ENHANCED OIL RECOVERY BY USING EM WAVE AND NANOPARTICLES

By

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FINAL PROJECT REPORT

Submitted to the Electrical & Electronics Engineering Programme
in Partial Fulfillment of the Requirements
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(Electrical & Electronics Engineering)

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CERTIFICATION OF APPROVAL

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CERTIFICATION OF ORIGINALITY

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

Mohd. Afik bin Mat Yusof

ABSTRACT

Production from heavy oil reservoirs has always been a challenge due mainly to one factor in particular high oil viscosity, implying low oil mobility within porous media.

Different methods have been implemented over the years in order to reduce oil viscosity. Well-known methods include steam injection (e.g., Steam Drive, Steam Assisted Gravity-SAGD), CO2 injection, chemical injection etc [1]. These types of application are mainly applied to onshore fields where space is available and operating costs are much lower with respect to offshore fields. Moreover they may not be feasible for shallow reservoirs where injection could be an issue due to uncertainties regarding the cap-rock sealing. The scope of this report is to present a patented non-conventional EOR method for heavy oil reservoirs using radio frequency/electromagnetic heating. An adequate completion design and well-reservoir connection is used for heating the oil. Consequently, oil viscosity may be reduced, thus allowing its continuous production to surface (eventually by means of an artificial lift system included in the well completion) [2]. This method could be also suitable for offshore fields because it does not require high energy consumption, or large surface areas, or high operating costs. It can also be suitable for those shallow reservoirs not suitable for injection processes. This paper presents details of this new technology and associated simulation results showing its range of implementation.

ACKNOWLEDGEMENTS

I would like to show my highest gratitude to The Almighty God for giving me the chance to complete this project. Throughout finishing the project, there were many people who helped me a lot. Their contributions to my project can never be paid. I want to take this opportunity to thank them and hopefully they can keep the good work up ahead. My most gratitude goes to my supervisor, Prof. Dr. Noorhana Yahya for guiding me throughout the last two semesters. Without her support, I would never be able to achieve this. Last but not least, to all the postgraduate students who were always there to help me whenever I needed them. Only God can pay all of your kindness. To my beloved family, thank you for always believing in me, supporting me and making me believe to finish my study.

Only God knows how to pay all of your kindness.

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LIST OF ABBREVIATIONS

EOR	Enhanced Oil Recovery
DAS	Data Acquisition System
B	Magnetic field,
μ_0	Permeability
I	Current
R	Distance
CST	Computer Simulation System
T	Tesla

CHAPTER 1
INTRODUCTION

1.1 Background of Study

Existing EOR methods in Oil and Gas Industry

Enhanced Oil Recovery (abbreviated EOR) is a normal term for techniques for increasing the amount of crude oil that can be extracted from a well. The term sounds funny in the sense of 'recovering', because it is more to find another method to re-extract the oil that we have already found. Using EOR, 30-60 %, or more, of the reservoir's original oil can be extracted compared with 20-40 % using primary and secondary recovery [2]. Enhanced oil recovery is also called improved oil recovery or tertiary recovery (as opposed to primary and secondary recovery). EOR generally involves four methods, which are listed below;

i. **Thermal recovery** which is about the injection of hot steam to the second drilled hole. The steam will be used to heat the crude oil either during its flow upward in the drill head or in the pool, which would allow it to flow more easily toward the drill head. The introduction of heat such as the injection of steam is to lower the viscosity or thin the heavy viscous oil and improve its ability to flow through the reservoir [2, 3].

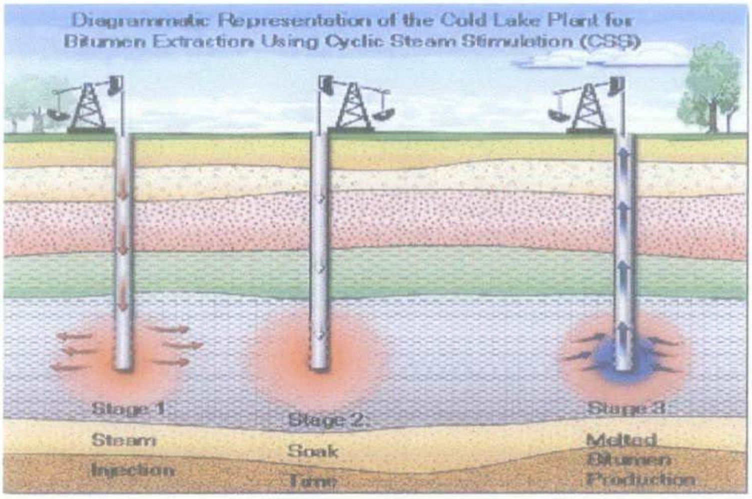

Figure 1 : Thermal recovery [2]

ii. **Chemical injection** is applied by injecting the chemical substances like polymer into the reservoir to reduce the oil viscosity and increase the water viscosity [3].

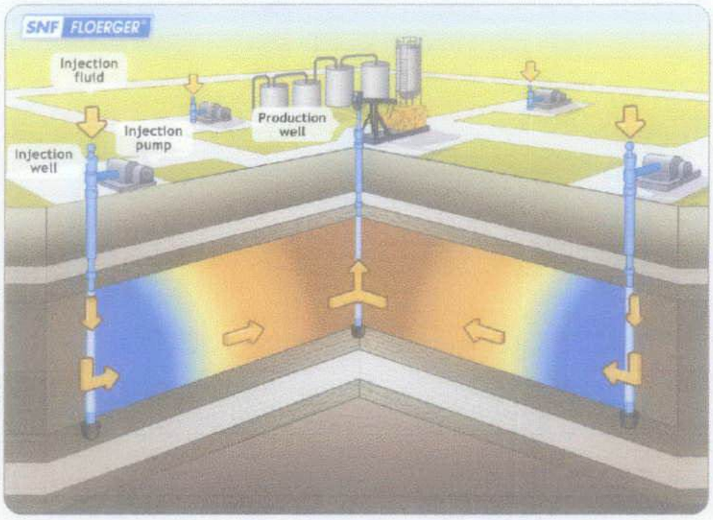

Figure 2 : Chemical injection [2]

iii. **Gas injection** method is using the carbon dioxide gas, $C0_2$ or other natural gases like nitrogen where those gases are injected to the reservoir. The expansion of the $C0_2$ gas into the reservoir cause the oil is breaking up into droplet and easier to be pumped. Some of the natural gases used for injection purpose dissolve in the oil so as to lower the viscosity of the oil thus aiding in its enhanced extraction [2].

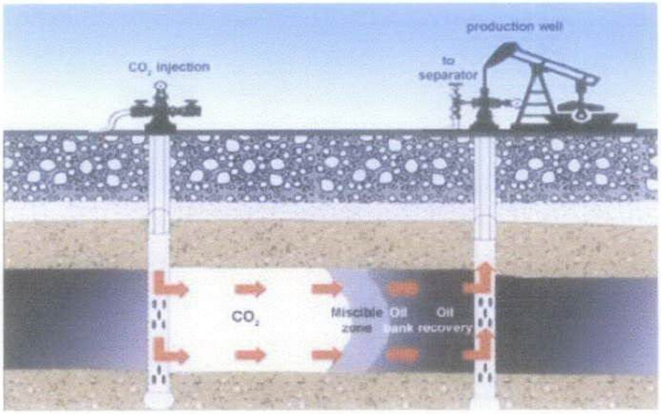

Figure 3 : Gas Injection [3]

iv. **Ultrasonic approach** where by using this method, the oil trapped in the rock matrices is being 'vibrated' and then pumped up [3].

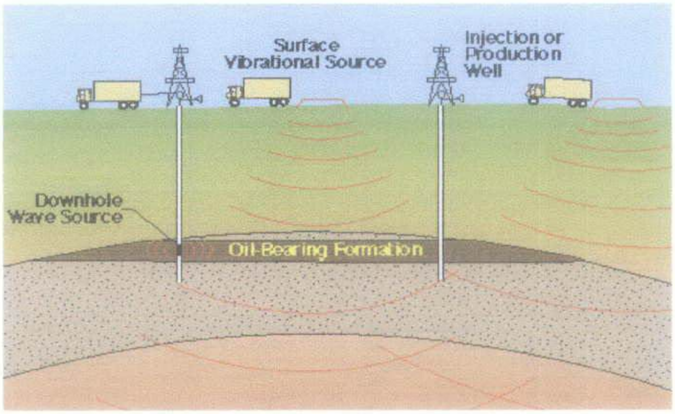

Figure 4 : Ultrasonic Approach [3]

As we notice, the price of crude oil per barrel changes everyday due to these reasons. Once a well is found, it is analyzed in detail before getting the work done. Things like the depth of the reservoir, the amount of crude available, and so on will be taken into account. If the method used is gas injection, the concentration of the gas (in this case, CO2) has to be decided to avoid unwanted problem to occur afterwards. If the method used is chemical injection, the concentration of the substance has to be accurate. The most commonly used chemical substance in chemical injection is alkaline solution [4].

Problem Statement

Primary and secondary recovery method is not cost effective due to excessive heat loss and thorough overburden. In fact, the injected foreign material is not reusable. High pressure and low temperature below 1000 m beneath sea level leaves the oil in high viscosity. The world is facing a problem on how to reduce the viscosity of the oil, hence, improve the mobility.

1.2 Objective and Scope of Study

- To design a transmitter that can transmit powerful EM waves to the sample based on the previous transmitter design.
- To calculate the oil recovery by using electromagnetic waves with the presence of nanofluids, ZnO (tertiary recovery).

