بِسْمِ اللّهِ الرَّحْمَنِ الرَّحِيم

Sudan University of Science and Technology

College of Postgraduate Studies

كلية الدراسات العليا

Experimental Investigation of Using Steam Flooding in Fula North East Reservoir – Sudan

تجارب إستقصائية لإستخدام الحقن بالبخار لمكمن حقل الفولة الشمالي الشرقي - السودان

A Thesis Submitted in Partial Fulfillment of requirements for the Degree of MSc in Petroleum Reservoir Engineering

By

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"Dedicated to my beloved Parents, my Brothers & my gorgeous wife"

For their love, Endless Support, Encouragement & Sacrifices

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ABSTRACT

Thermal recovery methods and especially steam flooding have long been considered as the most effective methods to extract heavy oil reservoirs. These highly viscous hydrocarbon deposits are proven to constitute a huge proportion of total world oil reserves. Large volumes of heavy oil in Fula North East Oilfield SUDAN have a high viscosity (2019 centipoise at reservoir temperature 43°C) are located in heterogeneous porous media containing high permeable wormholes or non-permeable shale barriers.

The main objective of this study is to investigate the feasibility of using Steam Flooding in Fula North East (FNE) - Sudan. FNE reservoirs are high porosity (30%), permeability (1000-3500 mD), and unconsolidated in nature. the fluid properties include a viscous crude range from 15 to 17.7 API. The corresponding viscosity is 2019 cp at reservoir conditions (Temperature 43C and Reservoir Pressure 571 Psi).

The research-based on physical simulation to scale of a Steam flood using one core sample from well#FNE-135 to represent the reservoir, steam core flood experiments were conducted By (STEAMFLOOD 700) station in Petroleum Labs, Research and Studies (PLRS), to study the efficiency of Steam flood in order to decrease the viscosity and improve oil recovery. The core sample was aged with crude oil at 43°C for 21 days to conduct the best conditions before the experimental.

The experimental of steam flooding in core scale showed that the oil viscosity decreasing from 2019 cp at reservoir temperature 43° C to 1.5cp due the steam injection, which the mobility ratio was improved, furthermore, the residual oil saturation reducing from 80.1% by water flooding to 53.8% by steam injection, as well, the recovery factor RF increasing by steam flooding from 8.6% to 30.1%, moreover, the displacement sweep efficiency ED improved from 9% by cold production to 38% by steam flooding, also the experiment showed clear incremental in formation volume factor due to effect of the steam injection compared to cold production.

التجريد

تعتبرت طرق الاستخلاص الحراري المحسن وخاصة الحقن بالبخار أكثر الطرق فعالية لأستخلاص النفط من مكامن النفط الثقيلة. وقد ثبت أن هذه المكامن ذات الهيدروكربونات عالية اللزوجة تشكل نسبة كبيرة من إجمالي احتياطيات النفط العالمية. توجد كميات كبيرة من النفط الثقيل بحقل الفولة جنوب غرب السودان في وسائط مسامية غير متجانسة تحتوي على ثقوب عالية النفاذية .

الهدف من هذه الدراسة هو دراسة جدوى حقن البخار في منطقة الفولة حقل شمال شرق الفولة FNE. الذي يتميز بمسامية عالية (~ 30٪) ، ونفاذية تتراوح بين md(1000-3500), وطبقات غير متماسكة . وكذلك يحتوي هذا الحقل علي خام ذو لزوجة عالية للغاية تتراوح كثافتة النوعية API من 15 إلى 17.7 ولزوجة 2019 سنتي بواز في ظروف الخزان (درجة حرارة 43°C و ضغط مكمن 571psi).

هذا العمل هو إجراء تجارب لحقن البخاري باستخدام عينة صخرية core plug واحدة من البئر FNE-135 # تمثل حقل FNE، وأجريت تجارب حقن للمياه والبخار في محطة (STEAMFLOOD 700) بالمعامل والبحوث والدراسات النفطية (PLRS) لدراسة كفاءة حقن البخار من أجل تقليل اللزوجة وتحسين استخلاص النفط. تم تشبيع العينة الصخرية بالنفط الخام عند تشبع الماء الاولي و تركت لمدة 21 يوما عند درجة حرارة 43 درجة مئوية وضغط مكمن psi571 قبل أجراء الاختبار لاستعادة الخصائص التبللية بقدر الامكان.

أظهرت النتائج أن لزوجة الزيت انخفضت من 2019 سنتي بواز عند درجة حرارة الخزان 43 درجة مئوية إلى 1.5 سنتي بواز نتيجة للحقن بالبخار ، مما أدى إلى تحسين نسبة حركة بين النفط والماء ، علاوة على ذلك ، قل تشبع الزيت المتبقي من 80.1٪ إلى 53.8٪ عن طريق الحقن بالبخار ، كذلك ، زاد معامل الاستخلاص RF عن طريق الحقن بالبخار من 8.6٪ إلى 30.1٪ ، علاوة على ذلك ، تحسنت كفاءة أزاحة النفط الخام ED من 9٪ بالإنتاج البارد إلى 38٪ عن طريق الغمر بالبخار ، وكذلك أظهرت التجربة زيادة واضحة في معامل التكوين الحجمي نتيجة لتأثير الحقن بالبخار مقارنة بالإنتاج البارد.

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Nomenclature:

API	American Petroleum Institute
Bbl. /d	Barrel per Day
BOBP	Barrel Oil per Day
CHOPS	Cold Heavy Oil Production with Sand
cP	Centipoise
CP	Cold Production
CSS	Cyclic Steam Stimulation
ED	Displacement Efficiency
EOR	Enhanced Oil Recovery
EUR	Estimated Ultimate Recovery
FNE	Fula North East
IOR	Improve Oil Recovery
MMBBL	Million Barrels
MMSTB	Million Stock Tank Barrel
NP	Cumulative Production
OOIP	Original Oil in Place
PLRS	Petroleum Labs, Research and Studies
RF	Recovery Factor
SF	Steam Flooding
STB/D	Stock Tank barrel per day
STOIIP	Stock Tank Oil Initial In Place
WF	Water Flooding
%	Percent
°C	Degree Celsius

CHAPTER ONE

INTRODUCTION

1.1. General Introduction:

Enhanced oil recovery (EOR) is the implementation of various techniques for increasing the amount of crude oil that can be extracted from an oil field. Enhanced oil recovery is a part of improved oil recovery (IOR) (as opposed to primary and secondary recovery). According to the US Department of Energy, there are three primary techniques for EOR: thermal recovery, gas injection, and chemical injection. Sometimes the term quaternary recovery is used to refer to more advanced, speculative, EOR techniques. Using EOR, 30 to 60 percent, or more, of the reservoir's original oil can be extracted, compared with 20 to 40 percent using primary and secondary recovery. Figure 1.1 shows improve and enhanced oil recovery categories.

Thermal methods have been tested since 1950’s, and they are the most advanced among EOR methods, as far as field experience and technology are concerned. They are best suited for heavy oils (10-20° API) and tar sands (≤10° API). Thermal methods supply heat to the reservoir, and vaporize some of the oil. There are many variations for this process including cyclic steam injection (“huff ‘anpuff”, where steam is first injected, followed by oil production from the same well), continuous steam injection (where steam injected into wells drives oil to separate production wells), hot water injection, and steam assisted gravity drainage (SAGD) using horizontal wells, among others. Another set of thermal methods, in situ combustion or fire flooding, involves injection of air or oxygen.

Cyclic Steam Stimulation CSS is also known as steam soak, or huff and puff. In thisprocess steam is injected into a well bore out to a heated radius of a few tens of meters. Then the original steam injector is converted to a producer and a mixture of steam, hotwater, and oil produced. CSS is the most common steam injection process today. Mostof the time most of the wells are producers: there are no dedicated injectors. CSS is oftenused as a precursor to steam drive discussed next.

Steam Drives. Also known as steam flooding, in this process steam is injected intodedicated wells and the fluids driven to a separate set of producers. Combined CSS andsteam drives often recover more than 50% of the original oil in place. This combination I the first commercial EOR process and has been so since the mid-50s. Perhaps morethan 2 billion barrels of oil have been produced in this manner to date.

In-situ CombustionThis process is an attempt to extend thermal recovery technology to deeper reservoirs and/ or more viscous crudes. In recent years it has become known as high-pressure air injection. In-situ combustion recovers 10-15% of the original oil in place.

Scaled laboratory EOR core flooding experiments provide important data such as hydrocarbon recovery potential, fluid mobility and sweep efficiency at lower costs than field pilot studies. With modern imaging tools, such laboratory experiments offer a unique opportunity to learn about in-situ processes that play a role in steam induced thermal EOR and allow benchmarking with computer simulation tools.

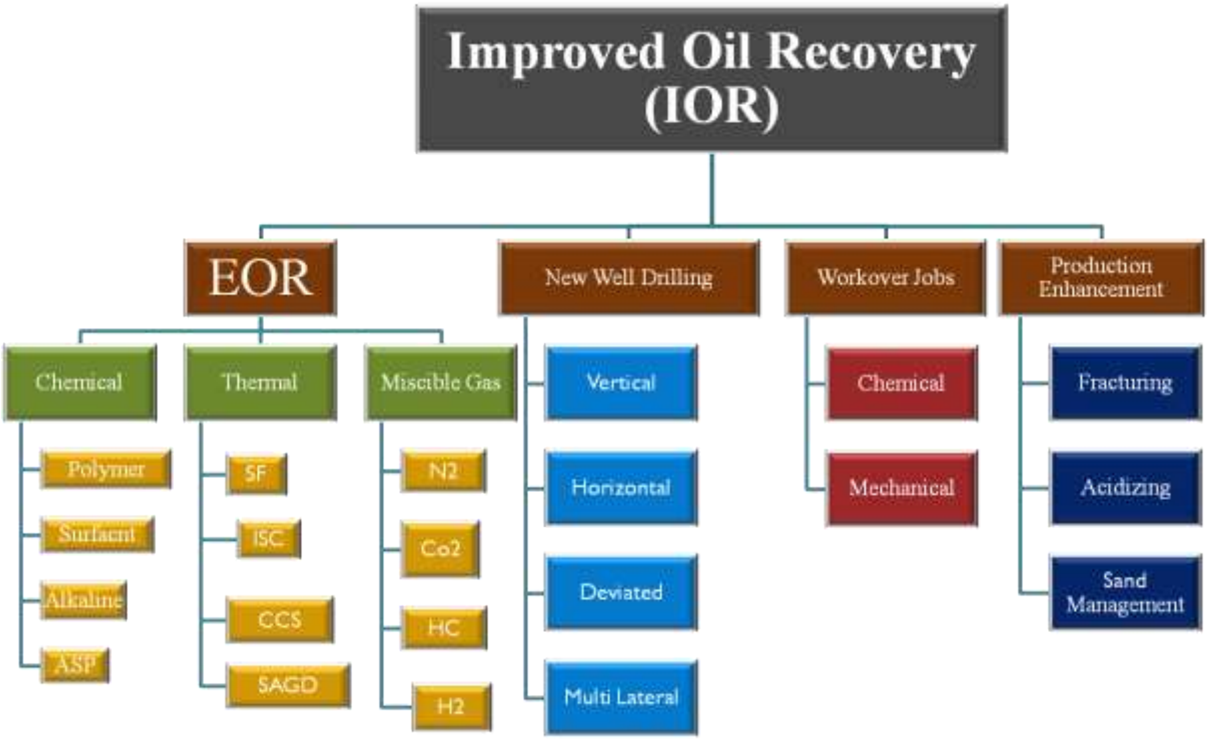

Figure 1.1 Improve and Enhanced Oil Recovery Categories

1.2. Problem Statement:-

FNE oil field has heavy oil with API of (15-17.7) and viscosities are in the range of (727-3800 cp), the field is suffering from low productivity due to high viscous oil, since 2010 only 11 MMBBL has been produced by cold production and cyclic steam stimulation.

Currently the recovery factor of the **FNE** fields is about **3.5%,** so the need of increasing the recovery factor by studying the feasibility of using Steam flooding is so important.

1.3. Research Objectives:-

The main objective of this research is to increase the heavy oil recovery in Fula North East field by using steam flooding.

Other sub objectives:

1. To evaluate the behavior of reducing of the oil viscosity in core flood scale.
2. Calculate the reduction of the residual oil saturation.
3. Determining the performance of Improve sweep efficiency by steam injections.
4. Study the Increasing of formation volume factor in term of steam injection.

1.4. Thesis Outline:-

Chapter two of this thesis talk about the theoretical background of the research and literature review, while chapter three summarized the methodology, Chapter four is including the experiment, results and discussion and chapter five is conclusions and recommendation.

CHAPTER TWO
THEORETICAL BACKGROUND AND LITERATURE REVIEW

The general mechanism of oil recovery is movement of hydrocarbons to production wells due to a pressure difference between the reservoir and the production wells. The recovery of oil may be subdivided into three major categories those are primary, secondary and tertiary recovery which known as Enhanced oil Recovery. Figure 2-1 illustrates the concept of the three oil recovery categories.

