Modeling of Resistivity of Sand Pack and Core Injected with Nanoparticles

By

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the

Petroleum Engineering Programme

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PETROLEUM ENGINEERING

Approved by,

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(Prof. Dr. Mariyamni Bt Awang)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

September 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.

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AISHAH SAKINAH BT ABDUL HAMID

Abstract

Nanotechnology has immersed in oil and gas industries through different disciplines such as production, exploration and refinery. Many researches have been established on nanoparticles application in Enhanced Oil Recovery (EOR), detection of hydrocarbon and down-hole equipment. The small size of nanoparticles which is much smaller than the pores throat size enables them to be easily injected into the formation without damaging the formation. The dielectric property of Nanoparticles can be used to modify or enhance the electrical property of a porous medium. This research was an effort to study the effects of nanoparticles on resistivity measurements that can be used in reservoir characterization to improve the resistivity reading and help in determination of rock properties. It can be useful for identification of low resistivity pay zone and to increase efficiency of resistivity logs. Resistivity change due to presence of nanoparticles was studied by using different types of nanoparticles which were Zinc Oxide, Aluminum Oxide, Nickel Iron Oxide, Manganese Iron Oxide and Silicon Oxide. Nanoparticles were injected into sand pack and the resistivity changed of the sand pack was measured using SCIP tester. Zinc Oxide nanoparticles gave the highest resistivity change while Silicon Oxide nanoparticles gave the lowest resistivity change. Zinc Oxide nanoparticles gave higher resistivity change due to its dielectric material properties that reduce the electric conductivity at the rock surfaces. The effect of different nanoparticles concentration was also studied by using different concentration of Zinc Oxide and Silicon Oxide nanoparticles. The results shown that different concentration of nanoparticles gave different resistivity reading. Another experiment was carried out using cores to find the effect of resistivity change in different rock permeability. It was observed that in high permeability, the change of resistivity was higher compared to cores with low permeability. Zinc Oxide nanoparticles is the most suitable nanoparticles to be used to give porous medium distinctive resistivity change which were also influenced by the porosity and permeability of the rock properties.

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CHAPTER 1

1.0 Introduction

1.1 Background of Study

Nanotechnology advancement has opened a new area of study in oil and gas industry. Currently, nanotechnology has pierced through different Petroleum discipline from Exploration to Reservoir, Drilling, Completion, Production and Refinery (Diasty & Ragab, 2013). The ability of the small nanometer sized particles to modify and manipulate reservoir fluids properties or improve strength of certain down-hole equipment pushes the current technology in oil and gas industries to a different level.

One of the famous applications of nanoparticles was in Enhanced Oil Recovery. Nanoparticles could be used to change the wettability of a formation and also improved the sweep efficiency by reducing the fluids viscosity. For example, Aluminum Oxides nanoparticles dispersed in brine and distilled water improved the oil recovery by reduction of oil viscosity (Ogolo, Olafuyi, & Onyekonwu, 2012). High strength nanostructured materials were also used in flow control and completion devices such as fracturing balls, discs, and plugs which were prone to early yielding and shape changes (El-Diasty & Ragab, 2013). In reservoir characterization, nanoparticles were used as Nano-reporters in hydrocarbon detection by releasing hydrophobic cargo when encounter with hydrocarbon (M.Berlin, Yu, Lu, E.Walsh, Zhang, & Zhang, 2011).

However, there were few studies on using nanoparticles to the current wireline logs to assist in reservoir characterization. Understanding the reservoir properties is the most important part in reservoir characterization and formation evaluation. Porosity, permeability and water saturation are basic parameters used to describe hydrocarbon potential in the formation. These properties are determined by various means in the industry such as from logging tools, core analysis and well test. Porosity is usually determined indirectly from porosity logs such as sonic logs, density logs and neutron logs or directly from core analysis in laboratory. Wireline logs measure the porosity indirectly and require some calibrations with known standards (Bodwadkar & Reis, 1993). Permeability of a formation could be measured from core analysis using Darcy equation or well testing.

These basic parameters could all be directly determined from core analysis. However, core analysis could only provide values of the porosity, permeability and water saturation at certain depths where the core was obtained. Wireline logs in the other hand provided values for the entire formation even though some calibration is needed. Many studies have been done to measure accurate values of these parameters using wireline logging tools due to its ability to provide continuous measurement. Various methods and calculations had been published to measure these values in-situ such as core porosity measurement using Carman-Kozeny, gamma rays (Bodwadkar & Reis, 1993), permeability prediction using an electro kinetic approach (Glover, Zadjali, & K.A.Frew, 2006), and correlation between rock permeability and formation resistivity (Ling, 2012) .

Electrical resistivity is one of the oldest wireline logs. It is used to detect presence of hydrocarbon. High resistivity reading in resistivity log indicates presence of hydrocarbon bearing zone. Previous studies had shown there were relationships existed between electrical resistivity with porosity, water saturation and permeability (Archie, 1941) (Glover, P.G.Meredith, P.R.Sammonds, & S.A.F.Murrell, 1994). The electric current flow and fluid flow in porous medium were related to the porosity and pore interconnections (Saner, Kissami, & Nufaili, 1997). Pore connection is associated with the permeability of a porous medium.

Understanding the effects of nanoparticles had on electrical resistivity might improve current technology in determination of the rock properties. Degree of electrical potential changes in formation after injected with nanoparticle could give information about the properties if the formation. It was important to study the changes of electrical resistivity nanoparticle had on formation with regard of rock properties such as porosity and permeability to see if any relationship exist. Besides that, different degree of resistivity change on different water saturation was also worth to study. This could be beneficial for low resistivity pay where the resistivity of oil bearing and water bearing resistivity were nearly equal due to drilling mud invasion or presence of conductive clay in the formation. In this study, the change in electrical resistivity of sand pack injected with nanoparticles was measured to study its relationship with rock properties.

1.2 Problem Statement

Porosity and permeability are properties that are used to estimate hydrocarbon potential in a formation. The accuracy in measuring these properties is very crucial in estimation of initial oil and gas in play. Over estimating or underestimating will cause error in hydrocarbon estimation. There are many methods available to determine these parameters and one of them is core analysis. Core analysis can provide accurate and reliable data however it is expensive, time consuming and can only provide measurement for selected depth. Downhole measurements such as nuclear magnetic resonance and resistivity log are preferred as it can give continuous reading.

Huge interest on nanoparticles in oil and gas industry has raised the question how nanoparticles can improve or assist current wireline logging in reservoir characterization. This project was to study the possibility of using nanoparticle in determination of rock and fluid properties through electrical properties so that continuous rock properties could be obtained.

1.2.1 Problem Identification

Many studies have been established on nanoparticles on Enhanced Oil Recovery and down-hole equipment. However there are few studies on how nanoparticles can be used to assist in determination of rock properties. This research was aimed to study the possibility of using nanoparticles to improve determination of rock properties using electrical resistivity change caused by nanoparticle. Before electrical changes can be used to help in reservoir characterization, a relationship between the electrical properties and formation properties needed to be studied.

1.2.2 Significant of the Project

There are currently few studies done to study the effects of nanoparticles on electrical resistivity. This project will give new knowledge on changes of electrical properties due to presence of nanoparticles related to the reservoir properties to close the knowledge gap. Any relationship existed might be used on resistivity log to determine the rock properties.

1.3 Objectives

The main objective of this project was to study the effects of nanoparticles had on electrical resistivity that could be used to determine the rock properties. This will see the potential of nanoparticles to assist or improve the resistivity logs in reservoir characterization. In order to achieve the main objective, there were three sub-objectives that needed to be achieved:

- Measure electrical resistivity for different rock permeability after injected with nanoparticle
- Measure resistivity in sand pack injected with different nanofluids concentration
- Measure resistivity of sand pack with different oil saturation injected with Nano fluid

1.3.1 Scope of Study

The scopes of study for this project were electrical resistivity, nanoparticles and rock properties. Resistivity study includes factors affecting resistivity in porous media and degree of change of resistivity in sand pack after injected with nanoparticles. Nanoparticles study covered the type and concentration of nanoparticles. Both nanoparticles and resistivity study were used to relate with rock properties. This project was experiment based to test the possibility of using nanoparticles to improve measurement of rock properties or reservoir characterization using electrical resistivity.

