Sudan University of Science and Technology
College of Petroleum Engineering & Technology
Petroleum Engineering Department

Experimental Study of the Effect of Salinity and Relative Permeability on Water flooding
Case Study: X Sudanese Oil Field

دراسة معملية لتأثير الملوحة والنفاذية النسبية على الغمر المائي

دراسة حالة: X حقل نفط سوداني

This dissertation is submitted as a partial requirement of

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الأيـة

بسم الله الرحمن الرحيم

قال تعالى:

مَا عِنْدَكُمْ يَنْفَدُ ۖ وَمَا عِنْدَ اللَّهِ بَاقٍ ۗ وَلَنَجْزِيَنَّ الَّذِينَ صَبَرُوا أَجْرَهُمْ بِأَحْسَنِ مَا كَانُوا يَعْمَلُونَ

سورة النحل الآية (96)

صدق الله العظيم

DEDICATION

It differs from everyone, not because every girl likes her father, but because this man is just like heaven, this man personified me from life and white roses

My Father

Between love and mercy there is

My Mother

For those who teach me the meaning of wisdom and liability, those their smiles make me forget the black dots in my life, for the source of cool and light

My Sisters, Brothers

They will always be the shoulder that supports me and leans on it, they are the best thing that happened to me in my life

My Friends

It is not easy for us to do this work in this form without the kind, experienced and confident guidance of our supervisor:

T. Fatima Khaled

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Finally, Thanks to all our families and friends for encouragement in many moments throughout our study

Abstract:

Water flooding is the most widely used technique in secondary recovery methods in the oil industry that can affect any reservoir when applied it the efficiency of improvement of the recovery on the reservoir when water flooding is applied depend many parameters.

The objective of this study is to study and evaluate the relative permeability and analyses the effect of salinity in water flooding and calculation the recovery factor of the oil producing in sandstone reservoir.

Recent studies showed that salinity concentration of the injection is more important factor rather the amount of water injection.

Laboratory experiment had been carried to determine the recovery factor by using three sandstone core samples. four different concentrations of salinity 35*1000 ppm, 25*1000 ppm ,10*1000 ppm and 1.044*1000 ppm, respectively. was used in water flooding for the core samples.

Based on the results obtained, the highest total recovery by water flooding was 4.699% with 1.044*1000 ppm salinity, it also showed that oil recovery is increase when concentration of the salinity decrease.

Obtaining accurate relative permeability curves from core-flood experiments is imperative for characterizing a reservoir and for estimating its production capability. This paper is concerned with the unsteady-state relative permeabilities that are obtained from water-flood experiments conducted in a water-wet medium.

The effect of relative permeability on oil recovery was studied by using a base flood by formation water (FW) for each core.

Injection was continued at constant rate, pressure drop was continually monitored, and cumulative production of displacing fluid was measured as a function of time. Relative permeability of each phase was calculated independently with the JBN method. The results gave recovery factor between 44-56% from the samples.

التجريد:

غمر المياه هو الأسلوب الأكثر استخداماً في طرق الاسترداد الثانوية في صناعة النفط والتي يمكن أن تؤثر على أي خزان عند تطبيقها. تعتمد كفاءة تحسين الاسترداد على الخزان عند تطبيق الغمرعلى العديد من المعلومات.

الهدف من هذه الدراسة هو دراسة وتقييم النفاذية النسبية وتحليل تأثير الملوحة في غمر المياه وحساب معامل استخلاص الزيت المنتج في مكامن الحجر الرملي.

أظهرت الدراسات الحديثة أن تركيز الملوحة للحقن هوعامل أكثر أهمية بدلاً من أن كمية المياه المحقونة بالمختبر قد أجريت لتحديد معامل الاستعادة باستخدام ثلاث عينات أساسية من الحجر الرملي. أربعة تراكيز مختلفة للملوحة1000* 35 جزء في المليون و1000*25 جزء في المليون و1000*10 جزء في المليون و1000*1.044 جزء في المليون على التوالي. تم استخدامه في غمر المياه للعينات الأساسية.

بناءاً على النتائج التي تم الحصول عليها ، كان أعلى معدل استرجاع نتيجة غمر المياه 4.699٪ مع ملوحة 1000*1.044 جزء في المليون ، كما أظهرت زيادة استخلاص الزيت عند انخفاض تركيز الملوحة.

يعد الحصول على منحنيات النفاذية النسبية الدقيقة من تجارب الفيضانات الأساسية أمرًا ضروريًا لتوصيف الخزان ولتقدير قدرته على الإنتاج. يتم النظر في هذه الورقة مع النفاذية النسبية للحالة غير المستقرة التي تم الحصول عليها من تجارب فيضان المياه التي أجريت في وسط الماء. تم دراسة تأثير النفاذية النسبية على استخلاص النفط باستخدام الفيضان الأساسي بمياه الطبقة (FW) لكل عينة.

استمر الحقن بمعدل ثابت ، وتمت مراقبة انخفاض الضغط باستمرار ، وتم قياس الإنتاج التراكمي للسائل المزاح كدالة للوقت. تم حساب النفاذية النسبية لكل مرحلة بشكل مستقل باستخدام طريقة (JBN). اعطت النتائج معامل استرجاع بين 44-56% من العينات.

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Nomenclature

Ø= Porosity, %

V_g= Grain volume, cc

V_d = Deal volume, cc

V_c= Cup volume, cc

V_b= Bulk volume, cc

W_{brine}= Water brine

W_{sat}, = Water saturation, %

W_{dry}= Water dry,

ρ_{brine}=Density brine,

Q= Flow rate, STB/day

P= Pressure, Pisa

L= Length, ft

K= Permeability, md

A= Area, across

N= Nitrogen, poise

So_r= Residual oil saturation, %

K_w= Water permeability,

S_w = Water saturation, %

Sw_i= Initial water saturation, %

$S_o = Oil\ saturation$, %

$Kr_o = Residual\ oil\ permeability$, md

$Kr_w = Residual\ water\ permeability$, md

RF= Recovery Factor, %

$\mu_o = Oil\ viscosity, cp$

$\mu_w = Water\ viscosity$, cp

V_w= Water pore volume, cc

V'_w = Average water volume, cc

V_p= Pore volume, cc

V_o= Oil pore Volume, cc

V'_o = Average oil volume, cc

$P*_o$= Fixed oil pressure used for direct SCAL algorithm (dimensionless)

$P*_w$= Fixed water pressure used for direct SCAL algorithm (dimensionless)

t_{BT}= Time at breakthrough, sec

T= Time, sec

P'= Average pressure, Pisa

N= Nitrogen, poise

JBN= Jonson-Bossler-Naumann

FW= Formation Water

SFW= Simulated Formation Water

Chapter 1

1.1 INTRODUCTION:

It has become increasingly necessary to produce oil field more economically and efficiency as a result of the ever-increasing demand for petroleum worldwide .since a significant number of prominent oil fields are mature field and the number of new discoveries per year is decreasing .it is become more imperative to use secondary oil recovery processes .

Over the years, water flooding has been most widely used secondary oil recovery method after the exhaustion of the primary depletion energy of the reservoir (Craft and Hawkins 1991). Water flooding basically involves pumping water through an injection well in to the reservoir.

The water then forces itself through a pore space and sweeps the oil toward another set of wells known as producer .as a result there is an increment in the total oil production from the reservoir (Precious Ogbeiw, et al 2017).

Water is an efficient agent for displacing light or medium gravity oil in a relatively homogeneous formation where high permeability channels are not encountered.

The efficacy of the displacement depends on many factors; one of the most important properties needed to make a water flood prediction is the water-oil relative permeability. it`s important for estimating the flow of reservoir fluids.

The results from core floods need to interpret to determine relative permeability, the conventional Johnson Bossler and Naumann (JBN) interpretation method use oil production and pressure drop data to calculate relative permeability.

Water flooding has been applied as secondary recovery method with no or little regard to the effect of the injected water salinity on oil recovery.

In recent years, the water injection process is being rigorously studied experimentally by assessing the impact of water chemical modification on the final oil recovery. However, modification of the water composition has shown to be an excellent way to increase oil recovery from both sandstones and carbonates. This study aims to investigate the effects of injected water salinity on oil recovery.

1.2 Problem statement:

In X West block Sudanese field oil production decreased due to reservoir pressure decline. This research is an evaluation of recovery in sandstone formation by difference salinities water flooding using laboratory cores. Specifically, investigation whether low-salinity water flooding after high salinity water injection can improve oil recovery from reservoir.

1.3 Objectives:

1. To displace more oil from the reservoir and increase the ultimate recovery of oil.
2. To determination the relative permeability the water flooding experiment.
3. To obtaining accurate relative permeability curves from core-flood experiments for characterizing a reservoir and for estimating its production capability.
4. To measure the overall pressure and cumulative production of displacing the effluent phase ratio versus time during two-phase displacements by using JBN method.
5. To investigate the effects of the water salinity on oil recovery

1.4 Methodology:

Starting by preparation the samples and fluid, then the conventional core analysis used measurement porosity and permeability lab experiment. Then saturated the samples with brine. Used measurement stablishing Swi, start water flooding experiment and then calculate recovery factor, relative permeability curves used CYDAR software. After that was used different salinity.

Chapter 2

Literature Review & Theoretical Background

2.1 Literature Review:

2.1.1 Relative Permeability:

The results of Islam and Bentsen (1986) depicted an increase in the effective permeability of water with the flow rate and a decrease in the effective permeability of oil.

Peters and Khataniar (1987) conducted constant-rate experiments in sand-packs and they reported seeing an increase in the relative permeability of water curves and a decrease in the oil curves with increase in the flow rate.

Mohanty and Miller (1991) also observed an increase in the relative permeability of water curve with increases in the flow rate; experiments were conducted on a consolidated core.

Chang, Mohanty, Huang and Honarpour (1997) used consolidated cores and reported a difference in the relative permeability of oil curve between the two flow rates that were used in their experiments.

Marcelo M. Kikuchi, Celso C.M Branco,Euelides J. Bonet, Rosangela M.Zanoni, Carlos M. Paiva(2005) comparison of oil/water relative permeability curves measured by unsteady state and steady state methods in rock samples.

LIAN Peiqing, CHENG Linsong and LIU Lifang (2011) Conducted experiments on the oil-water relative permeability of carbonate cores from the carbonate reservoir and compared differences in the relative permeability curve between natural matrix cores and artificial fracturing cores. The experiment result shows that after the fracturing process the oil-water relative permeability curve rises or drops more dramatically, the relative permeability at the isopotal point gets higher, the saturation of remaining oils gets bigger, a two-phase flow area of the tested cores becomes narrower and the final displacement recovery efficiency decreases.

