TECHNICAL UNIVERSITY OF CRETE

SCHOOL OF MINERAL RESOURCES ENGINEERING

"**Single Well Tracer Test for Residual Oil Estimation**"

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Chania, 2018

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A thesis submitted in partial fulfilment of the requirements for the degree of Master of Science in Petroleum Engineering

Acknowledgments

Firstly, I would like to express my deepest appreciation to my supervisor Dr. Christos Chatzichristos for his continuous support, his patient guidance and immense knowledge. I am also indebted to Professor Pasadakis N. and Professor Kalogerakis N. for accepting being members of the examination committee.

In addition, a special word of gratitude is due to all my professors in Petroleum Engineering department of Technical University of Crete for their guidance and their support during the academic year.

I would also like to extend my thanks to my colleague Miltiadis Konstadinopoulos for the academic year 2016/ 2017 for his social and professional support.

Last but not least, I would like to THANK my friend Hassan Tzampaz, for his extraordinary support during the academic year and helping me achieve my goals. I wouldn't make it without you.

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Abstract

Tracer techniques are a powerful diagnostic tool in numerous Scientific disciplines (Bjornstad et al.,1990; Divine and McDonnell, 2005) and for technologies in many industrial sectors. Tracer tests were first used in the early 1900s in hydrology (Du and Guan, 2005; Guan etal.,2005). Today, these tests are used with increasing frequency in oil field applications (Bingyu et al.,2002; Bjornstad, 1991; Jin et al.,1997) when no other investigation technique is applicable. Tracer tests provide a better understanding of the studied oil reservoir (including inter well connections, connections between layers and heterogeneities) (Coronado and Ramirez-Sabag, 2008; Coronado et al., 2009; Guan and Du, 2004; Manich and et al., 2010; Nugroho and Ardianto, 2010; Sinha e tal., 2004).

The Single-well Tracer Test is a test used extensively to measure the S_{or} (Residual oil) in watered-out reservoirs. Also, it is implemented in order to evaluate enhanced oil recovery (EOR) using chemicals, such as Alkaline/Surfactant/Polymer flooding.

Single-Well Chemical Tracer (SWTT) tests offer an in-situ method for determining the Residual Oil Saturation (R_{OS}) of a reservoir that has numerous advantages, compared to more conventional methods such as core analysis and well logging. It can also be used to enhance the understanding of heterogeneity in the subsurface. Over the past 50 years numerous SWCT and IWCT (Inter-Well Chemical Tracer) tests have been conducted in fields around the world. Most of these tests focused on measuring the R_{OS} as an aid to planning improved oil recovery processes, and to understand the results of these tests.

In this work, tracer responses to two different commercial simulators (C.M.G. Stars and Eclipse Schlumberger) are analysed using numerical modelling. Two methods are applied: use of a multi-component reservoir simulation model, with chemical reactions to represent the reactive hydrolysis behaviour of the tracer (C.M.G. Stars); and a simplified approach using tracer tracking in a conventional black oil simulation model (Eclipse, Schlumberger). The models' results are validated against field data and it is

shown that the simulation results are consistent when varying grid thickness and keeping other parameters unchanged. When different rock and fluid properties are introduced, numerous peaks are observed, illustrating delays in tracer arrival times due to flow irreversibility.

The reservoir simulation models can be used for forward modelling and sensitivity studies to design SWTT tests, and for interpreting saturation measurements obtained in such tests. They can also be used for other applications, in conjunction with other data sources such as well logs.

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Chapter 1

Introduction

1.1   Introduction

In Petroleum Reservoirs only a small fraction of the original oil in place is economically recovered by primary, secondary, and tertiary recovery mechanism. A considerable amount of hydrocarbons ends up unrecovered or trapped due to microscopic phase trapping in porous media which results in an oil recovery factor typically less than 50 %. Waterflooding is by far the most widely used method to increase oil recovery. The oil that remains in the porous media after waterflooding is called remaing oil saturation (ROS) which is larger than the relative permeability residual oil saturation (S_{orw} or simply S_{or}). This residual oil saturation varies depending on lithology pore size distribution, permeability, wettability, fluid characteristiscs, recovery method and production scheme. The S_{or} represents a statistical over a wide range of pore scale residual saturations with in a representative elementary volume. Determination of residual oil saturation of a reservoir is a key parameter for reserve assessment and recovery estimates. Further, reliable S_{or} data is important for investigation of potential incremental recovery under Enhanced Oil Recovery (EOR) methods.

Various residual oil techniques are available both at laboratory and field scale. None of the techniques can be regarded as a single best method of determining S_{or}. Depending on the complexity of the reservoir under study. Combinations of methods are always

advisable for appropriate S_{or} determination. This project thesis studies only the Single well tracer test (SWTT)

The first SWTT for S_{or} (Residual oil) was run in the East Texas Field in 1968[1]. Patent rights were issued in 1971. Since then, numerous oil companies have used the SWTT method. More than 400 SWTT have been carried out, mainly to measure R_{OS} (Remaining oil saturation) after water-flooding.

The SWTT has gained considerable recognition over the past decades because of increasing interest in the quantitative measurement of S_{or}. Some experts consider the SWTT to be the method of choice because of its demonstrated accuracy and reasonable cost[34]

Residual oil saturation is a basic item of data for many aspects of reservoir engineering. This number is required for normal material-balance calculations. Residual oil saturation is extremely important determining the economic attractiveness of a planned waterflood or a proposed tertiary recovery operation. Finally, in some areas proration is related to attainable residual oil saturaion.

Core analysis and well logging, the two most widely used methods for measuring residual oil saturations, are subject to a variety of well-known limitations. One principal common fault is that both methods yield values that are averages over very small reservoir volumes where the tracer test technique for residual oil measurement represents and average over as much as several thousand barrels of pore space

Before any field-wide application of prospective improved oil recovery (IOR) or enhanced oil recovery (EOR) techniques, it is expedient and important to assess the efficacy and recovery potential of the specific IOR/ EOR technique, particularly relevant for redevelopment of mature oil-fields[5,6] (Babadagli, 2007 and Al- Mutairi et al., 2011). These objectives require measuring and comparing the remaining oil saturation (ROS) or residual oil saturation (S_{or}) before and after the IOR/ EOR pilot.

Single-well chemical tracer test (SWTT) is one of the proven technologies to estimate the amount of oil remaining after flooding. It exploits the difference in travel time between injected ester and the alcohol generated in-situ by hydrolysis. It was pioneered

by Esso in the early seventies[2] (Deans, 1971) and has been used extensively worldwide since then. The principle of the SWTT is illustrated in Figure 1.

SWTTs have been used to identify EOR potential as well as to evaluate the effect of EOR in numerous on-shore and some off-shore locations[78910] (Deans and Carlisle, 2007; Seccombe et al., 2008; Zainal et al., 2008; Jerauld et al., 2010; Skrettingland et al., 2011). It has also been used to evaluate polymer, surfactant and alkaline-surfactant-polymer (ASP) floods (Hernandez et al., 2002; Zainal et al., 2008; Oyemade et al., 2005; de Zwart et al., 2011; Callegaro et al., 2014), as well as the potential effect of low-salinity water flooding to reduce remaining oil saturation and enhance oil production (Mcguire et al., 2005; Seccombe et al., 2008; Jerauld et al., 2010; Skrettingland et al., 2011; Callegaro et al., 2014).

Tracer tests were first developed in the early 1900s for application in monitoring the movement of groundwater. Tracer applications in reservoir studies have been reported since the mid-1950s (Du et al. 2005). Deans (1971) proposed the functionality of SWTT tests in reservoirs. The first field application of SWTT tests was coordinated by Deans and his colleagues at Esso Production Research Company in the East Texas Field in 1968 (Deans and Carlisle 1986). The research they conducted focused on utilising the chromatographic separation of tracers. This involves the injection of a tracer into the formation and through monitoring the arrival times of the different tracers during production a ROS measurement can be attained. It provides a more economical alternative than IWCT tests, which involve the deployment of two wells, an injector and a producer that often cover large distances of the field. SWCT tests enables near wellbore measurements over shorter testing periods and avoid complexities associated with connectivity of flow between wells.

The demand for SWTT tests increased due to the increasing need for reservoir characterisation and application of enhanced oil recovery techniques. Numerous published papers described the use of SWTT testing to enhance conventional methods of determining fluid saturations such as core analysis and well logging, due to its in-situ nature and ability to access a broader volume of the reservoir (De Zabala et al. 2011; Skrettingland et al. 2011, Jin et al. 2015).

Previous SWTT tests involved using it as a means to measuring the ROS in reservoirs due to its importance in ascertaining which recovery method will help achieve maximum recovery (Pathak et al. 2011; Teklu et al. 2013, Cubillos et al. 2015). Its function of measuring heterogeneity has been studied to a lesser extent with few recent papers that focus on analysing different tracer responses to variances in heterogeneity (Descant et al. 1989). More recent papers seem to indirectly test heterogeneity when implementing SWTT tests along with EOR techniques in heterogeneous reservoirs such as carbonates (Abdulla et al. 2013, Fahad et al. 2015). Heterogeneity is an important parameter that needs more in-depth analysis.

Numerical modelling can be used to simulate SWTT tests in reservoirs. Modelling of SWTT tests can use chromatographic separation of tracers in conjunction with a tracer reaction model (Tomich et al. 1973) or in conjunction with a fluid drift model (Tomich and Deans 1975; Descant et al. 1989, Al-Shalabi et al. 2015).

In this thesis reservoir simulation is used as a tool to investigate tracer responses to variations in reservoir properties in the near-wellbore region, such as grid cell thickness, reaction rate concentration and partition coefficient. The project is organised as follows: first a brief background theory and application of SWCT tests is provided, followed by a description of the implementation and validation of numerical methods. Then a number of sensitivity analysis cases are introduced to explore SWTT responses to different reservoir models. Finally, discuss the results and present the concluding remarks.

1.2   Why SWTT

1.2.1 Introduction

Finding oil is hard enough, but then there is the small matter of working out how much of it there is in a find and how much of it is usable- and that is not easy either.

Measuring volumes of recoverable oil and gas underground is not an exact science: the hydrocarbons are held in rock pores kilometers below the Earth's surface, and sometimes under kilometers of sea, too.

Meanwhile, the technology available is improving all the time, enabling more oil to be extracted than would have been possible previously. And then there is the oil price – a reservoir that is not commercially recoverable when oil is trading at 70 $ a barrel might look attractive at 110 $ a barrel.

The total amount of oil in a reservoir is known as oil-in-place. However, on average, two-thirds of the oil in a reservoir stays in the ground because the cost of extracting it exceeds the oil's market value – so only about a third of a field's oil tends to be produced.

There are numerous reasons why some – or indeed all- of a discovery might not be commercial. The field might consist of multiple reservoirs and faults, which make it more difficult – and expensive – to produce from parts of it. If it's offshore, it may not be practical to drill the necessary number of wells from one platform. Or perhaps the oil might be too thick and viscous to pump to the surface without costly special equipment.

The portion of the oil-in-place estimated to be commercially recoverable is known as the reserves.

Despite their inexact nature, reserve estimates are important in projecting long-term flows of oil and gas to world markets, and they determine the economic viability of individual fields. They are also the most important measure of oil company's value: profitability today depends on production, but reserves – effectively the firm's savings in its deposit account- indicate long-term potential.

In an effort to provide the best overview of this potential, reserves are ranked according to the probability of being able to produce them. The estimates of proved reserves must be substantiated with detailed evidence on the rock's electrical resistance, the oil's chemical composition, the deposit's depth and the intensity of oil flows, and by making comparisons with reservoirs nearby or elsewhere in the world with similar characteristics.

To do this, geoscientists use a variety of measuring techniques, such as well-logging-in which tools are lowered down the well on an electrical wire to measure the properties of the rock around the borehole- and core sampling, in which a physical sample of the subterranean rock is retrieved for analysis. From the information gathered, geoscientists, can generate a profile of the reservoir and its reserves, as well as identifying the best sites for drilling and forecasting the field's likely production profile.

In 2004, reserves-accounting standards, which get pretty technical, became headline news when Shell admitted that it had been exaggerating its proved reserves. The company has misled markets not about how much oil and gas were down there, but about the certainty – and probably the speed- with which the oil and gas could be developed. In a controversy that eventually saw the company's boss ousted, Shell cut its proved reserves- those that were very certain to be developed- by over 20%, reclassifying those reserves in the probable- less certain – category instead. And the company's shares took a battering.

The proportion of a filed's oil that can be recovered is called its recovery factor. A field with 30 million barrels of reserves and 100 million barrels of oil-in-place would have a recovery factor of 30%. Sometimes, as much as 70% of a field's oil can be recovered and sometimes as little as 5%. But worldwide, the average is about 35%. Recovery factors tend to rise over time, as technology improves. For example, when Alaska's Prudhoe Bay field entered production in 1977, its developers expected to recover 10 billion barrels of oil. Present expectations are for ultimate recovery of 15 billion barrel.

Single well tracer test becomes crucial after secondary recovery process and especially after water flooding or gas flooding where residual oil is reached its value. The process comes out with the residual oil value with a small percent of uncertainty compared to logging and seismic operations.

On this thesis work, simulation of single well tracer test has been done, comparing the results from two different commercial simulators (Stars CMG and Eclipse Schlumberger) against field and already interpreted data.

