Chair of Reservoir Engineering

Master Thesis

Reservoir Characterisation using Tracers: Analytical versus Numerical Methods

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Danksagung / Acknowledgement

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Kurzfassung

Auf der Suche nach Möglichkeiten, die Effizienz der Entölung vorhandener Erdöllagerstätten kontinuierlich zu steigern, steigt das Interesse an fortschrittliche Gewinnungsmethoden. „Enhanced Oil Recovery“ beschreibt die Anwendung von modernen Prozessen und Technologien um den Entölungsgrad von zurzeit produzierenden Lagerstätten zu erhöhen. Der Erfolg von tertiären Ölgewinnungsprojekten hängt zu einem Großteil von einem soliden Verständnis von Fließdynamiken und der Verteilung von Porenvolumen ab. Ein Tracer-Test zwischen einzelnen Bohrlöchern stellt einen Ansatz mit einzigartigen Möglichkeiten dar, mit dem man Informationen bezüglich der Lagerstättenkonnektivität und der Heterogenität gewinnen kann.

Bei Tracer-Tests zwischen Bohrungen wird eine lösliche Substanz der Flüssigkeit einer Injektionsbohrung hinzugefügt. Die zeitliche Abstimmung sowie die Form der Tracer-Rückgewinnungskurve verraten Informationen über das Porenvolumen zwischen unterschiedlichen Bohrlöchern. In den letzten Jahren wurden neuartige Hilfsmittel für Tracer-Tests entwickelt.

Das vorwiegende Ziel dieser Arbeit ist es, das Verständnis von analytisch abgeleitetem zusammenhängenden Porenvolumen und des Heterogenitätsindex von konservativen Tracer-Daten zu verbessern, sowie Möglichkeiten zur Interpretation anhand numerischer Simulationen zu finden.

Lagerstättensimulation mithilfe finiter Elemente wird verwendet um das Fließverhalten von Tracern in einer Erdöllagerstätte zu modellieren und um synthetische Tracer-Produktionskurven zu generieren. Tracer-Daten werden analysiert und danach in Kombination mit den Modelparametern interpretiert.

Durch diese Arbeit wird bewiesen, dass das zusammenhängende Porenvolumen, welches aufgrund von Tracer-Daten abgeschätzt wurde, als Maßstab für das geflutete Porenvolumen dient und zur Bewertung der Echtzeit-Verdrängungseffizienz verwendet werden kann. Der Heterogenitätskoeffizient, beschrieben in einer F-PHI-Kurve welche durch Tracer-Daten gewonnen werden kann, stellt eine kombinierte Messung von statischer und dynamischer Heterogenität des Systems dar.

Abstract

In the quest for recovery factor improvement for existing petroleum reservoir, there is a continuously growing interest in enhanced recovery methods. Enhanced oil recovery is the application of advanced processes and technologies in order to increase recovery factor in already produced reservoirs. The success of enhanced recovery projects rely to a large extent on a sound understanding of flow dynamics and pore volume distribution. Inter-well tracer tests present an approach with unique abilities that can be used to obtain information about the reservoir connectivity and heterogeneity.

In inter-well tracer tests, a soluble material is added to the fluid in an injection well. The timing and the shape of the back produced tracer curve revels information about the inter-well pore volume. In the last several years, new tools for tracer tests have been developed.

The main goal of this thesis was to improve the understanding of analytically derived connected pore volume and heterogeneity index from conservative tracer data and how can they be interpreted in the vicinity of numerical simulation.

Finite element reservoir simulation is conducted to model the flow of the tracer in the reservoir and to generate synthetic tracer production curve. Tracer data will be analyzed and afterwards interpreted in relationship to the model parameters.

It was proven through the thesis that connected pore volume estimated from tracer data is a measure of the swept pore volume and can used to estimate real time sweep efficiency. Heterogeneity coefficient delineated in F-PHI curve extracted from tracer data is a combined measure of static and dynamic heterogeneity of the system.

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Abbreviations

S	host phase saturation
C	flowing tracer concentration
C a	adsorbed tracer concentration
ρr	mass density of rock formation
ϕ	porosity
ρ	host phase density
T	transmissibility
B	host phase formation volume factor
Dz	Cell center depth.
μ	host phase viscosity
kr	host phase relative permeability
V	block pore volume
Q	host phase production rate
P	host phase pressure
g	acceleration due to gravity
Dc	tracer diffusion coefficient
DF	diffusivity
Npe	Peclet number
Ej(t)	Residence time
xD	Dimensionless position
tD	Dimensionless time
mp	Tracer produced mass
Mi	Tracer injected mass
$\bar{V}_s$	Total swept pore volume
F	Flow capacity
Φ	Storage capacity

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1 INTRODUCTION

1.1 Background

Enhanced oil recovery is the application of advanced technologies in order to economically recover bypassed oil from already produced reservoirs. In order to successfully implement an EOR project, a sound understanding of the reservoir structure and properties prior to field scale implementation is of critical importance. Means of achieving this purpose include repeat seismic interpretation, detailed reservoir simulation, production log analysis, fall off pressure tests and tracer tests.

Several EOR methods consist of fluid injection at selected points into a reservoir to sweep the residual oil. In any fluid injection operation, the high-permeability streaks receive substantial quantities of the injected fluid. [1] This disproportionate distribution of the injected fluids reduces the volumetric sweep efficiency of the reservoir and hence, lowers the process efficiency. Therefore, detection of the high-permeability zones and channels would be helpful in understanding and increasing the efficiency of injection projects.

In this regard, fall off pressure tests and tracer tests provide a valuable source of information about the direct connectivity between a pair of injector and producer, as well as about the level of heterogeneity. However the pressure tests tend to measure average properties between wells and indicate the existence of a permeability trend, tracer tests provide more rigorous quantification of the heterogeneity in addition to the swept pore volume. For these reasons, tracers have gained growing attention in the last decades, and a succession of advancements in design, implementation and interpretation of tracer tests was achieved. [2]

Tracers can be broadly classified -according to their properties- into two categories:

- **Radioactive tracers:**

They are chemical compounds which contain radioactive isotopes that disintegrate to a stable state and may emit beta or gamma radiation that can be detected [1]. The most common radioactive tracers are tritium and tritiated water. Tritiated water can for instance be detected in very low concentrations. On the other hand, Tritium has very little penetration power and, therefore, is increasingly safer to use. [2] However, with the development of chemical tracers, radioactive tracers are less used and substituted by chemical tracers without compromises in measurement sensitivity or accuracy of the tests.

- **Chemical tracers**

Chemical tracers for water are categorized into dyes, ionic and organic tracers. Dyes, such as rhodamine and fluorescein are better to be used when exposure to rock material is minimum. Ionic tracers are typically anions of water soluble salts, such as Br- and SCN- , and can be detected to very low concentrations. Organic tracers are usually alcohols such as tertiary butanol TBA. [2]

From the practical point of view, tracer falls into two categories according to phase in which they exist: conservative and partitioning.

- **Conservative tracers,**

Also known as “non-partitioning” or “passive” tracers move at the same velocity of the water phase without interaction with other existing phases in the reservoir. A conservative tracer must be stable under reservoir conditions and must have low to no adsorption to rock material. Conservative tracers can provide direct information about the fluid flow between wells.

- **Partitioning tracers**

Partitioning tracers are additionally soluble in the oil (or gas) phase present in the reservoir. Tracer solubility in the oil or gas phase results in a retardation of the advancement of the tracer front. Tracer molecules will diffuse from the tracer slug into the stationary oil or gas due to concentration gradient. After the slug advancement, the tracer diffuse back to the water phase due to the concentration gradient reversal. It is this chromatographic delay that serves as the basis for residual oil saturation determination. [3]

Tracer injection can be done in two modes for different purposes: single well or interwell.

- **Single well chemical tracer test (SWCT)**

SWCT is an in-situ method to measure saturations, either residual oil or less frequently the connate water saturation. This method consist of measuring the difference in arrival time between one partitioning and one conservative tracer in the vicinity of one well. The tracers are either both injected or one of them is in-situ produced. After the tracer is injected, the well is shut in and afterward back-flowed. The difference in arrival time between the partitioning tracer which contacts both phases and the conservative tracer is proportional to the residual oil saturation.

- **Interwell tracer test**

Injection is an operation performed between two or more wells. The tracer is injected in one well and afterward recovered from one or more producer. The tracer breakthrough time, the tracer recovered mass and the produced tracer curve vs time or pore volume injected contains very valuable information about the interwell pore volume and rock properties which is be the main subject of this thesis.

1.2 Literature review

The scope of this review lies is interwell field tracer tests and related studies in the petroleum industry.
Interwell tracer tests have been used in the petroleum industry since the 1950s. Tracers were initially used in a qualitative way to prove communication between a pair of wells. In the last decades, the value of tracer tests has been further recognized as more rigorous analytical and numerical interpretation tools were developed. Interpretation tools will be discussed separately and in more details in the Chapter 2. Interest in tracer tests has been increasingly growing and several tracer tests have been successfully designed and implemented providing reliable and valuable information were derived.

For instance, Sylte et al., [5] analyzed two different tracer studies in terms of breakthrough time in the Ekofisk field in order to identify the flow mechanism taking place in a pilot waterflood. The travel time of tagged water from injector to producer is normally a function of the interwell distance and the directional conductivity, which is in fact a function of the reservoir properties such as permeability and thickness, but also a function of other factors such as different flow mechanisms. The tracers were injected at different times. The ones that were injected at the start of the waterflood showed a delay relative to the response from a later tracer injection. The delay was explained on the basis that tagged water injected initially presumably interacted with the water wet reservoir that was undersaturated with respect to water and therefore imbibed into it. The oil was displaced in the process and production of water and associated tracer was delayed until the imbibition was satisfied. This was confirmed by the relatively faster breakthrough of the tracers injected at a later stage, indicating that flow mechanism changed from imbibition to normal convective and dispersive processes.

Nitzberg and Broman [4] reported a tracer survey in the Prudhoe Bay field north Alaska that was used to adjust kv/kh ratio. Detailed analysis of injection and production of tritium tracer in one inverted five spot pattern showed that water was moving differently than anticipated by reservoir simulation model and core data. Early breakthrough of the tracer in the surrounding wells showed that much of the injected water moved out through a “thief zone”. Comparison of this behavior to modeling prediction led to a reduced estimate of kv/kh and a refined reservoir description and reservoir management strategy.

Simulation of tracer data has been recognized to be a reliable tool to integrate real flow data into the system and to history match the reservoir performance. Tracer production curve is a function of different static and dynamic properties in the scale of well to well space, and therefore matching the tracer curve, in combination with other data sources, can yield to a significant decrease in data uncertainty. Several cases, where tracer data was used in the history matching, are reported. For instance, Gilliand and Conley [6] reported a tracer study in the Big Muddy field were four tracers were injected in a preflush for a low tension polymer pilot flood. The initial model that consisted of a three layered system based on the log and core data delivered a poor fit for the tracer curve. The use of streamlines simulation indicated the need to enlarge the five spot pilot section initially considered in order to include additional potential flow path. With adjustments in the longitudinal and transverse dispersity, and the addition of reversible adsorption for the tracers, the fit was significantly improved. These parameters that were generated in correspondence to the tracer data were also beneficial in simulating low-tension polymer flood that would be otherwise unobtainable. This proves the advantage and reliability of tracer data to improve simulation efficiency.

Gaibor and Rodriguez [7] used tracer data to validate a numerical simulation model and reduce associated risk and uncertainty in the design of polymer injection by comparing the breakthrough time anticipated by the model to the real data. Consistency between the two validated the assumed continuity in the interwell space.

During EOR projects, tracers can present a valuable tool to assess the efficiency of the flood as well. Recent development of tracer quantitative analysis allowed the deduction of the sweep efficiency from tracer data. Comparing the sweep efficiency at different stages of the flood can reveal information about the performance of the flood and to what extent it has changed or improved the displacement. Polymer flood for instance aim to improve lateral and vertical sweep by reducing mobility ratio, which is why tracer tests before, during or after polymer flood should show different behaviors.

Dugstad, Oyvind et al. [8] used tracer technology in order to improve the understanding of CO_2/foam EOR method. Radioactive tagging of water, CO_2 and the foaming agent enabled detection of the variation of the surfactant solution flow rate along with the accessible pore volume. It was concluded from the tracer survey that the transport of the individual components was different and that the tracer technology is a powerful tool to investigate the transport mechanism in such flooding schemes.

Clemens et al.[9] reported a tracer study in the 8TH reservoir in the Matzen Field Austria, where polymer injection pilot was applied. The tracer implied that the reservoir was heterogeneous with high velocity flow paths and that the flow field was dramatically modified by increasing polymer injection. Tracer breakthrough times were delayed as anticipated due to the change in sweep efficiency and flow dynamics. Matching the tracer curve with numerical simulation was also performed to quantitatively assess parameters that are considered critical to the polymer injection project such as residual resistance factor (RRF), adsorption and dispersity.

1.3 Thesis outline

The main goal of the thesis is to improve the understanding of the two main quantities derived from tracer data: connected pore volume and heterogeneity coefficient. The focus of this thesis lies on interwell conservative tracers.

In Chapter 2, analytical methods that are currently in use for tracer interpretation are explained, as well as their theoretical background and assumptions. Advancements and difference between the two main methods were also investigated.

In Chapter 3, numerical simulations are performed systematically in order to build a fundamental understanding of the analytically derived properties. The degree of complexity was increased gradually: 1D core plug simulation was performed and compared to lab experiment results in order to benchmark and quantify the effects of numerical dispersion on the tracer dilution curve. Inverted five spots well scheme with homogeneous and layered heterogeneity were then simulated: tracers were injected through one well and recovered in the four surrounding producers. Additional surrounding patterns were also considered in order to check the effect of confinement and pattern efficiency. Afterwards, a heterogeneous reservoir sector with bivariate histograms for porosity and permeability is simulated. The same five spots configuration is used. Interpretation of polymer effects on sweep efficiency improvement was carried out using tracer extracted swept pore volume and heterogeneity index.

In Chapter 4, the results of all the proposed simulations are presented and discussed with the help of detailed description of illustrative figures.

Finally, in Chapter 5, a conclusive summary is provided to give a general overview to the reader on the most significant results of this thesis.

2 ANALYTICAL METHODS FOR TRACER DATA INTERPRETATION

Tracer interpretation can be performed basically on three levels of complexity, qualitative analysis, quantitative analytical interpretation and numerical simulation. [1]
The first level, the easiest and most straightforward is qualitative assessment. The fact that the tracer breakthrough in one producer confirms the connectivity with an injector is already valuable information. Additionally, a quick look at the tracer production curve is sufficient to get an impression about the level of heterogeneity in the interwell space. In the idealistic perfect homogeneous case (Figure1-a), tracer curve would manifest as a perfect Gaussian distribution. A high level of heterogeneity (Figure1-b) would be manifested in a tracer curve with more than one peak usually. The existence of high permeability zone can also be qualitatively deducted from the breakthrough time. However, it is noteworthy that the breakthrough time is usually extracted by extrapolating backward to time zero, and therefore the accuracy of this calculation is limited by the sampling frequency. In case multi-moded distribution, the relative amplitude of the peak can reveal how much of the tracer volume is flowing within a certain layer. During a qualitative interpretation of the tracer curve, the water cut (or GOR in case of gas tracer) should be displayed as well. If, for instance, a gas tracer breakthrough without a significant increase in the GOR, it means that it was flowing as dissolved gas in the oil phase, which is different from the case if it was flowing Within a separate gas phase.

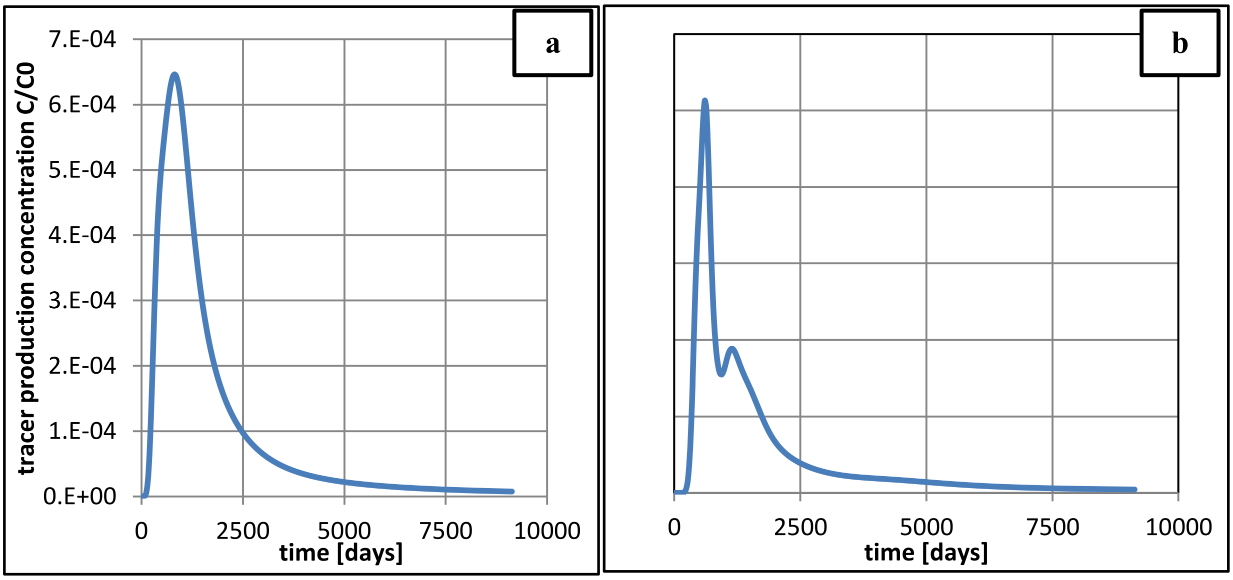

Figure 1: Tracer curve, concentration versus time: a) tracer production curve in homogeneous model b) tracer production curve for more heterogeneous case

The second, more robust level of interpretation is the quantitative analysis. This consists of the evaluation of tracer mass recovery as function of time given by the tracer response curve. As the tracer is usually recovered from more than one producer, the relative mass recovered at each well, when compared to the other producers and to the total mass injected, contains a lot of information about the interwell space and the pore volume where tracer is preferentially flowing. Moreover, the ratio of mass recovered over mass injected can be used to establish surveillance model and to allocate the water-flooding volumes between

injectors and producers. The Method of moments (MOM) which consists of residence time distribution analysis is used to perform the quantitative analysis.
The third level of interpretation includes numerical simulation, where tracer analysis are carried out in combination with a reservoir simulator applied for the particular field into which the tracer has been injected. As discussed in the literature review section, tracer analysis, when simulated, can help to validate numerical models (or some specific assumptions) and to improve its efficiency and accuracy by history matching.

2.1 Method of moments

2.1.1 Basics and assumptions

The method of moments consists of deriving the temporal moments from the tracer response curve. This technique has its roots in the chemical process industry, where it was originally developed for closed reactor vessels but has been applied to more general conditions of open boundaries, characterization of fractured media under continuous tracer reinjection and estimates of flow geometry. [10]
MOM has a rigorous mathematical basis and offers additional information on the subsurface. The analysis is useful independently, as well it can also be used to constrain numerical models by defining interwell volume and flow geometry. [10]
The method of moment and its applications are all based on the analysis of tracer residence time distribution. The tracer particles actually travel through different paths, therefore different amount of time is required of them to travel from the inlet to the outlet. The distribution of such time periods is called exit age distribution, or residence time distribution of the tracer in the system.
Assumed conditions for the application of the method of moments are summarized below [10] :

1. Steady state injection and extraction :

If the flow field is under transient flow regime, the streamlines are likewise transient and swept volumes, flow geometry, etc., are functions of time. For that reason, a steady flow field is most frequently introduced before conducting the tracer test. Numerical modeling is a useful means of determining the duration of “pretest injection” required to establish steady state flow.

G.Shook [10] considers that a less than 20% perturbation form the constant injection rate can be handled and does not severely affect the moments. Nevertheless, variations in the flow rates are better to be recognized and considered.

2. The tracer(s) is ideal and conservative :

The tracer is assumed to be insignificantly soluble in all phases but one phase and does not tend to adsorb on the rock surface neither to affect flow properties (density, viscosity ...). It is noteworthy that some numerical simulators currently can model tracer adsorption and partitioning. It is only that the method of moments, with its current formulation, does not consider such properties. Implementing these properties in numerical simulation is undoubtedly of advantage when it comes to history matching and tracer curve interpolation.

The residence time distribution is referred to as E (t) and has units of (1/t) and it is defined as:

$$E(t) = \frac{C(t)Q_p(t)}{M} \quad \textbf{Eq.}1$$

With C(t) being the produced tracer concentration reported as mass per unit volume, Qp(t) being the production rate and M being the total mass of tracer injected. If the system has multiple producers (j) with production rate Q_j, the residence time distributions can be defined between each injector and producer pair (j) as :

$$E_j(t) = \frac{C_j(t)Q_{pj}(t)}{M} \quad \textbf{Eq.}2$$

In a closed system (100% tracer recovery), the normalization by total injected tracer mass ensures that:

$$\sum_j \int_{-\infty}^{\infty} E_j(t).dt = 1 \quad \textbf{Eq.}3$$

Three temporal moments exists that can be derived:

The zero order moment:

$$m_0 = \int_{-\infty}^{\infty} E_j(t)dt \quad \textbf{Eq.}4$$

This is equal to:

$$m_0 = \int_{-\infty}^{\infty} E_j(t)dt = \int_{-\infty}^{\infty} \frac{C_j(t)Q_{pj}(t)}{M}dt = \frac{1}{M}\int_{-\infty}^{\infty} C_j(t)Q_{pj}(t)dt = \frac{m}{M} \quad \textbf{Eq.}5$$

With m being the total mass recovered from the producer j at infinite time. This ratio can be used as a weighting factor to allocate the ratio of injected water that is flowing between the injector and the producer j.

The first order moment:

$$m_1 = \int_{-\infty}^{\infty} E_j(t)t dt \qquad \textbf{Eq.}6$$

The second order moment:

$$m_2 = \int_{-\infty}^{\infty} E_j(t)t^2 dt \qquad \textbf{Eq.}7$$

The first moment represents the average residence time for tracers between the injections well and producer j and it is referred to as the mean residence time. Although this quantity is not of big importance in itself, it is directly related to the mean pore volume which will be discussed later in this chapter. The second order moment is related to the dispersion of the tracer and can be related to the Péclet number.

Tracer production data can be plotted as a function of cumulative injected volume instead of time. This can be done either during reporting or by converting time data to volume based data. In such case, the method of moment is carried out similarly but with volume difference as the integration variable. In this case, with C=f (v), the first moment of distribution is equivalent to:

$$\bar{V} = \frac{\int_0^\infty CVdV}{\int_0^\infty CdV} \qquad \textbf{Eq.}8$$

Since the actual tracer sample data is composed of discontinuous measurements, the integral can be approximated by the summation as shown below:

$$\overline{\mathrm{V}} = \frac{\sum_0^\infty \mathrm{CVdV}}{\sum_0^\infty \mathrm{CdV}} \qquad \textbf{Eq.}9$$

From the temporal moments previously derived, information about swept pore volume and reservoir heterogeneity can be extracted.