1.4 Relevancy and Feasibility of the Project

This project was an effort to improve electrical resistivity tools by using Nanotechnology. There were few studies on how nanoparticles can affect electrical resistivity which was one of widely used parameters in formation evaluation. So this study was carried out in search of knowledge regarding nanoparticles and electrical resistivity in determination of rock properties

For 8 months period, this project was considered feasible because it covered a small scope of study. This was an experimental project where the result were analyzed and discussed on how nanoparticles affect resistivity measurement for rock properties determination. All the equipment is available in UTP laboratory.

CHAPTER 2

2.0 THEORY AND LITERATUR9E REVIEW

This part discusses theories and previous studies that were used as references.

2.1 Definition

2.1.1 Porosity

Porosity is defined as the ratio of the pore volume in a reservoir rock to the total volume and is expressed as a percentage

$$\emptyset = \frac{V - Vs}{V} = \frac{Vp}{V} = \frac{Pore\ Volume}{Total\ Bulk\ Volume} \tag{1}$$

Pores volume gives information on how many fluids can be hold inside the rock. The more porous a reservoir rock, the greater the capacity to store hydrocarbon. However, not all the pores contain producible fluids, so a term effective porosity is used to describes the pores that occupied by mobile fluids or that contained producible fluids. Effective porosity is defined as ratio of volume of interconnected pores and the dead end to the total volume. Many factors affect the porosity of formation rocks such as the grain size, grain shape, sorting, clay content, compaction and cementation (Dandekar, 2006).

2.1.2 Absolute Permeability

Permeability determines the production capability of a reservoir. Absolute permeability is permeability when the porous medium is 100% saturated with a given fluid. It is a property of the rock alone and not the fluid that flow through. Permeability can be defined as the ability to flow or transmit fluid through porous medium (Dandekar, 2006). Absolute permeability can be determined using the Darcy's Law:

$$Q = \frac{kA\Delta P}{\mu L} \tag{2}$$

Where Q=Flow Rate (m^3/sec), k=Absolute Permeability (m^2/millidarcy), A=Cross-sectional Area (m^2), ΔP= Flowing Pressure Drop, N/m and μ=N sec/m^2.

Permeability can be measured from direct core measurement, well test interpretation, estimating from nuclear magnetic resonance (NMR) logs and calculating from other properties such as porosity using correlation (Ling, 2012).

2.1.3 Water Saturation

Water saturation is defined as the fraction or percent of the pore volume occupied by water. Fluid saturation is generally reported as a fraction of the effective pore volume rather than total pore volume.

$$S_w = \frac{volume\ of\ water}{pore\ volume} \tag{3}$$

Accurate water saturation is important because hydrocarbons in place are calculated by simple volumetric balance of hydrocarbons present in the effective pore space of the system.

$$S_g + S_o + S_w = 1 \tag{4}$$

If a reservoir is 50% saturated by water, the other half available will contain hydrocarbon. Overestimate or underestimate of initial water saturation can lead to error in calculating initial oil or gas in place (Dandekar, 2006).

2.2 Nanoparticles

Nanoparticles are defined as the simplest form of structures with sizes in the nanometer range. Any atoms that are bonded together with a structural radius less than 100 nanometer can be considered a nanoparticle. The small nature or nanoparticles results in useful characteristics such as increase surface area to which other materials can bond to (Diasty & Ragab, 2013). Nanoparticles reduced size associated with high surface over volume ratios that increase as the nanoparticles size decrease. As the particle size decrease to some extent, a large number of constituting atoms can be found around the surface of the particles, which makes them highly reactive with prominent physical properties (Vaseem, Umar, & Hahn, 2010). Nanoparticles which are smaller than the pore size and pore-throat size of the formation make it possible for it to be injected into the formation without damaging the formation.

Numerous researches were carried out on nanoparticles usages in oil and gas industries. The nanoparticles injection in an oil reservoir may modify the rheology, mobility, wettability, and other properties of the fluids and therefore need comprehensive investigation. Different types of nanoparticles gave different effects for its application. Certain nanoparticles were more suitable to be used as tracers for oil and gas while others were used in the oilfield to enhance water injection by changing the wettability of reservoir rock through their adsorption on porous wall (El-Amin, Sun, & Salama, 2013) . While many studies were done on nanoparticles, there was still little knowledge about the effect of nanoparticles on resistivity logs. Few studies have been carried out to study electrical conductivity of nanoparticles as compared to thermal conductivity.

In 2009, Sunvakar Ganguly et al carried out an experiment to study effective electrical conductivity of aluminum oxide Nano fluids. The results showed that electrical conductivity increased almost linearly with function of both volume fraction of nanoparticles and bulk temperature of the suspension. The results were compared with prediction from Maxwell’s model, the first theoretical approach used to calculate the effective electrical conductivity of a random suspension of spherical particles. The model which used larger particle size predicted the conductivity increase in nanoparticle-fluid mixtures. The increased of electrical conductivity in colloidal Nano suspensions was due to the Electrical Double Layer (EDL) which increased the numbers of ions surrounded the particles (Ganguly, Sikdar, & Basu, Experiemental Investigation of the Effective Eectrical Conductivity of Aluminium Oxide Nanofluids, 2009).

In 2012, another experiment was conducted to study electrical conductivity of ceramic (CuO and Al_2O_3) and metallic (Cu) Nano fluids by Sarojini et al. The result shown that, electrical conductivity increased in both water based and ethylene glycol based, when the nanoparticles concentration increased and the particles size reduced. As the particle size decreased, its surface area increased. There was also rise in electrical conductivity of Nano fluids having low electrolyte concentration, whereas a decrement was observed in Nano fluids of high electrolyte concentration due to reduce of surface conductance. However, presence of surfactant was found to reduce the electrical conductivity as it increased the stability of Nano fluids by increased its viscosity. Sarojini reported that there was no significant effect of fluid temperature on the electrical conductivity in the range of 30-60^{o} C. From the result also, it was observed that the electrical conductivity increased linearly with concentration for ceramic (CuO and Al_2O_3) Nano fluids and increased nonlinearly for metallic (Cu). Metallic Nano fluids shown less conductivity enhancement than oxides (Sarojini, Manij, Singh, & T. Pradeep, 2012).

Zinc Oxide (ZnO) is a commonly used nanoparticle with lot of application such as gas sensor, chemical sensor, bio-sensor, cosmetic, optical and electrical devices, solar cells and drug delivery (Vaseem, Umar, & Hahn, 2010). The properties of Zinc Oxide can be seen as in Table 1 in Appendix. ZnO is also one of good electrical conductors. ZnO nanoparticles can be used to reinforce electrical conductivity of poly vinylidene fluoride films (Vaseem, Umar, & Hahn, 2010). Shen et al observed increase in electrical conductivity with increasing fraction of ZnO (Shen, H.Wang, M.Dong, Ma, & Wang, 2012). Other than that, Nickel Zinc ferrite is one of magnetic nanoparticles that are also used in electronic devices and electromagnetic. Nickel Zinc Ferrite shown higher electrical conductivity ability in the presence of water compared to in dry environment. (S.A.Saafan, T.M.Meaz, E.H.El-Ghazzawy, Nimr, M.M.Ayad, & M.Bakr, 2010).

2.3 Electrical Resistivity of Rock

The uses of remote sensing instruments located in wellbores for in situ estimates of bulk formation resistivity have been among the primary observation tool used for more than a half-century, and resistivity estimates remains as an important element for formation evaluation (Kennedy, 2006). Resistivity log is mainly used to determine the hydrocarbon and water bearing zones. The rock’s matrix or grains are mainly non-conductive, thus the ability to transmit current is almost entirely a function of water in the pores.

$$r = \frac{\Delta E}{I} \tag{5}$$

Where r = resistance (ohm, Ω), ΔE = the potential difference across the sample (volts, V), I = the current flowing through the sample (amperes, A). Resistance describes the properties of a material to resist the passage of a current for a given applied potential difference. Resistivity is the resistance per unit length and area of a sample. The unit used is Ωm.

$$R = \frac{\Delta EA}{IL} \qquad (6)$$

Where R = the resistivity of the sample (Ω.m or ohm.m), A = the cross-sectional area of the sample perpendicular to the current flow (m2) and L = the length of the sample (m). Electrical resistivity is one of the parameters that are widely used to relate rock properties. Electrical properties of rocks depended on composition or bulk properties, micro structure such as geometrical arrangements of constituents and interfacial effects (C.Ruffet & GueGuen, 1993).