Mahesh Ediriweera and Britt M. Halvorsen (2015) this research is done to investigate the influence of the relative permeability on oil recovery. Simulations are done for different relative permeability curves and various residual oil saturations. The main focus is the impact on total flow rates and water breakthrough time. Results show that the total oil production and the water breakthrough time are strongly affected by the relative permeability and residual oil saturation. The impact of relative permeability is much higher than the residual oil saturation in petroleum processing.

Walid Mohamed, Saber Elmabrouk and Hisham Khaled (2017) three core plugs of different petro physical properties were used to conduct core flooding tests where the variations in oil residual saturation and oil-water relative permeability were measured and compared with JBN, Person's correlation and Corey's model. Relative permeability and residual oil saturation obtained by Person's correlation were lower than those of JBN and Corey's model. It was observed that as core plug permeability increases, water breakthrough slightly increases.

Obinna Ezeaneche, Monica Wobo, Chidinma Uzoho and M.O. Onyekonwu (2020) studied the impact of altering end point saturation on relative permeability curve and how it influences oil recovery was investigated. The study reveals the need for an accurate determination of residual oil saturation as it was seen to have an impact on forecast and history match.

2.1.2 Salinity:

G. Tang and N. R. Morrow (1999), some of the remaining oil, which has a negative charge, is stuck on the positively charged clay surface. The additional oil production is associated to the release of these oil droplets that are attached to clay particles.

P. L. McGuire *et al.*, (2005), Pilot tests were conducted on two Alaskan fields and both showed positive impact of low salinity water. The injection water was switched to low salinity water while production was closely monitored from a nearby producer. The production wells from both tests showed an increase in oil production as soon as the low salinity water breakthrough occurs. Production rates doubled on the first year. The reduction in oil saturation in one of these tests was measured to be 10% compared to lab prediction of 13%.

A. Lager, K. J. Webb, and C. J. Black, (2009) Reducing water salinity in sandstone reservoirs has been demonstrated to be a very effective way to recover more oil. Successful core flooding experiments showed an increase in oil recovery of 5%-20% when water salinity is lower than 5 k ppm.

A. Yousef et al., (2012) A pilot test was conducted under similar conditions on a well located on an area flooded with seawater. A slug of twice diluted water was injected followed by another slug of ten time's diluted water. Oil saturation was monitored at each staged using a tracer and it showed a reduction of oil saturation units by 3% and 6%, respectively.

H.H. Al-Attar, M.Y. Mahmoud, A.Y. Zekri, R. Almehaideb, M. Ghannam (2013) presents the results of flooding tests on selected carbonate core samples. The field injection waters were diluted to salinities of 5000 and 1000 ppm and the optimum salinity was determined and then modified by varying the sulfate and calcium ion concentrations. The experimental results revealed that a significant improvement in the oil recovery can be achieved through alteration of the injection water salinity. Reducing the salinity of water from 197357 to 5000 ppm resulted in an improvement of oil recovery from 63-84.5 %.

T.s.E. Chavez-Miyauchi, A. Firoozabadi, G.G. Fuller (2016) Investigate interfacial viscoelasticity of two different oils in terms of brine concentration and a nonionic surfactant. Oil recovery increases by 5-10 % low salinity brines. By using a small amount of a nonionic surfactant with high salinity brine, oil recovery is enhanced 10% with no pressure fluctuations.

Dwiky Pobri Cesarian (2019), Laboratory experiment had been carried out to determine the recovery factor by using sandstone core. Sodium Chloride (NaCl) was used to control the salinity concentration in water flooding with range of 1000-14000 ppm. Based on the results obtained, the highest total oil recovery by water flooding was 57.8% with 4000 ppm as the optimum salinity, which 14.6% higher than oil recovery by 14000 ppm. The results also showed the change in end-point value of relative permeability. It also showed that water cut tend to increase as the salinity increase, while breakthrough time tend to decrease as the salinity increase.

2.2 Theoretical background:

2.2.1 Introduction:

In the primary recovery phase of oil production both gravity and the natural pressure of the reservoir drive oil into the production well. Typically, only about 10% of the original oil in the reservoir can be produced in the primary recovery phase.

During primary recovery, water that exists naturally in the oil reservoir is produced alongside the oil. Upon reaching the surface, the produced oil and water are separated. The oil is held in storage tanks and then transported for sale. The water, or oilfield brine, is held in a storage tank for later use.

Once the pressure in the reservoir has begun to drop, it is necessary to utilize secondary recovery techniques to continue to produce oil from the reservoir at an economical rate.

Secondary recovery techniques will help maintain the pressure in the reservoir and extend a well's productive life. One of the most common secondary techniques, water flooding, uses the injection of water into the reservoir to drive more oil towards the production well. Water injection is used to prevent low pressure in the reservoir the water replaces the oil which has been taken, keeping the production rate and the pressure the same over the long term.

Tertiary oil recovery is considered if cost to production ratio of secondary oil recovery process becomes no longer economical. The ultimate target of tertiary oil recovery, also known as enhanced oil recovery (EOR) is to improve the overall oil sweep efficiency. In EOR processes, the recovery factor increases to about 30-60% (Sino Australia Oil and Gas Ltd, 2013). An EOR process increases hydrocarbon production by altering formation properties (Needham and Doe, 1987).

2.2.2 Water flooding:

Water flooding is the most widely used fluid injection process in the world today. It has been recognized since 1880 that injecting water into an oil-bearing formation has the potential to improve oil recovery. However, water flooding did not experience field wide application until the 1930s when several injection projects were initiated, and it was not until the early 1950s that the current boom in water flooding began. Water flooding is responsible for a significant fraction of the oil currently produced in the United States. Many complex and sophisticated enhanced recovery processes have been developed through the years in an effort to recover the enormous oil reserves left behind by inefficient primary recovery mechanisms. Many of these processes have the potential to recover more oil than water flooding in a particular reservoir. However, no process has been discovered which enjoys the widespread applicability of water flooding. The primary reasons why water flooding is the most successful and most widely used oil recovery process are:

1. General availability of water
2. Low cost relative to other injection fluids
3. Ease of injecting water into a formation
4. High efficiency with which water displaces oil

2.2.2.1The efficiency of improvement of the recovery on the reservoir when water flooding is applied depends on the following parameters:

1. Depth of Reservoir:

The depth of the reservoir can affect the water flooding greatly. So, as the reservoir depth increases, the pressure required for injection increases.

2. Fluid Saturation:

Water flooding depends on the amount of oil existed in the reservoir. As the saturation of oil is high in the reservoir, the water flooding can apply in order to get more oil and increase the ultimate recovery of oil. While, as the saturation of oil in the reservoir is low, water flooding design will be unsuccessful.

3. Reservoir Geometry:

The geometry and shape of formation have a great effect on the water flooding efficiency. Because the reservoir geometry can indicate how many wells can be drilled, where the location of wells and the type of pattern is for the reservoir that will control the recovery efficiency.

5. Uniformity of Reservoir and Continuity of Reservoir:

The success of water flooding technique is determined by the extension of the reservoir and the length of san cannel in the reservoir.

6. Fluid Properties:

Properties of reservoir fluid in order to know the type of fluid in the reservoir and the quality of oil; heavy oil or light oil, these properties will be measured and make the experimental analysis for the reservoir fluids before starting water flooding technique to be capable to displace oil from the reservoir and ensure the success of project.

7. Rock Properties and Reservoir Criteria:

The rock properties effect on the efficiency of water flooding. Core data such as rock porosity, rock permeability with fluid saturation can affect greatly on project success (El-hoshoudy AN, et al 2019).

2.2.2.2 The variables which usually have the greatest impact on water flood behavior:

Water flood recovery is dependent on a number of variables. The variables which usually have the greatest impact on water flood behavior are listed below:

1. Oil saturation at the start of water flooding, S_o
2. Residual oil saturation to water flooding, $So_r(Sor_w)$
3. Connate water saturation, Sw_c
4. Free gas saturation at the start of water injection, S_g
5. Water floodable pore volume,V_p, BBLS (This takes into account the permeability or porosity net pay discriminator).
6. Oil and water viscosity, μ_o *and* μ_w.
7. Effective permeability to oil measured at the immobile connate water saturation, $K_o(Swi_r)$.
8. Relative permeability to water and oil, Kr_w *and* Kr_o.
9. Reservoir stratification, (Dykstra-Parsons coefficient, V)
10. Water flood pattern (symmetrical or irregular).
11. Pressure distribution between injector and producer.
12. Injection rate, BWPD.
13. Oil formation volume factor, B_o.
14. Economics.

2.2.3 Relative permeability:

Relative permeability is an essential Petro-physical property required for description of multi-phase flow in petroleum reservoirs. It is a direct measure of the ability of the porous medium to produce one fluid when two or more fluids are present. This flow property is the result of the composite effects of porosity, pore geometry, wettability, saturation history, reservoir temperature, reservoir pressure, and overburden pressure and rock type.

The relative permeability curves are very important in the study of reservoir productivity. They are used in predicting production rate and recovery from the reservoir during all recovery stages (primary, secondary, and tertiary).

There are two basic approaches for determination of relative permeability curves from laboratory core flow tests: steady and unsteady state method. In the steady – state method, the fluids are injected simultaneously into core plugs. In the unsteady- state method, a fluid is injected to displace another fluid present in the plug.

2.2.3.1 Common uses of relative permeability data:

1. Evaluation of residual saturations and displacement efficiency for water flooding.
2. Evaluation of flow characteristics in multiphase reservoir situations.
3. Prediction of reservoir performance and recoverable reserves.
4. Reservoir optimization for primary, secondary, and tertiary depletion operations.

2.2.3.2 Steady state method:

In steady state method, two immiscible fluids are injected co-currently at a specific ratio through the core until the same production ratios are achieved from the outlet of the core. In this method, the relative permeability values can be calculated directly using Darcy’s law. Although a steady-state test facilitates the direct determination of ***k*** r curves, it is a very time-consuming and costly method with some limitations such as neglecting capillary effects, one-dimensional flow in the core, and isothermal and incompressible fluid. Moreover, the ratio of the injected fluids is not technically allowed to be less than a certain value, hence the relative permeability at low saturations cannot be measured. An alternative technique for determining the relative permeability values is the unsteady-state method (Cinar et al. 2007).

