RELATIVE PERMEABILITY HYSTERESIS

By

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DRAFT REPORT

Submitted to the Mechanical Engineering Programme

in Partial Fulfillment of the Requirements

for the Degree

Bachelor of Engineering (Hons)

(Mechanical Engineering)

Universiti Teknologi Petronas

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CERTIFICATION OF APPROVAL

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Serdar Halliyev

A project dissertation submitted to the

Mechanical Engineering Programme

Universiti Teknologi PETRONAS

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Bachelor of Engineering (Hons)

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Approved:

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Ms. Faiza Mohd Nasir

Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

November 2008

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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SERDAR HALLIYEV

ABSTRACT

Significant amount of oil is left in the reservoir after the natural pressure of the reservoir finishes. That's why engineers use some methods such as EOR and IOR. By using these techniques some more oil can be produced. When we use these methods we need to consider two- or three-phase flows very well. Even though there pretty much work has been done about the two-phase flow, generally engineers ignore the hysteresis effect. Ignoring hysteresis will give different results which will influence the efficiency and performance of the process.

The purpose of the project is to conduct some experiments to calculate the relative permeability values and observe the hysteresis effect in multiphase flow. The scope of the report is two-phase flow, relative permeability and hysteresis effect. The methodology consists of surfing the web, utilizing library resources, Society of Petroleum Engineers (SPE) files, and the other articles related to fluid flow, enhanced oil recovery, relative permeability, WAG applications and hysteresis effect and conducting set of experiments to obtain data related to saturation and relative permeability.

The outcome of the report is that objectives were achieved. With reference to all of the concepts elaborated in Chapter 2, some results were obtained after considering all parameters from the several experiments. The findings were analyzed and evaluated. From the experiments, raw data were obtained and they were used to calculate relative permeability values. And graphs were constructed to observe the hysteresis effect.

In conclusion, the relative permeability hysteresis was observed in this experiment and it was changing after each cycle. Obtained experimental results were compared with previous results and they follow the same trend. The data was acceptable and sufficient to construct the saturation versus relative permeability graphs. So hysteresis does exist in two-phase flow and after each cycle the curves are differ from the previous curves.

ACKNOWLEDGEMENT

Throughout the progress of my Final Year Project, I would like to acknowledge Final Year Project supervisor who is Ms. Faiza Mohd Nasir. During the progress of the FYP, Ms. Faiza provided feedback that is related to the project as well as provided her valuable experience on the subject. She guided me so that I could succeed my objectives within the time frame provided.

The next acknowledgement would be tributed to my advisor Prof. Dr. Birol Demiral who introduced me the aspects needed to do my FYP and the methods which are to be used to analyze the project so that the needed result can be obtained. Besides that, Prof. Birol always encouraged me to do the best and that the project can be solved by different ways and that it is important that we do not wander away from the main objectives. Also he emphasized on useful sources and correct procedure to achieve the goals.

I also would like to thank Mr. Mohd Riduan b. Ahmad, the technician of the Relative Permeability machine, who helped me a lot with patience to achieve my goals. He was always with me whenever I needed any help regarding the machine and experiment even though the experiments continued till late midnight.

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CHAPTER 1
INTRODUCTION

1.1 Background of Study

In the oil production, after a while reservoir pressure reduces and natural drive becomes insufficient to extract oil. Engineers came up with some solutions for that problem. Secondary and tertiary oil recovery methods are applied to get more oil production. Enhanced oil recovery and improved oil recovery are some of the techniques used to improve the performance and the recovery. With these techniques 30-60 %, or more of the reservoir's original oil can be extracted compared with 20-40 % using the standard techniques.[1]

A significant quantity of oil remains in an oil reservoir after waterflooding. Some of this oil may be economically produced by WAG injection, an EOR method, which has been successfully used in some reservoirs.[2] When we use enhanced oil recovery method we obtain multiphase flow. In multiphase flow in porous media, relative permeability is a dimensionless measure of the effective permeability of each phase. It can be viewed as an adaptation of Darcy's law to multiphase flow. In applications, relative permeability is often represented as a function of water saturation, however due to capillary hysteresis, one often resorts to one function or curve measured under drainage and one measured under imbibition.[3]

1.2 Problem Statement

As the time passes engineers need to come up with some methods to support the reservoir pressure, since the natural pressure decreases gradually. When they use some methods such as EOR or IOR**,** two-phase or three-phase flow occur**s** in the reservoir. For most of the reservoirs two-phase flow approach can be enough. But this can be improved by using three-phase flow approach which is very troublesome and tedious. Understanding some of the characteristics of multiphase flow such as relative permeability, hysteresis effect during draining- imbibitions cycles, saturation and entrapment of displacing phases are very important to get desirable results.

1.3 Objectives

- To measure relative permeability values
- To analyze the effect of relative permeability hysteresis during multiphase flow

1.4 Scope of Study

- Extensive literature review has been done throughout the research period about relative permeability and the hysteresis effect occurring during the drainage and imbibitions cycles.
- Experimental set-up preparation have been done and required materials, samples, items for the experiment have been obtained from respective places and the time available for both technician and the apparatus have been booked.
- Machine for the experiment has been adjusted to operate properly.
- The experiments have been done and data required has been obtained for our report. The relative permeability data will be measured and analyzed in terms of hysteresis effect.

1.5 Significance of Study

Relative permeability is one of the main characteristics of the fluid flow. The determination of relative permeability allows comparison of the different abilities of the fluids to flow in the presence of each other, since the presence of more than one fluid is generally inhibits flow. Relative permeability hysteresis becomes very important during EOR techniques like WAG injection, waterflooding, etc. Ignoring it may give us different results which will affect the production performance and recovery.

CHAPTER 2
LITERATURE REVIEW

2.1 Reservoir Fluid Fundamentals

All practical fluid flow equations are based on two concepts: the Darcy equation and material balance. The simpler concepts of reservoir engineering are based on of these concepts. However, the more complex concepts – and quite of the most useful ones – are based on both material balance and Darcy equation.

Fluid flow can be categorized or characterized so many different ways that it is virtually impossible to consider all of the possibilities. Fluid flow can be categorized according to the geometric configuration involved, the compressibility of the fluids, and the constancy of flow rates and pressure with respect to time. Also, flow can be single or multiphase. A particular working equation will probably apply to only one combination of each of these classifications, which makes it virtually impossible to consider all of the possible combinations. Consequently, the means of accounting for the various classifications are given, but the engineer must devise the derivations for peculiar cases may be encountered.