In aqueous salt-solution, the ions of the solid separated and were free to move. In rock at Earth's surface, the conduction was dominated by electrolytic conduction in aqueous solution of common salts distributed through the pores of the rock and at the rock water interface. The rock matrix itself was normally an insulator. The electrical resistivity usually depends on porosity and the pore structure of the rock, amount of water saturation, salinity of the water and temperature (Hersir & Arnason, 2010)

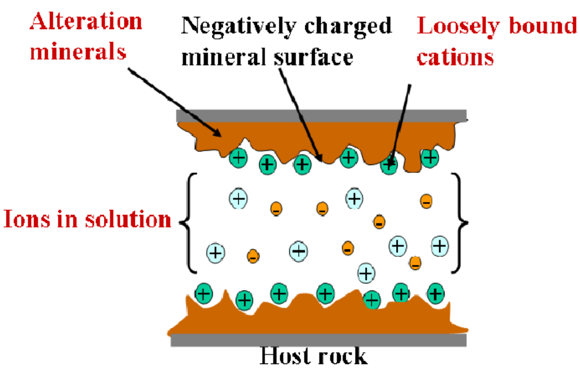


Figure 1: Ions in Solution

Conductance of a rock when filled with fluid was not only determined by the conductance of the pore fluids but also by the relatively high conductance of the interface between the rock and the pore fluid. At the interface an ionic double layer exists where the rock surfaces were usually negative charged and the solution oppose this negative surface. Cations accumulated to restore electroneurality. The excess of cations close to the rock surface over the number of cations in the bulk of the fluid caused an excess conductance along the surface over the bulk fluid conductance. This excess conductance was called the surface conductance (H.Van Olphen and M.H. Waxman). The total conductivity of a rock was influenced by conductivity of current and the dissipation at the surface. The conduction current were due to transport of charge carriers such as cations and anions, and the dissipation current were from the result of drifting of the ions, liquid viscosities, local forces, interaction between the dipoles of formation water and charges on the inner surface of pore structure (Nover & G.Will, 1989).

In a study done by M. Ahmadi, A. Habibi and P. Pourafshary, zeta potential was measured to study the change in total energy of interactions because of alterations in colloidal forces. The presence of nanoparticles on the surface grains affected the structure of the Stern Layer and Electric Double Layer and altered the zeta potential. Any increase in the concentration of nanoparticles reduced the zeta potential (M.Ahmadi, 2013). Zero zeta potential was obtained when there was a balance of concentration of ions or additives in the surface and surface charge of solid, this was when the zeta potential equal to the potential of the bulk fluid. Zeta potential had a different value when the charge is different from the surface charge and when the Stern layer needed an excess amount of ions to equalize with the surface charge

2.3.1 Electrical resistivity and Porosity

Usage of electrical resistivity to determine reservoir characteristics has made famous by G.E. Archie. In 1941, Archie introduced a simple relation between the resistivity of formation and resistivity of brine saturating the cores by equation:

$$R_o = FR_w \tag{7}$$

Where Ro= resistivity of sand when all the pores are filled with brine, Rw= resistivity of the brine and F= formation resistivity factor (Archie, 1941).

Formation resistivity factor is an intrinsic property of a porous medium, which is depending to the degree of efficiency or inefficiency for the electrolyte-filled pores, or effective pores, to conduct electrical current through the medium. Formation resistivity factor is only related to the insulating medium, it is independent of the electrical conductivity of the electrolyte in its pores. In other words, formation resistivity factor is a single number for a certain rock sample no matter what electrolyte is used in the experiment as far electrolyte does not alter the rock. It is determined by rock type, the textural of rock, effective porosity, pore throat size, geometry of the pore, and connection and distribution of pores (Ling, 2012). Deep and shallow resistivity tools read different volume of formation. In homogeneous reservoir, the differences in resistivity reading can be the result of water saturation. However, in heterogeneous reservoir, the differences between two readings of two resistivity readings could also be resulted from rock properties and other resistivity-dependent petrophysical parameters (Saner, Kissami, & Nufaili, 1997).

Archie plotted the formation resistivity factor against the permeabilities and porosities of his experiment results and realized that there was a consistent behavior between the porosity and the formation resistivity factor as in the equation:

$$F = \emptyset^{-m} \qquad (8)$$

$$F = \frac{a}{\emptyset^{m}} \qquad (9)$$

Where F=formation resistivity factor, $\emptyset$= porosity fraction and m= the cementation exponent (the slope of the line in Archie's plot). In 1952, Winsauer and others modified the Archie's equation by introducing a constant 'a' which was dependent of lithology of the formation. Determination of value a and m from experiments was done by Winsauer (1952), Carathers (1968) and Timur et al (1972) (See Appendix1).

Combining the equations 7 and 8:

$$R_o = R_w \emptyset^{-m} \qquad (10)$$

$a \approx 1$, taken as 0.81 for sandstones and 1 for carbonates, and m ≈ 2.

If formation resistivity factor, F, and porosity,$\emptyset$, values were known, a plot of log F and Log $\emptyset$ can be used to estimate the parameter of a and m. Porosity value can be measured by any techniques mentioned before, The resistivity of the core plug saturated with 100% brine can be measured using a conductivity bridge.

The resistivity of the brine could be determined by a platinum electrode dipped into brine, forming an element of the bridge circuit (Dandekar, 2006).

The constant a is the intercept obtained from log-log plot of formation resistivity factor vs. porosity. Archie suggested a range of values for different type of rock. For consolidate sandstone, m range between 1.8 and 2.0. For unconsolidated clean sandstone, m appears to be about 1.3. Loosely or partly consolidated sands, value of m range between 1.3 and 2.0 (Archie, 1941).

The equation established by Archie was for clean sandstones and is not compatible for all type of rocks. The resistivity did not always correspond to porosity even in the same kind of rock due to different mineral composition and pore geometry (Matsui, Park, Park, & Matsuura, 2000).

In 1952, Wylie and Spangler developed a relationship between the formation factor and other properties of rocks such as porosity and tortuosity. The relationship was developed on the basis of simple pore capillary models:

$$F = \frac{\tau}{\emptyset} \tag{11}$$

Where F= Formation resistivity factor, $\emptyset$=porosity, and τ = tortuosity and is defined as (L_a/L), L_a the effective path length through the pores, L the length of the core (Dandekar, 2006).

2.3.2 Electrical Resistivity and Permeability

The relationship between rock resistivity to porosity and water saturation are both presented by Archie's Law. Permeability however is more complex. Rock permeability is determined by rock type, textural of rock type, effective porosity, pore throat size, geometry of the pore, and connection and distribution of pores (Ling, 2012). Many studies have been done to relate permeability with electrical resistivity. There was no direct relationship exist between porosity and permeability because permeability depended on continuity of pore space whereas porosity indicates availability of a pore space. However, in 1927, Kozeny developed the most fundamental and popular correlations expressing permeability as a function of porosity and specific surface area (Dandekar, 2006). Kozeny's correlation was based on analogy between Darcy's Law and Poiseuille's equation (Refer Appendix 2)

The correlation of porosity and permeability depends on the pore heterogeneity and pore geometry (Saner, Kissami, & Nufaili, 1997). The transport properties of rock such as the fluid permeability and electrical conductivity were defined not by the proportion of fluid volume saturating pores and cracks in the rocks, but also by the way the pore volume is inter-connected. Measurement of the complex electrical conductivity of samples saturated weak electrolytes at a range of frequencies gave information about the efficiency with which conduction occurs across grain surfaces within the rock (Glover, P.G.Meredith, P.R.Sammonds, & S.A.F.Murrell, 1994).

Many researches were carried out to relate permeability to electric resistivity. For example in 1997, Salih Saner, Mimoun Kissami and Subhi Al Nufaili suggested a relationship between permeability, water saturation and rock resistivity. Helium porosity and gas permeability measurements were carried out on 75 carbonate core plugs and were plotted against the formation factor. The study showed that it was possible to calculate permeability if the water saturation and resistivity of formation was known. In real application, resistivity can be calculated with resistivity logs, and water saturation can be obtained from several logs, so the permeability could be calculated (Saner, Kissami, & Nufaili, 1997).