Primary methods that use natural reservoir energy (gas cap drive, solution gas drive, water drive, liquid and rock expansion drive and combination drive) and secondary pressure maintenance methods (water, gas and combination of water and gas injection) leave behind more than half of the original oil in place.

2.1 Oil Recovery

The terms primary oil recovery, secondary oil recovery, and tertiary (enhanced) oil recovery are traditionally used to describe hydrocarbons recovered according to the method of production or the time at which they are obtained.

2.1.1 Primary oil Recovery

Primary oil recovery describes the production of hydrocarbons under the natural driving mechanisms present in the reservoir without supplementary help from injected fluids such as gas or water. In most cases, the natural driving mechanism is a relatively inefficient process and results in a low overall oil recovery. The lack of sufficient natural drive in most reservoirs has led to the practice of supplementing the natural reservoir energy by introducing some form of artificial drive, the most basic method being the injection of gas or water.

2.1.2 Secondary oil recovery

Secondary oil recovery refers to the additional recovery that results from the conventional methods of water injection and immiscible gas injection. Usually, the selected secondary recovery process follows theprimary recovery but it can also be conducted concurrently with the primary recovery. Waterflooding is perhaps the most common method of secondary recovery. However, before undertaking a secondary recovery project, it should be clearly proven that the natural recovery processes are insufficient; otherwise there is a risk that the substantial capital investment required for a secondary recovery project may be wasted.

2.1.3 Tertiary oil recovery (Enhance Oil Recovery)

Tertiary (enhanced) oil recovery is that additional recovery over and above what could be recovered by primary and secondary recovery methods. Various methods of enhanced oil recovery (EOR) are essentially designed to recover oil, such as (Thermal, Chemical and Gas Injection), commonly described as residual oil left in the reservoir after both primary and secondary recovery methods have been exploited to their respective economic limits.

The Intention of EOR is to improve sweep efficiency by reducing the mobility ratio between injected and in-place fluids, eliminate or reduce the capillary and interfacial forces to improve displacement efficiency and act in both phenomena simultaneously.

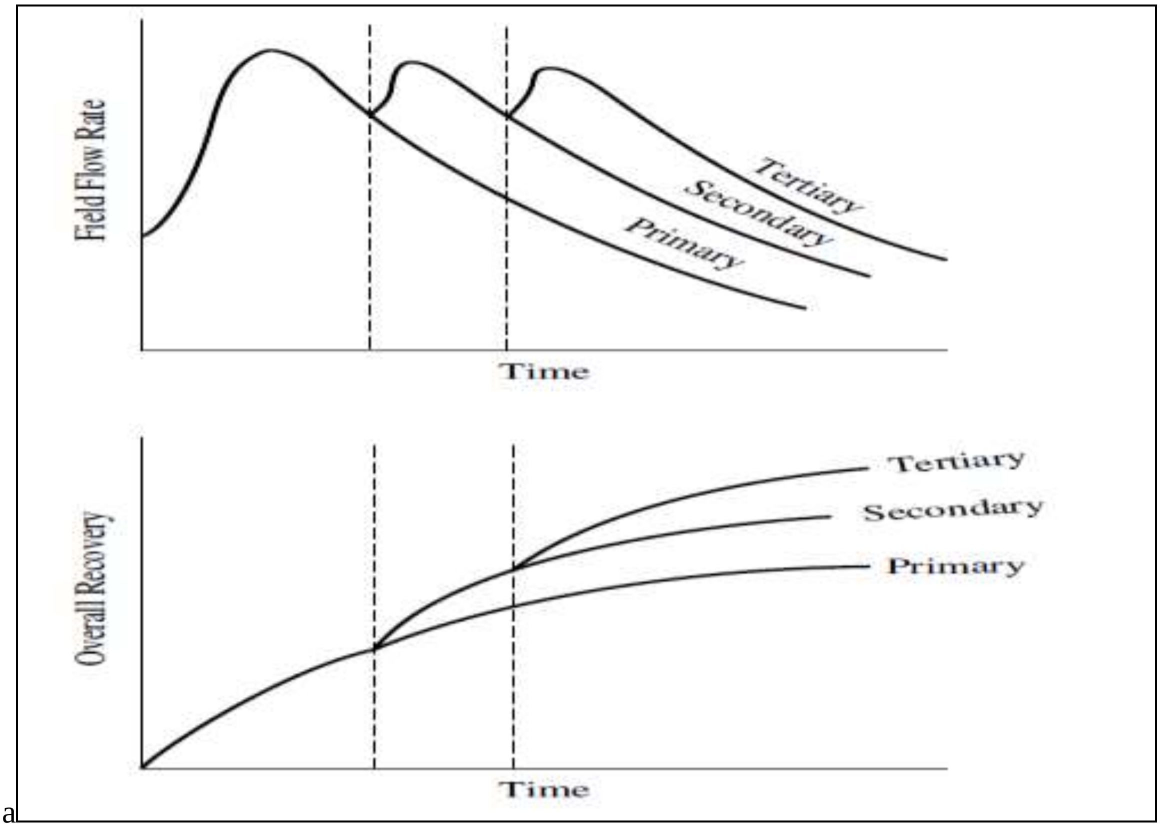

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Figure 2.1 Oil recovery Categories (Tarek Ahmed, 2010)

2.1.4 Thermal recovery

Thermal recovery processes rely on viscosity reduction of the oil through heat that is injected (steam or hot water injection) or generated in-situ (in-situ combustion) and are well suited for efficiently unlocking these heavy oil resources. Accordingly, to current U.S. Department of Energy data, thermally enhanced recovery techniques account for about 50% of the domestic Enhanced Oil Recovery (EOR) production. Steam flooding, cyclic steam stimulation, and hot water flooding are widely used, but other processes, such as in-situ combustion (ISC) and increasingly steam-assisted gravity drainage (SAGD) are applied and are attractive to recover heavy oil resources.

A large part of the world oil resource exists in the form of heavy oil, which is usually defined as oil with API gravity less than 22 and viscosity typically larger than 100cp. Estimated original oil in place of more than 1.8 trillion barrels is present in Venezuela, 1.7 trillion barrels in Alberta, Canada, and 20- 25 billion barrels on the North Slope of Alaska. The development of such resources by traditional methods (primary depletion, water flood) is often inefficient due to the high viscosity of the heavy oil. At such high viscosities, the oil flows extremely slowly or not at all. For example, the bitumen resources in Athabasca oil sands typically have an extremely large viscosity of about 106cp.

2.1.4.1 Steam Injection for EOR

Steam flooding and stimulation processes have proven to be the most promising method for the commercial in situ recovery of heavy oil. For high quality and thick oil reservoirs, these processes can achieve an oil recovery factor of over 30% OOIP. However, for thin, deep and offshore oil reservoirs, they are uneconomic due to the excessive heat loss to the overburden and great heat requirement to heat the oil portion in the reservoir.

The primary function of thermal recovery methods is to reduce the viscosity of oil. Moreover, when the oil trapped by capillarity is heated, its light components are distilled and become mobile. Steam also lowers Interfacial tension.

❖ Criteria for selection of steam flood:

The main advantage of steam injection over other EOR methods is that steam can be applied to a wide variety of reservoirs. Reservoir parameters beneficial to steam are:

- Oil gravity above 12°API.
- Oil viscosity between 100 and 10,000 cP at reservoir temperature.
- Permeability above 50mD.
- Porosity above 25%.

However, steam injection has the following limitations:

- Steam flooding is not used for carbonate and formations where water sensitive clays are Present.
- In high depth reservoir, maintaining steam quality is not possible.
- Because of very high temperature, special metallurgy tubing is required in producers and injectors.
- Cost per incremental bbls is high.

❖ Performance of steam flooding:

As the steam moves away from the injection well, its temperature drops as it continues to expand inresponse to pressure drop. At some distance from the well, the steam condenses and forms a hotwater bank. In the steam zone, oil is displaced by steam distillation and steam drive. In the hotwater zone, physical changes in the characteristics of the oil and reservoir rock take place andresult in oil recovery.

However, when steam is injected, it usually forms a finger-like channel through the easiest conduitand quickly reaches the producing well. With time and continued injection, the steam finger, beingless dense than the surrounding oil, travels upward in the reservoir and blankets the oil. The gravityoverride by the steam results in the upper one-third of the reservoir being swept by steam and theremaining two-third being swept by hot water, thus resulting in unequal vertical sweep efficiencies.

- **Properties of steam**

When a gram of water is heated at a constant pressure, it will reach a maximum temperature, TS, called the saturation temperature, before it is converted into steam. With continued supply of heat, the water temperature does not change until all the water is converted into steam. The steam at TS and PS (saturation pressure), is called saturated steam.

Further heating of the steam to a temperature TS up above TS, while maintaining the pressure at PS,converts the steam from saturated to superheated steam.

If the amount of heat applied to the water at the saturation temperature TS is XL (where X is a fraction and *l* the amount of heat required to change water to steam) only the fraction X of the water will be converted into steam. The steam in this case would be a mixture of saturated water and saturated steam. This steam is termed wet of quality X.

Most steam generated for injection to an oil-bearing formation will be approximately 80% quality, or that is, will contain 80% saturated vapor, with the remainder being liquid.

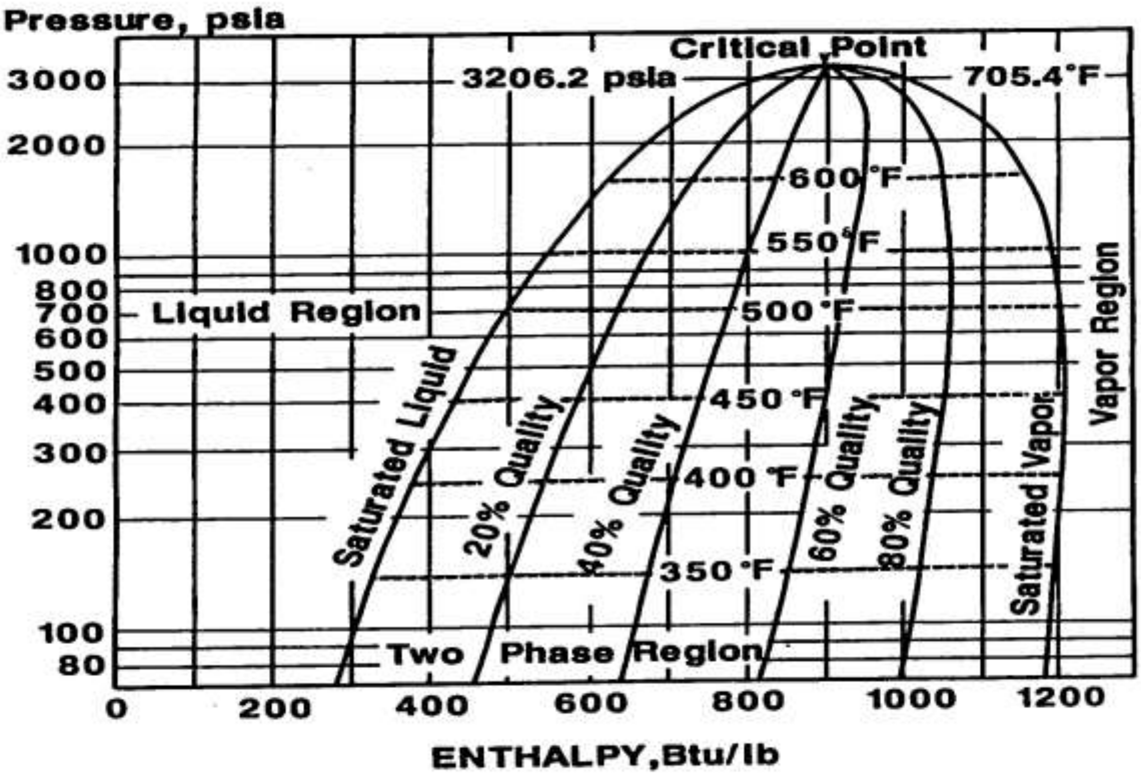

Figure 2.2 .Pressure-Enthalpy chart fore saturated steam showing steam quality lines (Teknica, 2001)

2.1.5 EOR Screening:

Considers various criteria, which are in the nature of the reservoir rock, oil density, permeability, viscosity of crude oil, depth, water, and saturated with oil is the salinity of the first step to evaluate and determine the appropriate method for improved extraction of oil and to determine a way of extraction methods triple it is important identify the different factors that affect and limit the possibility of using this method Steam injection of economic projects to extract oil is when the depth of the reservoir is less than 3,000 feet, crude oil density of about 30, 200 milliseconds Darcy permeability, porosity of more than 25% and thermal methods successfully applied in the sandstone layers. The degree of saturation of original oil prominent role in determining the use of a particular method roads thermal mostly been applied in the case of a high degree of saturation in oil and due to the crude oil may be heavy in this case and thus lower the degree of saturation.