2.2.3.3 Unsteady state:

Unsteady-state method which is much quicker than the steady-state test. In the unsteady-state test, one fluid (which is immiscible with the fluid in the core) is injected through the core to displace the resident fluid inside the core. Then the fluid production and pressure across the core are measured against time. Since the flow in the porous media is occurring under the unsteady-state condition, the relative permeability data cannot be obtained directly from Darcy’s equation. The production data are analyzed, and a set of relative-permeability curves is obtained using various mathematical methods.

The Buckley-Leverett equation for linear displacement of immiscible and incompressible fluids is the basis for all analyses. This equation relates the saturation levels, at each point and time, to capillary pressure, the ratio of fluid point and time, to capillary pressure, the ratio of fluid viscosities, the flow rates, and the relative permeability’s. The Johnson-Bossler-Naumann method is the most commonly used for analysis.

2.2.3.4 Overview JBN Method:

As introduced, the JBN method is a popular and fast unsteady-state method of determining relative permeability across a range of saturations (Welge, 1952; Johnson et al., 1959). An invading phase is injected into a core fully saturated with a defending phase. During the displacement, both the overall pressure drop and the effluent phase ratio are measured versus time. By applying fractional flow theory ((Buckley and Leverett, 1942) (essentially just the continuity equation) to the Darcy-Buckingham equation and a mathematical inversion, one can obtain the relative permeability’s to both the defending phase (d) and the invading phase (I) at the core outlet. Two main assumptions are stable displacements and incompressible fluids, which can be satisfied by maintaining a high flow rate and a high experimental pressure. The JBN method also assumes no capillary or gravitational forces.

2.2.4 Effect of Water Salinity:

Modifying water salinity to increase oil recovery is a relatively new method that could be applied in many oil fields to unlock millions of barrels of oil. Seawater and saline aquifers are typical sources of water in conventional water injection projects. Several studies, supported by field tests, suggest that additional oil can be recovered by reducing salinity and/or adding some key ions to the water salts. Oil reservoirs are classified into sandstones and carbonates and each has relatively different properties and characteristics. Modifying water salinity could impact oil recovery in both types although the mechanism and approach could be different (Mohammed Alshakhs, 2013).

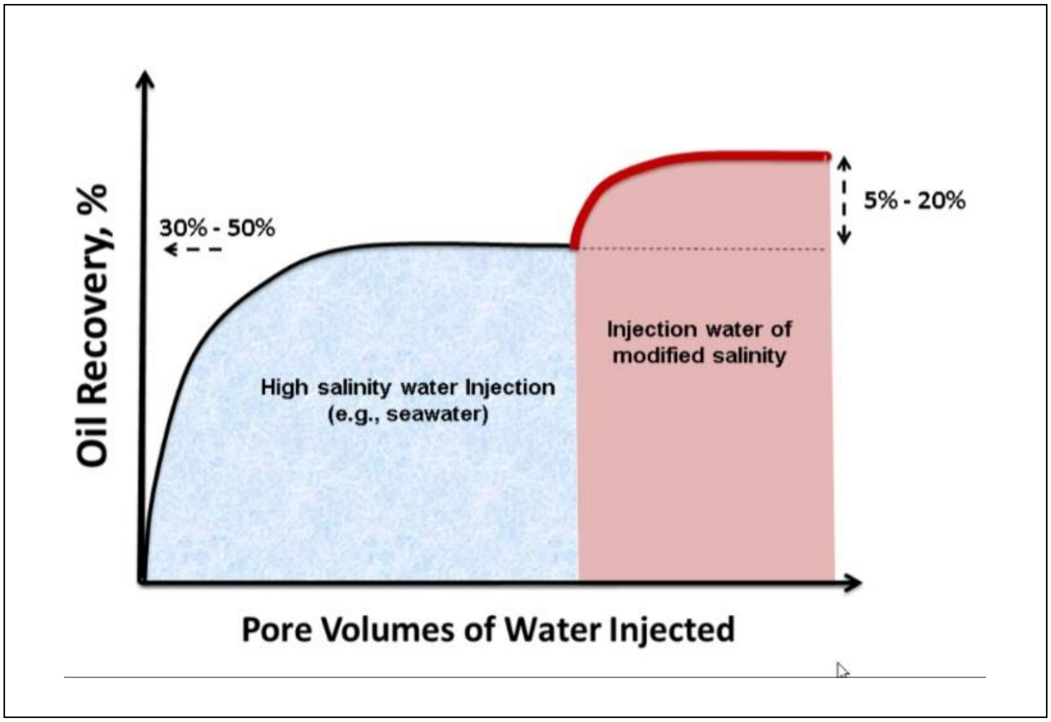


Figure 2.1: schematic of oil recovery profile showing the impact of modifying water salinity.

Schematic of oil recovery profile showing the impact of modifying water salinity. A typical recovery range of high salinity water injection is 30-50%. Modified water could be injected after production plateau is reached. The new water could increase incremental recovery by 5-20%.

Chapter 3

Methodology

3.1 Experimental Material:

3.1.1 Crude Oil:

Iso bar oil used in this experimental with viscosity 1.565 cp.

3.1.2 Sample Preparation

The core is put in cutting machine to slapping it. plugging the core by plugging machine after showering it, put core in Trimming to become like cylindrical form and finally the Soxhlet method was utilized as a method of cleaning.to clean the core plugs is put in Methanol and Toluene. Then put core in furnace to drying.

3.1.3 Fluid Preparation:

Simulated formation water (SFW) will made according to the formation water salinity (ppm) provided by X field given in **Tale 3.1** Before use, the SFW was filtered through a 0.45 µm filter and degassed then density and viscosity was measured.

Iso bar oil sense tic was used to establishing Sw_i for preparing before water flooding experiment

Table3.1: Concentrations of Ions in Water

Na^+	389.7
Ca^{2+}	4.79
Mg^{2+}	0.77
K^+	9.6
SO_4^{2-}	12.49
HCO_3^-	565.7
Cl^-	18.43

Table3.2: Fluid Properties Used in the Core-flood Test

Brine Density (g/cm^3)	0.999
Brine Salinity (g/l)	1.044
Oil Viscosity (cp)	1.2
Oil Density (g/cc)	0.96
Brine viscosity (cp)	1

3.2 Description the component of the experiments:

3.2.1 Distiller:

Water stills, also called laboratory water distillers, heat water to a volatile vapor phase thus separating it from nonvolatile impurities. Distilled water systems remove more than just charged ions-they can filter out microbes, nonvolatile organic compounds, most minerals, and many chemicals.

Figure 3.1: Distiller

3.2.2 Tarre weight:

It’s an accurate scale in which the salts that are used in the preparation of brine are weighed.

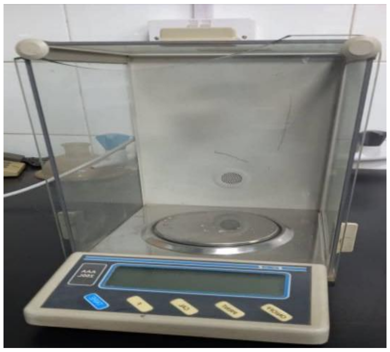


Figure 3.2: Tarre Weight

3.2.3 Stirrer:

It’s a centrifugal device with the help of a magnetic metal piece. The process of mixing brine (distilled water+ salts).

Figure 3.3: Stirrer

3.2.4 Filtration:

The distilled water is filled from the impurities in the salts and the device is connected to vacuum pump to speed up the filtration process.

Figure 3.4: Filtrated

3.2.5 Vacuum pump:

It mainly contains a vacuum pump which was affixed to evacuate the core that sited in core chamber for the purpose of water saturation.

Figure 3.5: Vacuum Pump

3.2.6 Degasser:

After stirrer put the brine in degasser by using vacuum pump for period of times appears bubble of gases absorbed this bubble of air vacuum pump.

Figure 3.6: Degasser

3.3 Conventional Core Experiment:

3.3.1 Effective porosity determination by helium porosimeter:

The helium porosimeter uses the principle of gas expansion as described by Boyle's law. A known volume (reference cell volume) of helium gas, at a predetermined pressure, is isothermally expanded into a sample chamber. After expansion, the resultant equilibrium pressure is measured. This pressure depends on the volume of the sample chamber minus the rock grain volume, and then the porosity can be calculated.

$$porosity = \frac{pore\ volume}{bulk\ volume} = \frac{bulk\ volume - grain\ volume}{bulk\ volume} \quad (3\text{-}1)$$

$$\phi = \frac{Vp}{Vb} \times 100\ \% \quad (3\text{-}2)$$

Figure 3.7: Digital Helium Porosimeter

3.3.2 Porosity Determination by Liquid Saturating:

Measuring the pore volume of plug sample from the different in its weight when dry and when saturated with brine. A clean, dry sample is weighed and then evacuated for several hours in a vacuum chamber, A de-aerated brine is introduced into the chamber and pressure to ensure complete saturation. The saturated sample is then weight again. The different in weight divided by the density of the brine is the pore volume. Also measure the weight of the sample immersed in the brine.

Figure 3.8: Check Saturation

3.3.3 Permeability Measurement:

Permeability is measured by passing N_2 through a plug sample of measured dimensions and then measuring flow rate and pressure drop. Darcy equation used for determining permeability.

$$K = \frac{Q \times U \times L}{A \times \Delta P} \qquad (3\text{-}3)$$

$$A = \frac{\pi}{4} \times D^2 \qquad (3\text{-}4)$$

Figure 3.9: Digital Gas Permeameter

3.4 Core Holder:

A portable apparatus provides on-site permeability measurements and formation evaluation by core sample extracted from an underground reservoir. Core sample: A cylindrical rock (1-1/8" to 5-1/4" diameter and 30 to 60 ft long) sample taken from the formation for geological analysis to perform laboratory evaluation of basic properties.

Figure 3.10: Core Holder

3.5 Saturator pump:

Used vacuum pump, chamber include samples. First, evacuate the system from air, even the sample after that we inject the brine in the chamber containing a sample. start with small value of pressure, after that we increase the pressure gradually. Until 2000 psi and let it overnight, we check it if on decrease in the pressure that mean they are fully saturated.

Figure 3.11: Saturator Pump

3.6 Pharmacia pump:

The High Precision Pump P-500 is the ideal solvent delivery system for general liquid chromatography and other applications where precise and constant flow at pressures from 0–4 MPa (600 psi) is required. The design features of the P-500 create a dependable laboratory instrument for use with the high-performance chromatography media for FPLC, and also provide complete compatibility with standard separation methods. Excellent chemical resistance allows the pump to be used with corrosive liquids and organic solvents. The Pump P-500 is a valuable contribution to any chromatographic application and is an integral part of the FPLC System. The characteristic of this Pump is:

1. Flow rate range 1-499 ml/h, increment 1 ml/h.
2. Pharmacia part # 19-4301-01
3. Max pressure 5.0 Mpa (750psi)

4. Old piston design
5. The maximum flow rate for the pump is 500 cc/h.

Figure 3.12: Pharmacia Pump

3.7 Pressure drop (ΔP):

Used to measure absolute permeability set the device in certain pressure and open one of three valves, open pump in flow rate after period of time then record pressure drop recycle this process in many flow rates in different period of time then record the pressure drops. Joint with Pharmacia pump.