Permeability and electric conductivity somehow has similar behavior in porous medium. Glove et al (1994) measured the permeability of sandstone samples under compaction pressure that reduces the porosity. The permeability decreased as the effective pressure increased. It was also observed that electrical conductivity undergoes similar decreases upon the application of raised effective pressure (Glover, P.G.Meredith, P.R.Sammonds, & S.A.F.Murrell, 1994). In 2005, Glover et al published method predicting permeability using electro kinetic theory using relationship based on electro-kinetic and extended it to allow transformation between the mean grain size of a rock and its mean pore throat size. Li (2007) derived a model to infer relative permeability from resistivity index using similarity between fluid flow in a porous medium and electricity flow in a conductive body.

Kegang Ling (2012) derived a rigorous relationship between permeability and formation resistivity factor starting from multiple-capillary tubes concept. His coloration provides a way to calculate permeability from resistivity factor which is often available from special core analysis.

$$k = \frac{A_{rock}}{8\pi\tau^3} \emptyset^2 \quad (12)$$

$$F = \frac{\tau^2}{\emptyset} \quad (13)$$

$$kF = \frac{A_{rock}}{8\pi\tau^3} \emptyset^2 \frac{\tau^2}{\emptyset} \quad (14)$$

$$kF = \frac{\emptyset A_{rock}}{8\pi\tau} \quad (15)$$

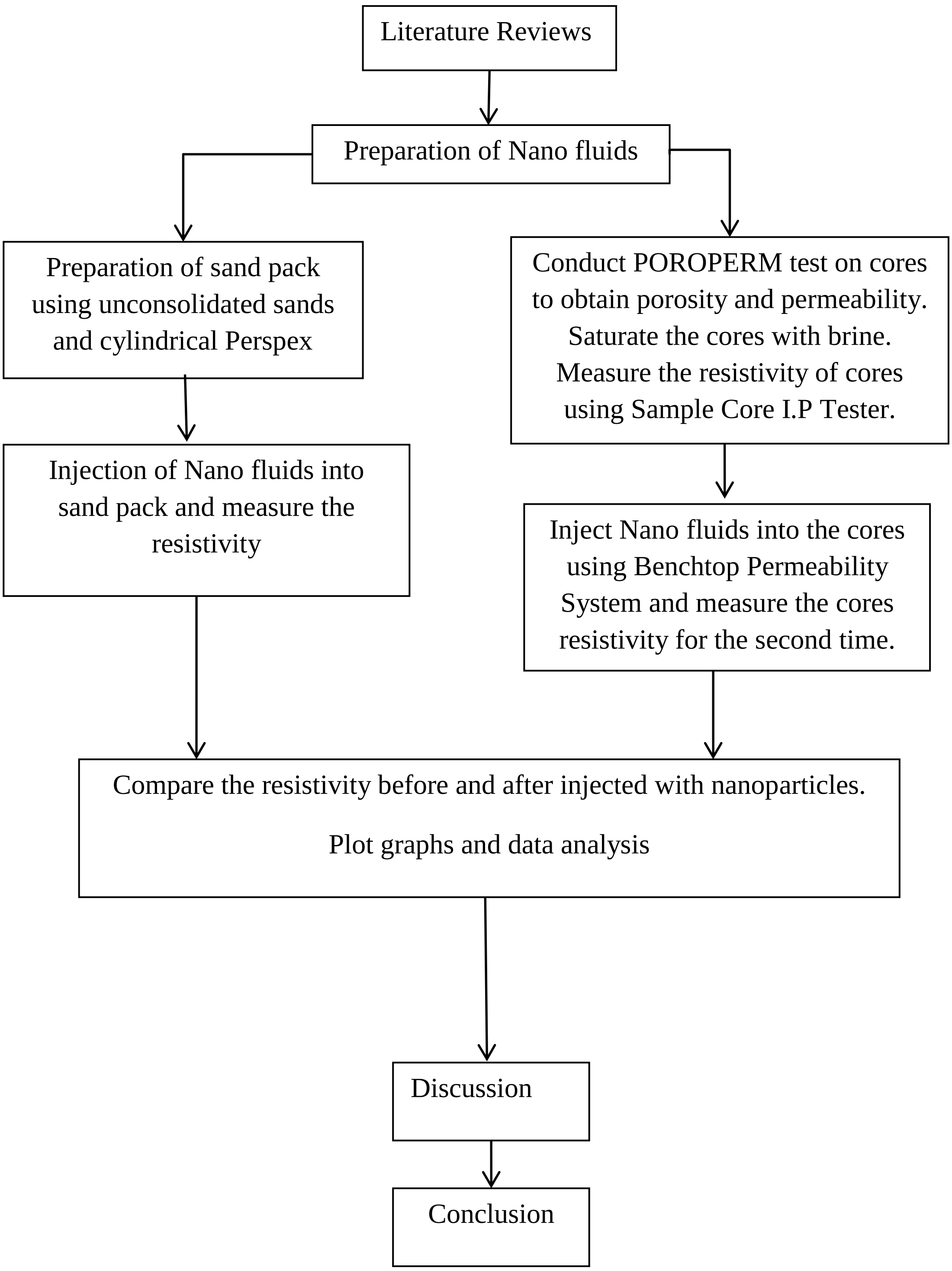
$\tau = \emptyset^{1-m}$, m= 2

Where τ= tortuosity, A= cross section area of rock, k=permeability and F=formation resistivity factor.

CHAPTER 3

3.0 METHODOLOGY

3.1 Research Methodology



3.2 Project Activities

This research required experiment in laboratory. The experiment is divided into two, first using core and second using sand pack

POROPERM

Figure 2 :POROPERM

POROPERM instrument is a permeameter and porosimeter used to determine properties of plug sized core sample. It directly measures gas permeability, pore volume and grain volume.

1. Cleaned barea sandstones cores sample were selected.
2. The core samples were weighed and the dimensions of core samples were recorded to be entered in computer.
3. Core sample was placed inside the core holder.
4. Helium Gas inlet was opened.
5. Upstream pressure was set at 250 psi and confining pressure was set at 400 psi
6. Result was recorded after 30 minutes.

Vacuum Pump

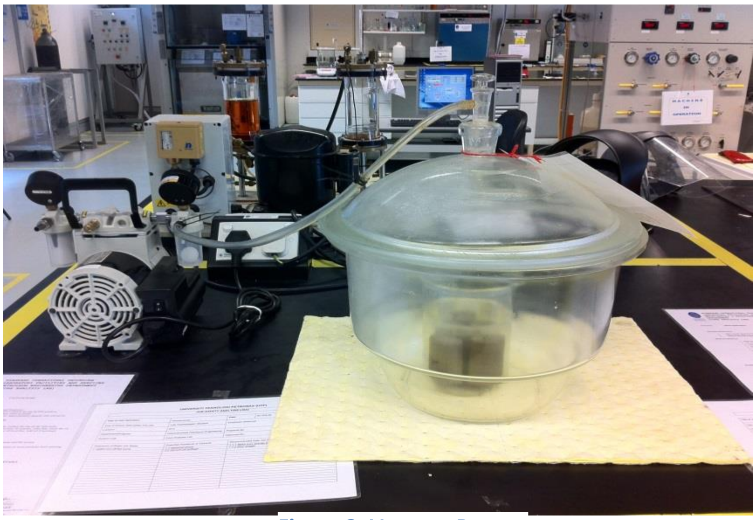


Figure 3: Vacuum Pump

1. All three cleaned cores were saturated with brine in 1000ml beaker.
2. The beaker was placed in vacuum pump to ensure all the pores are saturated with brine.
3. The vacuum was switched on for 30 minutes and the beaker was left for 6 hours inside the vacuum pump.
4. The weights of cores were recorded.