CHAPTER 2
LITERATURE REVIEW

2.1 Electromagnetic Wave

Maxwell's four equations describe the electric and magnetic fields arising from varying distributions of electric charges and currents, and how those fields change in time. The equations were the mathematical distillation of decades of experimental observations of the electric and magnetic effects of charges and currents. It states that the magnetic field produced (B) is proportionally related to the current and the type of material used. The bigger current flow inside a conductor, and the higher the permeability of the material used, the bigger B field is produced. Magnetic field (B) and the electric field (E) is propagating together perpendicularly with the same amplitude where the reduction in B field intensity will cause the same amount of reduction in E field as well [15].

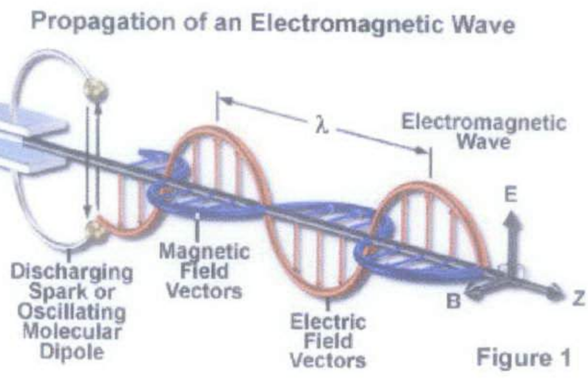

Figure 5 : Electromagnetic Wave Propagation [15]

Based on Maxwell equation;

$$\oint \vec{B} \cdot d\vec{\ell} = \mu_0 \left(I + \frac{d}{dt}\left(\varepsilon_0 \int \vec{E} \cdot d\vec{A} \right) \right) \qquad (2.1)$$

The equation can be simplified to be [7];

$$B = \frac{\mu_0 I}{2\pi r} \qquad (2.2)$$

Where,

B = Magnetic field,

μ_0 = Permeability

I = Current

r= Distance

Maxwell's equations describe the propagation of an electromagnetic field as a coupled process, propagating as a three-dimensional, polarized, vector wave field. At low frequencies and high losses, the equations reduce to the diffusion equation and are called electromagnetic induction. At the high frequencies of radar, the energy storage in dielectric and magnetic polarization creates wave propagation. In the ideal, lossless case (vacuum), the electric and magnetic fields are in phase, orthogonal polarized vector fields, propagating at the speed of light. In real materials, they are out of phase, not completely polarized, propagating with a velocity lower than the speed of light in vacuum, scattered by changes in electric and magnetic properties, and with all of the preceding varying as functions of frequency [16].

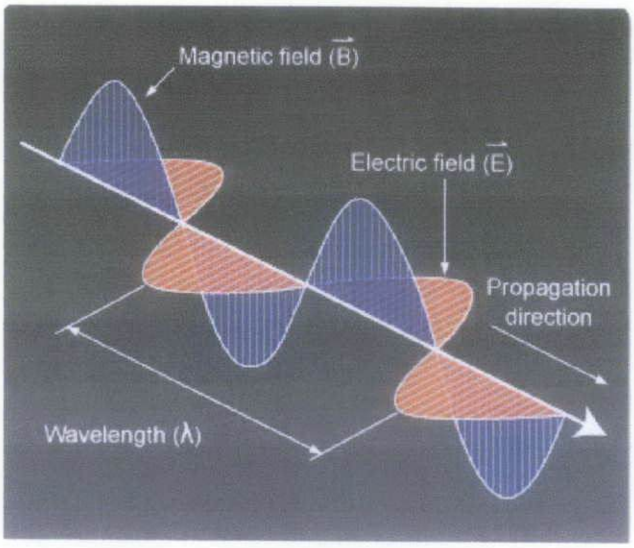

Figure 6 : E-field and B-field propagation [15]

2.2 EM Transmitter and Receiver

Reviewed by Prof. David Jenn from Naval Postgraduate School, radiating systems must operate in a complex changing environment that interacts with propagating electromagnetic waves. Commonly observed propagation effects are depicted in Figure 7.

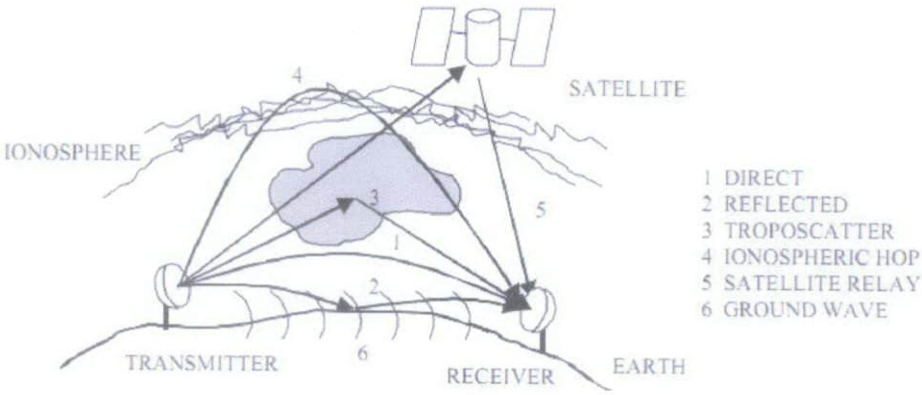

Figure 7 : Effects on waves [6]

2.3 Radiation and Antennas

Material, shape and size of a transmitter determine how effective it is in extracting energy from the radio wave. Usually an antenna is designed so that it can radiate or receive electromagnetic energy with directional and polarization properties suitable for the intended purpose or application. In order to design a transmitter, it is important to know the resistance of the antenna itself. The radiation and resistance properties of an antenna are governed by its shape and size and the material of which it is made [].

The resistance and conductivity of an antenna has the relationship as follows;

$$R = \frac{\rho l}{A} \text{ and } \rho = \frac{1}{\alpha} \tag{2.3}$$

Where; R= Resistance

ρ = Resistivity

α = Conductivity

l = Length

A = Area

Radiation sources are classified into two groups; currents and aperture fields. The dipole and loop antenna are examples of current sources while a horn antenna is one of the aperture source examples. For current radiation source, the time- varying currents flowing in the conducting wires give rise to the radiated electromagnetic field. In aperture source, the electric and magnetic fields across the horn's aperture serve as the sources of the radiated field. The aperture fields are themselves induced by time- varying currents on the surfaces of the horn's walls, and therefore ultimately all radiation is due to time- varying currents [7].

2.4 Skin Depth

Skin depth is defined as the depth to which electromagnetic radiation can penetrate a conducting surface decreases as the conductivity and the oscillation frequency increase. This demo compares the skin depth of AM and FM radio frequencies, and shows just how small these distances are. It is very important in electromagnetic wave concept. EM energy decays exponentially in conductive rocks over a distance given by the skin depth [9]:

Skin depth = 500 meters x square root (resistivity/frequency).

In the seabed logging application, the skin depth equation $\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$ is referred so that we could know how much EM waves would penetrate and diffuse into the reservoir, where σ is electrical conductivity, μ is magnetic permeability and ω is the angular frequency of the current.

CHAPTER 3
METHODOLOGY

3.1 Tools and Equipments

HARDWARE:

I. Transmitters with magnetic feeders
II. Receiver
III. Function generator
IV. Glass beads sample
V. Data acquisition system (DAS) Model NI PXI-1042
VI. Weighing Apparatus
VII. Caliper

SOFTWARE:

I. CST (Computer Simulation Technology)
II. Microsoft Office

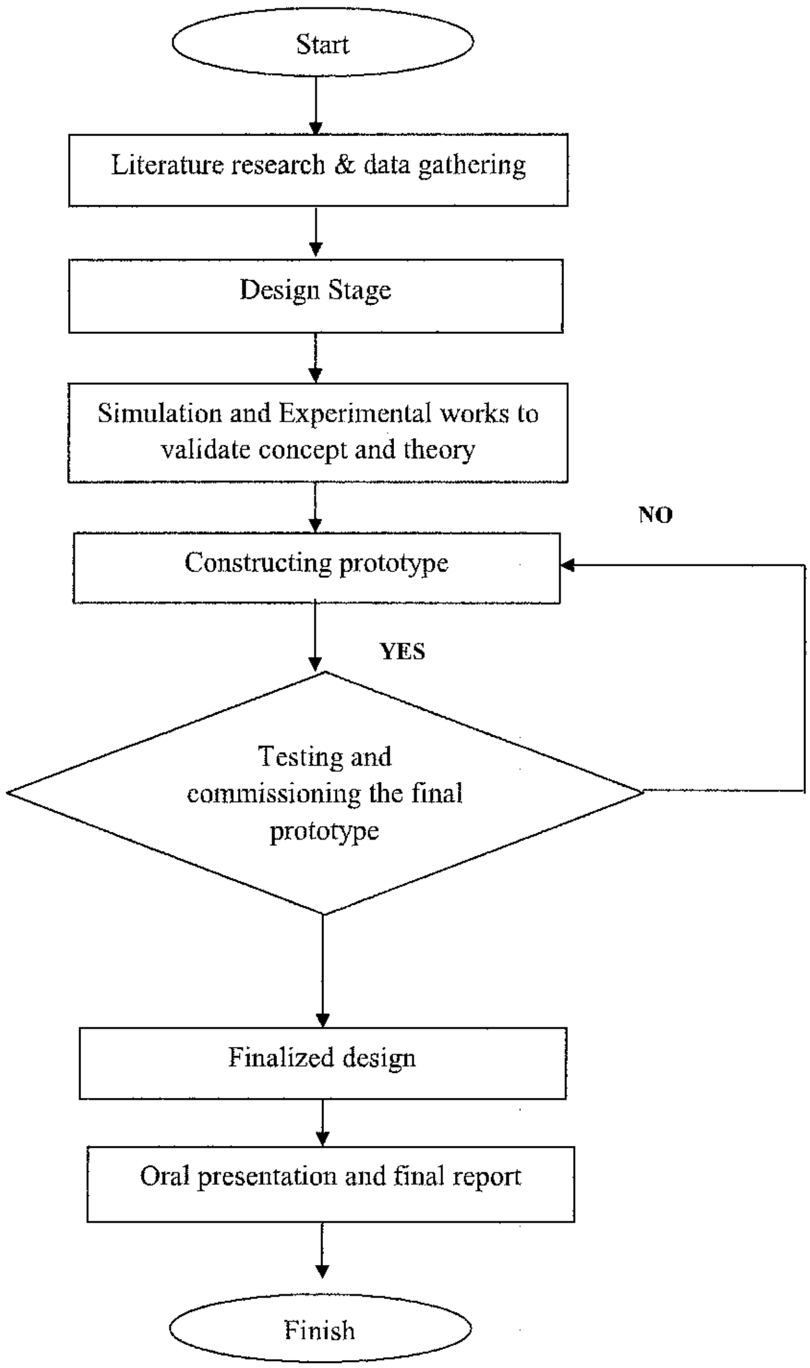

Figure 8 : Flowchart of the project

3.2 Understanding Electromagnetic Wave

In the 1860's, James Clerk Maxwell developed a scientific theory to explain electromagnetic waves. He noticed that electrical fields and magnetic fields can couple together to form electromagnetic waves. He summarized this relationship between electricity and magnetism into what are now referred to as "Maxwell's Equations." [15, 16]

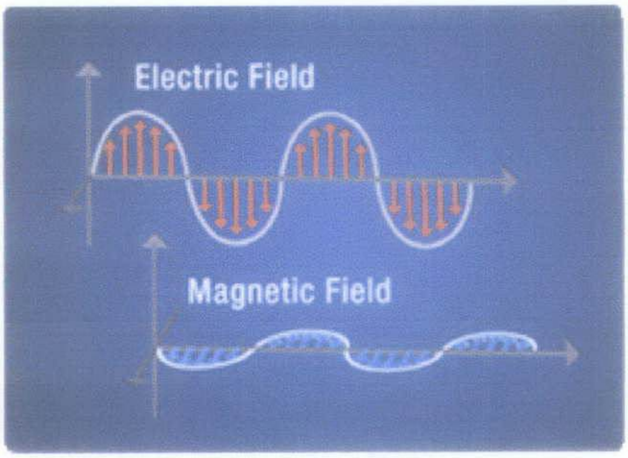

Figure 9 : B-field and E-field [6]

Electromagnetic waves are formed by the vibrations of electric and magnetic fields. These fields are perpendicular to one another in the direction the wave is traveling. Once formed, this energy travels at the speed of light until further interaction with matter. Heinrich Hertz, a German physicist, applied Maxwell's theories to the production and reception of radio waves. His experiment with radio waves solved two problems. First, he had demonstrated in the concrete, what Maxwell had only theorized — that the velocity of radio waves was equal to the velocity of light. This proved that radio waves were a form of light. Second, Hertz found out how to make the electric and magnetic fields detach themselves from wires and go free as Maxwell's waves — electromagnetic waves [15].

Electromagnetic waves are created by the vibration of an electric charge [15]. This vibration creates a wave which has both an electric and a magnetic component. An electromagnetic wave transports its energy through a vacuum at a speed of 3.00×10^8 m/s (a speed value commonly represented by the symbol **c**). By having certain kind of transmitter design, we could have a transmitter that can transmit more EM wave which can provide better electric charge vibration which can help to improve the oil mobility that trapped inside the reservoir [17].

3.3 Shape of the transmitter

In order for the antenna to be able to transmit powerful electromagnetic wave, the shape designed must be optimum in the sense of wave propagation. Meaning to say that the antenna must transmit the wave to a certain point where the constructive interference occurs at its maximum. Based on the literature review, it is stated that the curve shape is classified as the aperture field radiation sources where both electric and magnetic fields across the curve are focused to a point, in which, higher EM waves propagation produced [].

3.4 Destructive and Constructive Interference

The transmitter was also designed to be in hexagon shape with curve copper windings and has six different supply sources compare to the previous design (Figure 9) which has straight copper windings and has only one supply source. The purpose of having the 6 curves winding shape is as it can provide a sharp and focus EM field. The winding wires was made from the copper since it is a highly conductive material which then will governs to the bigger amount of induced current. Six supplies were connected to each 1 m (six segments) of copper winding to create the constructive interference and this allows a higher EM waves transmission [17, 18].

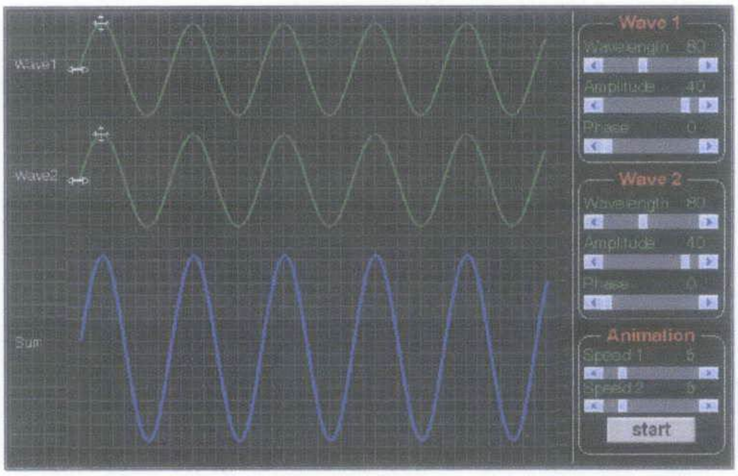

Figure 10 : Constructive interference [33]

When two sources are transmitting wave at the same time, there will be constructive and destructive interference [29]. When destructive interference occurs, the resulting wave will be zero. Meanwhile, if constructive interference occurs, the resulting wave will be doubled. The following figure explains how this phenomenon.

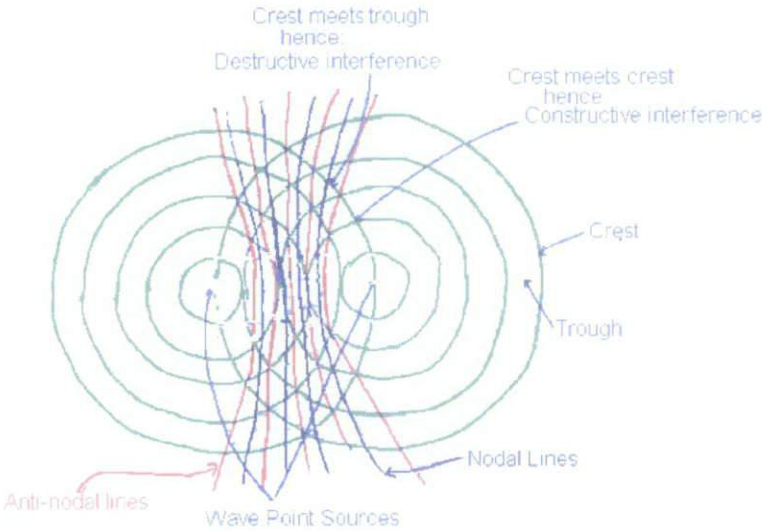

Figure 11 : Destructive and constructive interference [33]

Whenever the EM field traveling along the rocks (where there are oil trapped) it will carry along the energy and this cause the oils trapped are going to vibrate and thus will help them to release from the rock and become as the droplets. The skin depth theory is referred in order to know how much EM waves could penetrate and diffuse into the reservoir [18].

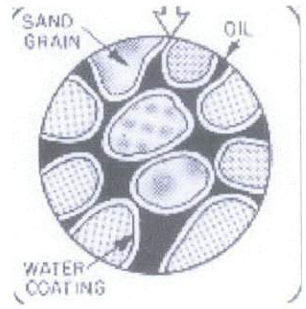

Figure 12 : Oil trapped in between rocks [29]

3.5 Constructing Prototype

3.5.1 Transmitter

The transmitter is fabricated with six segments, in which each is supplied with 1 kHz from different power supply. Number of supply will affect the maximum B-field produced by the transmitter.

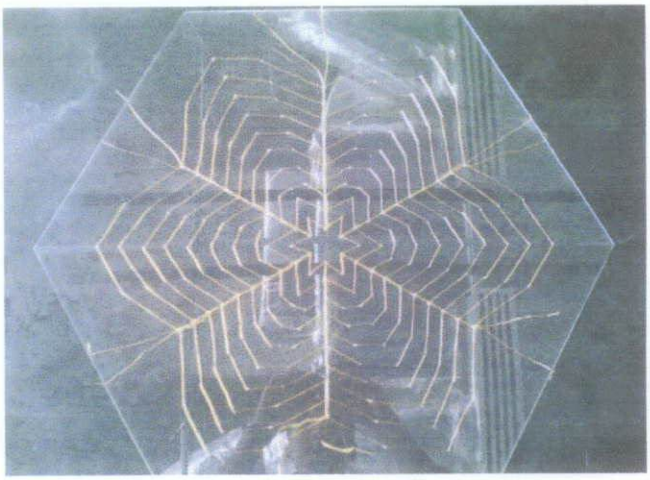

Figure 13 : Designed EM transmitter

3.5.2 Data Acquisition System (DAS)

DAS and Fluxgate Magnetometer were used in order to detect and store the data of the EM waves that transmitted through the core rock.