The single-well chemical tracer test (SWTT) is an in-situ method for measuring fluid saturations in reservoirs. Most often, residual oil saturation (S_{or}) is measured; less

connate water saturation (S_{wc}) is the objective. Either saturation is measured where one phase effectively is stationary in the pore space (i.e., is at residual saturation) and the other phase can flow to the wellbore. Recently, the SWTT method has been extended to measure oil/ water fractional flow at measured fluid saturations in situations in which both oil and water phases are mobile which not the main subject in this thesis work.

The SWTT test is used primarily to quantify the target oil saturation before initiating improved oil recovery (IOR) operations, to measure the effectiveness of IOR agents in a single well pilot and to assess a field for by-passed oil targets (Figure 2). Secondarily, it is used to measure S_{wc} accurately for better evaluation of original oil in place (OOIP). Fractional flow measurement provides realistic input for simulator models used to calculate water-flood performance.
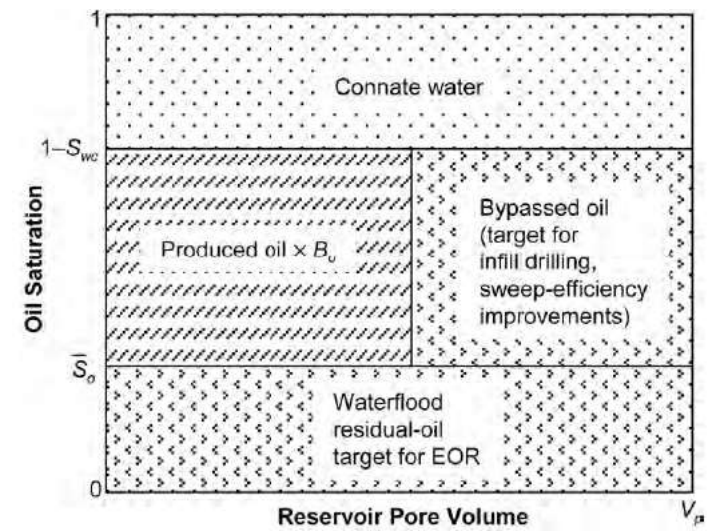

Figure 2: A schematic figure of a by passed oil in an elementary pore space

The following chapters familiarizes the reader with the SWTT method.

Chapter 2

The Single-Well Chemical Tracer Test Method for measuring the residual oil saturation

2.1.1 Introduction

In SWTT tests, the tracers injected are often inert and have no impact on the chemical aspects of the subsurface. There is a strong reliance on the in-situ hydrolysis of the tracer to recover interpretable results. It involves tracer injection into an oil-bearing formation where one of the phases is mobile (water) and the other phase is immobile (oil) (Deans 1971). In SWTT operations, a primary tracer bank consisting of about 1% by volume (Deans and Carlisle 1986, de Zwart et al. 2011) of the partitioning tracer - an ester such as ethyl acetate(For intermediate reservoir temperatures) or ethyl formate (for lower reservoir temperatures)- is dissolved in formation water and injected into the reservoir at residual oil conditions (Tomich et al. 1973). The mobile phase is the chosen carrier fluid (Cooke 1971).

An ester is desirable due to several of its characteristics such as being soluble in both the water and oil phases (Abdulla et al. 2013; Al-Shalabi et al. 2015, Khaledialidusti et al. 2015). This is followed by a bank of tracer-free water. This tends to be from the formation being tested to avoid disrupting the wettability of the reservoir (Deans 1971). This pushes the tracer slug a desired distance into the formation and is often referred to as the 'push volume'. The well is then permitted to shut in, allowing a portion of the ester to hydrolyse, forming an alcohol - ethanol, which is the secondary, non-partitioning tracer (Tomich et al. 1973, Jerauld et al. 2010). An important characteristic of the alcohol is that it is only soluble in the water phase.

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Alcohol formation :   Ester $+ H_2O \rightarrow$ Alcohol + Acid.

The acid is produced as a by-product of hydrolysis but is not observed as it is consumed in the reservoir (Deans 1971). An important assumption is that hydrolysis occurring during injection is kept at a minimum to avoid flow reversibility effects.

Chromatographic retardation in different regions is achieved through differences in partition coefficients (Cooke 1971). The degree of retardation is dependent on the pore sizes and is subsequently a function of the saturation of the immobile fluid. This forms the fundamentals from which SWTT tests are based on, resulting in different tracer arrival times.

As the alcohol produced is only soluble in the mobile phase, it travels deeper into the reservoir than the ester and at a faster rate within a homogeneous environment. This leads to an earlier breakthrough of the alcohol at the well and is the result of the chromatographic separation of the tracers in the reservoir.

When there is a pressure gradient within the reservoir due to observation wells close to the test well, fluid movement in the formation may be induced which is known as fluid drift (Descant et al. 1989). Tomich and Deans (1975) implemented fluid drift in a numerical model to measure the ROS.

Conventionally the esters used in SWTT tests are more soluble in the oil phase and this is expressed by the partition coefficient, K_p (Deans and Carlisle 1986).

1. $$K_p = \frac{Concentration\ of\ ester\ in\ oil}{Concentration\ of\ ester\ in\ water}$$

The partition function is the ratio of tracer that has partitioned into the oil phase to that which has partitioned into the water phase, at equilibrium. A higher partition ratio indicates that more of the tracer has partitioned into the oil phase. Equation 1 is valid under the assumption that instantaneous equilibrium is achieved for the tracer between the two phases at residual conditions. The partition coefficient for different tracers has to be measured in the laboratory at reservoir conditions (Deans and Carlisle 1986).
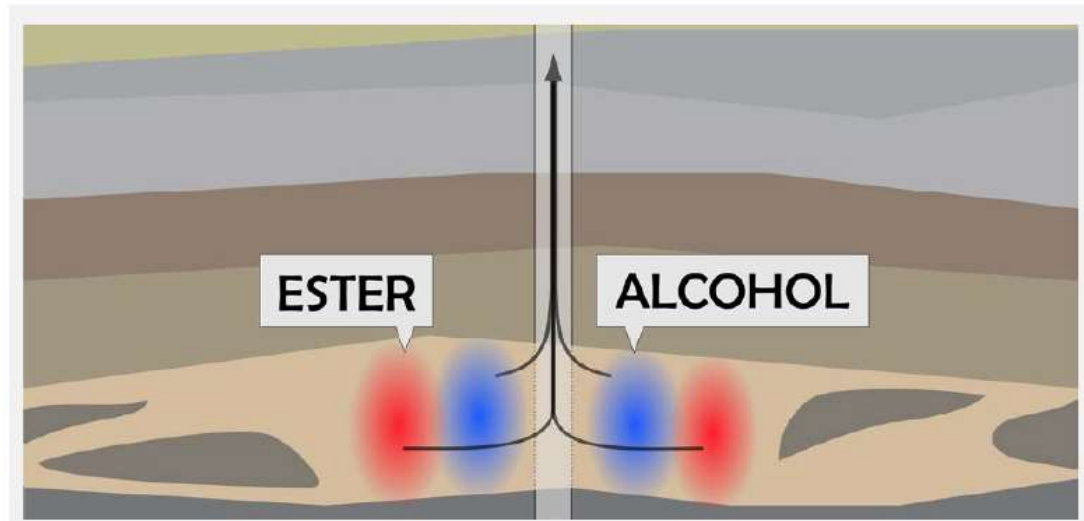
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Figure 2: The principle behind SWTT. An Ester in injected which partly hydrolyzes and produces Alcohol.

For the numerical models two methods were applied.

1.   Tracer Model: A commercial black oil reservoir simulator is used with an intrinsic tracer model. The hydrolysis reaction cannot be accounted for hence a workaround was implemented using two simulations. In the first one, only the injection stages are simulated whereby two partitioning tracers with the same partitioning ratio are injected. The second one starts from the last timestep of the previous simulation and models the production stage in which the partitioning ratio for one of the tracers is set to zero to represent the alcohol.

2.   Chemical Reaction Model: An industry standard commercial compositional reservoir simulator was used which allowed for user defined reaction modelling. The tracers are modelled as water components (Stars, C.M.G.).

The commercial black oil simulators are formulated to model up the phases of oil and water. The main assumptions made when using these two simulators is that flow is isothermal and that mass transfer within each gridlock of the model is instantaneous (Fanchi 2006). The Chemical Reaction model takes a much longer simulation time in comparison to the Tracer Tracking Model. It is necessary to tune the chemical reaction rates to match the partitioning tracer behaviour correctly.

2.2.2 Chemical Reaction Model

To reproduce the behaviour of partitioning tracers within the reservoir simulator a chemical reaction model must be applied. This model is based on the partitioning of tracers between two or more fluids. The velocity of a tracer depends on the stream it has partitioned into. A major assumption in this model is that the reservoir is at residual oil conditions (Deans 1971).

The chemical reaction model consists of a chemical equilibrium which represents the partitioning of the tracer and is governed by the partition coefficient K_e, and a hydrolysis reaction which forms the non-partitioning tracer.

2.2.3 Radial Model

A radial grid was used in both simulators. A sensitivity analysis was conducted on the number of 2-D grid cells, with a coarse grid with dimensions 20×1×1, an intermediate grid of dimensions 50×1×10 and a finer grid with dimensions 300×1×1. It was concluded that the intermediate model ensured reduction of numerical dispersion and compared well to the finer grid profiles, whilst requiring less cells. The outer radius of the model is 1000 m with an inner radius of 0.1 m to ensure that the tracer propagates out radially a sufficient distance into the reservoir without reaching the bounds of the reservoir to avoid pressure fluctuations. The average radius of investigation in this study is 10 m (30 ft.). Another sensitivity was conducted on the sizes of the grid blocks in the radial-direction. The geometric progression of cells in an outwardly direction provides a better support for radial inflow. The reservoir pressure is 1800 psi and is maintained in the model through the test. The well is at 2000 m depth, with all layers being perforated.
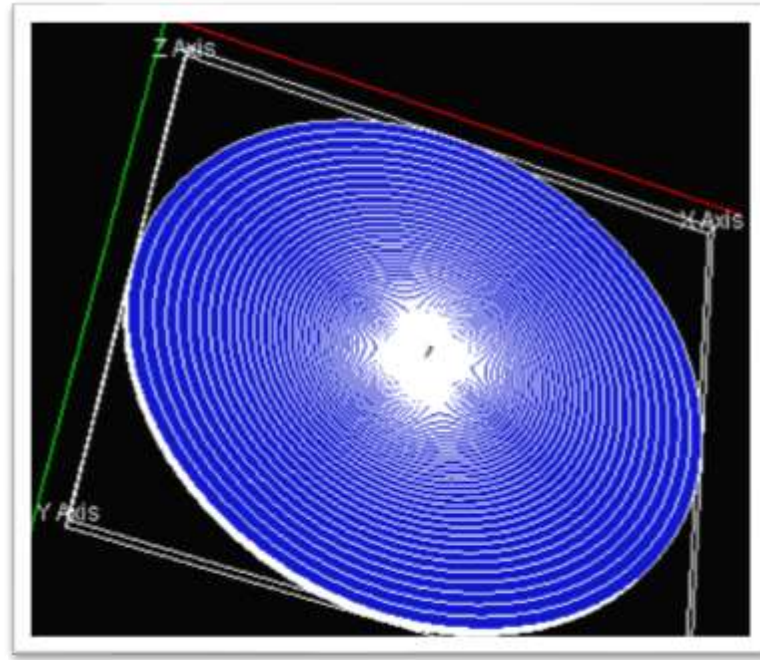
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Figure 3: Radial reservoir domain

2.2.4 Homogeneous Reservoir Case

The homogeneous model was created to analyse the production profiles within a fully homogeneous environment. This would act as a good benchmark from which a better understanding of tracer behaviour can be deduced when applied to more complex structures such as a heterogeneous reservoir.

The anticipated results for a homogeneous case would be the observation of smooth curves for the alcohol and the ester whilst the alcohol back produces more quickly (connoted by a shift to the left). This can be observed when looking at the tracer concentration profiles.

As a rule of thumb, when calculating the ROS using tracer arrival times, the soaking period is required to be greater than twice the transit time (Tomich et al. 1973) .

2.2.5 Partition Coefficient

The partition coefficient determines the amount of tracer that partitions into the oil and water phases, as discussed previously. This is an important parameter as it directly

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affects the amount of recoverable ester and alcohol that is produced. This was modelled using the homogeneous chemical reaction model. This was to ensure that the model has only one variable to show the true extent of varying K_e. The anticipated results are that the observed peaks are shifted as the partition ratio is increased. The concentration profile for the esters shows effects of flow reversibility as the peaks overlap. A noticeable trend is that as the partition coefficient is increased, the maximum concentration of ester produced marginally increases. This is because an increase in K_e denotes more of the ester has partitioned into the oil phase, rendering it unavailable for hydrolysis, and is hence back produced as ester. As for the alcohol, an increase in the partition coefficient seems to cause the peaks to shift to the left hand-side as anticipated and the magnitude of the peaks reduces as we increase K_e from 20 to 100.