Sample Core I.P. (SCIP) tester

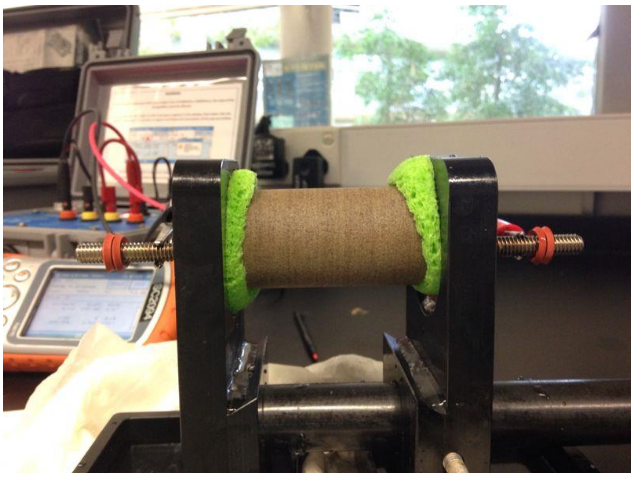
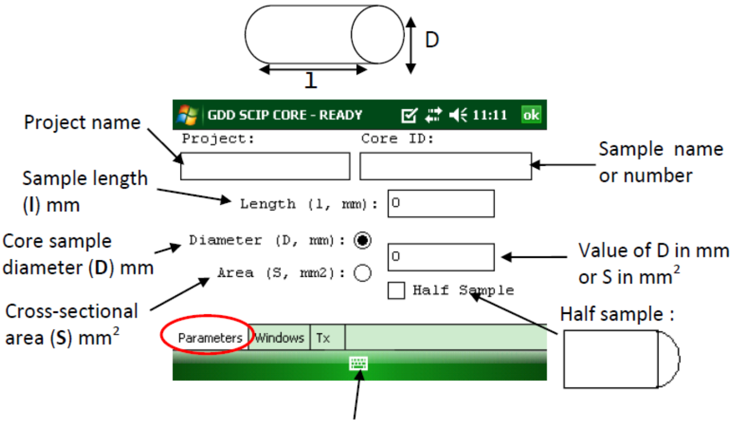


Figure 4: SCIP Tester

1. Parameters of core sample was set in the "Parameters' window



2. The cellulose sponges were soaked in copper sulphate solution. This is to increase the contact between the core sample and electrodes.
3. The core was placed between two electrodes
4. The signal timing was set and resistivity measurement was taken
5. Result was recorded in ohm.m

Benchtop Permeability System

Figure 5: Benchtop Permeability System

Benchtop permeability system is equipment used to perform simple liquid permeability test. In this experiment, the permeability system is also used to inject Nano fluids into the cores.

1. Core was placed inside the core holder.
2. Flow rate of 0.5 ml/ min was set on the computer.
3. Pump to reservoir was first opened to clean fluid inside the tube.
4. Close pump to reservoir, open pump to inject fluid into core.
5. Brine was first injected into the core to measure the permeability. The permeability value was recorded and compared with result from POROPERM. This usually takes three to four hours for the permeability value to stable.
6. Permeability of core was recorded and Nano fluids were injected to the core for about three hours.

3.2.1 Preparation of sand pack and determination of rock properties

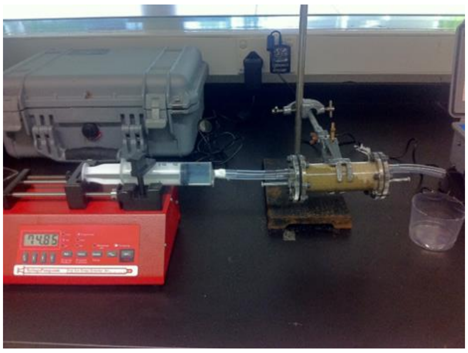


Figure 6: Sand pack experiment set up

Unconsolidated clean sands were filled into a cylindrical tube to act as a porous medium for the experiment. The reason sand pack was used because it was easier to be prepared. Because only sands are used, this experiment might produce different result with other porous medium that have other components such as clay or shales.

3.2.2 Preparation of Nano fluids

Five types of nanoparticles are chosen which are zinc oxide, aluminum oxide, silica oxide, nickel ferrite oxide and nickel zinc ferrite. Nanoparticles is weighted and dissolved in 1000 ml of brine. The resistivity of the electrolyte was measured. Solubility of nanoparticles in brine was recorded.

Figure 7: Preparation of Nano fluids

3.3 Gantt Chart and Key Milestones FYP1 and FYP2

Table 1: Gantt chart and Key Milestones FYP 1

No.	Detail/Week	3	4	5	6	7	8	9	10	11	12	13
1	Selection of title											
2	Preliminary Research Work											
3	Submission of Extended Proposal											
4	Proposal Defense											
5	Preparation of lab materials											
6	Submission of Interim Report											

Table 2 : Gantt chart and Key Milestones FYP 2

No.	Detail/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Project Work Continue							Mid Semester Break								
	Lab booking and tools preparation															
2	Poroperm and Permeability System															
	Resistivity of core sample															
3	Submission of Progress Report															
4	Project Work Continue															
	Resistivity of sand packs															
5	Pre- SEDEX															
6	Submission of Draft Project															
7	Submission of Dissertation (soft bound)															
8	Submission of Technical Paper															
9	Oral Presentation															
10	Submission of Project Dissertation (Hard Bound)															

3.5 Tools, Equipment and materials

1. Sample Core I.P. Tester (SCIP Tester)
2. POROPERM
3. Benchtop Permeability System
4. Nanoparticles
    - Zinc Oxide
    - Aluminum Oxide
    - Nickel Iron Oxide
    - Manganese Iron Oxide
    - Silicon Oxide
5. Sand Pack
    - Sand from Teluk Batik, Perak.
6. Oil and brine
    - Masila Oil
    - Brine 15000 ppm

CHAPTER 4

4.0 RESULT AND DISCUSSION

4.1 Findings

Experiment was performed in two parts first using core and second using sand packs. The reason core was also used was to observe the resistivity change in different permeability of rock. POROPERM machine and Benchtop Permeability System were used to measure the permeability and porosity and in the same time inject nanoparticles into the cores.

Resistivity of solution

	Brine	Zinc Oxide	Aluminum Oxide	Nickel Iron Oxide	Manganese Iron Oxide	Silicon Oxide
1st reading	4.12	3.887	6.172	3.967	6.079	2.586
2nd reading	3.883	3.718	6.166	3.984	6.132	2.599
3rd reading	3.924	3.920	6.124	4.081	6.180	2.611
Average	**3.980**	**3.841**	**6.153**	**4.010**	**6.130**	**2.598**

Table 3: Resistivity of Solution

Solution	Resistivity of solution (Rw)	Resistivity Change (ΔRw)	+Solubility
Brine	3.980		
Brine + Zinc Oxide	3.841	0.139	Insoluble
Brine + Aluminum Oxide	6.153	2.173	Insoluble
Brine + Nickel Iron Oxide	4.010	0.03	Insoluble
Brine + Manganese Iron Oxide	6.130	2.150	Insoluble
Brine + Silicon Oxide	2.598	1.382	Soluble

Table 4: Resistivity Change in Solution

POROPERM

Name	K(mD)	Porosity	Vol. Pore	Vol. Grain	Vol. Bulk	Dry Weight	Wet Weight
N2	83.47	18.02	14.47	65.80	80.27	172.82	186.13
N4	37.87	17.16	13.33	64.35	77.68	167.95	179.81
N6	53.39	19.14	15.52	65.55	81.06	173.84	188.64

Table 5: Result from Poroperm for N cores

Name	K(mD)	Porosity	Vol. Pore	Vol. Grain	Vol. Bulk	Dry Weight	Wet Weight
L1	36.12	18.73	16.72	72.58	89.3	186.80	201.47
L2	50.41	19.25	15.84	66.45	82.29	175.303	190.19
L3	16.75	18.80	16.19	69.92	86.11	191.074	206.23

Table 6: Result from Poroperm for L cores

The average permeability of cores from Benchtop Permeability System

	N2	6N	N4
1	43.581	47.525	31.669
2	43.399	47.954	32.12
3	44.415	49.289	32.171
4	43.309	48.171	32.019
5	44.51	48.062	32.429
6	43.22	47.103	32.069
7	44.415	46.689	31.918
8	44.133	47.846	32.222
9	43.399	47.631	34.236
10	45.184	53.918	36.519
Average	**43.957**	**48.419**	**32.737**

Table 7: Benchtop Permeability System Result N Cores

	L1	L2	L3
1	22.229	49.473	8.647
2	22.461	50.154	8.115
3	22.252	51.331	8.951
4	22.252	50.853	8.755
5	22.484	51.573	8.605
6	22.161	49.925	8.477
7	22.438	49.925	8.359
8	22.698	50.618	8.235
9	22.555	51.695	8.096
10	22.275	48.81	8.118
Average	22.3805	50.4357	8.4358

Table 8: Benchtop Permeability System Result L Cores

Sample Core IP Tester (SCIP)

Resistivity of core injected with brine (Ohm.m)

	N2	N4	6N
1st reading	5.112	6.25	5.9
2nd reading	5.194	6.265	5.98
3rd reading	5.238	6.273	6.032
Average	**5.181**	**6.263**	**5.971**