In many cases, the sampling program is either not finished or it has been stopped without following the tail of production curve. Tracer concentration frequently decline exponentially, such that ln(C) vs. time is linear. Therefore, to fit the missing data in the tail of the production curve, an exponential decline approximation can be applied as following,

$$\mathrm{C(t)} = \mathrm{b}e^{-at} \quad \text{for } t > t_b \qquad \textbf{Eq.}10$$

In the case where the concentration C is reported as a function of injected volume V,

$$\mathrm{C(V)} = \mathrm{C}_e e^{\frac{-(V-V_{e)}}{a}} \quad \text{for V> V}_\text{e} \qquad \textbf{Eq.}11$$

With $\mathbf{V_e}$ being the volume from which the exponential decline starts, **a** is the slope of the line C=F (V), and 1/a being the slope of the line.
Integration of the first moment becomes:

$$\begin{aligned} m_1 &= \int_{-\infty}^{\infty} E_j(t) \cdot t.dt = \int_0^{tb} E_j(t) \cdot t.dt + \int_{tb}^{\infty} E_j(t) \cdot t.dt \\ &= \int_0^{tb} E_j(t) \cdot t.dt + \frac{b}{a^2} e^{-atb}(1 + atb) \end{aligned} \qquad \textbf{Eq.}12$$

With discontinuous measurements reported against injected volume:

$$\bar{V} = \frac{\sum_0^\infty CVdV}{\sum_0^\infty CdV} = \frac{\sum_0^{Ve} CVdV}{\sum_0^{Ve} CdV} + \frac{\sum_{Ve}^\infty CVdV}{\sum_{Ve}^\infty CdV} = \frac{\sum_0^\infty CVdV + aCe(a + Ve)}{\sum_0^{Ve} CdV + aCe} \qquad \textbf{Eq.}13$$

Another method of considering incomplete tracer data set is to fit the whole curve with the 1D solution of the advection diffusion equation.

2.1.2 The Swept pore volume

In any recovery process that includes continuous water injection; two measures of recovery performance must be considered: the displacement efficiency and the sweep efficiency.
Fluid displacement efficiency (E_D) is also known as microscopic displacement efficiency. It is defined as the volume of oil displaced from the invaded region divided by the volume of oil initially in place in the invaded region. Fluid displacement efficiency is affected by rock wettability, capillary pressure, relative permeability, and fluid mobility ratios. If reservoir pressure is maintained at initial conditions and saturation within the invaded region is reduced to residual oil saturation, the displacement efficiency can be estimated with the expression:

$$E_D = 1 - \frac{S_{or}}{S_{oi}} \qquad \textbf{Eq.}14$$

Where S_{or} = residual oil saturation in the swept (invaded) region, and S_{oi} = initial oil saturation in the swept region.

The volumetric displacement efficiency, E_V , is also known as macroscopic displacement efficiency. It is the fraction of the reservoir volume swept by the displacing fluid. [11] It is composed of two parts, namely, areal sweep efficiency E_{AS} , and vertical sweep efficiency E_{VS} . Areal sweep efficiency is the fraction of the reservoir area contacted by the displacing fluid. Vertical sweep efficiency is the fraction of the vertical reservoir cross-section contacted by the displacing fluid. Volumetric displacement efficiency is the product of areal and vertical sweep efficiencies:

$$E_V = E_{VS} * E_{As} \qquad \textbf{Eq.}15$$

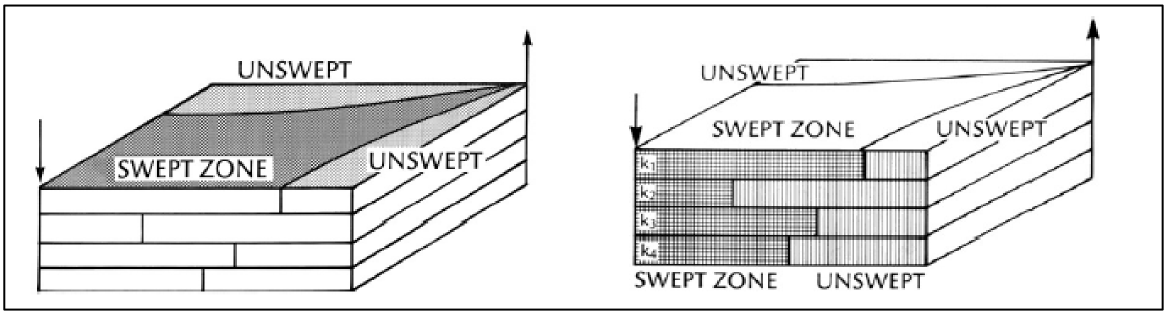

Figure 2 : Areal and vertical sweep efficiency

Along with increasing throughput (production time) the areal sweep efficiency is a function of mainly four parameters:

- Reservoir heterogeneity
- Flood pattern
- Mobility ratio
- Pressure distribution between injector and producers

Reservoir heterogeneity defines the favorable regions where the water will potentially flow. Directional trends in permeability, if existing, should be carefully considered in the design of the flood pattern and well placement in order to achieve the best sweep efficiency. Flood pattern is directly related to the well spacing. It is rationally a factor that will delineate the water movement in the reservoir rock. Several factors are imposed on the selection of the pattern, such as well placement restriction, the already existing producers as well as the size and structure of the reservoir.

Mobility ratio is the ratio of the displacing fluid mobility to the displaced fluid mobility. The mobility is a function of fluid viscosity and the phase relative permeability, and therefore it strongly affects the flow and the front advancement stability and consequently the swept area of a waterflood.

The pressure distribution is a function of the reservoir rock type and fluid saturation distribution, as well as precedent primary production and may also be affected by water injection. An efficient pressure monitoring during a waterflood leads to a better sweep efficiency.

The figure below shows the areal sweep efficiency of five spot patterns as a function of time for different mobility ratios.

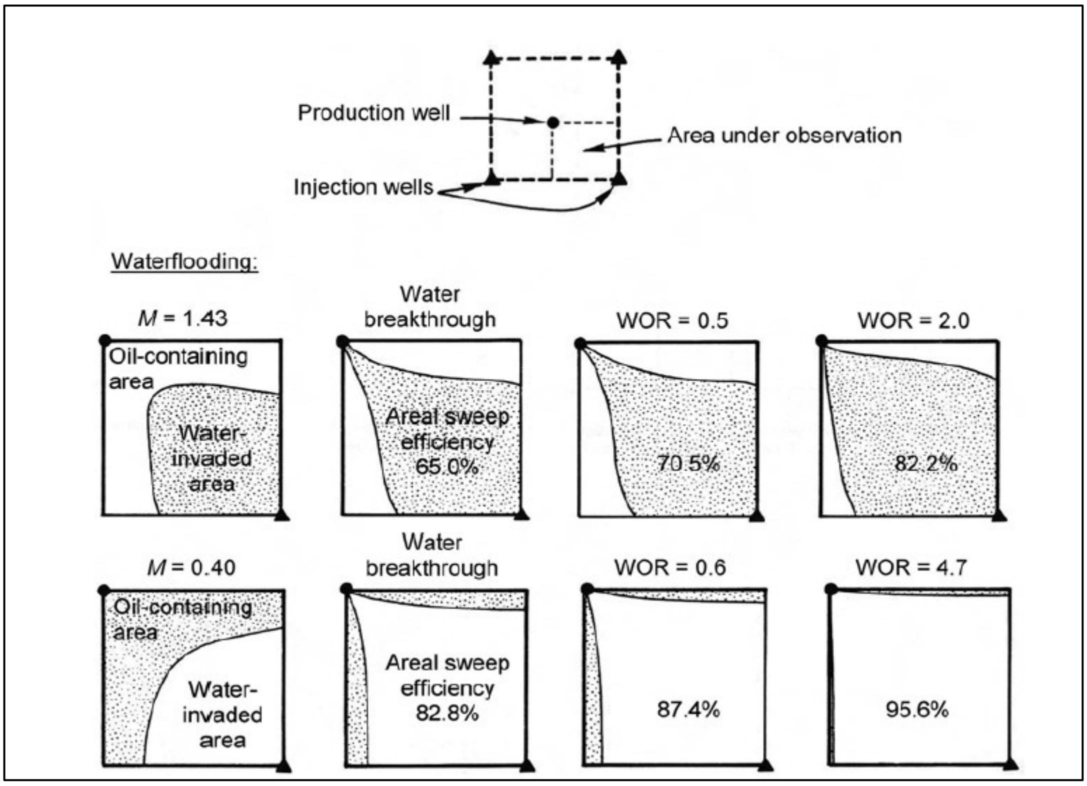

Figure 3: X-ray shadowgraphs of flood progress in experimental scaled five-spot pattern models. [1]

Any 2D approach to waterflood analysis is an approximation. How accurate an approximation it is will depend on how vertically stratified the reservoir is and how significant the gravity considerations are in the real reservoir compared to what the numerical modeling assumes about them. [1]

The vertical sweep efficiency, EV, is defined as the fraction of the vertical section of the pay zone that is the injection fluid. This particular sweep efficiency depends primarily on (1) the mobility ratio and (2) total volume injected. As a consequence of the non-uniform permeabilities, any injected fluid will tend to move through the reservoir with an irregular front. In the high permeable zones, the injected water travels more rapidly than in the less permeable ones. The greatest uncertainty in designing a waterflood scenario is considered to be the quantitative knowledge of the permeability variation within the reservoir. The degree of permeability variation is considered by far the most significant parameter influencing the vertical sweep efficiency. [12]

The calculation of vertical sweep efficiency consists of the allocation based on the vertical variation of the rock properties, mainly the Kh product. Basically two methods are traditionally used in calculating the vertical sweep efficiency E_V: the Stiles' method and (2) the Dykstra–Parsons method. These two methods assume that the reservoir is composed of an idealized layered system. The layered system is selected based on the permeability ordering approach with layers arranged in descending permeability order. Further details about heterogeneity quantification are presented later in this chapter.

The basis of these Traditional methods of sweep efficiency calculation lies in integrating the waterflood production and injection data. Bubble maps are usually used to convert the total

injected volumes in spherical area around injectors based on volumetric analysis. A more robust method is to use streamline simulation in order to integrate over the velocity field to calculate the flowing volume between injector and producers through different flow paths.
Tracer data is unique information that gives a direct real measurement of swept volume. It combines the use of injected and produced volumes with the possibility to estimate the sweep in a well to well (injector to producer) basis. Sweep efficiency calculation using tracers have been used for decades; however it has seen significant improvement in the past 10 years. The first approach is using the method of moment. The second approach is using the residence time distribution analysis and will be discussed in the next section. If the data is a function of time, the swept volume is derived from the first temporal moment as follow:
The mean residence time is:

$$t^* = \frac{\int_{-\infty}^{\infty} E_j(t)tdt}{\int_{-\infty}^{\infty} E_j(t)dt}$$ **Eq.**16

The swept pore volume is a function of the mean residence time as follow:

$$V_{sij} = \frac{m_{ij}}{M} q_{inj} t^* = \frac{m_{ij}}{M} (q_{inj} \frac{\int_0^{\infty} q_j C_{ij} tdt}{\int_0^{\infty} q_j C_{ij} dt})$$ **Eq.**17

If the data are reported as a function of injected volume,

$$V_{sij} = \frac{\int_0^{\infty} C(V).V.dV}{\int_0^{\infty} C(V).dV}$$ **Eq.**18

In the case of discontinuous data set:

$$V_{sij} = \frac{\sum_0^{\infty} C(V).V.dV}{\sum_0^{\infty} C(V).dV}$$ **Eq.**19

The swept pore volume for the entire pattern is simply the sum of the swept pore volume of all injector-producer pair calculated as above. Estimation of the sweep efficiency should incorporate the total pore volume of the reservoir estimated by either numerical simulation or volumetric data.

2.2 Residence time distribution analysis: RTDA

Residence time distribution analysis consists of exploiting the full distribution of the tracer response curve and not only its mean. Using the whole distribution of residence times allows for the calculation of flow geometry (as described in flow Capacity – storage Capacity or F-Φ curves), and swept volume as a function of time. This information provides the means of calculating sweep efficiency histories from tracer tests.

The residence time distribution analysis was first developed by G.Micheal G.Shook in 2003. It is based on the theory that the tracer particles breakthrough at different times because of the difference in the flow paths they travel through. This information could be exploited and translated into a measure of heterogeneity and contrast between flow paths as they depend of permeability and flow restrictions.

RTDA is based on the use of temporal moments in order to determine the flow and storage capacity of the reservoir from tracer data. The concept of flow vs. storage was developed originally in the petroleum literature to estimate injection sweep efficiency in layered media. The method relates the relative velocity of a given layer to its associated pore volume, usually in a flow-storage diagram. [13].

Assuming that different flow paths with different storage capacity (ϕ_i), permeabilities (k_i) and thickness (h_i) are arranged vertically and insulated with no cross flow. The flow capacity of any given streamline is proportional to the volume of fluid it carries and the flow path length itself. This relation is described by Darcy's law for single phase, steady state flow in a single layer i:

$$q_i = -\frac{k_i A_i}{\mu}\frac{\Delta P}{L_i} \qquad \textbf{Eq.}20$$

The different flow paths (or streamlines) can be rearranged in decreasing order of volumetric capacity.

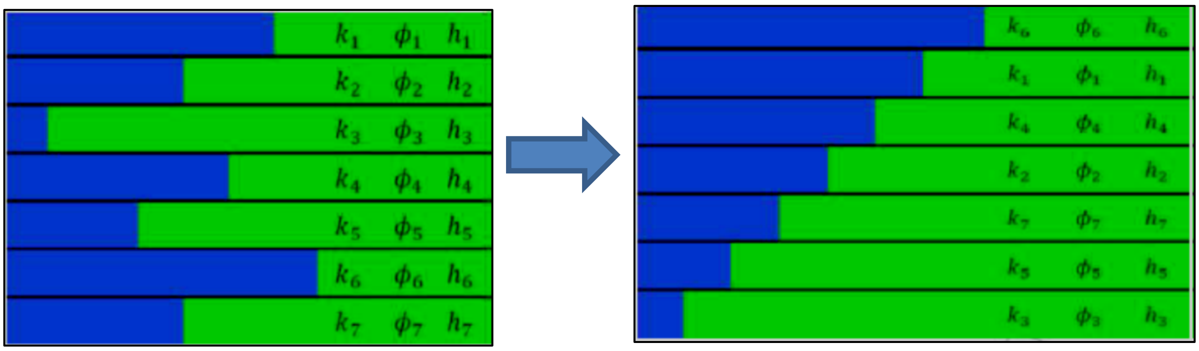

Figure 4: Multiple flow paths arranged in decreasing order

By arranging the streamlines in order of decreasing volumetric capacity and by assuming that injection and production pressures and fluid viscosity are equal, flow capacity can be defined at any streamline (i), as the sum of all streamlines whose velocity is greater than I, normalized by the ensemble properties. [10] The cumulative storage capacity Φ_i of these streamlines is simply the sum of their individual pore volumes:

Storage capacity:

$$\Phi_i = \frac{\sum_{j=1}^{i} Vpj}{\sum_{j=1}^{N} Vpj} \qquad \textbf{Eq.}21$$

Flow capacity:

$$\mathrm{F}_i = \frac{\sum_{j=1}^{i} {K_j A_j}\big/{L_j}}{\sum_{j=1}^{N} {K_j A_j}\big/{L_j}} \qquad \textbf{Eq.}22$$

These quantities can be estimated from tracer temporal moments. The storage capacity is the incremental first moment of the residence time distribution at time t, normalized by the first moment at infinite time.

$$\Phi_\mathrm{i}(\mathrm{t}) = \frac{\int_0^\mathrm{t} \mathrm{E}(\tau)\mathrm{d}\tau \Big/ \int_0^\infty \mathrm{E}(\tau)\mathrm{d}\tau}{\int_0^\mathrm{t} \mathrm{E}(\mathrm{t})\mathrm{tdt} \Big/ \int_0^\infty \mathrm{E}(\tau)\mathrm{d}\tau} = \frac{\int_0^\tau \mathrm{E}(\tau)\tau\mathrm{d}\tau}{\int_0^\infty \mathrm{E}(\tau)\tau\mathrm{d}\tau} = \frac{\int_0^\tau \mathrm{qCtdt}}{\int_0^\infty \mathrm{qCtdt}} \qquad \textbf{Eq.}23$$

The flow capacity is the cumulative tracer recovery at time t, normalized by the complete recovery. Implicitly assuming that the tracer does not affect the flow path and it only flows with the injected fluid, the flow capacity, which is the relative flow rate within a flow path, must be directly related to the proportional to recovery of the tracer:

$$\mathrm{F}_i = \frac{\int_0^t E(\tau)d\tau}{\int_0^\infty E(\tau)d\tau} = \frac{\int_0^t q_j C d\tau}{\int_0^\infty q_j C d\tau} \qquad \textbf{Eq.}24$$

With τ being the time variable.

The residence time distribution analysis allows the estimation of swept volume from tracer data as following [14] :

$$V_s(t) = \frac{m_{ij}}{Mi} \int_0^t q_i (1 - F_{ij}) dt \qquad \textbf{Eq.}25$$

The advantage of using residence time distribution is the possibility to directly estimate the reservoir volume swept as a function of time. As stated above, F represents the fraction of injected fluid that has broken through at time less or equal t, and therefore not contributing any further to contacting additional reservoir volume.

The sweep efficiency can be directly derived as the volume swept normalized by volume swept at infinite time, providing the opportunity to make engineering decisions based on the pore volume swept in a defined time scale.

$$E_V = \frac{\int_0^t q_i(1 - F_{ij})dt}{\overline{V_s}} \qquad \textbf{Eq.}26$$

V_{sij} , the total swept pore volume, can be estimated either from Eq 26 at infinite time, or by mean residence time from the method of moment.

Estimation of swept pore volume using residence time distribution has several advantages over method of moment. Theoretically, both methods should converge to the same answer at long time. However, RTDA does not require integrating time weighted quantities (E(t).t in the MOM).In field data, there is always more noise in the tracer concentrations as they approach detection limits, and weighting those data with large values of time can introduce significant error in the calculations. Therefore, MOM usually tends to overestimate the swept volume while the RTDA is more conservative. Additionally, RTDA, and the F-PHI derived properties are a valuable tool to assess heterogeneity.

2.2.1 The Heterogeneity coefficient: F-PHI plot

The Flow capacity – storage capacity diagram is constructed by plotting F (flow capacity) as a function of C (storage capacity). This plot is well known in reservoir engineering literature since decades and it is identified as the F-C curve. As previously discussed, it can be derived by assuming 2D, vertical cross section non-communicating layered reservoir, with different permeability k and porosity phi and thickness for each layer, but homogeneous within a given layer. It should be pointed out, that traditional method for plotting F-C diagram relies only on static data, and therefore, it is a static-derived estimate of heterogeneity.

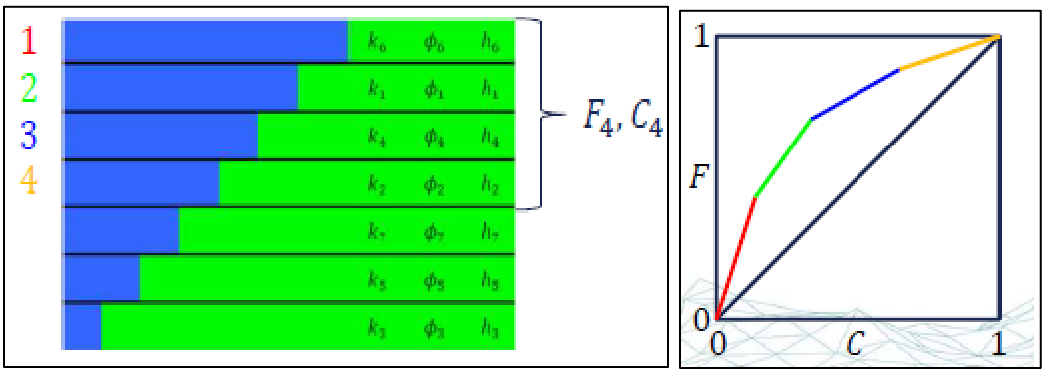

Figure 5: F-C static derived diagram from 2D layered reservoir

The slope of the curve is the fraction of interstitial velocity at that point with the respective capacity (volume that flows). With number of layers gong approaching infinity, (gradient in vertical permeability) the F(C) is smoother as the derivative is continuous.

The more the curve is shifted to the left, the more heterogeneous is the system. The closer it is to the 45° line, the more homogenous the different layers are.

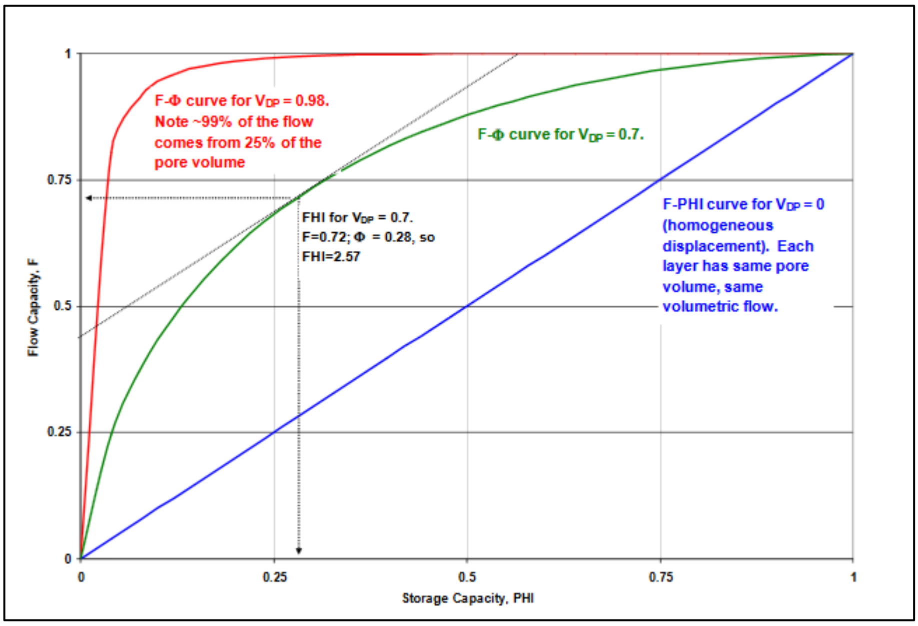

Figure 6: F-C diagram for different level of heterogeneity. The more the curve is shifted to the left the more volume is flowing through a smaller portion of the reservoir. The blue line represent total homogenous reservoir where all layers are with equal porosity and permeability

This can be assessed quantitatively using the Lorentz coefficient as follows, which represents the area above the line divided by the area below it.

$$L_C = 2\left\{\int_0^1 FdC - \frac{1}{2}\right\}$$ **Eq.**27

It is noteworthy that the layers are assumed of equal length, which is hardly true in a 3D real model. Streamlines are actually a function of the pressure distribution and therefore for a 3D model, layered heterogeneity, streamlines or flow paths of different length can be arise from flow dynamics.

Flow and storage capacities derived from tracer data are based on dynamic data which depend on the displacement process taking place. Therefore, heterogeneity assessed from tracer data is a dynamic property and does not necessarily represent the same quantity derived from the 2D layered reservoir simplification. To avoid ambiguity, G.Shook and Mitchell termed the diagram derived from tracer data as F- Φ diagram.

G.Shook [15] presented an example in 2D cross section of a layered reservoir where each layer has a constant permeability and porosity, though the properties of each layer are different. In this case, where all layers have equal length, F-C and F-PHI diagrams are expected to collapse in a single curve. This is a validation that tracer data reflect not only dynamic heterogeneity but static properties as well.

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Several other measures for heterogeneity can be used. Some of them can be extracted from F-PHI plot generated from tracer data. For example, the Dykstra Parson coefficient is a measure of heterogeneity that determines the permeability variation V_{DP} from the median and the variance of a sorted set of permeability. For example, the Dykstra-Parsons coefficient can also be estimated from the F-C plot. As originally defined, the Dykstra parsons coefficient V_{DP} was calculated from the best fit line of the log permeability data plotted on probability paper. The derivative of the F-C curve is the normalized interstitial fluid velocity), which is proportional to k/ϕ. Therefore, VDP can be estimated from the F-C plot as [10]:

$$V_{DP} = \frac{F'_{\phi=0.5} - F'_{\phi=0.841}}{F'_{\phi=0.5}} \quad \textbf{Eq.}28$$

G.Shook [16] published a comparison of four additional measure of heterogeneity (other than the Lorentz coefficient) that could be derived from dynamic data. These measures are:

Flow heterogeneity index: the ratio of the flow capacity to the storage capacity when the derivative of F-PHI curve is equal to 1

$$FHI = \left.\frac{F}{\Phi}\right|_{m=1} \quad \textbf{Eq.}29$$

Coefficient of variation:

$$C_V = \frac{\sqrt{V_{ar(\tau)}}}{t^*} \quad \textbf{Eq.}30$$

Where V_{ar} is the variance of time distribution derived from second temporal moment of tracer data. t^* being the mean residence time.
Sweep efficiency at 1 pore volume injected:

Sweep efficiency can be obtained from tracer data using **Eq.**10.