2.2 Characteristic of Darcy Equation

Darcy's Law is an empirical relationship derived for the vertical flow of fluid through packed sand. This equation is applicable only for low flow rate and it is very basic that it is impossible to deal with complex problems. But the continued use of this empirical equation to solve complex reservoir engineering problems seems analogous to using a horse to go to the moon. However, there appears to be no easy way to back up and start over with a more theoretical treatment of fluid flow, so we use Darcy's empirical relationship to the best of our ability.

2.2.1 Absolute Permeability

The Darcy work was never meant to apply to multiphase flow. It was meant to describe the flow of one fluid saturating 100% of porous media. Under these conditions the permeability to a particular fluid is independent of the nature (viscosity) of the fluid. We can think of the absolute permeability as a fixed characteristic of a particular porous media similar to the porosity of pore-size distribution.

2.2.2 Multiphase Flow

Since all hydrocarbon-bearing reservoirs contain water that may or may not be mobile, it is necessary to extend the permeability concepts and to use permeability as a function of the flowing-phase saturation. For example, the permeability of a particular porous media to oil when the oil saturation is 50% and the water saturation is 50% may only be 45% of the permeability exhibited when the formation is 100% saturated with oil. At 60% oil saturation and 40% water saturation, the permeability based on the flow rate of the oil may be 70% of the permeability of the formation when it is 100% saturated with oil. This ratio of permeability at a particular saturation to the permeability at 100% saturation is termed the relative permeability, k_r. Consequently, the effective permeability to the particular phases is the absolute permeability, k, multiplied by the relative permeability kr. Thus:

$$\mathbf{k_o=kk_{ro};\qquad k_g=kk_{rg};\qquad \text{and}\qquad k_w=kk_{rw}}$$

In these relationships, the subscriptr refers to relative, and the subscripts o, g, and w refer to oil, gas and water.

To obtain effective permeabilities to use in flow equations, the absolute permeability must be multiplied by the relative permeability to the flow phase of interest.[4] The units of relative permeability are dimensionless.

Initially, it might appear that the sum of the phase permeabilities equals the total or absolute permeability, which would mean that the relative permeabilities should sum to unity. However, that’s not true. When two or more phases are present, capillary forces exist that reduce the flow rate of each individual phase in a non-linear fashion. This means that the sum of the phase permeabilities is always less than the total or absolute permeability and the sum of the relative permeabilities is always less than 1. Indeed, at irreducible water saturation, the relative permeability to water becomes zero while the relative permeability to oil or gas is less than one because the immobile water is occupying some of the flow volume. Similarly, at residual oil saturations, the relative permeability to oil becomes zero while the relative permeability to water or gas is less than one.

Relative permeability is measured on cores in a process that core laboratories call special core analysis. Originally, these measurements were done with a series of steady-state experiments at different saturations. Then, the resulting relative permeabilities are plotted as functions of saturation. Rose states that this is still the most accurate method and the one that gives the most “believable” relative permeabilities. Because this method is time-consuming and expensive, unsteady-state methods are used more widely. In the unsteady-state method, the core is first saturated with water, then the water is displaced to the irreducible water saturation with oil (or gas), usually while a constant pressure drop across the core is maintained, and the phase production rates are measured as functions of time. Then, the oil is displaced by water to residual oil saturation while a constant pressure drop across the core is maintained and the phase production rates are measured as functions of time. The relative permeabilities can be calculated from production data.

Hysteresis occurs in relative permeability curves, which means the result differs depending on whether water is displacing oil, such as in a waterdrive or waterflood (imbibition), or oil is displacing water, such as in the oil-migration process (drainage). Hysteresis can be identified from different values of relative permeability from the two displacement tests discussed previously. Such displacements can be effectively conducted in a centrifuge.

Relative permeability is also function of wettability. For a given water saturation, water-wet rocks have a higher relative permeability to oil than oil-wet rocks and, conversely, water-wet rocks have a lower relative permeability to water than oil-wet rocks.[5]

2.3 Two-phase and Three-phase flows

Two-phase flow occurs when oil and water flow in the reservoir. Some sources contain models used to predict the relative permeability relationships when two-phases are flowing simultaneously in a porous, permeable medium. Because of the limited amount of the consistent experimental data available to determine the model parameters accurately, only the simpler models are usually considered. The typical description is given when one extends one of these models to three-phase gas/oil/brine flow assumes that one liquid phase strongly wets the rock matrix, the gas phase is “totally nonwetting” and the second liquid phase is of “intermediate wettability”. [6]

Three- phase flow occurs when the water saturation is higher than the irreducible level, and oil and gas are also present as mobile phases. This possible when gas is injected a reservoir, or when condensate appears as the reservoir pressure falls below the bubble point or dew point respectively. Gas injection is discussed in the following pages.
Wherever three- phase issues are relevant, three- phase relative permeabilities are important. Laboratory measured three- phase relative permeabilities are rare because they are difficult to obtain and they need sophisticated measurements and an appropriate interpretations.

There are two distinct classes of three- phase relative permeability data: related to drainage and related to imbibition. Drainage happens when the saturation changes in the way that the wetting- phase saturation changes. Imbibition refers to increasing wetting phase saturation.

Drainage relative permeability data can be used in such cases when some kind of gas is injected into the reservoir which results in wetting phase saturation reduction, in our case it is water. For example, enhanced recovery processes involving gases. And imbibition relative permeability data can be used when the water is injected which cause wetting phase saturation increase. For instance, in some reservoir production occurs by natural water drive.[7]

A proper modeling of tertiary recovery processes such as gas injection or WAG (Water Alternating Gas) requires an adequate three-phase flow model. This allows to better predict the recovery efficiency, gas storage reservoir performance as well as the well injectivity.

In the two-phase and three-phase flow we can observe the effect of hysteresis. In some of the cases engineers and scientists just ignore this characteristic. Hysteresis effect depends not only on the drainage/imbibitions process which is also called as saturation history but also on the cycle considered (displacement history) where cycle names the association of two consecutive displacements (drainage and imbibition).