Figure 3.13: Pressure Drop

3.8 Flooding apparatus:

Figure 3.14: The Relative Permeability System

3.8.1 Water flood Experiment Procedure:

In this research, three different plug samples taken from a Sudanese oil reservoir have 0been used to perform the unsteady state plug-flood experiments.

Water flooding tests were carried out into the plugs which were initially saturated with the oil and irreducible water (connate water). The experiments were performed at room conditions and under constant pressure drop across the plug; hence, the injection rate varies with time. The individual fluid production from the outlet of the core and the injection rate against the time were recorded as the experimental results. The detailed procedure for the experiments is described below:

1. The core plugs were cleaned with toluene and methanol through a Soxhlet extraction apparatus at 60-70 to remove residual hydrocarbons, formation brine, salts and other contaminants. They were dried in an oven at 70 for 24 h. A helium porosimeter and Gas permeameter were used to measure the porosity and permeability of the plug.
2. Each plug sample was placed in the core holder and then flooded continuously with brine using a constant pressure pump until the core was fully saturated with the brine. As fluid injection proceeds, brine injection rate is measured at different time steps if it reaches a stable constant value, the only produced fluid is brine which means the core is fully saturated with brine.
3. Crude oil was injected into the plug sample to displace the brine and establish the connate water saturation S_{wi} in the plug. The oil was injected at the representative fluid velocity in the reservoir and the flooding continued until no further brine was produced i.e., any remaining water in the plug is immobile.
4. Water was then injected to displace the oil in the plug. The cumulative oil production and fluid injection continued until no further oil was produced from the plug, i.e., residual oil saturation S_{or} was attained in plug. It should be noted that during the whole process the pressure drop across the plug was held constant.

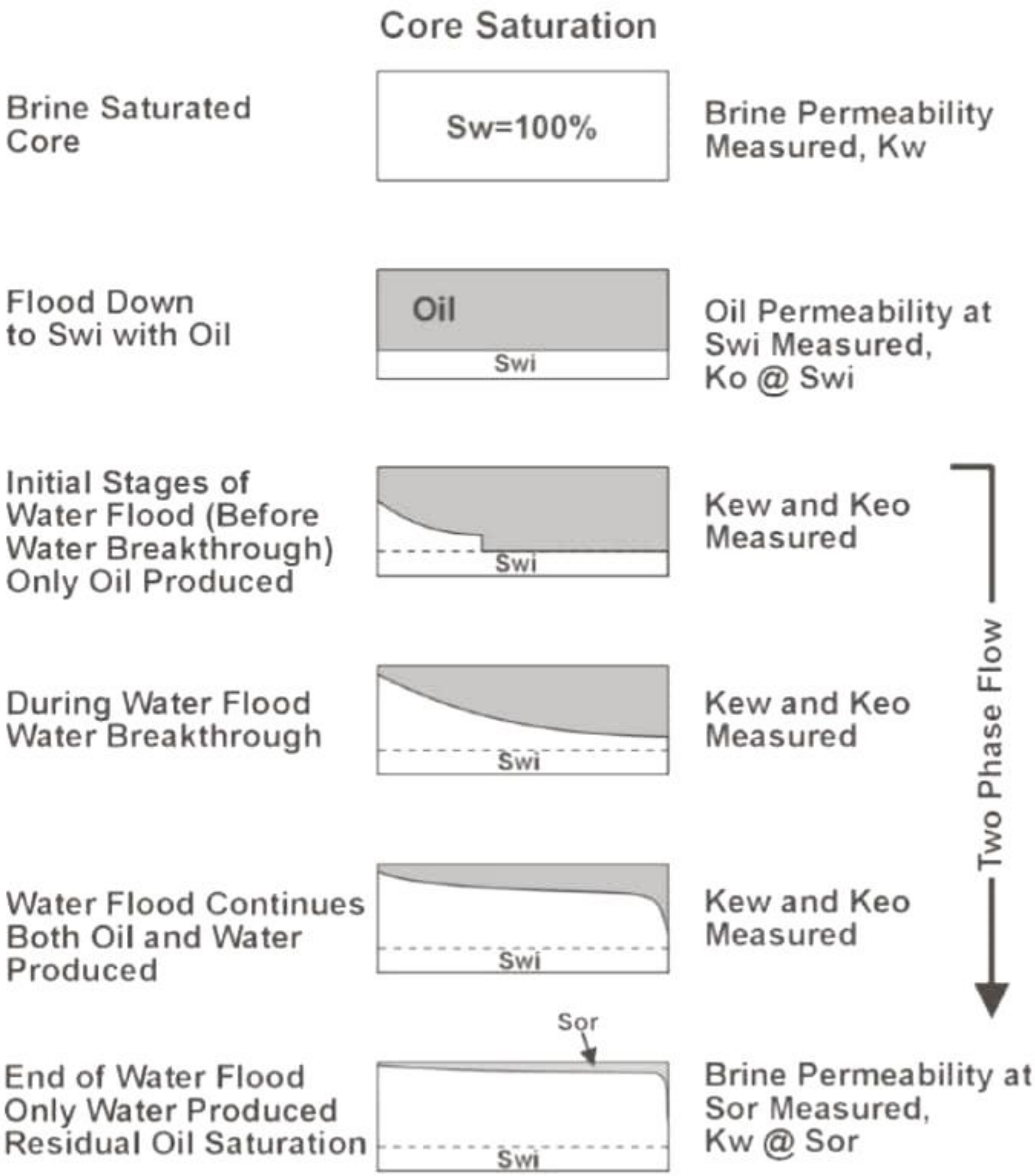


Figure3.15: Schematic of the Saturation Stead in the Plug for the Unsteady State Water flooding Test

3.8.2 Software for Core Analysis CYDAR:

Developed in collaboration with core analysis specialists, the software CYDAR offers a powerful solution for design and interpretation of conventional and special core analysis experiments. This Windows-based software is designed to be user-friendly, yet accurate and powerful. CYDAR covers a full range of experiment types, including:

- Mercury injection and withdrawal (MICP)
- Absolute permeability measurements
- Dispersion measurements
- Centrifuge (Pc and Kr) and two-phase flow experiments
- Relative permeability (steady and unsteady state)
- History matching
- Electrical measurements
- EOR – Enhance Oil Recovery
- Automatic reporting
- Data acquisition

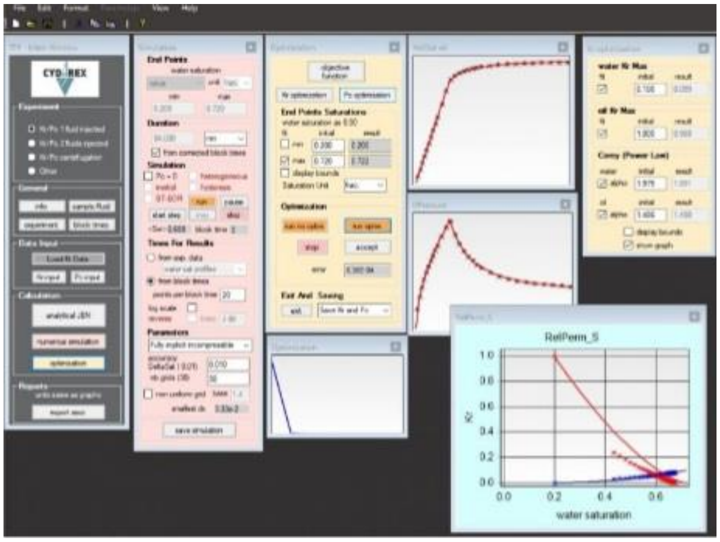


Figure 3.16: CYDAR Software Model

3.8.3 RELATIVE PERMEABILITY (JBN):

We use indices (W) for water and (O) for oil. Saturation and (Kr) are calculated at the outlet for a given time. For a constant rate without gravity effect:

$$S_w = Si_w + (tV'_w - V_w)/V_p \quad ; \quad S_o = Si_w + (tV'_o V_o)/V_p \qquad (3\text{-}5)$$

$$Kr_w = \frac{V'_w}{Q}\frac{P*_w}{P - tP'} \quad ; \; Kr_o = \frac{V'_o}{Q}\frac{P*_o}{P - tP'} \qquad (3\text{-}6)$$

The reference pressures (P*) are the pressures during flow of only water of only oil at the injection rate (Q):

$$P*_w = \frac{LQ\mu_w}{AK} \quad ; \quad P*_o = \frac{LQ\mu_o}{AK} \qquad (3\text{-}7)$$

Water volume and rate are derived from oil volume (no compressible flow):

$$V_w + V_o = Qt \quad ; \quad V'_w + V'_o = Q \qquad (3\text{-}8)$$

Saturation and (Kr) are given by:

$$S_w = Si_w + (V_o - tV'_o)/V_p \qquad (3\text{-}9)$$

$$Kr_w = \left(1 - \frac{V'_o}{Q}\right)\frac{P*_w}{P - tP'} \quad ; \quad Kr_o = V'_o \frac{P*_o}{P - tP'} \qquad (3\text{-}10)$$

Chapter 4

Results and discussion

4.1 Calculate the Helium Porosity:

Table4.1: Results of Porosity:

	Plug #1	Plug #2	Plug #3
Bulk volume (cc)	71.63	86.56	67.58
Grain volume (cc)	49.82	47.13	50.16
Pore volume (cc)	21.48	20.81	17.97
Core length (cm)	6.44	6.02	6.07
Core diameter(cm)	3.76	4.27	3.76
Porosity (%)	30.1	30.6	26.4

4.2 Calculate Air Permeability:

$$K = \frac{Q\times U\times L}{A\times \Delta P} \qquad (4\text{-}4)$$

$$A = \frac{\pi}{4}\times D^2 \qquad (4\text{-}5)$$

Range of confining 400 psi

Viscosity of N_2=0.00018 poise

Table4.2: Results of Air Permeability:

Sample	Length(cm)	Diam(cm)	P conf	P atm	P upstream (psi)	Rate(Q) %	Perm(md)
1	6.44	3.76	400	750	1.18	59.59	2374.432
2	6.02	4.27	400	750	1.03	27.77	923.935
3	6.07	3.76	400	750	4.14	13.81	13.576