Sweep efficiency at 1 pore volume injected

Several models with different Dykstra-Parson coefficient were simulated and different values for the heterogeneity coefficient measurement was plotted against discounted oil recovery, where injection/production rates were fixed and the incremental sweep efficiency was every quarter of the year converted to produced oil, then discounted to present with a specific discount rate in order to ensure consistency in comparing values at different point in time. Same rock average rock properties and flowing conditions are generated using Sequential Gaussian simulations (SGS). The comparison showed that the Lorentz coefficient in the most stable measure of heterogeneity. [14]
Therefore, in the course of this thesis, the Lorentz coefficient derived from F-Phi curve from tracer data is used as the measure of heterogeneity.

3 NUMERICAL SIMULATIONS

Operation of an oil field in a large waterflood is complicated by the mass of collected data that must be analyzed and used to optimize field operations. This is particularly true in heterogeneous reservoirs with odd pattern geometry. In order to handle the data load, oil companies usually resort to large computer-based simulators. Such simulators are governed by a set of transport equations that describe the movement of the reservoir fluids: oil, gas, and water. The equations are solved numerically by discretization techniques.

The simulator used in this thesis is Schlumberger Eclipse E100. It is a fully implicit, integrated finite difference, three phase general purpose black oil simulator.

In E100, tracers are enabled using the environmental tracer option. This option allows the modeling of contaminants and other substances as they flow within a host water, oil or gas phase. The option extends the modeling to account for adsorption of tracer on the rock surface, for decay of the tracer over time in case of radioactive tracer as well as diffusion. All three properties can be modeled together within a single tracer. [16]

The flow of a conservative tracer in a porous media is assumed to have no influence on the flow of the water and hydrocarbon phases or on the flow of other tracers. The tracers are therefore solved at the end of a time step after the oil, water and gas equations have converged. The governing equation of a tracer present in a single phase is:

$$\frac{d}{dt}\left(\frac{VSC}{B}\right)+\frac{d}{dt}\left(V_{pr}C^{a}\frac{1-\phi}{\phi}\right)=\sum\left[\frac{Tk_r}{B\mu}(\delta P-\rho g D_z)C+DFD_cS\delta C\right]+QC-V\frac{S}{B}\lambda C \qquad \textbf{Eq.}31$$

The equation expresses the mass balance of a tracer in a single grid block. In a grid block, the change over time of tracer volume ($\frac{d}{dt}\left(\frac{VSC}{B}\right)$) and the tracer being adsorbed to the rock ($\frac{d}{dt}\left(V_{pr}C^{a}\frac{1-\phi}{\phi}\right)$) is equal the sum of tracer flowing through the grid block either by convective or diffusive forces ($\sum\left[\frac{Tk_r}{B\mu}(\delta P-\rho g D_z)C+DFD_cS\delta C\right]$) and the source term that consists of the tracer volume exiting (QC) the grid block and the decay term ($V\frac{S}{B}\lambda C$).

Simulation of tracer response is of high interest. In fact, tracer response data are a function of the actual flow between injectors and the responding producers. In a multi-pattern waterflood, these data provide the only means of identifying the distribution of injected water. Simulation of the tracer pulses is the best way to integrate real flow data into the system since it forces the simulator to address the actual flow distribution and the response curve shapes, in addition to total fluid flow.

3.1 Simulation of a core plug

3.1.1 Benchmarking: Effect of numerical dispersion

Numerical smearing is a general problem that occurs when transport equations are solved via discretization techniques. Smearing of the numerical solution occurs both for saturation fronts and tracer fronts, but are particularly severe when solving the transport equations for tracer pulse injections. Moreover the residence time distribution analysis is sensitive to the total distribution of the response and therefore smearing out of the tracer curve could lead to errors in swept volume and heterogeneity estimation.
The effect of numerical dispersion for a pulse injection is more severe. Additionally, the number of grid cells and the grid size is a luxury that is not always provided and limited by the computational power as well as the pre-designed models. The problem is even more complicated for 3D cases with complex reservoir geometry. **Figure 7** shows the different behavior of the tracer production curve for different grid sizes.

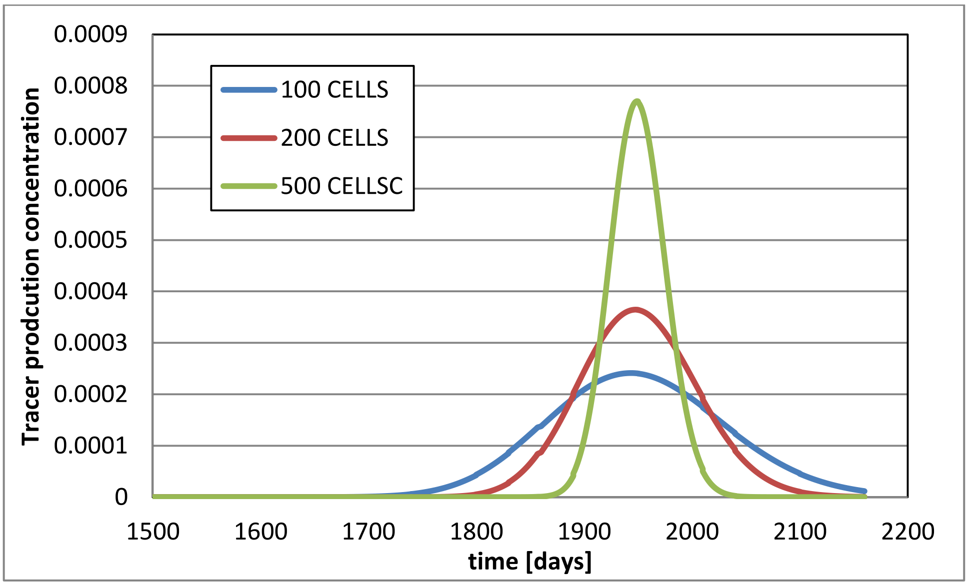

Figure 7: Tracer concentration for different grid sizes and grid numbers

In many cases, the main tool for reducing numerical dispersion in the tracer module is the use of a second-order numerical scheme for integrating the tracer equation. A separate grid-refinement option for tracer calculation is also available. In combination, these methods lead to a good resolution of narrow slugs propagating through the reservoir. The method of separate grid refinement is far less time consuming than performing the whole reservoir simulation on a refined grid. This tracer simulation module has been coupled to some of the standard reservoir simulation tools. [1]
Plug-ins that compute the tracer response curve separately from the numerical simulator exists in the market, allowing for a separate time and space discretization of the tracer equation. However they are not within the scope of this essay. The scope of this section is to investigate the minimum number of cells required to mimic the actual tracer behavior in a

core plug with an acceptable error. The tracer test was performed on a core plug experiment at OMV.

A core plug of the following properties was flooded by a continuous Uranine tracer injection with a concentration of 1.037 g/cm^3 at 0.5 cm^3/min of injection rate:

Permeability	2367	mD
Porosity	0.242551167	fraction
core length	7.321	cm
diameter	2.995	cm
Darcy Velocity	0.004435744	cm/min
Interstitial	0.000304798	cm/s

Table 1: Core plug properties

In order to check the plausibility of the data measured, the analytical equation for tracer transportation in 1D medium was evaluated, which is in fact the advection-diffusion equation with tracer concentration:

$$\frac{\partial C}{\partial t} + V\frac{\partial C}{\partial x} - D_L\frac{\partial^2 C}{\partial x^2} = 0$$ **Eq.**32

Where C is the tracer concentration, V is the interstitial velocity, x is the position, and D_L is the diffusion coefficient. The equation has the solution:

$$C_D = \frac{1}{2}erfc\left(\frac{x_D - t_D}{2\sqrt{t_D/N_{Pe}}}\right) + \frac{1}{2}\exp(x_D N_{Pe})erfc\left(\frac{x_D + t_D}{2\sqrt{t_D/N_{Pe}}}\right) = 0$$ **Eq.**33

With initial and boundary conditions as following:

$$C(x,0) = C_0\,, x \geq 0$$ **Eq.**34

$$C(x \to \infty, t) = C_0\,, t \geq 0$$ **Eq.**35

$$C(0,t) = C_{inj}\,, t \geq 0$$ **Eq.**36

For large Peclet number (N_{Pe}), if convection is dominant and the flow velocity is relatively large, the equation becomes:

$$C_D = \frac{1}{2} erfc\left(\frac{x_D - t_D}{2\sqrt{t_D/N_{Pe}}}\right) = \frac{1}{2}\left[1 - erf\left(\frac{x_D - t_D}{2\sqrt{t_D/N_{Pe}}}\right)\right] \quad \textbf{Eq.}37$$

Given that:

$$N_{Pe} = \frac{vL}{D_L} \quad \textbf{Eq.}38$$

$$t_D = \frac{vt}{L} \quad \textbf{Eq.}39$$

$$x_D = \frac{x}{L} \quad \textbf{Eq.}40$$

The equation becomes:

$$C_D = \frac{1}{2}\left[1 - erf\left(\frac{x - vt}{2\sqrt{D_L t}}\right)\right] \quad \textbf{Eq.}41$$

The diffusion coefficient for the Uranine is approximated to 2.35 m²/s [18]. With an interstitial velocity of 4.88E-05 m/s, and a characteristic length as the length of the core plug, the Pe > 1, the transport is advection dominated and the following match for the tracer curve was obtained. There is an acceptable match between the two curves and therefore the measured data is plausible.

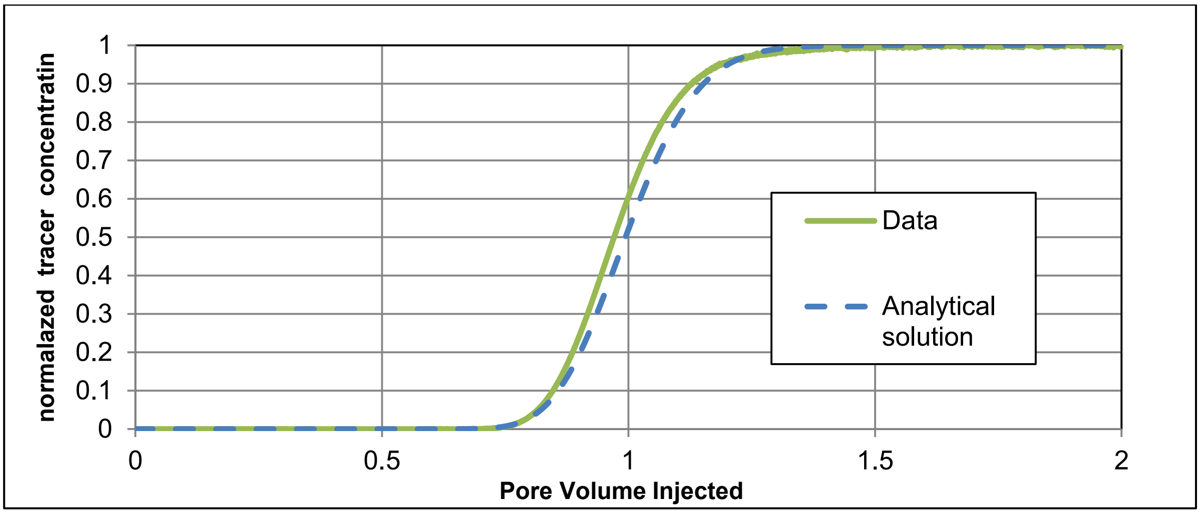

Figure 8: Tracer production curve for a core plug tracer test; Green: measured data, blue: Analytical

solution using advection diffusion equation. The satisfying match proves the plausibility of the measured data as well as the minor side effects such as rock adsorption as it was not modeled in the analytical equation.

Sensitivity on the minimum number of cells required to obtain the least possible numerical dispersion was performed. The numerical dispersion is proportional to the grid size. The higher the number of cells the lower is the grid size required and the less is the effect of numerical dispersion. It is known that time discretization has also an effect on the numerical dispersion, however it was not considered in this sensitivity study as it is a matter of the simulation setup afterwards and not of the model configuration.

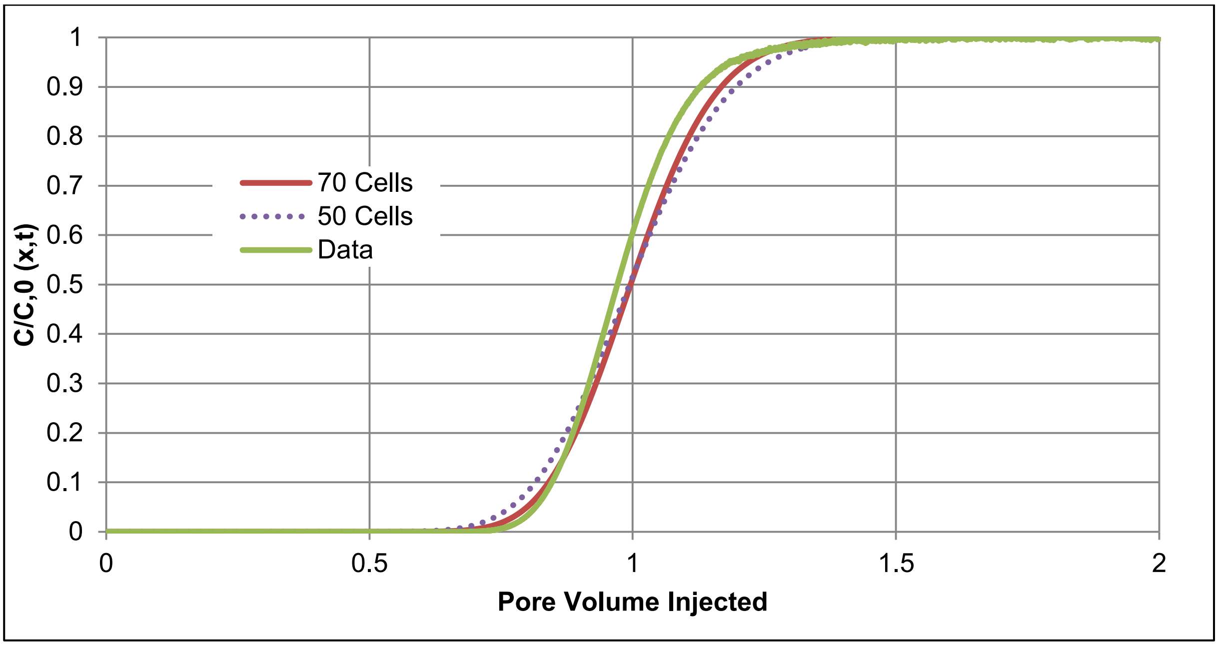

Figure 9: Simulation of the tracer test on the core plug with different grid sizes and grid numbers. 70 cells provide and acceptable match.

3.1.2 Single phase

A core plug of 11.44 cm^3 volume was flooded with tagged water under two different scenarios: 100% water saturation and 20% connate water saturation. SCN tracer was injected with a concentration of 7.34 10^{-4} gms/scc (73.4 ppm). The experiment is simulated using ECLIPSE E100 in order to compute the connected pore volume from the tracer production curve.

The core plug is discretized into 200 grid cells. The water and tracer are injected in one end and are collected in the other.

The connected pore volume is estimated using equation (41):

$$\overline{Vs} = \frac{m_p}{M_i} \frac{\int_0^\infty q \cdot Cdt}{\int_0^\infty Cdt} - \frac{V_{slug}}{2} \quad \textbf{Eq.}42$$

With $\overline{Vs}$ as the total swept volume connected pore volume, q the produced liquid flow rate, C produced tracer concentration; m_p total mass of produced tracer, Mi is the total mass of injected tracer V_{slug} is the volume of the water slug with tracer injection.

The volume of the slug could be neglected in the field scale operation as the tracer is usually injected as a single small pulse. However in the case of a core scale, care must be taken in the estimation of the slug volume as it can be a factor of the sample pore volume (usually 0.6 PV). In this case the volume of slug is estimated as following:

$$\overline{Vs} = \frac{m_p}{M_i} \frac{\int_0^{\infty} q_p C_{produced} dt - \int_0^{\infty} q_i C_{injected} dt}{\int_0^{\infty} C dt} \qquad \textbf{Eq.}43$$

In the case with only water phase, the connected pore volume must be equal to the actual pore volume of the sample, with a margin of error that is due to numerical dispersion. The connected pore volume calculated from the residence time distribution analysis linearly increases with time until the maximum concentration breakthrough. It is nothing but the cumulative injected pore volume until the peak concentration reaches the outlet, which is in fact the injected pulse smeared out due to the displacement and the dispersion.

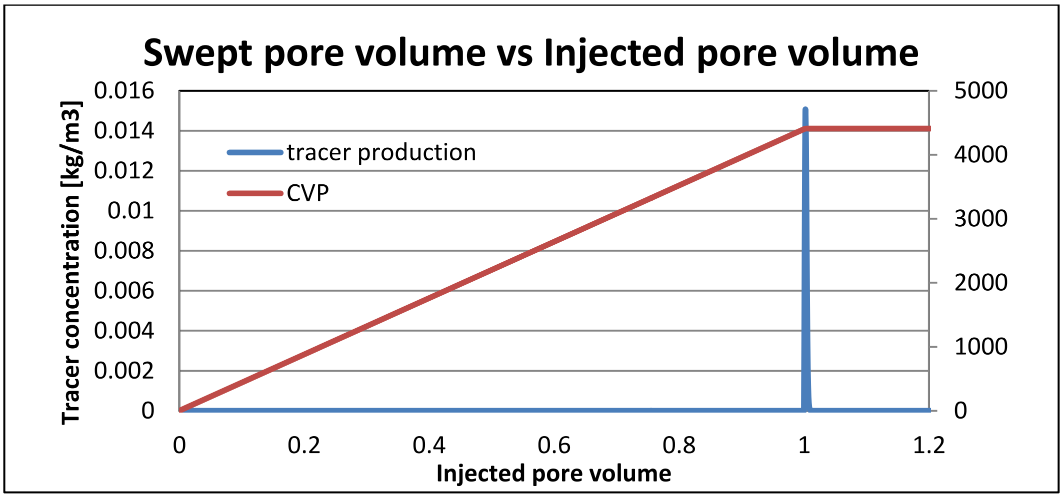

Figure 10: Tracer concentration and connected pore volume (or swept pore volume) plotted against pore volume injected

In order to have a track of where the tracer has been flowing, adsorption for tracer is activated. The tracer adsorption curve which is a Langmuir function is intentionally modified in order to reduce the adsorption rate in a way that it does not affect the tracer mass recovery or the tracer is order not to cause any retardation in the tracer response curve.
In order to insure that the adsorption rate is small enough, two tracers have been injected simultaneously and adsorption is activated for one of them. The response curves for the two tracers have to match.

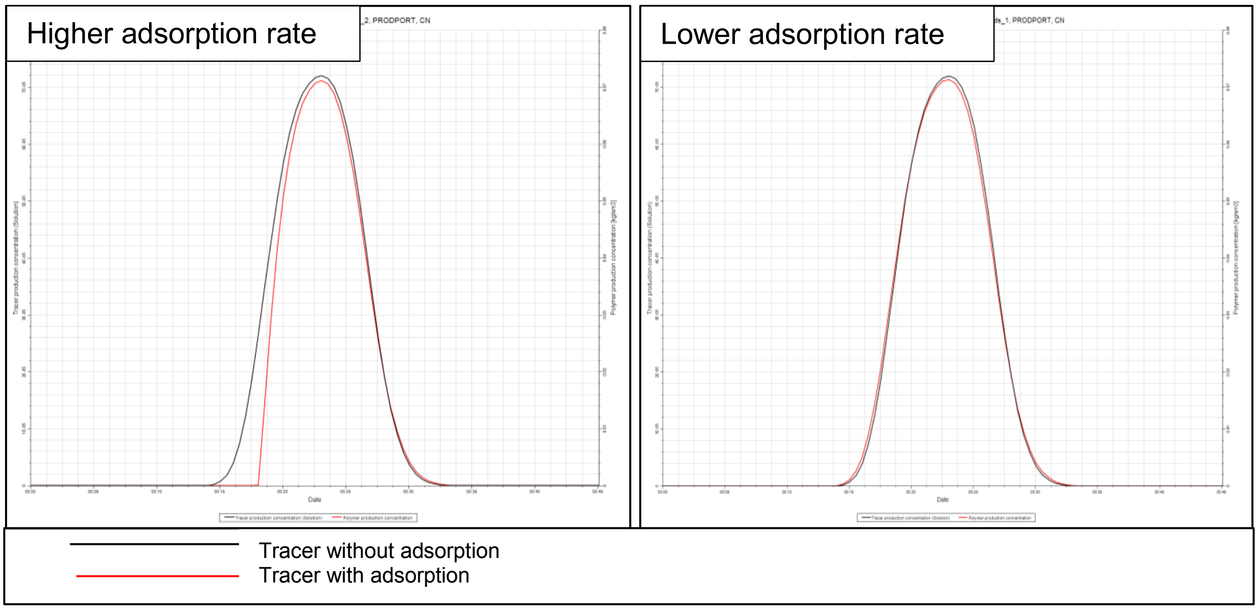

Figure 11: Tracer adsorption to track tracer movement history

The cells where the tracer was flowing are marked with tracer adsorption in the following Figure 12. The tracer pulse is moving and the connected pore volume is accumulating covering all the cells behind it.

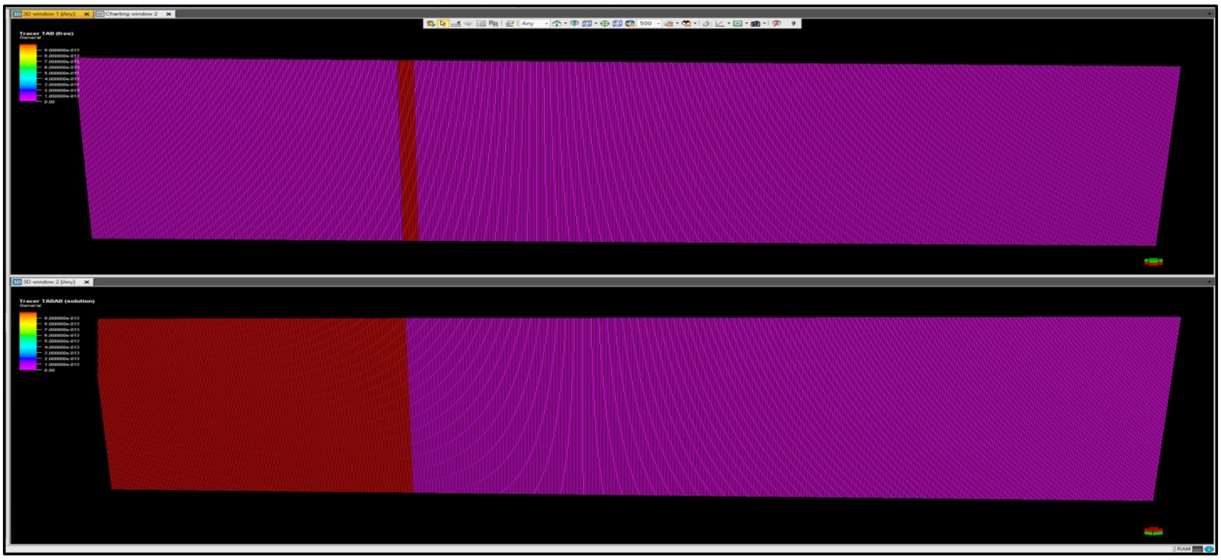

Figure 12: Tracer moving through the simulated core plug

Residence time distribution analysis can also be used to estimate time dependent heterogeneity index as following:

$$F = \frac{\int_0^t qCdt}{\int_0^\infty qCdt} \qquad \textbf{Eq.}44$$

$$\Phi = \frac{\int_0^t Ctdt}{\int_0^\infty Ctdt}$$ **Eq.**45

As the core plug was simulated with no heterogeneity, F-PHI curve should show a perfect correlation indicating homogeneity. However, it was remarked that when the injected slug is large compared to the core pore volume, the F-PHI curve is deviated from the homogenous line, meanwhile this deviation vanish when the injection is reduced to a pulse.