2.1.6 Relative Permeability:

Contrary to absolute permeability which refers to a single fluid, relative permeability is the ability of a fluid to flow in the presence of another fluid. Relative permeability is helpful in determining the ratios ${k_w}/{k_o}$, which is used to predict the performance of the reservoir.

The gas, oil, and water relative permeabilities are normally denoted by K_{rg}, K_{ro} and K_{rw}, respectively.

Relative permeabilities are usually expressed by the ratio of effective permeability to absolute permeability. Effective permeability is a relative measure of the conductance of the porous medium for one fluid phase when the medium is saturated with multiple fluid phases. Absolute permeability can be expressed as monophasic permeability or usually the effective oil permeability at irreducible water saturation.

The Unsteady State Method for relative permeability is based on the Buckley-Leverett two phases flow model. (Refer to literature). This model can be applied under the following assumptions:

- Immiscible and uncompressible fluids.
- No capillary pressure and No gravity.
- Unidirectional flow along the core axe.

2.1.6.1 Experimental runs are conducted as follows:

Figure 2.3 shows the relative permeability experiment steps**.**

The run consists of saturating a core sample with a wetting phase (brine),

And then displace it by injecting a non-wetting phase (oil) through the core sample until the sample reaches the irreducible wetting phase (S_{wi}),

Brine is then injected at a constant flow rate until the samples reached the residual non-wetting phase (oil) (S_{or}),

From the differential pressure, the flow rate and the cumulative production of injected and displaced fluids, the model permits the calculation of the relative permeability.

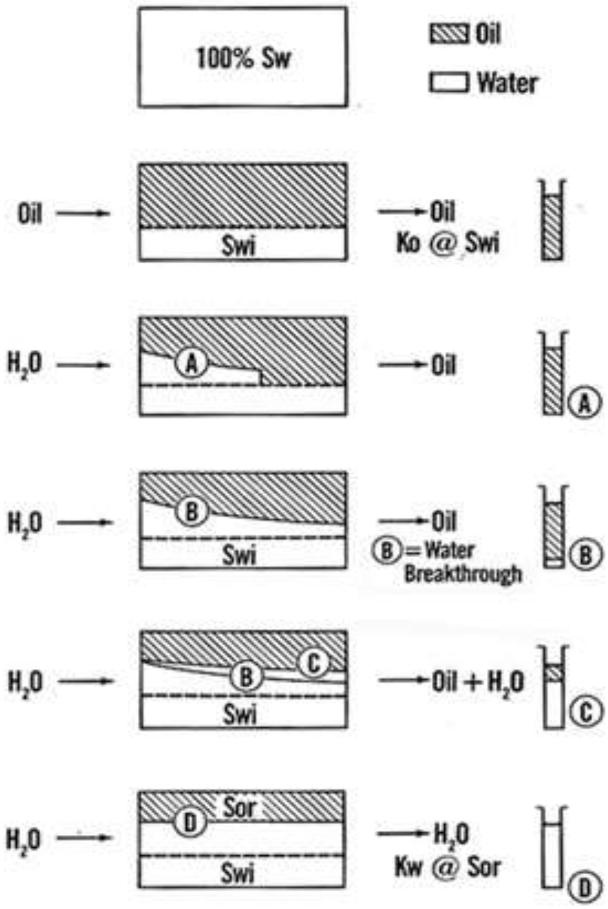

Figure 2.3 Relative Permeability experiment (Vinci Operating Manual, 2013)

2.1.6.2 Oil-water Relative Permeability Curves:

At the initial or irreducible water saturation, the oil relative permeability K_{ro} always equals 1 if the base permeability used is the effective permeability to oil atS_{wi}. At this point, K_{rw} is always equal to 0 because water is immobile.

At residual oil saturation, the oil relative permeability,K_{ro} always equals 0 because the oil phase is immobile (S_{or}). However, at this saturation water relative permeability is at its maximum value because water is the only phase that is mobile. Figure 2.4 presents a typical set of relative permeability curves for a water-oil system.

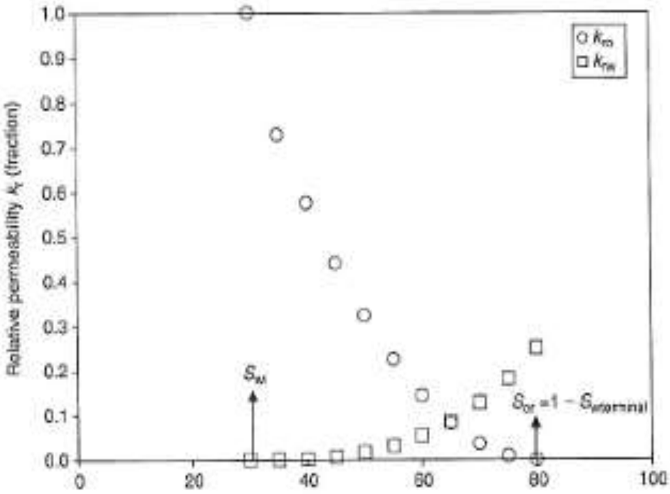

Figure 2.4 oil-water relative permeability curve (Vinci Operating Manual, 2013)

2.1.6.3 Gas-Oil Relative Permeability Curves:

At 100% liquid saturation, the oil relative permeability K_{ro} always equals 1 if the base permeability used is the effective permeability to oil at S_{wi}. At this point, K_{rg} is always equal to 0 because gas is immobile.

At the residual liquid-phase saturation, the oil relative permeability K_{ro} always equals 0 because the liquid phase is immobile. However, at this saturation, the gas relative permeability is at its maximum value because gas is the only phase that is mobile. Figure 2.5 presents a typical set of relative permeability curves for a gas-oil system.

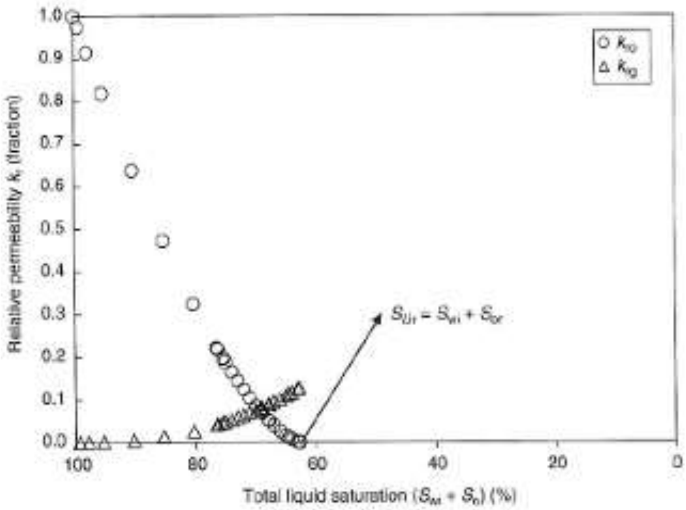

Figure 2.5 gas-oil relative permeability curve (Vinci Operating Manual, 2013)

2.2 Literature Review:-

Steam injection into heavy oils has been well characterized over the last 40 years, and, while steam has been injected into light oils almost as long, the mechanisms and effectiveness of this process are much less understood (Hoffman and Kovscek, 2004). Blevins et al. (1984) found that, regardless of differences in effective recovery mechanisms in heavy and light oil reservoirs, this process is an efficient enhanced oil recovery (EOR) method.

Steam flooding has wide application in recovery of heavy and light oil reservoirs. In the 1960s, one of the first light-oil steam flood field trials was initiated at the Brea Field near Los Angeles, California (Volek and Pryor, 1972). It should be emphasized that the development of further light oil projects was not as rapid as those on heavy oil, because water flooding is seen as less risky, with a lower initial investment than steam injection.

Hong (1986), as a researcher of this company, had been studying steam flooding in USA light oil reservoirs for ten years. The results showed that steam flooding is a good alternative for water injection. Also steam distillation is a main recovery mechanism in light oil steam flooding. Consideration of the details of reservoir geology is critical for evaluation of light oil steam flooding projects. The resulting steam projects may be considerably different in their implementation from conventional heavy oil steam floods in injection rates, well spacing and process optimization (Dehghani and Ehrlich, 2001).

Ovalles(2002). Study the Physical and numerical simulation of steam flooding to Lake Maracaibo reservoir, in Western Venezuela, showed acceleration in oil production with an increase of 14 to 20 % of oil recovery with respect to the original oil in place (OOIP) after water flooding. Additionally, the use of steam drive as a primary recovery method showed a further 5 % increase in cumulative oil production.

The cyclic steam stimulation process had been implemented in many Sudanese fields such as Bamboo Main oil field, Hilba, Fula Central, and FNE oil field and has been considering as the most successful EOR Projects in Sudan.

Wang, Ruifeng ET. all (2011): discussed the first cyclic steam stimulation (CSS) pilot test in Sudan, which was applied in FNE shallow heavy oil reservoir, CSS Pilot tests on two wells began in 2009. Convincible results have been monitored with well daily rates 3-4 times of cold production wells with low water cut. Another six CSS wells further came on stream from July. 2010, achieving similar positive results, conclusions drawn from pilot test were as follows: 1) Optimized perforation contributed to low water cut; 2) steam injection density was optimized around 120 t/m; 3) Natural gas as heating source greatly reduce operating cost.

Elbaloula ET. Al, (2016) provided a feasibility study from screening, design optimization as well as implementation of cyclic steam stimulation (CSS) in BBW 42 as first well in Grater Nail Operator Company in addition to various challenges and recommendations and the result show that the CSS can almost double the production from 280 BOPD up to 471 BOPD.

Elbaloula ET. Al. (2018), discussed the full-field implementation of CSS in the FNE Oil Field. The result showed that the CSS is very successful and the average oil rate is almost 1.6 times compared to cold production, the CSS only can increase the recovery percent from 32.5 to 34.2% which makes it a more attractive method as a development scenario for the FNE oil field, Also they highly recommended to go for steam flooding stage.

2.3 Fula North East field:

FNE Oilfield is geographically located in the southwest of Sudan, about 700 km from the capital, Khartoum; structurally located in the northeast of Fula sub-basin of Muglad basin and in the southwest of the Moga Oilfield.

FNE Oilfield exploration began in 1989, the first well FNE-1 has been drilled in 2005, and it was found one of the largest heavy oil fields in Petroenrgy (PE) block 6 Area. Then immediately the development and research began. The oilfield development Case was completed by Beijing Research Institute of Petroleum Exploration and Development in May 2008. The oilfield was put into development in June 2010. By May 2011 before the steam flooding study started, a total of 43 wells had been drilled, including one horizontal well; 36 wells have been put into operation, of which 23 wells are producing as cold, and 13 wells for steam stimulation; 33 wells were opened, with a daily oil production of 5722bbl, a daily fluid production of 6097bbl, a water cut of 6.1%, the total Original Oil In place (OOIP) is 298.7 MM STB, and the up to date recovery factor of reserves is 0.75%. The average daily production for steam stimulation is 2 to 3 times of the cold wells, Figure 2.6 shows the location map of the Fula sub basin in the Muglad basin including oilfields study area, while figure 2.7 shows Original Oil in Place, Reserve and Cum. Production for Fula North East Oilfield.

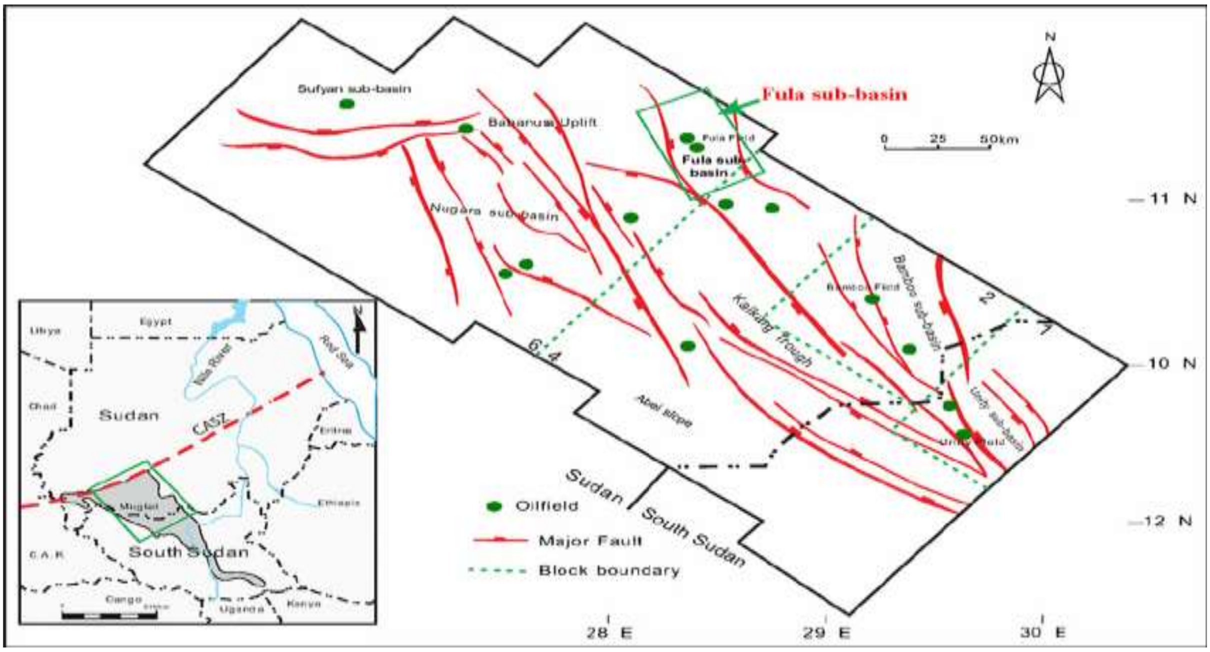

Figure 2.6 Location map of the Fula sub basin in the Muglad basin including oilfields study area (13th DTR, 2016).