4.3 Calculate Saturation Quality Check:

$$W_{brine} = W_{sat} - W_{dry} \qquad (4\text{-}1)$$

Calculate the pore volume (saturated brine volume):

V_p = Wsat – Wsat in sat / ρbrine (4-2)

Calculate porosity:

$\phi = V_p / V_b$ (4-3)

Table4.3: Sample Saturation Quality Check Results:

Sample	W_{dry}	W_{sat} in air	W_{sat} in sat	Sat %	Porosity %
1	144.67	166.92	89.12	96.39	30.1
2	136.77	157.61	84.49	97.90	30.6
3	145.57	163.59	90.36	97.14	26.4

4.4 Calculate Recovery Factor:

4.4.1 Connate water saturation:

$$S_{wi} = \frac{pore\ volume\ -(water\ volume\ -dead\ volume)}{pore\ volume}\ \text{x}100\% \quad (4\text{-}6)$$

Dead volume = 2.163 cc

4.4.2 Initial oil saturation:

$$S_{oi} = 1 - S_{wi} \quad (4\text{-}7)$$

4.4.3 Residual oil saturation:

$$S_{or} = \frac{Initial\ oil\ volume - Production\ oil}{Pore\ volume} \text{x}100 \quad (4\text{-}8)$$

4.4.4 Recovery factor:

The recovery factor is calculated from the ratio between expected ultimate recovery and original oil in place.

$$RF = \frac{S_{oi} - S_{or}}{S_{oi}} \quad (4\text{-}9)$$

Table 4.4: Calculate Recovery Factor:

Sample	Produce Volume of water(cc)	Initial water saturation (%)	Initial oil saturation (%)	Residual oil saturation (%)	Recovery factor (%)
1	18.13	25.70	74.30	34.85	53.35
2	17	28.23	71.77	31.64	55.91
3	14.48	30.78	69.22	38.16	44.87

Table4.5: Different Salinity Water Flooding Results Plug#1:

salinity, ppm*1000	injection vol. as (PV)	incr of oil,cc	incr.RF %	cum. RF%
35	25	0	0.000	0.000
25	25	0.05	0.313	0.313
10	25	0.325	2.036	2.350
1.044	25	0.75	4.699	7.049
Total	**100**	**1.125**	**7.049**	

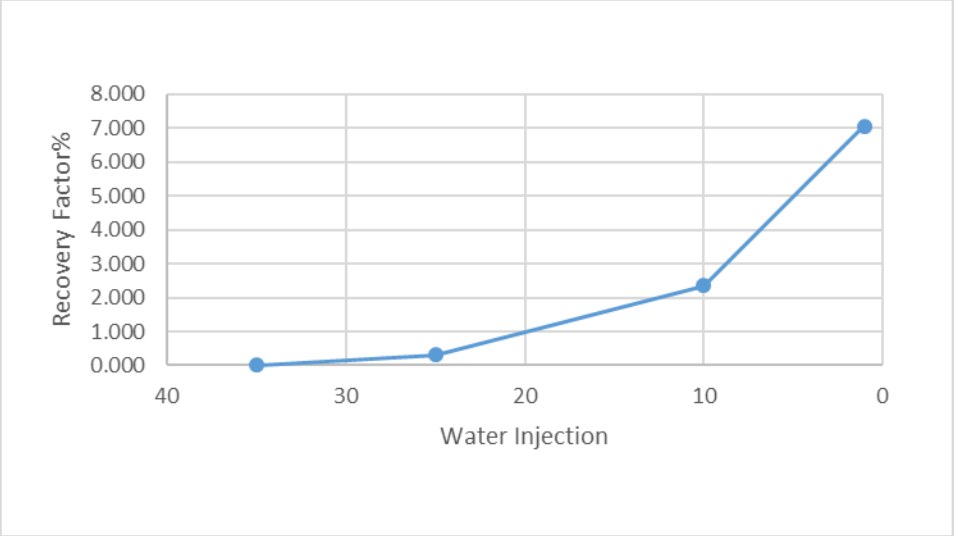


Figure4.1: Oil Recovery from Water Injection Plug #1

Table4.6: Different Salinity Water Flooding Results Plug#2:

salinity, ppm*1000	injection vol. as (PV)	incr of oil,cc	incr.RF %	cum. RF%
35	25	0	0.000	0.000
25	25	0	0.000	0.000
10	25	0.15	1.004	1.004
1.044	25	0.55	3.683	4.687
Total	**100**	**0.7**	**4.687**	

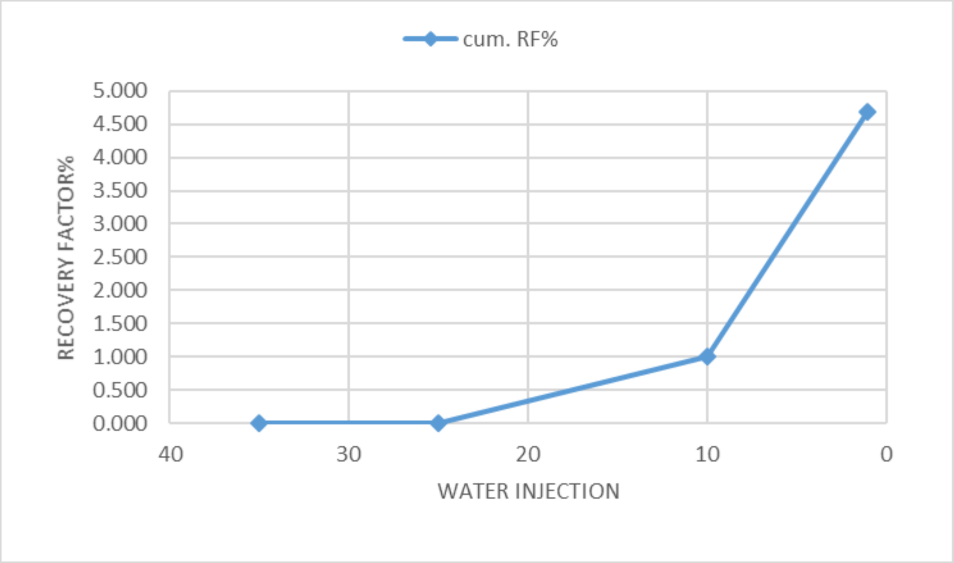


Figure4.2: Oil Recovery from Eater Injection Plug #2

Table4.7: Different Salinity Water Flooding Results Plug#3:

salinity, ppm*1000	injection vol. as (PV)	incr of oil,cc	incr.RF %	cum. RF%
35	25	0	0.000	0.000
25	25	0	0.000	0.000
10	25	0.05	0.402	0.402
1.044	25	0.15	1.206	1.608
total	**100**	**0.2**	**1.608**	

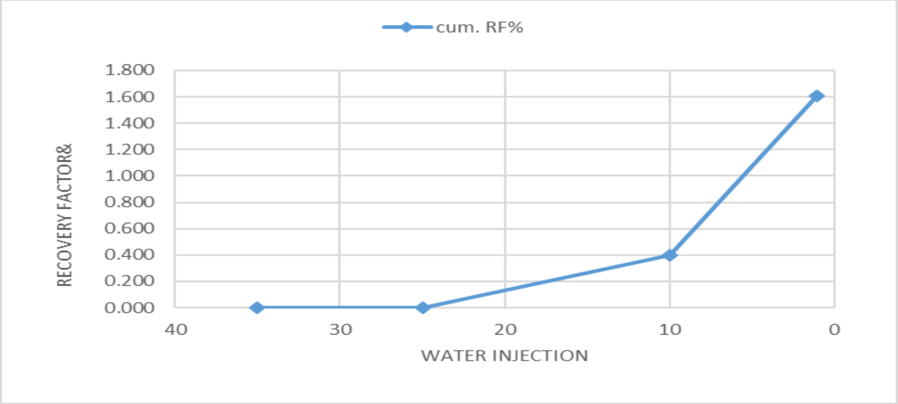
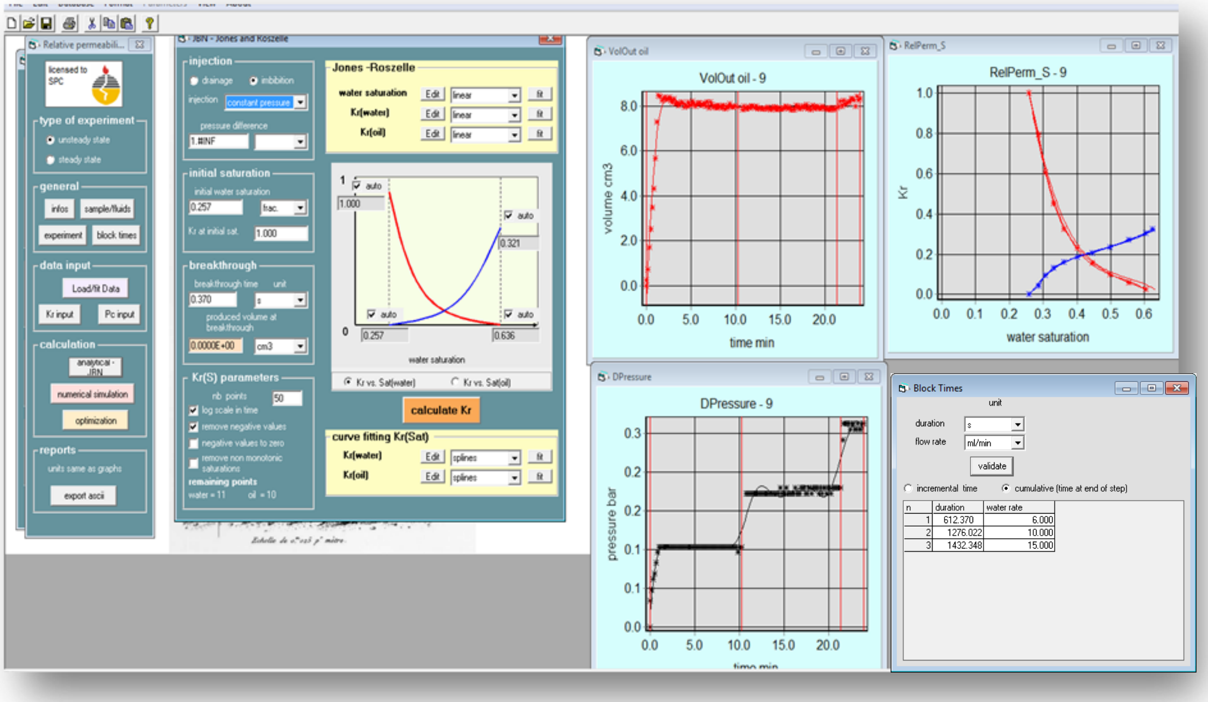


Figure4.3: Oil Recovery from Water Injection Plug #3

Table4.8: Summery of Relative Permeability End Point Results:

Property	Plug # 1	Plug # 2	Plug # 3
Depth (m)	1732.50	1733.58	1738.78
Porosity (%)	30.1	30.6	26.4
Permeability (md)	2284	884	10.7
Core length (cm)	6.44	6.02	6.07
Core diameter (cm)	3.76	3.78	3.76
Connate water saturation Sw_i (%)	25.70	28.23	30.78
Residual oil saturation Sor (%)	34.85	31.64	38.16
$K_o@Sw_i$	1729	622	11.4
$K_w@So_r$	27.83	99.5	1.14



injection: ○ drainage ● imbibition

injection: constant pressure

pressure difference: 1.#INF

Jones -Roszelle: water saturation linear; Kr(water) linear; Kr(oil) linear

initial water saturation: 0.257 frac.