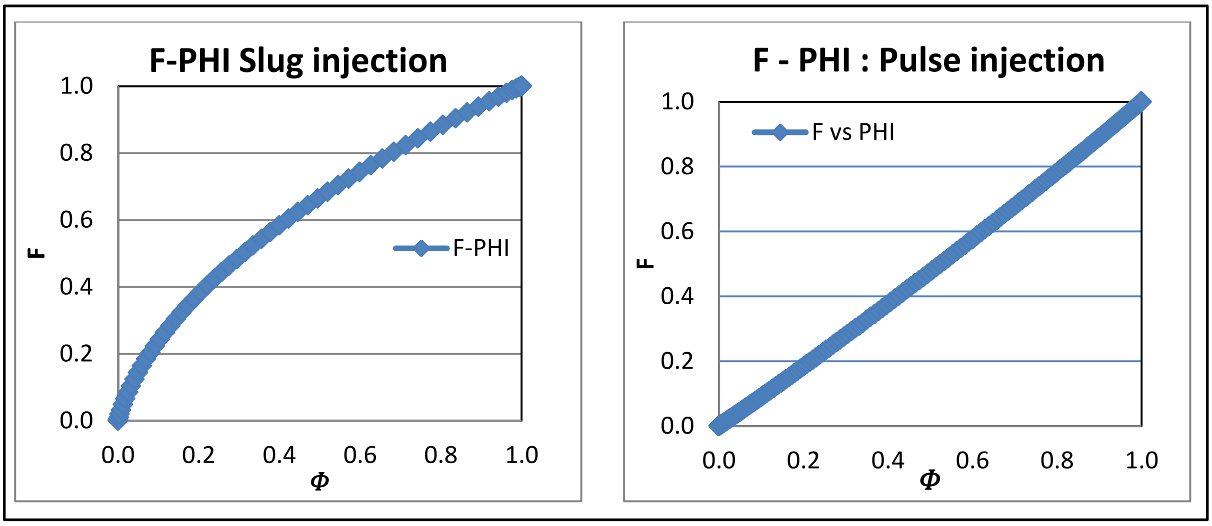

Figure 13: F-PHI plot for a homogenous plug with Sw=1. The slug size has an effect on the numerical dispersion and therefore the core appears more heterogeneous than it actually is. Reducing the slug size to a Dirac function ensure better estimation of heterogeneity as well as swept volume.

3.1.3 Two phases

In this section the core plug simulation is carried out with two phases: oil and water. In this case, the sweep efficiency is a function of mobility ratio. Therefore the swept volume calculated by the tracer will depend on the relative permeabilities as well as the wettability state.

The mobility ratio is the mobility of the displacing fluid divided by that of the fluid being displaced, such as oil. In case of water flooding, where water is displacing oil The mobility of the oil is defined ahead of the displacement front while that of the water is defined behind the displacement front, so the respective effective permeability values are evaluated at different saturations.

As the tracer is conservative, no partitioning of the tracer between the oil and water phase should occur. Therefore, the tracer can only represent the water phase. The swept volume is then a measure of water volume in the system. Sensitivity on several relative permeability curves is presented in the following table. As expected, the connected pore volume calculated using the method of moments or RTDA is equal to the volume of water in the simulated core plug at the end of the flood. Please refer to the appendix for relative permeability curves for the different cases.

Water Oil				
Effect of Corey exponents Sor=0.25 Swc=0.2				
Case	Nw	No	Connected pore volume	water volume
Kr5	4	3	6.875	6.869
Kr6	1	4	5.742	5.716
Kr7	2	4	6.150	6.137
Kr8	2	3	6.605	6.570
Kr9	2	3.4	6.719	6.238
Effect of wettability Nw=4 No=2				
Case	Sor	Swr	Connected pore volume	water volume
Water Wet	0.2	0.3	7.565	7.5637
Oil Wet	0.3	0.2	6.097	6.0943
Strongly water Wet	0.2	0.35	7.992	7.9928
Strongly Oil Wet	0.35	0.2	5.492	5.4967
Mixed Wet	0.22	0.22	6.919	6.9110

Table 2: Swept volume from tracer data compared to numerical simulation: sensitivity on different relative permeability curves

3.2 Synthetic case: Inverted five spot pattern

Production of any petroleum reservoir often involves a serious consideration of well placement. In so many cases, especially when an IOR/EOR project is to be implemented and injection of fluids is considered, the placement of wells must be designed in patterns that ensure the most efficient recovery. The flooding pattern for an individual field or part of a field is based on the location of existing wells, reservoir size and shape, cost of new wells and the recovery increase associated with various injection patterns. The flood pattern can be altered during the life of a field to change the direction of flow in a reservoir with the intent of contacting unswept oil. It is common to reduce the pattern size by infill drilling, which improves oil recovery by increasing reservoir continuity between injectors and producers. Common injection patterns are direct line drive, staggered line drive, two-spot, three-spot, four-spot, five-spot, seven-spot and nine-spot patterns.

In this section, an inverted five spot pattern is presented, which consists of an injection pattern in which four production wells are located at the corners of a square and the injector well sits in the center. As the goal is to understand the tracer behavior in heterogeneous reservoirs, one injector is considered in order to avoid confusion and interference between different flowing paths. Usually, flow in a homogenous five spot is symmetrical, and therefore to reduce computational load, only quarter of the pattern with one injector and one producer is modeled.

However, in this work, as the goal is to assess the heterogeneity and the tracer recovery from different wells, the full model was simulated. Moreover, the pattern was not confined in order to consider all possible flow paths that might converge from injector to the different producers.

The model used was a 200x120x11 grid, with a total number of 264000 cells, with homogenous 25 % porosity and 1000 mD permeability in the horizontal directions. Kv/Kh is equal to 0.1.

The model is initially water saturated to 100%. The boundary conditions were Neumann boundary conditions (no flow boundary) with no aquifer.

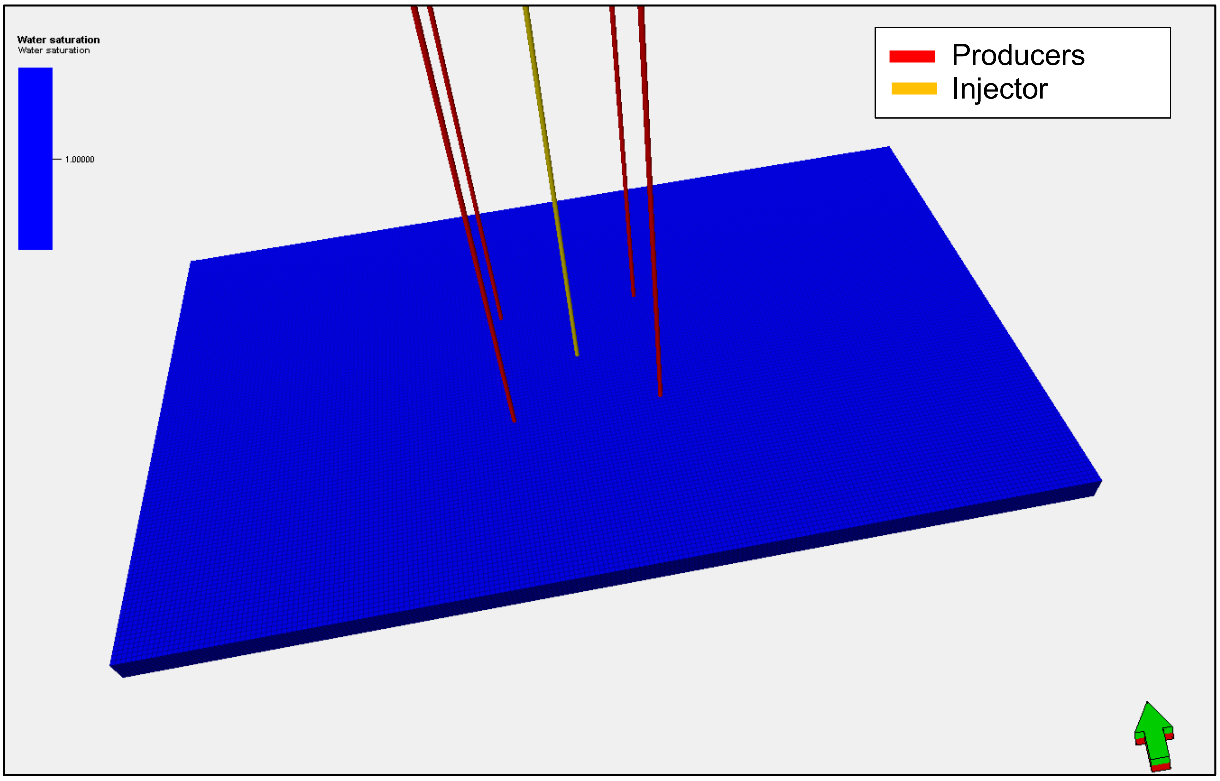

Figure 14: Inverted five spot model

3.2.1 Homogeneous case

Tracer transportation in any reservoir or flow system is mainly controlled by advection and mixing. Advection is the transport of fluids in the system where the sharp fronts between fluids are preserved. Mixing, on the other hand, is the local spreading and dilutions of the tracer concentration at the front of the displacement due to concentration gradient through the porous medium.

Eventhough convection is the main transport mechanism for conservative tracers, the tracer material will be subject to dilution before arriving to the producer well as an effect of pattern configuration and pattern size. The tracer curve in a linear displacement imitates the shape of the injected slug, with a broadening effect caused by dispersion as discussed in the previous section. However, in the case two or three dimensional flow geometry, tracer mixing will have an effect on the tracer curve observed at the producer.

The tracer breakthrough will be a function of the pattern breakthrough curve. M.Abbaszadeh-Dehghani and W.E Brigham [17], developed a mathematical model that describes the tracer breakthrough for several patterns based on the advection diffusion equation. The tracer breakthrough curve when a slug is injected into a five spot pattern is the difference in the breakthrough of the initially injected fluid and the chase fluid following the slug which is presented by the hatched area in the figure below. The dashed line is what the actual tracer producer curve would look like due to dispersion and mixing between the injected tracer and the reservoir fluids.

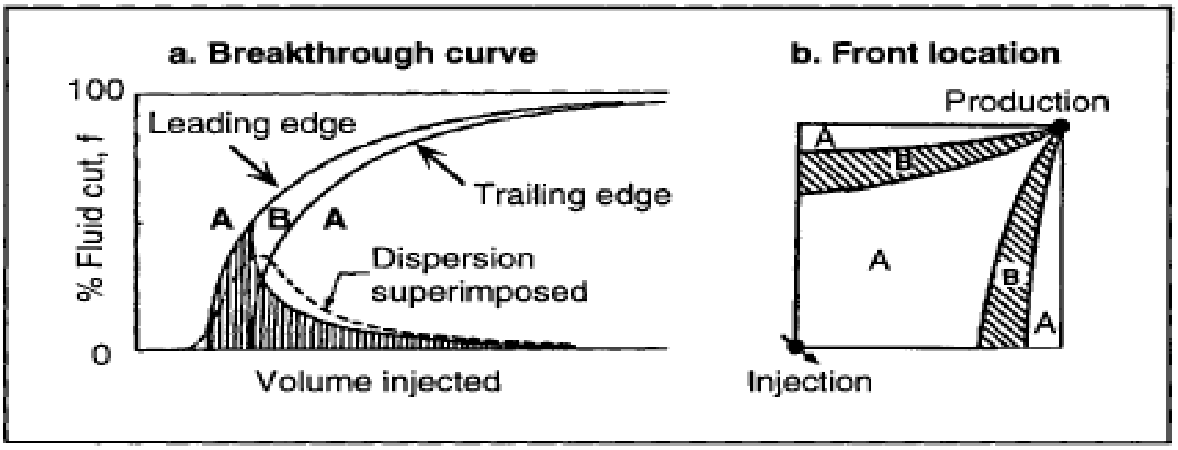

Figure 15: Tracer breakthrough curve in a five spot, here presented a quarter five spot (one injector and one producer)

In the case of a homogenous pattern, the trace production from the four well is the same. It can be seen that in the case of 100% water saturation, the sweep from different layers is conform. As the pattern is open (no confinement at any side) it can be seen that there was flow paths converging from outside into the producers. The connected pore volume calculated form RTDA is higher than the volume of the pattern.

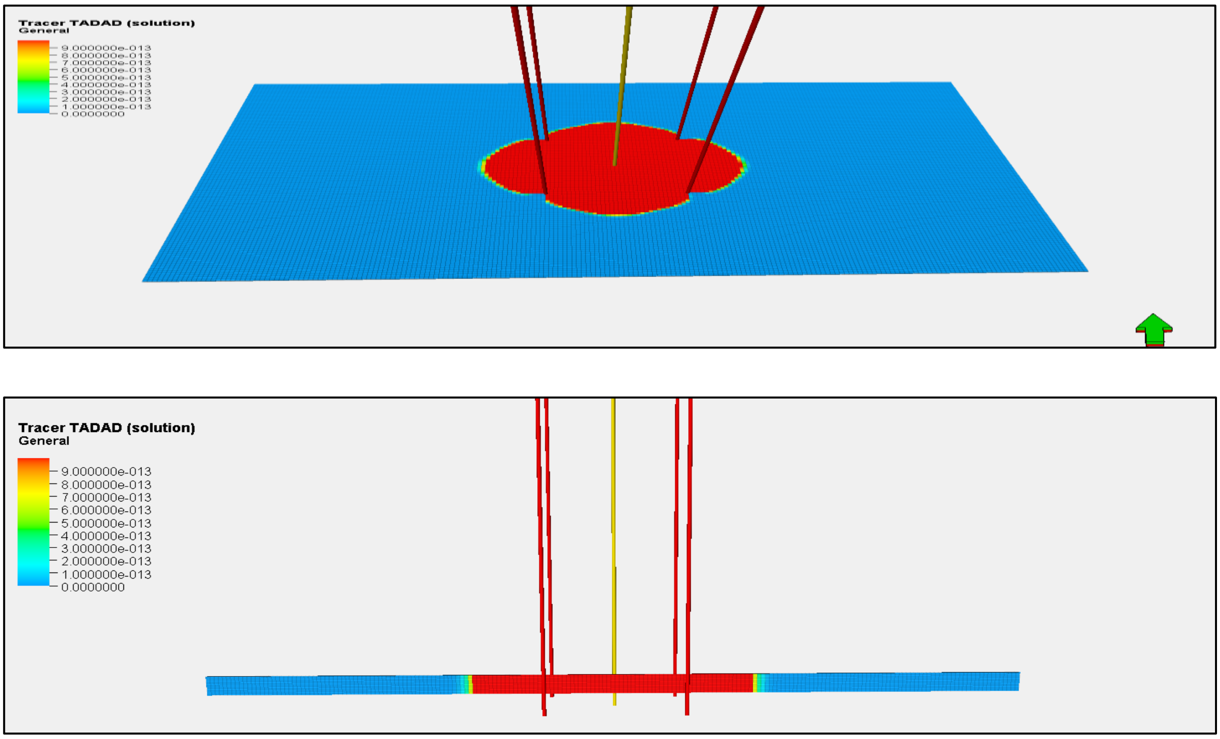

Figure 16: Tracer flow in a homogenous inverted five spot: tracer adsorption is applied in negligible quantities to mark the cells that have seen tracer concentrations.

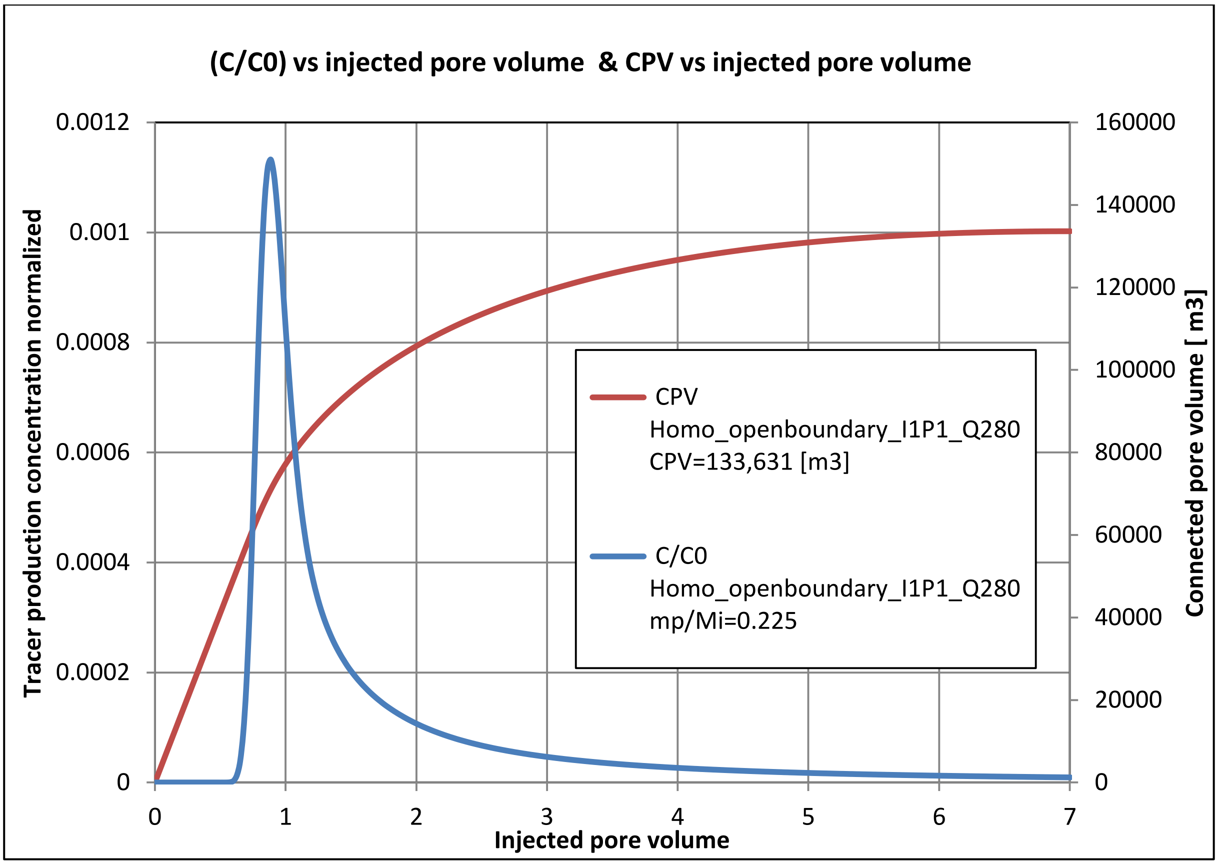

Figure 17: Swept volume estimation in inverted five spot pattern from well to well tracer curve

The mean of the distribution relative to the injected volume represents the mean volume injected. In a homogeneous, one-dimensional system, neglecting dispersion, the break-through, (BT), is a measure of the pore volume swept by the water. In a two- or three-dimensional heterogeneous reservoir, the BT response is a function of the pattern geometry and the heterogeneities. It is only an indicator of the volume swept by the fastest paths between injector and producer, not a measure of the total pore volume swept between injector and producer. The total pore volume swept by the injected water is the sum of all the paths by which the water moves between the two wells and is better measured by the mean of distribution.

The F-PHI curve for the homogenous inverted five spot patterns with 100% water saturation shows a level of heterogeneity with a Lorentz coefficient equal to 0.35, even though no spatial variation of rock properties is considered. This indicates that the F-PHI plot does not only reflect static heterogeneity but additionally the variance in flow paths followed by the tracer.

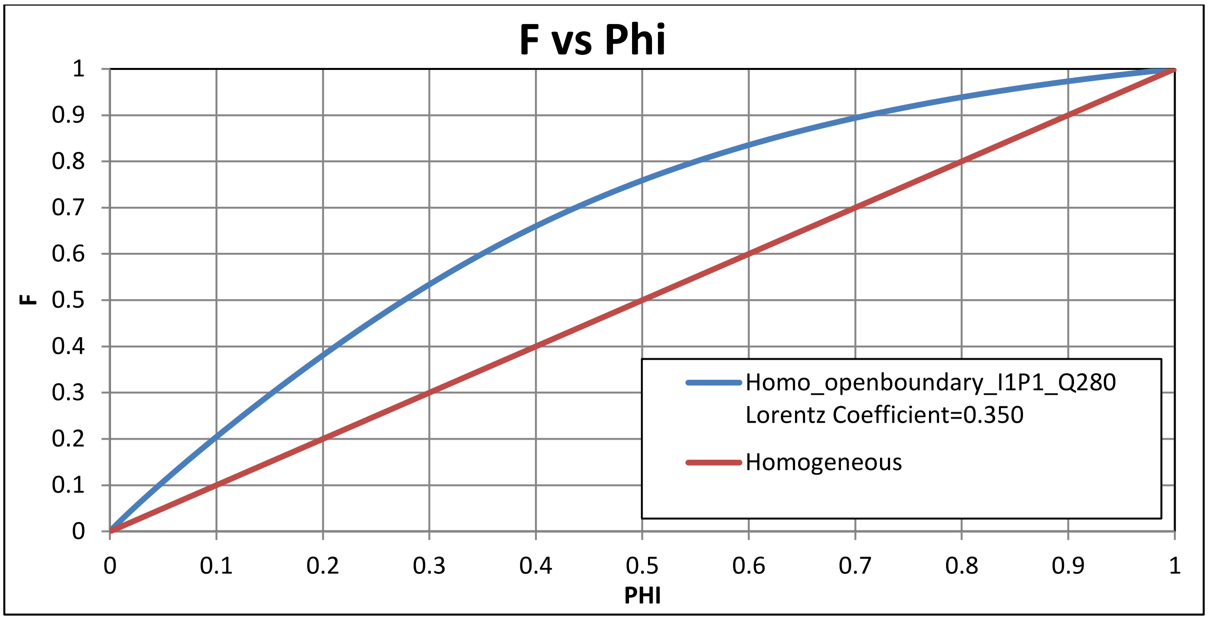

Figure 18: F-PHI curve for a pair of injector producer in water saturated inverted five spot patterns

Numerical dispersion has proven to have an effect on the broadening of the tracer curve and on the F-PHI curve in the case of 1D simulation. All Eclipse simulator keywords to reduce to control the dispersion have been applied with the finest possible time scale. The heterogeneity indicated in the Lorentz coefficient still however can be observed. For a confined model where 9 patterns of inverted five spots were simulated, there were no flow paths out of the pattern area and the Lorentz coefficient although decreased but still indicated some level of heterogeneity.