The tracer propagation in the grid cells for the case with a partition coefficient of 20 showed that during injection, the ester travels further into the reservoir as less ester has partitioned into the immobile phase and hence more of it is available for hydrolysis. This also means that during production, it takes much longer to back produce all of the alcohol due to the distance travelled into the reservoir. For the case with a partition coefficient of 10, it showed that during injection the ester does not travel as far into the reservoir because more of it has partitioned into the immobile phase, so the ester in the mobile fluid will propagate at a lower speed hence keeping it within close vicinity of the well, where it would hydrolyse to form the alcohol. This is then back produced at a much faster rate due to it being a shorter distance from the well. As less ester is available for hydrolysis at a higher K_P value, the maximum concentration of alcohol produced decreases as the partition coefficient is increased

2.2.6 Test schedule

It was important to ensure that the results obtained from these tests were representative of field conditions. The timescale of SWTT tests in the field tends to range between 8 to 10 days. The injection of the ester bank in formation water requires less time because as mentioned previously the ester typically makes up about 1% by volume of the first injection. This is followed by a bank of tracer-free water that is injected in large amounts at the same rate as the tracer bank to ensure complete hydrolysis of the injected tracer. This also ensures that the tracer is swept deep into the reservoir to ensure viable

measurements and results. The total injection continues until a volume of around 318 sm3 (2,000 barrels) is displaced into the formation (Deans 1971). The soaking period is important as this governs the amount of secondary tracer produced. The well is shut-in for a duration of 1-6 days depending on the reactivity of the ester deployed and the reservoir temperature (Deans and Carlisle 1986). In practice the shut-in period can range between 2-8 days to ensure complete hydrolysis of the ester (Fahad et al. 2015). It is required to be long enough for the hydrolysis reaction to proceed from 10% to 50% completion (Deans and Carlisle 1986, Jerauld et al. 2010). In this test the well was shut-in for 7 days after which the well is allowed to back-produce. The rate of production in literature is around 650 bbls/d which roughly equates to 100 sm3/d (Deans 1971). This is the rate applied in the tests to ensure all of the injected partitioning tracer and produced non-partitioning tracers in the formation are produced. To ensure the back production of all of the injected and produced tracers, the production time in this test has been prolonged to 12 days .

2.3   Measuring S_{or}

The industry still produces less than half the oil in the reservoirs discovered, and nearly all that oil is produced using traditional primary and secondary methods. Furthermore, as the cost of finding new reserves continue to increase, especially in the U.S.A., the oil remaining in oil fields become a significant economic target for infill drilling and IOR projects.

In every target field the quantity and location of the remaining oil must be determined. Figure 3 illustrates the principle of material balance, as applied to an oil reservoir. The entire area of the graph represents the reservoir pore volume (V_p), which is known with varying degrees of uncertainty. The produced oil, corrected back to reservoir conditions, is the middle area; its accuracy, however, depends on how thoroughly the production records are kept.
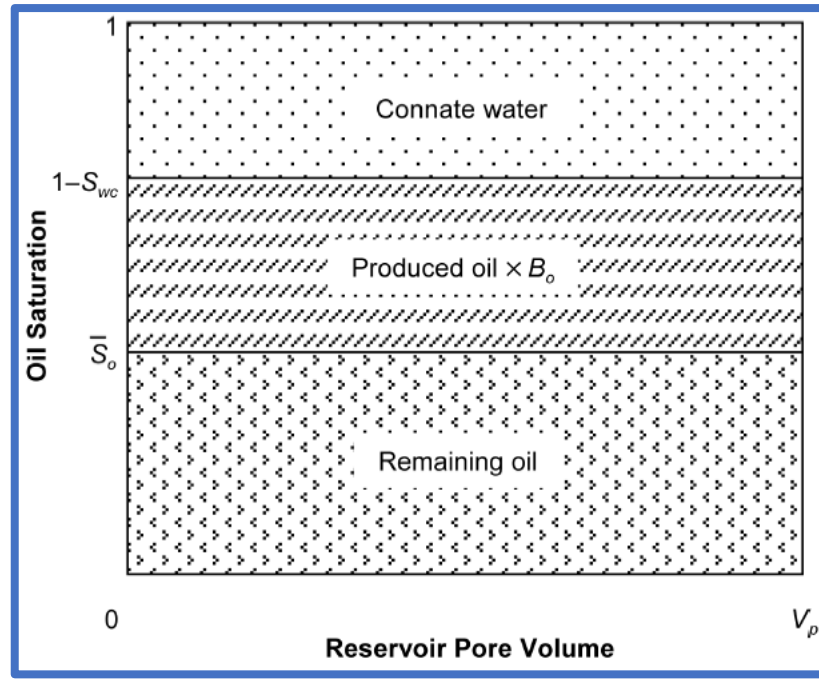
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Figure 3: Reservoir pore volume

The uppermost area is the connate water, which is known only as well as available methods and coverage of measurements allow. The lowermost area, the remaining oil, can be expressed as an average saturation of oil ($\hat{S}_O$), if the total pore volume (V_p), produced oil, and (S_{wc}) values are accurate then are acceptable.

If a given field has been water-flooded. The fraction of the OOIP displaced by the water is a critical parameter. Testing for S_{or} in watered-out wells in the field can determine the maximum water-flood displacement efficiency. A significant difference between the material- balance S_o and the measured S_{or} would indicate the presence of bypassed oil. This would signify that parts of the reservoir had not been contacted by injected water or had not received sufficient water throughput to reach S_{or}. This concept is shown in figure 4

A reliable in-situ measurement of S_{or} simultaneously defines the target for enhanced oil recovery (EOR) and allows estimation of the potential bypassed (mobile) oil in the field. This moveable oil is target for infill drilling and/ or flood sweep efficiency improvements.

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Because S_{or} varies greatly with formation type, oil/ water properties, and other variables that are not completely understood (e.g., wettability changes caused by water-flood practices). S_{or} measurements range from $< 10\% \, to \, 45\% \, >$. There is no reliable way to predict S_{or} with acceptable accuracy for most reservoirs. Laboratory core-floods performed at other than native state wettability are unreliable[11].

Well logs can give vertical profiles of S_{or} under optimal conditions, but their results are not absolute. Logs of all type require calibration by an independent method, which gives either a quantitative S_o at some point or an average S_o over some layer. Pressure cores or sponge cores can provide this calibration, but require a new well and are subject to saturation disturbances caused by mud filtrate invasion.

An advantage of the SWTT is that it pushes tracers beyond damaged regions near the well-bore and into layers that are not known to be at residual oil conditions.

In a SWTT, the formation volume sampled is large enough to be representative. A typical test quickly investigates hundreds of barrels of pore space in an existing watered-out well. The tracer-bearing fluids are produced back into the well without disturbing the formation, allowing further testing.

2.3.1 How the SWTT Works

The SWTT for S_{or} uses only one well and involves the injection and back production of water carrying chemical tracers. A typical target interval for SWTT is shown in figure 2. The candidate well should be completed only to the water-out zone of interest (zone at S_{or}). The water used normally is from the formation to be tested, and often is collected during the initial setup for the test.

The injected volume is divided into two parts: the partitioning tracer bank, which carries a small concentration of tracer (usually some type of ester) dissolved in water, and the push volume of water, which pushed the partitioning tracer bank away from the well-

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bore 10 to 30 ft. A material-balance tracer (normally a water-soluble alcohol) is added to the entire injected volume to differentiate it from the formation water being displaced. This injection step is shown in Figure 6
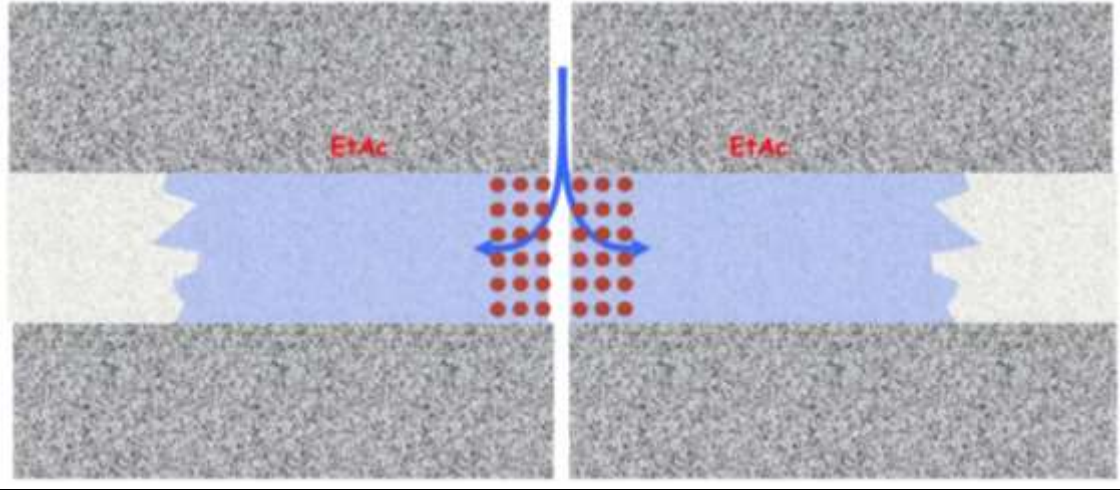
Figure 6: Ester injection through the carrier fluid (brine)

The primary tracer is an alkyl ester. The esters used in SWTT testing usually are more soluble in oil than in water. This solubility preference is expressed quantitatively by the ester's oil/ water partition coefficient, K_P:

$$2. \quad K_P = \frac{C_{eo}}{C_{ew}}$$

Where C_{eo} is the concentration of ester in oil; C_{ew} is the concentration of ester in water; C_{eo} and C_{ew} are values at equilibrium.

For example, if the partition coefficient is four, the ester prefers the oil phase four times more than the water phase. For each tracer to be used in each test, the actual value of K_e must be measured in the laboratory at reservoir conditions. Oil and water samples are collected from the target formation for this purpose.

As the ester tracer enters the pore space containing the residual oil, it partitions between the oil and water phases. The ester maintains a local equilibrium concentration in the oil phase, controlled by the ester's partition coefficient, even though the water is flowing.

Because the oil is stationary and the water is moving, the ester tracer moves more slowly through the reservoir pore space than does the water with which it was injected. the

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ester's velocity thus is a function of the partition coefficient, and the S_{or}. Figure 5.3 schematically shows the radial position of the injected ester and water. The tracer normally alcohol, is nearly insoluble n oil, so that it travels at approximately the same velocity as the water, reaching as far into the formation as the injected water volume.

After the ester and push injections are completed, the well is shut in for one to ten days (in our case for 3.5 days), depending on the reactivity of the ester and the reservoir temperature. This shut-in period allows some of the ester to react with water in the reservoir, which forms a new tracer in-situ, the secondary (or "product") tracer (Alcohol).

Reacting an alcohol and an organic acid makes an alkyl ester. At reservoir temperature, however, when dissolved in water, this ester slowly breaks down again into the alcohol and acid:

$$Ester + H_2O \rightarrow Alcohol + Acid.$$
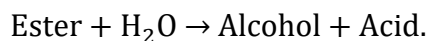
The shut-in period must be long enough for measurable alcohol to form in situ by this reaction.

It is the alcohol formed that makes the S_{or} measurement possible. The acid formed during the reaction is not observed because it is neutralized by the natural base components of the reservoir. The alcohol, however, is not in the original formation water, and can be detected at very low concentrations in the produced water, thus acting as a unique secondary tracer.

At the end of the reaction period, the remaining ester and the product alcohol tracers are located together 10 to 30 ft from the well-bore. The tracers then are ready to be back produced to the well-bore and monitored at the surface in the produced water.