As we have mentioned before, whatever the nature of a field, hydrocarbon or underground gas storage, exploitation often leads to large sweeping of the reservoir by fluids. For hydrocarbon reservoir, it can happen naturally when aquifer support is strong or when gas cap expands downwards. Most of the time, artificial pressure maintenance is needed and gas or (and) water are injected depending on reservoir properties and fluid availability. For almost two decades, WAG (Water Alternating Gas) injection strategies have been developed to improve sweep efficiency at both macroscopic and microscopic scales. A kind of WAG also occurs when old waterflooded reservoirs are converted into gas storage. Alternated sweeping of gas and water results from annual cycle of pressurization and depressurization. These examples illustrate that large parts of a reservoir can be subject to successive drainage and imbibition. This generates hysteresis on relative permeabilities that must be considered to make numerical simulations fully representative.

Hysteresis on relative permeabilities has been experimentally evidenced with various measurement methods in two-phase flow and more seldom in three-phase flow. Studies show that relative permeabilities are not only functions of saturations but also depend on the saturation history and especially their sense of variation. This kind of hysteresis is related to a strong decrease of the nonwetting phase mobility (referred from now as gas) during imbibition. Complexity is added in three-phase flow since relative permeabilities are found to depend also on cycle history if cycle denotes the association of two successive displacements (drainage and imbibition). This kind of hysteresis is mainly related to significant gas relative permeability reduction along the cycles.[8]

2.4 Relative Permeability Hysteresis Effect

Hysteretic behavior of relative permeability curves has long been recognized. Numerous laboratory studies have reported hysteresis of relative permeabilities for one-dimensional flow in cores and physical explanations of the phenomena have been presented.

Non-monotonic change of phase saturations takes place in almost every process of oil reeovery (waterflood in heterogeneous reservoirs, WAG injection, water coning, gravitational separation, steam and polymer huf-n-puf stimulations, etc.). Therefore, numerous researches were dedicated to the mathematical modelling of the two-phase history-dependent flow.

Formulae for the drainage, imbibition and scanning relative permeability curves have been developed by C. S. Land and J. E. Killough. In these works, the hysteresis between the primary drainage and imbibition curves have been considered, however, all the imbibition curves have been assumed to be reversible. This assumption is relevant with the simulation of creation of the initial saturation and further floods in the laboratory cores. More complex formulae for hysteretic relative permeability have been derived in.

The mathematical model for two-phase displacement honouring hysteresis consists on the basic mass balance equations and the modified Darcy's law. This model is the same as in the hysteresis free model; the only difference is the hysteretic parameter which shows the direction of the saturation process.

Introduction of the hysteresis into the Buckley-Leverett two-phase flow model changes the mathematical type of the governing equation as well as initial and boundary conditions. Therefore, a more detailed mathematical investigation which provides with the existence of the global solution is required. It is important for the development of numerical methods for reservoir simulators with hysteresis. A mathematical model for the two-phase flow with hysteresis was developed by D. Marchesirr, H. Medeiros and P. J. Paes-Leme. The model contains two unknowns: saturation and the number of previous drainages and imbibition in each point of the reservoir. The complete solution of the Riemann problem was obtained. The existence of the global solution has been established. This model considers two extreme fractional flow curves and the scanning curves are not incorporated.

A mathematical model for the fractional flow with scanning curves was proposed by Kb. Furati. The system contains two continuous unknowns: saturation and the hysteretic parameter, which is the maximum value of saturation which has been reached in each point of the reservoir. The author introduced immobile saturation shocks which allowed obtaining solution of the self-similar problem of the decay of the initial discontinuity. The Riemann problem was solved and the classification of self-similar configurations was presented. Self-sharpening solutions have been found for the waterflooding (one hyperbolic equation) and for the polymer flooding (system of two hyperbolic equations).[9]

The number of phases present in porous media is important when discussing hysteresis. The problem of hysteresis increases significantly when moving from two-phase to three-phase flow systems. On a macroscopic scale, the number of process paths increases from two-phase flow to three-phase flow. For the two- phase case, the only unknown part of the saturation trajectory is the endpoint, as compared with three- phase flow, for which the whole saturation trajectory is initially unknown. On the microscopic scale, displacement sequences that can occur in three-phase systems are not seen in two-phase systems. These include double-displacement mechanisms and the spreading behavior of the intermediate wetting phase.

Three-phase fluid flow experiments have been analyzed by use of relative permeabilities as function of two phases. Different research groups have reported contradictory trends in data, and several analytical correlation functions exist. The common bases for both interpretation of experiments and analytical correlation functions are relative permeabilities as functions of two- phase saturations and extrapolation of two- phase flow functions to three- phase flow functions.

The three- phase hysteresis problem is significantly more advanced than that for two-phase flow, for two reasons:

- the number of saturation directions increases
- the definition of hysteresis becomes ambiguous

Relative permeability is dependent on saturation and saturation history, in reservoir simulation hysteresis effects should be considered whenever the displacement mechanism is changed between drainage and imbibition. Saturation oscillations often occurring in WAG processes are causing hysteresis in relative permeability. In WAG simulations hysteresis description is therefore necessary in order to have a good description of the fluid flow. In standard simulations (without hysteresis) gas relative permeability data measured under drainage is normally used. This approach gives no possibility of accounting for trapped gas saturation during a WAG-flood, and may underestimate the oil recovery or the performance. Three-phase relative permeability data is very difficult to measure and little work has been published on this area. The standard procedure in numerical studies is to evaluate the three-phase relative permeability data from two-phase data. Using hysteresis in simulations the models normally allows for a simple Killough- or Carlson- hysteresis.

Different production strategies - water flooding, gas flooding and water alternating gas (WAG) injection was considered for the main area. The simulations showed that the WAG injection (with a water/gas ratio of 1:1) gave higher oil recovery than water injection and gas injection. It is caused by better sweep efficiency, a more stable displacement front, and lower residual oil saturation. The gas injection is showing override, whereas the water injection mainly displaces the bottom layers.

2.4.1 Theoretical models, two-phase, three-phase relative permeability and hysteresis models.

The displacement process for each phase and consequently the hysteresis effects depend on the distribution of the fluids in the pore space and so most hysteresis models are formulated with different behavior for the wetting, non- wetting and intermediate phases. After wettability, hysteresis is the most important phenomena affecting multi- cycle floods. It is also recognized that capillary pressure may also have an important role in the displacement process.

