New simplistic approach for MEOR modelling and uncertainty assesment

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NOVI SIMPLISTIČKI PRISTUP ZA MODELIRANJE MIKROBIOLOŠKOG POVEĆANJA ISCRPKA NAFTE I PROCJENA NESIGURNOSTI

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Sažetak

Mikrobiološko povećanje iscrpka nafte je jeftina i ekološki prihvatljiva metoda za pridobivanje dodatnih količina nafte. Mikrobiološko povećanje iscrpka nafte se bazira na metabolizmu mikroorganizama. Od 2012. Wintershall istražuje primjenjivost navedene metode u sklopu projekta "MEOR Studies". Ovaj rad napisan je u sklopu radnih paketa tri i četiri koji uključuju modeliranje efekata komercijalnim simulatorom i primjenu ležišne simulacije na pilot projektu. U radu je opisano modeliranje rasta bakterija, prikazano je modeliranje efekata koji utječu na dodatni iscrpak, utvrđen je novi simplistički pristup modeliranju te je provedena procjena nesigurnosti u komercijalnom simulatoru CMG STARS.

Ključne riječi: mikrobiološko povećanje iscrpka nafte, ležišna simulacija, CMG STARS, procjena nesigurnosti

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Abstract

Microbial enhanced oil recovery (MEOR) is highly potential EOR method, attractive from both economic and environmental perspective. MEOR is based on the life and metabolism of microorganisms. Wintershall is conducting "MEOR Studies" since 2012. This thesis is part of the project "MEOR Studies" work packages 3 and 4; MEOR implementation in commercial software CMG STARS and field simulation. In thesis are shown: modelling reaction kinetics, modelling MEOR effects, new simplistic approach for modelling MEOR and uncertainty assessment in CMG STARS.

Keywords: MEOR, reservoir simulation, CMG STARS, uncertainty assessment
Thesis contains: 54 pages, 6 tables, 34 figures and 65 references

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NOMENCLATURE

a_0 – imbibition index (m^3/s)

AD (c,t) – adsorption as a function of temperature and concentration (mol/m^3)

ADMAXT – maximum adsorption capacity (mol/m^3)

AK – absolute permeability (mD)

AKp (i) – effective permeability for phase p in block i (mD)

b_0 – coefficient associated with gravity (m^3/s)

c_i – concentration factor (mol/m^3)

E_a – activation energy (J/mol)

enrri – reaction order (-)

f_i (x_i) – mixing function for molar fraction x_i (-)

g – gravity constant (m/s^2)

h – bioreactor thickness (m)

k_r – calculated relative permeability (-)

k_{rA} – relative permeability of set A (-)

k_{rB} – relative permeability of set B (-)

k_{rnw} – relative permeability for non-wetting phase (-)

k_{ro} – relative permeability for oil (-)

krp – relative permeability for phase p (-)

k_{rw} – relative permeability for water (-)

k_{rwe} – relative permeability for wetting phase (-)

K_s – half rate constant in standard Monod equation (kg/m3)

L – core length (m)

M – mobility ratio (-)

Mm – molar mass for every component respectively (kg/mol)

N – normalizing factor (-)

n – stochiometric coefficient for every component respectively (-)

n_{rn}, n_{rb}, n_{pb}, n_{pm} – Stochiometric coefficients for components, respectively (-)

p – curvature exponent (default value is 1) (-)

P_c^* – capillary pressure at S_{wf} (Pa)

Q – injection rate (m^3/s)

q_w – imbibition rate of the wetting phase (m^3/s)

R – universal gas constant (8.314 $Jmol^{-1}K^{-1}$)

r – volumetric reaction rate ($molm^{-3}s^{-1}$)

Re – recovery by the spontaneous imbibition in the units of pore volume (-)

r_g – bacterial growth rate in standard Monod equation (1/s)

RKp (i) – permeability reduction factor for phase p in block i (-)

r_m – bioreactor radius (m)

r_{max} – maximum bacterial growth rate in standard Monod equation (1/s)

rrf – frequency factor (1/s)

RRF – residual residence factor, keyword rrft (-)

S – substrate concentration in standard Monod equation (kg/m3)

S_j – phase saturation (-)

S_{or} – residual saturation of oil (-)

S_w – saturation of wetting phase (-)

S_{wf} – water saturation behind imbibition front (-)

S_{wi} – initial water saturation (-)

S_{wr} – saturation of residual wetting phase (-)

T_{abs} – absolute temperature (°C)

t_{res} – bacteria residence time (s)

x – value (-)

x_A – interpolation parameter of set A (-)

x_B – interpolation parameter of set B (-)

$x_{j,i}$ – mole fraction of component i in fluid phase j (-)

Z – z value (-)

$\Delta\rho$ - density difference between the wetting and nonwetting phase (kg/m^3)

λ – pore-size-distribution parameter in Corey functions (-)

μ – calculated viscosity of mixture (cp)

μ_i – viscosity of component i (cp)

μ_o – oil viscosity (cp)

μ_w – water viscosity (cp)

ρ_j – phase mole density (mol/m^3)

σ - standard deviation (-)

ψ - mean value (-)

ω – final interpolation parameter (-)

ϕ – porosity (-)

1 INTRODUCTION

According to Manrique et al. (2010) considerable portion of current oil production comes from mature fields and the rate of replacement of the reserves by new discoveries has been declining over the last few decades. Also, over 50 percent of original oil in place stays in the reservoirs after primary and secondary recovery (www.glossary.oilfield.slb.com).

Therefore, additional oil produced with application of tertiary methods also known as enhanced oil recovery (EOR) could play a key role in meeting the energy demand in years to come.

EOR methods are using techniques that are altering original oil or rock properties, resulting with additional oil recovery that can be more than 15 % of original oil in place. The EOR techniques are classified under: gas injection, thermal injection, chemical injection and others. EOR methods are facing two big challenges: low oil price and environmental issues. Relatively low oil price presents challenge for EOR methods because of operational expenditure (OPEX) costs like surfactants or polymers, therefore the profit from EOR projects might be below the economic limit. Environmental issues are another important factor causing delay and stoppage of projects in various countries due to pollution or underground contamination concerns (Millemann et al, 1982).

Microbial enhanced oil recovery (MEOR) is highly potential EOR method, attractive from both economic and environmental perspective. MEOR is based on the life and metabolism of microorganisms. By stimulating bacterial growth with addition of nutrients, amount of bacteria is increasing, and bacterial metabolism is producing metabolites which can have beneficial effects on oil recovery (Alkan et al, 2015).

Wintershall is conducting "MEOR Studies" project for seven years and a field in Germany was selected for the pilot application. This thesis is part of the project "MEOR Studies" - work packages 3 and 4: MEOR implementation in commercial software CMG STAR and field simulation.

MEOR modelling concepts are previously investigated in work packages 3 and 4 and will be used as a basis to this work. In this work, the approach for matching of analytical and simulation

model with bacterial growth is presented, modelling of MEOR effects is described in more detail and new probabilistic approach of field simulation is discussed.

2 MICROBIAL ENHANCED OIL RECOVERY (MEOR)

2.1 Oil Recovery Mechanisms

MEOR is based on the life and the metabolism of microorganisms, therefore bacteria and nutrient are two main components of MEOR. Bacterial growth can be stimulated with addition of nutrients, consequently producing range of metabolites that can have beneficial effect on oil recovery (Table 2-1). The achieved recovery effects are similar to the mechanisms created by other EOR methods, with two main differences:

1. effects are created in-situ by the bacteria instead of material/energy sent from the surface
2. the recovery depends on the combination of various mechanisms rather than one dominating effect.

Table 2-1 Microbial Reaction products and their claimed effects for EOR (Adapted by Bryant and Lockhart, 2002)

Product	Effect
Acids	Increase rock porosity and permeability Produce CO_2 via reaction with carbonate minerals
Biomass	Selective plugging Emulsification through adhesion to oil Changing wettability of mineral surfaces Reduction of oil viscosity and pour point
Gases	Reservoir repressurization Oil swelling Increase permeability due to solubilization of carboante rocks Viscosity reduction
Solvents	Dissolution of oil
Surfactants	Lowering interfacial tension Emulsification
Polymers	Mobility control

	Selective plugging

MEOR is field specific method, since the conditions in oilfield can be very different in terms of pressure, temperature, salt content and microbial communities (Alkan et al, 2015)

MEOR processes relying on metabolites generated directly in the reservoir are called in-situ processes and are different in terms of the origin of bacteria:

- indigenous (already present in reservoir) or
- external (surface generated and injected) bacteria (Alkan et al, 2015).

The first type of process is preferred due to ability of indigenous bacteria to survive and grow at reservoir conditions. In case of injection of external bacteria, question of survival and breeding of bacteria is critical and more detailed investigations should be performed. The advantage of this method is ability to select wide range of the bacteria and their products that are suitable for achieving goals in the reservoir.

MEOR processes based on metabolites generation and then injection of them in reservoir are called ex-situ processes. Ex-situ processes are producing biosurfactants and biopolymers that are later injected in reservoirs. This approach is more expensive in comparison to in-situ.

Cui et al (2017) reported higher biosurfactant concentration, lower interfacial tension (IFT), smaller average diameters of emulsified crude oil in in situ approach while wettability alteration was similar for both ex-situ and in-situ approach. They also reported that recovery during flooding in sand pack experiments was around 7.3 % for in-situ case while for ex-situ was only 4.5 % of original oil in place.

Also, Bryant and Lockhart (2002) highlighted importance of chemical dissipation via dispersion or diffusion and consumption or retention via interactions with the rock and with the oil. Propagation in in-situ and ex-situ approach differs, Yakimov et al (1997) reported little or no oil recovered with injection of ex-situ generated chemicals even though the same chemicals did lead to oil recovery when generated in-situ.

In project “MEOR Studies” being conducted by Wintershall, in-situ approach was preferred (Figure 2-1), and the workflow was designed based on this selection.

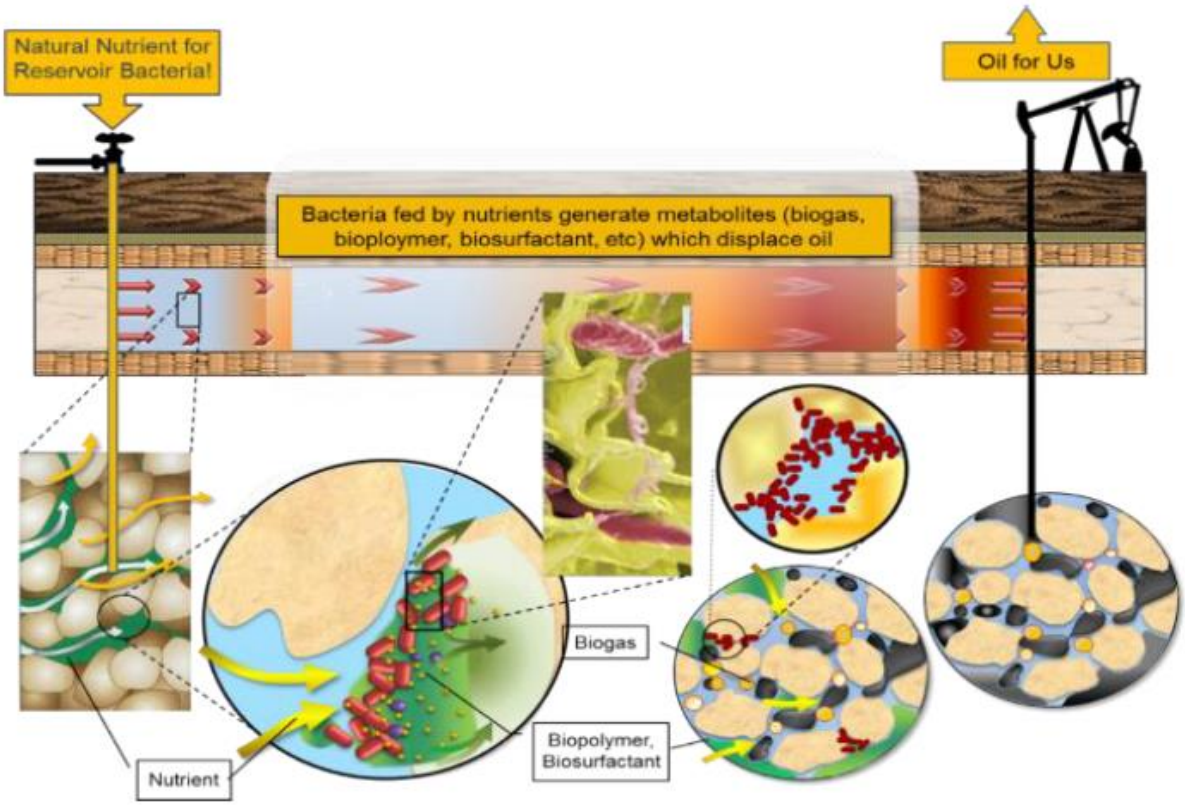


Figure 2-1 MEOR application and working principle (Alkan H., 2016, internal presentation)

Microbial EOR is low risk - high reward method that has multiple advantages (Al-Sulaimani et al, 2011):

- Can be implemented with operating costs similar to waterflooding
- Some bioproducts are more chemically stable in conditions of high temperature and salinity
- It is not depending on oil price as many chemical processes
- It is more environmentally friendly
- It does not require large amounts of energy

However, there are few disadvantages:

- No guarantee of success of bacterial growth, it is marginal in terms of incremental oil
- Reservoir souring risk in reservoirs with high sulfate content
- No commercial simulator for MEOR

2.2 Literature Survey

Beckman (1926) was the first who suggested the concept of bacterial metabolism as a beneficial one for oil recovery. Russia in particular was the country to give another big impulse in the birth of oil microbiology with scientists like Ginzburg-Karagicheva (1926) and Bastin (1926) who investigated microbial souring effect.