Figure 7 shows the chromatographic separation of the product alcohol and ester tracers. This separation occurs because the product alcohol and water velocities are essentially the same, whereas the ester production velocity is slower because the ester must partition between the oil and water phases during production in the same manner described in the injection step. For an animation of the entire process, see https://vimeo.com/82685062 and http://slideplayer.com/slide/4985706/.
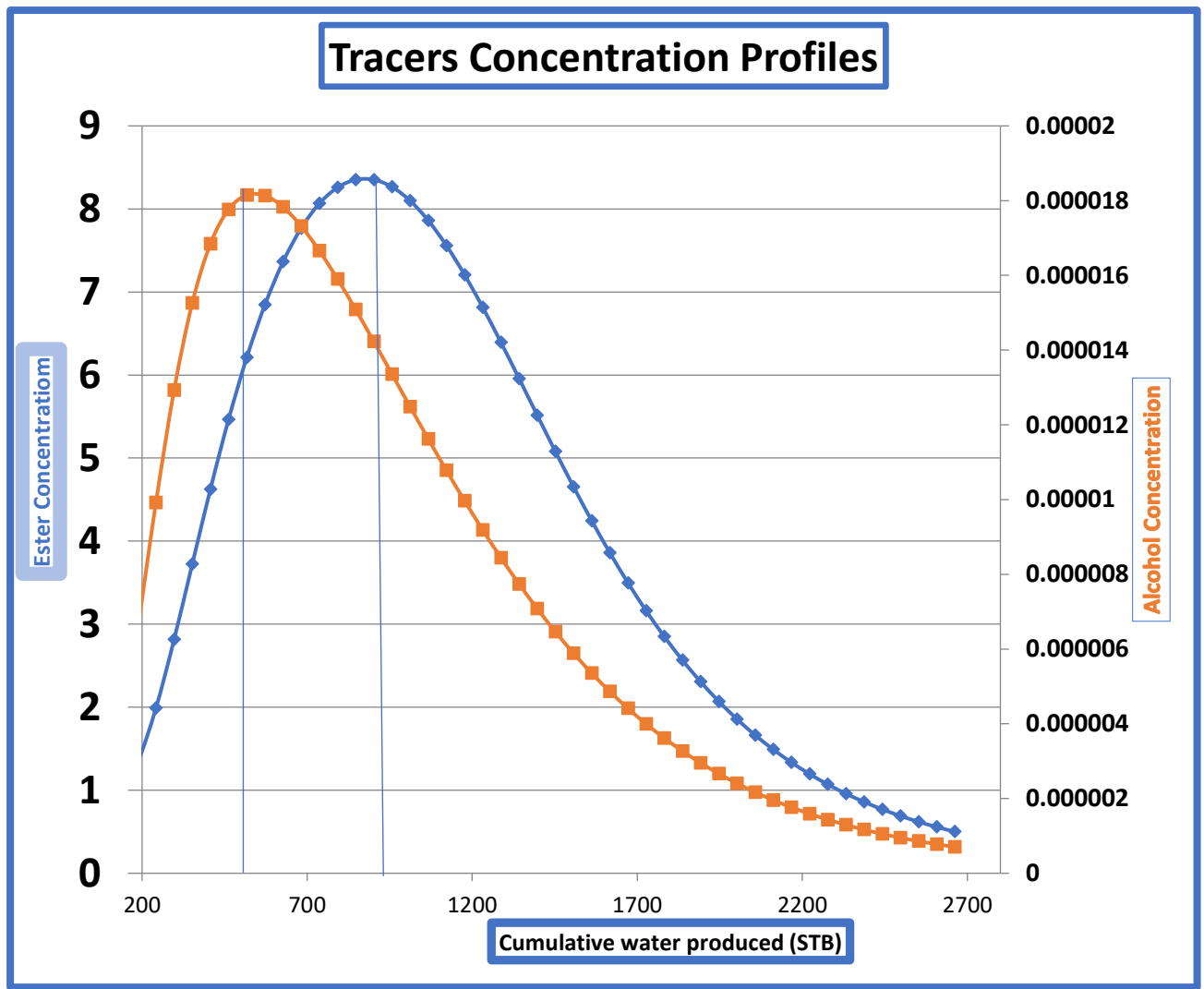
Figure 7: Tracer profiles as produced from Stars Simulator

Throughout the production period, samples of the produced water are collected frequently at the surface. Total produced volume is measured at the time each is taken. At a portable laboratory at the well-site, the samples are analyzed immediately for product alcohol and remaining ester tracer concentrations. A plot of concentration of tracers versus. total volume produced is developed during the production, as the samples are analyzed.

2.3.2 How the SWTT Test Works Quantitatively

The Single-Well Chemical Tracer Test Method for measuring the residual oil saturation

Before discussing the design and interpretation of SWTT tests, we need to establish the quantitative relationship between tracer velocity, the tracer distribution coefficient, and S_{or}. Figure 8 schematically shows a local population of ester tracer molecules in a control volume (V_C) of a pore. The tracer is assumed to be locally in equilibrium, even though the water phase is moving and the oil phase is fixed (residual oil conditions).
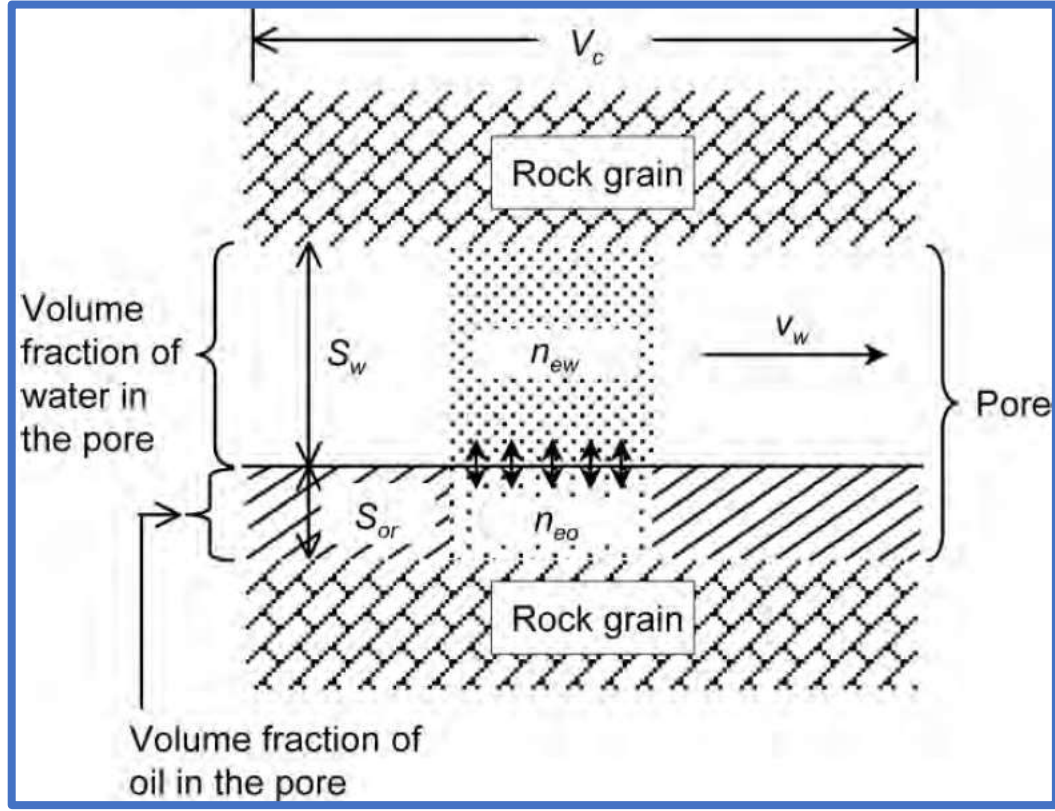
Figure 8: Ester distribution between oil and water pore.

The number of ester molecules in the water (n_{ew}) is given by

3. $$n_{ew} = C_{ew}S_wV_c$$

and the number of ester molecules in the oil (n_{eo}) is given by

4. $$n_{eo} = C_{eo}S_{or}V_c,$$

Where C_{ew} and C_{eo} are the concentration of ester (molecules/ unit volume) in water and oil, respectively; and S_w is the saturation of water, in fraction of PV.

We determine the retardation factor for ester (β_e) by dividing these two equations:

The Single-Well Chemical Tracer Test Method for measuring the residual oil saturation

5. $\quad \boldsymbol{\beta_e} = \dfrac{n_{eo}}{n_{ew}}$

The larger β_e is, the more the ester tracer is retarded by the residual oil. Substituting in equations 5.2 and 5.3 and cancelling V_c yields:

6. $\quad \boldsymbol{\beta_e} = (\dfrac{C_{eo}}{C_{ew}})(\dfrac{S_{or}}{S_w})$

Because $K_e = \dfrac{C_{eo}}{C_{ew}}$ (see eq. 5.1), the equilibrium distribution coefficient of ester between oil and water, and $S_w = 1 - S_{or}$, this becomes

7. $\quad \boldsymbol{\beta_e} = \boldsymbol{K_e}(\dfrac{S_{or}}{1-S_{or}}).$

The typical ester molecule spends a fraction of time (f_t) in water and the rest of its time $(1-f_t)$ in oil. Elementary probability theory requires that

8. $\quad \dfrac{n_{eo}}{n_{ew}} = \dfrac{1-f_t}{f_t}.$

The probable behavior of each tracer molecule is the same as the behavior of large population of identical molecules.

9. $\quad \dfrac{1-f_t}{f_t} = \boldsymbol{\beta_e}$

Solving for f_t:

10. $\quad \boldsymbol{f_t} = \dfrac{1}{1+\beta_e}$

The typical ester molecule will travel at the time-weighted average velocity:

11. $\quad \boldsymbol{v_e} = \boldsymbol{f_t v_w} + (\boldsymbol{1} - \boldsymbol{f_t})\boldsymbol{v_o}$

Where v_e, v_w, and v_o is the time-weighted velocities of the tracer molecule, water, and oil, respectively. Because v_o equals to zero, if oil is at residual saturation, the last two equations combine to give

12. $\quad \boldsymbol{v_e} = \dfrac{v_w}{1+\beta_e}$

The Single-Well Chemical Tracer Test Method for measuring the residual oil saturation

The above equation is the fundamental equation for tracer chromatography in a porous medium, Solving eq. 5.11 for β_e:

13. $\quad \boldsymbol{\beta_e = \dfrac{v_w}{v_e} - 1}$

If we can develop a way to measure v_e and v_w using an in-situ test, then β_e can be evaluated. We then ca measure K_e in the laboratory (at reservoir conditions) and substitute it into eq 5.6 to solve for S_{or}:

14. $\quad \boldsymbol{S_{or} = \dfrac{\beta_e}{\beta_e + K_e}}$

2.4 The SWCTT

Using the SWTT test avoids the problems of too-wide well spacing and excessive tracer dispersion caused by layering. In the SWCTT test, the tracer- bearing fluid is injected into the formation through the test well and then produced back to surface through the same well. The time required to produce the tracers back can be controlled by controlling the injected volume in the basis of available production flow rate from the test well.

In a single well test, tracers injected into a higher-permeability layer will be pushed farther away from the well than those in a lower-permeability layer as indicated in figure 5.8a; however, the tracers in the higher-permeability layer will have a longer distance to travel when flow is reversed. As the tracers profile in fig 5.8b show, the tracers from different layers will return to the test well at the same time, assuming that the flow is reversible in the various layers.

One possible way of avoiding this reversibility problem is to generate the second tracer in the formation instead of injecting it. The steps are: (1) Inject tracer A and push it into the target formation, as described above; (2) Stop flow to allow part of the injected A to react, forming tracer B in the same pore space where A is located, after the reaction time, A and B are together; (3) The fluid is then produced back into the test well; A and B must separate if their equilibrium distribution coefficients (K_A and K_B) are different and if residual oil is present. This concept is the basis for the SWCT test patent[2].

The Single-Well Chemical Tracer Test Method for measuring the residual oil saturation

The practicability of this method depends on finding suitable tracers. The demands on partitioning tracer A (Ester) are especially severe: inexpensive, available in reasonable quantities at high purity, nontoxic, not present in the reservoir fluids, and easily measured at low concentrations in water. It must have an appropriate K_P for the oil, water, and temperature of the target field, and, most importantly, it must react at a rate that allows formation of enough (but not too much) of a suitable tracer B (Alcohol). K_B must be different from KA, and tracer B also must be measurable at low concentrations in the produced water, and not be present in the reservoir fluids.

A methyl, ethyl, or propyl ester of formic or acetic acid has proved suitable in every reservoir tested. These simple chemicals are sufficiently soluble in water, and have an appropriate range of K_P values and reaction rates. They are relatively inexpensive and nontoxic at the concentrations used, and they react with water to produce alcohols, which are not found in crude oils and can be detected readily in the produced fluid.

For best results[12], choose an ester with a retardation factor (β_e) in the optimum range ($0.5 < \beta_e < 1.5$). This requires that K_e be in the range $0.5 (1.0 - S_{or}) / S_{or} < K_e < 1.5 (1 - S_{or})/S_{or}$. Use the best available estimate of S_{or} to fix this range. Then choose the optimum ester using available correlations[13] for the dependence of K_e on temperature and water salinity. In several past SWTT tests, two esters (e.g., methyl acetate and ethyl acetate) were used simultaneously to give two different depths of investigation for S_{or} in the same test. The multiple ester test design has become increasingly popular in recent years.

2.4.1 Test design

The design and implementation of a SWTT test for S_{or} is straightforward. Certain facts about the target formation are needed to begin test design. Some essential reservoir properties include oil cut of the test well; reservoir temperature; reservoir lithology; production rate; test interval size and average porosity; and formation water salinity.

Oil Cut of Test Well.

The Single-Well Chemical Tracer Test Method for measuring the residual oil saturation

Candidate wells for S_{or} measurement must be able to produce formation water to the surface. The produced fluid should be nearly all water to ensure that the test interval is at or near the S_{or}. In cases where the test interval produces high oil cut, water can be injected into the test interval before testing to water-out the zone before tracers are injected.

Reservoir Temperature.

Reservoir temperature dictates which esters are suitable for the SWTT. The formate esters hydrolyse approximately 50 times faster than do the acetate esters, and are used in the reservoir temperature range of 70 to 135°F. The slower-reacting acetate esters generally are used in the 130 to 250°F range.

Reservoir Lithology.

SWTT has been done in a variety of test conditions. In sandstone reservoirs, SWTT tests give satisfactory results for a wide range of test designs. Test timing, total injected volume, and the ester used can vary considerably for the same zone, with little effect on test interpretability. However, SWTT in carbonate formations require much more precise design. In a given carbonate test zone, subtle changes in test design can cause significant variation in the tracer profile shapes. Each of the past carbonate test designs has required significant tailoring to overcome the dispersed nature of the production profiles generally present in carbonate test results[14]. The reason for this dispersed nature is that the assumption of local equilibrium is not always valid for carbonate reservoir tests.

Production Rate.

The production rate of the candidate well controls the test size or volume to be injected. The amount of water that can be produced in one day is a normal test volume; two days' production is a practical upper limit. In normal productivity reservoirs, the injection is sized to give a 15- to 30-ft depth of investigation into the formation. The injection rate of the SWTT test usually is approximately the same as the well's production rate. Care must be exercised to avoid fracturing the formation during test injection.