There are two types of hysteresis models:

<u>Two- phase hysteresis models</u> – these are empirical models which include trapping of the non- wetting phase and permeability reduction when processes are reversed. Subsequent

saturation changes are considered to be reversible with no further permeability reduction. These two- phase hysteresis models have been the most commonly used.

Three- phase hysteresis models – which include trapping of the gas and reduction of wetting phase permeability in the presence of the trapped gas. The intermediate wetting phase permeability is calculated using an interpolation formula, which is modified to allow for the impact of trapped gas. A key feature of these models is the prediction of reduced gas permeability and increased trapping of the gas on the second and subsequent gas injection cycles.

2.4.2 Two- phase hysteresis models

The two- phase models of Carlson and Killough are very similar, predicting trapping of the non- wetting phase, and permeability reduction during imbibition process. It is also assumed that imbibition process is reversible. The trapped non- wetting phase is typically calculated by using Land's method. It is not clear how these models should be applied to three- phase situations; it is usually assumed that gas and water hysteresis is independent of the other phases present in the pore space and so the models can be applied directly to these phases. The intermediate wetting phase (oil) shows different behavior with respect to gas and water. It is usually assumed that the impact of these phases can be assessed independently before combining the data to obtain a three- phase value.

2.4.3 Three- phase hysteresis models

The three- phase models include such features as trapping of gas and reduction of water relative permeability in the presence of trapped gas. The processes are not considered to be reversible, and relative permeability may decrease with each change in direction of saturation.

I am going to mention about some of the three- phase models. They are described in terms of wetting phase, a non- wetting phase and intermediate phase. The approach when modeling a water-wet system is clear, while for an oil-wet system it is usual to swap the labels for the oil and water phases. The application to the intermediate-wet systems is unclear.

The three-phase models of Skauge and Egermann predict non-reversible hysteresis loops for the gas phase. The gas and water permeability generally reduce with each saturation cycle for increasing trapped gas saturations. The trapped gas saturations are calculated using Land's equation. Egermann's model also predicts the trapping of water by gas. The oil permeability usually increases as increased trapped gas saturation reduces the residual oil saturation. In Egermann's model the trapped gas saturation is considered to decrease as gas saturation increases which causes an increase in the residual oil saturation. These models do not include hysteresis in two-phase oil-water flow.[10]

The relative permeability models are generally empirical rather than theoretical.

Standard hysteresis models for non-wetting phase consist of one drainage relative permeability curve and one imbibitions curve connected at the same inflection point. These curves form an envelope in which the scaning-curves are generated. WAG cycles lead to oscillation of the water and gas saturation with time and position. The standard hysteresis model for the non-wetting phase allows for reduced mobility after primary processes within the given saturation range, but the same scanning curves are used for both drainage and imbibition.

If a hysteresis cycle is initiated at a given hysteresis inflection point on the primary drainage curve, the secondary imbibition and further drainage will follow the scanning relative permeability curve. If the secondary drainage continuous above the saturation of the hysteresis inflection point, the relative permeability will be defined equal to the primary drainage. The mobility during secondary drainage is inconsistent with experimental observations, where as an example gas injection after water flooding generally has considerably lower gas relative permeability than primary gas injection. Three-phase gas hysteresis model allows reduced mobility of gas in three-phase situations. Gas trapping is still according to the two-phase hysteresis method of Carlson (Land type relation). The stability of the Carlson two-phase hysteresis may be improved by the new three phase hysteresis code, as the imbibition gas relative permeability is defined by the maximum trapped gas saturation and thereby using the Land constant rather than table defined values. Linear interpolation between table values leads to oscillations in the calculated trapped gas, and thereby also oscillation in the imbibition gas relative permeability. The three-phase oil relative permeability will be generated by the Stone 1 method, and the residual oil saturation will be coupled to the trapped gas saturation. This enables the possibility of lower residual oil saturation in three-phase dominated zones and to describe residual oil saturation as function of trapped gas as experimentally observed in some references. The water three-phase relative permeability model has the flexibility of defining different water relative permeability for two-phase and three-phase situation and includes an interpolation regime for transitions between two-phase and three phase zones.

It has been shown by several independent sources that the classical methods for calculations of relative permeabilities do not apply to WAG injection. This is due to the complex flow pattern normally seen in this operation, where saturation increases and decreases repeatedly for the wetting and nonwetting phases (water and gas), and maybe even for the intermediate phase (oil). During the modelling of three-phase flow (oil, water and gas) the relative permeabilities are used as a parameter in the Darcy equation and in the mobility terms. Changes of the relative permeability may have a large influence on the simulation results. Whereas two phase relative permeability curves are routinely measured in laboratories, measurements of three phase relative permeability curves are very difficult. It is therefore common to use correlations for estimation of these curves. The most well known correlations for calculating three phase oil relative permeability are the Stone I and the Stone II methods. However, a special case arises in the simulation of processes where the saturation is oscillating, such as the WAG process where injection normally is made in slugs. In this case trapping of the gas phase may occur, when injected water invades areas already swept by gas. This phenomenon leads to hysteresis in the shape of the relative permeability curves, since the space available for liquid movement in the rock decreases (due to the presence of immobile gas). In such cases not only the three-phase relative permeability, but also the hysteresis must be modeled. Figure 2 shows a schematic representation of the WAG injection process with one injector at the left and one producer at the right. The WAG area is a 3 phase area where gas, oil and water are mobile. It is especially in this area that relative permeability and hysteresis effects will be important.
However, all zones maybe affected as all mechanisms affect each other and interact. The 3 phase relative permeability hysteresis model developed by Larsen and Skauge takes these processes into account.[11]

