RELATIVE PERMEABILITY HYSTERISIS EFFECT OF WATER-ALTERNATE-GAS (WAG) INJECTION

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To my beloved parents, friends, colleagues and lecturers.

Thank you for your support.

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ABSTRACT

Water Alternate Gas (WAG) injection enhanced oil recovery is said to recover nearly all residual oil where the water and gas sweeps alternately. It has been shown that combining water and gas injection in a WAG (water alternating gas) scheme can result in additional oil recovery from 5% to 10%. Interest in WAG injection has increasingly grown in recent times with many reservoirs around the world now is under WAG injection. In cases of limited rate of injection pressure, the key to overcoming gravity override by gas is the injectivity itself while in the cases of attic oil or cellar oil recovery, the key to exploiting the oil is the increased microscopic displacement efficiency by using water alternate gas injection method. Numerical simulation of WAG requires reliable three-phase relative permeability and hysteresis data which are normally obtained from models available in commercial simulators. This thesis utilizes real reservoir data to investigate the effect of relative permeability hysteresis of WAG injection simulation models using ECLIPSE (E300). By considering relative permeability hysteresis in WAG simulation, it helps to increase the oil recovery prediction as much as 11%. This is because hysteretic model accounts for the gas trapping effect during cyclic changes in saturation. The gas trapping effect is actually a beneficial process as it reduces the gas permeability, hence reduction in gas mobility. As a result, this will lead to better oil recovery. Hence, WAG injection can lead to improved oil recovery by combining better mobility control and contacting unswept zones, and by leading to improved microscopic displacement. The result of this work shows that a good understanding of the relative permeability hysteresis model in use is very important for a more robust reservoir simulation model for an optimum design of EOR facilities in the future.

ABSTRAK

"Water Alternate Gas (WAG) injection" ialah perolehan minyak tetingkat yang dikatakan boleh mengolah hampir semua tinggalan minyak di mana air dan gas bertindak berselang seli sebagai suntikan atau "injection". Gabungan "injection" air dan gas (WAG) mempertingkatkan lagi perolehan minyak tambahan daripada 5% kepada 10%. Kini, "WAG injection" semakin berkembang dibuktikan oleh banyak takungan minyak di seluruh dunia diaplikasikan dengan "WAG injection". Dalam kes suntikan bertekanan terhad, kunci untuk mengatasi impak graviti disebabkan oleh gas adalah kadar suntikan itu sendiri manakala dalam kes "cellar/attic oil", kunci kepada pengeksploitasian minyak adalah peningkatan kecekapan anjakan mikroskopik dengan menggunakan "WAG injection". Simulasi berangka "WAG injection" memerlukan tiga fasa, kebolehtelapan relatif dan data histerisis yang biasanya diperolehi daripada model yang terdapat di simulator industrial. Tesis ini menggunakan data takungan sebenar untuk mengkaji kesan histerisis ketelapan relatif dengan model simulasi ECLIPSE (E300). Ini juga berupaya membantu meningkatkan ramalan pemulihan minyak sebanyak 11% kerana model histeritik telah menunjukkan kesan pemerangkapan gas dalam perubahan kitaran dalam keadaan tepu. Kesan pemerangkapan gas sebenarnya adalah satu proses yang memberi manfaat kerana ia mengurangkan kebolehtelapan gas dan mengurangkan pergerakan gas. Oleh itu , "WAG injection" boleh membawa kepada perolehan minyak yang lebih baik dengan menggabungkan kawalan pergerakan yang baik terhadap zon tinggalan minyak Tesis ini menunjukkan bahawa model histerisis kebolehtelapan relatif adalah sangat penting untuk model simulasi takungan yang lebih kukuh untuk reka bentuk optimum kepada kemudahan EOR pada masa hadapan.