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2.5 Field procedures

After selecting the ester and sizing the test volume, determine the field-test location, production method, and safety requirements. Then, schedule and implement the test. Four lift methods have been used in SWTT testing. They are free flow, electric submersible pump, rod pump, and gas lift. These lift mechanisms are listed roughly in order of desirability, but all are satisfactory.

Before the field test, the candidate well should be produced long enough to establish the oil cut, measure the stabilized production rate, and clean up the tubular goods in the completion. Then accumulate produced water for the upcoming test in clean tanks near the well. Position the portable laboratory/pumping system near the test well.

Pure tracer chemicals usually are delivered to the wellsite in 55-U.S.-gal drums. The tracers either can be batch-mixed with formation water before injection, or continuously metered into the water during injection. For batch mixing, the tank can serve as the mixing vessels. With either batch-mixing or continuous metering, filter the water to one-micron or higher quality to prevent plugging when the fluids enter the reservoir. After a short period for analytical equipment checkout, inject the chemical solution of ester and push it according to test design. Samples of the injection water should be analyzed periodically to verify tracer concentrations, volume rate, and pressure information should be monitored carefully throughout the injection. Be careful not to part the formation by exceeding the fracture gradient. Once the injection is complete, the well is secured for the planned shut-in period. When the shut-in period is over, the well is placed on production.The produced water flows through a portable separator (if necessary) to the storage tanks on location, where its volume is carefully measured. Production volume also can be measured using a field production test separator, if one is available.

During production, water samples should be taken near the wellhead and analyzed on location for tracer concentrations. On-site chemical analysis is necessary to gather data that are accurate for the time of production, whereas sending the samples to a service laboratory for analysis would allow additional hydrolysis of the ester to take place

The Single-Well Chemical Tracer Test Method for measuring the residual oil saturation

during transport. At the time each sample is taken, the total production volume is recorded and plots of tracer concentration versus. volume produced are generated. These tracer concentration profiles are the essential field data for the SWTT test. Because of dispersion, the total produced volume required normally is two to three times the injected test volume. Injected volume usually is one day's production, and two to three days normally are required for the back-production phase of a SWTT.

2.5.1 Test Data Interpretation

Tomich et al.[1] report one of the earliest SWTT tests, which was performed on a Frio Sandstone reservoir on the Texas Gulf Coast. The results of this test are used here to demonstrate the details of SWTT interpretation for an ideal situation. The test well in the Tomich et al.[1] report was in a fault block that had been depleted for several years. Because of the natural water drive and high permeability of the sand, the formation was believed to be near true S_{or}. When the well was returned to production (gas lift), it produced 100% water at a rate of 1,000 BWPD. On the basis of observed reservoir temperature (160°F) and brine salinity [100,000 ppm] total dissolved solids (TDS), ethyl acetate was chosen as the primary tracer. Formation oil and water samples were obtained for laboratory measurement of K_e at reservoir temperature conditions. The value of K_e measured for ethyl acetate was 6.5 at these conditions.

The test injection consisted of 1,000 bbl of formation water carrying ethyl acetate (13,000 ppm) and methyl alcohol (5,000 ppm), followed by a push bank of 1,000 bbl of formation water carrying methyl alcohol (5,000 ppm), injected over a period of two days. An eight-day shut-in period followed. During the production period, samples were collected regularly and analyzed on site using gas chromatography. The observed data are plotted as tracer concentration versus. produced volume

In ideal cases, when enough data have been gathered to define the tracer profiles, it is possible to use Eqs. 5.11 through 5.13 to approximate S_{or} in the field. If product tracer B and unreacted ester A begin together in the formation, the produced volume when A arrives back at the well (Q_{pA}) is related to the produced volume when B arrives (Q_{pB}) by the formula:

15. $$Q_{pA} = Q_{pB}(1 + \beta_A)$$

where Q_{pA} and Q_{pB} are in bbl.

This suggests that if on the same graph we plot normalized concentration of A vs. volume produced Q_{pA} and normalized concentration of B vs. $Q_{pB}(1 + \beta_A)$, the two curves should coincide.

Because we do not know β_A, this must be done by trial and error (i.e., β_A is adjusted until the best possible match of the two profiles is found).

Fig. 5.13 demonstrates this procedure. Profiles from the SWCT test (Fig. 5.12) first were normalized by dividing each observed concentration by the peak value measured for that tracer. β_A then was varied to obtain the plot shown. The best-fit value for β_A was 0.97.

Using Eq. 5.13, the S_{or} is approximated as

16. $\quad S_{or} = \dfrac{\beta_A}{\beta_A + K_A} = \dfrac{0.97}{0.97 + 6.5} = \mathbf{0.13}$

Chapter 3

Equations

3.1   Introduction

Interpretation of SWTT based on analytical modeling is possible when the produced tracer curves display a single maximum or peak and a tail with decaying concentration that can be described with a known function (e.g. exponential, logarithmic) and assuming negligible hydrolysis during injection and production. In complex reservoir settings (e.g. multilayer test zones, drift, cross-flow), simulation tools capable of handling the hydrolysis reaction must be used (Jerauld et al., 2010; Skrettingland et al., 2011). In practice, coupled flow and chemical reaction simulators, such as STARS (CMG, 2012) and UTCHEM (2000), are often used. Other approaches, exploiting the decoupling of tracer and fluid flows, where the tracer problem is stated and solved based on previously solved and stored reservoir simulation runs is also possible (Eclipse) (Sagen and Huseby, 2009; Huseby et al., 2010).

The assumptions made in deriving the mathematical description of a tracer test are: the fluids are incompressible, the oil phase is immobile, the chemical reaction occurs only in the brine phase, equilibrium mass transfer is achieved the tracer mass flux is small compared with the mass flow rate of water and that the formation is homogeneous and isotropic.

Single-well tracer tests are based on injection of an ester into the reservoir. Some of the tracer (ester) hydrolysis during a shut-in period, producing alcohol. The subsequent production of the ester and the alcohol yields tracer production curves that can be used to directly estimate the oil saturation. Commonly utilized esters in SWTTs are propyl formate and ethyl acetate. Symbolically, the hydrolysis reaction can be written as

17. $CH_3\,COOCH_2\,CH_3 + H_2\,O \leftrightarrows CH_3\,CH_2OH + CH_3\,COOH$
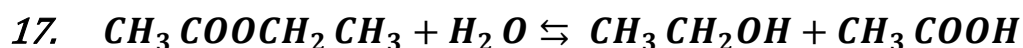
i.e. a reaction where ethyl acetate ($CH_3 \, COOCH_2 \, CH_3$) and water hydrolyses and forms ethanol ($CH_3 \, CH_2 OH$) and acetic acid ($CH_3 \, COOH$).

In water-flooded area close to residual oil saturation, oil flow rates may be negligible compared to the water flow rates. In such cases oil saturation can be determined by differences in retention times of a partitioning and non-partitioning (passive) water tracer. Oil saturation is given by the following expression

18. $S = \dfrac{(t_2 - t_1)}{(t_2 + t_1(K-1))}$

Where t_1 and t_2 are the retention times of the non-partitioning and partitioning tracer, respectively, S is the residual oil saturation, and K is the partition coefficient of the partitioning tracer. If K is known, the residual oil saturation can be estimated from the measured difference in the arrival times between the non-partitioning and the partitioning tracer.

Transport equation for partitioning tracers

If and only if the partitioning among the phases is an instantaneous process, a conservation equation for an arbitrary partitioning tracer component can be described by

19. $\dfrac{\partial}{\partial t}\left(\sum_{i=o,g,w} \varphi S_i K_i^q C^q\right) + \nabla \cdot \left(\sum_{i=o,g,w} v_i K_i^q C^q\right) - \nabla \cdot \left(\sum_{i=o,g,w} \varphi S_i D_i^* \cdot \nabla\left(K_i^q C^q\right)\right) = 0$

Partitioning is described by the coefficient,

20. $K_i^q = \dfrac{C_i^q}{C^q}$

where C_i^q is the concentration of q in phase i and C^q is concentration in a reference phase.

For oil/ water partitioning with water as the reference phase, this gives $K_o^q = \dfrac{C_o^q}{C^q}$ and $K_w^q = \dfrac{C_w^q}{C^q} = 1$. Furthermore in Equation 11 , φ is porosity, S_i is phase saturation (S_o, S_g, S_w, where the subscripts o, g and w indicate oil, gas and water phase respectively), v_i is the

velocity of phase i and D_i^* is the dispersion in phase i. The dispersion is a tensor quantity with different components $D_{\parallel}^*$ along and $D_{\perp}^*$ normal to the flow. In porous media dispersion is well described by

$$\frac{D_{\perp}^*}{D_m} = \frac{1}{\tau} + \beta_{\perp} N_{Pe}^{\alpha\perp} \quad \frac{D_{\parallel}^*}{D_m} = \frac{1}{\tau} + \beta_{\parallel} N_{Pe}^{\alpha\parallel}$$

Where τ the tortuosity of the porous medium and the α and β coefficients depend on the media. The Peclet number is given from velocity, molecular diffusion coefficient and grain size $N_{Pe} = \frac{vd}{D_m}$.

ESTER REACTION MODELLING

The hydrolysis of ester depends on pH and temperature (Wellington, 1994) and a full modeling of this reaction requires at least the four components in Equation 2 are taken into account. However, if we assume that water is abundant and that the buffering capacity in the formations are large enough to remove the acid ($R_1 COOH$) effectively, the reaction can be simplified and viewed as a "decay" of ester into alcohol:

21. $R_1 COOR_2 \rightarrow R_2 O$

With a constant reaction rate k.

In equation 2 the mass balance is inherently correct, which is not true for the simplified reaction (equation1). What is true is that one molecule of ester reacts so that one molecule of alcohol is produced. Consider a fixed space volume V. In principle, the reaction may take place in any of the phases present in the volume V. Reaction total loss of ester mass density in V, can be described by the equation

22. $\frac{\partial m_e}{\partial t} = \sum_{i=o,g,w} \varphi S_i k_i^e C_i^e$

Here, k_i^e is the rate of reaction 3, C_i^e is the ester concentration in phase i and m_e is the mass density of ester in volume V. Note that equation 4 is valid even when the saturations S_i and porosity φ vary in time.

Similarly, the mass density of the produced alcohol is given by

23. $\dfrac{\partial m_e}{\partial t} = \dfrac{M_a}{M_e} \sum_{i=o,g,w} \varphi S_i k_i^e C_i^e$

Where M_a and M_e are the molecular mass of alcohol and ester, respectively.

A physical interpretation of equations 4 and 5 can be given in a simple example. Consider a fixed volume V of water where the reactions 4 and 5 take place. The mass density m_e is then identical to the concentration C_{ew}. Likewise, m_a is identical to C_w^a. Equations 4 and 5 become (cancelling out the porosities):

24. $\dfrac{\partial C_w^e}{\partial t} = -k C_w^e$

25. $\dfrac{\partial C_w^a}{\partial t} = k C_w^e \dfrac{M_a}{M_e}$

Thus, the ester and acid concentration as a function of time becomes

26. $C_w^e(t) = C_0 e^{-kt}$ and $C_w^a(t) = C_0(1 - e^{-kt})\dfrac{M_a}{M_e}$

This means that while the ester is undergoing an exponential decay, the alcohol concentration grows accordingly. Note that the above equation is valid because water is the only phase. In general, the ester undergoes partitioning between water and oil, saturations may vary in time and space, the ester and alcohol components are subjected to varying phase velocities and are subjected to physical dispersion varying with the phase velocities. These effects must be accounted for the simulator used during the SWTT.

It should be noted that the above equations are valid because water is the only phase. In general, the ester udergoes partitioning between water and oil, the saturations vary in time and space, the ester and alcohol components are subjected to varying phase velocities and are subjected to physical dispersion varying with phase velocities. Therefore, the transport-reaction equation for ester as

27. $\dfrac{\partial}{\partial t}\left(\sum_{i=o,g,w} \varphi S_i K_i^q C^q\right) + \nabla \cdot \left(\sum_{i=o,g,w} v_i K_i^q C^q\right) - \nabla \cdot \left(\sum_{i=o,g,w} \varphi S_i D_i^* \cdot \nabla\left(K_i^q C^q\right)\right) = 0$

For alcohol

28. $\frac{\partial}{\partial t}\left(\sum_{i=o,g,w}\varphi S_i K_i^q C^q\right) + \nabla \cdot \left(\sum_{i=o,g,w} v_i K_i^q C^q\right) - \nabla \cdot \left(\sum_{i=o,g,w}\varphi S_i D_i^* \cdot \right.$
$\left. \nabla(K_i^q C^q)\right) = 0$

29. $C_w^a(t) = C_0(1 - e^{-kt})\frac{M_a}{M_e}$

Note that the 2-component system of equations above should be solved simultaneously. However, the equations are only 1-way dependent. Hence the simulator solves the ester equation first and then the second equation for the alcohol once the ester concentration Ce has been determined.

Because tracers do not influence the fluid flow in the reservoir, simulation of tracer transport may be performed in a separate module decoupled from the reservoir simulation itself. This was exploited by Sagen et al. (1996), who solved for tracer transport using flow solutions obtained through integration of a modular tracer code with a "host" reservoir simulator. This modular method allows coupling to any black oil or compositional simulators, if he necessary information can be obtained from the host reservoir simulator. It also allows for a separate time and space discretization of tracer equation, which was used by Sagen et al. (1996) to obtain accurate tracer flow solutions.