Zobell (1946) proved multiple beneficial MEOR mechanisms. By inoculating bacteria, he achieved the increase in pressure by CO_2 generation, porosity increase due to acidic metabolites and interfacial tension reduction between oil and water phase. He patented his findings as a "Bacteriological process for treatment of fluid-bearing earth formations".

In the 1950s the first field tests were conducted. In 1954. the first successful field application took place in Lisbon field, Arkansas and the oil production raised from 0.8 (0.127 m^3) to 2.1 (0.334 m^3) BOPD (Yarbrough and Coty, 1983). In the same decade, MEOR field tests and applications were performed in USSR (Kuznetsov, 1963); huff and puff was performed, and after 6 months of incubation production rate increased from 275 (43.72 m^3) to 300 (47.7 m^3) BOPD but fell on original level after 4 months. Field tests were also conducted in Czechoslovakia and Netherlands (Von Lucken, 2017).

In the 1960s, ex situ MEOR concept was initiated, by creating of metabolites in bioreactors under controlled conditions for injection into a reservoir. Hussain et al (1960) suggested using bacterially produced polysaccharide for thickening the injection water.

In the 1980s rDNA research and concept of control bacteria breeding conditions in ex situ approach was considered. Biotechnology was moving force for development of new ideas and concepts in the field of MEOR (Saxman and Crull, 1984). Permeability control or bio plugging was investigated by Knapp (1983), numerous core tests were performed with focus on permeability reduction due to microbial growth and retention. Bryant and Douglas (1988) ran series of lab tests on sandstone cores and reported additional recovery up to 32 % for light crude oil and up to 72 % for heavy oil. Bryant (1987) reported results from field test in Rocky Mountains where production increased from 26 (4.13 m^3) to 60 (9.54 m^3) BOPD. Field tests were also performed in USSR, where according to Belyaev et al (2004) 2 field tests were

performed resulting in summary of 2 300 and 470 00 tons of oil additionally recovered over a time span of 2 and 5 years respectively.

Banat et al (2000) reports that in 90s there was shift in research focus to in situ MEOR due to high costs associated with ex situ approach. In 1995. Banat investigated effectiveness of bio surfactants in previous field trials and concluded data provided is insufficient for drawing a conclusion. In 1992, Brown et al investigated the microflora of five different reservoirs and later sand pack and core studies were conducted which confirmed potential for permeability alteration. Vadie et al (1996) started pilot in situ MEOR field test in Alabama with goal of activation of the indigenous microflora with nutrient mix. Later retrieved core samples confirmed increase in the number of microbes. Wagner (1991) started field test in Germany and reported decrease in water cut from 88 % to 60 % while initial oil production of 12 (1.9 m^3) BOPD raised to 36 (5.72 m^3) after 3 months and to 72 (11.45 m^3) after one year. China also entered MEOR with Yuan and Wang (1991) reporting application of biopolymers.

From 2000s until now many papers, covering wide range of issues were published on MEOR (Zahner et al 2010, Zhu et al 2013, Town et al 2010, Nazina et al 2007, Lazar et al 2007). Based on the preferences of companies in-situ and ex-situ MEOR are both used. Microbiology evolved: genetical sequencing, bacterial culture isolation and custom nutrients formulation for stimulating wanted metabolites are state of the art. MEOR effects are being more thoroughly described and their understanding is increasing consequently better numerical models and simulation approaches are developing.

3 DESCRIPTION OF PROJECT "MEOR STUDIES"

In the next chapter "MEOR studies" project conducted by Wintershall is described, general information about field of interest will be shown and technical details of field and sector model will be explained.

3.1 Project "MEOR Studies" of Wintershall

As earlier mentioned, "MEOR Studies" project is ongoing for seven years, furthermore project is divided in the five work packages. First work package is common for all MEOR investigations, it is consisted of microbiology and chemical phenomena investigations, nutrient

development and testing and characterization of the enriched cultures in terms of produced metabolites. Second work package was devoted to dynamic tests including sand packs and corefloods to screen and to evaluate the dynamic performance of the microbial community stimulated by various nutrient solutions. In order to reproduce observed behavior and forecast performance third work package is involving development of a numerical simulator and implementation of the numerical modelling into commercial reservoir simulator CMG STARS. Fourth work package is translation of effects and behavior to field model. The planning and execution of a field pilot is the last work package of the "MEOR studies" and it is currently ongoing (Figure 3-1).

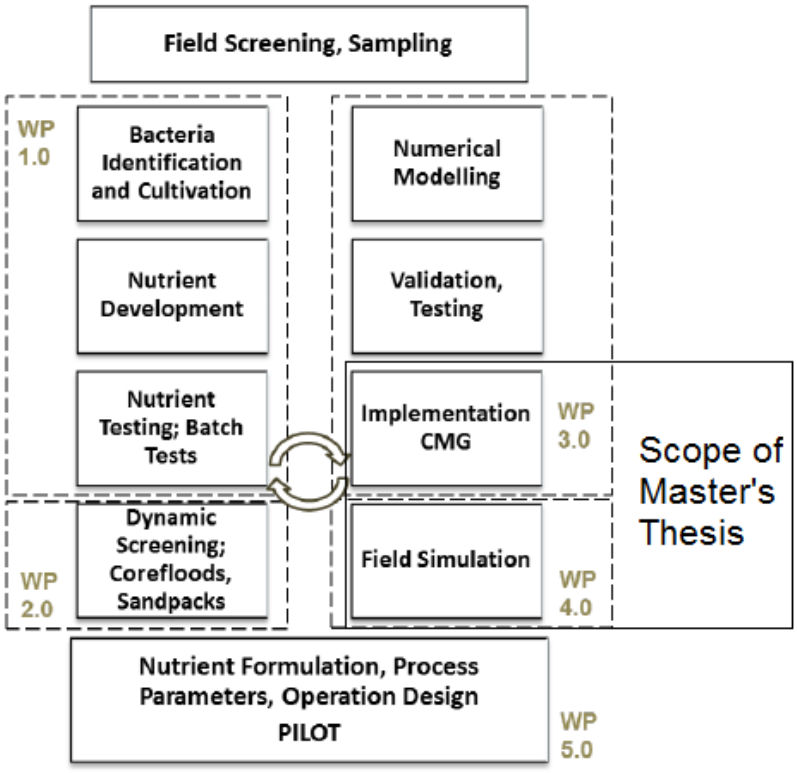


Figure 3-1 Structure of the project "MEOR studies" conducted by Wintershall and scope of the thesis (Adapted after Alkan et al, 2014)

3.2 Description of Field and Reservoir Model

MEOR field application is conducted on the field located in Northern Germany which is part of Lower Saxony Basin (Figure 3-2). The cretaceous reservoir lies on the eastern flank of an elongated anticline with NW-SE orientation. It is a sandstone reservoir with shale content increase from east to west and a very high permeability heterogeneity. The orientation of the

main faults is NW-SE and they are dipping towards NE. These faults are crossed by another fault system, approximately W-E oriented. The field is a mature oil field, producing since 1954, with an estimated recovery factor ranging from 28% to 43% (high uncertainty during the estimation of initial oil in place) and an average water cut of 97% (Michael Be, 2018).

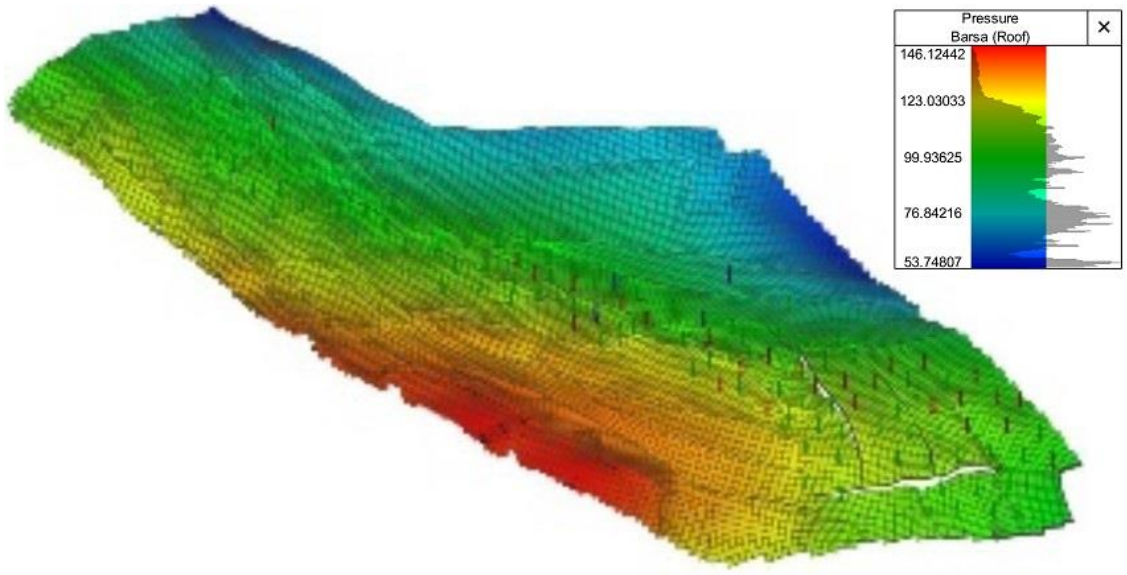


Figure 3-2 Full field model (tNavigator)

Selection of the field was based on the Wintershall's screening parameters where sulfate concentration and reservoir temperature are critical parameters (Figure 3-3). The sulfate content, either present in the formation or injection water, is the primary indication of the reservoir souring due to later microbial activity in reservoir. Reservoir temperature is another limiting due to microbiology activity at the temperatures higher than 80° C. Other parameters are not critical but low permeability is not preferred due to limited transport of microbes and high salinity may restrict the microbial vitality (Aditama et al, 2017).

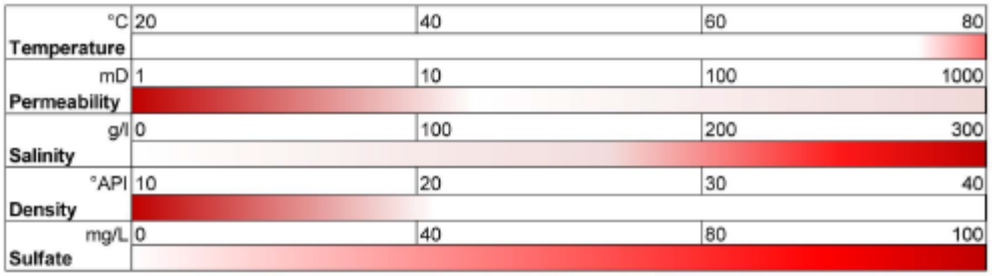


Figure 3-3 Screening parameters for MEOR application (Aditama et al, 2017)

Multi well test (MWT) as a part of the fifth work package in the project "MEOR Studies" is planed only on selected part of the full field reservoir model. For modelling purpose, a sector reservoir model was cropped from the full field reservoir model (Figure 3-4).

