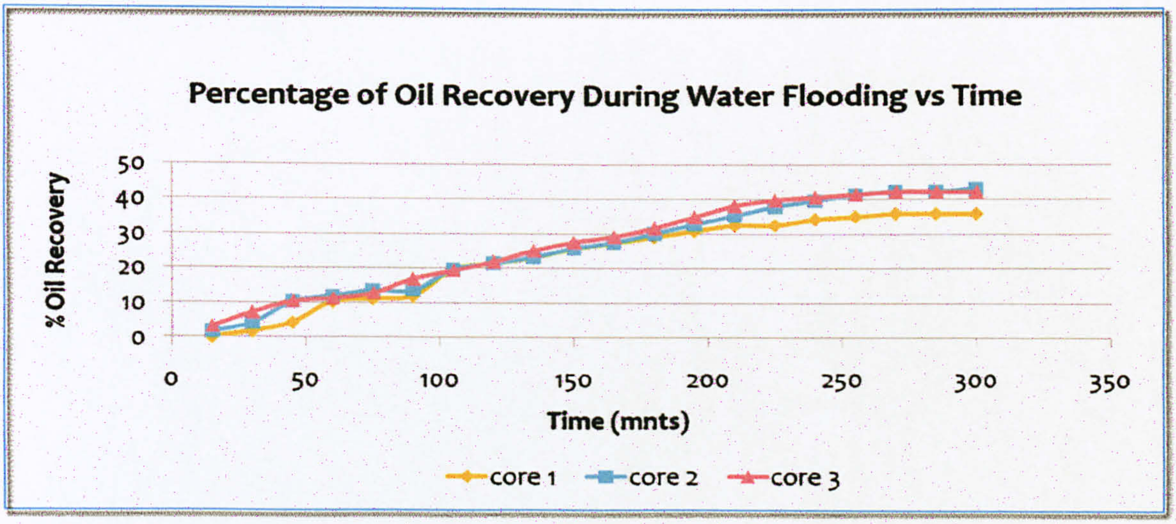

Figure 12 : Percentage of Oil Recovery During Water Flooding vs Time

4.3 Ultrasonic Stimulation

After the residual oil is obtained for each core sample, the core samples are placed inside the ultrasonic bath for further oil recovery. It was noted that the highest frequency of the ultrasonic device is 40 kHz. The results of experiment are shown below:

Ultrasonic Power (%)	Heating Temperature (^{O}C)	Time (minutes)	Cumulative Volume Oil Collected (mL)
10	60	0	0
		40	0
20	60	80	0
		120	0
30	60	160	0
		200	0
40	60	240	0.2
		280	0.37
50	60	320	0.46
		360	0.55
60	60	400	0.63
		440	0.63

Table 5 : Tabulated Data for Secondary Recovery of Core Sample 1

Ultrasonic Power (%)	Heating Temperature (^{O}C)	Time (minutes)	Cumulative Volume Oil Collected (mL)
10	60	0	0
		40	0
20	60	80	0
		120	0
30	60	160	0
		200	0
40	60	240	0
		280	0
50	60	320	0.1
		360	0.13
60	60	400	0.2
		440	0.34
70	60	480	0.34
		520	0.44
80	60	560	0.59
		600	0.65

90	60	640	0.65
		680	0.72
100	60	720	0.72
		760	0.72

Table 6 : Tabulated Data for Secondary Recovery of Core Sample 2

Ultrasonic Power (%)	Heating Temperature (^{O}C)	Time (minutes)	Cumulative Volume Oil Collected (mL)
40	50	0	0
		40	0
		80	0
		120	0
75	60	160	0
		200	0.1
		240	0.1
100	60	280	0.23
		320	0.23
90	70	360	0.3
		400	0.32
80	70	440	0.34
		480	0.34
		520	0.44
		560	0.46
		600	0.51
		640	0.53
		680	0.62
		720	0.62
		760	0.62