Partitioning coefficient and hydrolysis reaction rate

Equation 10 gives a relation between saturation, retention times and partition coefficients in SWTTs. For field applications, the saturation S is unknown and subject to estimation based on production curves and known values of K.

The hydrolysis is controlled by a reaction rate, which depends on pH and temperature. Temperature may be uncertain for reservoir applications but can usually be assumed to be constant during a SWTT. In reservoir applications pH can be considered to be unknown, ans is also difficult to control in experimental setups. One reason for this is that a product in the hydrolysis reaction is an acid. Rather than attempting to estimate a

hydrolysis rate, we treat hydrolysis rate as a matching parameter. Note that for field applications for the estimation of the saturation of oil or water, an accurate knowledge of the reaction rate is not necessary. It is sufficient to know that the reaction rate is large enough that the ester will hydrolyze to produce alcohol in quantifiable amounts and that the reaction rate is small enough that not all the ester will hydrolyze.

3.2 Stars

Water and Oil Phase Tracers

The use of chemical or radioactive tracers is an important experimental means of establishing the separate, tortuous flow paths of gas, water and oil phases as they flow through a porous medium. [15] The most important idea is that this information is scale dependent, and useful data emerges at any scale, fom small cores to field wide levels. Tracers   profiles are normally analyzed in terms of effective dispersion coefficients for unit mobility displacemet. The influence of permeability variation (as measured, for example by Dykstra- Parsons coefficient) and auto correlation lengths on these effective coefficients has been subject to renewed interest.

Tracers are normally chosen such that they partition into one phase only and which don't interact in any way with the other phases present (e.g. don't absorb on the rock or don't blug flow pathways, etc.). In specific cases, tracers partitioning into another phase can prove useul – e.g. radioactive water injected as steam can also be analyzed in produced water and steam phases. As referenced above, tracer analysis has been primarily employed to yield well to well communication information. However, single well tracer studies are also used to determine residual oil satrurations.

Overview

These equations are the result of expressing all the relevant physical phenomena in mathematical form. The equations are reviewed here so that the user of a isothermal

model can understand why input data is required, where it is used, and how the various property models are related to the final result.

There is one conservation equation for each chemical component for which a separate accounting is desired, along with some equations describing phase equilibrium between phases. There exists a set of these equations describing for each region of interest, which is usually a discretized grid block. Lastly, there is an equation describing the operating condition of each injection and production well.

Conservation Equations

A conservation equation is constructed for each component of a set of identifiable chemical components that completely describe all the fluids of interest.

3.2.1 Chemical Reaction and Interphase Mass Transfer Source/Sink Terms

The reaction source/sink term for component i is

$$V \sum_{k=1}^{n_r} (s'_{ki} - s_{ki}) r_k$$

1. S'_{ki} is the product stoichiometric coefficient of component I in reaction k.

2. S_{ki} is the reactant stoichiometric coefficient of component I in reaction k.

3. r_k is the volumetric rate of reaction k.

3.3   Eclipse

3.2.1 The Environmental tracer model

As for passive tracers, the flow of an environmental tracer through theporous medium is assumed to have no influence on the flow of the water and hydrocarbon phases as well as the flow of tracers. Environmetal tracers are therefore solved in a similar fashion to passive tracers at the end of a time step after convergence of the oil, water and gas equations.

For an environmental tracer present in a single phase the governing equation is

30. $\frac{\partial}{\partial t}\left(\frac{VSC}{B}\right) + \frac{\partial}{\partial t}\left(V\rho_r C^a \frac{1-\Phi}{\Phi}\right) = \Sigma\left[\frac{Tk_r}{B\mu}(\delta P - \rho g D_z)C + DFD_C S\delta C\right] + QC - V\left(\frac{S}{B}\right)\lambda C$

Where,

S denotes the host phase saturation, C denotes the flowing tracer concentration, C^a denotes the adsorped tracer concentration, ρ_r denotes the mass density of the rock formation, Φ denotes the porosity, ρ denotes the host phase density, μ denotes host phase viscosity, D_Z denotes the cell center depth, B denotes the host phase formation volume factor, T denotes the transmissibility, k_r denotes the host phase relative permeability, V denotes the block pore volume, Q denotes the host phase production rate, P denotes the host phase pressure, g denotes the gravity acceleration, D_C denotes the tracer diffusion coefficient, DF denotes the diffusivity, λ denotes the tracer decay constant and Σ denotes the sum over neighboring cells.

Chapter 4

Refined Cells

4.1   Introduction

In solving fluid flow problems, we need to be aware that the underlying physics is complex and the results generated by a code are at best as good as the physics (and chemistry) embedded in it and at worst as good as its operator. Elaborating on the latter issue first, the user of a code must have skills in a number of areas. Prior to setting up and running a simulation there is a stage of identification and formulation of the flow problem in terms of the physical and chemical phenomena that need to be considered.

Typical decisions that might be needed are whether to model a problem in two or three dimensions, to exclude the effects of temperature or pressure variations on the density of fluid flow, to choose to solve the flow equations or to neglect the effects of small air bubbles dissolved in the reservoir water. To make the right choices requires good modelling skills, because in all but the simplest problems we need to make assumptions to reduce the complexity to a manageable level whilst preserving the salient features of the problem at hand. It is the appropriateness of the simplifications introduced at this stage that at least partly governs the quality of the information generated by CFD, so the user must continually be aware of all the assumptions, clear-cut and tacit ones, that have been made. Performing the computation itself requires operator skills of a different kind. Specification of the domain geometry and grid design are the main tasks at the input

stage and subsequently the user needs to obtain a successful simulation result. The two aspects that characterise such a result are convergence and grid independence. The solution algorithm is iterative in nature, and in a converged solution the so-called residuals – measures of the overall conservation of the flow properties – are very small. Progress towards a converged solution can be greatly assisted by careful selection of the settings of various relaxation factors and acceleration devices. There are no straightforward guidelines for making these choices since they are problem dependent. Optimisation of the solution speed requires considerable experience with the code itself, which can only be acquired by extensive use. There is no formal way of estimating the errors introduced by inadequate grid design for a general flow. Good initial grid design relies largely on an insight into the expected properties of the flow. A background in the fluid dynamics of the particular problem certainly helps, and experience with gridding of similar problems is also invaluable. The only way to eliminate errors due to coarseness of a grid is to perform a grid dependence study, which is a procedure of successive refinement of an initially coarse grid until certain key results do not change. Then the simulation is grid independent.

Preliminary simulations were performed with varying grid block refinements both around the wellbore and the reservoir itself. Cells of 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.5, 2.0, 3.0, 4.0, and 5.0 (Δr) were used. Figure …. shows the simulation results in terms of the reactive and product tracers' profiles. As expected due to lower numerical dispersion, higher peak concentrations are obtained with finer grids. However, in terms of the conventional SWTT interpretation which uses the reactive and product tracers' peaks to estimate the residual oil saturations, an estimate of residual oil that is consistent with the simulation input value was obtained with refined cells of 1.0 ft.
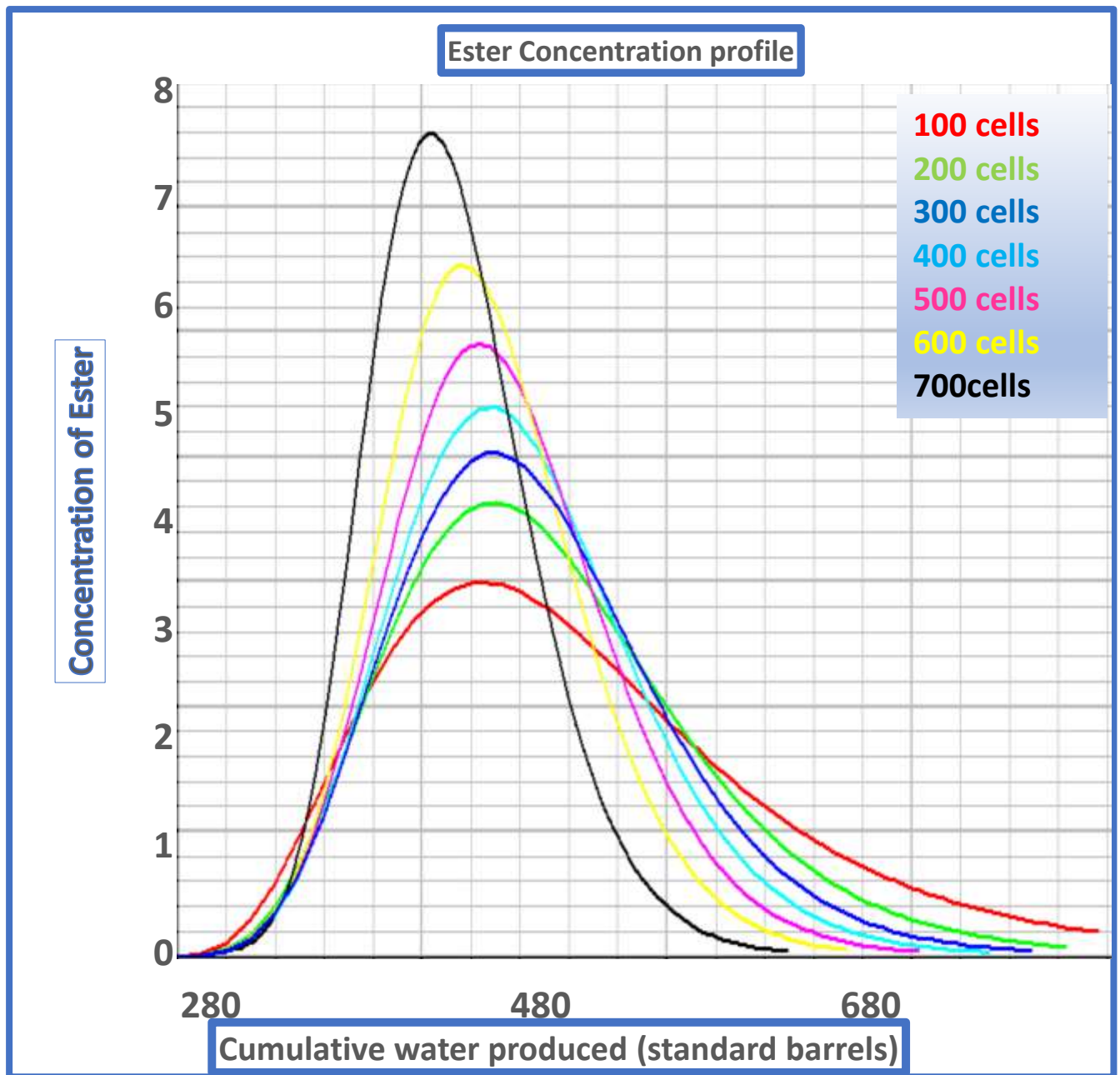
Refined Cells

Figure 4: Effect of refining grid size of the SWTT simulation

The same procedure applied to both simulators so that the simulation is grid independent.

Chapter 5

Partition Coefficient

5.1   introduction

The partition coefficient determines the amount of tracer that partitions into the oil and water phases. This is an important parameter as it directly affects the amount of recoverable ester and alcohol that is produced. This was test it using the homogeneous chemical reaction model (Stars C.M.G. Stars.

The quality of the numerical simulation it can be seen by means of least square difference between numerical solution and field data. For each individual scenario of different residual oil saturations performed partition coefficient analysis in order to match the field data.

In the following diagrams it can be seen an upward trend of the Ester while increasing the Partition coefficient.