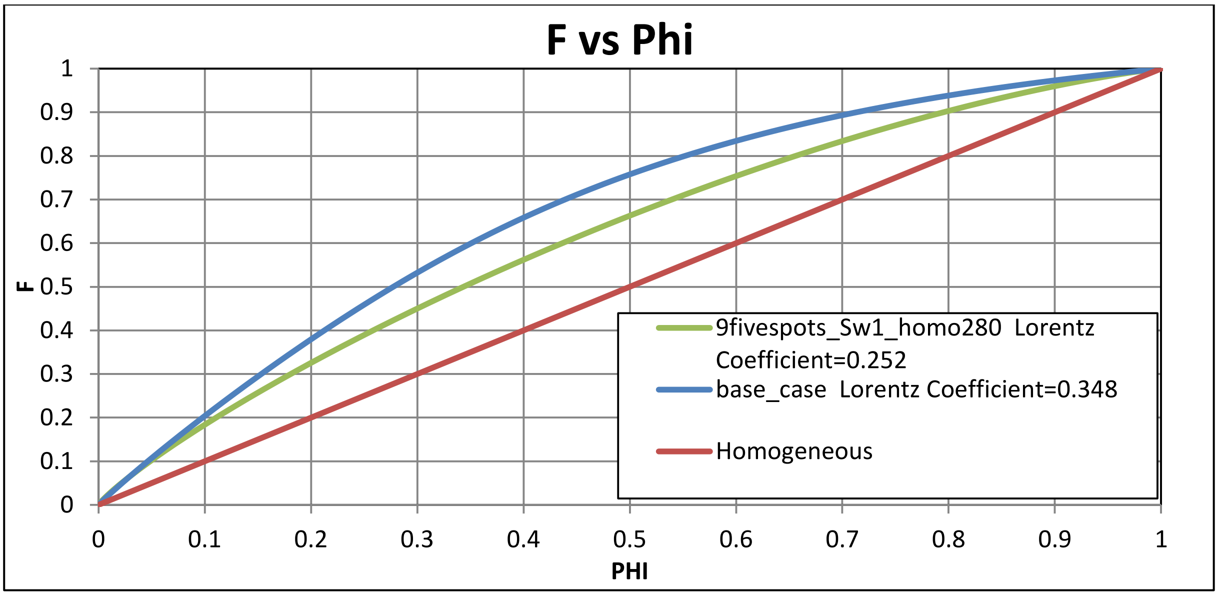

Figure 19: F-PHI plot from well to well tracer curve for a homogeneous water saturated confined inverted five spots pattern

A low permeability box is between an injector and one of the four producers is implemented. The purpose is to check how this will affect the shape of the F-PHI curve. The permeability barrier will eliminate the flow short flow paths going directly from the injector to producer, leaving only the flow path that are going around it. The F-PHI curve as a measure of the difference in the length of flow paths and the tracer velocities within them, it is illustrated that there is a reduction in the Lorentz coefficient and this test resulted in a shift of F-PHI curve a to a more homogeneous state.

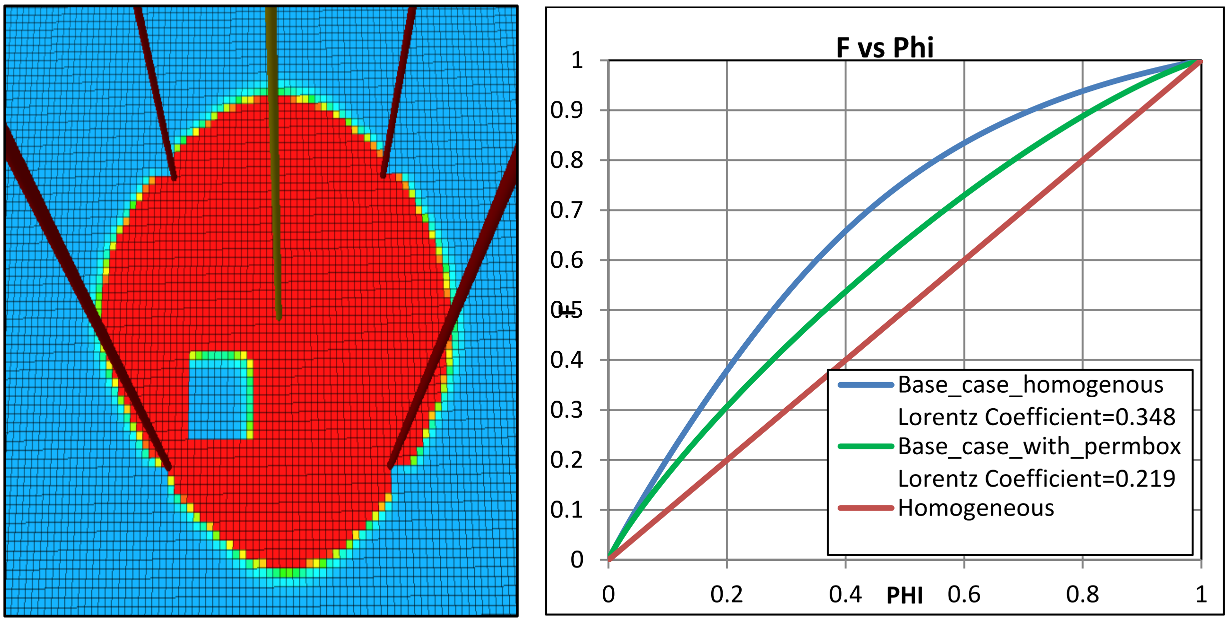

Figure 20: Permeability barrier box and the corresponding F-PHI curve for a confined 9 patterns of inverted five spot setting

Many of reported tracer tests are concerned with fields at or near residual oil, and with some kind of tertiary recovery process, where water is the only flowing phase. In such cases, the tracer response curve can be used to determine sweep efficiency and directional permeability as well as potential improvement by EOR mechanisms. Qualitative data on reservoir flow barrier and channels can also be extracted from the tracer data. [18] Tracing water swept regions of an oil field allows taking advantage of the steady state condition to obtain accurate and non-disturbed tracer information.

Torsten et al. [9] reported the results of several a tracer test carried out by OMV in the 8TH reservoir in the Matzen Field for the purpose of understanding the level of heterogeneity and the flow mechanisms in a polymer pilot. Pre and post-polymer tracer tests allowed a deeper understanding of the effect of polymers on the mobility ratio and the potential increase in oil recovery.

A model with similar properties to the 8TH reservoir is used in this section. Initialization of the model at current water cut of 96% at that field wad achieved by setting average oil saturation at 55% according to the relative permeability curves provided.

The tracer curve for the two phase system is marked by an earlier breakthrough time due to smaller volume to be swept by the tracer.

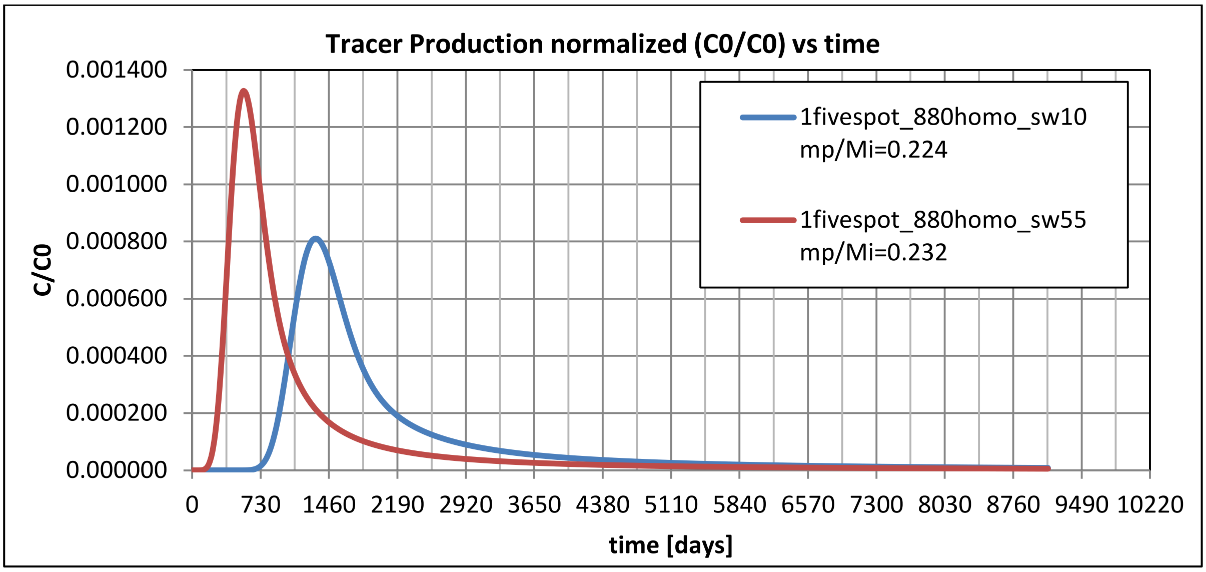

Figure 21: Tracer response curve for two phase model

Additionally, the F-PHI curve reflected more heterogeneity. Although rock properties are intact for the two cases compared in the figure 22 below, there was a significant increase in the heterogeneity index. This proves that the F-PHI curve as a measure of heterogeneity is largely affected by flow dynamics and does not exclusively represent the static properties.

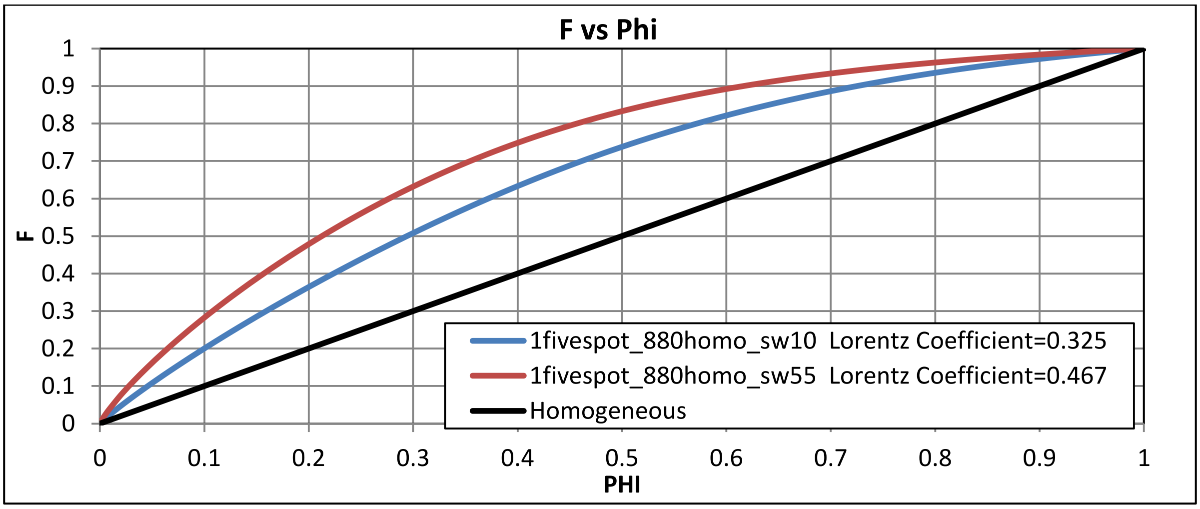

Figure 22: F-PHI curve for two phase model

The connected pore volume computed from tracer data using RTDA is presented in figure 24. Compared to the fully water saturated case, the swept volume for a water saturation of 55% is decreased by 40%. This is in alignment with the sensitivity of the 1D case in chapter section 3.1 of this chapter in which it was shown that the connected volume from the tracer corresponds to the water volume in the interwell space in contacted with the tracer. It is noteworthy that this kind of direct volumetric information is unique to tracers only.

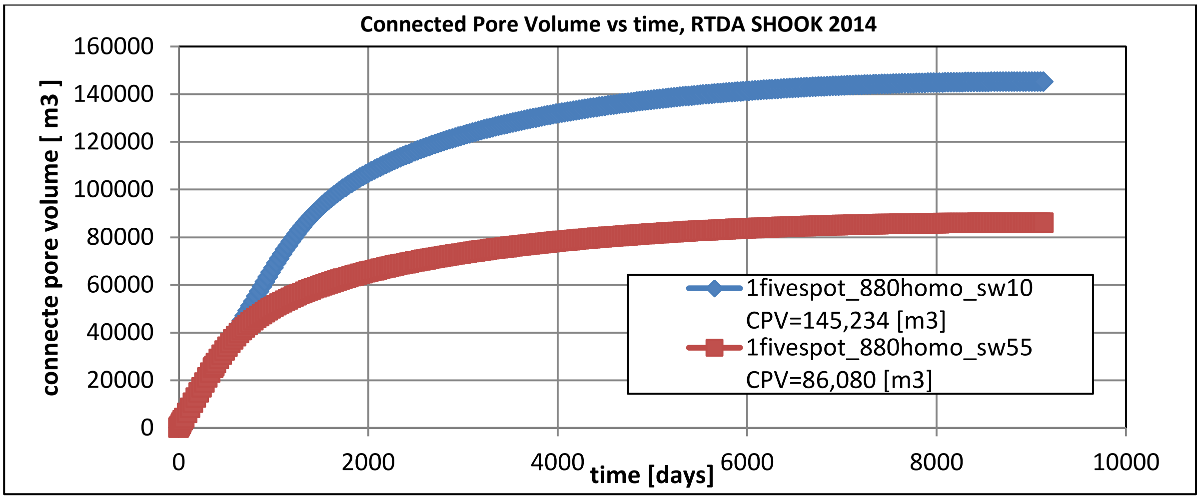

Figure 23: Connected pore volume from tracer data: Blue: Sw= 100 %, red : Sw=55%

3.2.2 Layered heterogeneity

Reservoirs often are sedimentary deposits laid down in a body of water over a long period of time. After deposition, they undergo further physical and chemical changes. As a result of the non-uniform nature of deposition and secondary alteration, heterogeneities develop within the reservoirs. The severity of the heterogeneity depends on the lithology and the external forces acting upon the system. In general, sandstones reservoir tend to be more uniform than limestones or carbonate reservoirs. [17]
The sediments are generally deposited areally, therefore lateral uniformity is usually expected over wide ranges of a reservoir and used for well correlation. However, in the vertical direction, a variation of reservoir properties is anticipated due to the differences in the depositional time and environment. The scheme of layered heterogeneity is generally a fair representation for many sandstone reservoirs. Interlayer communication is controlled by the existence or absence of thin shale layer that prevent interlayer fluid transport.
The simulation of reservoirs as though they are composed of parallel non communicating layers has been broadly used in several reservoir engineering calculations. For instance Dykstra & Parson presented a method for calculating vertical coverage in water flooding operations, and it has been found to match results in a satisfying way. [17]
Fitch, [19] successfully matched the results of a miscible test by a stratified model without cross flow. The success in matching the miscible and immiscible displacement indicates the reasonability of the layered reservoir modeling concept.

Similarly, the flow of tracers in heterogeneous reservoirs can be modeled by a stratified system. Since the tracer material is miscible with the injected fluid as well as the same phase existing in the reservoir, and has the same density and viscosity as these fluids, cross-flow can occur only as a result of lateral dispersion. [17] Therefore, as the lateral dispersion for conservative tracers is much smaller than longitudinal dispersion, the results of tracer flow in stratified reservoir, with or without cross flow between layers would be similar. Therefor for simplicity of modeling, in this section no cross flow is considered.

In a simplistic case of a 2D model, 5 layers of different permeability have been introduced. The layers are laterally continuous and there is no cross flow allowed. Tracer is injected at inlet and produced at the outlet located in the opposite section of the block. The permeability for the layers is as 1800, 2000, 2400, 2800 and 3000 mD. The porosity is 0.22 and the length is 2000m. The layers are of equal thickness.

The model is initially at connate water saturation and water is injected until steady state condition is achieved. The tracer is then injected. Steady state condition is ensured first in order to avoid integration ambiguities in the RTDA for the tracer curve as flow rates can be excluded from the integral.

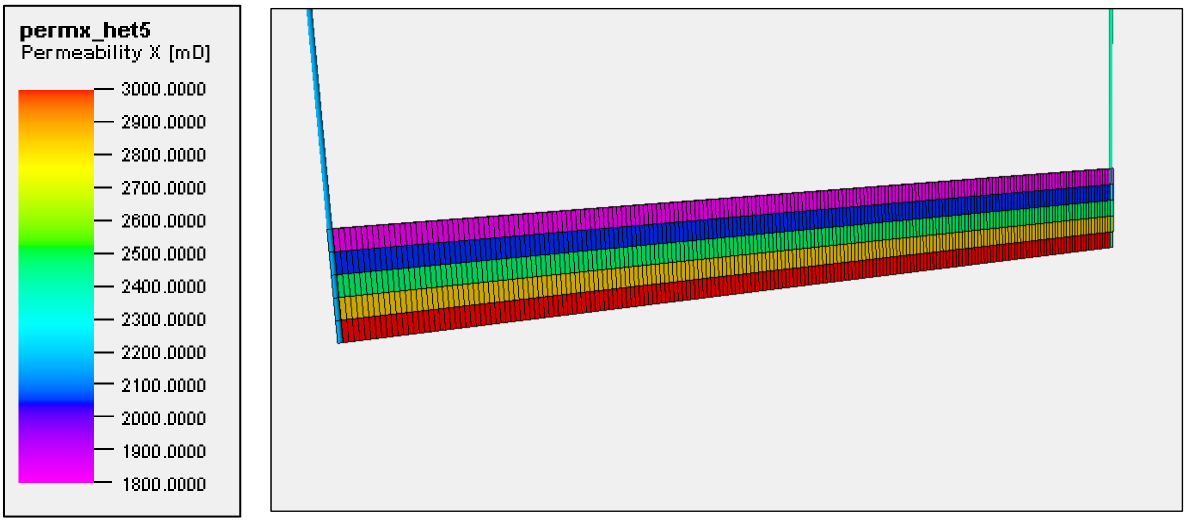

Figure 24: Layered heterogeneity for 2D model

The tracer production curve shows the corresponding tracer peak for each layer (figure 25). As no cross flow is allowed and significant contrast exists between the different layers, the tracer breakthrough at different times without interference.

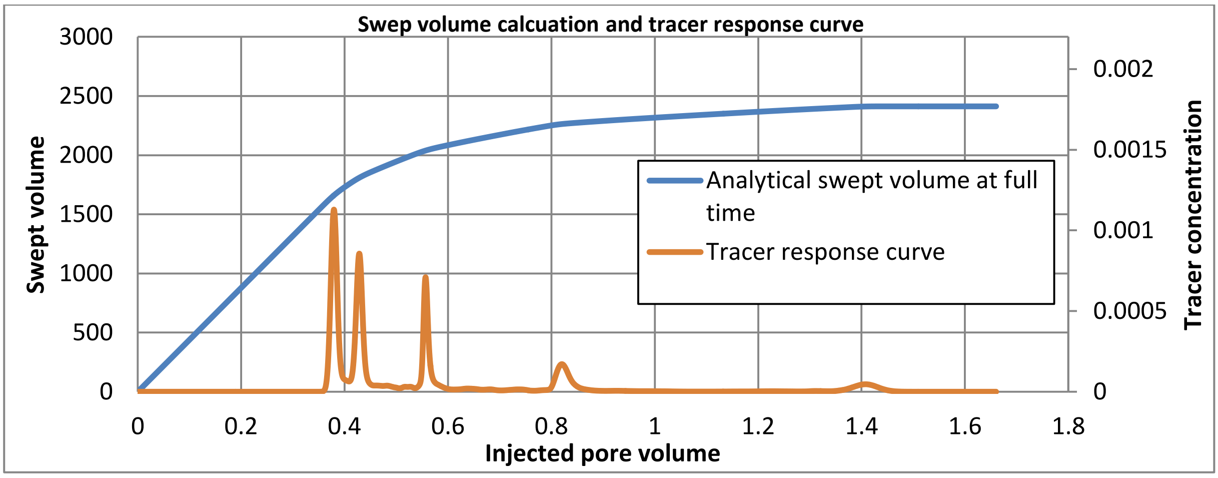

Figure 25: Tracer response curve and analytically derived swept volume

Using **Eq.**11 and **Eq.**18, a static flow capacity storage capacity curve was computed. Comparing this curve with the tracer generated curve gives an acceptable match. This confirms that the tracer F-PHI plot is indeed a measure for the static heterogeneity as well as for the dynamic heterogeneity.

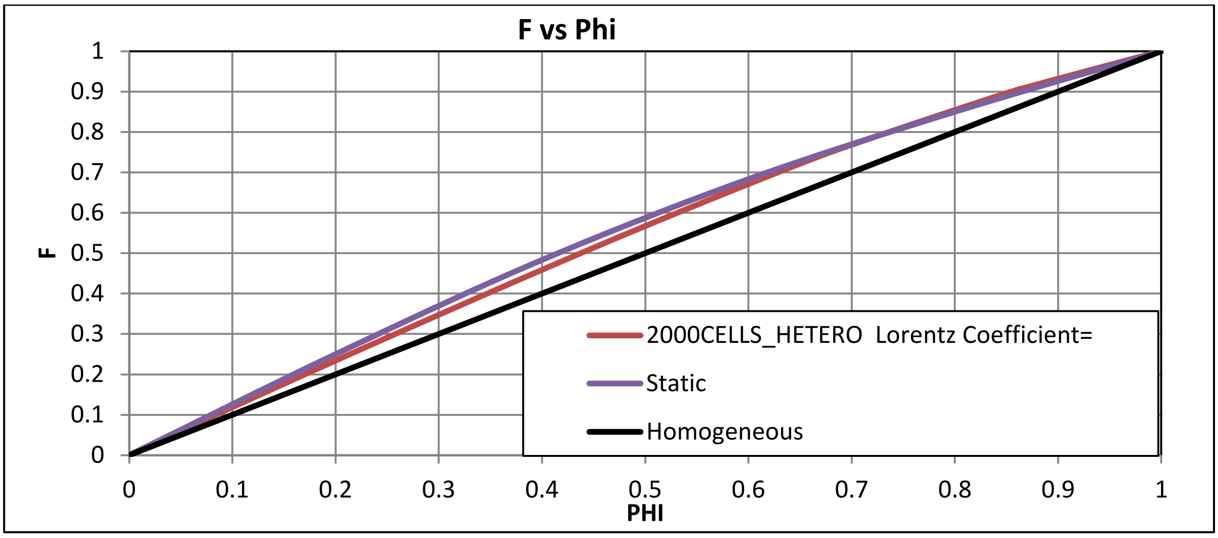

Figure 26: F-PHI curve for 2D layered reservoir

The tracer production curve when oil saturation is at 57% shows qualitatively a level of heterogeneity. More than one tracer peak indicates that there is a contrast between flow paths velocities. The different permeability values do not however breakthrough is separate peaks, this is due to interference. Another indication of the heterogeneity contrast between the homogenous case and the layered case is the difference in breakthrough time. The tracer production curve is shifted to the left indicating that the first tracer breakthrough is controlled by a high permeability streamline. The tracer breakthrough in the heterogeneous case occurs after 90 days of injection compared to 820 days in the case of homogenous settings.