Figure 2.7 OOIP, Reserve and Cum. Production for FNE (Elbaloula. H, 2016).

The 13 CSS Wells have been completed with heat compatible casing and cement. Steam quality of 75% was injected for 6-12 days and wells were subjected to soaking of 3-5 days. Putting on production an improvement of three to five folds has been realized compared to primary production and first cycle is sustaining more than six months. Actual results are better than predicted in simulation studies with lower steam intensity of 120 m3/m compared to plan 160m3/m.

Screening for FNE Oilfield with Similar international Heavy Oil Oilfield produce as Thermal Recovery:

Most of the previous research and studies confirm that FNE oil field is suitable for thermal enhanced oil recovery and the cyclic steam injection wells reward more than double production compare to cold wells, according to the common standards for heavy oil thermal recovery, comparatively analyze the geological features of FNE Oilfield and consider that FNE oilfield is suitable for heat mining development.

Table 2.1Screening Criteria for Thermal Recovery (Elbaloula. H, 2016)

Item	CSS	SF	FNE Felid
Pay depth m	<1700	<1300	550
Pay thickness m	10~35	7~60	30
NTG	>0.35	>0.4	0.6
Horizontal perm. md	>200	>200	4000
Porosity %	>20	>20	32
Oil saturation %	>60	>45	70
Dead oil viscosity cp	/	<10000	2019(43℃)
Reservoir pres. psi	<1885	<725	610

CHAPTER THREE
EXPERIMENTAL MATERIALS, APPARATUS AND PROCEDURE

3.1MATERIALS:

The reservoir brine or brine analysis, unadulterated reservoir oil sample and the core plugs are required for the core flooding tests.

3.1.1 Formation Water:

Produced water sample from the well FNE-19 was analyzed at water lab in Petroleum Laboratories, Research and Studies (PLRS). Table 3.1 lists the component used to prepare the Synthetic Formation Brine (SFB).

Table 3.1Formation Water Properties

pH	7.74 @ 26 ℃
SG (60/60F)	0.9974
Resistivity ohm-meter at 75 of Deg	21.2
Total Dissolved Solids (mg/liter)	344.13
Sodium Chloride Salinity Equivalent (mg/liter)	29.17
Dissolved Oxygen (mg/liter)	1.0
Sulfide (S2–) by SM 4500-S2–D (µg/L)	0.248

Cations	**mg/liter**	**meq/liter**
Sodium (Calculated)	5	0.2
Potassium	55	1.4
Calcium	27	1.4
Magnesium	13	1.0
Barium	5	0.1
Ferric	0.20	0.007
Ferrous	Nil	Nil
Total Iron	0.20	0.007
Anions	**mg/liter**	**meq/liter**
Chloride	18	0.5
Sulphate	Nil	Nil
Bicarbonate	221	3.6
Carbonate	Nil	Nil
Hydroxide	Nil	Nil

3.1.2 Crude Oil:

The crude oil properties obtained from well FNE-1 in Table 3.2. Dead crude oil was analyzed at crude lab in Petroleum Laboratories, Research and Studies (PLRS).

Table 3.2Crude Oil Properties

T E S T S	Result
Density @ 60 °F g/cc	0.93502
API°	17.4
Total acid number, mg KOH/ gm	8.07
Total base number, mg KOH/ gm	9.84
Asphaltene content, wt.%	0.18
Atmospheric viscosity at 43 °C , (CP)	2019
Atmospheric viscosity at 60 °C, (CP)	449.2
Atmospheric viscosity at 80 °C, (CP)	149.7
Atmospheric viscosity at 100 °C, (CP)	61.0

3.1.3 Rock Samples:

The native core plugs (9B) was selected from well FNE-135 and analyzed at conventional core analysis lab in PLRS. The plug represent to pay zones Bentiu formation. Table 3.3 shows Mounting and corrected length and diameter, and table 3.4 shows the physical properties and lithological discretion of sample (9B).

Table 3.3 Dimension

SN	Mounting		Actual	
	Length	Diameter	Length	Diameter
9-B	6.842	3.837	6.602	3.757

Table 3.4 Rock Physical Properties

SN	Depth	Gas Permeability md			Helium Porosity	Pore Volume	Grain Density	Lithological Description
		HK	VK	LK				
9-B	531.27	3124.94	1987.96	3017.52	34.92	25.5	2.61	Light grey, coarse grain, moderate sorted, Poor cut.

Sample	Porosity (%)	Ka (mD)	Porosity (fr)	RQI	Phiz	FZI
9-B	34.9	3124.9	0.35	2.97	0.54	5.5
4-A	35.1	3166.8	0.35	2.98	0.54	5.5
4-B	33.2	2386	0.33	2.66	0.50	5.4
7-A	36.1	3056.8	0.36	2.89	0.57	5.1
1-A	35.4	2525	0.35	2.65	0.55	4.8
5-A	39.2	3147.2	0.39	2.81	0.65	4.4
11-A	37.7	2591.1	0.38	2.60	0.61	4.3
12-A	37.3	2423.8	0.37	2.53	0.60	4.2
1-B	33.7	1568.3	0.34	2.14	0.51	4.2
8-A	37.7	2410	0.38	2.51	0.61	4.1
8-B	38.1	2440.9	0.38	2.51	0.62	4.1
9-A	39.1	2664.9	0.39	2.59	0.64	4.0
3-A	37.1	1974.4	0.37	2.29	0.59	3.9
10-A	30.8	891.1	0.31	1.69	0.45	3.8
12-B	31.9	980.6	0.32	1.74	0.47	3.7
2-A	40.7	2554.1	0.41	2.49	0.69	3.6
6-A	41.6	2784	0.42	2.57	0.71	3.6
6-B	35.4	1351.4	0.35	1.94	0.55	3.5
3-B	39.9	2198	0.40	2.33	0.66	3.5
10-B	34.3	1163.1	0.34	1.83	0.52	3.5
7-B	37.6	1687.5	0.38	2.10	0.60	3.5
13-B	38.3	1813.8	0.38	2.16	0.62	3.5
11-B	34.4	1129.2	0.34	1.80	0.52	3.4
14-A	39.4	1914.1	0.39	2.19	0.65	3.4
13-A	37.9	1586.1	0.38	2.03	0.61	3.3
2-B	41.9	2365	0.42	2.36	0.72	3.3

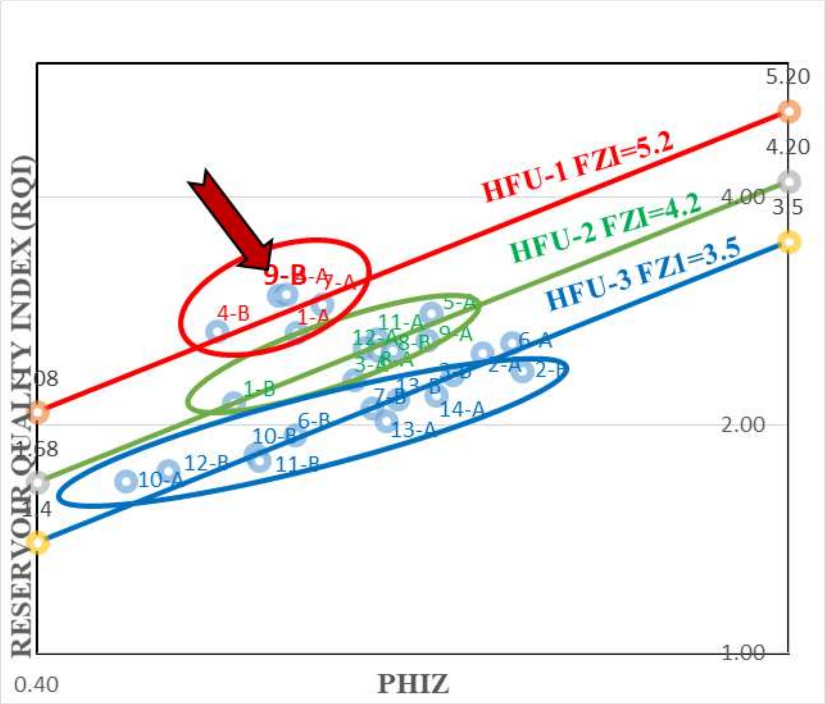

Figure 3.1 Show Hydraulic Flow Units (HFU), Flow Zone Indicator (FZI)

3.2APPARATUS AND EQUIPMENT:

In order to run the coreflood experiments the following equipmentare required:

3.2.1 Preparation Equipment:

Slabbing machine:

Utilized either to slab core samples in two halves or to trim full diameter rock samples.A variable rate feed mechanism enables the long section cuttings of ultra-high density core in one pass without fracturing, grooving or chipping.

Plugging machine:

The heavy diamond-tooled drill press is specially designed to deliver various core sample sizes.

Trimming machine:

Bench top tool designed to cut preset core sample lengths. The quality of the saw blade allows for extreme precision of the end face after trimming of 0.002 inch (5/100 mm)

Mounting:

Utilized to mounting the unconsolidated core sample to prevent the sample from being damaged during analysis.

3.2.2 Analytical Equipment:

Soxhlet:

To remove the oil, water and salts from native core plugs. Oil and water were removed using toluene while salts by using methanol.

UV:

To ensure that core plugs are cleaned by looking in change of color.

Digital Vernier Caliper:

The dimension (length and diameter) of the core plugs was measured using vernier.

Helium Porosmeter:

The helium porosity of the core samples was measured using Helium Porosmeter at conventional core analysis lab in PLRS.

Air Permeameter:

The air permeability of the core sample was measured using helium air permeameter at conventional core analysis lab in PLRS.

Manual Saturator:

Fully saturation of core sample with brine done by manual saturator manufactured by Vinci.

3.2.3 Experimental Equipment:

STEAMFLOOD 700:

The STEAMFLOOD 700 system is designed to perform steam injection tests on core samples inorder to enhance oil recovery through thermal expansion and lowering of viscosity. These tests canbe realized at reservoir conditions (high pressure and high temperature).

The steam generator can inject hot water, low quality steam, saturated steam or superheatedsteam as displacement fluid.

The slim tube provided with the equipment is used for measurements of Minimum Miscible Pressure (MMP).

Confining and pore pressure can be up to 700 bars or 10,000 psi maximum. Temperature can beup to 200°C. The pore pressure is measured at inlet and outlet ports of the core sample by usingrelative and differential pressure transducers. All wetted components are made of Stainless Steel316, Hastelloy C-276 or Titanium TA6V for chemical compatibility and corrosion resistance. Figure 3.2 shows the STEAMFLOOD 700 station.