Table 9: Resistivity of N cores injected with brine Ohm.m

Resistivity of core injected with 1 gram Zinc Oxide Nano fluids (Ohm.m)

Core	N2	N4	6N
1st reading	10.822	10.654	10.733
2nd reading	10.770	10.989	10.744
3rd reading	10.653	11.080	10.702
Average	**10.748**	**10.908**	**10.726**
Difference in resistivity	N2	N4	6N
	5.567	4.645	4.755

Table 10: Resistivity of N Cores injected with Zinc Oxide NP

Resistivity of core injected with brine (Ohm.m)

	L1	L2	L3
1st reading	11.987	12.604	11.057
2nd reading	11.901	12.516	10.916
3rd reading	11.902	12.535	10.845
Average	**11.93**	**12.551**	**10.939**

Table 11: Resistivity of L cores injected with brine (Ohm.m)

Resistivity of core injected with 1 gram Silicon Oxide Nano fluids

Core	L1	L2	L3
1st reading	12.915	14.238	11.835
2nd reading	12.921	14.410	11.858
3rd reading	12.834	14.280	11.925
Average	**12.890**	**14.309**	**11.872**
Difference in resistivity	L1	L2	L3
	0.96	1.758	0.933

Table 12: Resistivity of L cores Injected with SIlicon Oxide NP (Ohm.m)

Sand pack

Sand pack was used as a replacement for core to investigate which nanoparticles give the highest resistivity change in sand. Below were the result for resistivity before and after nanoparticles were injected into the sandpack. Compared to the core, resistivity change in sand pack was more obvious because more void spaces were available in unconsolidated sand.

Dimension of sand pack

Length of sand pack : 122mm

Diameter of sand pack : 36 mm

a) Nanoparticles Injected: Zinc Oxide (Ohm.m)

Solution injected into sand pack	Brine	Zinc Oxide
1st reading	3.180	2.667
2nd reading	3.207	2.549
3rd reading	3.259	2.487
Average	**3.22**	**2.568**

Table 13: Resistivity sand pack injected with Zinc Oxide NP (Ohm.m)

b) Nanoparticles Injected: Aluminum Oxide (Ohm.m)

Solution injected into sand pack	Brine	Aluminum Oxide
1st reading	3.298	3.086
2nd reading	3.287	3.155
3rd reading	3.236	3.173
Average	**3.273**	**3.138**

Table 14: Resistivity sand pack injected with Aluminum Oxide (Ohm.m)

c) Nanoparticles Injected: Nickel Iron Oxide (Ohm.m)

Solution injected into sand pack	Brine	Nickel Iron Oxide
1st reading	3.492	3.652
2nd reading	3.502	3.625
3rd reading	3.455	3.574
Average	**3.483**	**3.617**

Table 15: Resistivity sand pack injected with Nickel Iron Oxide (Ohm.m)

d) Nanoparticles Injected: Manganese Iron Oxide (Ohm.m)

Solution injected into sand pack	Brine	Manganese Iron Oxide
1st reading	3.599	3.274
2nd reading	3.677	3.308
3rd reading	3.621	3.302
Average	**3.632**	**3.294**

Table 16: Resistivity of sand pack injected with Manganese Iron Oxide (Ohm.m)

e) Nanoparticles Injected : Silicon Oxide (Ohm.m)

Solution injected into sand pack	Brine	Silicon Oxide
1st reading	2.944	2.873
2nd reading	2.917	2.857
3rd reading	2.928	2.859
Average	**2.929**	**2.863**

Table 17: Resistivity of sand pack injected with Silicon Oxide (Ohm.m)

Crude Oil

Crude Oil Injected: 5ml

Solution injected into sand pack	Brine + 5ml Crude Oil	1g Zinc Oxide
1st reading	4.550	4.399
2nd reading	4.558	4.435
3rd reading	4.518	4.450
Average	**4.542**	**4.425**

Table 18: Resistivity of sand pack with 5ml crude oil injected with Zinc Oxide NP (Ohm.m)

Crude Oil Injected: 10ml

Solution injected into sand pack	Brine + 10 ml Crude Oil	1g Zinc Oxide
1st reading	9.398	8.255
2nd reading	10.032	8.548
3rd reading	10.374	8.578
Average	**9.934**	**8.460**

Table 19: Resistivity of sand pack with 10ml crude oil injected with Zinc Oxide NP (Ohm.m)

Crude Oil Injected: 15ml

Solution injected into sand pack	Brine + 15 ml Crude Oil	1g Zinc Oxide
1st reading	22.894	13.484
2nd reading	20.545	13.751
3rd reading	19.295	13.595
Average	**20.911**	**13.610**

Table 20 : Resistivity of sand pack with 15ml crude oil injected with Zinc Oxide NP (Ohm.m)

Concentration

Solution injected into sand pack	0.002 wt.% Zinc Oxide	0.003 wt.% Zinc Oxide	0.004 wt.% Zinc Oxide
1st reading	2.954	3.346	3.600
2nd reading	2.921	3.388	3.619
3rd reading	2.897	3.497	3.609
Average	**2.924**	**3.410**	**3.609**

Table 21: Resistivity of sand pack injected with different concentration of Zinc Oxide NP (Ohm.m)

Solution injected into sand pack	0.002 wt.% Silicon Oxide	0.003 wt.% Silicon Oxide	0.004 wt.% Silicon Oxide
1st reading	2.725	2.555	2.670
2nd reading	2.726	2.555	2.671
3rd reading	2.746	2.561	2.690
Average	**2.732**	**2.557**	**2.685**

Table 22: Resistivity of sand pack injected with different concentration of Silicon Oxide NP (Ohm.m)

4.2 Discussion

Permeability

The relationship between rock permeability and resistivity change was measured using three cleaned sandstone cores. Firstly, brine was injected into the core using and resistivity was measured. After injected with Nano fluids, the resistivity of the core was measured for the second time. It was observed that after injected with nanoparticles, all the cores' resistivity increased. The increase of resistivity for the lowest permeability was the smallest, while the resistivity change for the highest permeability was the highest.

Core	**K(mD)**	**Porosity**	**Brine (Ohm.m)**	**Brine + NP (Ohm.m)**	**Change in resistivity (Ohm.m)**
L1	36.12	18.799	11.93	12.89	0.96
L2	50.406	19.247	12.551	14.309	1.758
L3	16.75	18.724	10.939	11.872	0.933

Table 23: Resistivity of L Cores before and after injected with Silicon Oxide NP (Ohm.m)

Core	K(mD)	Porosity	Brine (Ohm.m)	Brine + NP (Ohm.m)	Change in resistivity (Ohm.m)
N2	83.466	18.024	5.181	10.748	5.567
N4	37.865	17.158	6.263	10.908	4.645
N6	53.39	19.14	5.971	10.726	4.755

Table 24 : Resistivity of N cores before and after injected with Zinc Oxide NP (Ohm.m)

The resistivity increment was because nanoparticles had covered the surface of the rock grains and reduced the zeta potential at the surface of the grains. The zeta potential is potential at the shear plane between solid and liquid, this was proved by a study done by M. Ahmadi (2013) shows that the zeta potential for high concentration of Nanoparticles was lesser than in low concentration of nanoparticles. The presence of nanoparticles on the grain surface affected the Sterm layer and the Electric Double Layer (EDL).

When nanoparticles covered the surface of core grains, the conductivity at the surface was reduced thus increases the overall resistivity. The higher the permeability, the higher the change of resistivity observed in the cores as the surface area between the pore fluids and grains surface is larger. In low permeability, the resistivity change was smaller because the fluid inside the pore is not easily to be displaced and the surfaces were smaller. Zinc Oxide gave higher resistivity change compared to Silicon Oxide. This is because it is a dielectric material. When a dielectric is placed in an electric field, electric charges do not flow through the material as they have no free electrons, instead electric polarization occurred. Due to the dielectric polarization, the negative charges are displaced toward the field which has large amount of cations and positive charges shift in the opposite direction. This creates an internal electric field that reduces the overall field within the dielectric itself. Other nanoparticle that is dielectric material is the Aluminum Oxide.