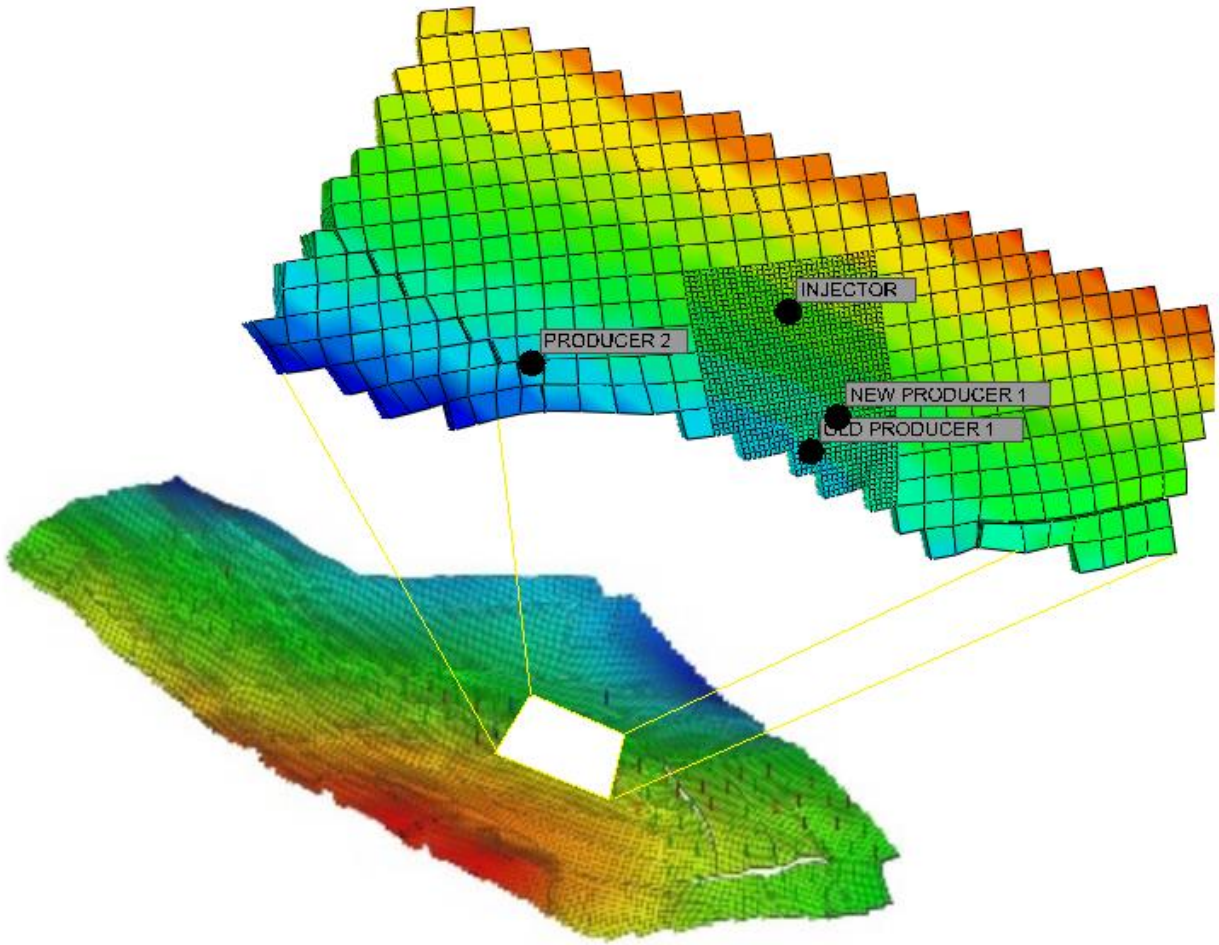


Figure 3-4 MEOR sector model and fine grid refinement

During the cropping process, the following properties were exported from the full field model:

- Corner point grid
- Grid porosity and permeability
- Net to gross (NTG)
- Grid pressure and initial saturations
- Faults
- Well trajectories (Be, 2018)

Additionally, the newly drilled well "NEW PRODUCER 1" and fault were added to model after new interpretation of the seismic data following tracer test. Tracer test did not show connectivity between "OLD PRODUCER 1" and "INJECTOR" so "NEW PRODUCER 1" was drilled. Fault was modelled with reduced transmissibility and was placed between "OLD PRODUCER 1" and "INJECTOR"; "NEW PRODUCER 1" overcomes the fault for connectivity to be achieved. Also, previously near-wellbore region was refined for easier observation of near wellbore effects. Sector model was initialized with 5 different rock types and relative permeability sets for each (Table 3-1).

Table 3-1 MEOR Sector model properties

Grid Type	Corner Point
Number of the cells (active)	34506 (20769)
Grid Size	50·50·1.3
Grid Refinement	16617 active blocks 10·10·1.3
Porosity Range	0.018-0.29
Permeability Range	1-6130 mD
Average Pressure	110 bar
Average Temperature	37.7 ° C
Well Spacing	Injector – New Producer 1 = 180 m Injector – Producer 2 = 430 m
Well Rates	170 m3/day
Number of Rock Types	5

Rock types distribution were based on permeability cut-off values and due to lack of laboratory data, relative permeabilities and capillary pressures were previously generated with Corey correlation. Endpoint saturations were obtained from the available experimental data. Importance of multiple rock types for MEOR application will be shown in later chapters.

3.3 Numerical Modelling of MEOR

Through the history there were numerous attempts to model bacteria behavior, bacteria transport and MEOR effects.

Knapp et al (1983) and Updegraff (1982) were among the first authors who tried to model kinetics of bacterial growth, bacterial transport and phenomena of microorganism penetration and plugging. Islam (1990) used a multi-dimensional model which considers multi-phase flow in porous media to model MEOR effects such as plugging, IFT reduction and oil viscosity reduction. The model introduced bacterial growth kinetic as a function of nutrients consumption, governed by Monod equation (year). Chang et al. (1991) developed a three-dimensional, three-phase, multiple-component numerical model for microbial transport simulation. Model considered dispersion, convection, bacterial growth and decay rates, nutrients consumption, chemotaxis and bacterial adsorption and was calibrated with laboratory experiments.

Zhang et al. (1992) developed a three-phase, multi-species, one-dimensional model capable of predicting biomass growth, metabolic activity, nutrients consumption and permeability modification effect during MEOR. Desouky et al. (1996) developed an one-dimensional model with five components (oil, water, bacteria, nutrient and metabolites) that considers adsorption, diffusion, chemotaxis, bacterial growth and decay, nutrients consumption and plugging effect.

Delshad et al. (2002) added MEOR to their in-house chemical flooding simulator UTCHEM. UTCHEM is capable to simulate: permeability reduction due to microorganism retention, formation of bioproducts, nutrients destruction, and growth of biomass. Thullner et al. (2004) built a simulation model for microbial reactive transport in groundwater including bio-clogging.

Sugai et al. (2007) conducted one of the first MEOR simulation works that considered the change in water viscosity due to biopolymer formation. Behesht et al. (2008) developed a three-

dimensional, multi-component transport model with two separate terms to account for the dispersion, convection, injection, bacteria reaction kinetics and accumulation. Wettability alteration from oil wet to water wet and the reduction in IFT effect simultaneously on the relative permeability and capillary pressure curves were also incorporated. Nielsen (2010) proposed a reactive transport model that includes convection, bacterial growth, nutrients consumption and surfactant production. MEOR effect modeling was incorporated in an existing streamline simulator and a finite difference simulator to consider reservoir heterogeneity and gravity effect. Shabani-Afrapoli et al. (2012) tested capabilities of commercial simulators: coreflooding experiment with ECLIPSE 100 and micromodel flooding experiment with COMSOL. Due to the simulator limitations only three MEOR effects were considered: IFT reduction, wettability alteration and pore plugging without reaction kinetics. Sivasankar et al (2015) developed a one-dimensional, multi-phase, multi-species reactive transport model to simulate MEOR process under different pH and temperature conditions. Nmegbu and Ene (2017) based their work on an assumption that continuous biomass accumulation could lead to excessive permeability reduction, resulting in flow restriction and a more tortuous reservoir. The development of the model was based on the classical material balance principle, where both static and dynamic adsorption of bacteria, nutrients and metabolites were considered. Most of these attempts were performed in academic and noncommercial software that are limited at reservoir scale computations, making them inappropriate for reservoir modelling.

Currently there is no commercial reservoir simulator that can model MEOR although most of mechanisms are mathematically very well described. The major reason for this is growth behavior under standard reservoir modeling scheme. The difficulties of isolation of the individual mechanisms from laboratory works and calibrating the empirical parameters of the proposed model are other handicaps for an appropriate modeling (Bueltemeier et al, 2014).

In this project the commercial simulator STARS has been chosen for its modeling flexibility and reaction kinetics module. Multiple works have been performed to prove capability of STARS to model effects (Gaich 2016, Be 2018) and bacterial growth (Bultemeier, 2014) within the work package 3 of the project.

Research work has been started with modelling options for bacterial growth, and modelling efforts were made to translate the bacterial growth to the production of the metabolites, which

in term were used to incorporate the EOR mechanisms modelled in conventional way in STARS. In this work, a slightly different, however easy to apply, way to model MEOR is applied. At final stage of the study, modelling concept is developed by introducing the probabilistic approach.

4 MODELLING MEOR WITH CMG STARS

In this chapter efforts to match growth curves of bacteria, nutrient consumption curve and metabolite production curve will be shown.

4.1 MEOR Batch Experiments

Batch experiments are static experiments in closed bacterial culture system, isolated from environment with specific nutrient, temperature, pressure and other environmental conditions to optimize growth (Figure 4-1).

In order to deliver data on microbial growth for mathematical modeling a growth experiment was performed with the enrichment culture derived from the formation water of the field studied. The enrichment contains a mixed culture of Halanaerobium strains and Geotoga. The nutrient media contains 100% original injection water (salt content 165 g/l). As nutrients sucrose and yeast extract were added in different dilutions. The pH was adjusted to 6.5 and the growth temperature was 37°C matching reservoir conditions. The cultures were incubated in anaerobic serum bottles with no agitation for two weeks until growth ceased.

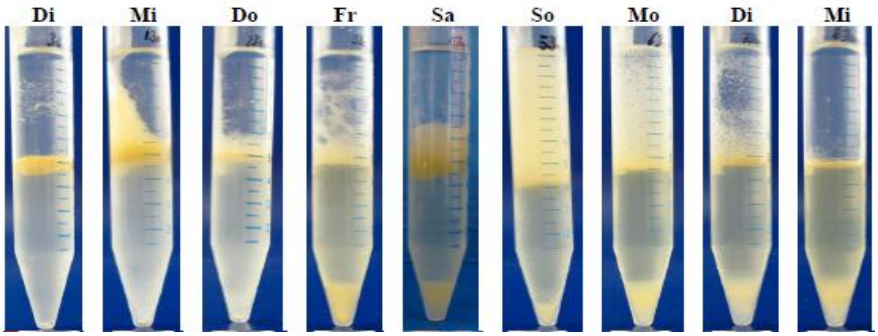


Figure 4-1 Batch experiment (internal source)

Bacterial amount is measured by extinction in optical density (OD). The optical density at 600 nm was determined using a photometer. Curves of bacterial growth for five different dilutions were obtained (Figure 4-2).

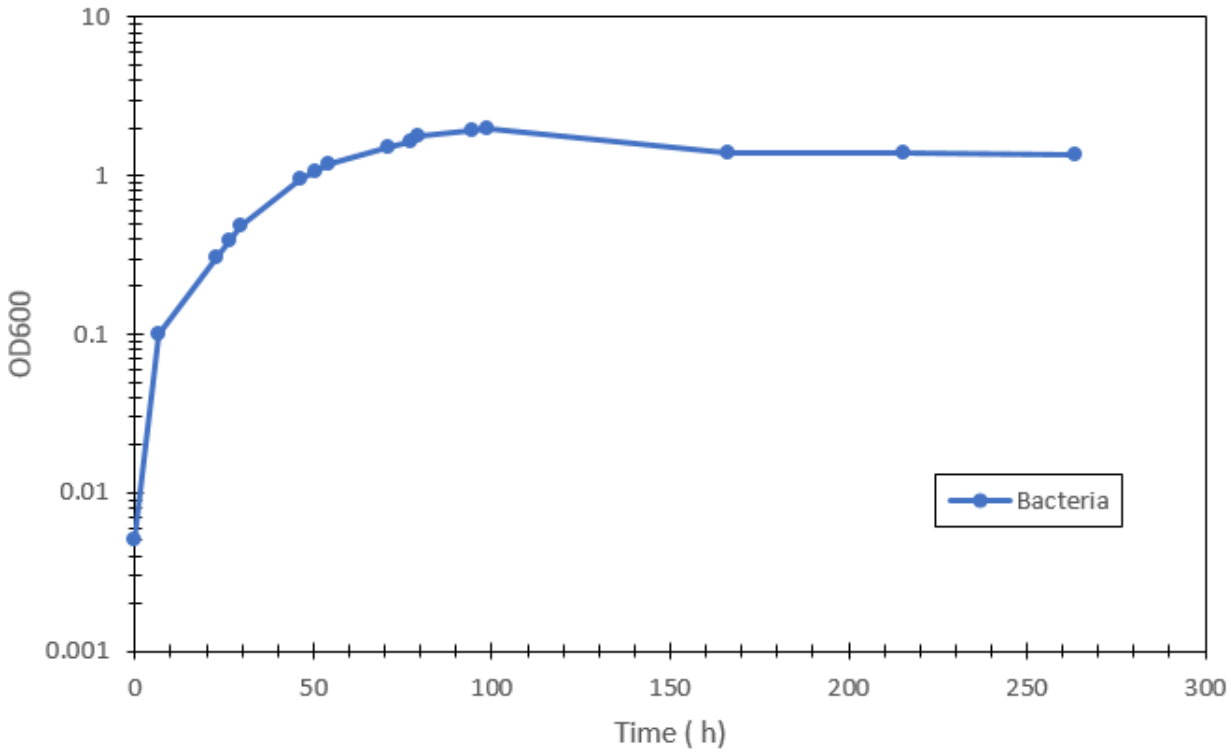


Figure 4-2 Bacteria growth curve

Samplings were performed at least three times per day, every morning at 7 am, at 11 am and at 3 pm. After sampling, multiple analyses were performed: optical density (OD), pH, cell counting by microscopy, viscosity, IFT measurements and High-performance liquid chromatography (HPLC). HPLC is a technique in analytical chemistry used to separate, identify, and quantify each component in a mixture. HPLC measurement was used for determining acids, solvents and sugars in batch experiment. With HPLC, nutrient consumption curve and metabolite production curve were obtained (Figure 4-3).