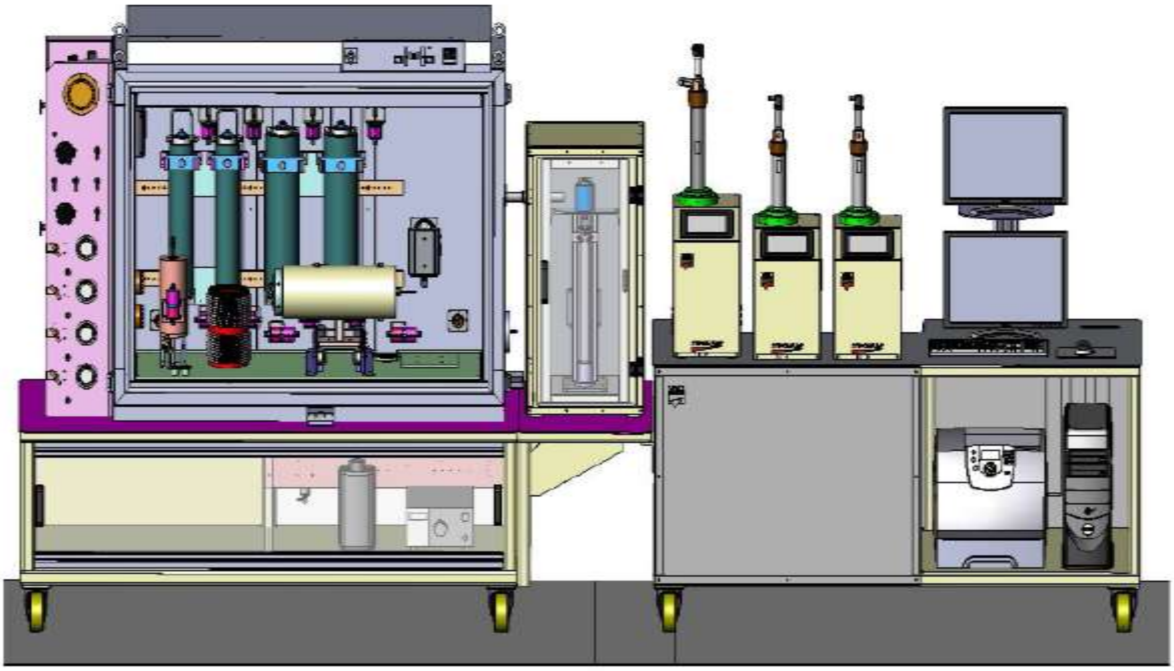

Figure 3.2 Core Flooding System with Steam Injection (Vinci Operating Manual 2013)

This system includes 3 double pumps, an oven, 4 piston accumulators, 2 gas regulators, a mass flow controller, a steam generator, a slim tube, 3 core-holders, a visual cell, 2 back pressureregulators, a level tracker, a pressure measurement system and a gas meter.

Syringe pump

The benchtop dual pump from Vinci is a syringe pump used to inject the fluid into the core at constant flow rate. The pump was filled with distilled water to displace the fluid in the accumulator into the core holder for oil/ water/ polymer flood experiments. Figure 3.3 shows the Syringe Pump.

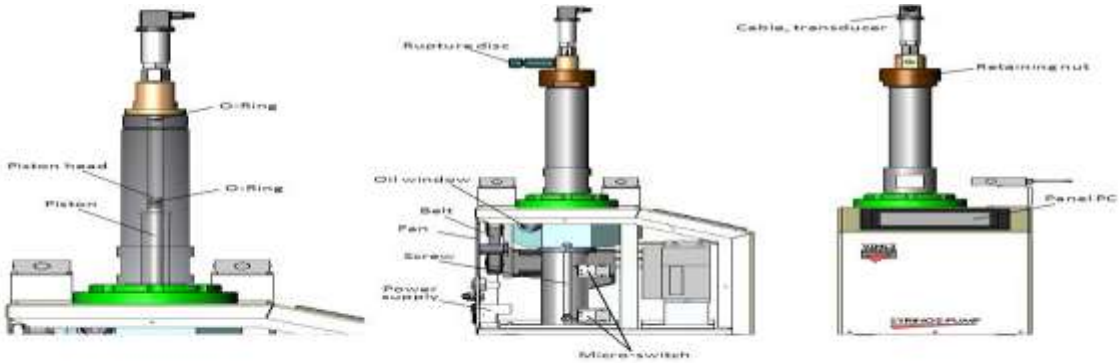

Figure 3.3 Syringe Pump (Vinci Operating Manual 2013)

Titanium Accumulators

These accumulators used to maintain process fluid at reservoir conditions during the test. Accumulators are cylinders equipped with two end plugs and a floating piston. To inject fluid into the core, the column was oriented vertically and distilled water from the pump was injected at the bottom to displace fluid in the accumulator. Figure 3.4 shows the accumulator.

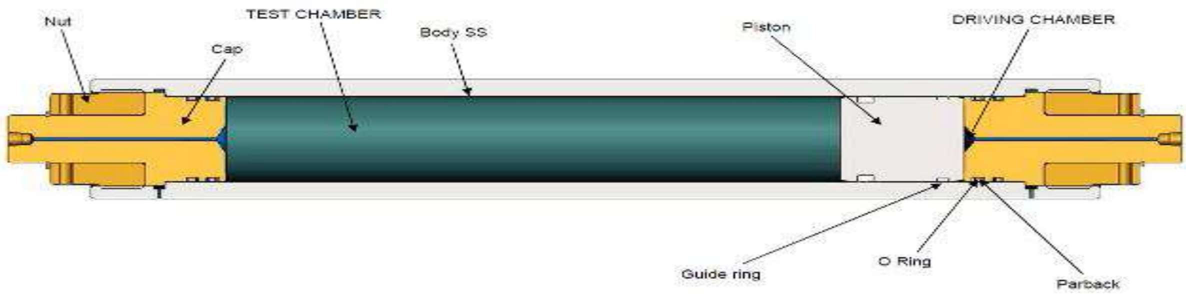

Figure 3.4 Accumulator (Vinci Operating Manual 2013)

Core Holder

A titanium core holder manufactured by Vinci was used in this work. The core holder has 1.5 inch internal diameter, one foot length and two pressure taps at the inlet and outlet. Figure 3.5 shows the core holder.

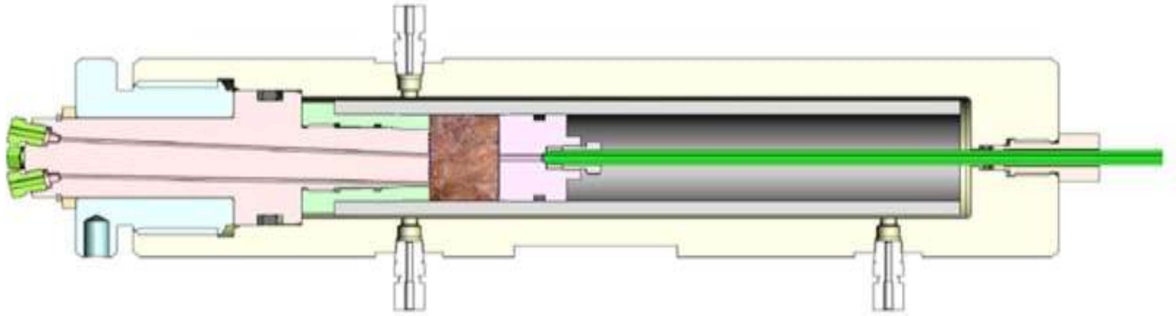

Figure 3.5 Core Holder (Vinci Operating Manual 2013)

Steam Generator

The high-pressure, high-temperature steam generator is made of a heated aluminum barrel which is coiled by a 1/8’’ tube. The water which is injected by the HPLC pump circulates through the tubing and is converted into steam. The whole is insulated with jacket. A thermoelectric heating cartridge is inserted in the aluminum barrel to provide the heat to the water circulating in the 1/8tube. The temperature of the generator is measured by a PT 100 probe and a temperature regulator controls and regulates the power of the heating element to maintain a set temperature of the steam.

The steam generator is mounted inside the oven in order to prevent heat losses from the steam generator to the core. The steam generator is kept on power at all times. To permit studies with short steam injection cycles, a valve is used to temporary stop the steam flow from the main flow loop to a second steam condenser and back pressure controller. Figure 3.6 shows the steam generator unit.

This steam generator has the following features:

- Temperature range: up to 300°C
- Pressure range: up to 1,000 psi
- Stability: +/- 0.5°C

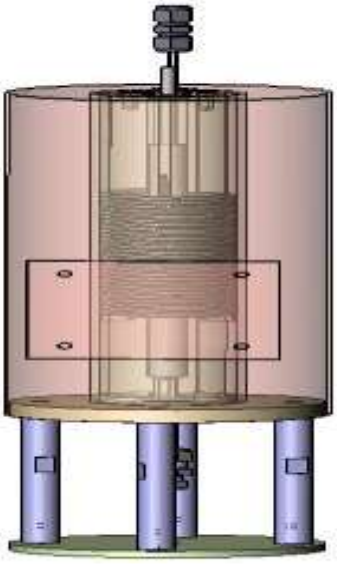

Figure 3.6 Steam Generator(Vinci Operating Manual 2013)

Condenser:

The condenser is based on a recirculating chiller. The 6-liter circulating bath is designed to provide precise temperature control of fluids. Figure 3.7 shows the steam condenser unit.

- Temperature: -20°C to 100°C
- Pump flow rate: 9 to 15 L/min
- Circulating fluid:
    - o Distilled water for a temperature between 10°C and 90°C
    - o mixture of ethylene glycol and water for temperatures below 10°C

Figure 3.7 Steam Condenser (Vinci Operating Manual 2013)

Level Tracker

The level tracker is an atmospheric pressure volume counter based on light attenuation sensor. In the glass tube, the light attenuation is different in liquid and in air. The tracker moves to be on the level of the liquid-air interface, and the equivalent volume is counted. Figure 3.8 shows the level tracker.

Figure 3.8Level Tracker (Vinci Operating Manual 2013)

BPR (Back Pressure Regulator)

The BPR is a dome-loaded type, which controls the upstream back pressure to whatever pressureis applied to its dome. It is designed to operate using compressed gas in the dome and water, oil orgas in the body. The two sections are separated by a piston.

HPLC Pump

The LabAlliance Series III pump is an HPLC injection pump. It has flow rate from 0.01 to 10 cc/min, Pressure: from 0 to 6,000 psi, Pump head made from Stainless Steel.

Pressure Transducers

The pressure at the inlet and outlet measured by the pressure transducer from 0 to 700 bar. There are three set of pressure transducers to accurately measure the pressure drop in the system. All the transducers need to be zero before starting any experiment.

Data Acquisition System

Signals from pumps and pressure transducers were collected in Excel file, .24h which collect data for each 24 hours with controlled interval.

Convection Oven

Convection oven is set to reservoir temperature so the accumulators and core holder were placed inside the oven. The temperature displayed in the remote control.

Remote control

The applilab software has been developed by programmers from Vinci Technologies in order to control the process parameters simultaneously from one central unit.

EV1000

EV1000 electromagnetic viscometer was used for viscosity measurement. This apparatus is designed to provide high accuracy viscosity measurements at high pressure (up to 15000 Psi) and high temperature up to 200C as maximum. Figure 3.9 shows the EV1000 electromagnetic viscometer device.

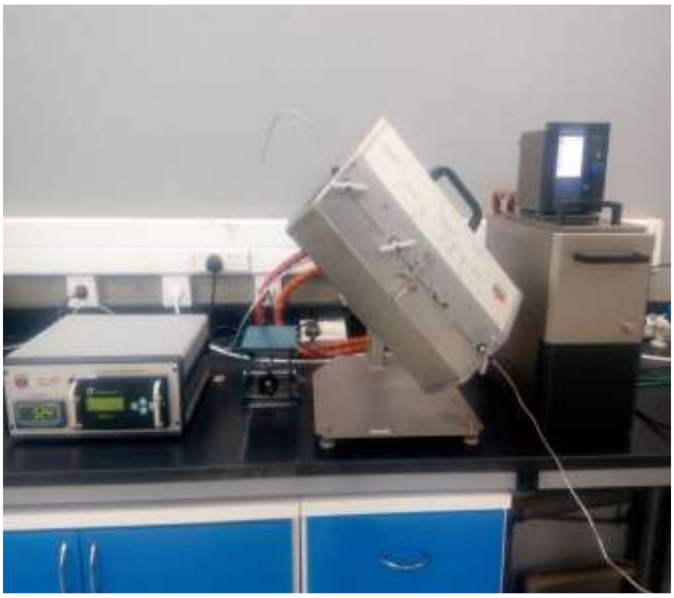

Figure 3.9: EV1000 electromagnetic viscometer device

3.3PROCEDURE:

3.3.1 Fluid Preparation:

Synthetic Formation Brine (SFB)

Deionized water and salts were mixed in the appropriate proportion as shown in Table 3.1. Ten liters of synthetic formation brine was mixed at a time. Every brine stock was filtered through 0.45 µm cellulose filter.

This Synthetic formation water is used to saturate the sample as well as in the injection process to ensure that it is free of impurities and bacteria. Figure 3.10 shows the synthetic formation brine prepared in PLRS.

Figure 3.10 SFB

Crude Oil

FNE-1 crude oil was separated from water by using Separation Funnel placed in convention oven and set temperature to reservoir temperature 43C, Let it stand undisturbed for some time so that separate layers of oil and water are formed by gravity, Water will be lower layer and oil will be upper layer then open the stopcock of the separating funnel and pour out the lower layer of water carefully. Also it filtered with Sartorius- Stedim filter before use. The viscosity of the oil is measured using EV1000 at thermal EOR lab in PLRS.

Figure 3.11 Separation Funnel (SCAL LAB PLRS)

Figure 3.12 FNE-1 Crude oil

3.3.2 Core Preparation:

The cores were slabbed into 1/3 and 2/3 sections. The 1/3 section (Set B) was polished and photographed under white and Ultra Violet light. Three core plug samples were drilled parallel to the bedding (Horizontal Plugs) in the reservoir quality sandstone. All of the samples were drilled using air as a lubricant, because the cores were varying between poorly consolidated to consolidated, to preserve the integrity of the poorly consolidated samples.The plug samples were trimmed to produce right cylinders. The plug samples were mounted in a heat shrinkable tube to prevent the sample from being damaged during analysis.