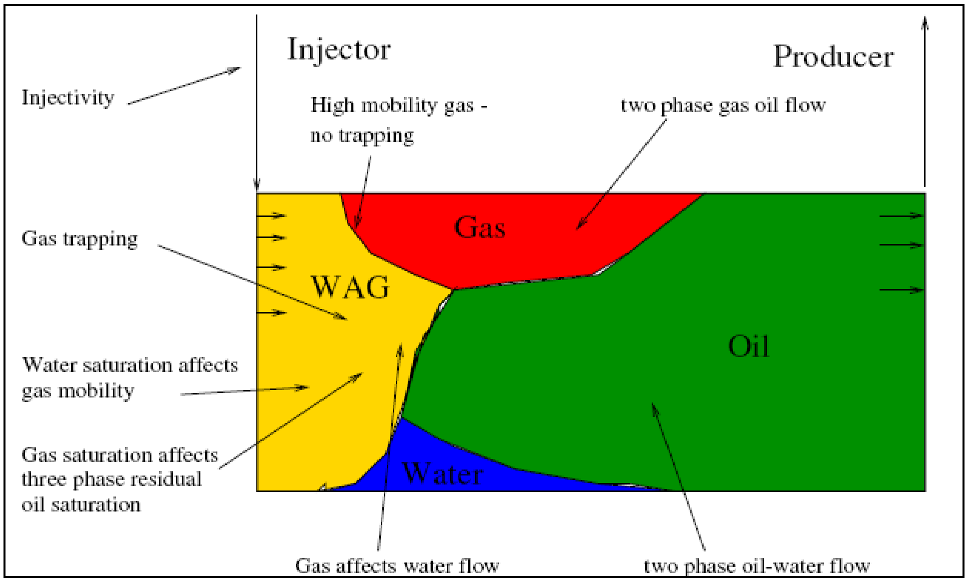

Figure 1: Principal Drawing of a WAG displacement and schematic outline of multiphase flow mechanics (after *J. R. Christensen, M. Larsen,and H. Nicolaisen),*

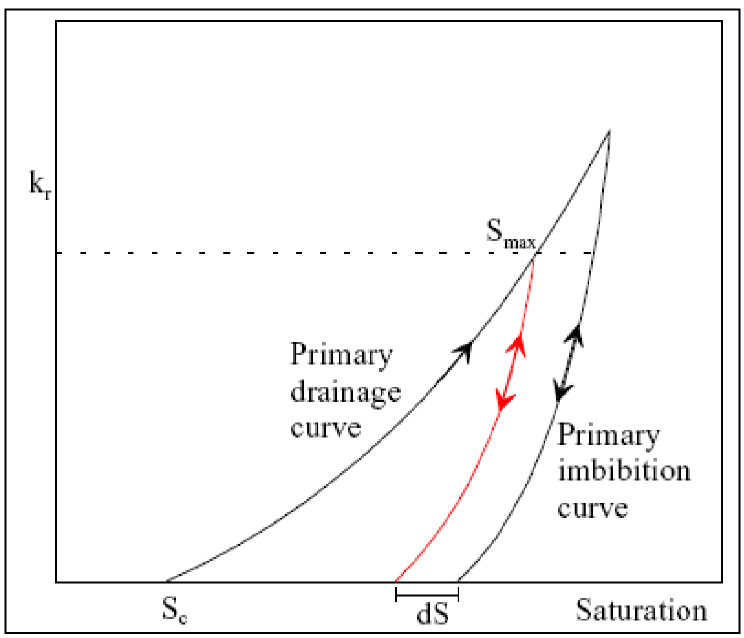

Figure 2: Standard hysteresis model (after *J. R. Christensen, M. Larsen,and H. Nicolaisen*)

CHAPTER 3
METHODOLOGY

3.1 Procedure Identification

There are some procedures to be followed in order to carry out and implement the project. This is to ensure that the project can be accomplished within the given timeframe.

3.1.1 Data Research and Gathering

In this stage of my project, thorough research about the relative permeability hysteresis is being done. We are trying to get all the sources available about the topic from internet, library books, SPE archives. We also refer to the articles and works done by others on this subject.

3.1.2 Experiment Type Selection

We planned to conduct several experiments related to water injection applications. In this experiment there are two phases are present which are brine and oil.

The results obtained from the experiments were compared with the real life applications. Previously we were planning to do experiment for a three-phase relative permeability. Unfortunately, because of unforeseen errors we had to modify some of the details depending on the machine capability. Now we are doing two-phase relative permeability experiment.

Laboratory measurement techniques for obtaining the two- phase relative permeability data based on the flow experiments are well established over the years. Essentially two different types of flow experiments can be conducted in reservoir rock samples from which relative permeability data are determined. These methods are called steady state

(SS) and unsteady state (USS). Depending on the situation both of the methods can be useful.

Two-phase (Liquid & Liquid) Relative Permeability experiments were conducted. Oil and water (brine) were used as the liquid phases Experiment steps are:

1. Saturation by water and determination of absolute permeability $\rightarrow$ k
2. Drainage $\rightarrow$ k_{roD} & k_{rwD}
3. Imbibition $\rightarrow$ k_{roI} & k_{rwI}

   1 Cycle

4. 2-4 steps were repeated as many times as required.
5. 1-4 steps are one set of experiment. It was done as many times as necessary to develop hysteresis data

3.1.3 Relative Permeability Equipment Performance

Before we proceeded to the main experiment we had done the test runs to make sure everything was all right. And we did slight modifications on the machine operation with the help of equipment provider. We adjusted the pressure fluctuations, software and equipment communication.

3.1.4 Equipment Testing and Analysis

In this stage, we tested the machine performance to observe that it is acceptable and we could proceed with our set of experiments.