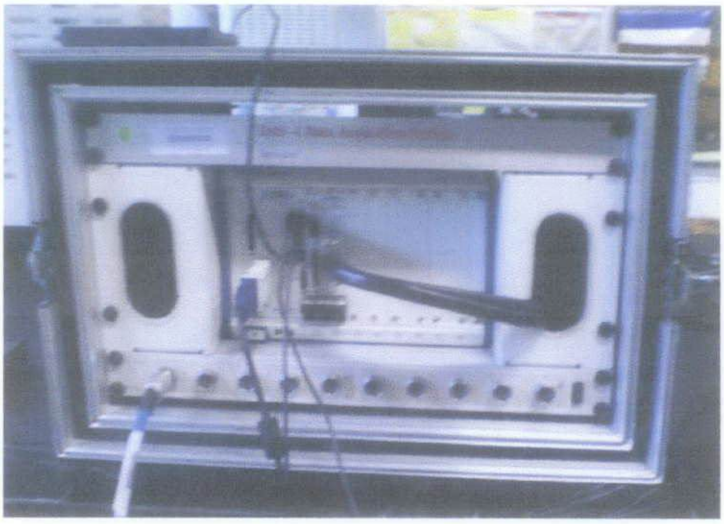

Figure 14 : Data acquisition system (DAS)

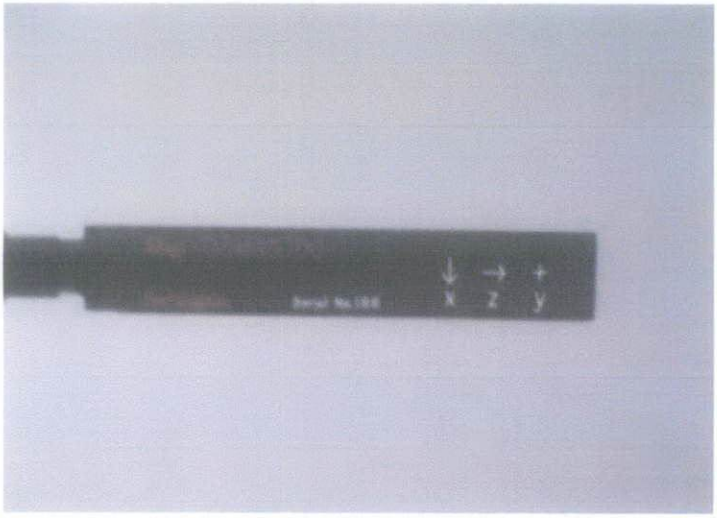

Figure 15 : Fluxgate Magnetometer

The device is capable of measuring the strength of any component of the Earth's magnetic field by simply re-orienting the instrument so that the cores are parallel to the desired component.

3.5.3 Function Generator

Figure 16 : Function generator [6]

Function generator is a device that generates frequency that will be supplied to the transmitter.

3.5.4 Glass Beads Sample

Figure 17 : Glass beads sample

Glass beads sample is used to imitate the actual environment of the reservoir. Core rock sample can be used to replace glass beads sample.

3.5.5 CST (Computer Simulation Technology) software

CST SUITE simulation software is comprehensive and user-friendly software for electromagnetic simulation. This is one of the most efficient and accurate computational solutions to electromagnetic related design in the world. It comprises CST's tools for the design and optimization of devices operating in a wide range of frequencies. Low frequency, high frequency, thermal and mechanical effects are some of the features. Analyses may include thermal and mechanical effects, as well as circuit simulation.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Experiment on Straight and Curve Rod

This experiment was done to compare between a curve and a straight rod in terms of electromagnetic waves distribution. In this experiment, both rods are supplied with frequency of 5 kHz, 50 kHz, 500 kHz and 5 MHz, one at a time. Then, the transmitted frequency of both rods is measured with a receiver.

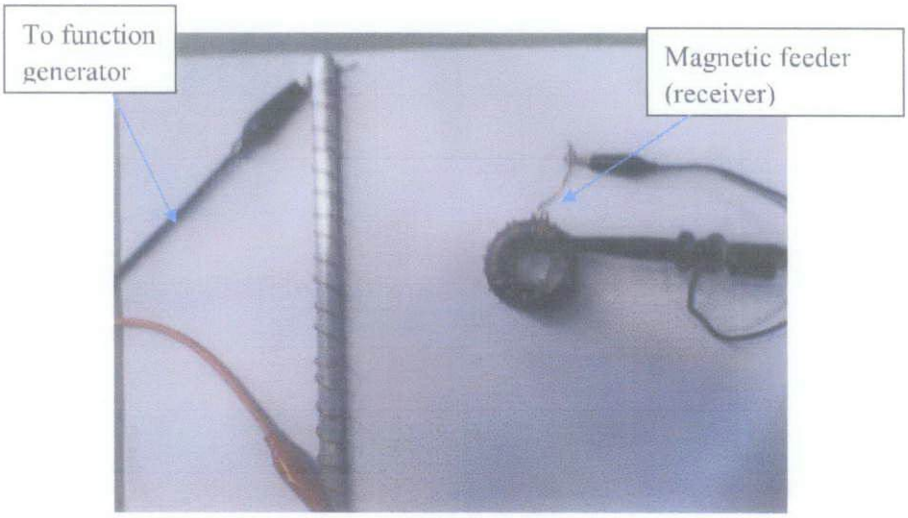

Figure 18 : A straight aluminum rod

Figure 18 shows a straight aluminum rod is being used as transmitter. Frequency from the function generator is supplied to the rod, and received frequency is received by the magnetic feeder.

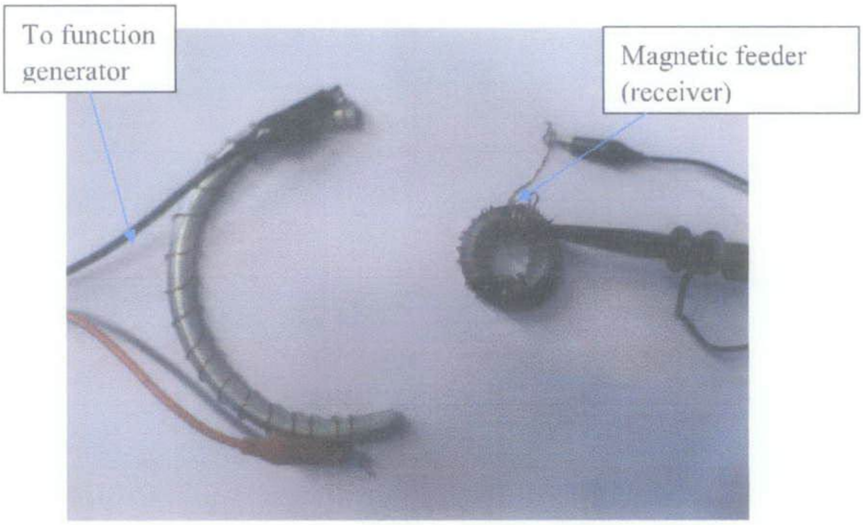

Figure 19 : A curve aluminum rod

Figure 19 is the same as Figure 18 except that the transmitter used is curve rod. The results of both experiments are recorded in Table 1 and 2.

Table 1 : Frequency transmitted from a straight rod

Transmitted	Received
5 kHz	5 kHz
50 kHz	50 kHz
500 kHz	500 kHz
5 MHz	5 MHz

Table 2 : Frequency transmitted from a curve rod

Transmitted	Received
5 kHz	9.98 kHz
50 kHz	101.2 kHz
500 kHz	1.13 MHz
5 MHz	9.96 MHz

From the results, it is shown that for the straight rod transmitter, the received frequency is the same as the transmitted. It tells that for a straight transmitter, the magnetic field is equally distributed to all directions.

While for the curve transmitter, the magnetic field is focused to a certain point. When the transmitted is 5 kHz, the received frequency is 9.98 kHz. The increment is about 99.6 %. As the transmitted frequency is varied, the received frequency also varies. From the results shown, we could conclude that there will be different patterns of how E-field and B-field are distributed between those two transmitters, based on the frequency experiment. As expected, with curve copper wire, the B-field distribution is likely more focusing rather than B-field in straight wire which is equally distributed. This focusing characteristic is very important to design a powerful transmitter.

4.2 Supply Connection (series/parallel)

Equipments and materials used:

1. Function generator 5 MHz
2. Straight aluminium rods (transmitter) with length of 15 cm
3. Magnetic feeder with frequency supply equal to 1 Khz
4. Fluxgate magnetometer, Bartington
5. Wire clippers

The experiment needs to be conducted because the designed transmitter is having more than one wire. Different type of supply will show different behaviour to the magnetic field production. Three straight aluminium rods are used. Magnetic feeders are used to enhance the magnetic field. Without it, magnetic field produced can be too small and difficult to be analyzed.

The purpose of this experiment done was to investigate the significant of having different type of supply connections which are series connection or parallel connection when having more than one wire in one time. Due to the availability of materials in lab, the experiment conducted was on the three straight aluminium rods with 15cm long and 1cm in diameter. In the first run, one straight rod with magnetic feeder was supplied with 1 KHz frequency. Then, the experiment was furthered by considering two and three aluminium rods with magnetic feeder by applying both type of supply connections, series and parallel. The B-field distribution produced by the aluminium rods then has been identified by the fluxgate magnetometer.