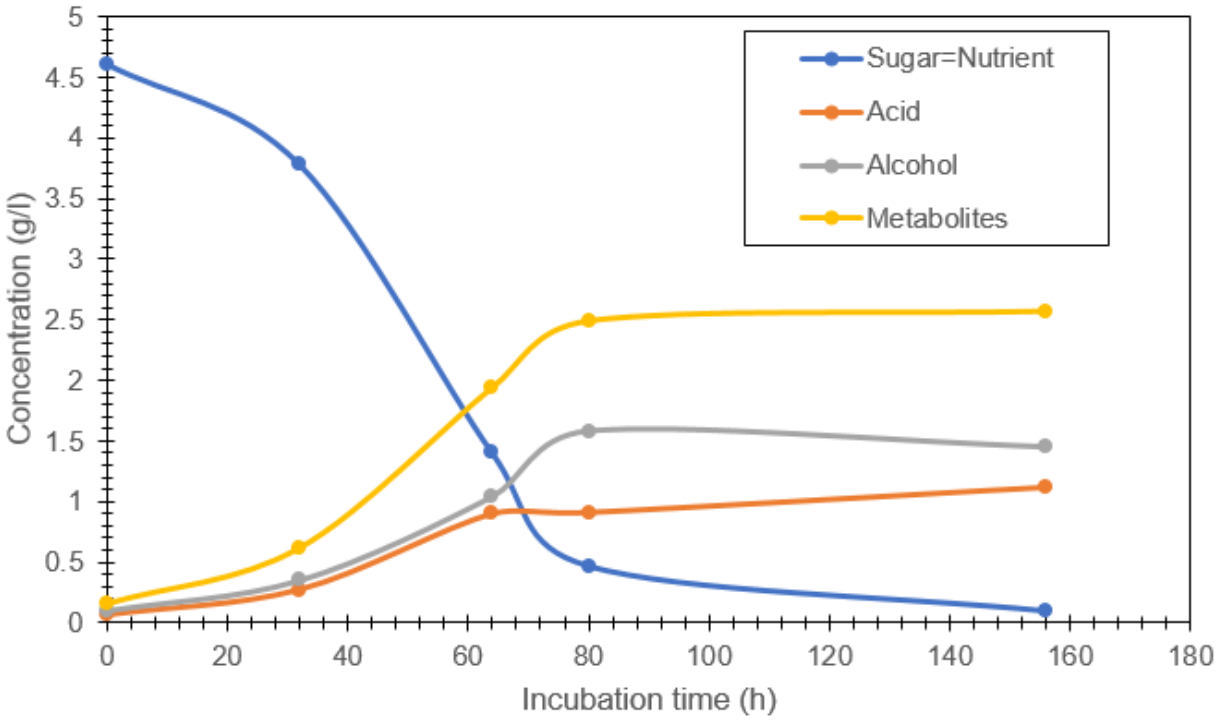


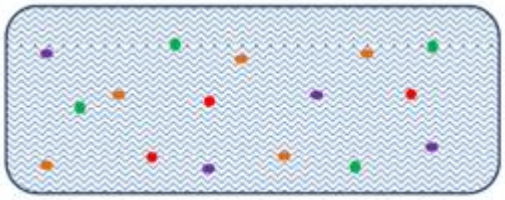
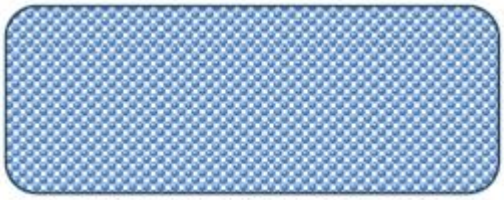
Figure 4-3 Nutrient consumption and metabolite production curve

Sugar is nutrient in this case and decreasing trend in sugar concentration proves that there is bacterial consumption of nutrient. Acids and alcohols are product of bacterial metabolism and their concentration is increasing so long as there is enough nutrient for bacterial activity. Also, it can be concluded that metabolites will decay after some time as it can be observed on alcohol curve. For the purposes of simulation acids and alcohols are grouped together in lumped metabolite component.

4.2 Modelling Batch Experiments

In order to reproduce growth curves with the help of reaction kinetics module components, Bacteria, Nutrient and Metabolite were created in CMG STARS and properties like molar weight, density and viscosity were assigned. For the purpose of chemical reaction module, STARS deals with components in moles and mol fraction. Laboratory curves for bacteria growth, nutrient consumption and metabolite production were given in OD or g/L, however, CMG STARS cannot work with optical density and g/L, therefore conversion to mol fraction is needed (Table 4-1).

Table 4-1 Conversion scheme (adapted after Bueltemeier et al, 2014)

Laboratory	**Simulation**
	
Water medium containing bacteria, nutrients and metabolites dispersed in solution or grouped together. Number of bacteria measured in OD and concentration of metabolites and nutrient in g/L.	Uniform aqueous phase, dissolved bacteria, nutrients and metabolites transported as tracers. Quantity of bacteria, nutrient and metabolites in moles and mole fraction.

Another issue is bacteria optical density to mole fraction conversion, in terms of bacteria's molar mass. Bacteria are living organisms (and not a chemical compound), so defining their molar mass was a challenge to be solved. Following assumption was made to make conversion possible: OD is equal to g/L. Previous attempts were based on recalculation of optical density to number of cells based on linear regression between them and then multiplying with approximate volume of one cell to obtain volume fraction in the end, but molar mass was still based on assumption. However, assumption that OD is equal to g/L is valid for purposes of conversion, OD is converted to mol fraction for input data and after achieving results reconverted back in OD. This principle is simpler and time saving in comparison with the previous one and both of them are based on assumption of molar mass. This pragmatic assignment has no relevance for modelling and no effect on the results.

4.2.1 Modelling Reaction Kinetics

Bacterial growth is commonly modeled by Monod equation. Monod kinetics was investigated to account for all kinds of product, cells and substrate inhibition with variations of the basic equation. It should be mentioned that Monod equation is empirical; a statistical analysis on its validity has been reported in Kana and Matsumura (2012) with 1042 data points. Monod

equation successfully reproduced the literature data with an average error less than 5 %. The simplest form of the Monod equation is given for the bacterial growth rate r_g, as follows (Bueltemeier, 2014):

$$r_g = \frac{r_{max} \cdot S}{K_s + S} \tag{4-1}$$

Where:

r_g – Bacterial growth rate in standard Monod equation (1/s)

r_{max} – Maximum bacterial growth rate in standard Monod equation (1/s)

S – Substrate concentration in standard Monod equation (kg/m^3)

K_s – Half rate constant in standard Monod equation (kg/m^3)

However, CMG STARS does not have incorporated Monod equation, reactions can only be modelled as chemical reactions.

Basic relation of microbial metabolism can be written as:

$$nutrients + bacteria \rightarrow more\ bacteria + metabolite(s) \tag{4-2}$$

In CMG STARS, reactions are requiring stochiometric coefficients for reactants (keyword: STOREAC) and products (keyword: STOPROD), but reaction does not need to be chemically correct, that leaves space for adjustment of reaction in matching process.

$$n_{rn} \cdot nutrients + n_{rb} \cdot bacteria \rightarrow n_{pb} \cdot bacteria + n_{pm} \cdot metabolite(s) \tag{4-3}$$

Where:

n_{rn}, n_{rb}, n_{pb}, n_{pm} – Stochiometric coefficients for components, respectively (-)

However, for validation of reactions mass balance should be conserved.

$$\sum n_{reac,i} \cdot Mm_{reac,i} = \sum n_{prod,i} \cdot Mm_{prod,i} \tag{4-4}$$

Where:

n – stochiometric coefficient for every component respectively (-)

Mm – molar mass for every component respectively (kg/mol)

Due to previously assigned molar masses for components sometime is necessary to add component to the side of products for mass balance to be achieved, usually water is added which does not affect the numerical precision. In case of need for component addition to the side of reactants for mass balance to be achieved then alternative solution is needed, because reactant concentrations are used for calculation of the reaction rate as it will be shown later.

In addition to first relation of microbial metabolism, two additional relations were formed to account for decay of bacteria and metabolites as observed in laboratory. To simulate decay of the bacteria, the definition of a separate reactions is needed, one for every component that decays. The easiest approach is to define a reaction where the component decays into its reference phase, e.g. bacteria decay to water (Bueltemeier, 2014).

$$Bacteria \rightarrow Water \tag{4-5}$$

$$Metabolites \rightarrow Water \tag{4-6}$$

After defining reaction relations, reactions kinetics should be determined. In the model the kinetics is modelled with *RXORDUSE *DEN_COMP option. This *RXORDUSE option specifies that the reaction order is applied to concentration based on phase volume instead of gross volume. The reaction rate is then established with the following steps (STARS manual).

The concentration factor c_i for fluid component i is:

$$c_i = S_j \cdot (\rho_j \cdot x_{j,i})^{enrri} \tag{4-7}$$

Where:

c_i – concentration factor for fluid component (mol/m^3)

S_j – phase saturation (-)

ρ_j – phase mole density (mol/m^3)

$x_{j,i}$ – mole fraction of component i in fluid phase j (-)

enrri – reaction order (-)

The reactant concentration factors are calculated depending on their concentration in a reference phase and reactants are considered as tracers in water and oil phases (Alkan et al, 2015). Reaction order is normally 1 for reacting aqueous components.

The expression for volumetric reaction rate, r, is then:

$$r = rrf \cdot e^{\left(\frac{-Ea}{(T+273.15)\cdot R}\right)} \cdot \prod c_i \quad (4\text{-}8)$$

Where:

r – volumetric reaction rate ($molm^{-3}s^{-1}$)

rrf – frequency factor (1/s)

E_a – Activation energy (J/mol)

T – temperature (°C)

R – universal gas constant (8.314 $Jmol^{-1}K^{-1}$)

c_i – concentration factor (mol/m^3)

Frequency factor is the constant part of the expression, it is given by keyword FREQFAC. Activation energy provides the temperature dependence, by setting the activation energy equal to zero an isothermal reaction is obtained. This simplification is made; because the application can be assumed as an isothermal one as only nutrient solution is injected being heated up in the reservoir in a short time as it advances into porous media (Alkan et al, 2015).

4.2.2 Calibration of Growth Modelling

A simple model was created in CMG STARS to simulate the batch experiments. The model consisted of one cell representing the batch bottle, volume was set to the volume of bottle, porosity was 0.999 and it was completely saturated with water. Components were initialized in solution after the conversion to mole fraction. Frequency factor and stochiometric coefficients were used as a matching parameter while bacteria growth curve, nutrient consumption curve and metabolite producing curve were used as a three objective functions. There was in total 9 matching parameters. Matching was done in spreadsheet (MS Excel) for static conditions,

because of the faster calculation and checked in CMG afterwards. Matching process was performed for “1C” concentration (Figure 4-4).

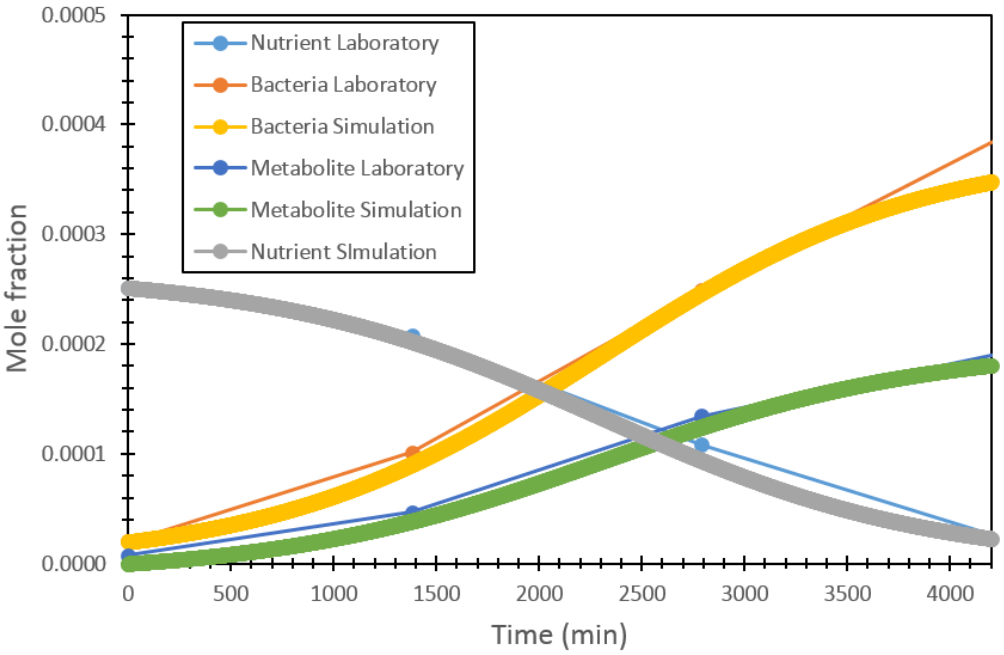


Figure 4-4 Numerical match to experimental data for “1C” concentration

The match of experimental data was satisfying for all three curves, but further checks would be performed because match was made to only one concentration. High number of matching parameters is leaving possibility of non-unified solution; in other words, there could be multiple solutions that would give good match. Obtained frequency factor and stochiometric coefficients were therefore used as an input to modelling processes for the concentration “2C” and ”0.5C” to check their validity for different solutions (Figure 4-5 and 4-6).