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LIST OF ABBREVIATONS

EOR	-	Enhanced Oil Recovery
CO_2	-	Carbon Dioxide
PV	-	Pore Volume
WAG	-	Water Alternate Gas
MMP	-	Minimum Miscibility Pressure
S_{wc}	-	Connate Water Saturation
S_w	-	Water Saturation
K_{rw}	-	Relative Water Permeability
S_{orw}	-	Residual Oil Saturation
CH_4	-	Methane
Sg_{trap}	-	Trapped gas saturation
Sg_m	-	Maximum gas saturation
Sg_{cr}	-	Critical gas saturation
Sg_i	-	Historical maximum of gas saturation
FOPT	-	Total Field Oil Production
Q_w	-	Water Injection Rate
Q_{CO2}	-	Carbon Dioxide Injection Rate
B_w	-	Water Formation Volume Factor

WOPR	-	Well Oil Production Rate
WWCT	-	Well Water Cut for Producer

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CHAPTER 1

INTRODUCTION

1.1 Background of the study

More than half the original oil typically remains in oil reservoirs after primary and secondary recovery operations. Primary recovery refers to production of oil because of its natural energy; fluids expand as pressure falls to push out some oil and gas. Expansion of associated aquifers and gas caps also help in pushing out oil. Primary recovery efficiency varies greatly from reservoir to reservoir and is typically in the range of 5-20%. Secondary recovery refers to injection of immiscible fluids, such as water and gas, to recover oil. These fluids displace oil from the pore space immiscibly. Secondary recovery efficiency is typically another 10-20%. Oil is left behind in bypassed regions as well as in swept zones at certain part of reservoir mainly because of permeability heterogeneity, lack of conformance at the wells, pattern orientation, and sometimes-viscous fingering. Oil is also left behind in the swept zones because of capillary forces in immiscible displacements during secondary recovery. Tertiary recovery techniques (also called enhanced oil recovery (EOR) techniques) are needed to recover additional oil from existing fields.

One of the commercially successful EOR method is miscible flooding is. It constitutes the injection of (Carbon Dioxide) CO_2, hydrocarbon gases, and even nitrogen or flue gas. Typically 10-50% (Pore Volume) PV of the injectant is injected in the case of CO_2 or hydrocarbon gases. A much larger amount of nitrogen or flue gas can be injected because they are cheaper. These gases can be injected in different modes:

- Miscible gas injection followed by dry gas injection
- Miscible gas injection followed by water injection or water-alternating-gas (WAG) injection.

It is believed that in recent years there has been an increasing interest in water-alternating-gas (WAG) processes, both miscible and immiscible which is known as an oil recovery method which initially aimed to improve sweep efficiency during gas injection. In some recent applications, produced hydrocarbon gas has been reinjected in water-injection wells with the aim of improving oil recovery and pressure maintenance. Oil recovery by WAG injection is believed has been attributed to contact of unswept zones, especially recovery of attic or cellar oil by exploiting the segregation of gas to the top or the accumulating of water toward the bottom. Because the residual oil after gas flooding is normally lower than the residual oil after water flooding, and three-phase zones may obtain lower remaining oil saturation, the suitable method is WAG injection where the combination of both methods mentioned above has the potential for increased microscopic displacement efficiency to overcome lower residual oil after water flooding. Thus, WAG injection can lead to improved oil recovery by combining better mobility control and contacting unswept zones, and by leading to improved microscopic displacement. A typical WAG injection process can be described as follows:

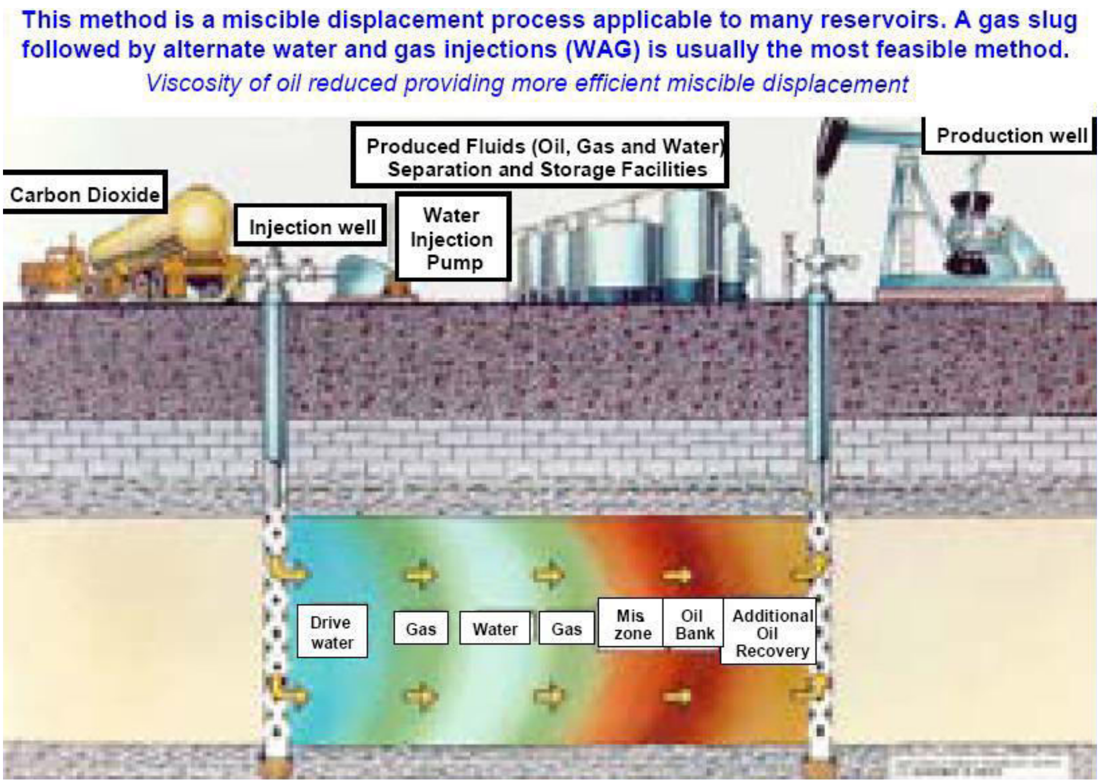


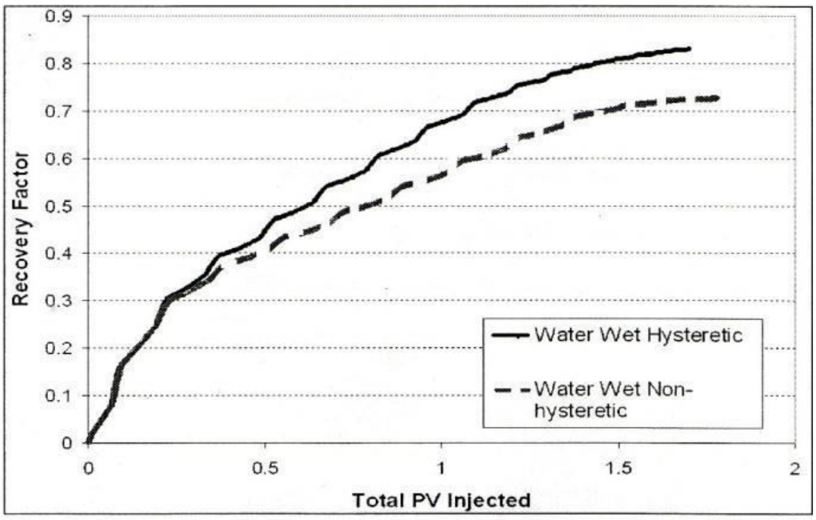
Figure 1.1.1: Conceptual diagram of an idealized CO2-WAG injection process

The CO_2 is typically injected in an alternating water and gas (WAG) process. It is injected at a pressure greater than its MMP (Minimum Miscibility Pressure) where the CO_2 acts to increase the volume of the oil miscible phase and lower its viscosity, freeing it from trapped pore spaces. As illustrated above, the water is being injected behind a "slug" of CO_2 that creates a zone which helps release the oil that had previously been trapped when using only water. This process leads to improved oil recovery by combining better mobility control and contacting unswept zones, and by leading to improved microscopic displacement.