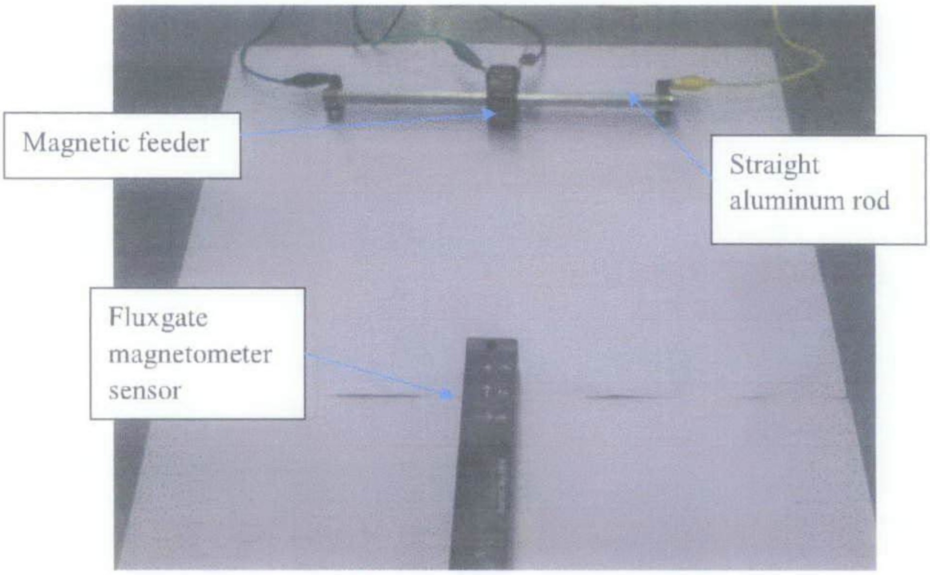

Figure 20 : 1 straight rod

Figure 20 shows a straight aluminum rod and a magnetic feeder both supplied with 1 kHz frequency. The produced magnetic by the rod is measured by the fluxgate magnetometer sensor.

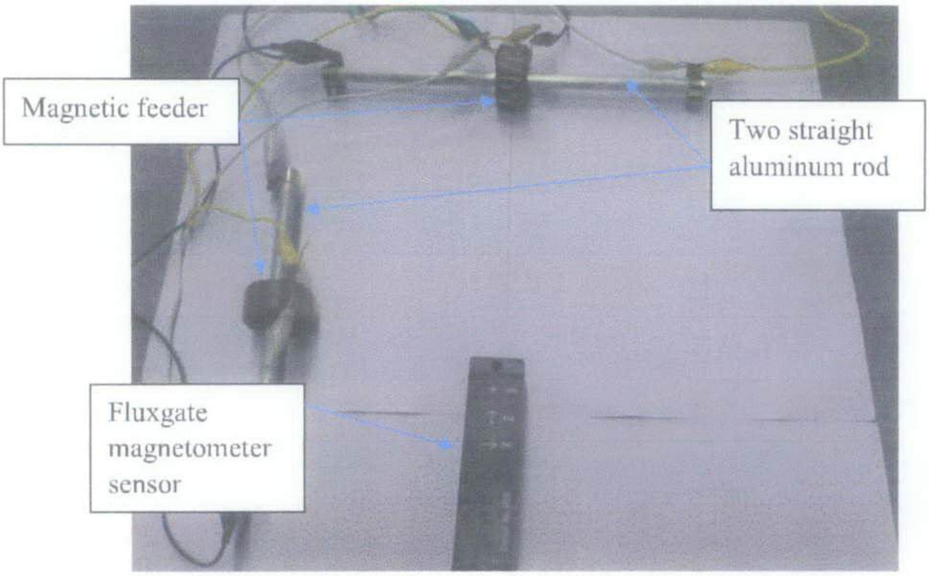

Figure 21 : Two straight rods in parallel

Figure 21 shows two straight aluminum rods and magnetic feeders connected in parallel to each other.

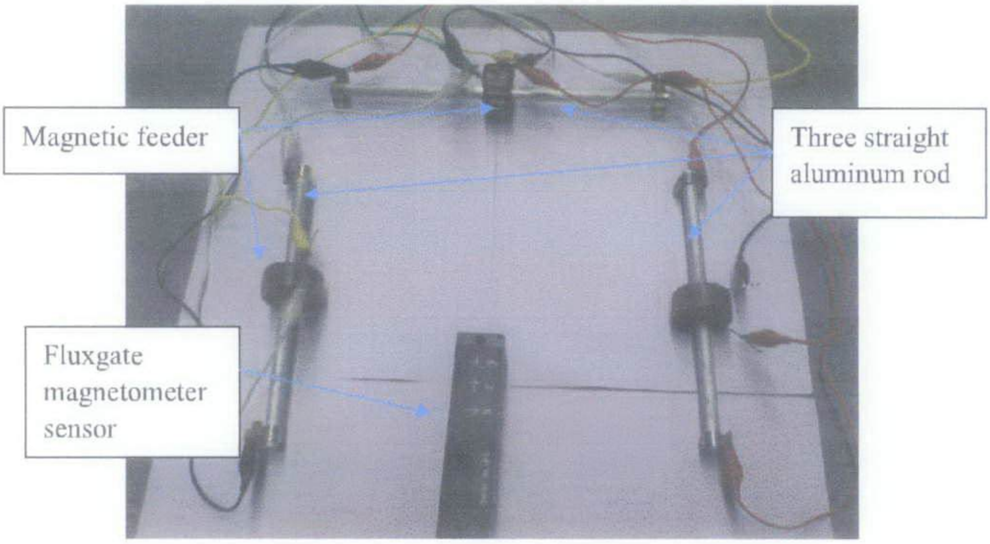

Figure 22 : Three straight rods in parallel

Figure 22 shows three aluminum rods and magnetic feeders being connected in parallel. All the results are tabulated in Table 3 to 7.

Results:

Table 3 : Magnetic field produced by 1 straight rod with one power source

#Run	B-field value (T)
1	4.09E-08
2	4.01E-08
3	4.22E-08
4	4.12E-08
5	4.13E-08
6	4.02E-08
7	4.03E-08
8	4.06E-08
9	4.18E-08
10	4.11E-08
Average	**4.10E-08**

Table 4 : Magnetic field produced by 2 straight rods with parallel power source

#Run	B-field value (T)
1	9.09E-07
2	9.11E-07
3	9.23E-07
4	8.55E-07
5	9.12E-07
6	9.11E-07
7	9.06E-07
8	8.95E-07
9	9.20E-07
10	9.26E-07
Average	**9.07E-07**

Table 5 : Magnetic field produced by 3 straight rods with parallel power source

#Run	B-field value (T)
1	1.71E-6
2	1.78E-6
3	1.68E-6
4	1.55E-6
5	1.56E-6
6	1.49E-6
7	1.66E-6
8	1.70E-6
9	1.59E-6
10	1.56E-6
Average	**1.63E-06**

Table 6 : Magnetic field produced by 2 straight rods with series power source.

#Run	**B-field value (T)**
1	5.23E-07
2	5.15E-07
3	5.24E-07
4	5.22E-07
5	5.22E-07
6	5.24E-07
7	5.16E-07
8	5.24E-07
9	5.25E-07
10	5.25E-07
Average	**5.22E-07**

Table 7 : Magnetic field produced by 3 straight rods with series power source

#Run	**B-field value (T)**
1	7.52E-08
2	7.51E-08
3	7.51E-08
4	7.52E-08
5	7.51E-08
6	7.51E-08
7	7.51E-08
8	7.50E-08
9	7.50E-08
10	7.53E-08
Average	**7.51E-08**

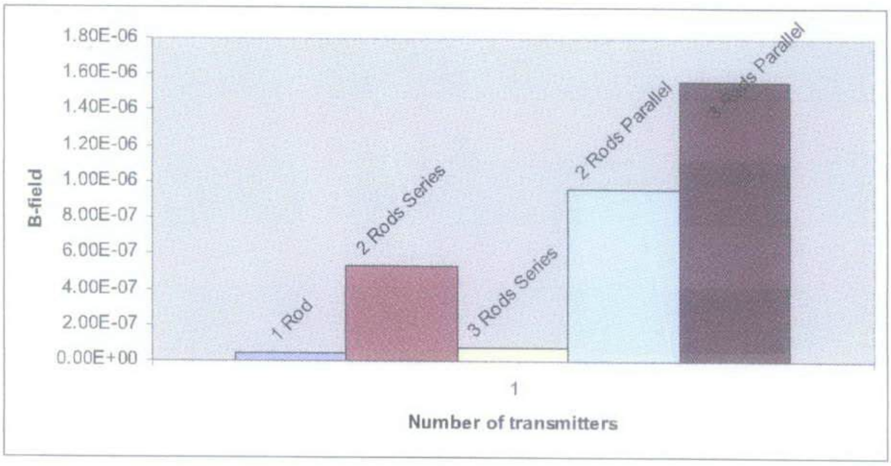

Figure 23 : Number of transmitter(s) Vs. B-field

Figure 23 summarizes the results of the magnetic field produced for one straight rod, two and three rods connected in series, and two and three rods connected in parallel.

Results in Table 3 to Table 7 were analyzed and plotted in the bar chart as shown in Figure 23. From the Figure 23, the three straight aluminium rods with parallel power source has the highest value of magnetic field produced (1.63E-6). Parallel connection produce higher magnetic field because the connection provides the interference of waves where in this case, constructive interference was occurred. Two interfering waves have a displacement in the same direction and increase the value of magnetic field.

4.3 Experimental Works on Aluminum Rod and Aluminum Wire

Equipments and materials used:

1. Function generator 80 MHz
2. Curve aluminium rod with diameter of 10cm without magnetic feeder
3. Curve aluminium wire with diameter 10 cm without magnetic feeder
4. Wire clippers
5. Oscilloscope
6. Magnetic feeder (as receiver)

The fourth experiment was conducted in order to investigate the significant of material used for the transmitter design purpose which is between the aluminium rod and aluminium wire. For this experiment, aluminium curve rod (10 cm diameter) and aluminium curve wire (10 cm diameter) without magnetic feeder were used. Both were supplied with 80 MHz frequency. Oscilloscope was used to record the average transmitted frequency that mostly appeared on the screen.

Figure 24 and 25 shows how a curve rod and wire is being used as transmitters and the received frequency is received by the receiver.