The cores were placed in soxhlet to remove oil and water then the solvent was changed to methanol after ensure that they were cleaned by toluene to remove salts. After cleaning, the plugs was dried in the 60 C oven till it has constant weight. The porosity of the samples was measured using helium porosmeter, also the air permeability using helium was measured.

The samples were weighted before put them in the manual saturator. In the saturator the brine was vacuumed and pushed to the samples container until the pressure reached 2000 psi, the pressure was monitored if it is been less to recover it again for 2 days. Fully saturated core samples weighted to calculate the pore volume.

Figure 3.13Core Sample

3.3.3 Core flood Description:

In this study used one samples of core to run the experiment,

The plug (9B)was placed in the Steamflood 700 core holder with confining pressure of 3750 psi, pore pressure 527 and 43 C temperature.Then, the core is flooded with the reservoir brine and its brine permeability was measured.

After that the core sample was saturated with oil (by oil flooding) at irreducible water saturation (S_{wi}). After reaching $S_{wi}$the flooding system was put in aging period for 15 days to restore the initial wettability, also the effective oil permeability was measured at different flow rate.The end point for water-oil relative permeability will be measured. The irreducible water saturation and initial oil in place are also determined.

Water flooding (cold water production) was conducted to determine residual oil saturation and effective water permeability when the pressure drop across the sample stabilized. The water flooding started with 0.2 ml/min flow rate till no oil produced then the rate shifted to 0.5 ml/min. The pressure drop across the plug was measured for 5 flow rates (1-5 ml/min) to calculate the effective water permeability. The residual oil saturation was estimated based on the total oil volume produced.

The steam generator was set at temperature 248c and pressure 527 Psi to produce superheated steam then use the HPLC pump to injection the superheated steam into the core, continued steam injection for 90 minutes and at the end of the experiment the volume of produced oil was recorded. Also residual oil saturation and recovery factor was estimated.

3.4 Data Analysis:

All the equation used for calculations in core flood experiments are described below:

3.4.1 Pore Volume (Saturation):

The pore volume calculated based on mass balance. After the full saturation of core when the pressure stabilized in 2000 psi for 2 days. The saturated samples weighted.

$$V_p = \frac{W_{sat} - W_{dry}}{\rho_w} \qquad (3.1)$$

Where:

V_p = Pore volume.

W_{sat} = Saturated weight with brine.

W_{dry} = Dry weight.

ρ_w = Brine density.

3.4.2 Pore Volume (under stress):

The pore volume estimated after applying 527 psi using mineral oil hand pump to fully saturated core with brine. The squeezed volume due pressure will subtracted from saturated pore volume.

Squeeze pore volume = saturated pore volume – squeezed volume due to confining.

3.4.3 Porosity (saturation):

The porosity is the saturated pore volume divided by bulk volume.

$$\emptyset = \frac{V_p}{V_b} \qquad (3.2)$$

Where:

$\emptyset$ = Porosity

V_p = Bore volume

V_b = Bulk volume

3.4.4 Porosity (under stress):

The porosity equal squeezed pore volume divided by bulk volume

$$\emptyset = \frac{V_{p\ squeeze}}{V_b} \qquad (3.3)$$

3.4.5 Initial Water Saturation

The initial water saturation was estimated by injecting more than 6 pore volume. Initial water saturation was water produced divided by squeezed pore volume.

$$S_{wi} = \frac{V_{p\ squeeze} - V_w}{V_{p\ squeeze}} \qquad (3.4)$$

Where:

S_{wi}= Initial water saturation

V_w= Water produced

3.4.6 Initial Oil Saturation

After oil flood in aging cell to establish the initial water saturation by injecting about 6 pore volumes. The oil saturation was estimated by mass balance as in the equation below:

$$S_{oi} = \frac{V_w}{V_{p\ squeeze}} \qquad (3.5)$$

Where:

Soi =Initial Oil Saturation

3.4.7 Residual Oil Saturation

The residual oil saturation from waterflooding was calculated when there no oil was been produced. The difference between initial oil volume and oil produced by waterflooding divided by squeeze pore volume was residual oil saturation.

$$S_{or} = \frac{V_{oi} - V_{oPWF}}{V_{p\ squeeze}} \qquad (3.6)$$

Where:

S_{or} = Residual Oil Saturation

V_{oi} =Initial oil volume

V_{oPWF} =Oil produced by water flooding

Steam flood residual oil saturation was the difference between the remaining oil volume and oil produced by Steam divided by squeeze pore volume.

$$S_{orSF} = \frac{V_{or} - V_{oPSF}}{V_{p\ squeeze}} \qquad (3.7)$$

Where:

S_{orSF} = Residual Oil Saturation after Steam Flooding.

V_{or}=Remaining oil volume before Steam Flooding.

V_{oPWF} =Oil produced by SteamFlooding

3.4.8 Effective Oil/ Water Permeability

Permeability to each flowing phase in the presence of another fluid is defined as effective permeability to that phase and calculated as follows:

$$ke_{o/w} = \frac{(\mu_{o/w} \cdot q_{o/w} \cdot L)}{(A.\Delta P_{o/w})} \qquad (3.8)$$

Where:

$ke_{o/w}$ = effective permeability to oil /water.

$\mu_{o/w}$ = viscosity of oil/water.

$q_{o/w}$ = flow rate of oil/ water.

$\Delta P_{o/w}$= pressure drop during oil/ Water.

3.4.9 Oil Recovery

The oil recovery factor of water flooding can be calculated by the produced oil divided by initial oil volume.

$$RF_{WF} = \frac{N_{p\ water}}{OIP} \qquad (3.9)$$

Where:

RF_{WF} = Recovery Factor by water flooding

$N_{p\ water}$ = Oil produced by water flooding.

OIIP = Oil Initial in Place.

The oil recovery by Steam flooding was calculated by oil produced using steam divided by initial oil volume in place.

$$RF_{SF} = \frac{N_{p\ steam}}{OIP} \qquad (3.10)$$

Where:

RF_{SF} = Recovery Factor by water flooding

$N_{p\ Steam}$ = Oil produced by Steam flooding.

OIIP = Oil Initial in Place.

3.4.10 Displacement Efficiency (ED):

The Sweep Efficiency after water flooding can be calculated by the difference between initial oil volume and residual oil saturation after water flooding divided by initial oil volume.

$$ED_{after\ WF} = \frac{S_{oi} - S_{orWF}}{S_{oi}} \qquad (3.11)$$

Where:

S_{oi} = Initial Oil Saturation.

S_{orWF}= Residual Oil Saturation after Water Flooding.

The Sweep Efficiency after steam flooding can be calculated by the difference between initial oil volume and residual oil saturation after steam flooding divided by initial oil volume.

$$ED_{after\ SF} = \frac{S_{oi} - S_{orSF}}{S_{oi}} \qquad (3.12)$$

Where:

S_{orWF}=Residual Oil Saturation after Steam Flooding.

CHAPTER FOUR
RESULTS AND DISCUSSION

4.1Experiment (9B)

A single fully saturated core plug with brine (9B) was loaded to Steamflood 700. Table 4.1 shows 9B rock properties. After loading the sample 3750 psi confining pressure was applied using distill water pump to measure squeeze pore volume. The volume squeezed due to applying pressure was 6.4 cc according to this, the pore volume corrected to squeeze pore volume and porosity to overburden which are 19.98 cc and 25% respectively.

Table 4.1: Saturated Sample Properties B9

Depth (mKB)	531.27
Bulk Volume (cc)	78.40
Dry Weight (g)	140.89
Saturated weight (g)	167.33
Saturated pore volume (cc)	26.38
Saturated porosity (%)	33.65
Squeezed pore volume (cc)	19.98
Porosity after squeeze (%)	25.48

Figure 4.1: Core Plug

Once the correction of pore volume and porosity finish the Steamflood 700 oven need to stabilize at reservoir temperature 43 (°C). After temperature stabilization we increase confining pressure, back pressure regulator and pore pressure simultaneously using distill water pump. When the system reaches reservoir condition, 3750 psi confining, 2008 psi back pressure and 527 psi pore pressure was let for 24 hours for pressure stabilization as shown in Figure 4.2.

4.1.1 Absolute Water Permeability

The Steamflood 700 was ready to start base or absolute water permeability calculation by measuring the pressure drop across 9B for each flow rate using Applilab macro. The base permeability is calculated based on Darcy's single phase, steady-state and horizontal flow. Five different flow rates 1-5 ml/min were applied and the pressure drop across 9B due it was recorded as in Table 4.2 and Figure 4.3 shows the linear regression of permeability calculation which is 2314.5mD.

Table 4.2: Record of pressure drop across 9Bat different 5 flow rates

Water					
Flow Rate (ml/min)	1	2	3	4	5
Delta P(Psi)	0.05	0.1	0.12	0.18	0.2
R.squared	0.9757				
Permeability (mD) calculated by linear regression = **2314.5 md**					

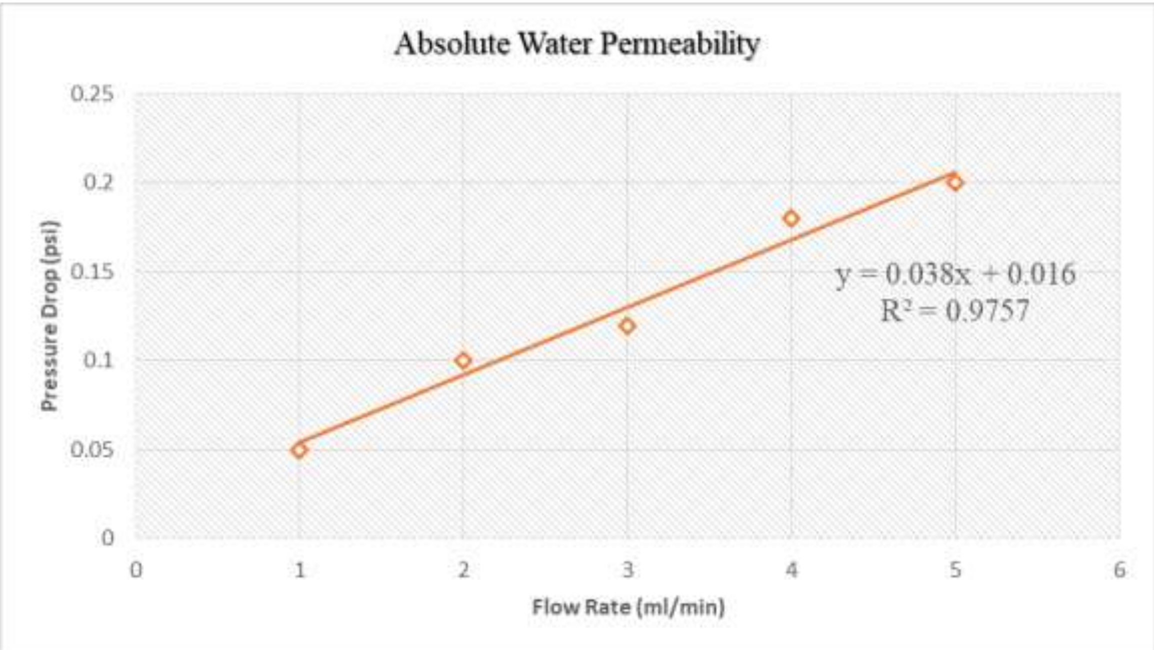

Figure 4.2: Linear regression for absolute water permeability calculation

4.1.2 Oil Injection (Drainage process)

After base water permeability calculation the initial water saturation was established by injecting oil until the water volume and (delta P) are stabilized. The volume of water produced by oil injection was 2.48 cc. So the initial water saturation as a percentage was 12.4% PV when injecting 0.1 ml/min oil through oil accumulator using distill water pump. Initial oil volume was 17.5 cc (87.6% of squeeze pore volume). The effective oil permeability was calculated using linear regression at initial water saturation. The pressure drop across the sample was recorded for 5 flow rates (0.5, 1, 1.5, 2 &2.5 ml/min) as in Table 4.3. The effective permeability of oil at initial water saturation was 2297.6 mDarcy after injecting 5 pore volumes.

Figure 4.3 shows a diagram describing the drainage process and the water volume produced by injection oil.