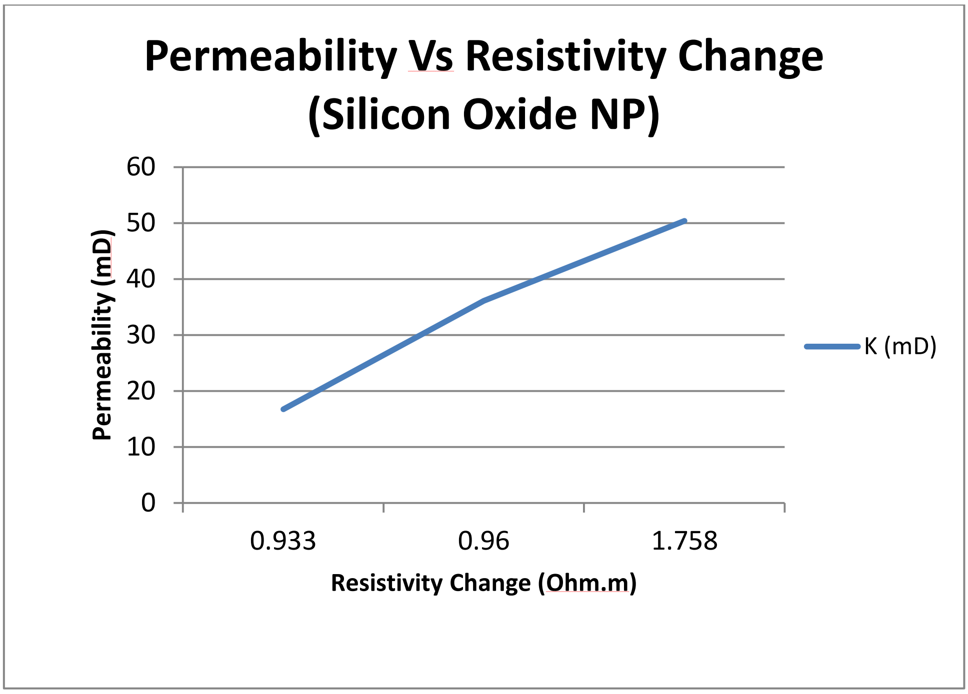


Figure 8: Permeability Vs. Resistivity Change SiO

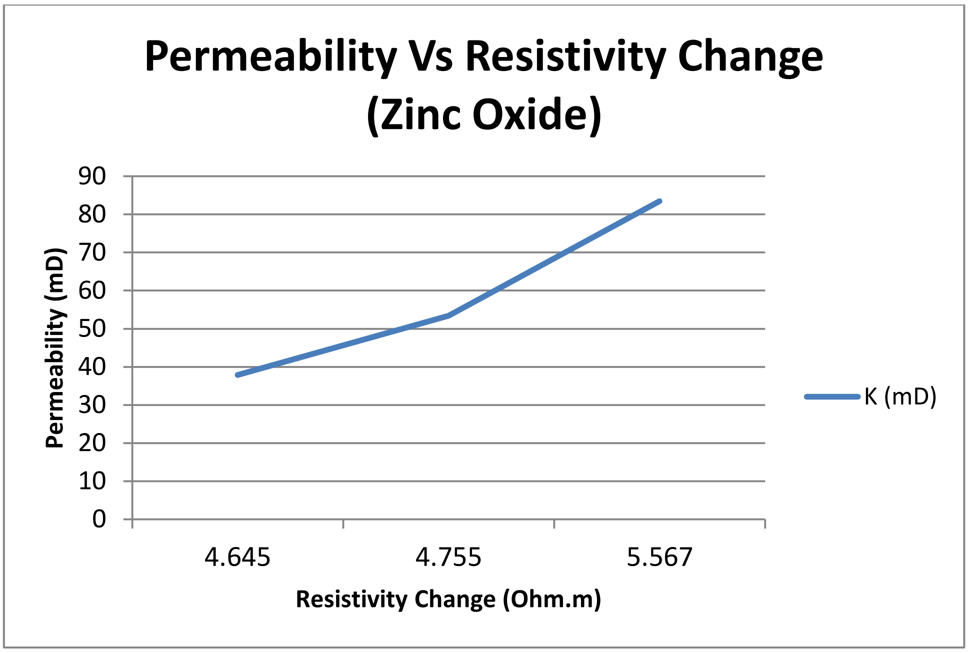


Figure 9: Permeability Vs. Resistivity Change ZnO

Other than resistivity change, permeability was calculated using the resistivity value of core injected with Nano fluid and was compared with the resistivity of injected with brine only. The permeability values were calculated using Kegang Ling-equation (15) in literature review. The permeability calculated was compared with permeability from POROPERM test and Benchtop Permeability System (BPS).There were no connection between the bulk resistivity of core injected with Nano fluid to the permeability however it did provide a nearer value than core injected with brine only. The bulk resistivity value was influenced mostly by the porosity.

	L1	L2	L3
Diameter	3.84	3.76	3.82
Radius	1.92	1.88	1.91
Area	11.55	11.12	11.45
Brine	3.98	3.98	3.98
Resistivity Core Before	11.93	10.94	12.55
Porosity	18.73	19.24	18.80
Tortuosity	0.05	0.05	0.05
F	3.00	2.75	3.15
Calculated K	53.79	59.57	51.06
K Poroperm	36.12	50.41	16.75
%Difference	-48.92	-18.16	-204.81
K BPS	26	49	8.118
%Difference	-106.88	-21.56	-528.92

	L1	L2	L3
Diameter	3.84	3.76	3.82
Radius	1.92	1.88	1.91
Area	11.55	11.12	11.45
Brine + SiO	2.60	2.60	2.60
Resistivity Core After	12.89	11.87	14.31
Porosity	18.73	19.24	18.80
Tortuosity	0.05	0.05	0.05
F	4.96	4.57	5.51
Calculated K	32.50	35.83	29.23
K Poroperm	36.12	50.41	16.75
% Difference	10.03	28.93	-74.52
K BPS	26.00	49.00	8.12
% Difference	-24.99	26.88	-260.10

Comparison of permeability from resistivity with POROPERM and BPS values (Silicon Oxide NP)

	N2	N4	N6
Diameter	3.76	3.76	3.75
Radius	1.88	1.88	1.88
Area	11.08	11.12	11.07
Brine	3.98	3.98	3.98
Resistivity Core Before	5.18	6.26	5.97
Porosity	18.02	17.16	19.14
Tortuosity	0.06	0.06	0.05
F	1.30	1.57	1.50
Calculated K	110.02	82.74	107.54
K Poroperm	83.47	37.87	53.39
% Difference	-31.81	-118.52	-101.42
K BPS	43.96	32.74	48.42
% Difference	-150.29	-152.75	-122.10

	N2	N4	N6
Diameter	3.76	3.76	3.75
Radius	1.88	1.88	1.88
Area	11.08	11.12	11.07
Brine + ZnO	2.60	2.60	2.60
Resistivity Core After	10.75	10.91	10.73
Porosity	18.02	17.16	19.14
Tortuosity	0.06	0.06	0.05
F	4.14	4.20	4.13
Calculated K	34.62	31.01	39.08
K Poroperm	83.47	37.87	53.39
%Difference	58.52	18.10	26.81
K BPS	43.96	32.74	48.42
%Difference	21.24	5.27	19.29

Comparison of permeability from resistivity with POROPERM and BPS values (Zinc Oxide NP)

Type of Nanoparticles

From the table, when different types of Nano fluids with 0.001% concentration were injected into the sand pack, the values of resistivity were slightly reduced except for Nickel Iron Oxide. For low concentration of nanoparticles, the ions of the nanoparticles dispersed in the solution and help in electrical conductivity. This caused the resistivity of porous medium to reduce. From the table, Zinc Oxide nanoparticles gave the highest resistivity change while Silicon Oxide gave the lowest change in resistivity.