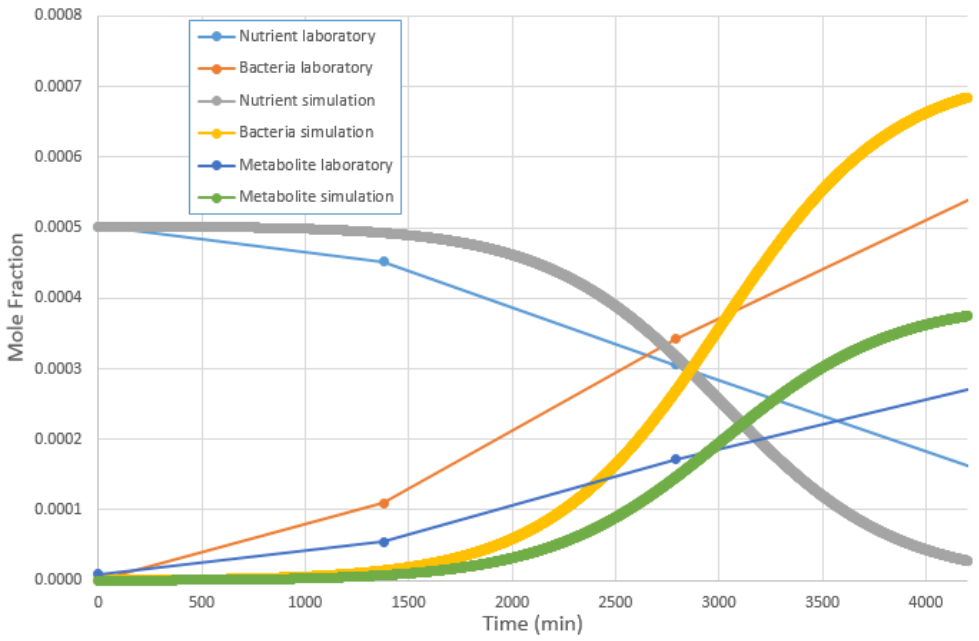


Figure 4-5 Numerical match to experimental data for "2C" concentration

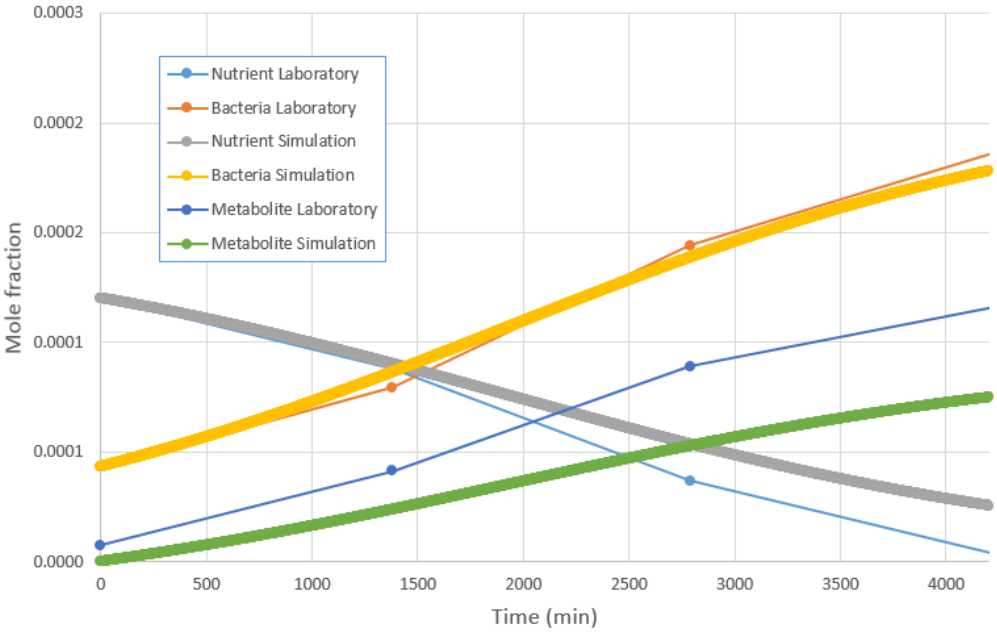


Figure 4-6 Numerical match to experimental data for "0.5C" concentration

Simulation runs were performed for both concentration with parameters obtained earlier, curves were obtained and converted back to original units for the comparison with laboratory ones. Modelling of "0.5C" was satisfying while modelling of "2C" did not show a good match to experimental data. Regressed matching parameters are shown in table 4-2.

Table 4-2 Regressed matching parameters

REACTION 1 = Growth			FREQFAC	50
REACTANTS	STOREAC	PRODUCTS	STOPROD	
Bacteria	0.9	Bacteria	2.5	
Nutrient	1.1	Metabolite	0.87	
REACTION 2 = Bacteria decay			FREQFAC	0.01
REACTANTS	STOREAC	PRODUCTS	STOPROD	
Bacteria	0.0006	x	x	
REACTION 3 = Metabolite decay			FREQFAC	0.05
REACTANTS	STOREAC	PRODUCTS	STOPROD	
Metabolite	1	x	x	

4.2.3 Growth under Dynamic Conditions

After achieving match for static conditions, attempts to match bacteria amount for dynamic conditions in sand packs were made. Regressed matching parameters from batch experiment were used as an input for bacterial growth in sand pack model. However, multiple challenges were faced during this process. Main challenge was reproducing bacteria transport in porous media. Chang et al (1991) build model and microbial transport formulation that was considering dispersion, convention, chemotaxis, clogging/declogging and injection/production of bacteria in aqueous phase. This shows complexity of the phenomena and the number of effects that need to be taken in account for correct modeling of bacteria transport.

In this case due to the use of commercial simulator, bacteria were modeled as tracer in water phase, therefore retention of bacteria in porous media or their delay in flowing phase was not possible. This caused problems because stream of bacteria was too fast to achieve adequate time of retention for reaction to take place in right extent.

One of the proposed solutions was modelling adsorption of bacteria. But retaining liquid component with the adsorption option leads to unavoidable deactivation of the component (Behr et al, 2017). In other words, everything that is adsorbed is removed from chemical reaction, this is putting another challenge for replicating the growth in flowing conditions.

The other solution was introducing into the model a new solid non-movable component and propose the partitioning of total bacteria amount to liquid and solid fractions modeled by the example of Behr et al (2017). However, having nutrient consumption and metabolite production in direct relation with bacteria adding two additional equation would cause even bigger complexity and uncertainty into system of equation.

Another problem of laboratory data, bacteria would adsorbed inside of sand pack or core and therefore the amount of bacteria was not constantly obtained in outflow. Additional issue observed is movement of bacteria inside of the core that can occur periodically. The only trustworthy data was concentration of nutrient in the outflow but because of modeling approach it is directly connected to amount of bacteria and as earlier mentioned transport of bacteria is main problem and uncertainty.

Because of all mentioned challenges, modelling of MEOR with reaction kinetics module was revised and further steps with new modelling approach are discussed in Chapter 6: "New Simplistic Approach for Modelling MEOR".

4.3 Modelling MEOR Effects

In this chapter theoretical background of the microbial enhanced oil recovery (MEOR) effects will be more thoroughly explained, CMG STARS calculation principles will be described, and modeling efforts and workflows will be shown.

Following MEOR effects are discussed:

- Wettability alteration
- Selective plugging
- Water viscosity increase
- Oil viscosity reduction

4.3.1 Wettability Alteration

According to Feng et al (2002) wettability alteration mechanism is combination of bacterial growth behavior and production of biosurfactants. When bacteria are interacting in groups they seem to expand in circles from top view, but on the side view they expand in layers, resulting in layered disbands of oil. Observation showed that process that the disbanding process starts in some local places and expands with the time (Figure 4-7). Additionally, concentrated surfactants produced by bacteria in location are making solid surface trend to water wet.

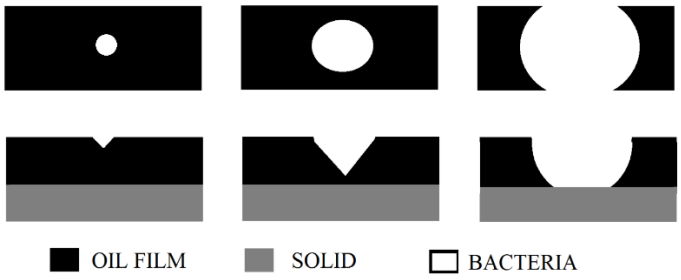


Figure 4-7 Bacteria behavior top and side view (adapted after Feng et al, 2002)

Wettability alteration is always considered as one of the main MEOR effects leading to additional oil. To investigate the wettability alteration and its extent, spontaneous imbibition (SI) experiments were performed with sandstone cores having various petrophysical properties and initial states. Amott type glass flasks are used and reservoir temperature is applied. The recovery is compared with benchmark experiments performed with sterile formation water (Alkan et al, 2016)

The oil release curve in SI experiments followed the reference curve first which typically exhibits an oil release of 0.32±0.02 of original oil in place (OOIP). After approximately two days the oil release increased suddenly reaching to 0.62±0.03 of OOIP at the end of the fourth day (Alkan et al, 2019) (Figure 4-8). This behavior corresponds to the growth of the bacterial community suggesting the effect of the MEOR on imbibition behavior.

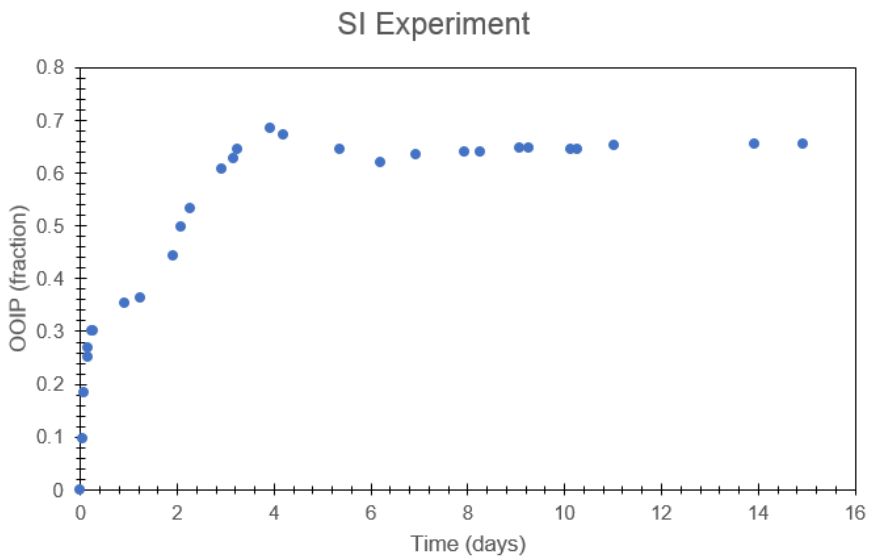


Figure 4-8 Spontaneous imbibition results (Alkan et al, 2019)

Oil recovery curves from the experiments were used as objective functions and the numerical data (the oil released from core cells into the Amott flask cells) were matched with experiment's oil release. The original capillary pressure curve was derived from reference SI and core flood experiments in oil-water-rock system with the approach proposed by Li and Horne (2005).

The capillary pressure, Pc, could be calculated using the following equations:

$$P_c^* = \frac{1}{S_{wf} - S_{wi}} \cdot \frac{a_0}{b_0} \cdot \Delta\rho \cdot \mathrm{g} \cdot \mathrm{L} \qquad (4\text{-}9)$$

Where:

P_c^* – capillary pressure at S_{wf} (Pa)

S_{wf} – water saturation behind imbibition front (-)

S_{wi} – initial water saturation (-)

a_0 – imbibition index (m^3/s)

b_0 – coefficient associated with gravity (m^3/s)

$\Delta\rho$ - density difference between the wetting and nonwetting phase (kg/m^3)

g – gravity constant (m/s^2)

L – core length (m)

a_0 and b_0 could be determined from the linear correlation between the imbibition rate and the reciprocal of the recovery by spontaneous imbibition in fluid-fluid-rock systems. Straight line is expected from which the values of the two constants, a_0 and b_0, could be obtained from a linear regression analysis:

$$q_w = a_0 \cdot \frac{1}{Re} - b_0 \tag{4-10}$$

Where:

q_w – imbibition rate of the wetting phase (m^3/s)

a_0 – imbibition index (m^3/s)

b_0 – coefficient associated with gravity (m^3/s)

Re – recovery by the spontaneous imbibition in the units of pore volume (-)

The relative permeabilities were also generated for reference case by Brooks and Corey (1964) set of correlations.

$$k_{rwe} = \left(\frac{S_w - S_{wr}}{1 - S_{wr}}\right)^{\frac{2+3\lambda}{\lambda}} \tag{4-11}$$

$$k_{rnw} = \left(\frac{1 - S_w}{1 - S_{wr}}\right)^2 \cdot \left(1 - \left(\frac{S_w - S_{wr}}{1 - S_{wr}}\right)^{\frac{2+\lambda}{\lambda}}\right) \tag{4-12}$$

Where:

k_{rwe} – relative permeability for wetting phase (-)

k_{rnw} – relative permeability for non-wetting phase (-)

S_w – saturation of wetting phase (-)

S_{wr} – saturation of residual wetting phase (-)

λ – pore-size-distribution parameter in Corey functions (-)

The modelling of the wettability alteration effect can be described as follows: As the component metabolite is generated from the bacterial growth reaction or injected in the reservoir, part of it will adsorb on the rock surface. The adsorption of the component metabolite will change the wettability of the rock in the direction of more water-wetness through interpolation of provided

capillary pressures and relative permeabilities between waterflooding and MEOR flooding. Increasing metabolite adsorption means an increased shift to more water wet wettability in the model. The relative permeability and capillary pressure acting in MEOR were regressed applying the same methodology this time using the MEOR experimental data.