The best matching curves are the ester with partition coefficient 100 while all the rest models are supplementary in order to understand the hydrolysis behavior.
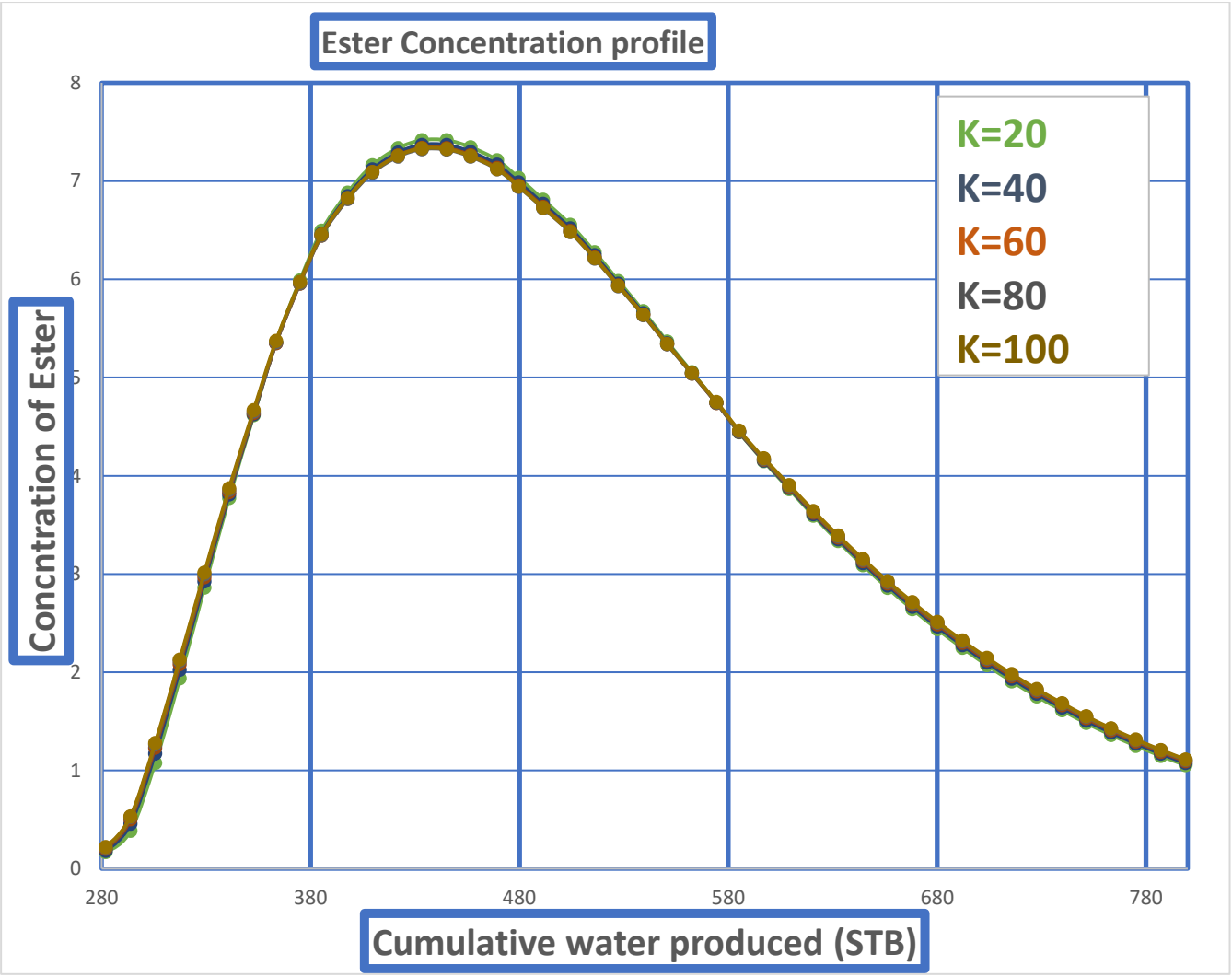
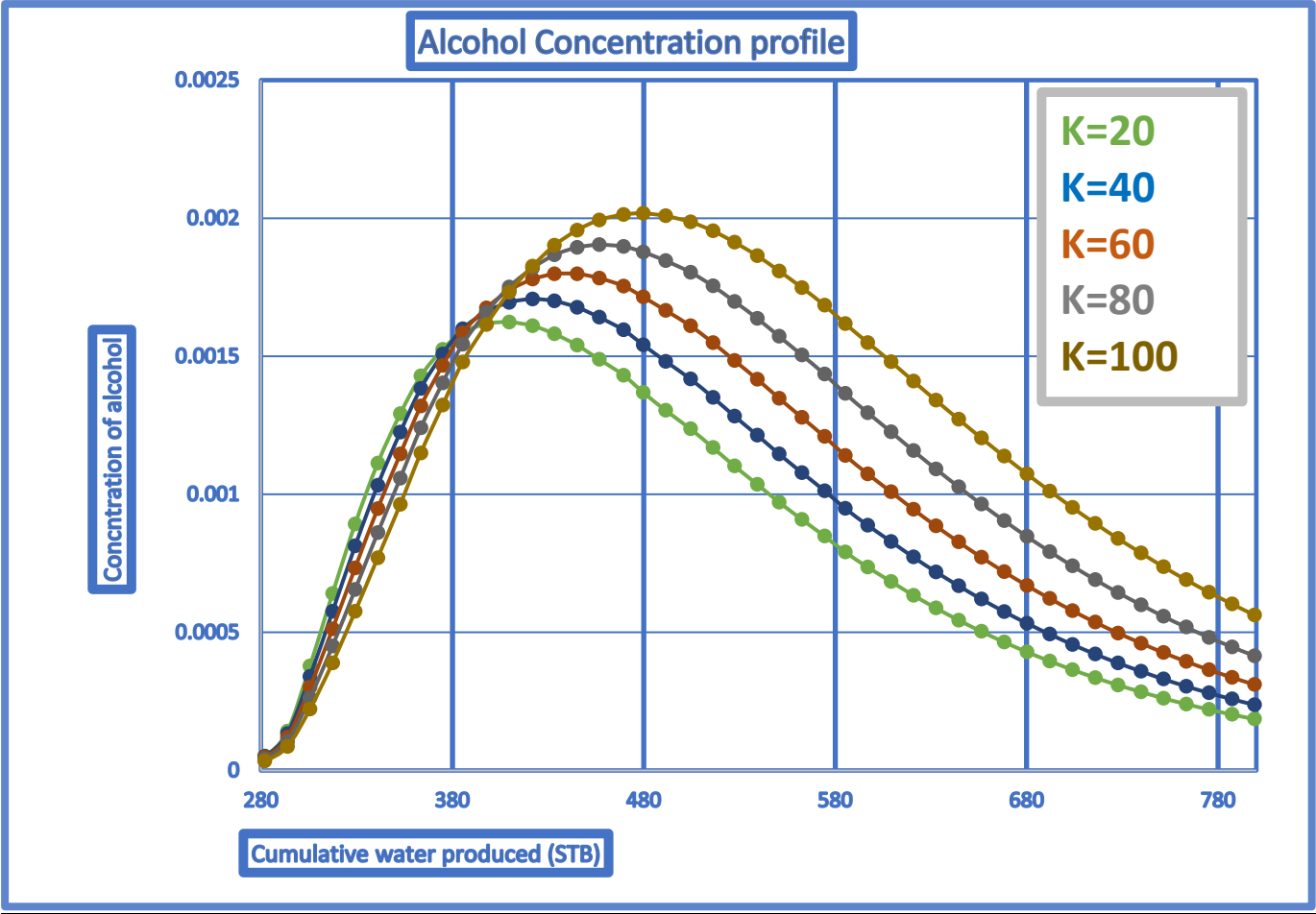*Figure 59: Ester concentration profiles with various Partition coefficients*

Figure 610: Alcohol concentration profiles with various partition coefficient

Chapter 6

6.1 Conclusion

Most reported SWTT operations use ethyl acetate (EtAc) as a reacting tracer in addition to normal propyl alohol (NPA) and isopropryl alcohol (IPA) as a cover-tracer and mass-balance tracers. These tracers are at concentrations of about 1%[16] (Wellington and Richardson, 1994; Seccomble et al., 2008; Skrettingland et al., 2011), which requires large amounts (≈ 1000 kg) of highly flammable and volatile liquid tracers, with obvious health and safety issues. Depending on reservoir conditions, such as temperature, alternative esters (e.g., methyl or propyl formates) are sometimes used, albeit at similar quantities and with comparable properties.

Furthermore, the large amounts of ester and alcohol tracer used in SWTT operations also pose several technical risks and uncertainties. The first potential problem is that large amounts of chemicals – that are often good solvents for oil, may unintentionally introduce some uncertainties in the oil saturation measurement in the near well bore zone. This as an obvious disadvantage, given that SWTT is used to measure oil saturations resulting from the drainage strategy deployed prior to the SWTT. A second issue is that during hydrolysis, acid is formed in addition to alcohol according to the reaction 1.

The amounts of acid produced may affect pH in the near well zone, unless it is neutralized by the buffer capacity present in the reservoir. Because the hydrolysis rate depends on pH, the formation of acid in the reaction may inadvertently affect the reaction[16] (Wellington and Richardson, 1994). This is another source of uncertainty that may affect the results as hydrolysis rate is important during design and evaluation of SWTT results.

In the single-well tracer test, a primary tracer bank consisting of ethyl acetate tracer dissolved in formation water is injected into a formation that is at residual oil saturation. This bank is followed by a bank of tracer-free water. The well is then shut in to permit a

portion of the acetate to hydrolyze to form ethanol, the secondary tracer. Finally, the well is produced and the concentration profiles of the two tracers are monitored.

Ethyl acetate is soluble in both the water and oil phases, but ethanol is, for all practical purposes, soluble in the water phase. As a result, the ethanol travels at higher velocity and returns to the wellbore earlier than does the ethyl acetate. The difference in arrival times can be used to determine the residual oil saturation through the use of computer programs that simulate the tracer test (the greater the oil saturation, the greater the difference in arrival times). Numerous field tests have demonstrated the reliability and applicability of this technique.

Since 1971, the SWTT technique has been used in more than 200 sandstone and carbonate reservoirs. The SWTT is used to quantify oil near the well region only (Deans and Carlisle, 1986; Sinha et al., 2004; Valestrand et al., 2010). However, the SWTT generally yields more rapid results. Thus, the SWTT was the most frequently used application of partitioning tracers for measuring the SOR in the 1990s (O' Brien et al., 1978; Tang,1995) and it is still considered more practical than any other application for SOR measurements. (Somaruga et al., 2001).

After a shut-in period of several days, the two tracers, ester and alcohol, are back produced. The interpretation of this test requires the knowledge of the partition coefficient K_{ow} and the hydrolysis rate of the ester in the reservoir (determined in laboratory studies) (O' Brien et al., 1978). The difference in time between the alcohol (which travels faster than the ester) and ester peaks is a direct measure of the SOR, for a homogeneous system (Buijse et all., 2010; O' Brien et al., 1978; Deans, 1978).

The most commonly used tracers are esters of formic and acetic acids (Keller and Linda, 1972): methyl acetate (K_{ow} =0.869; K_{ow}=1.92 (Deans, 1978; Dijk et al., 2010;Sheely and Baldwin, 1982; Tang and Zhang, 2001)), ethyl acetate (K_{ow}=2.786 (Keller and Linda, 1972); K_{ow}= 4.65 (Buije et al., 2010; Chang et al., 1988; Cockin et al., 2000; Deans, 1978; Hernandez et al., 2002b; Jerauld et al., 2010; Tomish et al., 1973; Wellington and Richardson, 1994)), isopropyl acetate (K_{ow}= 8.478; K_{ow}= 8.20 (Deans, 1978; Sheely and Baldwin, 1982)), ethyl formate (Bragg et al., 1978; Gardien et al., 1996; Shook et al., 2009; Stoll et al., 2010; Taluldar and Instefjord, 2008), or propyl formate (Bragg et al., 1978; Cayias et al., 1990; Myal and Wesson, 1981; O' Brien et al., 1978; Sheely, 1978).

Among these compounds, propyl formate was one of the first tracers used because of its fast reaction rate (Deans and Mut, 1997). The low molecular-weight esters, particularly ethyl acetate, are suitable for temperatures up to 121 °C (Deans and Ghosh, 1994). However, methyl formate is insuitable because it hydrolysis too rapidly under reservoir conditions (Tang and Zhang, 2001)

These tracers are always co-injected with non-partitiong tracers, usually alcohols (NPA, IPA, n-propanol, methanol, 2-propanol) (Cockin et al., 2000; Game, 1992; Hernandez et al., 2002b; McGuire et al., 2005; Othman et al., 2007; Stoll et al., 2010; Tang and Zhang, 2001; Wellington and Richardson, 1994) They are useful for the material balance (to identify the water that contained the ester, Cockin et al., 2000). They are also used as backup tracer (n-propanol) (Hernandez et al., 2002b)

In Certain test, butanol (a partitioning tracer with a K very close to that of the primary tracer, methyl acetate) was also co-injected with the primary tracer (Tang and Zhang, 2001).

Tracer concentration (alcohol, ester) are generally analyzed on site by GC methods (Deans, 1978; Dijk et al., 2010; Hernandez et al., 2002b; Othman et al., 2007; Sheely and Baldwin, 1982; Tang and Zhang, 2001), particularly headspace gas chromatography (Garnes, 1992).

The passive tracer has the same physico-chemical properties as the fluid in which it is injected (water). Also called a "non-partitioning" or "aqueous" tracer, it moves at the approximate velocity of the water phase without chemical reaction or interaction (sorption, ion-exchange) with reservoir phases (formation water, oil) or with the rock as it moves through the oil reservoir (Asadi and Shook, 2010; Guan and Du, 2004; Huseby et al., 2009; Oyerinde, 2004; Shook et al., 2009). In fact, a tracer classified as passive will never be totally passive because of the small amount of adsorption and desorption that occurs.

The partitioning tracer is soluble in both the oil and water phases (Knaepen et a., 1990). This partitioning phenomenon with the oil phase (physical and chemical interactions with the rock or the fluids) causes a "chromatographic delay" in the response of the partitioning tracer in comparison with the passive tracer (Jin et al., 1997; Oyerinde,

2005; Tang, 1995). Four mechanisms can affect this delay: a partitioning tracer in comparison with the other fluids (oil), adsorption to the rock, ion exchange, and size exclusion. The first mechanism is the most recognized.

Recommendations for Further Study

1. It is recommended to apply this study in reservoirs where oil is mobile as it is difficult to always ensure that the reservoir is at residual and hence the effects of mobile oil will be of significance. The reaction model and analytical tracer **model** will have to be modified to account for another mobile phase.

2. It is also recommend to expand this study through its application in fractured reservoirs and faults.

3. Investigation of the effects of fluid drift, to ascertain whether permeability heterogeneity can be observed in line with the results found Descant et al. (1989).