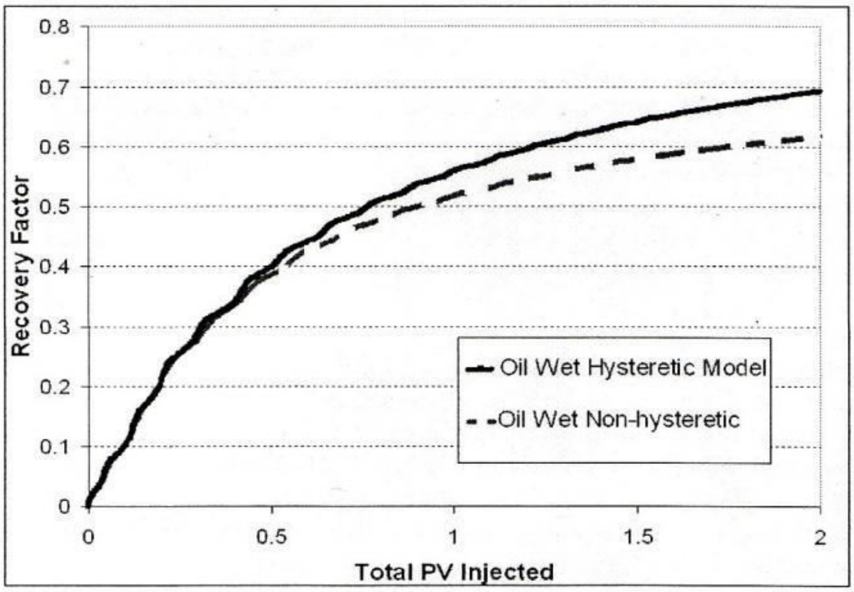
In WAG injection process, during each injection period, there are cyclic changes in fluid saturation due to the different type of fluid injected (i.e. water and CO_2 gas). These changes reflect the fluid displacement mechanisms in the reservoir, specifically drainage (non-wetting phase displaces wetting phase) and imbibition (wetting phase displaces non-wetting phase) processes which will generate hysteresis on relative permeabilities. Based on the conceptual study done by Faiza M Nasir and

M Sanif Maulut (2009), it is found that by considering the relative permeability hysteresis effect in WAG simulation, the oil recovery prediction is higher than the non-hysteretic model by as much as 10%. This is due to the fact that the hysteretic model accounts for the gas trapping effect during cyclic changes in saturation. It is because the gas trapping effect will reduce the gas permeability, hence reduction in gas mobility. Thus, this will give better oil recovery.

Please refer to Figure 1.1.2 below to see the difference in oil recovery for water-wet and oil-wet systems based on the conceptual study mentioned above.



a) Oil recovery for hysteretic and non-hysteretic water-wet models

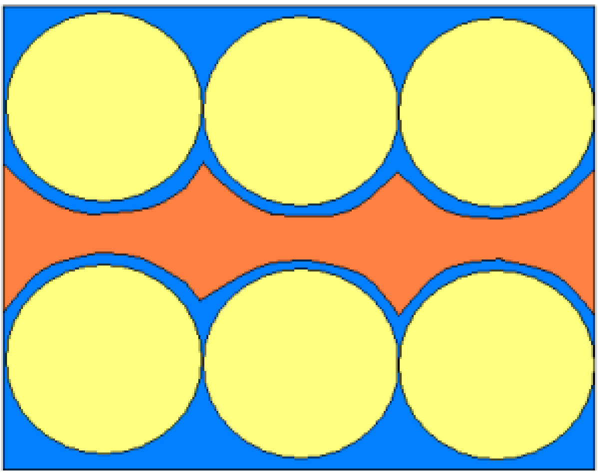


b) Oil recovery for hysteretic and non-hysteretic oil-wet models

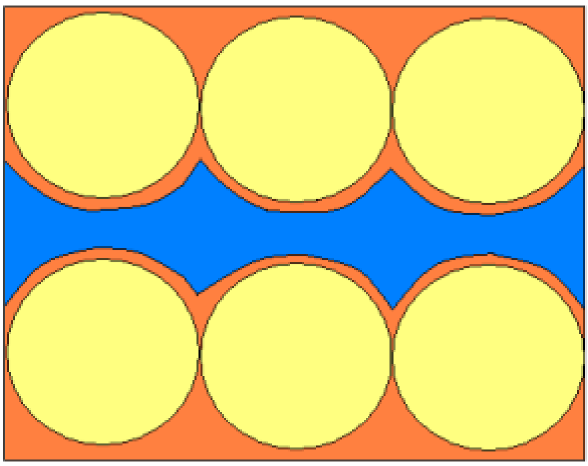
Figure 1.1.2: Oil recovery for hysteretic and non-hysteretic models for water-wet and oil-wet systems