Nanoparticles	**Brine (Ohm.m)**	**Brine + Nanoparticles (Ohm.m)**	**Resistivity Change (Ohm.m)**	**Solubility in water**
Zinc Oxide	3.22	2.568	0.652	Insoluble
Aluminum Oxide	3.273	3.138	0.135	Insoluble
Nickel Iron Oxide	3.483	3.617	-0.134	Insoluble
Manganese Iron Oxide	3.632	3.294	0.338	Insoluble
Silicon Oxide	2.929	2.863	0.066	Soluble

Table 25: Comparison of sand pack resistivity for different type of nanoparticles

Concentration of Nanoparticles

Other than types of the electrolytes in porous medium, the concentration of electrolytes also influenced the resistivity. Two types of nanoparticles, Zinc Oxide and Silicon Oxide with different concentration were used. From the observation, the resistivity change for different concentration for Zinc Oxide and Silicon Oxide were varies. For Zinc Oxide, at low concentration 0.001 wt.% the resistivity decreased, the resistivity then increased when higher concentration 0.002% to 0.004% of Zinc Oxide Nanoparticles was injected. For Silicon Oxide, the resistivity decreased at 0.001 wt.% until 0.003 wt.%. The resistivity then increased at 0.004%. At low concentration, the nanoparticles dispersed in the solution and helped in electric conductivity inside the pores. At high concentration, nanoparticles started to stick and covered the surface of the rock thus lowered the surface charges on the grain surface. Different from Zinc Oxide nanoparticles, Silicon Oxide nanoparticles needed more concentration to cause the resistivity to increase. This was due to the solubility of Silicon Oxide nanoparticles in brine as observed during preparation of Nano fluids; this makes it more tend to disperse in the solution than to stick at the grain surface.

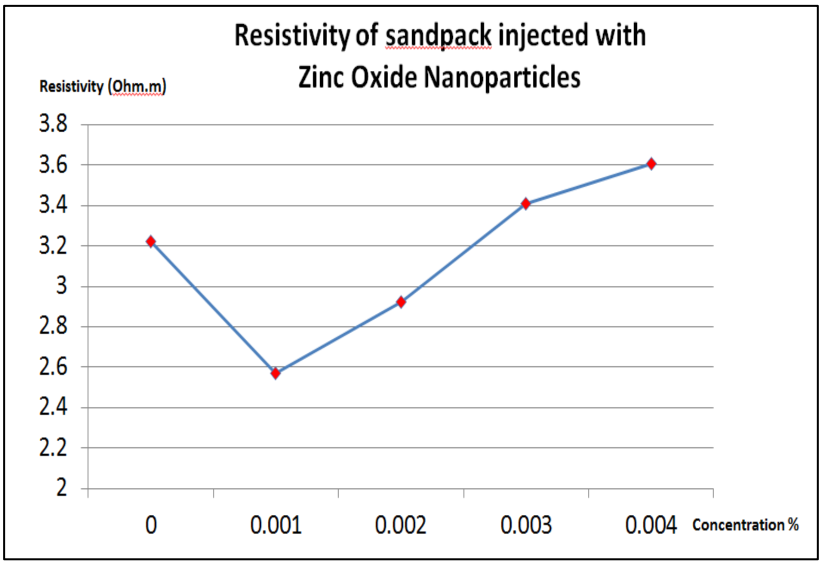


Figure 10: Resistivity of sand pack injected with different concentration of Zinc Oxide

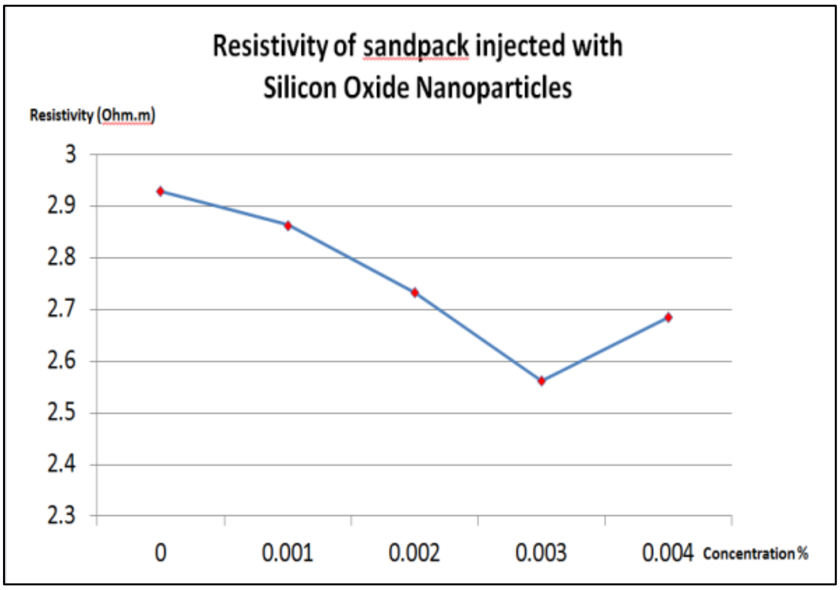


Figure 11: Resistivity of sand pack injected with different concentration of Silicon Oxide

Presence of Crude Oil

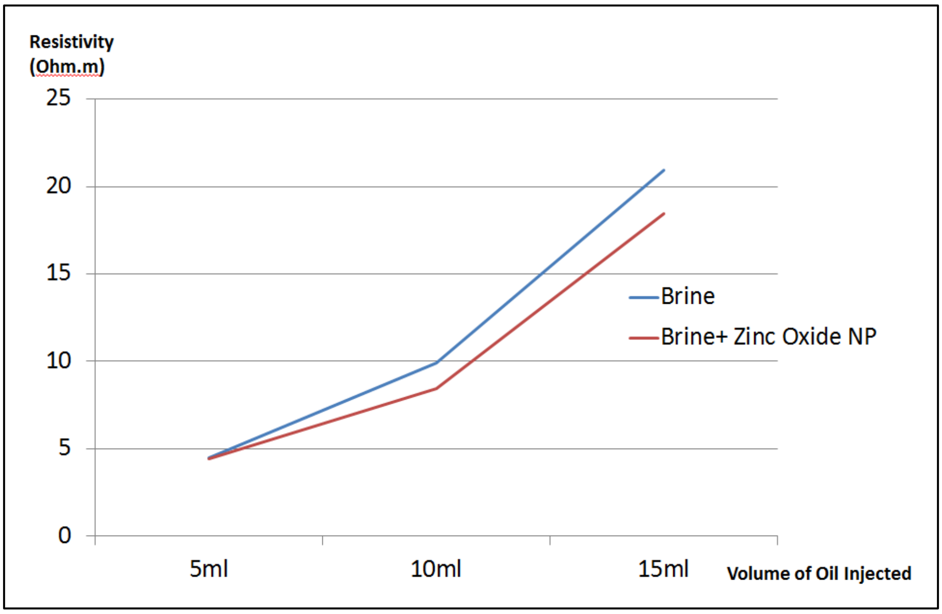


Figure 12: Resistivity of sand pack with different crude oil concentration

Another experiment was set up to study the affect of crude oil. In presence of hydrocarbon, for 0.001% concentration of Zinc Oxide nanoparticle, there were reduction in resistivity measured after injected with Zinc Oxide nanoparticles. The presence of hydrocarbon gave high resistivity when compared to sandpack without any presence of crude oil. For high volume of crude oil, the resistivity change was higher compared to low volume of crude oil.

CHAPTER 5

5.0 CONCLUSION AND RECOMMENDATION

In conclusion, the objectives of this research were to study the effect of nanoparticles on electrical resistivity in porous medium were achieved. The first sub-objective was to measure electrical resistivity for different rock permeability after injected with nanoparticles. The resistivity change after injected with nanoparticles shows there were relationship exist between the degrees of resistivity change with the core permeability. The resistivity of the porous medium injected with nanoparticles however could not provide accurate calculation for permeability; nevertheless it did provide better permeability values than resistivity from core injected with brine only when compared with permeability obtained from POROPERM and permeability system. Zinc Oxide nanoparticles provide a higher resistivity change when compared to Silicon Oxide nanoparticles as it is a dielectric material. Second sub-objective was to measure resistivity in sand pack injected with different Nano fluids concentration. The concentrations of nanoparticles did influence the resistivity change. At high concentration, the nanoparticles reduced the conductivity at the pores surface thus increase the total resistivity of the porous medium. At low concentration, the nanoparticles dispersed in the electrolyte and help in conductivity of the porous medium. Third sub-objective was to measure resistivity of sand pack with different oil saturation injected with Nano fluid. The resistivity decrease after sand pack was injected with low concentration of Zinc Oxide Nanoparticles.

For expansion and continuation, to clearly define the resistivity changes and the permeability relationship, more core samples are needed to provide more values. By this method, more varies permeability values and resistivity changes can be obtained and a curve can be plot so that the relationship will be clearer. Other study that could also be considered is to study the water saturation or oil saturation by injecting different oil volume inside the porous medium. The resistivity change in porous medium after injected with nanoparticle is study to see if any relationship exists with the water saturation value.

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