The two sets interpolation scheme of CMG provides a flexible tool for representing bacterial metabolism effects on wettability alteration through interpolation of relative permeabilities and capillary pressure. Relative permeability and capillary pressure are calculated from rock fluid sets A and B based on phase interpolation parameter (keyword DTRAPW for water and keyword DTRAPN for oil, one for every set in every phase) and current value of interpolation component:

$$k_r = (1 - \omega) \cdot k_{rA} + \omega \cdot k_{rB} \tag{4-13}$$

$$\omega = \left(\frac{x_i - x_A}{x_B - x_A}\right)^p \tag{4-14}$$

Where:

k_r – calculated relative permeability (-)

k_{rA} – relative permeability of set A (-)

k_{rB} – relative permeability of set B (-)

ω – final interpolation parameter (-)

x_i – current value of interpolation component (-)

x_A – interpolation parameter of set A (-)

x_B – interpolation parameter of set B (-)

p – curvature exponent (default value is 1) (-)

The effect of wettability alteration on the oil production can be considerable causing an increase of more than double of initial spontaneous imbibition and the increase is connected to growth of bacteria (Figure 4-9).

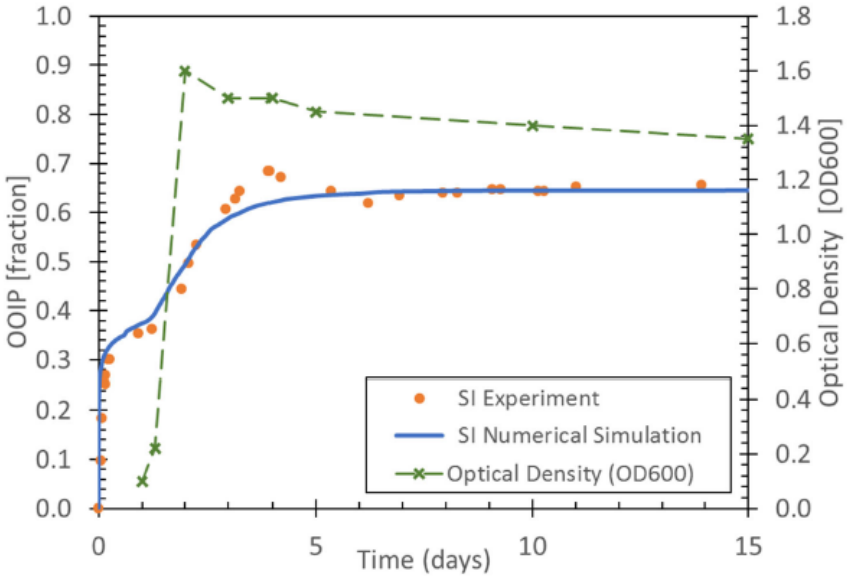


Figure 4-9 Experimental and calculated SI behavior and growth curve for the bacteria (Alkan et al, 2019)

The match was achieved with both, wettability alteration based on interpolation in combination with kinetics module and with restart file.

4.3.2 Selective Plugging

Selective plugging or bio plugging can be the most efficient EOR mechanism within MEOR. Theoretical explanation behind bio plugging is that due to fluid distribution, smaller pores are saturated with oil while bigger pores are mostly saturated with water. Bacteria and metabolites are present in water phase so during the growth and increase in the number of bacteria, volume of bacteria will increase too. Bacteria volume increase together with adsorption will plug bigger pores and redirect flow to smaller pores that are usually less permeable one. On this way bio plugging is reducing saturation of oil in pores that in waterflood will not be affected (Figure 4-10).

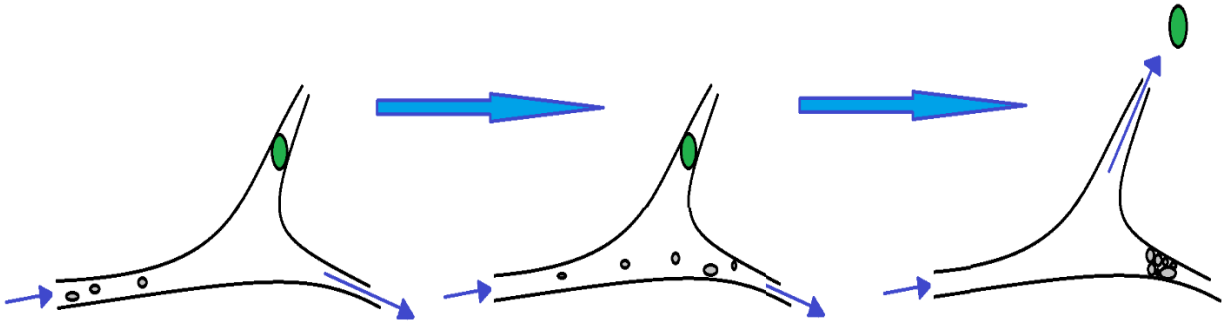


Figure 4-10 Plugging of the pores by bacteria in MEOR (adapted after Strappa et al, 2004)

In the tests dynamic tests were performed in micromodels, during the examination it was observed that bacteria are grouping in bigger pores and redirecting flow to less permeable zones.

Bacterial growth was investigated in both batch cultures and under dynamic conditions. To visualize cell adhesion and also biofilms, specific fluorescent dyes were used. In batch experiments with high concentrations of nutrients, agglomeration of cells was very distinct after three weeks, with cell clumps reaching a diameter of up to ~70 µm. The cell clumps were mostly loosely associated to the sand particles (Figure 4-11). Up to this time point, mostly single cells were visible in the medium, whereas after four weeks of incubation, many cells were observed being attached to the surface of some particles (Alkan et al, 2016).

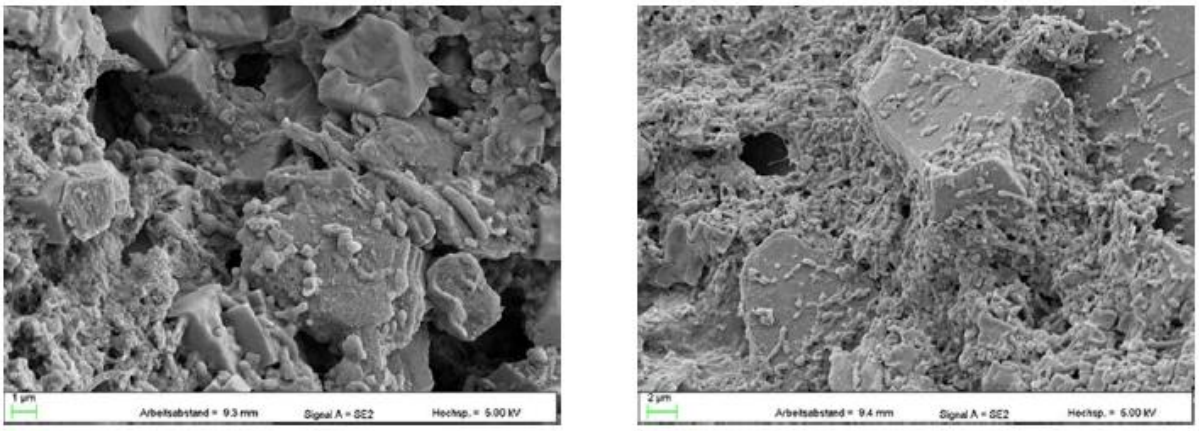


Figure 4-11 Biofilm formation in porous media (Alkan et al, 2016)

An estimation of this value from a microbiological point of view is challenging and constitutes one of the biggest uncertainties in this approach, given that the MEOR metabolites and bacteria themselves have a behavior that is significantly different from conventional synthetic polymers

and surfactants with a clear and defined molecular structure and characteristics. Lastly, the adsorption curves are so far not being generated experimentally. Other premises that have been assumed are that the entire pore volume is accessible for metabolite adsorption, and that adsorption is irreversible. (Alkan et al, 2015)

Adsorption or mechanical entrapment can cause blockage which amounts to a reduction in the effective permeability. This is accounted for by the permeability reduction factors:

$$RKp = 1 + (RRF - 1) \cdot \frac{AD(c,t)}{ADMAXT} \quad (4\text{-}15)$$

Where:

RKp – permeability reduction factor (-)

RRF – residual residence factor, keyword rrft (-)

AD (c,t) – adsorption as a function of temperature and concentration (mol/m^3)

ADMAXT – maximum adsorption capacity (mol/m^3)

Effective permeability of the block is then calculated as:

$$AKp(i) = AK \cdot krp/RKp(i) \quad (4\text{-}16)$$

Where:

AKp (i) – Effective permeability for phase p in block i (mD)

AK – Absolute permeability (mD)

krp – relative permeability for phase p (-)

RKp (i) – permeability reduction factor for phase p in block i (-)

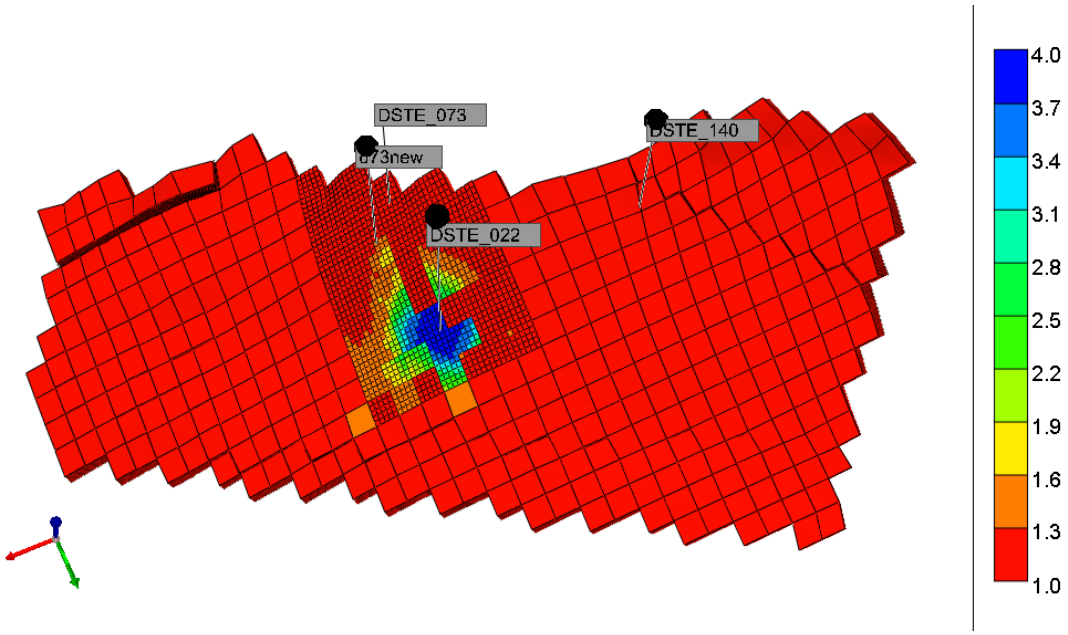


Figure 4-12 Adsorption and RRF in one layer

Different residual residence factors were set for different rock types to account for selective plugging of higher permeable zones (Figure 4-12).

4.3.3 Increase in Water Viscosity

The reason for water viscosity increase is that the bacteria are producing exopolymeric substances (EPS) e.g. polysaccharides during growth. This bio polymer compounds are then acting as a viscosifying agents in situ. With the assumption that oil viscosity and relative permeabilities would not change the same increase in water viscosity would reduce mobility ratio. Lower mobility ratio is considered beneficial due to higher mobility of displaced phase (oil) than the displacing phase (water) which would result in better displacement efficiency and higher recovery (Alkan et al, 2014).

$$M = \frac{k_{rw} \cdot \mu_o}{\mu_w \cdot k_{ro}} \tag{4-17}$$

Where:

M – mobility ratio (-)

k_{rw} – relative permeability for water (-)

k_{ro} – relative permeability for oil (-)

μ_o – oil viscosity (cp)

μ_w – water viscosity (cp)

The rheology of the aqueous phase in the presence of nutrients was investigated during the growth of the MEOR microorganisms. The viscosity of the aqueous phase after MEOR treatment shows slightly pseudoplastic rheology which can be an advantage in the reservoir in terms of conformance control. Some of the measurements were performed with cell-containing fluid samples while some of the measurements were performed with cell-free samples. In both cases, a significant increase in viscosity in comparison to formation water was observed (Alkan et al, 2016).