Table 7: Tabulated Data for Secondary Recovery of Core Sample 3

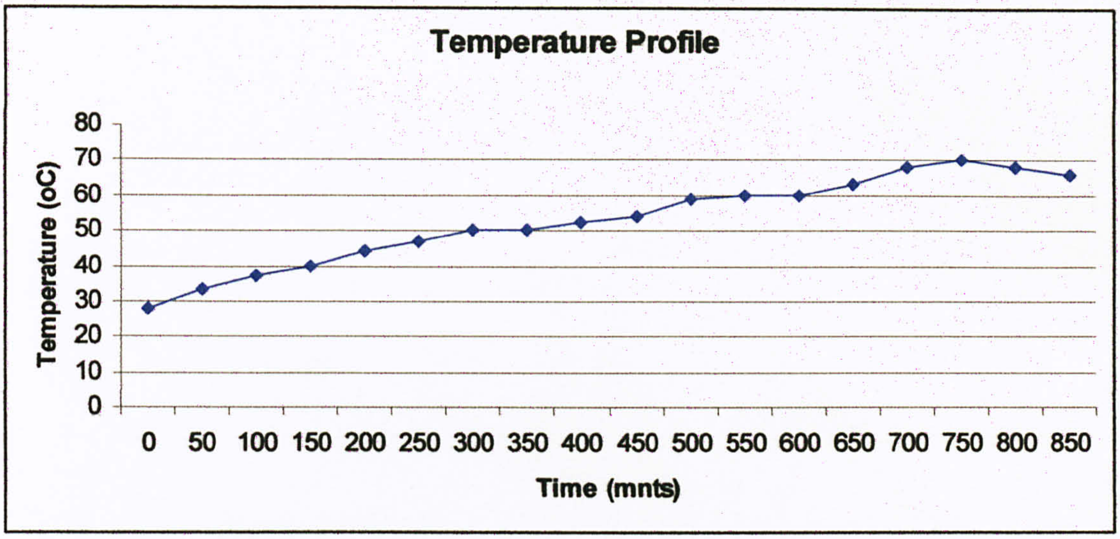

Figure 13: Temperature Profile vs Time

4.4 Final Porosity and Permeability Measurement

Core	Length (cm)	Diameter (cm)	Bulk Volume (ml)	Pore volume (ml)	Porosity (%)	Area (cm^2)	Weight (g)	Permeability (md)
1	4.711	3.791	52.06	15.54	29.57	56.53	103.924	131.75
2	6.024	3.673	65.32	15.61	23.92	71.36	133.122	209.61
3	5.020	3.804	57.39	13.65	23.71	60.48	117.441	135.27

Table 8: Final Characteristics of Core Samples

4.5 Detailed Calculation of the Experiment

a. Brine water calculation

The concentration of brine used is 25, 000 ppm. To produce the brine with the concentration of 25, 000 ppm, the below salts were used. These salts are prepared per 1 L of water.

- 80% x 25grams = 20 grams NaCl
- 10% x 25grams = 2.5 grams KCL
- 10% x 25grams = 2.5 grams $CaCl_2$

B. Tubing line volume measurement

The tubing line is measured for precise and accurate volume of oil recovery value. The volumes of lines are:

- Front tubing line : **1.4 ml**
- Back tubing line : **0.8 ml**

C. Oil recovery calculation by water injection

The amount of oil saturated inside the core sample is equal to the amount of water collected. Thus,

Volume of saturated oil = Volume of water collected – tubing volume

$$\text{Oil Saturation, So} = \frac{\text{Volume of saturated oil, Vo}}{\text{Volume of pore spaces}} \times 100\%$$

$$\text{Recovery percentage} = \frac{\text{Volume of oil displaced}}{\text{Volume of oil initially in-place}}$$

1. Core sample #1

Volume of saturated oil = 13.9ml – 2.2ml
= **11.7 ml**

$$\text{Oil saturation, So} = \frac{11.7\text{ ml}}{13.77\text{ml}} \times 100\% = \mathbf{85.4\ \%}$$

$$\text{Recovery percentage} = \frac{4.2\text{ ml}}{12.8\text{ ml}} \times 100\% = \mathbf{32.81\%}$$

2. Core sample #2

Volume of saturated oil = 13.8 ml – 2.2ml
= **11.6 ml**

Oil saturation, So $= \frac{11.6\ ml}{15.65ml} \times 100\%$
= **74.12 %**

Recovery percentage $= \frac{5.0\ ml}{11.6ml} \times 100\%$
= **43.10%**

3. Core sample #3

Volume of saturated oil = 14.5ml – 2.2ml
= **12.3 ml**

Oil saturation, So $= \frac{12.3ml}{13.77ml} \times 100\%$
= **89.93 %**

Recovery percentage $= \frac{5.2\ ml}{12.3\ ml} \times 100\%$
= **42.27%**

D. Oil recovery calculation by ultrasonic wave

1. Core sample #1

Volume of oil collected = **0.63 ml**

Recovery percentage $= \frac{0.63\ ml}{7.5\ ml} \times 100\%$
= **7.33 %**

2. Core sample #2

Volume of oil collected = **0.72 ml**

Recovery percentage $= \frac{0.72\ ml}{6.6\ ml} \times 100\%$
= **10.9 %**

3. Core sample #3

Volume of oil collected = **0.62 ml**

Recovery percentage $= \frac{0.62\ ml}{7.1\ ml} \times 100\%$
= **8.73 %**

4.6 Discussion of Experiment

4.6.1 Factors Affecting the water flooding stimulation

In water injection, viscosity of oil is one of the most important physical oil properties. The low viscosity of oil needs to be achieved to make sure the ease of flow of oil from inside the core sample to the surface. If the viscosity of oil is high, the corresponding liquid flow will be low and the affects the oil recovery.