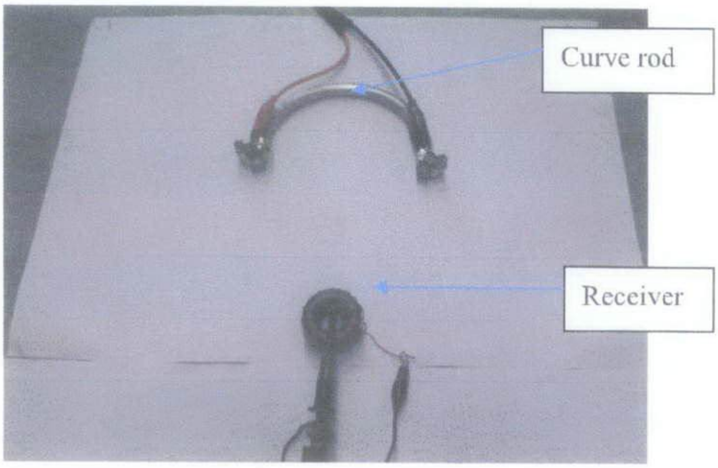

Figure 24 : Curve aluminum rod

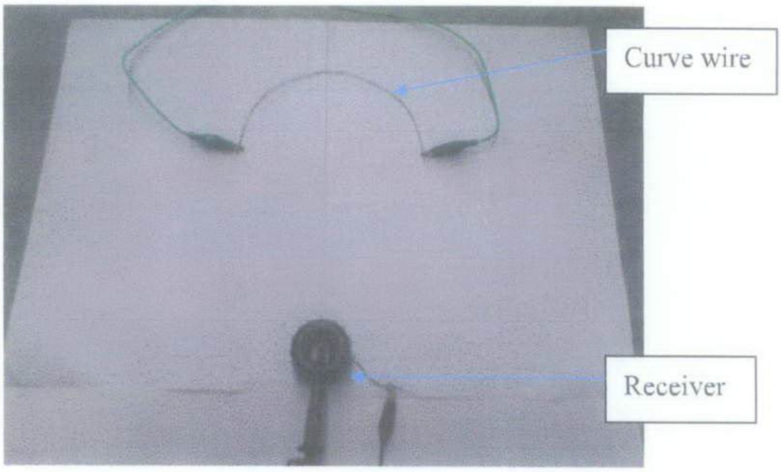

Figure 25 : Curve aluminum wire

Table 8 : Frequencies received for 1 curve aluminum rod and wire.

#Run	1 Curve Aluminum Rod (Hz)	1 Curve Aluminum Wire (Hz)
1	149.20	210.10
2	148.10	218.00
3	160.00	207.00
4	161.20	204.00
5	160.20	209.40
6	165.30	207.30
7	161.20	208.30
8	152.00	209.40
9	155.00	207.00
10	151.50	208.30
Average	**156.37**	**208.88**

Based on the result in Table 8, with an aluminum curve wire without magnetic feeder, the value of frequency received is 208.88 MHz compare to aluminum rod, 156.37 MHz which shows that copper wire has a better ability to transmit higher frequency compared to the aluminum rod. This is due to the higher purity in aluminum wire rather than purity in aluminum rod.

The increment of frequency is about 33.6% if we use aluminum wire as the transmitter rather than aluminum rod. Therefore, it was decided to design the transmitter in hexagon shape with the wire windings rather than to have transmitter with six connected rods.

4.4 Effect of B-field produced by various number of supply

This experiment is to investigate the effect of number of supply of the antenna. Since the antenna has six segments, the supply can vary between one, two, three and six. Theoretically, the more supply given to the antenna, the bigger the B-field produced. All the data and results are tabulated and analyzed.

Table 9 : Antenna is fed with one supply

#Run	Magnetic field, T
1	1.30E-07
2	1.29E-07
3	1.30E-07
4	1.30E-07
5	1.30E-07
6	1.30E-07
7	1.30E-07
8	1.30E-07
9	1.30E-07
10	1.30E-07
Average	**1.30E-07**

Table 9 shows the magnetic field produced when the antenna is fed with one frequency supply.

Table 10 : Antenna is fed with two supplies

#Run	Magnetic field, T
1	1.92E-07
2	1.92E-07
3	1.92E-07
4	1.91E-07
5	1.92E-07
6	1.91E-07
7	1.91E-07
8	1.91E-07
9	1.91E-07
10	1.91E-07
Average	**1.91E-07**

Table 10 shows the magnetic field produced when the antenna is fed with two frequency supplies.

Table 11 : Antenna is fed with three supplies

#Run	Magnetic field, T
1	6.44E-07
2	6.37E-07
3	6.48E-07
4	6.49E-07
5	6.46E-07
6	6.45E-07
7	6.24E-07
8	6.48E-07
9	6.47E-07
10	6.49E-07
Average	**6.44E-07**

Table 11 shows the magnetic field produced when the antenna is fed with three frequency supplies.

Table 12 : Antenna is fed by six supplies

#Run	Magnetic field, T
1	7.70E-07
2	6.67E-07
3	7.86E-07
4	7.15E-07
5	8.03E-07
6	6.78E-07
7	8.43E-07
8	6.12E-07
9	7.99E-07
10	6.04E-07
Average	**7.89E-07**

Table 12 shows the magnetic field produced when the antenna is fed with six frequency supplies.

Result Analysis

Let us consider the results of the B-field produced at distance, d=0cm for all cases. In the first run, the antenna is fed with one supply connected in parallel to each segment. At d = 0 cm, the average B-field produced is 1.3E-7. When the antenna is fed with two supplies, the B-field is 1.91E-7. The increment is about 47 %. For the antenna fed with three supplies, the B-field is 6.44E-7. That is almost 400 % increment from the original value. When six different supplies are used to feed the antenna, the value of B-field produced is 7.89E-7. The increment is 507 %. The results clearly show that having different supply for each segment will increase the value of B-field. Hence, the designed antenna is having six different supplies for each segment. Figure 25 summarizes the results of the experiment in chart.

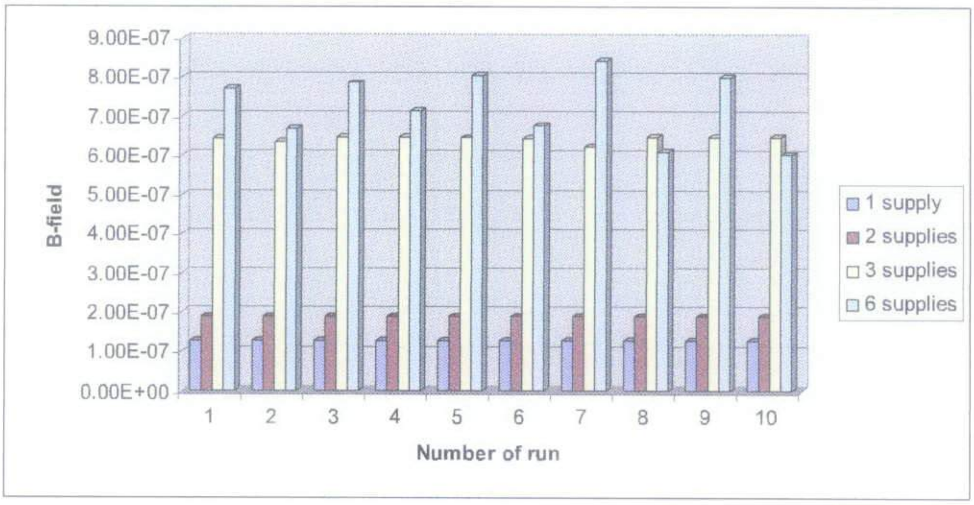

Figure 26 : Effect of different number of supply

Figure 26 summarizes the results of the tabulated data in Table 9 to 12.

Instead of having one supply of 1 kHz connected in parallel, we use six supplies with each one connected to each segment. By doing so, the B-field can be amplified to a higher value.

4.5 Effect of number of winding to the magnetic field strength

Previously, the designed antenna only has five winding. In this project, the number of winding is increased one at a time to see how the strength of magnetic field varies. An experiment is conducted where the hexagonal antenna is used. The number of winding starts with five, and due to the size limitation, it can only be up to ten windings.

Table 13 : Effect of number of winding to the strength of magnetic field.

Run#	Magnetic field in 5 windings, T	Magnetic field in 6 windings, T	Magnetic field in 7 windings, T	Magnetic field in 8 windings, T	Magnetic field in 9 windings, T	Magnetic field in 10 windings, T
1	1.59E-07	3.49E-07	3.27E-07	7.70E-07	8.70E-07	1.24E-06
2	2.27E-07	2.59E-07	3.33E-07	6.67E-07	7.67E-07	1.53E-06
3	2.96E-07	2.02E-07	4.45E-07	7.86E-07	6.86E-07	1.48E-06
4	2.54E-07	3.76E-07	3.09E-07	7.15E-07	6.15E-07	1.49E-06
5	1.54E-07	2.09E-07	4.36E-07	8.03E-07	8.21E-07	1.28E-06
6	2.85E-07	3.92E-07	4.39E-07	6.78E-07	7.23E-07	1.51E-06
7	1.38E-07	2.26E-07	3.04E-08	8.43E-07	8.43E-07	9.57E-07
8	1.55E-07	2.40E-07	4.34E-07	6.12E-07	6.54E-07	1.45E-06
9	1.30E-07	3.21E-07	3.32E-07	7.99E-07	6.20E-07	1.54E-06
10	2.95E-07	3.88E-07	3.49E-08	6.04E-07	8.02E-07	1.11E-06
Average	2.09E-07	2.96E-07	3.12E-07	7.28E-07	7.40E-07	1.36E-06

Table 13 shows the values of magnetic field produced when the antenna is having 5, 6, 7, 8, 9 and 10 windings.