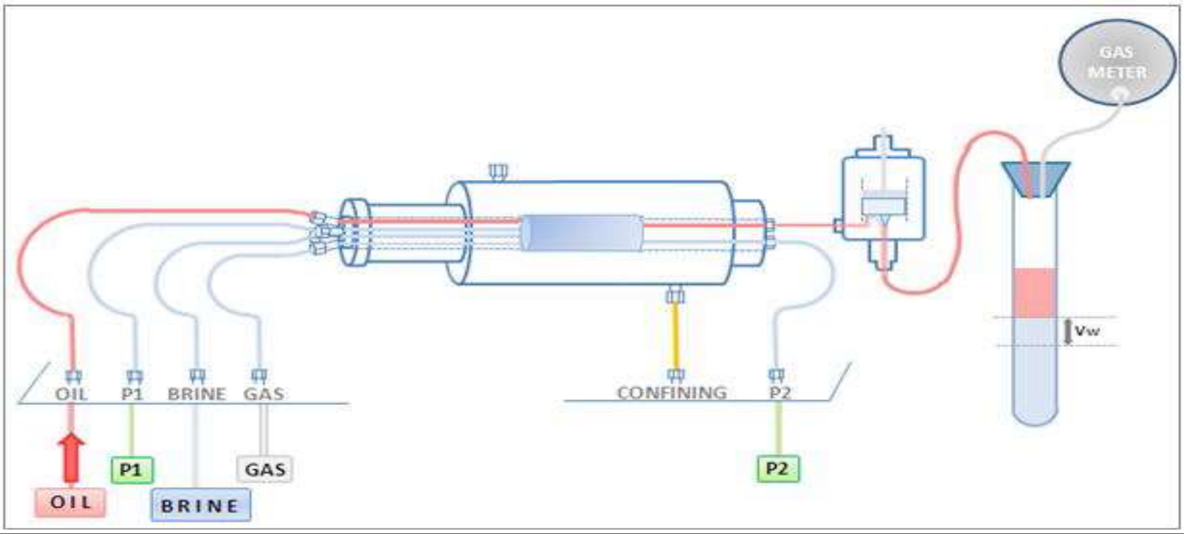

Figure 4.3: Injecting Oil to establishing Swi (9B)

Table 4.3: Pressure drop to calculate effective oil permeability at Swi

Oil Injction (Ko@Swi)					
Flow Rate (ml/min)	0.5	1	1.5	2	2.5
Delta P(Psi)	60.4	121.6	186.8	252.4	315.4
R.squared	0.9999				
Permeability (mD) calculated by linear regression = **2297.6 md**					

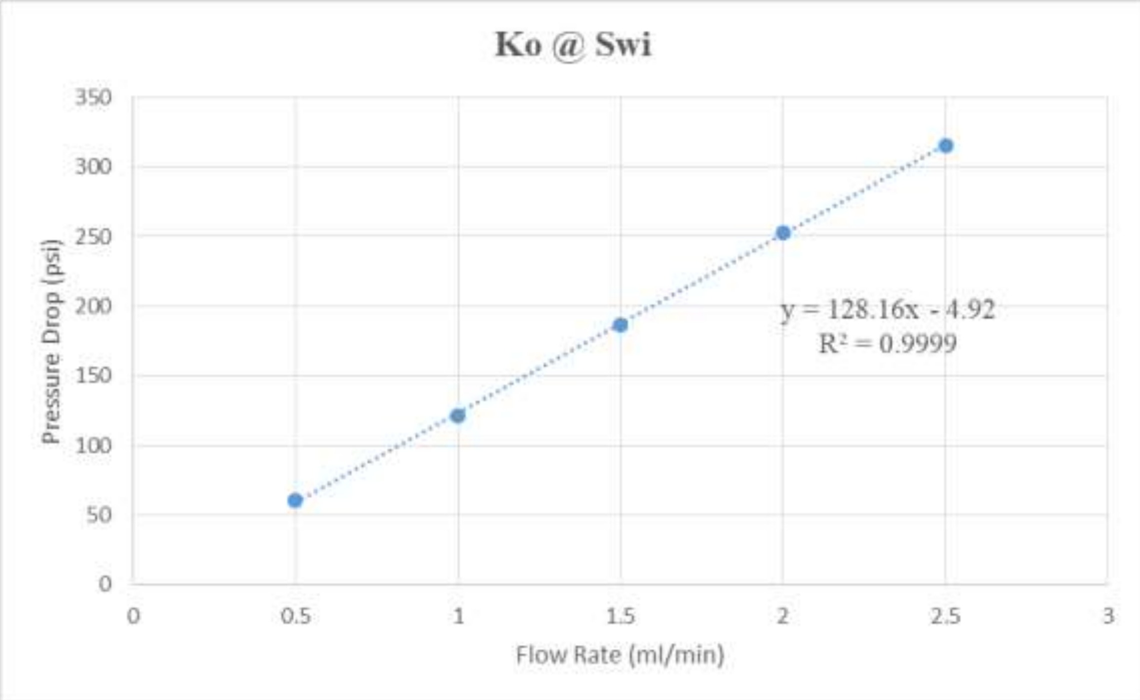

Figure 4.4: Linear regression to calculate effective oil permeability at S_{wi}

Figure 4.5 shows the volume of water produced after Drainage process and table 4.4 shows the Initial Water Saturation and Original oil in place Calculation after Oil Injection:

Table 4.4

Pore Volume	**19.98 cc**
Produced water	**17.50 cc**
Residual water	**2.48 cc**
S_{wi}	**12.4 % PV**
Volume of Oil (S_{oi})	**17.50 cc** **87.6% PV**

Figure 4.5 Water Produced after Drainage process

.

4.1.3 Aging

After oil flooding and reaching S_{wi} 9Bwas put in aging period for 15 days at reservoir conditions (T= 43 °C & P= 571 Psi).

4.1.4 Water flooding (Imbibition process)

2.5 ml/min was the flow rate for water flooding and the effluent collected to calculate the produced oil, recovery factor, and residual oil saturation. The water flooding was stopped when there was no oil was produced and (delta P) is stabilized. Then five flow rates (0.5, 1, 1.5, 2& 2.5ml/min) were conducted to calculate the effective water permeability at residual oil saturation as in Table 4.4. The effective water permeability at S_{or} was 180.6 MD after injecting 5 pore volumes (99.9 cc). The total oil produced by water flooding was 1.505cc so the residual oil saturation after water flooding was 80.06%, the recovery factor was 8.6% and the sweep efficiency was 9%.

Figure 4.5 shows a diagram describing the Imbibition process and the oil volume produced by injection water (cold production).

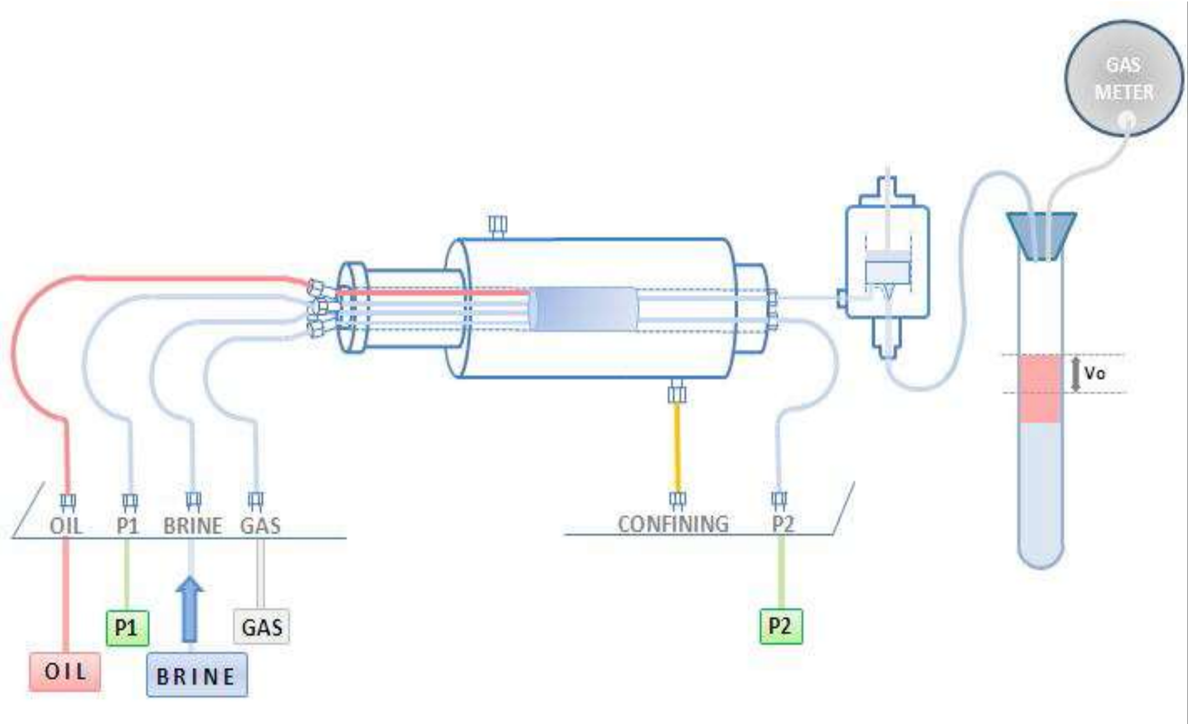

Figure 4.6 Injecting water to establishing S_{or} (9B)

Table 4.5: Pressure drop to calculate effective water permeability at residual oil saturation

Watere flooding(Kw@Sor)					
Flow Rate (ml/min)	0.5	1	1.5	2	2.5
Delta P(Psi)	0.41	0.66	0.95	1.16	1.41
R.squared	0.998				
Permeability (mD) calculated by linear regression = **180.6 md**					

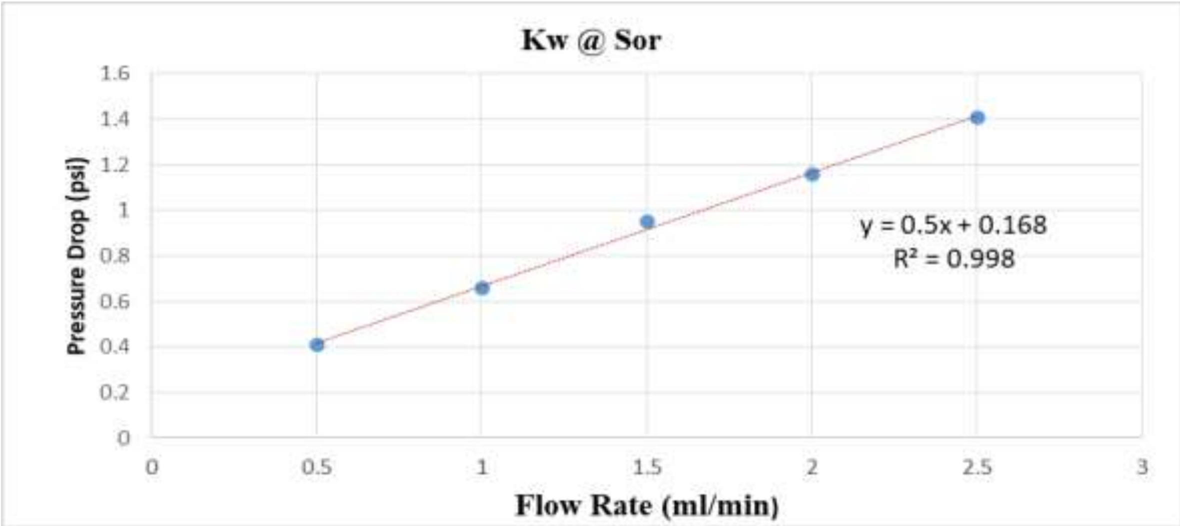

Figure 4.7 Linear regression to calculate effective water permeability at S_{or}

Figure 4.8 shows the volume of oil produced by cold production and Table 4.6 shows the Residual oil saturation, Recovery factor and Displacement Efficiency calculation after Steam flooding:

Table 4.6

Oil produced by CP	**1.505cc**
SOR after CP	**80.06%**
RF after CP	**8.6%**
ED after CP	**9 %**

Figure 4.8 Oil Produced by CP

4.1.5 Steam flooding For EOR

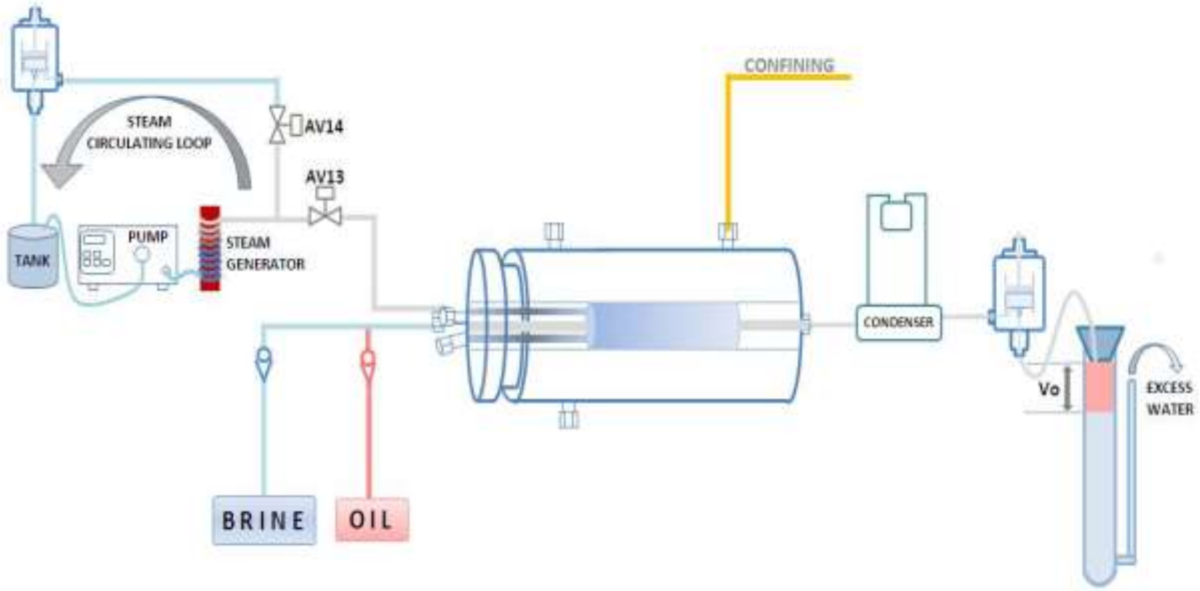

Figure 4.9: Injecting Steam (9B)

The Steam vapor was produced in a steam generator, Then the HPLC pump was adjusted to inject the stem into core sample (9B), The Steam flood started with 1.0 ml/min then five flow rates were applied (1, 2, 3, 4 & 5 ml/min) to calculate the effective permeability of Steam after pressure stability as in Table 4.5 and Figure 4.9. The effective Steam permeability at SORsteam was 42.6 mD. The total oil produced by Steam flooding was 5.26cc, sothe residual oil saturation after Steam flooding was 53.81%, the recovery factor was 30.06% and the sweep efficiency was 38%.