Literature review

Paper no	Year	Title	Journal	Authors	Contribution
U.S. Patent No 3,590,923	1971	Method of Determining Fluid Saturations in Reservoirs	U.S. Patents	Deans, H. A.	The first paper to present the injection of partitioning tracers into the reservoir to help in collecting measurements of the residual oil saturation (i.e. the first paper to present SWCT tests as it is understood today).
SPE 3792	1973	Single-Well Tracer Method to Measure Residual Oil Saturation	SPE International	Tomich, J. F., Deans, H. A., And Shallenberger, L. K.	First paper to present an analytical method for describing the process of SWCT tests. This model is then proven by through a comparison study with four field tests.
SPE 20303	1989	The Use of Single Well Tracer Testing to Estimate Heterogeneity	SPE International	Descant, F., Blackwell, R., Pope, G. A., and Sepehrnoori, K.	First paper to explore the application of SWCT tests to estimate permeability contrasts in a layered reservoir.
SPE 8838	1980	Single-Well Tracer Tests for Evaluating Chemical Enhanced Oil Recovery Processes	SPE International	Sheely, Q. C., Jr., and Baldwin, D. E., Jr.	First to propose the testing of an enhanced oil recovery process (surfactant injection) using SWCT tests in the Muddy Field, Wyoming. This involved the injection of multiple reactive tracers.
SPE 129877	2011	Snorre Low-Salinity-Water Injection-	SPE International	Skrettingland, K., Holt, T., Tweheyo, M.	First to utilise SWCT test field pilots in measuring remaining oil

		Core Flooding Experiments and Single-Well Field Pilot		T., and Skjevrak, I.	saturation post seawater flooding and low salooding on the Snorre field.
SPE 174397	2015	The Value of Inter-well and Single Well Tracer Technology for De-Risking and Optimizing a CEOR Process-Caracara Field Case	SPE International	Cubillos, H., Yuste, E., Bozorgzadeh, M., Montes, J., Mayorga, H., Bonilla, S., Quintanilla, G., Lezana, P., Panadero, A., and Romero, P.	A study involving the implementation of ASP injection (EOR) in the Caracara Sur Field, Colombia. This involved the application of SWCT tests before and after the surfactant injection to monitor the residual oil saturation and evaluate the effectiveness of the EOR process.
SPE 28591	1997	Chemical Tracer Studies To Determine Water Saturation at Prudhoe Bay	SPE International	Deans, H. A., and Mut, A. D.	First to apply the SWCT method in measuring the residual water saturation in the Ivishak reservoir, Prudhoe Bay.
SPE 14886	1986	Single-Well Tracer Test in Complex Pore Systems	SPE International	Deans, H. A., and Carlisle, C. T.	Development of a model that reproduces the unique features associated with SWCT tests in carbonate formations. It involve modifying the "dead-end" pore model in order to reproduce features from different chemical tracer tests in complex pore systems, such as West Texas Dolomites,

					Canadian Reefs and other carbonate formations.
SPE 2152	1968	New Single-Well Test for Determining Vertical Permeability	SPE International	William, A., and Burns, Jr.	First to devise a well test for in-situ measurements of vertical permeability.
SPE 718	1963	Theory of Tracer Flow	SPE International	Bischoff, K. B., and Worcester, D. A.	The first analysis of the theory of the dispersion of tracers in flowing streams. A model was devised which accounts for both molecular diffusion and turbulent mixing.
SPE 5840	1976	Description of Field Tests To Determine Residual Oil Saturation by Single-Well Tracer Method	SPE International	Sheely, C. Q., Jr.	These details the field tests conducted for Single-Well Tracer Tests.
SPE 155608	2012	Single Well Chemical Tracer Tests - Fast and Accurate Simulations	SPE International	Huseby, O., Sagen, J., and Dugstad, Ø.	Simplification of the SWCT test model. A fast post-processing tracer simulation technique is introduced to solve single well tracer transport in real-life reservoir cases.
SPE 174378	2015	Numerical Interpretation of Single Well Chemical Tracer (SWCT) Tests to Determine Residual Oil Saturation in Snorre Reservoir	SPE International	Khaledialidusti, R.., Kleppe, J., and Skrettingland, K.	Numerical interpretation of SWCT test after high salinity water flooding in the Snorre Reservoir.
-	1986	Single Well Chemical Tracer Test Handbook,	Chemical Tracers, Inc Handbook	Deans, H. A., And Carlisle, C. T.	A handbook expanding on the analytical model presented by Deans (1971).

		second edition			Explains the structure and time frame of SWCT tests and also compares numerical results to case studies on field tests.
SPE 129724	2010	Interpreting Single Well Chemical Tracer Tests	SPE International	Jerauld, G. R., Mohammadi, H., and Webb, K. J.	Analysis of SWCT tests in high and low salinity water flooded reservoirs.
SPE 124614	2009	Determining Reservoir Properties and Flood Performance From Tracer Test Analysis	SPE International	Shook, G. M., Pope, G. A., and Asakawa, K.	Describes new analysis methods developed recently. Compares between analytical and experimental data.
SPE 173994	201 5	Single-Well Chemical Tracer Modeling of Low Salinity Water Injection in Carbonates			
SPE 175282	2015	Simulation of Single Well Chemical Tracer Tests Conducted in Carbonate Reservoir	SPE International	Al-Mutairi, F., Tiwari, S., Baroon, B., Abdullah, M., Pathak, A., and Gammiero, A.	This paper presents the findings from a simulation conducted of SWCT tests in a Carbonate Reservoir and compares it to results collected from SWCT test that were carried out in conjunction with water flood and ASP EOR techniques on the SAMA field in Kuwait.
PETSOC -98-01-06	1998	Well-to-well Tracer Tests and Permeability Heterogeneity	Journal of Canadian Petroleum Technology	Ghori, S. G., and Heller, J. P.	First paper to describe the possibility of obtaining quantitative information about the permeability heterogeneity of underground reservoirs from well-to-well tracer tests.

IPTC-14560	2012	Single-Well Chemical Tracer Test Experience in the Gulf of Guinea to Determine Remaining Oil Saturation	International Petroleum Technology Conference	Romero, C., Agenet, N., Lesage, A. N., and Cassou, G.	First paper to focus on the results of the SWCT test carried out on an offshore field in the Gulf of Guinea and how the information was used to improve the assessment of the reservoir's current residual oil saturation.
SPE 77874	2002	Advance on the Tracer Test Technology Among Wells	SPE International	Bingyu, J., Xinguang, S., Qinglin, W., Qun, L., Anjian, L., Tongjing, L.	First to review the development of tracer test technology amongst wells in oil fields.

U.S. Patent No 3,590,923 (1971)

Method of Determining Fluid Saturations in Reservoirs

Authors: Deans, H. A.

Objective of Paper:

To present a method for determining the residual oil saturation and water saturations of a reservoir through the chromatographic separation of injected partition tracers.

Contribution to the understanding of Single-Well Chemical Tracer tests in Heterogeneous Reservoirs:

The first paper to present the injection of partitioning tracers into the reservoir to help in collecting measurements of the residual oil saturation (i.e. the first paper to present SWCT tests as it is understood today).

Methodology used:

Injecting a partitioning tracer into a reservoir at residual oil which partitions into the oil and water phases.

A secondary tracer is produced in-situ during shut-in which is only soluble in water.

Since both these tracers have different partition coefficients between the carrier fluid and the mobile phase, they are chromatographically retarded in their passage through the formation by different amounts which is a function of the saturation of the immobile phase.

Conclusion reached:

A method is devised for determining relative amounts of two fluid phases in a subterranean reservoir formation.

Comments:

 Deans, H. A is regarded as the forefather of SWCT tests.

An important paper which laid out the fundamentals of SWCT tests

It gauged the application of tracers in reservoir operations to ascertain the residual oil saturation

SPE 3792 (1973)

Single-Well Tracer Method to Measure Residual Oil Saturation

Authors: Tomich, J. F., Deans, H. A., and Shallenberger, L. K.

Objective of Paper:

To present a mathematical model that describes the functioning of SWCT tests and apply this to a numerical model whose results was then compared with that gathered from the field.

Contribution to the understanding of Single-Well Chemical Tracer tests in Heterogeneous Reservoirs:

First paper to present an analytical method for describing the process of SWCT tests. This model is then benchmarked against results collected from four field tests. Developed a single-well chemical tracer model for measuring the residual oi saturation.

Methodology used:

Introduced mathematical model correlating the retardation factor to the velocity of the tracer in a specific phase. The important assumptions made for this model to work were that the fluids are incompressible, the oil phase is immobile and that the chemical reaction occurs only in the water phase.

Enhanced on the idea of chromatographic separation of tracers using this mathematical model by showing that two tracers that have different distribution coefficients will have different velocities, and will hence separate in a manner that is analogous to that in a chromatographic column.

This model was then applied to measuring the residual oil saturation of a field using the different arrival times of the tracers. This was modelled in a numerical simulator and benchmarked against measurements that were taken from four different field tests.

Conclusion reached:

Development of a new single-well chemical tracer method/model that can measure the residual oil saturation and this has been proved using field data.

Realisation of the wide range of applications of SWCT tests,

Comments:

An important paper in presenting the analytical method that is still being used to this day to validate numerical models of SWCT tests and was subsequently relied upon in this study.

SPE 173994 (2015)

Single-Well Chemical Tracer Modeling of Low Salinity Water Injection in Carbonates

Authors: Al-Shalabi, W., Luo, H., Delshad, M., and Sepehrnoori, K.

Objective of Paper:

Investigation of SWCT tests of low salinity waterflood injection (LSWI) in carbonate reservoirs using reservoir simulation.

Contribution to the understanding of Single-Well Chemical Tracer tests in Heterogeneous Reservoirs:

An extensive analysis of SWCT tests of LSWI in carbonate reservoirs to present a new approach to estimating the residual oil saturation in reservoirs with different degrees of heterogeneity.

Methodology used:

1D radial and Cartesian models were created with an emphasis on the importance of capturing heterogeneity and how this affects the residual oil saturation measurement.

SWCT tests are conducted in the first phase whereby tracer is injected with seawater before the well is shut in. In the second phase, low salinity water is injected followed by the implementation of the SWCT test.

Conclusion reached:

A numerical approach was proposed for estimating the residual oil saturation for complex heterogeneous reservoirs as the analytical model for estimating the residual oil saturation was found to only be applicable to homogeneous reservoirs with symmetric effluent tracer concentrations.

Comments:

This study shows one of the important applications of SWCT tests in EOR techniques.

Low salinity water flooding effects the wettability state of the reservoir and hence SWCT tests can be used to measure the residual before and after the implementation of LSWI.

SPE 175282 (2015)

Simulation of Single Well Chemical Tracer Tests Conducted in Carbonate Reservoir

Authors: Al-Mutairi, F., Tiwari, S., Baroon, B., Abdullah, M., and Pathak, A.

Objective of Paper:

To present a mathematical model that describes the functioning of SWCT tests and to apply this to a numerical model whose results was then compared with data gathered from the Sabiriyah Mauddud field.

Contribution to the understanding of Single-Well Chemical Tracer tests in Heterogeneous Reservoirs:

This paper presents the findings from a simulation conducted in SWCT tests in a Carbonate Reservoir and compares to those collected from SWCT test that were carried out in conjunction with water flood and ASP EOR technique in the Sabiriyah Mauddud reservoir, Kuwait.

Methodology used:

It aims to compare the results collected from this with those collected from a SWCT test on the SAMA reservoir in Kuwait.

A radial model was created and used for carrying out sensitivity analysis and history matching with actual data on total dispersion, diffusion coefficient, drift model and dual porosity and permeability.

They tried to match the simulation results with actual results collected from the SWCT tests in SAMA reservoir through history matching these different cases to find the best fit.

Conclusion reached:

A good match was realised between the numerical simulator results and the field data collected from the SAMA field.

It was also concluded from the study that dispersivity is a main parameter in controlling the flow of chemical tracers in the SAMA field.

Comments:

This paper is important in matching the numerical interpretation of SWCT test with results collected from tests made in the SAMA field.

SPE 8838 (1980)

Single-Well Tracer Tests for Evaluating Chemical Enhanced Oil Recovery Processes

Authors: Sheely, C. Q., Jr., and Baldwin, D. E., Jr.

Objective of Paper:

Discusses the theory, design, operation, results and interpretation of the single well surfactant test that was conducted in the Big Muddy Field.

Contribution to the understanding of Single-Well Chemical Tracer tests in Heterogeneous Reservoirs:

This paper presents the method for testing enhanced oil recovery processes in a single well. This is done by utilising single-well tracer tests which determine residual oil saturation, therefore enabling the measurement of oil displacement due to an EOR process.

Methodology used:

This paper analyses the implementation of single-well surfactant test on Big Muddy Field in Wyoming (US).

It presents the single well chemical tracer test theory as presented by Deans (191).

This is used as the basis for evaluating tertiary plug processes as opposed to the more conventional, expensive and time consuming method of piloting chemical EOR processes.

The aim is to compare the results from a previously implemented pilot EOR test with the single-well surfactant test which is based on mathematical models and laboratory data. An analysis of different chemical formulations is also coordinated to show its effect on the single-well surfactant test.

Conclusion reached:

The implementation of single-well chemical tracer tests of surfactant flooding and successfully implementing it in the Big Muddy Field.

Comments:

The relevance of this paper to the proposed study is that the study can be related to persisting production issues and integrating EOR methods within simulated scenarios would be highly desirable for the industry. This focuses on surfactant/polymer flooding mechanisms.

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Final Results