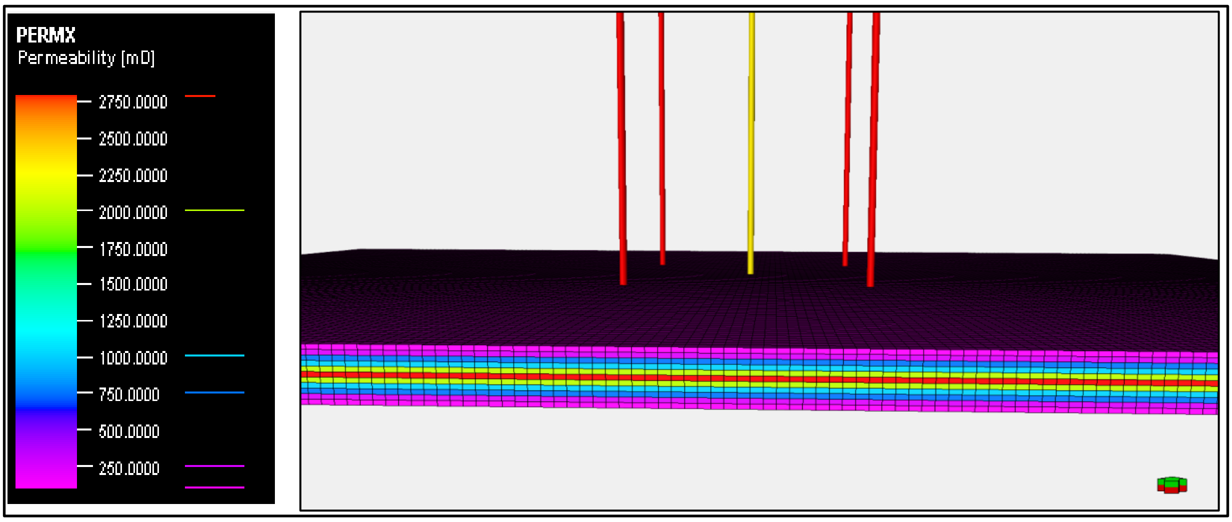

Figure 27: Stratified reservoir model, 11 layers with 1000 md permeability average

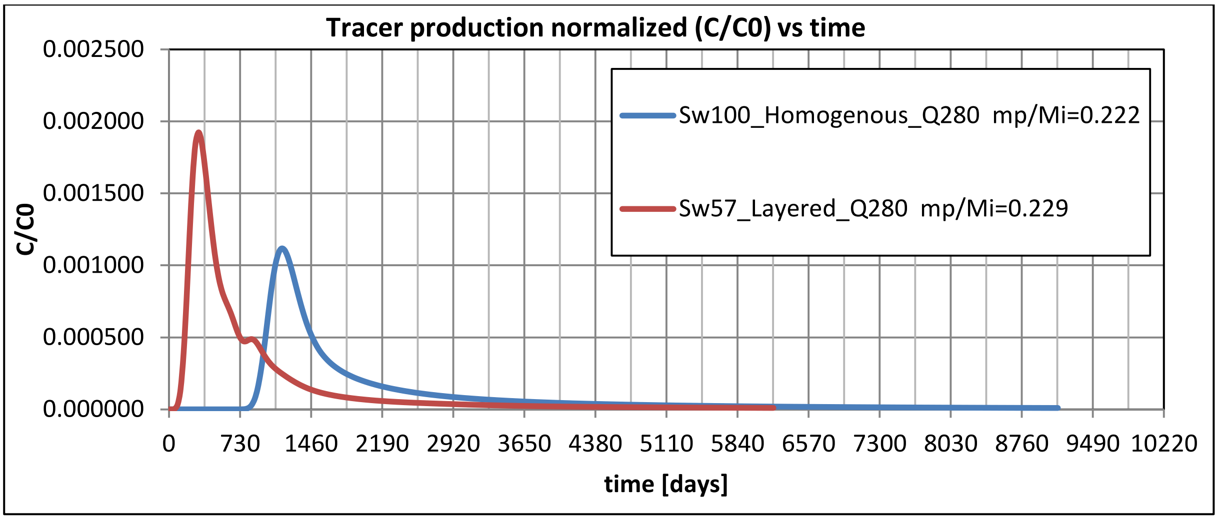

Figure 28: Tracer curves for homogenous and layered heterogeneity in inverted five spot patterns, red: layered, blue: homogenous.

In the F-PHI diagram in **figure 29**, the Lorentz coefficient for the layered system is 0.49 compared to 0.36 in the homogenous case. The static F-C was constructed using equations 21 and 22 by arranging layers in increasing permeability and by assuming no vertical communication between layers.

The static F-C curve and the F-PHI curve derived from the tracer data matches. This indicates that for layered heterogeneity reservoir the tracer data reflects the vertical heterogeneity accurately. In the other hand, the homogenous model reflects a level of heterogeneity as well which is due to the difference in the streamlines and their breakthrough times. This indicates that static heterogeneity more dominant effect on tracer breakthrough time than the distribution of the streamlines within each of the laterally homogenous layers.

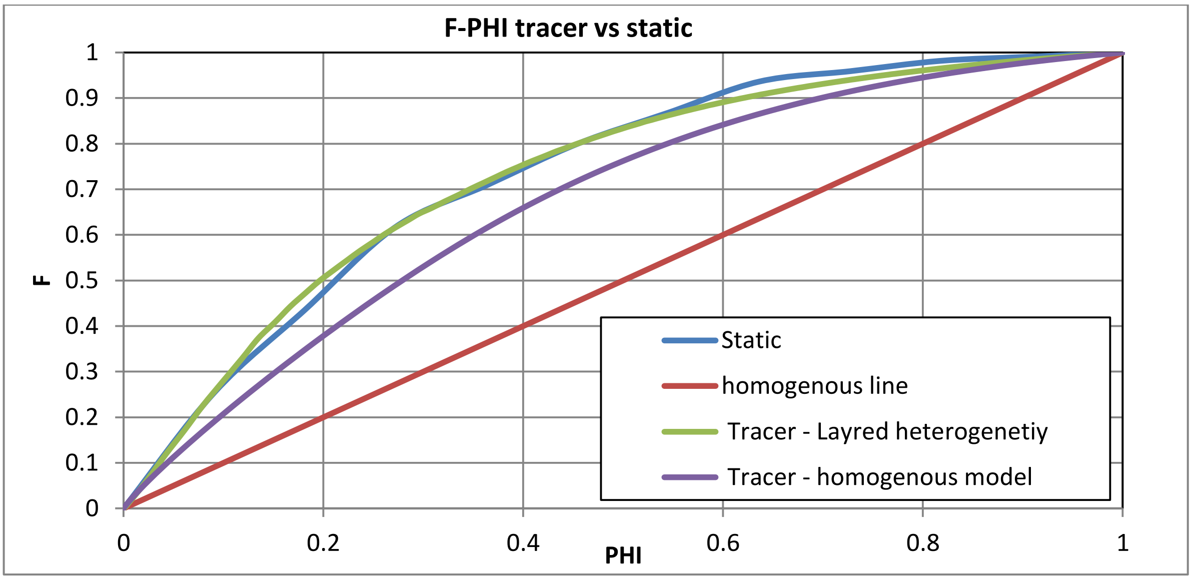

Figure 29: F-PHI curve from static and tracer data for layered heterogeneity 3D model

3.2.3 Polymer Injection

Polymer injection is an EOR method that aims to improve the volumetric sweep efficiency by increasing the water viscosity and therefore reducing the mobility ratio. Bringing down the mobility ratio to values lower than 1 will eliminate viscous instabilities in the displacement front and will increase oil production by imposing a more uniform sweep. Polymer also improves the sweep by affecting the relative permeability of the water.
Polymer flooding is relatively cost intensive, therefore it has to be economically justified. Usually, polymer flooding is conducted on a pilot scale before being implemented in a field scale. Sound understanding of the reservoir properties and flow dynamics is a key factor in the success of the flood. Additionally, understanding of the polymer effect and the potential increase in the recovery is of critical importance. Tracer injection is one method that can be used in the direction of both goals.

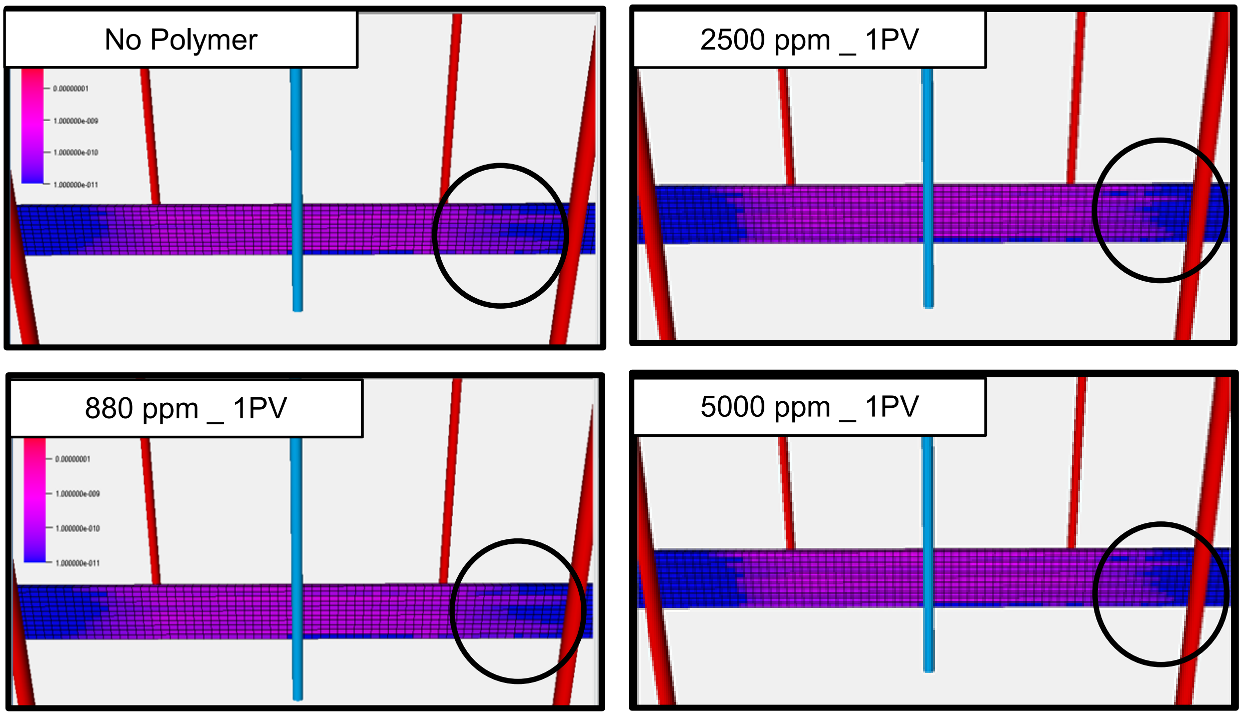

Figure 30: Polymer effect on sweep efficiency improvement, fingering due to high mobility ratio (black circle) is stabilized with polymer injection. The effect is more visible for higher polymer injection concentration from 880 ppm to 2500 ppm to 5000 ppm.

A single well chemical tracer can be used prior to an EOR project to measure the oil saturation in the reservoir on a well scale. An alternative option is to use partitioning interwell tracers (PITT) to estimate the residual oil in the interwell space and assess the potential additional recovery. If a conservative tracer is injected as a narrow slug simultaneously with the polymer slug, information about flow direction and the sweep before and after the polymer flood can be obtained by analysis of the tracer production curve. [20] Changes in swept volume caused by the chemical EOR operation can thus be monitored. Both for continuous and pulse injection reliable conservative water tracers with the minimum rock interaction are required.

The effect of polymer is a function of the type of polymer that controls the viscosity function of polymer solution, the injected concentration and the size of the polymer slug injected.

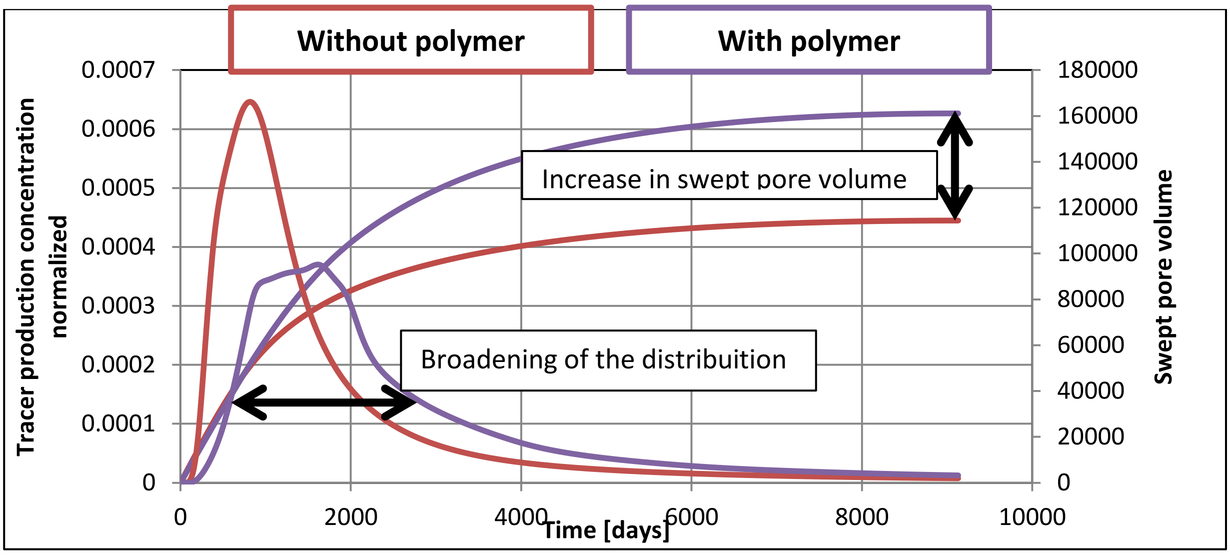

Figure 31: Tracer curve and swept pore volume: the effect of polymer

For the synthetic bivariate petrophysical model, the effect of polymers can be observed qualitatively by means of tracer marking on two levels: within each individual layer, the sweep is more uniform and stable. From a cross section view, the polymer injection reduces the viscous instabilities of the displacement. More stable front is achieved with more polymers being injected. Figure 31 delineate the effect of increasing pore volume of injected polymer.

The effect of polymer injection can also be observed in the tracer curve and F-PHI plot. As the displacement front is more uniform, tracer would eventually breakthrough with more homogenous behavior. This is reflected in the tracer response curve by a broader distribution and in the F-PHI plot by a lower Lorentz coefficient.

A later breakthrough is also observed and it is due to the retardation is high velocity flow path that are caused by non-uniform displacement and mobility ratio effect.

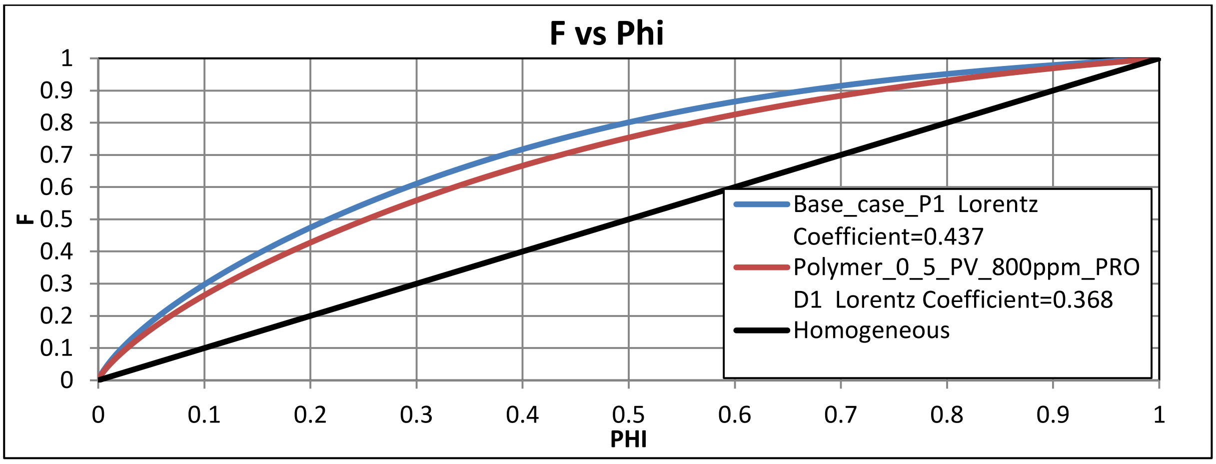

Figure 32: F-PHI plot before and during polymer injection

4 RESULTS AND DISCUSSION

- **Extrapolation importance:**

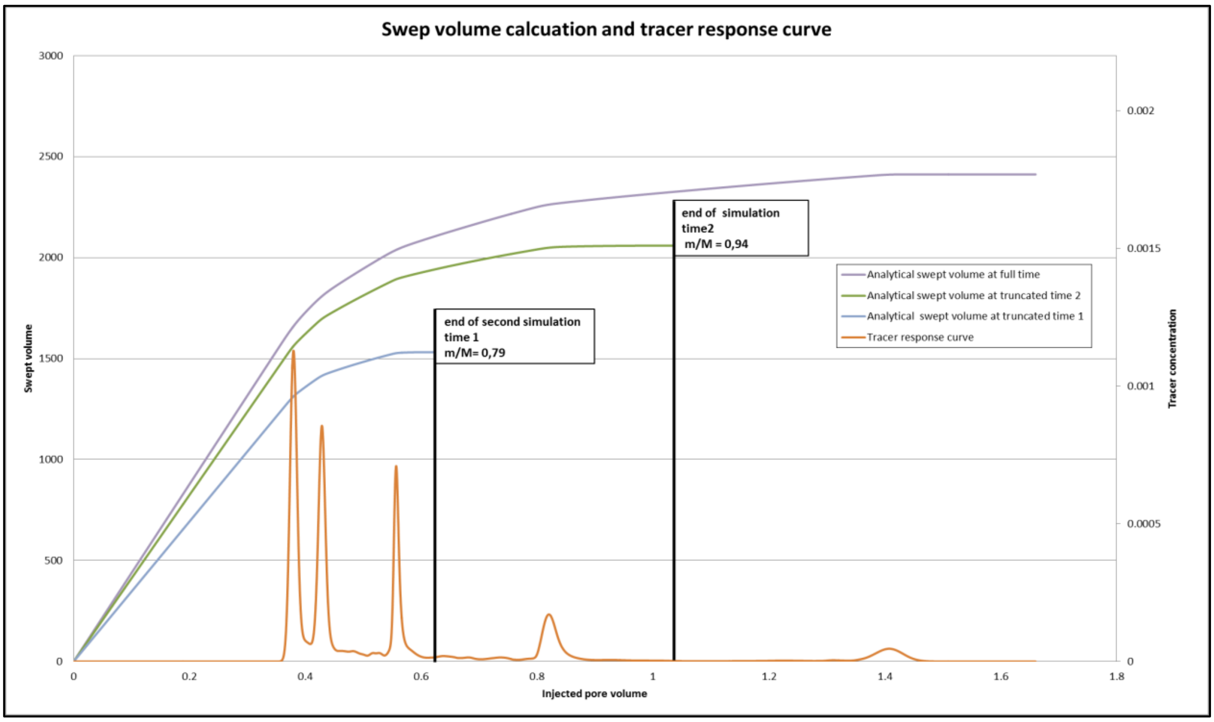

Figure 33: Swept volume derived from layered 2D model

Figure 34 shows that if one of the peak concentrations is missed due to sampling stopping or wrongly extrapolated to zero without considering the other peaks, the connected pore volume could be underestimated. This is due to the fact that the RTDA analysis takes into account the total mass recovered at infinite time in the m/M ratio. This ratio has to be an input in order to calculate the swept volume as a function of time. Caution must be taken in the extrapolation and geological configurations should be combined with tracer data to ensure consistency.
Several methods for extrapolation exist, the simplest is the extrapolation of tracer curve with exponential decline that is often adequate and provides a reasonable approximation of the actual decline.

- **The F-PHI curve and the heterogeneity index**

Using RTDA, tracer data can be used to compute the flow capacity vs storage capacity curve. From this curve Lorentz coefficient, a measure of the level of heterogeneity can be calculated. The flow capacity curve is used in reservoir engineering literature as simplistic measure to static heterogeneity. In a 2D case where several layers with different rock properties were simulated, it was proven that F-PHI curve extracted from tracer reasonably represents the static one when the layered heterogeneity assumption is valid. Several concentration peaks can be observed in the tracer response curve as an indication of a specific rock type. This can be used qualitatively to conclude the presence of a high velocity flow path in the system (thief layer, fracture...). The amplitude of the peak can reflect, qualitatively, the relative volume of this flow path.

For more developed representation of reality, in a 3D case, the F-PHI curve is certainly not only a measure of the static properties but also of the flow dynamics. For instance, the tracer flowing in a homogeneous inverted five spot is still reflecting a level of heterogeneity that is due to the difference in breakthrough time for the different streamlines where the tracer can be flowing. The dynamic heterogeneity is a function of flow rate, mobility ratio and pattern performance and efficiency, as well as static heterogeneity imposed by the reservoir rock properties. By the nature of the tracer analysis tools currently existing, no spatial distribution of rock properties can be obtained by tracer data alone, however, they can be a valuable tool of interpretation once combined with the other data sources.

- **Flow rate perturbation and operational fluctuation:**

The fluid rates of wells in the field are often constrained by several factors which are in most cases independent. Several events can cause fluctuation and perturbations in the flow rates. Such events have proven to affect the tracer flow and thus on the estimated quantities derived from tracer data.

For instance, the shut in of two diagonal producers in an inverted five spot pattern could impose a new preferential flow direction due to the change in the pressure profile. This may induce a change in certain flow path of the tracers. A restoration of the initial flowing condition could establish the original pressure distribution and therefore restore initial streamline distribution. This event introduces a delay in the tracer breakthrough that could be seen as a longer flow path and therefore the level of heterogeneity might be changed. For the well receiving higher flow rate, faster breakthrough is expected and potentially additional flow paths are activated. This will be seen as an increase in the heterogeneity index. For the well in which the flow rate is reduced or shut, the delay is seen as more homogenous. **Figure 35** and **36** illustrate this effect for a previously described simulated scenario. Producer 2 and Producer 4 are shut-in initially for a short period of time whereas producer 1 and producer 4 take the extra rates to ensure the 100% voidage.

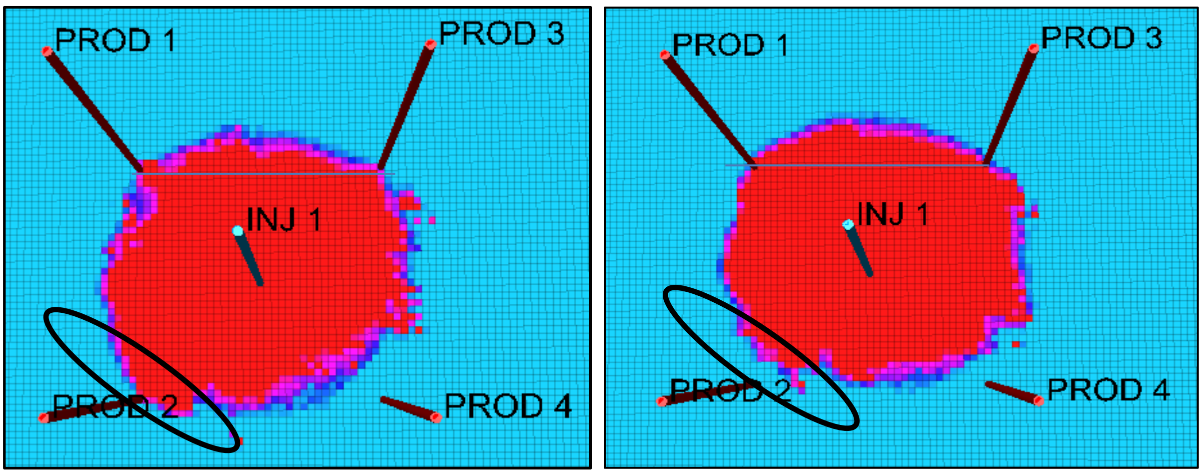

Figure 34: Change in tracer flow path due to flow rate perturbation

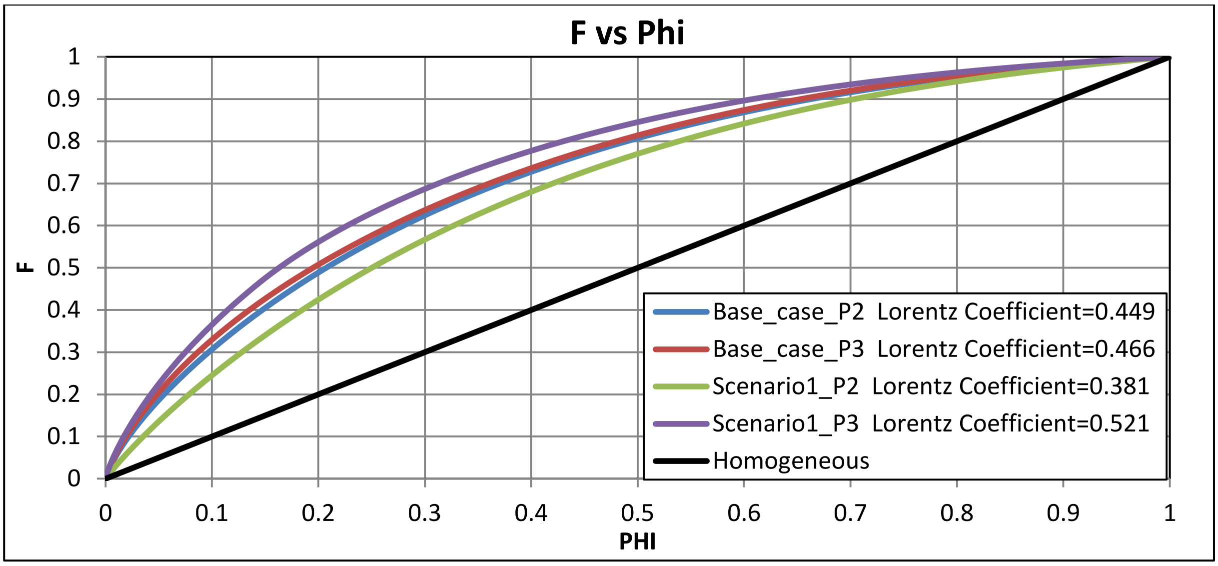

Figure 35: Heterogeneity change due to flow rate fluctuation

The severity of the flow rate perturbation effect on the tracer flow and heterogeneity level decreases with more confinement of the pattern. Simulation of nine five spot patterns in the same model showed for the same scenario negligible effect. This is mainly due to the availability of flow paths where the trace could potentially flow through.