Kr at initial sat.: 1.000

breakthrough time: 0.370 unit: s

produced volume at breakthrough: 0.0000E+00 cm3

nb points: 50

☑ log scale in time

☑ remove negative values

☐ negative values to zero

☐ remove non monotonic saturations

remaining points water = 11 oil = 10

☑ auto 1.000 ☑ auto 0.321 ☑ auto 0.257 ☑ auto 0.636

● Kr vs. Sat(water) ○ Kr vs. Sat(oil)

curve fitting Kr(Sat): Kr(water) splines; Kr(oil) splines

Block Times

duration: s

flow rate: ml/min

○ incremental time ● cumulative (time at end of step)

n	duration	water rate
1	612.370	6.000
2	1276.022	10.000
3	1432.348	15.000

Figure4.4: CYDAR Model JBN method Plug No.#1

Table4.9: Unsteady State Relative Permeability Plug#1:

Sw	Kro	Krw
25.7	0.7960	0.000
28.7	0.6070	0.043
30.7	0.4510	0.094
33.1	0.3270	0.133
36.2	0.2290	0.163
40.0	0.1550	0.186
44.6	0.1010	0.208
49.7	0.0590	0.236
55.3	0.0250	0.273
60.4	0.0000	0.303
62.4	0.0000	0.324

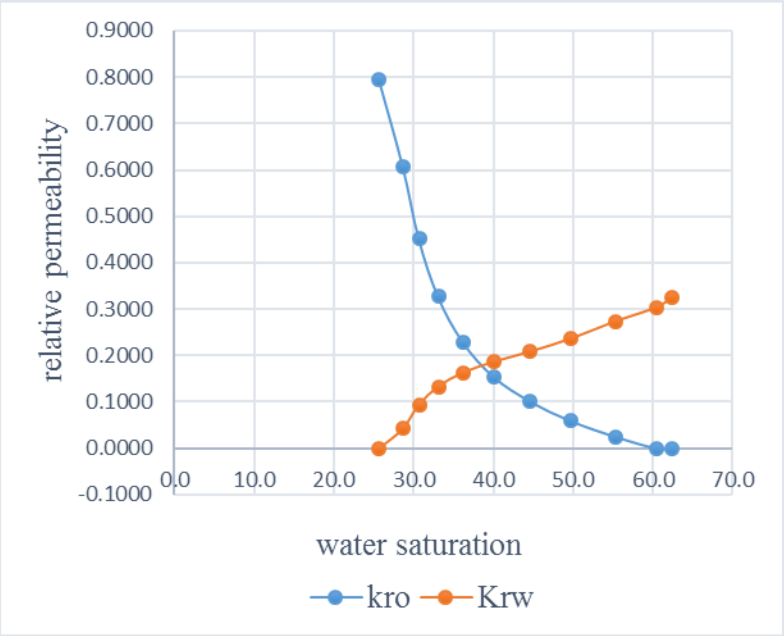


Figure4.5: Relative Permeability Curve Plug #1

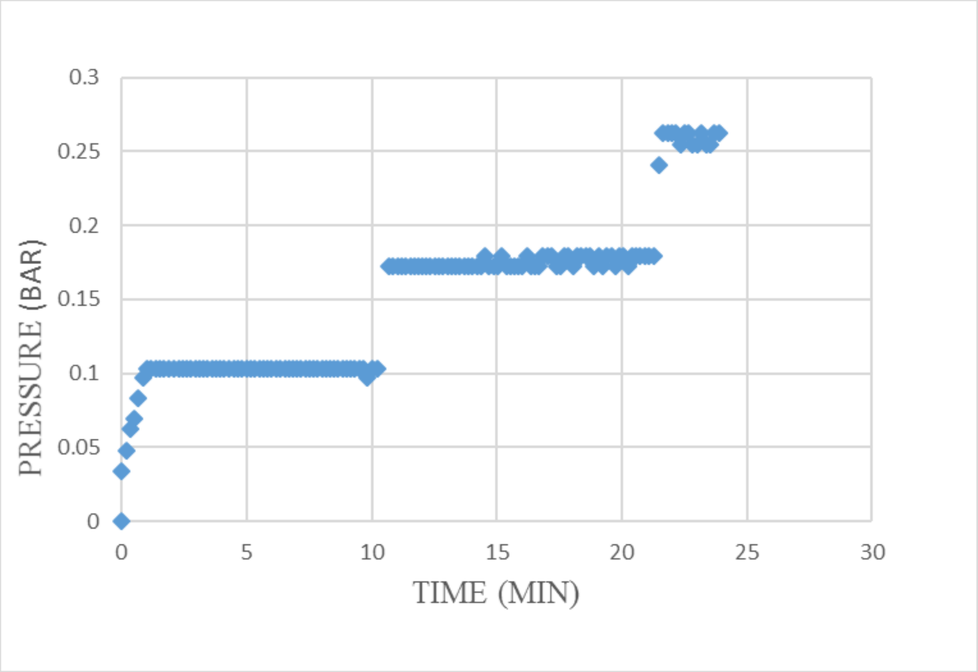


Figure4.6: Pressure as a function of time Plug #1

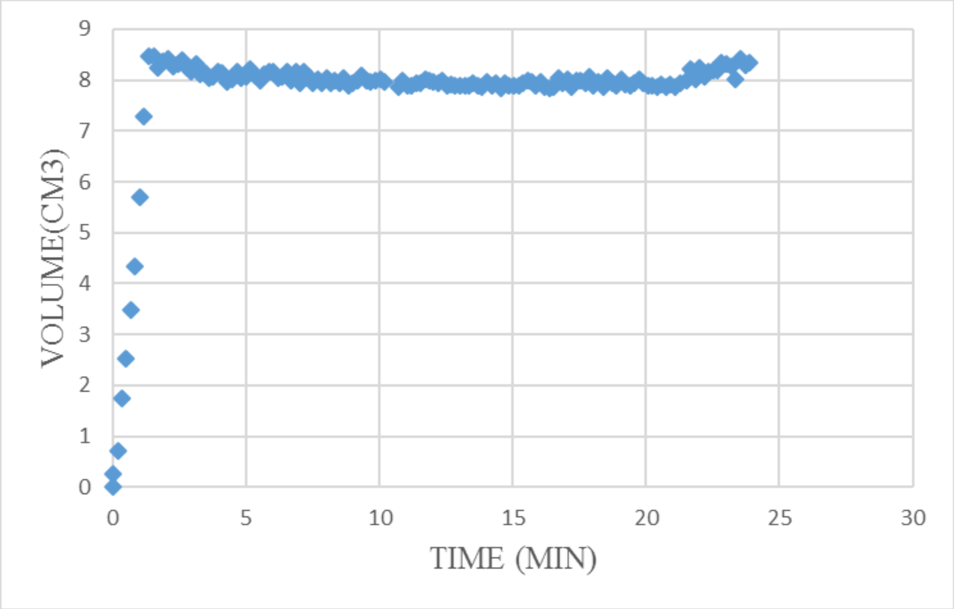
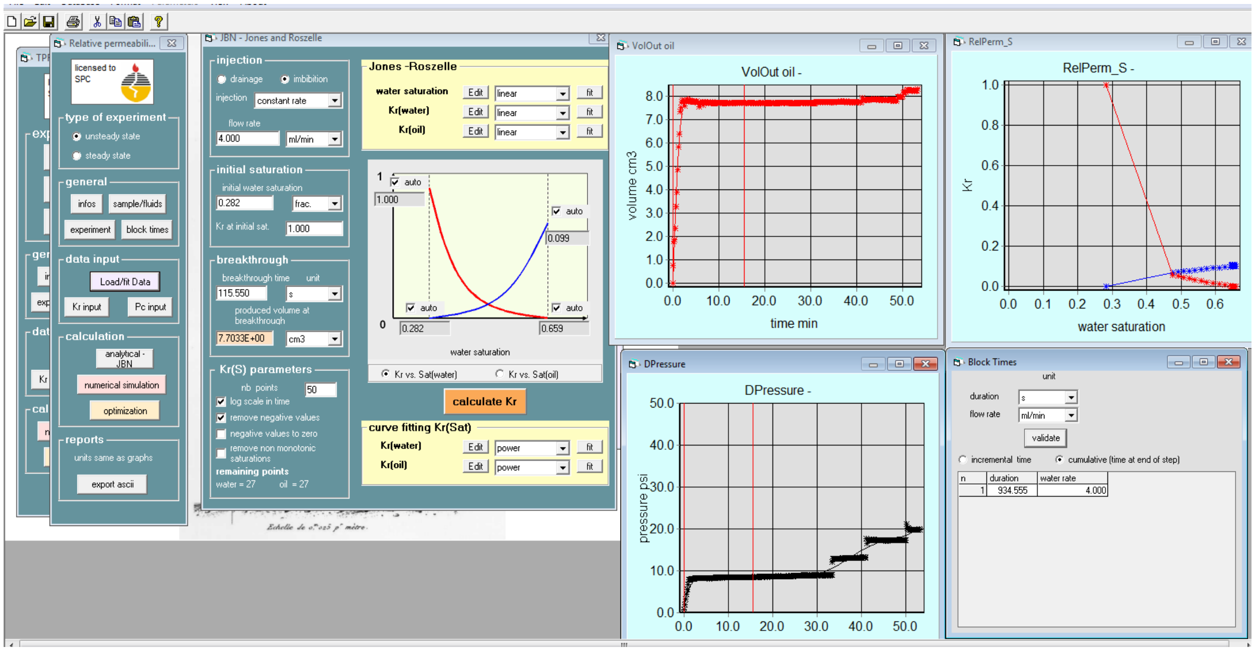


Figure4.7: Cumulative Production of Displacing Fluid Plug #1



type of experiment: ● unsteady state ○ steady state

injection: ○ drainage ● imbibition

injection: constant rate

flow rate: 4.000 ml/min

initial water saturation: 0.282 frac.