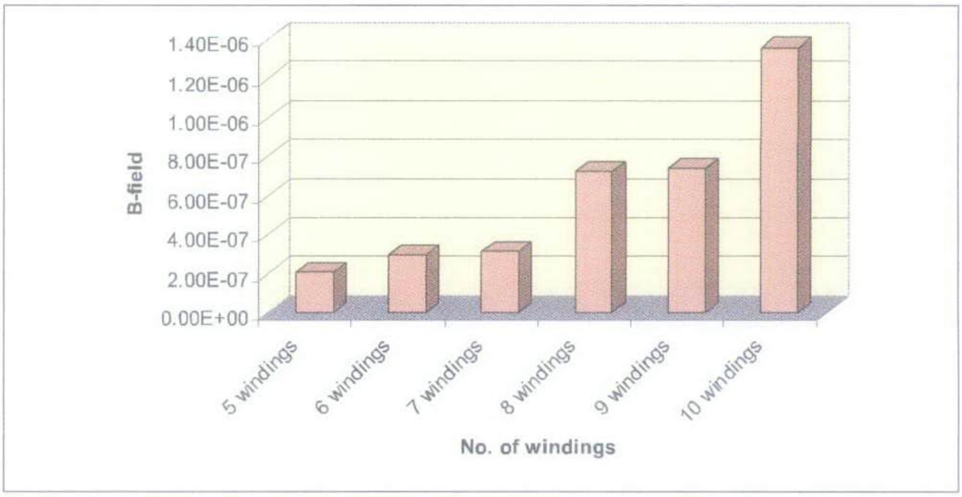

Figure 27 : Effect of number of windings to B-field

Figure 27 clearly shows that by increasing the number of windings, the magnetic field also increase proportionally.

Theoretically, more winding will result to stronger magnetic field. The experimental works proves that. At 5 windings, the average magnetic field is 2.09E-08. When one more winding is added, the magnetic field increases to 3.36E-08, about 60.76 %. As more windings are added one at a time, the strength of magnetic field also increases. At ten windings, where the maximum magnetic field is produced, the increment is about 550.7 %. Hence, the designed transmitter is having ten windings.

4.6 Porosity and Permeability Test for Glass Beads Sample

Permeability is defined as the ability of a porous material (e.g., a rock or unconsolidated material) to allow fluids to pass through it. In this case, we are using PVC column packed with glass beads as sample. Hence, we need to know its permeability. In this experiment, we want to investigate the characteristics of the sample that represents the actual reservoir, which is the glass beads sample. The characteristics evaluation of the sample includes porosity, pore volume and also the permeability. The glass beads size that available in the lab is (30 – 60) μm, (90 – 150) μm, and (425 – 600) μm. But for the experiment, we are only using only one mixture because we do not need to do comparison between different pore sizes sample. The mixture that we use is 150g (30 – 60) μm and 150g (90 – 150) μm.

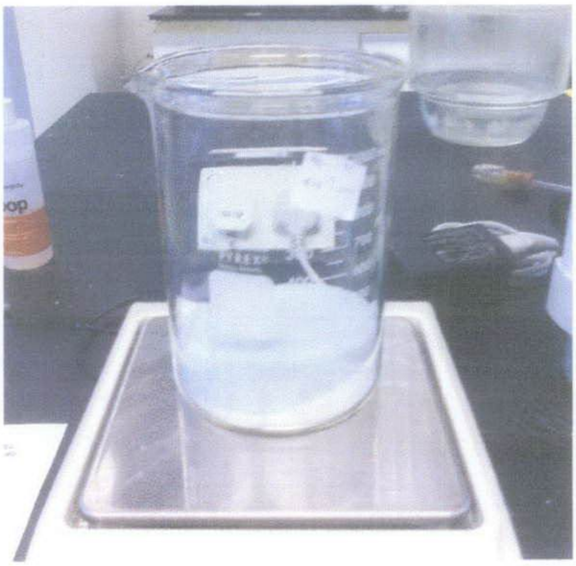

Figure 28 : Glass beads sample

After the glass beads sample is packed inside the PVC cylindrical column, the weight of the PVC cylindrical column is recorded. Figure 29 shows the setup for the experiment. A pump is used to pump brine water to the PVC column at an approximately constant flow rate; 2ml/min. The experiment is stopped when the pressure becomes constant, the experiment will be stopped.

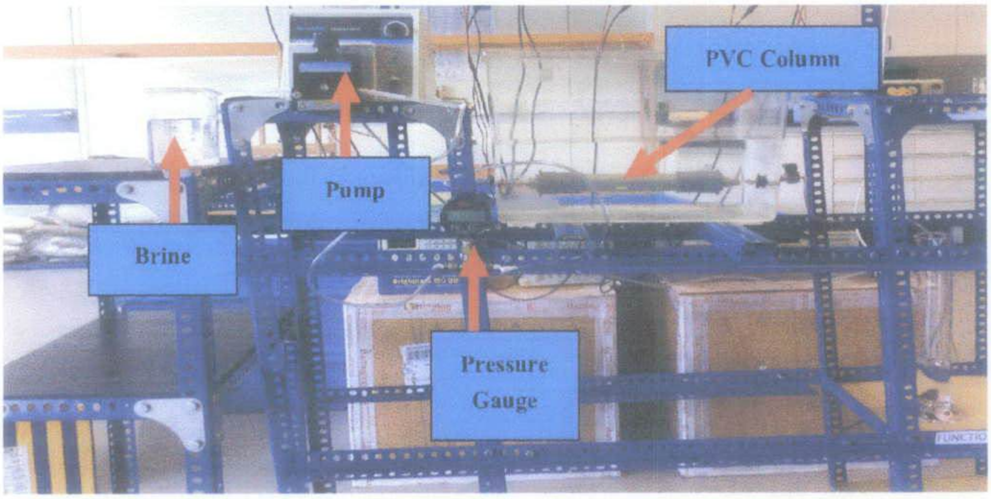

Figure 29 : Experiment setup for oil recovery

Figure 29 shows the experimental setup for oil recovery procedure.

The area and length of the PVC column is known. Expressing Darcy's formula, we have:

$$k = \frac{Q\mu L}{A\Delta P} \tag{2.4}$$

Where;

Q = the flow rate (ml/s)

μ = the viscosity of the fluid (cp)

L = the length of the cylindrical PVC column (cm)

k = the permeability of the sample (mD)

A = the area of the cylindrical PVC column (cm^2)

ΔP = Pressure (atm)

Once the PVC column with glass beads is saturated with brine, the weight is recorded.

Table 14 : Measurement for permeability test

Flow rate, Q (ml/s)	0.0333
Viscosity of brine, μ (cp) (at room temperature)	1.02
Length of PVC column, L(cm)	22
Permeability, k (mD)	535.81
Area of PVC column, A (cm^2)	7.0686
Pressure, ΔP (atm)	0.1973

Table 14 and 15 shows the parameters for permeability and porosity test that will be used in the oil recovery calculation.

Table 15 : Measurement for porosity test

Dry weight (PVC + glass beads) (g)	487.98
Wet weight (PVC + glass beads + brine) (g)	536.74
Pore mass @ brine mass (wet weight – dry weight) (g)	43.76
Brine density (20kppm at room temperature) (g/cm^3)	1.0106
Pore volume, Vv (Brine mass/brine density) (cm^3)	43.30
Bulk volume, VT (L x A) (cm^3)	155.5092
Porosity (%)	27.84

The purpose of evaluating porosity and permeability of the sample is important because it is strongly related to the oil recovery calculation. Sample with higher porosity means that more oil can occupy the room inside the sample, compared to lower porosity sample.

4.7 Oil Recovery Calculation

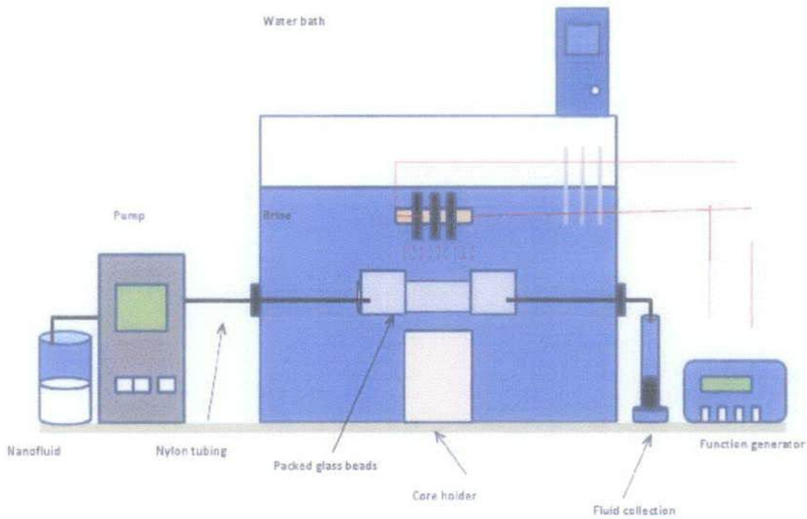

Figure 30 : Schematic setup for oil recovery

4.7.1 Calculation of pore volume

The sample (glass beads) is saturated with brine. The values for Q (flow rate), μ (brine density), L (length of the PVC column) and A (area) are fixed, where

$Q = 2$ ml/min

$\mu = 1.02$ cp

$L = 22$ cm

$A = 7.0686 \text{ cm}^2$

By using Darcy formula, permeability of the glass beads pack is calculated.

$$\text{Using Darcy's Law, Permeability, } k = \frac{Q\mu L}{A\Delta P}$$

The sample is saturated with brine until it reaches constant pressure. At constant pressure of 2.8 Psi or 0.1973 atm, permeability is 535.81 mD.