According to the source of the Figure 1.1.2 by Faiza M. Nasir and M Sanif Maulut, a reservoir is characterized as a water-wet system if water tends to adhere to its rock surface, hence allowing better flowing condition for oil through its pores. In this situation, the wetting fluid is water meanwhile the non-wetting fluid is oil. On the other hand, for an oil-wet reservoir, the oil tends to spread over the rock surface. Here, the wetting fluid is oil and the non-wetting fluid is water.

For better understanding about these two types of reservoir, please refer Figure 1.1.3 below.



(a) Water Wet (most fields)



(b) Oil Wet (clay and carbonates)

Figure 1.13: Wettability characteristics of a reservoir

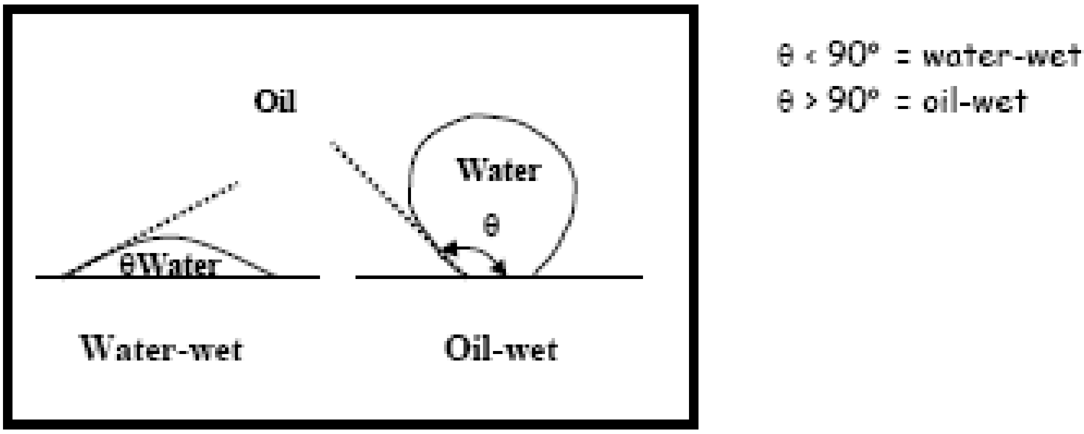


Figure 1.1.4: Contact angle for the water-wet and oil-wet systems

1.2 Hysteresis effect

Hysteresis effect is defined as a path-dependent of relative permeability curves during drainage and imbibitions cycles. In fact, these flow paths are governed by fluid distribution in pores, the pore size distribution and interaction between fluid and the rock. The imbibitions oil and gas relative permeability curves are generally lower than the drainage curves at the same saturation. The relative permeability values are a non-unique function of saturation which have different values when a given phase saturation is being increased than when it is being reduced. Thus, neglecting relative permeability hysteresis effect can have significant results into poor sweep efficiency hence less effective oil recovery anticipated in WAG injection procedure. Apart from that, WAG has also been used to improve oil recovery by increasing the sweep efficiency as residual oil to WAG is less than water and. Therefore, WAG injection is aimed at avoiding gravity segregation and provide dispersed flow zone.

1.3 Problem Statement

Hydrocarbon recovery using WAG injection is associated with high residual oil leading to less oil productivity. This problem comes with the process of injecting water and gas alternatively with periods of injection governed by the particularities of the reservoir, which has been historically used to reduce residual oil. This large amount of oil that remained underground unproduced is attributed by a situation known as gas fingering in which fingers of gas penetrates and leaving large amounts of oil behind due to the higher gas mobility which then becomes highly detrimental to oil recovery. Therefore, the water injected alternatively with the gas stabilises the gas movement. During the WAG injection, saturation changes due to the different type of fluid injected into the reservoir and these changes reflect the imbibition and drainage processes which will generate hysteresis on relative permeabilities. Based on Figure 1.1.2, it is proved that the hysteretic model gives higher prediction of oil recovery compared to non-hysteretic model as the hysteretic model accounts for the gas trapping effect. This effect is actually a beneficial process that helps to reduce the gas permeability which then leads to the reduction in gas mobility. When gas mobility is reduced, it is more difficult for the gas to displace the water from high permeability zone, thus it is more preferentially redirected into zones of lower permeability. As a result, this will improve the overall conformance and sweep efficiency, hence give better oil recovery.