- **The effect of polymer**

Tracers can be used as a valuable tool to investigate the efficiency of an EOR method during the pilot phase. Tracer injected prior and after polymer flooding for instance can reflect the level of improvement in the sweep efficiency in terms of increased calculated swept pore volume, as well as the reduction of the heterogeneity index. A successful polymer flood should reflect a broader tracer production curve as the flow is more uniform.

As the heterogeneity index form tracer data reflects the dynamics of the flow, less heterogeneous tracer flow in the presence of polymer is an indication of a more stable and uniform displacement front.

Effect of polymer can be observed from tracer data in three levels: the tracer curve, the F-PHI plot and the swept pore volume. A successful polymer flood should be improve the sweep efficiency by reducing the mobility ratio, this should result is a more stable displacement front and therefore lower flow in the highly permeable streamlines. This will result in a later tracer breakthrough from those streamlines compared with the case of no polymer injection. Therefore the tracer curve will be shifted to the left and the broadening of the distribution.

The F-PHI curve (Figure 32) as a measure of heterogeneity is affected by the dynamics of the flow. Improvement in sweep efficiency and a more stable displacement is reflected in the F-PHI curve by a lower heterogeneity and lower Lorentz coefficient.

Retardation of some of the tracer particles breakthrough after polymer injection translates that more volume is being swept. (Figure 31)

5 CONCLUSIONS

The main goal of this thesis was to improve the understanding of analytically derived connected pore volume and heterogeneity index from conservative tracer data and how they can be interpreted in the vicinity of numerical simulation.

Two methods were used for the quantitative analysis of tracer data. The first method was the method of moment (MOM) which computes the mean of temporal moments from tracer data. Different information could be derived from different order of the temporal moments. The second method was the residence time distribution analysis (RTDA), which permits more rigorous exploitation of the tracer curve based on the assumption that different breakthrough time for different tracer particles is due to the difference in the length and velocity of the flow paths they flow through. This method allows the derivation of sweep efficiency as a function of time as well as generation of F-PHI plots that reflects the level of heterogeneity from well to well space.

The several simulations cases and sensitivities presented in this thesis proved that the connected pore volume derived analytically from tracer data represents the swept volume between the pair of injector, where the tracer has been injected into the reservoir, and the producer where the tracer has been recovered. The swept volume corresponded to the volume of water contacted and occupied by the water phase during the flood operation. As conservative tracers are assumed not to diffuse in the oil or other existing phases in the reservoir, the swept volume was definitely a measure of water volume and not of the hydrocarbon phase.

Tracer data has a unique ability to give a rigorous, mathematically sound, and physically reasonable estimate of the pore volume swept and not only the sweep efficiency. This can be exploited in combination with other sources of data to assess potential of an EOR project for instance. It was shown in the thesis that efficiency of polymer in mobility ratio reduction and sweep efficiency improvement is reflected in the tracer data by a higher swept volume and a more homogenous distribution in both the tracer response curve and the F-PHI curve.

Nevertheless, care must be taken in the following aspects of tracer interpretation:

- The RTDA, although claims to permit a real time estimation of swept volume, it requires the full specter of the tracer data. Therefore, careful extrapolation of tracer data, after a clear exponential decline was observed, is of extreme importance. Working with incomplete dataset could introduce an underestimation error for the total set. A careful sampling and interpolation and the combination of other data sources is undoubtedly of great advantage.
- Fluctuation of flow rates, at the production or injection wells had a minor effect on the tracer curve and its interpretation. However major events at those could cause significant in the pressure distribution and therefore in the tracer flow direction. Therefore it is important to report the flow rates along with the tracer data.

The flow capacity-storage capacity curve -termed F-PHI curve- that is derived from tracer data reflected a combination of dynamic and static heterogeneity.
The static heterogeneity represents the level of contrast between rock properties in the reservoir. Tracer data are more sensitive to vertical heterogeneity. The spatial distribution of flow properties is not obtainable from tracer testing. While pore volume calculations and flow geometry (F-Φ) estimates from tracer tests are robust, the analysis could not determine the specific location of the flow path distribution. Furthermore, estimates of flow geometry, etc., are volume-averaged (or streamline-integrated) properties, thus, point values could not be determined uniquely.

The dynamic heterogeneity is a measure of the contrast in flow path lengths. A tracer injected in a homogenous five spot pattern would reflect a level of heterogeneity that is due to different streamlines that the tracer is flowing through. A suggested approach was to combine the tracer response curve and the F-PHI plot in order to approximate the level of static heterogeneity. An anomaly with high contrast of rock properties, thief layer for instance, could be distinguished by an early breakthrough and a separate peak.

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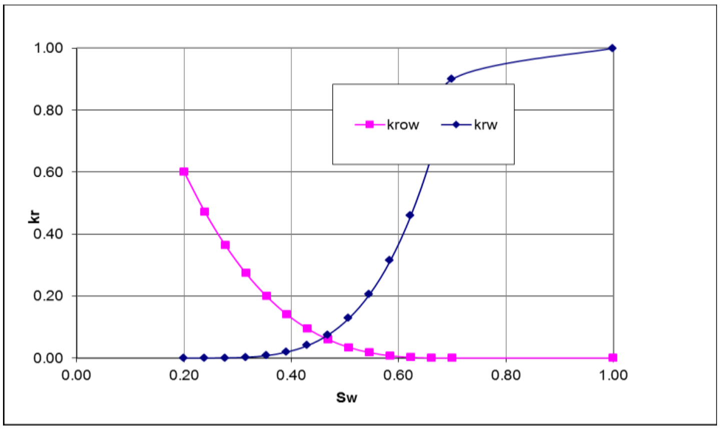
APPENDICES

Appendix A

Relative permeability functions used in the sensitivity of core plug simulations

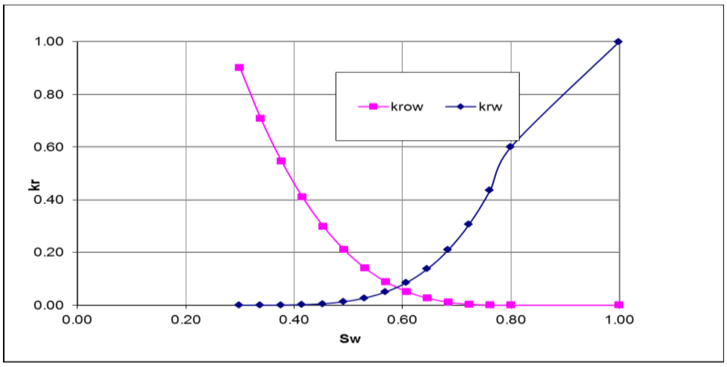
oil wet Nw=4 No=2 Sor=0.3 Swr=0.2

Sw	Krw	Kro
0.200000	0.000000	0.600000
0.238462	0.000032	0.471916
0.276923	0.000504	0.363496
0.315385	0.002552	0.273100
0.353846	0.008067	0.199090
0.392308	0.019695	0.139827
0.430769	0.040839	0.093673
0.469231	0.075659	0.058990
0.507692	0.129071	0.034137
0.546154	0.206747	0.017478
0.584615	0.315115	0.007374
0.623077	0.461360	0.002185
0.662	0.653	0.000
0.7	0.9	0



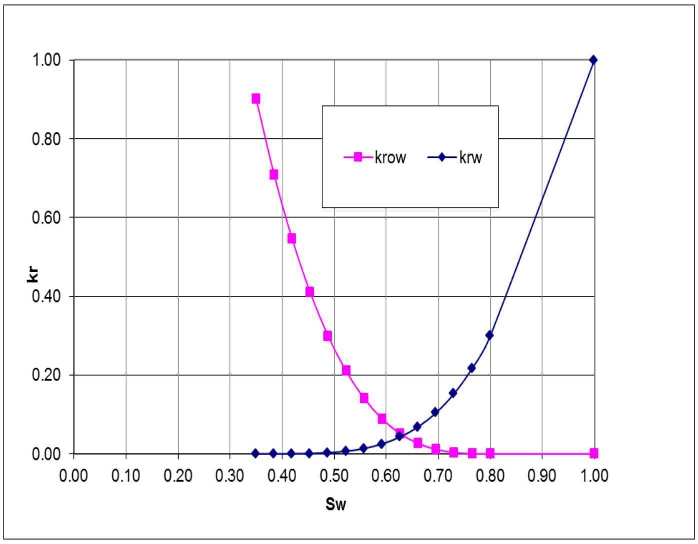
water wet Nw=4 No=2 Sor=0.2 Swr=0.3

Sw	Krw	Kro
0.300000	0.000000	0.900000
0.338462	0.000021	0.707874
0.376923	0.000336	0.545244
0.415385	0.001702	0.409650
0.453846	0.005378	0.298635
0.492308	0.013130	0.209741
0.530769	0.027226	0.140510
0.569231	0.050439	0.088484
0.607692	0.086047	0.051206
0.646154	0.137831	0.026218
0.684615	0.210077	0.011061
0.723077	0.307573	0.003277
0.762	0.436	0.000
0.8	0.6	0

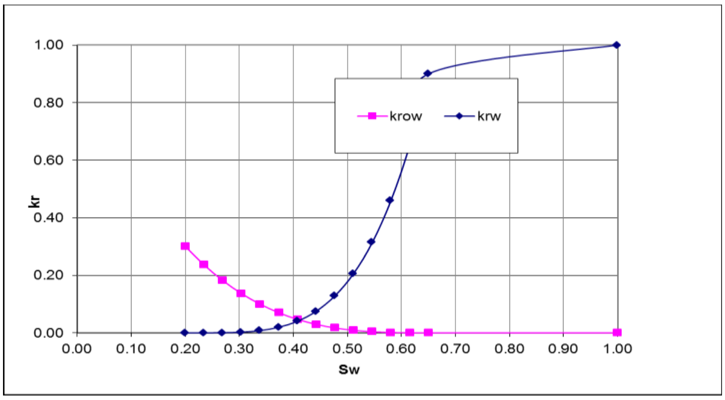


strongly water wet Nw=4 No=2 Sor=0.2 Swr=0.35

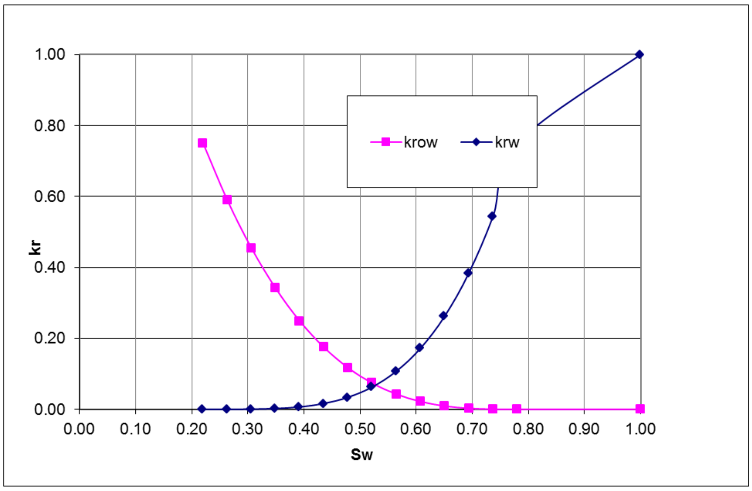
Sw	Krw	Kro
0.200000	0.000000	0.600000
0.238462	0.000032	0.471916
0.276923	0.000504	0.363496
0.315385	0.002552	0.273100
0.353846	0.008067	0.199090
0.392308	0.019695	0.139827
0.430769	0.040839	0.093673
0.469231	0.075659	0.058990
0.507692	0.129071	0.034137
0.546154	0.206747	0.017478
0.584615	0.315115	0.007374
0.623077	0.461360	0.002185
0.662	0.653	0.000
0.7	0.9	0



strongly oil wet Nw=4 No=2 Sor=0.35 Swr=0.2		
Sw	Krw	Kro
0.200000	0.000000	0.300000
0.234615	0.000032	0.235958
0.269231	0.000504	0.181748
0.303846	0.002552	0.136550
0.338462	0.008067	0.099545
0.373077	0.019695	0.069914
0.407692	0.040839	0.046837
0.442308	0.075659	0.029495
0.476923	0.129071	0.017069
0.511538	0.206747	0.008739
0.546154	0.315115	0.003687
0.580769	0.461360	0.001092
0.615	0.653	0.000
0.65	0.9	0



Mixed wet Nw=4 No=2 Sor=0.22 Swr=0.22		
Sw	Krw	Kro
0.220000	0.000000	0.750000
0.263077	0.000026	0.589895
0.306154	0.000420	0.454370
0.349231	0.002127	0.341375
0.392308	0.006722	0.248862
0.435385	0.016412	0.174784
0.478462	0.034032	0.117091
0.521538	0.063049	0.073737
0.564615	0.107559	0.042672
0.607692	0.172289	0.021848
0.650769	0.262596	0.009217
0.693846	0.384467	0.002731
0.737	0.545	0.000
0.78	0.75	0



Static F-C curve calculations for layered heterogeneity

Table 3: F-C curve 2D layered heterogeneity

Layer n°	PHI	K	F
1	0.2	3000	0.25
2	0.4	2800	0.483333
3	0.6	2400	0.683333
4	0.8	2000	0.85
5	1	1800	1

Table 4: F-C curve 3D layered heterogeneity

Layer n°	PHI	K	F
1	0.090909	2800	0.254545
2	0.181818	2000	0.436364
3	0.272727	2000	0.618182
4	0.363636	1000	0.709091
5	0.454545	1000	0.8
6	0.545455	750	0.868182
7	0.636364	750	0.936364
8	0.727273	250	0.959091
9	0.818182	250	0.981818
10	0.909091	100	0.990909
11	1	100	1

Appendix B

Polymer injection: Synthetic bivariate petro physical model used

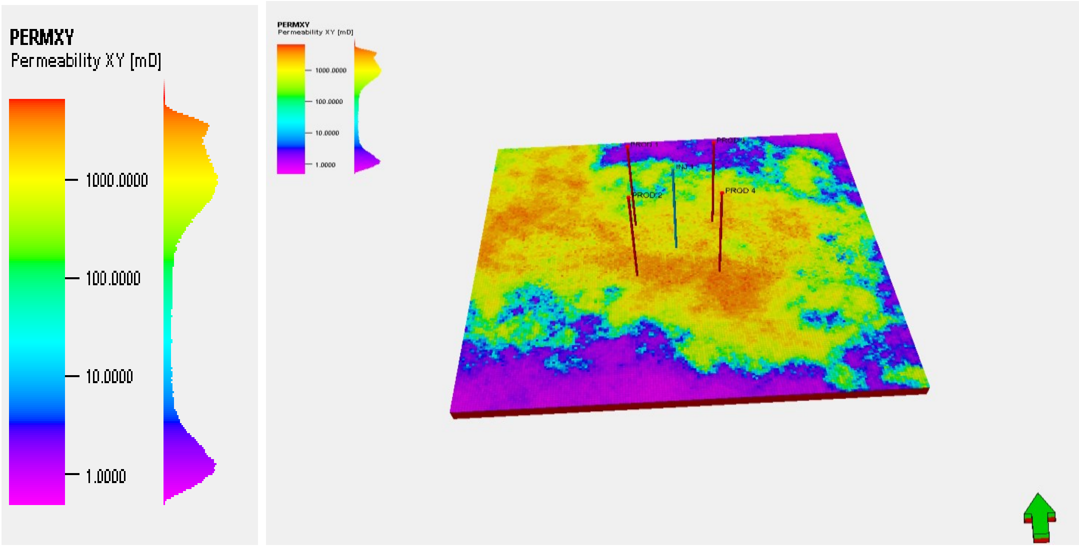


Fig. B 1: Synthetic bivariate petrophysical model permeability

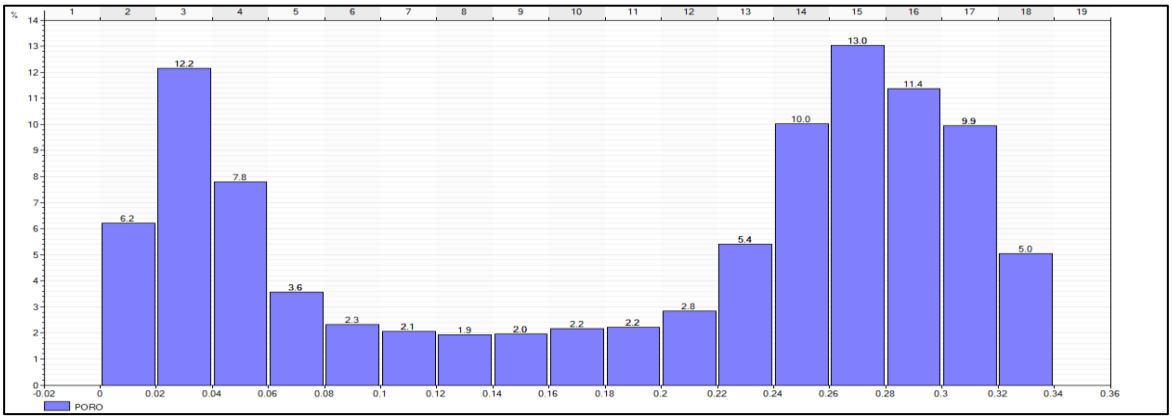


Fig. B 2 : Synthetic bivariate petrophysical model permeability

Polymer injection: Effect of different polymer concentration on the sweep efficiency in one layer

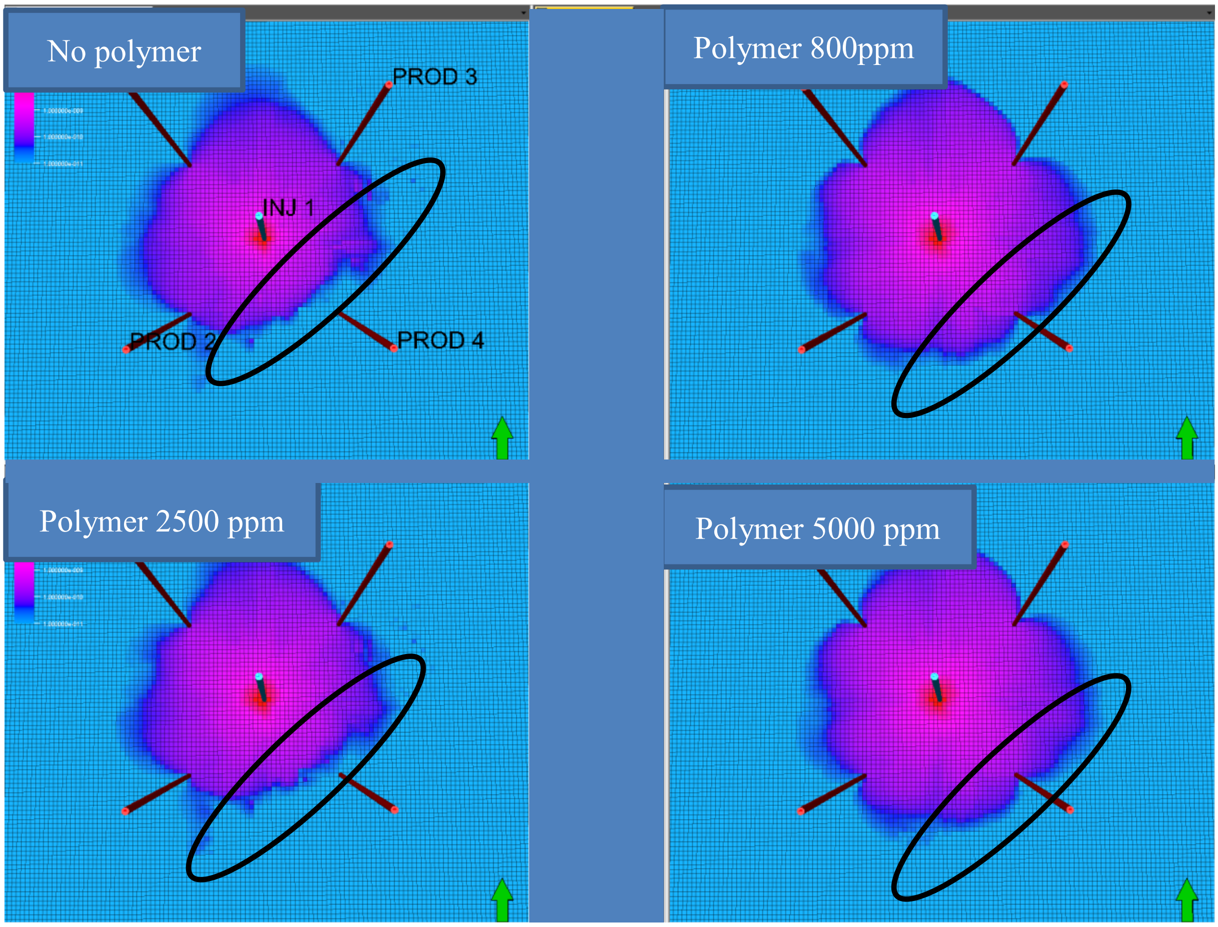


Fig. B 3 : Effect of different polymer concentration: tracer adsorption used to map the injection fluid