Table 4.7: Pressure drop to calculate effective Steam permeability

Steam flooding(Kw@Sor)					
Flow Rate (ml/min)	1	2	3	4	5
Delta P(Psi)	0.9	1.4	1.8	2	2.4
R.squared	0.9818				
Permeability (mD) calculated by linear regression = **42.6 md**					

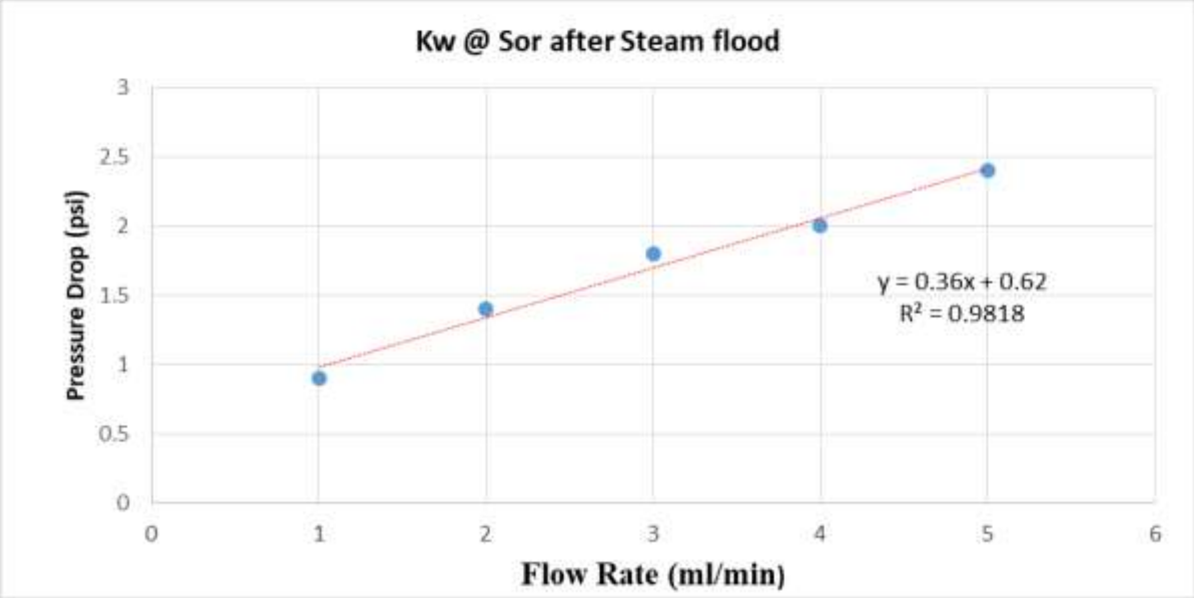

Figure 4.10: Linear regression to calculate effective Steam permeability

Figure 4.11 shows the volume of oil produced by steam flooding and Table 4.8 shows the Residual oil saturation, Recovery factor and Displacement Efficiency calculation after Steam flooding.

Table 4.8

Oil Produced by SF	**5.26 cc**
S_{or} after SF	**53.81 %**
RF after SF	**30.06 %**
ED after SF	**38 %**

Figure 4.11 Oil Produced by SF

4.1.6 Crude Oil Viscosity

Table 4.6 contains the viscosity data measured by an electromagnetic viscometer device (EV 1000), which shows the oil viscosity decreases with the increase of temperature.

The viscosity of the oil at steam temperature 248° C was extrapolated for the viscosity data, because the maximum temperature we can reach with (EV 1000) apparatus to measure the oil viscosity is 145° C.

Table 4.9 Viscosity Data

piston	T c	Visc
500-10000	30	10193
	35	6523
	40	4037
	43	2019
	50	1274
	55	941.8
	60	519
50-1000	65	358.2
	70	269.6
	75	205.1
	80	159
	85	127.6
	90	103.8
	95	82.38
	100	64.9
5-100	105	51.05
	110	42.31
	115	35.16
	120	30.1
	125	25.81
	130	22.24
	135	19.47
	140	16.97
	145	14.82
	248	1.5

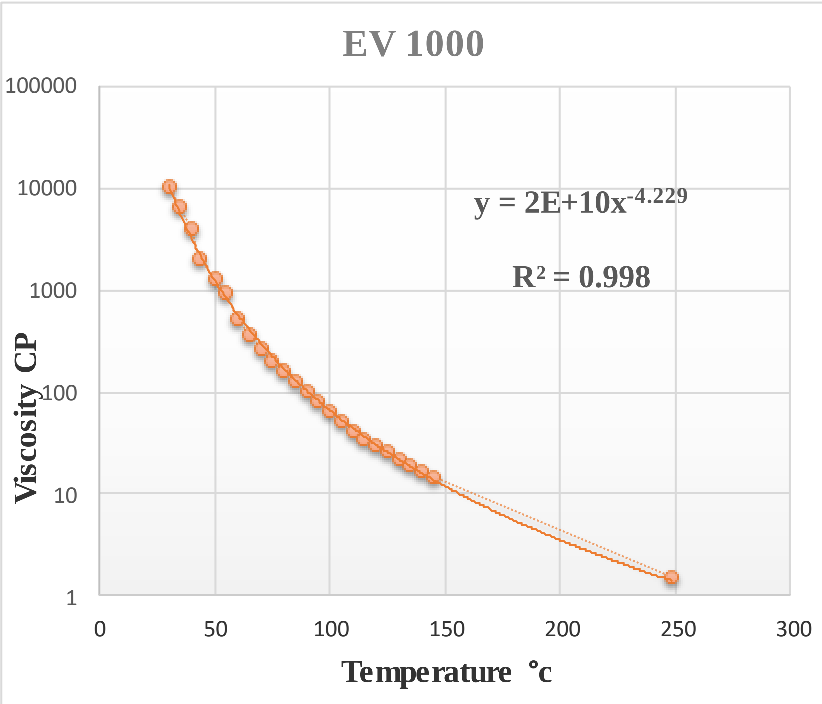

Figure 4.12: Viscosity of heavy crude oil versus temperature

4.1.7 Experiment Summary

Temperature °C	K_w mD	$K_o@S_{wi}$ mD	$K_w@S_{or}$ mD	K_r		Recovery Factor (R.F)	Residual Oil Saturation (S_{or})
				w	o	%OOIP	%OOIP
43 (water flooding)	2314.5	2297.6	180.8	0.08	1.0	8.6	80.06
248 (steam flooding)			42.6	0.02		30.1	53.81
Total Recovery Factor						**38.7**	

Table 4.10 Tabulated data

The table shows the recovery factor increasing by using steam flooding more than water flooding (cold production). Therefore the residual oil saturation reducing by using Steam flooding.

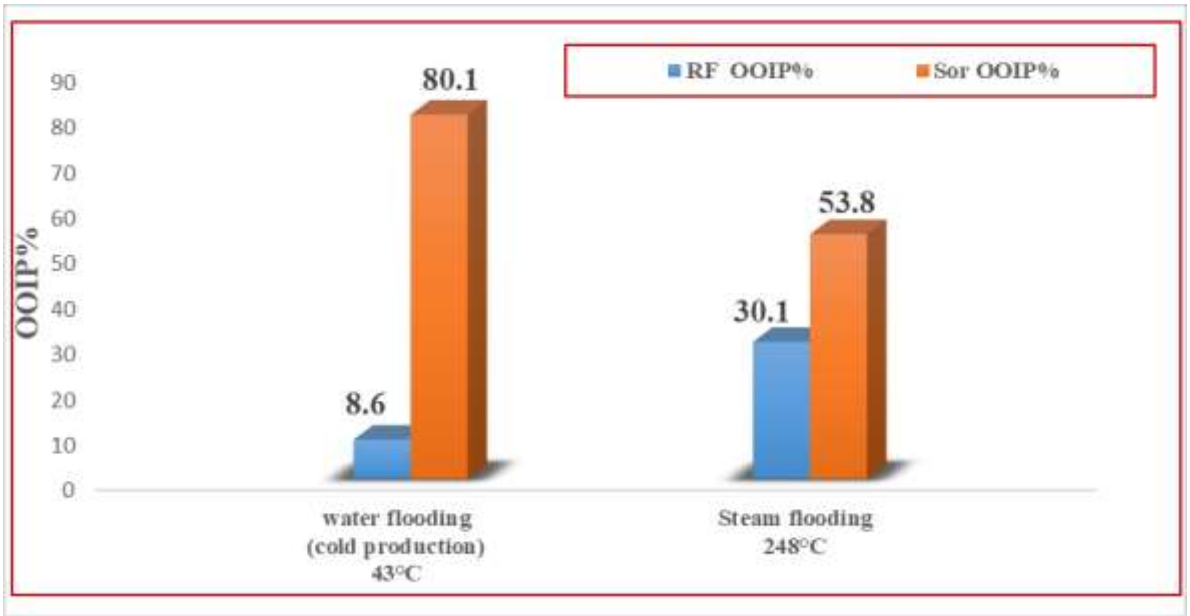

Figure 4.13: Recovery Factor (R.F) and Residual Oil Saturation (S_{or})

Figure 4.14 shows the core sample (9B) after dismounting from the core holder after the steam flooding experiment is finished.

Figure 4.14: Sample (9B) after Steam Flooding

CHAPTER FIVE
CONCLUSION AND RECOMMENDATION

The experimental study done aimed to investigate the effect of Steam flooding in core flood system for reducing viscosity and increasing oil recovery of FNE field.
Steam injection test was performed on a real core sample (9B) from Sudanese heavy oil field (FNE) well FNE-135 under same reservoir condition.

5.1 CONCLUSION

The experimental of steam flooding in core scale showed the following results:

- The oil viscosity decreasing from 2019cp at reservoir temperature 43° C to 1.5cp due the steam injection, which the mobility ratio was improved.
- The residual oil saturation S_{or} reducing from 80.1% by water flooding to 53.8% by steam injection.
- The recovery factor RF increasing by steam flooding from 8.6% to 30.1%.
- The displacement sweep efficiency ED improved from 9% by cold production to 38% by steam flooding.
- The experiment shows clear incremental in formation volume factor due to effect of the steam injection compared to cold production.

5.2 RECOMMENDATION

- Steam distillation can effectively enhance heavy oil recovery during steam injection process in heavy oil reservoirs. However, the mechanism of steam distillation is complex, and the changes in oil properties during distillation remain unclear so we need more study the gas drive mechanism by steam in term of Vaporizing and distilling condensable hydrocarbon in the Fual North East crude oil.

- In terms of sandstone reservoirs that contain much amount of feldspar and clays, the temperature degrees should not exceed 250° C if we use steam injection for long period (not continuous).This is because the feldspar and the clays will change to other minerals by chemical reaction that block pore spaces, So we need more studies like sedimentology and petrography.
- By steam flooding in Fula North East, we can improve sweep efficiency and mobility ratio by reducing oil viscosity, but the recovery factor still low additionally, we can use polymer flooding to increase water viscosity and thus get more oil out of the reservoir and increasing the recovery factor.
- Further, the steam flooding laboratory data should be run in simulation modeling for Quality Control (QC) of the results.

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