Many studies point out the factors affecting the hysteresis in the reservoir whereby these studies mainly focusing on capillary pressure and relative permeability effects on hysteresis. From this thesis, the main focused will be on relative permeability hysteresis effect for oil recovery investigation. It should be reminded that this investigation and observation is only based on the conceptual model which represents a quarter of a five-spot pattern in a homogeneous three-dimensional reservoir with a dimension of 2500x2500x150 ft (to reduce the complexity of the reservoir in order to quickly observe the effects of the relative permeability hysteresis, the model is discrete into 15x15x9 grid blocks). However, the effect on the real model (real reservoir) is unknown yet. Therefore, a study which focuses on the data set from real reservoir need to be conducted so that this theory can be proved accurately for the incremental of oil recovery percentage.

1.4 Objective and Scope of Study

Main objective: - To investigate and predict the oil recovery by studying hysteresis effect on WAG injection.

Sub-objectives:

To achieve the main objective, these sub-objectives need to be highlighted:

1. Decrease severity of viscous fingering to increase sweep efficiency and gas overriding phenomena as a factor of mobility ratio for both oil and water
2. Accounting for the high residual oil saturation in the reservoir

The objective of this project is to study the influence of the relative permeability hysteresis phenomena of the WAG injection process with the oil recovery by using the ECLIPSE Black Oil Reservoir Simulator (E300). For that purpose, data set from the real reservoir (i.e. Angsi) will be used as the input of the simulation. Throughout the simulation, the two-phase hysteresis model (Killough's) with Stone1's interpolation method is used. This model is used because it is able to predict the trapping of the non-wetting phase and reduction of permeability during the imbibition process.

Normally, relative permeability hysteresis effect is ignored during the simulation because of its unknown impact. Therefore, this study is done to evaluate the importance of considering hysteresis effect for WAG injection process which is believed to have some influences on the outcome of oil prediction based on the previous conceptual study. Since this project emphasizes on the use of data from the real reservoir, the result obtained can be compared with the conceptual study to see either the relative permeability hysteresis consideration in WAG injection process facilitate to increase the oil prediction in the real reservoir or not at all.

The scope of study in this project is to understand the importance of properly established the wettability characteristics of a reservoir before further study on the WAG injection process is done. This is because different characteristic gives different result since they have different properties. Besides that, the effect on considering relative permeability hysteresis phenomena after applying WAG injection to the reservoir will be analyzed too. This process is important in order to see whether this consideration helps in increasing the prediction of oil recovery or not. If the result obtained shows the significant value of considering relative permeability hysteresis, therefore it is no doubt to include and consider the relative permeability hysteresis effect in WAG simulation so that the oil in the reservoir is not being underestimated and being left unswept. If the reservoir is underestimated, it may cause difficulties during the production process since the facilities involved in the oil production may have been under designed. Apart from that, the most important thing that needs to be understood clearly is the use of simulation software which is ECLIPSE Black Oil Reservoir Simulator (E300) as it is used throughout the project.