Due to sugar in nutrient formulation, nutrient solution is also causing slight increase in water viscosity. In previous work, Gaich (2016) and Be (2018), nonlinear mixing rule was applied for both components to account for water increase while SHEARTAB function was applied to account for shear thinning effect.

The nonlinear mixing option partitions all the components into two groups: those that are key components (call it set S), and those are that are not. The xi (mole fraction) of these two groups sum to 1.

$$\sum_{i=S} x_i + \sum_{i \neq S} x_i = 1 \tag{4-18}$$

Where:

x_i – molar fraction of component (-)

To accomplish nonlinear mixing via alternate weighting factors, x_i is replaced with $f_i(x_i)$ for each i=S and with $N \cdot x_i$ for each i≠S, where N is a normalizing factor derived as follows.

$$\sum_{i=S} f_i(x_i) + N \cdot \sum_{i \neq S} x_i = 1 \tag{4-19}$$

$$N = \frac{1 - \sum_{i=S} f_i(x_i)}{(\sum_{i \neq S} x_i} \tag{4-20}$$

Where:

$f_i(x_i)$ – mixing function for molar fraction x_i (-)

N – normalizing factor (-)

As it can be seen in table 5-1. the function fi(xi) has three possible distinct ranges of xi values.

Table 4-3 Mixing function values

RANGE	VALUE
$0 \leq x_i < x_{low}$	$f_i(x_i) = x_i \cdot (f1/x_{low})$
$x_{low} \leq x_i \leq x_{high}$	$f_i(x_i)$ from table look-up and interpolation
$x_{high} < x_i \leq 1$	$f_i(x_i) = f11 + (x_i - x_{high}) \cdot (1-f11)/(1-x_{high})$

Further investigation showed that CMG does not support more than one nonlinear mixing function. Ten combinations of different mole fractions for metabolite and nutrient were initialized in CMG and viscosity was monitored while at the same time viscosity was calculated with given set of formula. Calculated and simulated values did not match therefore one component (either metabolite or nutrient) should be switched to linear mixing rule (Figure 4-13).

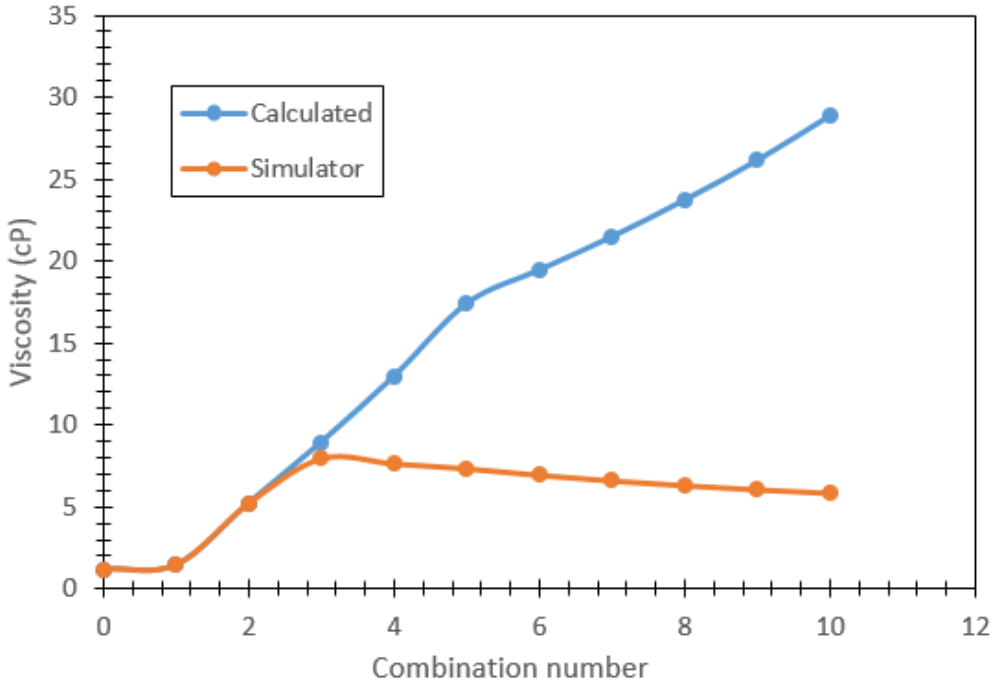


Figure 4-13 Viscosity values for different mole fraction combinations

As the incubation period is short, the injected nutrient solution will be quickly converted to metabolites by bacteria as it continues its movement in the reservoir, therefore it is convenient to use the viscosity of the metabolites as a representative case for the viscosity of the displacement phase viscosity (Alkan et al, 2014). The nutrient was set to linear mixing rule. In the linear-log mixing rule the mole fraction xi act as weighting factors.

$$\ln(\mu) = \sum_i x_i \cdot \ln(\mu_i) \tag{4-21}$$

Where:

μ – calculated viscosity of mixture (cp)

x_i – molar fraction of component i (-)

μ_i – viscosity of component i (cp)

4.3.4 Decrease in Oil viscosity

Feng et al (2002) reported that certain bacteria have ability to create up to 5 ml of gas per 100 ml of fluid. As the solubility of CO_2 is higher than other gas components it can be assumed that all of the gas generated is directly dissolved in reservoir fluids because of homogenous, slow dispersion of the nutrient and metabolite solution throughout the porous media. In addition, the gas dissolved in the oil creates a swelling effect (Alkan et al, 2014)

Alkan et al (2014) also reported that generated amount of gas could vary between 30 and 80 μmol/L depending on the nutrient concentration with approximately 80 % being CO_2 (Figure 4-14). With the solubility of CO_2 in oil 6-7 times higher than its solubility in the water with the given salinity; valid assumption is that CO_2 will preferentially dissolve in the oil phase. With everything considered, reduction of the viscosity up to 3 cP could be achieved. This amount of gas would also result in 2 – 3 % volume increase.

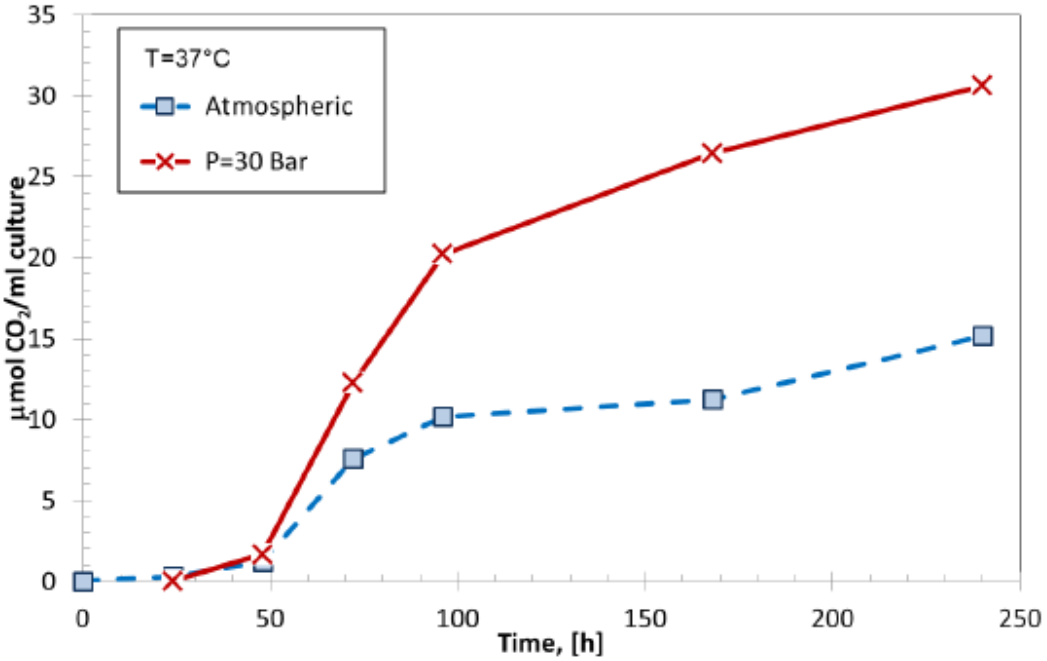


Figure 4-14 CO_2 generation by batch microbial incubations grown at atmospheric and reservoir conditions (Alkan et al, 2014)

Viscosity of the oil was measured in correlation with mole fraction of CO_2 and the experimental obtained was used on the formulas to create mixing functions (Figure 4-15). CO_2 partioning between oil and water phase is described in (Be, 2018).

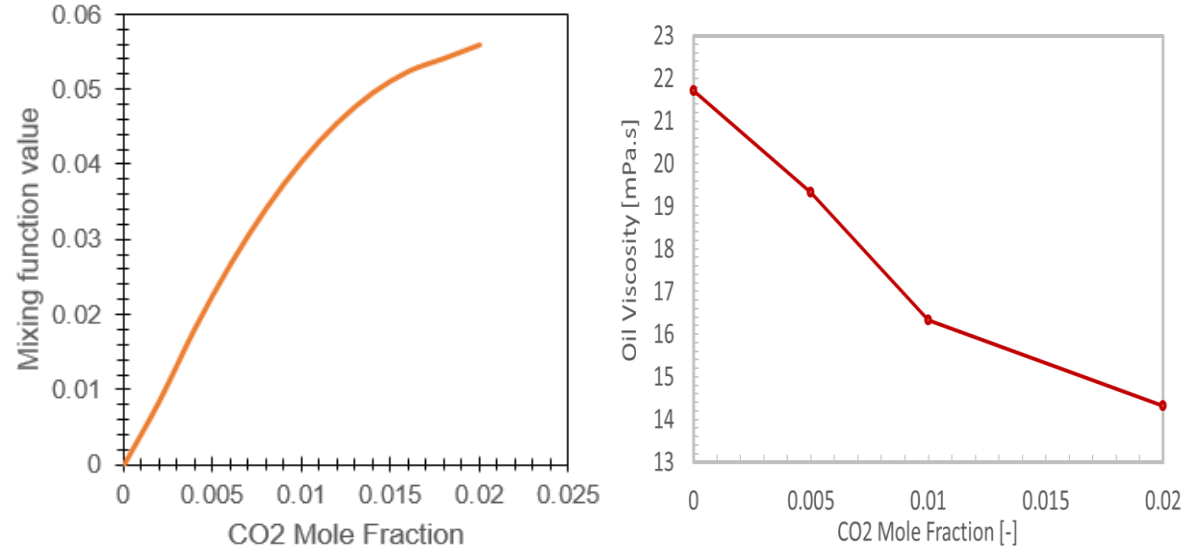


Figure 4-15 Mixing function value and viscosity in dependence of CO_2 mole fraction

5 NEW SIMPLISTIC APPROACH FOR MODELLING MEOR

Technical limitations of CMG described in chapter 4 in terms of bacteria transport modelling yielded need for simpler approach. Spirov et al (2014) tried to implement bacterial producing CO_2 effect with simple approach of injecting calculated amount of CO_2 that would be developed in field. This approach could be translated to every effect, consequently injecting one component for every MEOR effect. Injection concentration would fit maximal possible amount that was developed for predetermined amount of bacteria and nutrient in lab experiments. As can be seen on Figure 5-1 maximal number of bacteria is achieved after some time, and it is not increasing afterwards, in our case this was max 5 days.

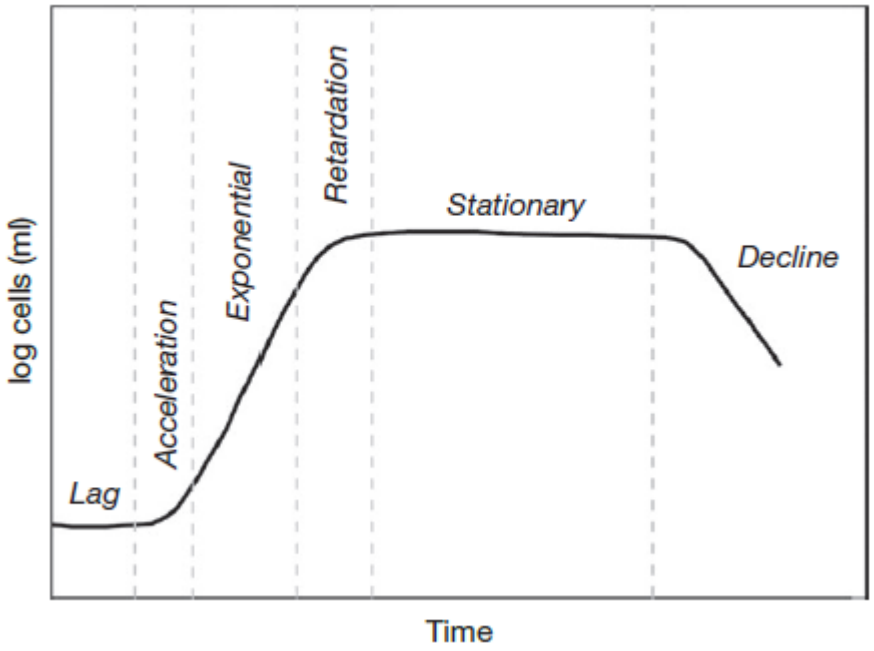


Figure 5-1 Typical bacteria growth curve

To control the validity of this new approach on simulation results simple analytical model was developed in excel to calculate radius of bioreactor after which bacteria and metabolite amount would reach their maximum amounts. Bioreactor radius was calculated with rearranged formula for residence time in simple cylindrical reservoir:

$$t_{res} = \frac{r_m^2 \cdot h \cdot \phi \cdot \pi \cdot (1 - S_{or})}{Q} \tag{5-1}$$

Where:

t_{res} – bacteria residence time (s)

r_m – bioreactor radius (m)

h – bioreactor thickness (m)

S_{or} – residual saturation of oil (-)

Q – injection rate (m^3/s)

ϕ – porosity (-)

The analytical model is assumed as homogeneous, with constant porosity of 0.2, constant residual oil saturation of 0.2, reservoir thickness of 10 m, injection rate was set to 170 m^3/ day and injection time was sufficient to develop maximum amount of components, 5 days. Calculated bioreactor radius is 13 m, which is relatively small compared with distance between injector and producer which is 180 m (Figure 5-2).