Pore volume is calculated as follow:

Table 16 : Pore volume calculation

Dry weight (PVC + glass beads) (g)	490.32
Wet weight (PVC + glass beads + brine) (g)	532.77
Pore mass @ brine mass (wet weight – dry weight) (g)	42.45
Brine density (20kppm at room temperature) (g/cm^3)	1.0106
Pore volume, Vv (Brine mass/brine density) (cm^3)	42.00

4.7.2 Calculation In Primary And Secondary Stage

Original Oil in Place (OOIP) can be calculated as follows:

OOIP = volume of water displaced during the oil injection
= 38 mL

Volume of water displaced = volume of oil injected into the sample

Assuming 1cm3 = 1 mL, the pore volume is 42 mL

Percentage of OOIP = volume of water displaced/pore volume*100
= 38/42*100
= 90.48 % with 9.52 % of brine

Residual Oil In Place (ROIP) is the remaining oil after brine is injected until there is no more oil drop from the outlet tube.

Volume of oil collected = volume of oil during water flooding
= 28 mL

ROIP = OOIP – volume of oil during water flooding
= 38 mL – 28 mL
= 10 mL

Percentage of ROIP = 28 mL/38 mL*100
= 73.67 %

Up to now, we have recovered 73.67 % of oil for secondary recovery.

4.7.3 Calculation for Oil Recovery Using EM Waves

The last stage is we recover the remaining oil using EM waves. The sample is exposed to EM waves for twelve hours and the percentage of collected oil is calculated.

Remaining Oil in core sample = 10 ml

Recovered Oil = 1.3 mL

Percentage recovery = 1.3 mL/10 mL*100

=13 %

The recovery was calculated to be 13 % by EM waves and the presence of nanofluids, ZnO. However this percentage could be not too accurate since there is probably water inside the core but not been measured. This percentage can be higher if the sample is exposed longer to the EM waves and the by improving the transmitter.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion and Major Findings

The results of this experiment consist of three main parts;

i) the designed antenna

ii) enhanced of magnetic field strength by varying the number of supply and windings

iii) oil recovery by using EM wave and the presence of nanofluids, ZnO.

i) Experimental results show that the hexagon-shaped antenna is the best shape for enhanced oil recovery application rather than other shape like triangle, rectangle, heptagon and so on. Rather than using aluminum or copper rod as the transmitter, copper wire which is winding in curve shape would be better due to the high purity and more EM waves can be generated. Curve winding is chosen to be the design due to its ability to transmit the better concentrated and focused EM waves compared to the straight pattern. By having parallel connection sources of frequency in the curve winding, more EM waves could be produced. This is due to the constructive interference that happens while the EM waves are propagated.

ii) The existing designed hexagonal antenna also has six segments in which they are supplied by only one supply sources. In this case, each of the segments is fed with independent sources. By doing so, the connected curve wires do not share the supply from the same function generator. This will result in the massive increment of magnetic field produced. However, the strength of magnetic field also depends on the size, material and number of turns of the antenna. In this project, the size used is for lab scale only. The material used is copper in which it is a highly conductive material, compared to other common material like aluminum. The antenna is fixed to have six segments because only in that shape, it can transmit powerful magnetic field. But the windings are not fixed. Theoretically, more windings will result to stronger magnetic field because more constructive interference will occur around the copper wire. Experimental works show that it works that way. The number of winding was initially only five but it is increased one at a time until it reaches its maximum. Since the project is only using lab scale, the size of the antenna is limited. Thus, the maximum number of winding used in this project is ten.

iii) In this project, the oil recovery by using EM waves and nanofluids (ZnO) is approximately 13 %. By using appropriate temperature and pressure, the recovery percentage can be achieved higher. For future works, different nanofluids can be used to replace ZnO. For example, Al_2O_3.

5.2 RECOMMENDATION

1. In this project, the distance between the transmitter and receiver are not varied. In order to make a better transmitter, the distance should go more than that. For future works, it is recommended to make an antenna that can transmit electromagnetic wave for greater than 70 m.
2. Increase the transmitter windings.
3. The frequency fed to the transmitter is 1 kHz for each segment. For future experiment, the frequency should be varied
4. Design a smaller transmitter but powerful by using carbon nanotubes as the winding instead of copper winding.
5. Increase the pressure in the glass beads sample to get more recovery.
6. The distance between core sample and detector should be varied so that more accurate data could be measured.
7. The sample should be exposed to the EM waves for a longer time to see the recovery.
8. For future works, different kinds of nanofluids can be used instead of ZnO to increase the oil recovery. The most common used nanofluids other than ZnO is Al_2O_3.

REFERENCES

[1] Swapan Das "Electromagnetic Heating in Viscous Oil Reservoir" International Thermal Operations and Heavy Oil Symposium, Calgary, Alberta, Canada October 2008.

[2] "SNF – Manufacturer of Polymers For EOR" retrieved from http://www.snf-oil.com/, January 2011.

[3] "Electromagnetic Wave Propagation" retrieved from http://micro.magnet.fsu.edu/primer/java/polarizedlight/emwave/index.html, January 2011.

[4] Alex Becker, Ki Ha Lee, and Lou Reginato, "Field Test of a Wideband Downhole EM Transmitter" July 2009.

[5] James J. Sheng "Modern Chemical Enhanced Oil Recovery" Edition 1, Chapter 1 – 12, 2010.

[6] "Constructive and Destructive EM Wave" retrieved from http://library.thinkquest.org/19537/Physics5.html, January 2011.

[7] Keller, Edward A. "Environmental Geology", "Harvesting Oil from the Earth" 7th Edition: New York: Prentice Hall, 1996.

[8] Fred Vermeulen, Bruce Mcgee "In Situ Electromagnetic Heating for Hydrocarbon Recovery and Environmental Remediation" Journal of Canadian Petroleum Technology, Vol. 39 (8), 2000.

[9] A. Amarnath "Enhanced Oil Recovery Scoping Study", EPRI, Palo Alto, CA: 1999. TR-113836, October 1999.

[10] Orange Cast "Gary Dolberry on Enhanced Oil Recovery" retrieved from http://hubpages.com/hub/Gary-Dolberry-on-Enhanced-Oil-Recovery, February 2011.

[11] L.O. Loseth, H.M. Pedersen, T. Schaug-Pettersen, S. Ellingsrud and T. Eidesmo "A scaled experiment for the verification of the SeaBed Logging Method", Vol. 64 (3-4), pp. 47-55, 2008.

[12] "Marine EM Methods Steven Constable" retrieved from

http://www.searchanddiscovery.net/documents/2005/constable/index.htm, March 2011.

[13] "Propagation of Electromagnetic Wave" retrieved from

http://www.physicsclassroom.com/mmedia/waves/em.cfm, March 2011.

[14] Peter Roberts "An Integrated Approach To Assessing Seismic Stimulation of Oil Production" retrieved from

http://www.ees.lanl.gov/ees11/geophysics/stimulation/fossil.html, March 2011.

[15] S.S Wadader and A.Bansal "Enhanced Oil Recovery of Ugnu Tar Sands of Alaska Using Electromagnetic Heating with Horizontal Wells", EMERTEC Developments Inc. and, U.of Alaska Fairbanks

[16] Fawwaz T.Ulaby, "Magnetostatics, Electromagnetics for Engineers", Pearson Education International, The University of Michigan, 2005.

[17] Peter Signell "Electromagnetic Waves from Maxwell's Equations" Michigan State University.

[18] Shahbender, Babah, Wendt, Frank.S Gordon, Irwin, Gries, Robert Jr. "Television Receiver Ferroresonant High Voltage Power Supply Using Temperature Stable Core Material", IPEXL.

[19] New Energy Forms-Tesla Wireless Technology, April 2007.

[20] "The Global Community For Sustainable Energy Professionals" retrieved on from www.leonardo-energy.org, April 2011.

[21] Nur Azliza Ahmad "Development of A Powerful EM Transmitter" Universiti Teknologi PETRONAS, 2011.

[22] "Maxwell Equation and Electromagnetic Wave" retrieved from http://galileoandeinstein.physics.virginia.edu/more_stuff/Maxwell_Eq.html, April 2011

[23] Karl J.Ellefsen, Jared D.Abraham, David L. Wright and Aldo T.Mazzela. "Numerical Study of Electromagnetic Waves Generated by a Prototype Dielectric Lagging Tool."

[24] Mark R. De Guire "Intro To Material Science and Engineering - Electrical Conductivity", pg 17.2 rev. April 2000.

[25] Foy Johnson "Enhanced Oil Recovery " retrieved from http://liquidgoldinternational.com/information-on-enhanced-oil-recovery/enhanced-oil-recovery-2, April 2011.

[26] R.S. KA, Technologies Inc.,and M.F.Fontaine, Texaco EPTD "Pilot Testing of a Radio Frequency Heating System for Enhanced Oil Recovery from Diatomaceous Earth"

[27] D. Alan. Chave, Steven C. Constable, and R. Nigel Edwards "Electrical Exploration Methods For The Seafloor" Electromagnetic Methods in Applied Geophysics, SEG, 1982.

[28] Nur Shahida Salleh "Enhanced Oil Recovery Using EM Wave" Universiti Teknologi Petronas, 2010.

[29] M. Kashif "Oil Recovery By Using EM Wave" Journal of Applied Science Network for Scientific Information, Vol. 11(7) pp. 1366-1370, 2011.

[30] Michael Wilt "The Leading Edge", pp. 487-489, 2009.

[31] A.K. Burnham "Slow Radio Frequency Processing of Large Oil Shale Volumes To Produce Petroleum-Like Shale Oil" August 20, 2003.