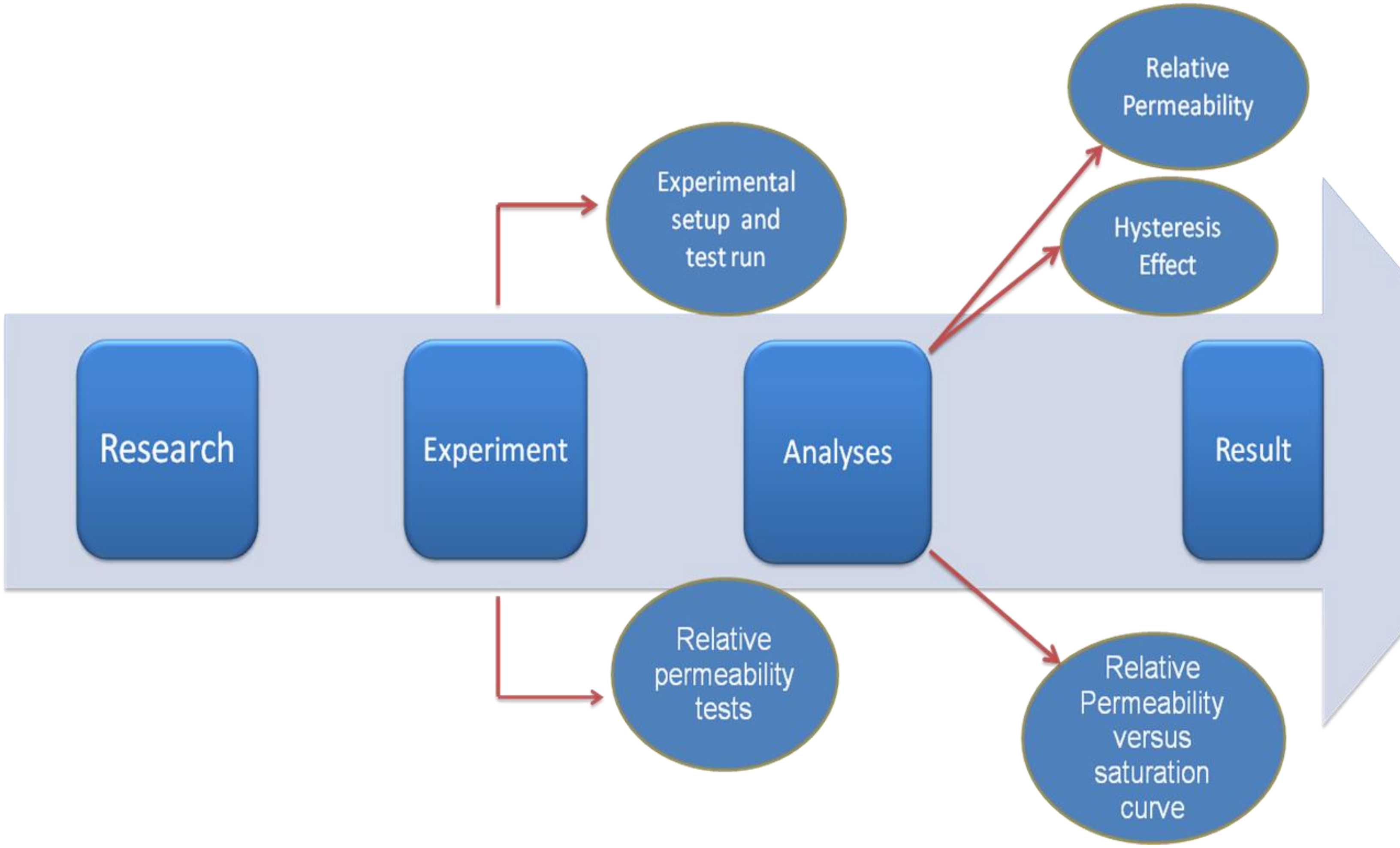

Figure 3: Flow Chart

3.2 Tools and Equipments

Below all of the equipments and tools that were used in the experiment are described.

3.2.1 System and Major equipment Description

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

The core holder supplied as part of this system can also be installed into a X-ray core scanner for measurement of the in-situ. Test conditions can be up to 10000 psig flowing pressure, and up 10000 psig overburden (confining) pressure, at 177^{o}C (350^{o}F). The pressure at the inlet of the core sample, the pressure at the outlet of the core sample and the overburden pressure are all measured using individual pressure transducers. Likewise, the differential pressure across the core is measured with a differential-pressure transmitter.

Fluids produced through the core sample are collected in a beaker after the back pressure regulator, or the fluids are injected into a two phase separator for production measurement at pressure and temperature.

The system is also designed for the measurement of gas or liquid permeability. A single phase of gas can be injected through the core sample. Two fluids can be injected simultaneously in order to measure relative permeability.[7]

Figure 4: Relative Permeability Machine (Outside View)

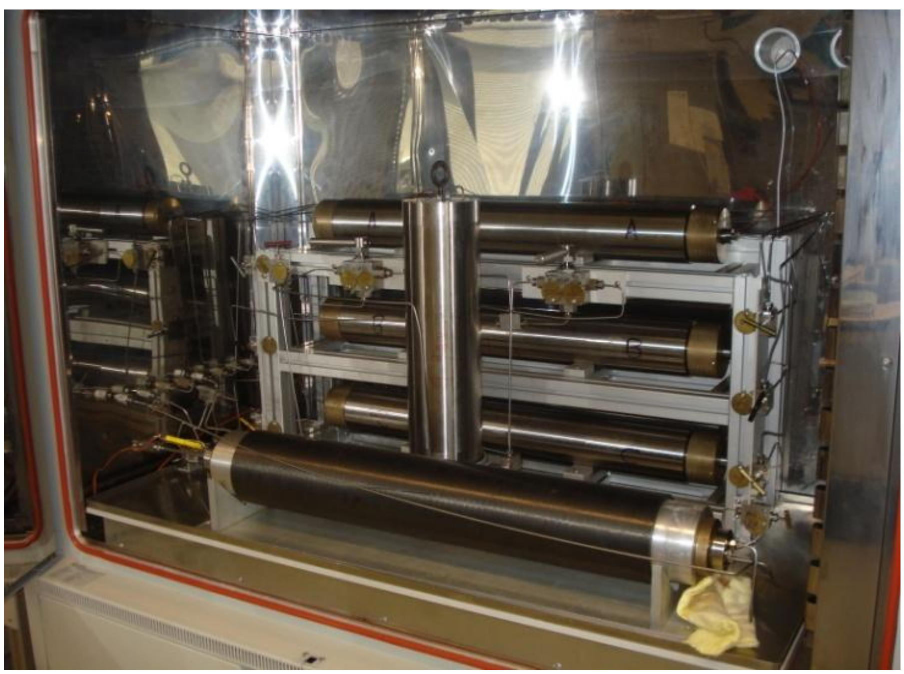

Figure 5: Relative Permeability Machine (Inside View)

3.2.2 Viscosimeter

Viscosimeter was used to measure the viscosity of the crude oil obtained from one the Malaysian fields.

3.2.3 Software

For the Relative Permeability Equipment there is special software programmed for it. That’s SmartFlood. User can see all of the processes done by the machine in the screen and can control some of the parameters such as flow rate, core parameters, some of the calculations but need to change the core holder joints and accumulators manually.