Since this project focuses on the real reservoir data set, the real characteristic of the reservoir should be known beforehand. There are two types of reservoir which are water-wet and oil-wet where both characteristics can be distinguished conveniently using the Relative Permeability Curve as illustrated in Figure 1.4. The criteria used to evaluate the curve are explained in Table 1.4

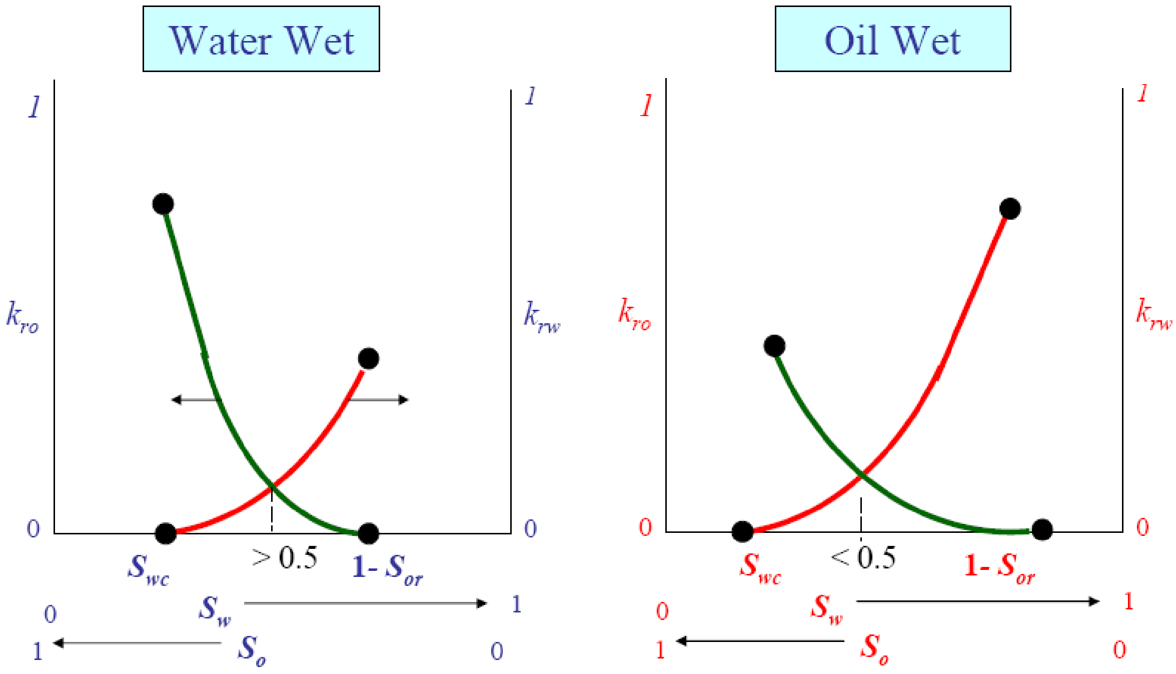


Figure 1.4: Typical Relative Permeability Curve for water-wet and oil-wet systems

Table 1.4: Summary of Key Parameters Used

	Water Wet (%)	Oil Wet (%)
S_{wc} (connate water saturation)	> 20-25	< 15 (usually 10)
S_w@k_{rw} = kro (water saturation when water relative permeability equals the oil relative permeability)	> 50%	< 50
k_{rw}@S_{orw} (endpoint water relative permeability)	< 0.3	> 0.5 to 1.0

1.5 Significance and Relevancy of the Project

WAG injection is one of the most relevant EOR methods use in the tertiary recovery of hydrocarbons. Selection and optimization of WAG injection processes are very crucial in reserves recovery in reservoir engineering section. The main concern in the industry is the cost factor where the cost of equipments, injection criteria, types of injections chemicals used are screened properly to maximize recovery and minimize cost. Thus, it would be of great advantage if the performances of the most of reservoirs recovery factors are optimized. Thus this project will assist in:

- The reduction of residual oil in the reservoirs/fields by optimizing sweep efficiency and increased recovery due to the relative permeability hysteresis effect in WAG cycles
- Carters for trapping of fluids (oil and gas) as a result of irregular reservoir geometries
- Decreasing viscosity of heavy oil hence oil flow easily to the producer wells and avoid gas fingering.

1.6 Feasibility of the Project within the scope and time frame

- Time allocated approximately 12 weeks
- Sufficient for data acquisition and analysis on each procedures & compilation
- No equipment or lab experiment needed
- Simulations : ECLIPSE software (E300)
- Sufficient research paper/journal
- Reference books & manual available

Therefore, all the necessary equipment and the information are available for the study and the project is expected to be finished within the time frame.

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