Kr at initial sat.: 1.000

breakthrough time: 115.550 unit: s

produced volume at breakthrough: 7.7033E+00 cm3

Kr(S) parameters

nb points: 50

☑ log scale in time

☑ remove negative values

☐ negative values to zero

☐ remove non monotonic saturations

remaining points: water = 27 oil = 27

Jones -Roszelle

water saturation: linear

Kr(water): linear

Kr(oil): linear

☑ auto 1.000 ☑ auto 0.099 ☑ auto 0.282 ☑ auto 0.659

● Kr vs. Sat(water) ○ Kr vs. Sat(oil)

curve fitting Kr(Sat)

Kr(water): power

Kr(oil): power

units same as graphs

Block Times unit: duration: s; flow rate: ml/min

○ incremental time ● cumulative (time at end of step)

n	duration	water rate
1	934.555	4.000

Figure4.8: Model JBN method Plug No.#2

Table4.10: Unsteady State Relative Permeability Plug#2:

Sw	Krw	Kro
28.2	0	1
47.6	0.066	0.056
49.1	0.07	0.05
50.7	0.074	0.044
52.3	0.078	0.032
54.0	0.081	0.033
55.7	0.085	0.027
57.4	0.088	0.022
59.2	0.09	0.017
60.9	0.093	0.13
62.7	0.095	0.009
64.3	0.098	0.005

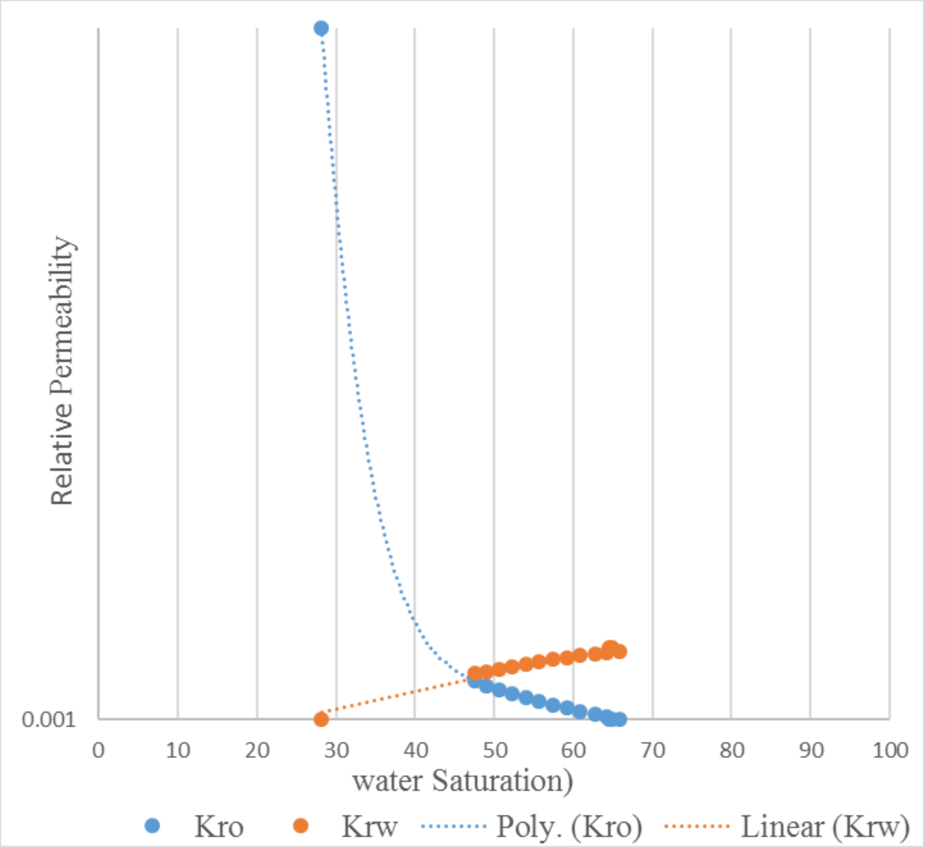


Figure4.9: Relative Permeability Curve Plug #2

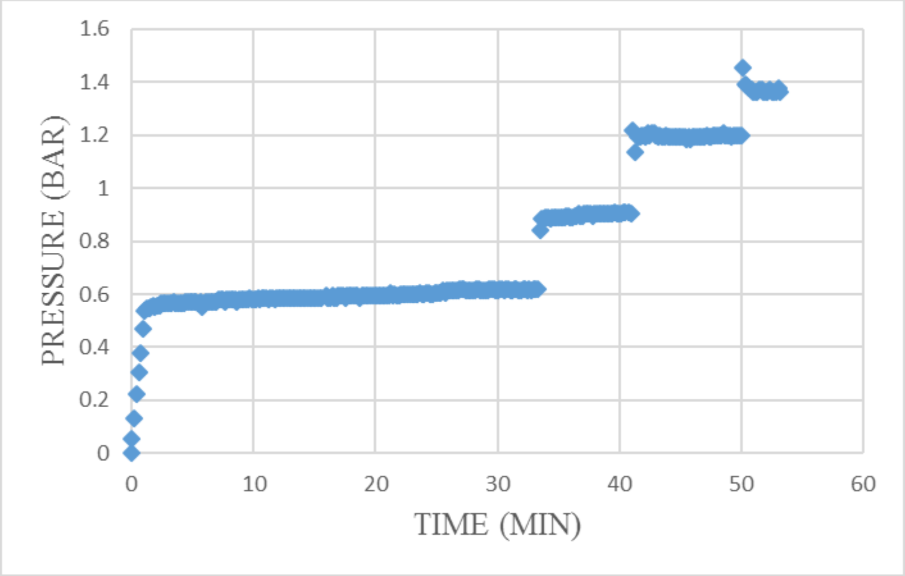


Figure4.10: Pressure as a function of time Plug #2

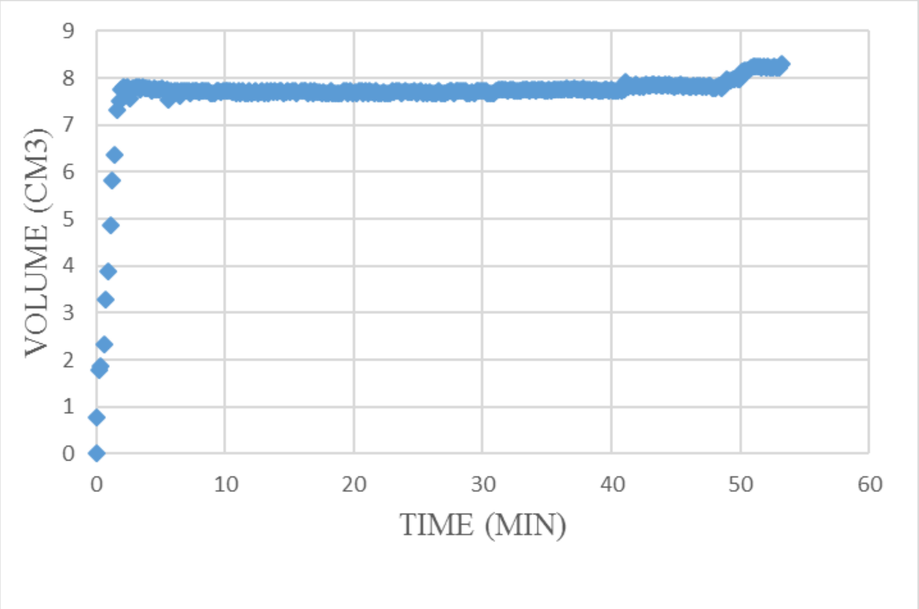
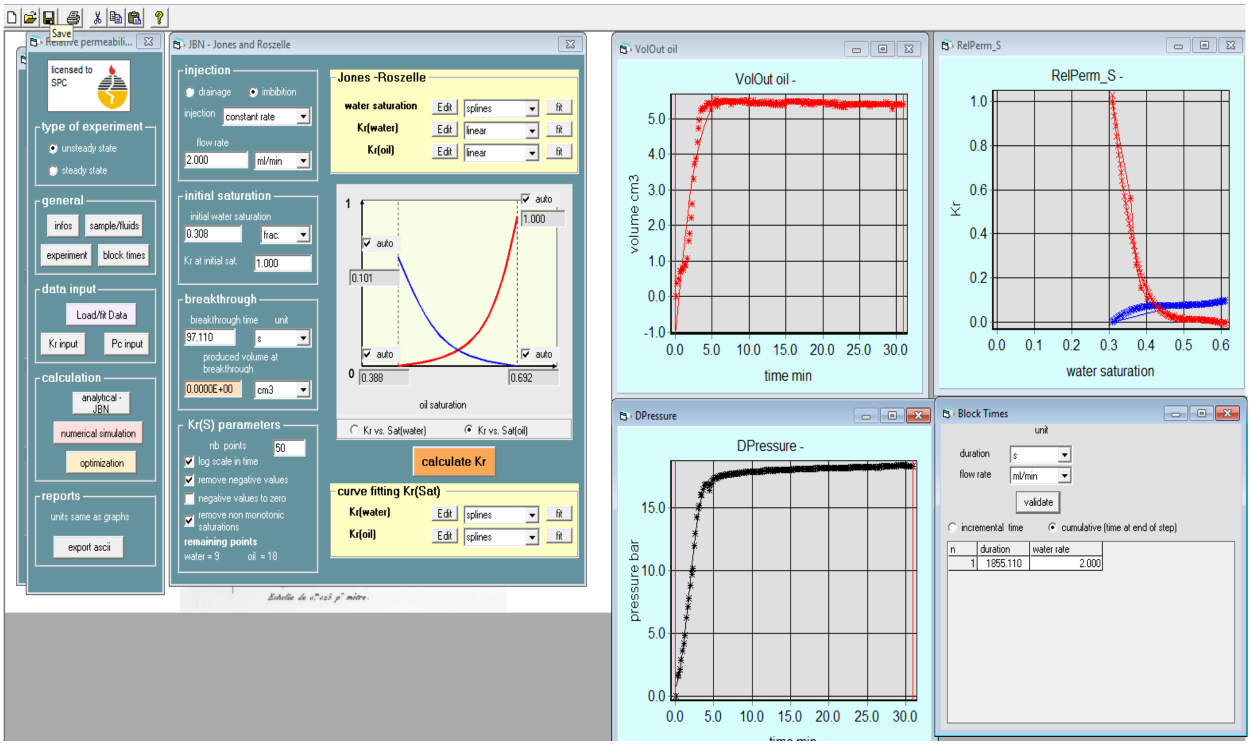