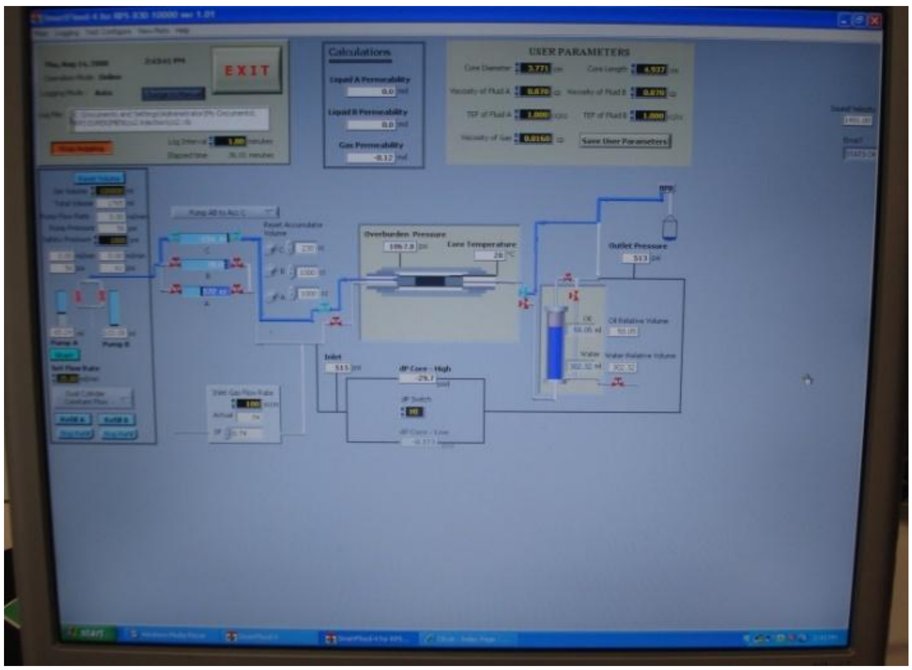

Figure 6: SmartFlood Software for Relative PermeabilityMachine

CHAPTER 4

RESULTS AND FINDINGS

With reference to all of the concepts elaborated in Chapter 2, some results were obtained after considering all parameters from the several experiments. The findings were analyzed and evaluated. From the experiments, raw data were obtained and they were used to calculate relative permeability values. From the experimental steps shown above absolute permeability was calculated because it is needed to find relative permeabilities during the cycles.

Absolute Permeability is needed when we want to calculate the relative permeability. Since,

$$k_{effective} = k_{relative} * k_{absolute};$$

In order to calculate the absolute permeability we use the Darcy Equation,

$$Q = k * \frac{A}{\mu} * \frac{\Delta P}{L};$$

Where Q: flow rate;

A: Area of the core sample;

μ : Viscosity of the fluid;

ΔP : Pressure difference in psi;

L: Length of the core sample.

$$\frac{Q}{A} = \frac{k}{\mu} * \frac{\Delta P}{L}; \qquad \textbf{(}\text{Eq. 1}\textbf{)}$$

Equation 1 is a linear equation which looks like y=mx where m is the slope. In our case,

$$m = \frac{k}{\mu};$$

From the graph we can calculate the the absolute permeability.

$$0.0145 = \frac{k}{1.007} \quad \rightarrow \quad k = 0.0146$$

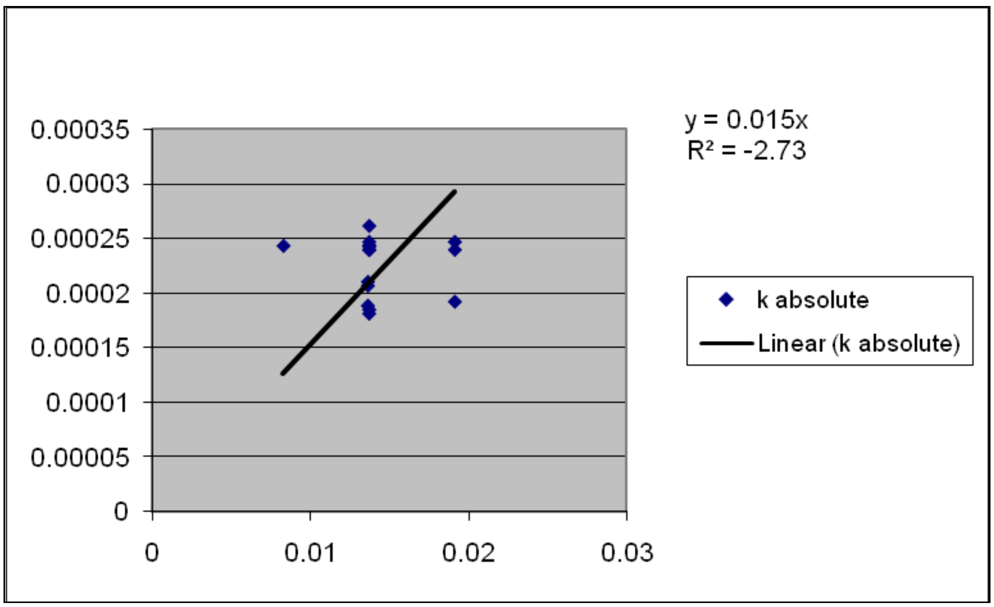

Figure 7: Absolute Permeability

Drainage and imbibition cycles are done sequentially. Each cycle has its specific relative permeability curve. A special case arises in the simulation of processes where the saturation is oscillating after each step the relative permeability curve differs from the previous curve. This phenomenon is the hysteresis effect in the shape of the relative permeability curves, since the space available for liquid movement in the rock decreases (due to the presence of immobile fluids). In such cases not only the two-phase relative permeability, but also the hysteresis must be modeled. There are many models available but as it was mentioned before none of them can be the general solution for all of the multiphase relative permeability conditions. Each of them focuses on some of the factors only. That's why there is a need to find the general solution. At the same time for different reservoirs under different conditions suitable model can be used to get the better oil production. But it is not my concern. The main objective of this project is to observe the hysteresis effect after each drainage and imbibition cycles. And ignoring the hysteresis effect may affect reservoir performance and recovery.