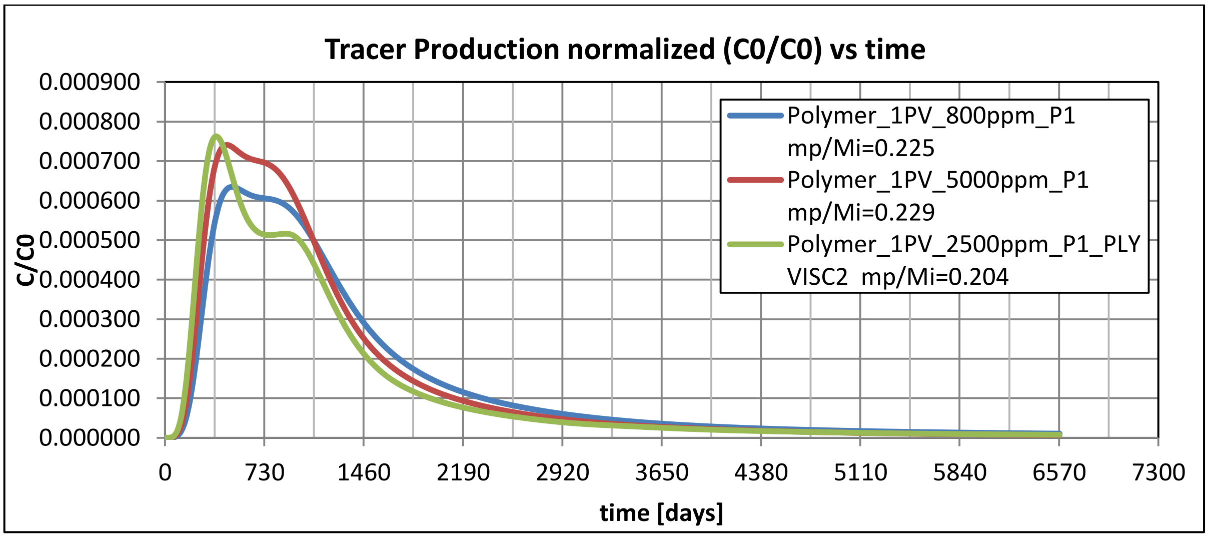


Fig. B 4: Tracer production curve for different polymer concentrations

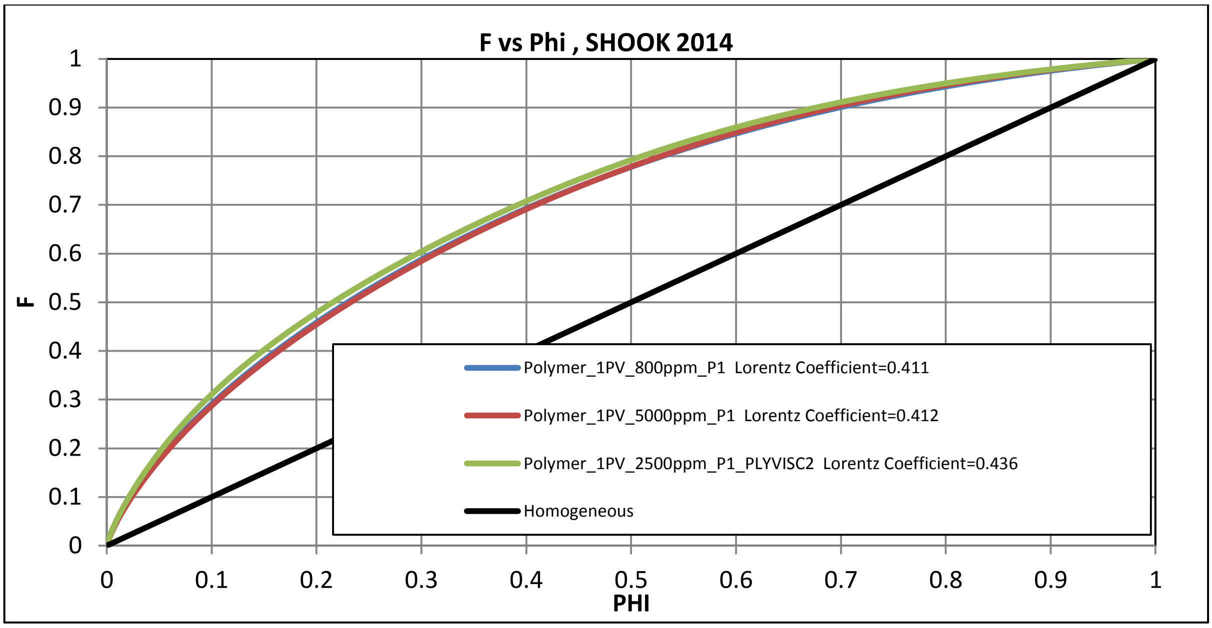


Fig. B 5: F-PHI plot for different polymer concentration injected

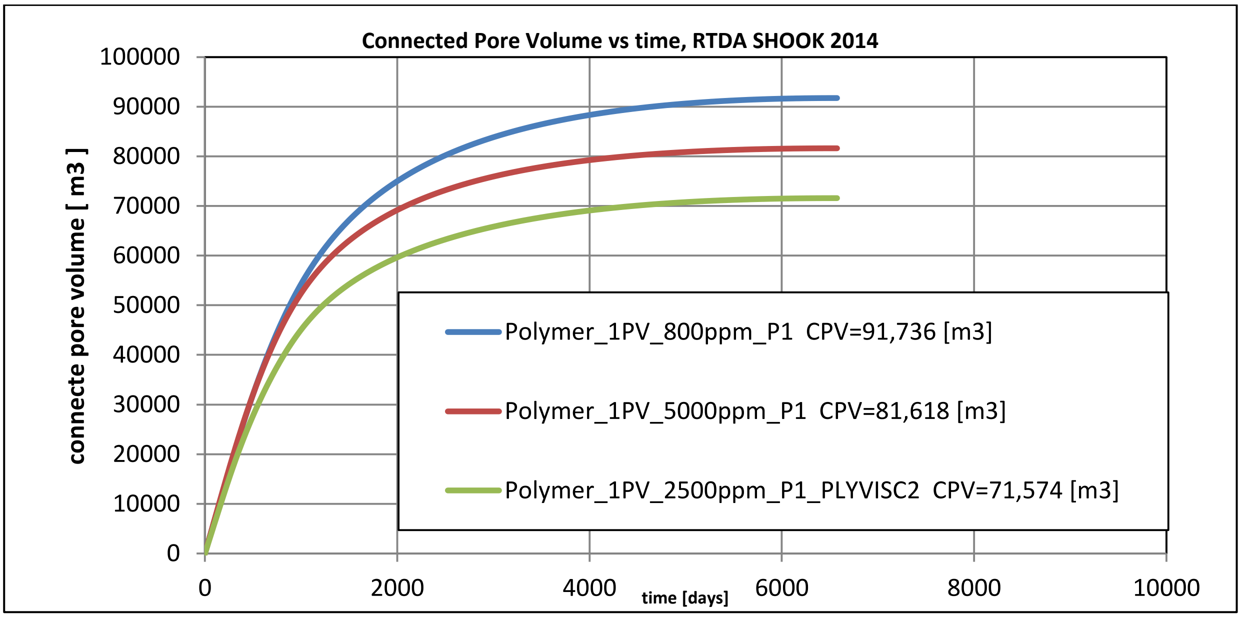


Fig. B 6: Swept pore volume from different polymer concentration injected

Appendix C

Flow perturbation scenarios

Scenario 1

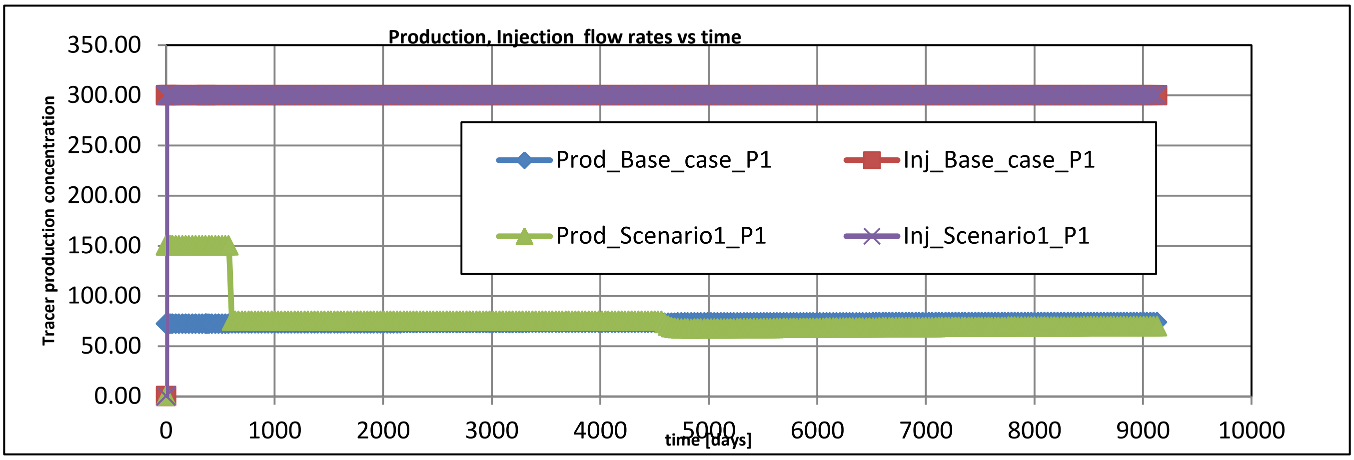


Fig. C 1: Flow rate fluctuation scenario 1

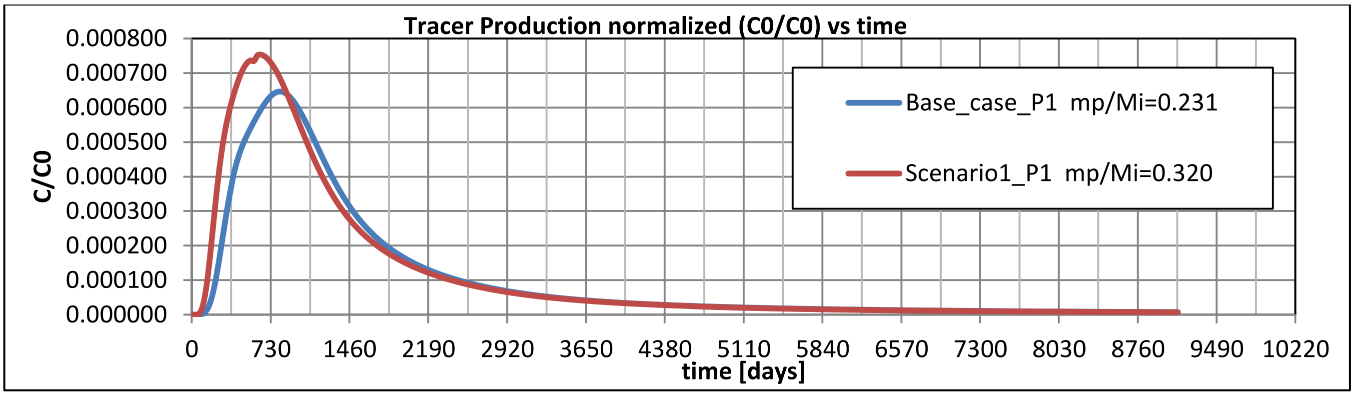
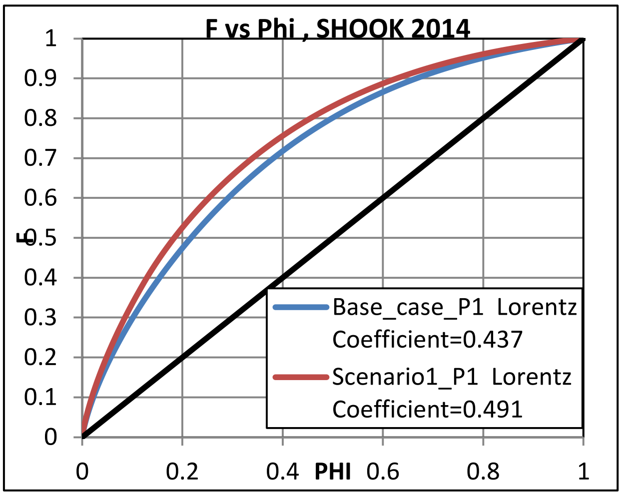


Fig. C 2: Tracer production curve for flow rate fluctuation scenario 1



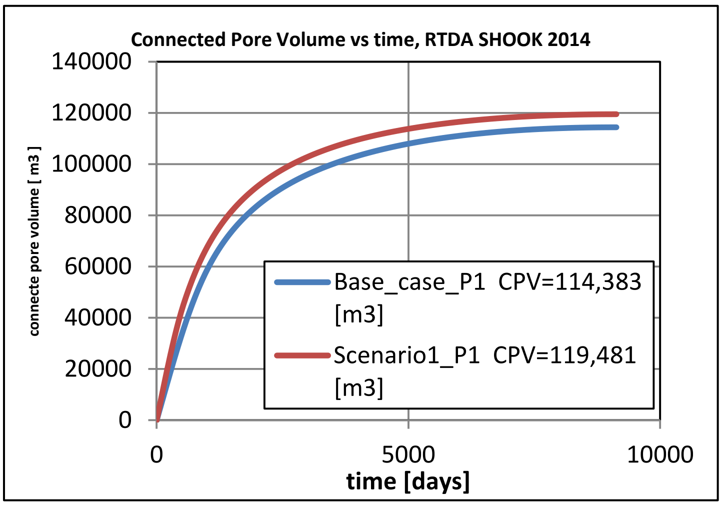


Fig. C 3: F-PHI curve for scenario 1

Fig. C 4: F-PHI curve for scenario 1

Scenario 2

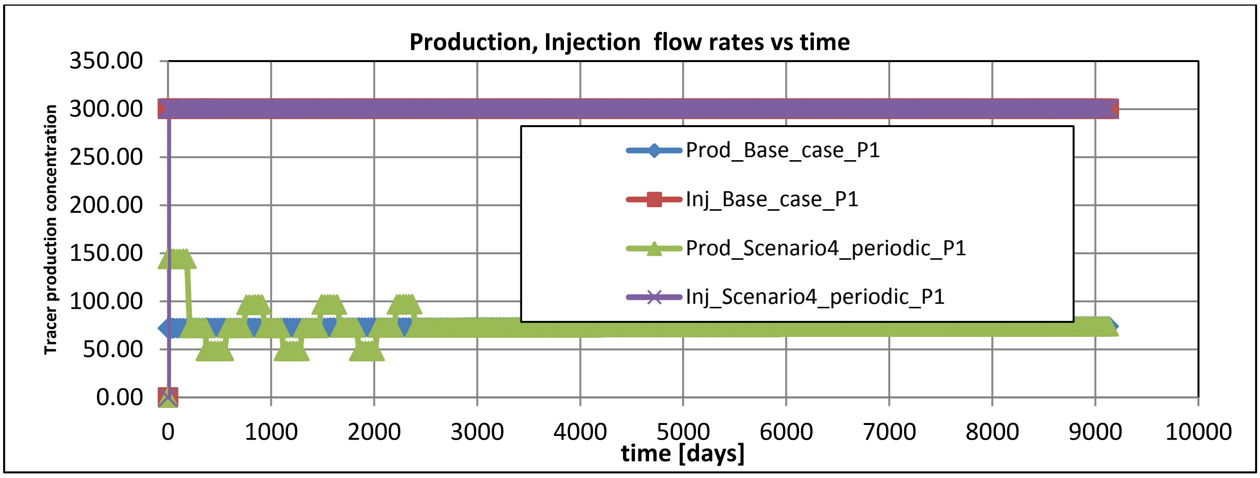


Fig. C 4: Flow rate fluctuation scenario 1

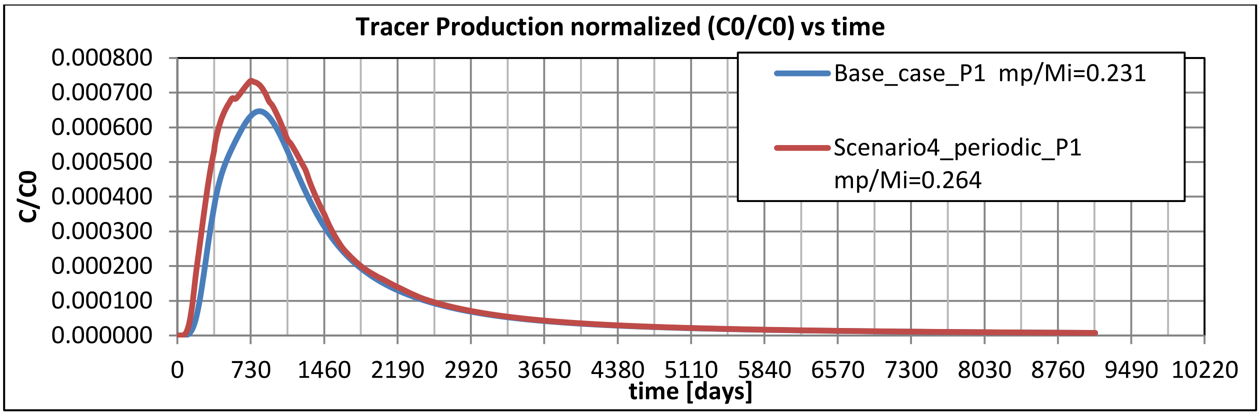
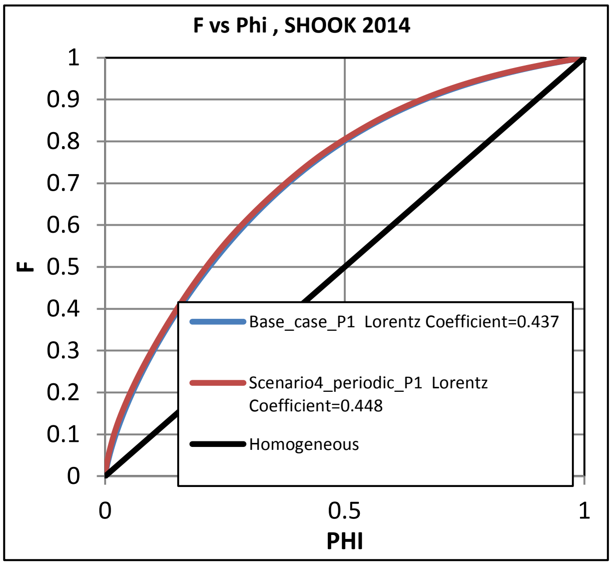


Fig. C 5: Tracer production curve for scenario 2 and base case



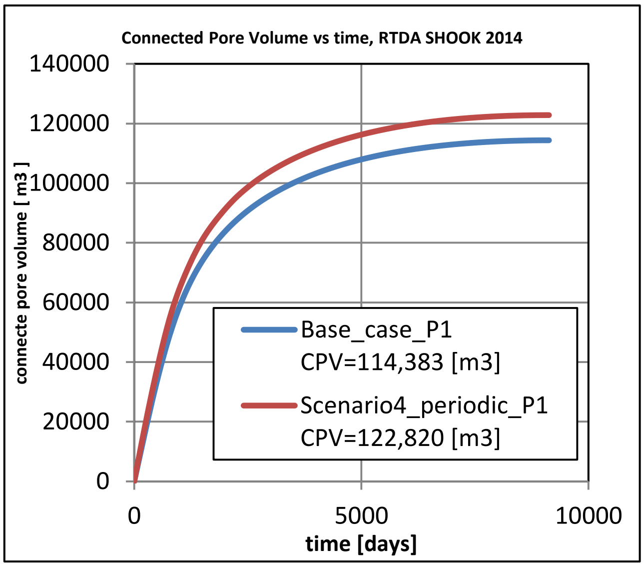


Fig. C 6: F-PHI curve for scenario 2 and base case

Fig. C 7: F-PHI curve for scenario 2 and base case

Scenario 3

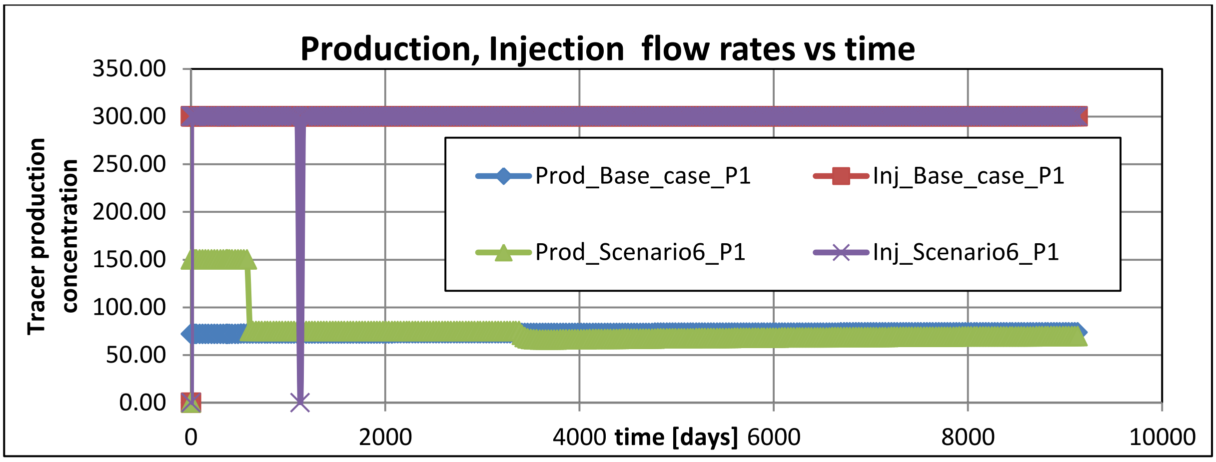


Fig. C 8: Flow rate fluctuation scenario 3

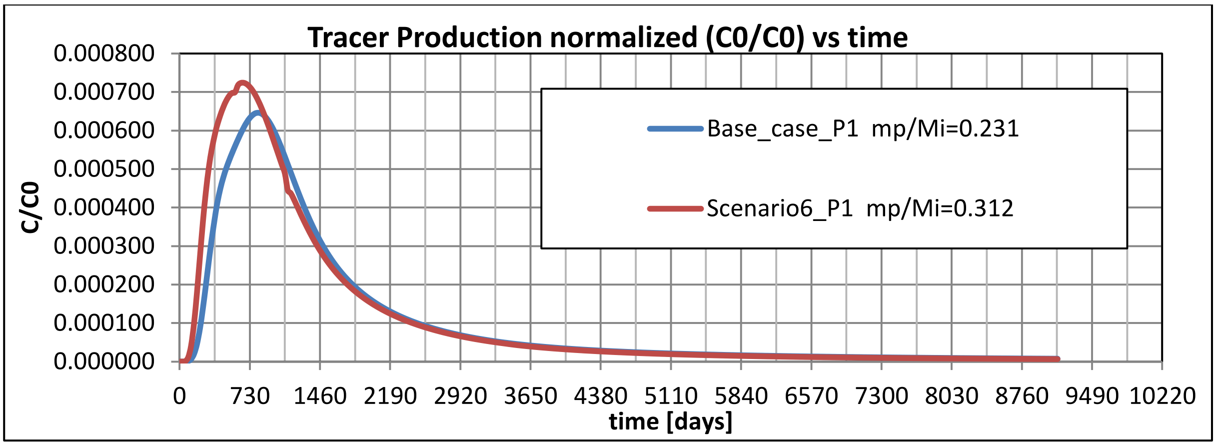
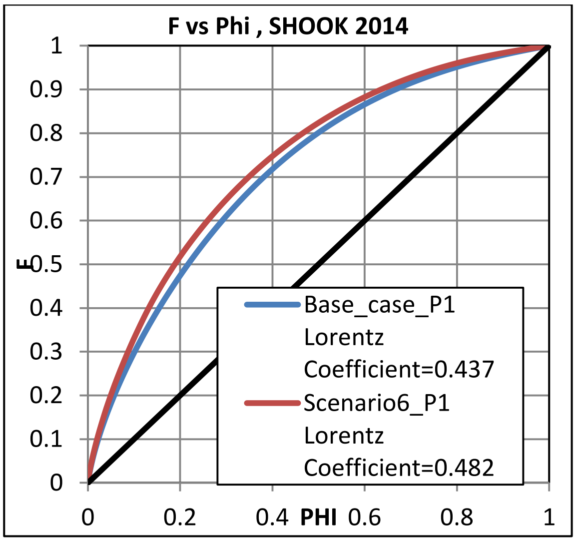


Fig. C 9: Tracer production curve for scenario 3 and base case



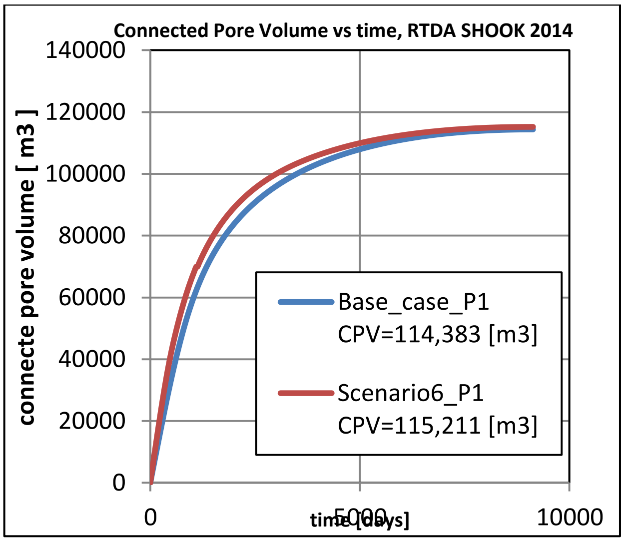


Fig. C 10: F-PHI curve for scenario 3 and base case

Fig. C 11: F-PHI curve for scenario 3 and base case