Figure4.11: Cumulative Production of Displacing Fluid Plug #2



type of experiment
● unsteady state
○ steady state

general

data input

calculation

reports
units same as graphs

injection
○ drainage ● imbibition
injection: constant rate
flow rate: 2.000 ml/min

initial saturation
initial water saturation: 0.308 frac.
Kr at initial sat.: 1.000

breakthrough
breakthrough time: 97.110 unit: s
produced volume at breakthrough: 0.0000E+00 cm3

Kr(S) parameters
nb points: 50
☑ log scale in time
☑ remove negative values
☐ negative values to zero
☑ remove non monotonic saturations
remaining points
water = 9 oil = 18

Jones -Roszelle
water saturation: splines
Kr(water): linear
Kr(oil): linear

☑ auto 1.000
☑ auto 0.101
☑ auto 0.388
☑ auto 0.692

○ Kr vs. Sat(water) ● Kr vs. Sat(oil)

curve fitting Kr(Sat)
Kr(water): splines
Kr(oil): splines

unit
duration: s
flow rate: ml/min

○ incremental time ● cumulative (time at end of step)

n	duration	water rate
1	1855.110	2.000

Figure4.12: CYDAR Model JBN method Plug No.#3

Table4.11: Unsteady State Relative Permeability Plug#3:

Sw	Kro	Krw
30.8	1.0000	0.000
31.7	0.8840	0.013
35.4	0.4490	0.052
37.5	0.2830	0.065
38.5	0.2280	0.069
39.4	0.1820	0.072
40.0	0.1560	0.073
42.2	0.0880	0.077
50.4	0.0130	0.078
54.4	0.0120	0.082
55.3	0.0120	0.083
56.30	0.01	0.09
56.90	0.01	0.09
57.80	0.01	0.09
58.70	0.01	0.09
59.00	0.00	0.09
59.60	0.00	0.09
60.90	0.00	0.10
61.20	0.00	0.10

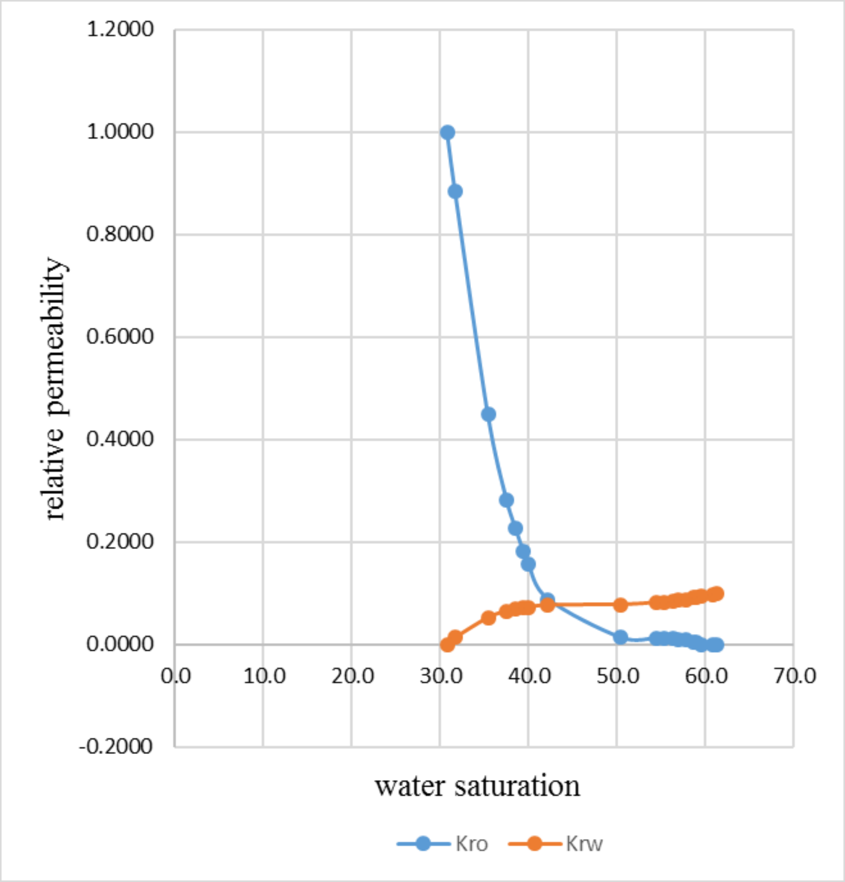


Figure4.13: Relative Permeability Curve Plug #3

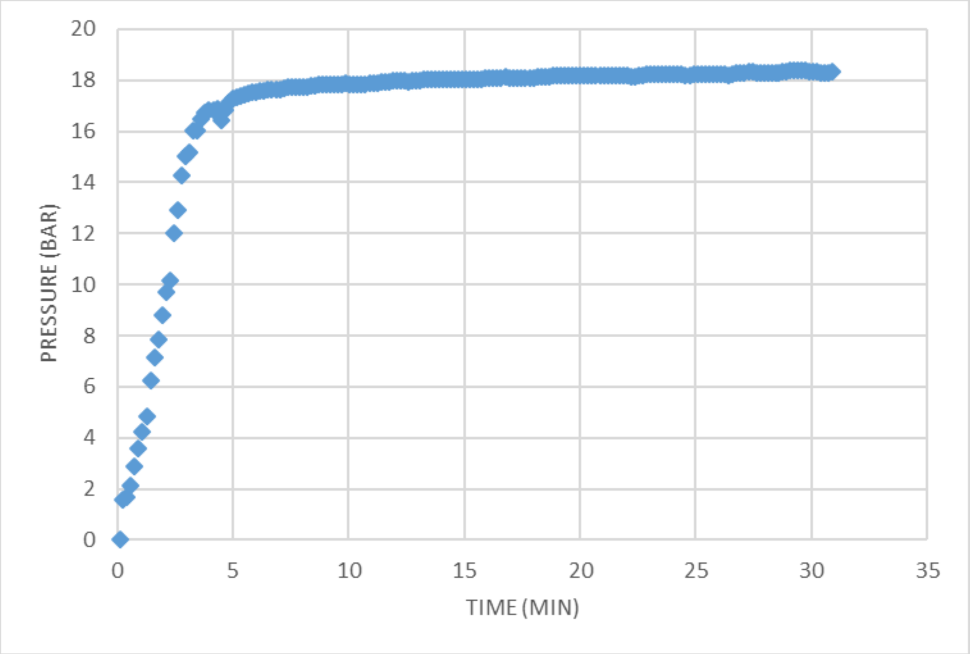


Figure4.14: Pressure as a function of time Plug #3

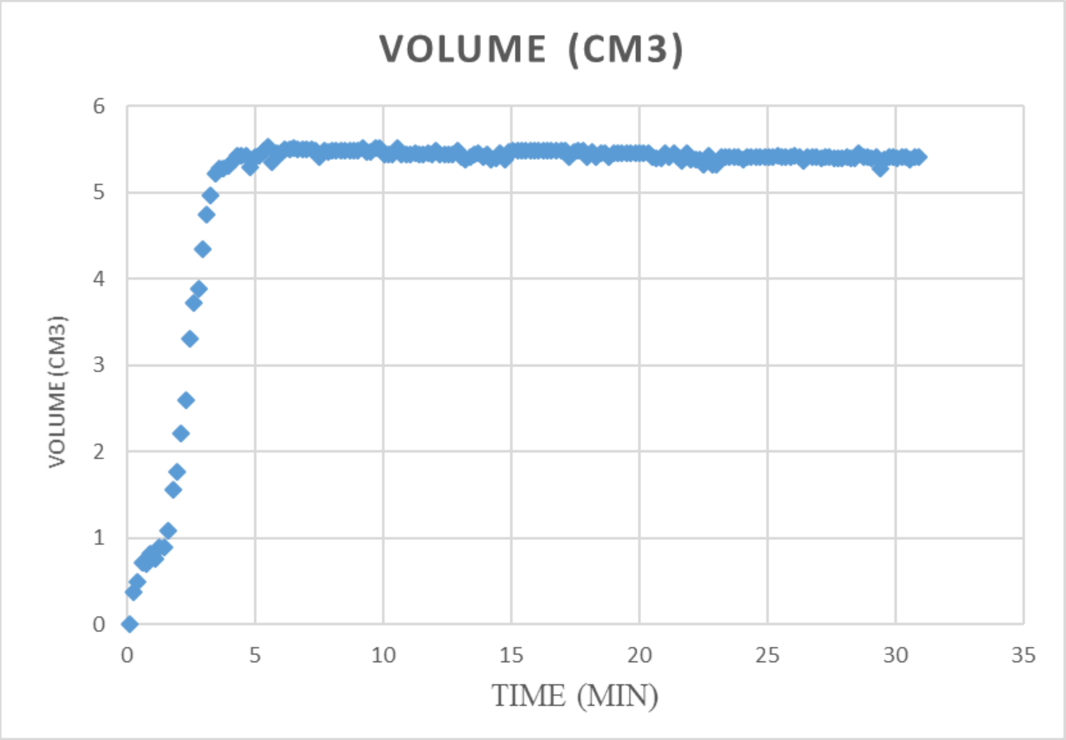


Figure4.15: Cumulative Production of Displacing Fluid Plug #3

Chapter 5

Conclusion & Recommendations

5.1 Conclusion:

Three sandstone core plugs were used in this study the average porosity of this samples is 25%, and the permeability range from 10-4000 md, reservoir depth from 1730-1740 m.

Water flooding experiment for this study the recovery factor between 44-56%.

After core flooding sequence and procedures were completed, all required data were gathered and calculated relative permeability Relative permeability is one of essential tools to predict the performance of reservoirs produced by water flood or natural water drive.

Correct estimation of residual oil saturation (So_r) and relative permeability using Relative Permeability System **(Figure 3.12)** is vital as such experimental values will guide engineer in calibrating his dynamic model and also reduce cases of law confidence reserve forecast.

After used different salinity the additional recovery factor. When the concentration of the salinity decreased.

5.2 Recommendation:

1. For more study the wettability restriction using before waterflooding.

2. Study the effect of further law salinity water concentration

3. Running a history match on available field data to determine relative permeability after having preliminary insight from the current results, would help to gain a more realistic understanding of relative permeability behavior.

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