After finding absolute permeability and obtaining data from the experiment we can calculate effective permeability and then relative permeabiltity. For effective permeability we use Darcy Equation

Table 1: Saturation and Relative Permeability Values

Sw	Kro	Krw
0.831184	0	0.221642
0.709788	0	0.158132
0.599772	0.297594	0.006942
0.593323	0.321811	0.000487
0.593323	0.348106	0
0.593323	0.725977	0
0.788695	0.635542	0.482071
0.929059	0.110488	0.2861
0.942337	0.088996	0.267029
0.974583	0	0.270781

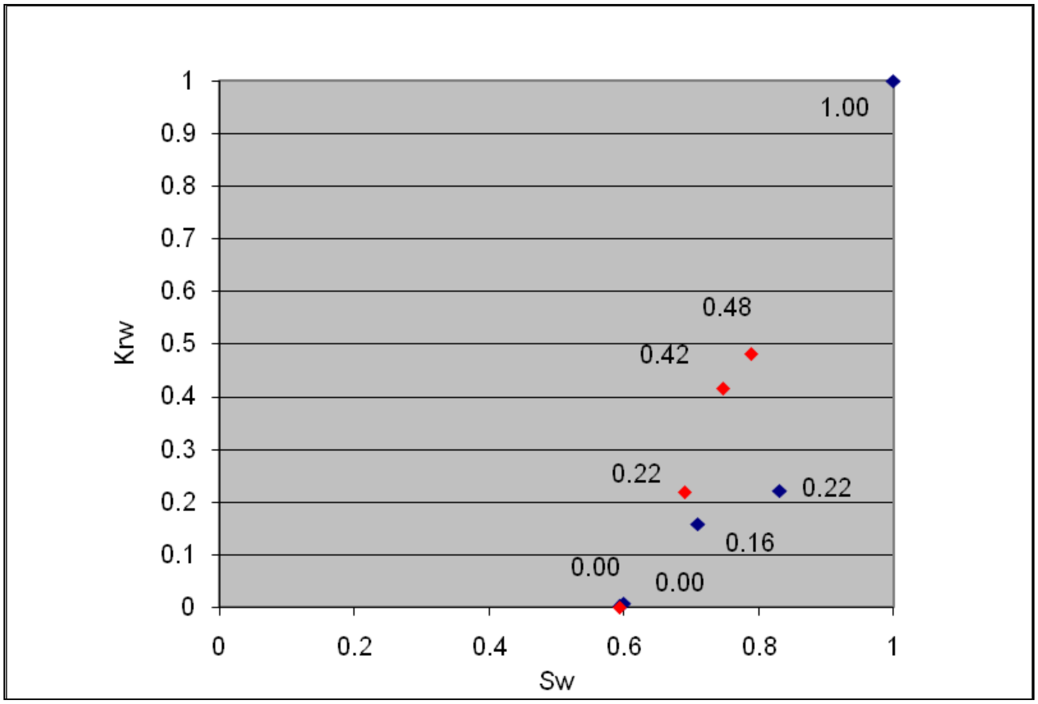

Figure 8: Saturation of water VS. Relative Permeability of water Curve

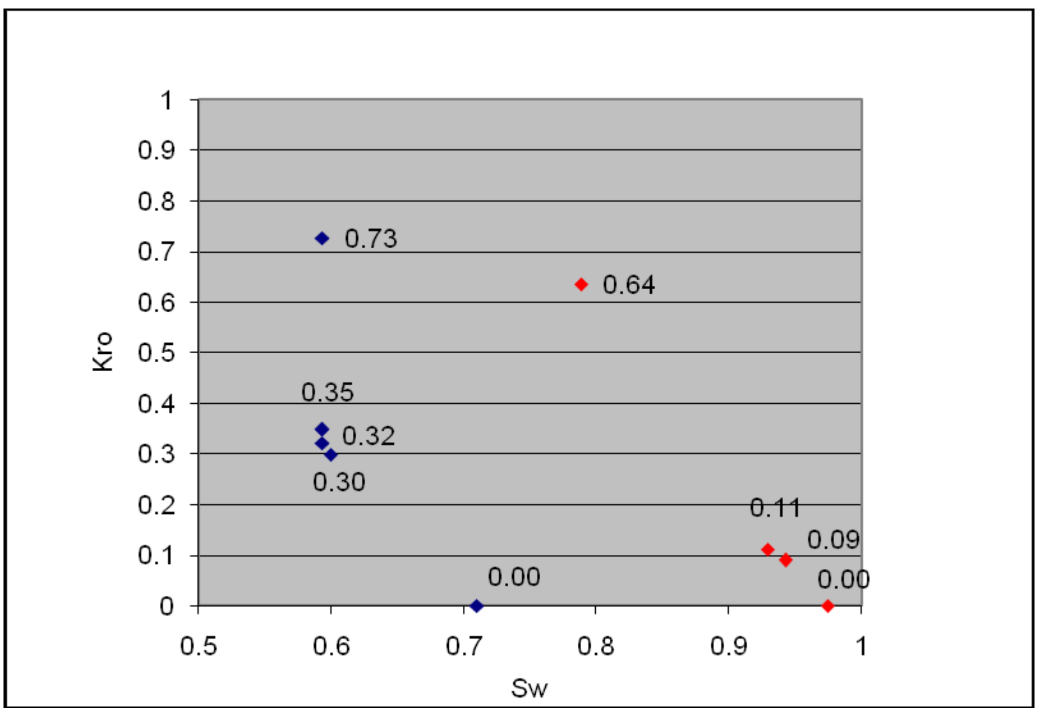

Figure 9: Saturation of water VS. Relative Permeability of Oil Curve

As we can observe from the table and graphs relative permeability values are changing depending on the saturation of the core with water. Blue points represent drainage cycle and red points represent imbibitions cycle. From these two graphs hysteresis effect can be observed because the drainage and imbibitions cycles have different curves.

CHAPTER 5
CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

It can be concluded that the relative permeability hysteresis was observed in this experiment and it was changing after each cycle. Obtained experimental results were compared with previous results and they follow the same trend. The data was acceptable and sufficient to construct the saturation versus relative permeability graphs. So hysteresis does exist in two-phase flow and after each cycle the curves are differ from the previous curves. Ignoring the hysteresis effect or considering few cycles for hysteresis will not give the best performance and recovery for the reservoir.

5.2 Recommendation

From the experiment, more accurate data can be obtained when the machine operates properly and with better knowledge of the machine functions.

This experiment can be extended to three-phase flow and the relative permeability hysteresis can be observed and analyzed. The machine should be upgraded so that the machine can calculate three-phase relative permeability. Otherwise the machine has many functions and because of some missing parts it is limited to perform only for two-phase flows. After upgrading to three-phase system the machine will be able to handle different types of gases which will be a great chance for our final year students and post-graduate students to conduct their researches on the multiphase flow.

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