At the same time in multiphase flow through porous media is due to capillary pressure which is also affected by viscosity and gravitational force.

4.6.2 Ultrasonic Effects on experiment

In ultrasonic stimuation, cavitation plays an important process. The effectiveness of cavitation in ultrasonic stimulation requires some parameters need to be fulfilled. The parameters such as temperature, viscosity of oil and amount of gas content in the liquid. These parameters will affect the intensity and the effectiveness to dislodge the oil from cores by implosion of bubble during cavitation.

In this experiment, the viscosity needs to be lower as possible to make the trapped oil in the core sample easily to be moved. Thus, the temperature must be at optimum to achieve the lowest viscosity of oil as possible. In this experiment the optimum temperature is 71 ^{0}C.

In addition, the ultrasonic device also has 'degas' button to increase cavitation effectiveness. Degas will eliminate dissolve gas in the liquid as much as possible. Gaseous which dissolve in the liquid is released during the bubble growth phase of cavitations (violent implosion). At the same time the higher the temperature, the lower the amount of gas dissolve in the liquid.

Basically, the main concept in ultrasonic stimulation is ultrasonic cavitation. This is the phenomenon whereby the principle of ultrasonic cleaning can be understood. In a liquid medium the ultrasonic waves, generated by an opposite electronic ultrasounds generator and a special transducer suitably mounted under the bottom of a stainless steel tank, produce compression and vacuum waves at a very high speed, the speed depending on the working frequency of the ultrasonic generator. They normally work at a frequency between 28 and 50 kHz. The pressure and vacuum waves in the liquid cause the phenomenon known as "ultrasonic cavitation".

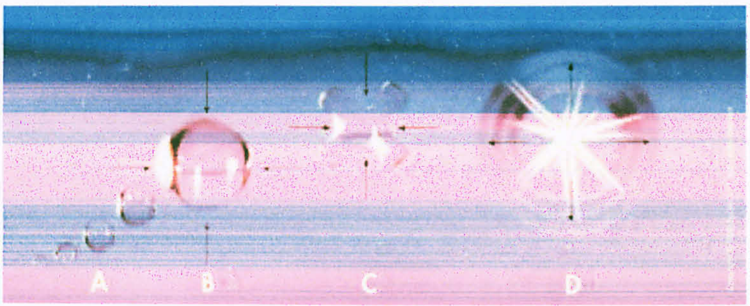

Figure 14 : Cavities Formation [14]

During the vacuum phase (A) numerous bubbles of gas are formed in the liquid and which enlarge for the duration of the acoustic vacuum phase. This formation of microscopic bubbles of gas is the start of cavitation.

During the second phase of ultrasonic compression (B), the numerous pressure exerted on the newly expanded bubble compresses the same, hugely increasing the temperature of the gas contained in it (C) until the bubble collapse on itself, imploding with a consequent vast release of impact energy (D).

The impact energy caused by implosion of the gas bubble hits the surface of the object to be cleaned, interacting both physically and chemically. In physical terms a "micro brushing" effect is achieved at very high frequency with the cleansing effect of the chemical substance present in the detergent of the ultrasonic bath [14]. **In this, project, the author was not using any chemical substance/surfactant as detergent. The explanations are for understanding and reference for future work.**

The temperature of the aqueous solution in an ultrasonic cleaning bath is very important, as the cavitation intensity varies as the temperature varies. It also increases as the temperature increases up to around 70°C and then decreases and stops completely at the temperature of boiling liquid. If there is chemical or detergent being used, another important parameter to be considered is the vapor pressure of the detergent solution used.

Vapor tension or pressure refers to the following concept: if we consider a liquid in a closed and temperature controlled recipient, the surface molecules which have sufficient energy, change to the vapor state and occupy the available space above the liquid.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

The ultimate aim of this research is to investigate the effect of wave simulation as new proposed method to improve oil recovery after water flooding and to identify the recovery mechanism. In this progress report, the first phase of experiment which was water flooding was successfully conducted. The residual oil remain in the core shows that there is still limitation of water flooding which can only displaced a certain amount of oil. The remaining oil which is also known as residual oil is then further recovered by ultrasonic stimulation. The author has found that the ultrasonic stimulation is a potential energy source for tertiary recovery. The average oil recovery during ultrasonic stimulation is 9%. It is concluded that the main factor of oil recovery during ultrasonic stimulation is the high local heating in the pores which caused the trapped oil in the core sample to be dislodged.

In addition, there are a few recommendations for future work since this project has potential and need to be further studied. One of the recommendations is to add surfactant into the ultrasonic bath during ultrasonic stimulation. Since the experiment is only ran at the highest frequency of 40kHz, a higher frequency need to be tested on the core sample since from the experiment result stated that as the frequency getting higher the oil recovery oil increases. To obtain more accurate result, the experiment needs to be done at the reservoir conditions which has high pressure and high temperature.

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