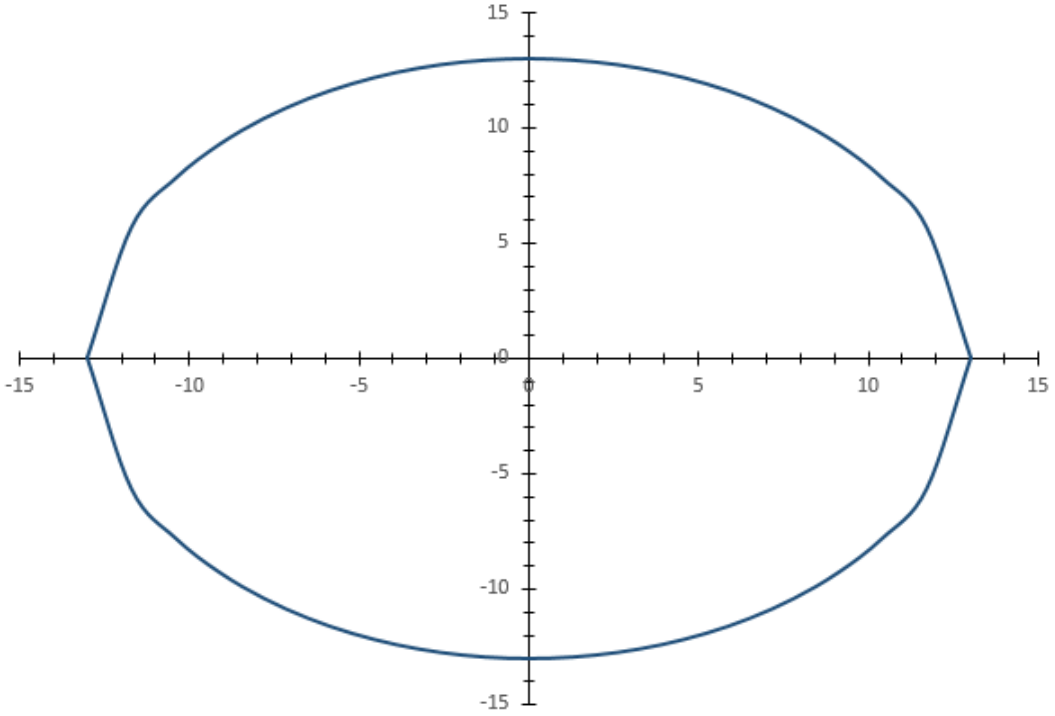


Figure 5-2 Bioreactor geometry around the injector well after analytical calculation

Runs were performed on sector CMG STARS model to validate the analytical prediction. Tracer test was performed, tracer was injected for 5 days with 170 m^3/day and the obtained radius for bioreactor was 18 m (Figure 5-3). CMG STARS sector model is taking heterogeneity, relative

permeabilities and other relevant factors that were not accounted in analytical model into consideration.

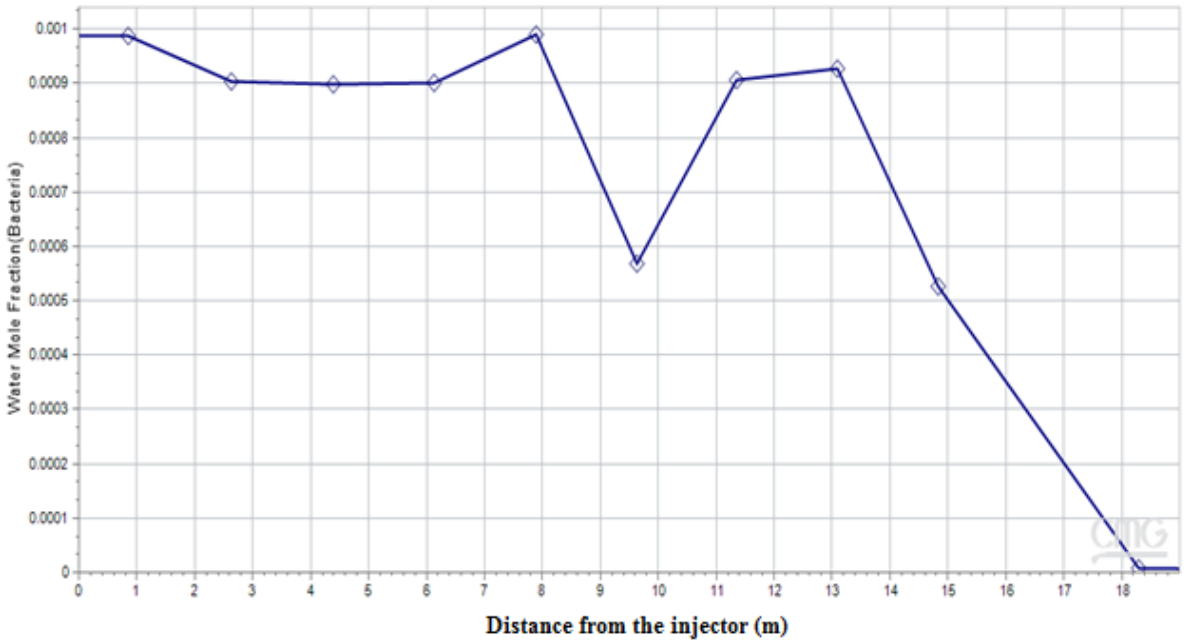


Figure 5-3 Bacteria propagation in reservoir modeled in sector model

Sweep area and sweep volume (reservoir thickness is 10 m) were approximated based on streamlines from tNavigator. Volume of bioreactor is 10179 m^3 while sweep volume is 794823 m^3, volume of bioreactor is only 1.28 % of sweep volume which implies that effect on final production will be almost negligible (Figure 5-4).

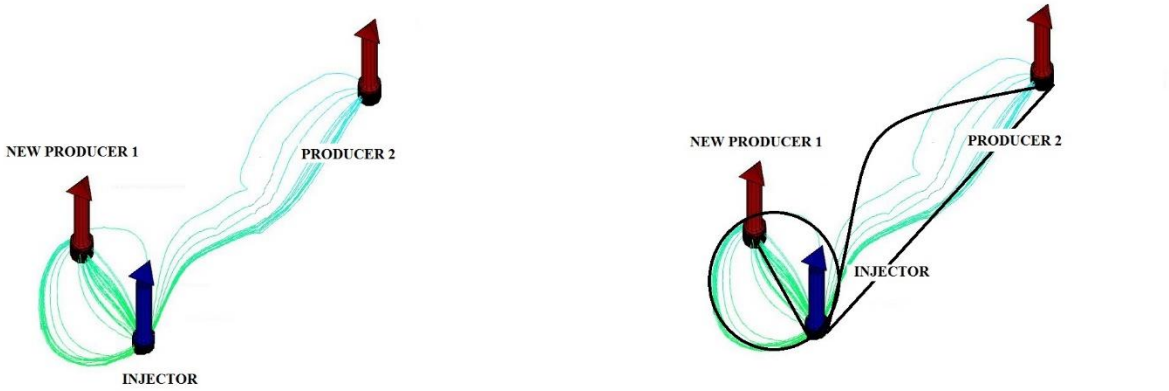


Figure 5-4 Swept volume approximation in sector model

Relatively small bioreactor volume is one of the reasons why reaction kinetics can be neglected for modelling the MEOR, the other ones are:

- Lower simulation time without reactions
- Known amount of metabolites generated in model
- Known distribution and front of components
- Simplification of modelling process
- Reduced uncertainty in the model

For further testing, four components were created in CMG STARS, one for every effect: wettability alteration, selective plugging, CO_2 oil viscosity reduce and metabolite water viscosity increase. Injection molar fractions of every component were set to maximal concentrations obtained in laboratory experiments. 5 runs were performed, one with all effects accounted and 4 in which every time different effect was disabled to see their contribution to final oil recovery.

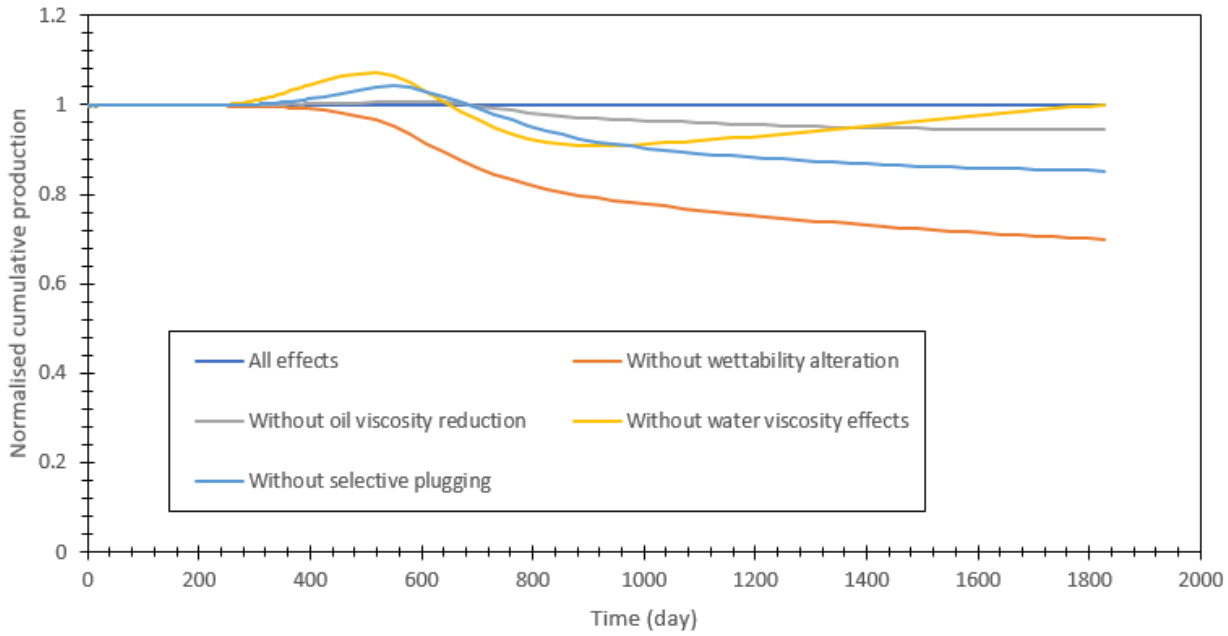


Figure 5-5 Normalized cumulative productions

Cumulative oil production for every case was divided with cumulative oil production for all effects to see dynamic of change (Figure 5-5). As can be seen biggest effect are wettability change and selective plugging as theoretically assumed in earlier chapters. On the other side,

without metabolite effect would be similar but with different time dynamic. This can be explained with viscosity shear thinning rheology of metabolite.

6 UNCERTAINTY ASSESSMENT AND RESULTS

In oil and gas industry, uncertainty analysis is frequently used tool for obtaining probabilistic distribution of oil, gas and water production profiles. Uncertainty assessment investigates the variation in simulation results due to uncertainty in input parameters. Uncertainty assessment involves the following:

1. Available simulation results to develop a response surface (RS) for each objective function of interest (such as NPV, oil rate and cumulative oil production) with respect to each of the uncertain variables (e.g. porosity, permeability, endpoint saturations, and oil viscosity).

2. Using the response surface, conduct a Monte Carlo (MC) simulation to select large numbers (tens of thousands) of variable value combinations and determine the value of the objective functions for each combination. The results of uncertainty assessments are probability and cumulative density functions for each objective function (CMOST manual).

Best- and worst-case data set for every effect were obtained from laboratory experiments. CMOST software from CMG was used for uncertainty assessment and Monte Carlo method was selected for the analysis. The purpose of Monte Carlo simulation is to perform risk analysis by building models of possible results by substituting a range of values (a probability distribution) for any factor that has inherent uncertainty (palisade.com).

Randomization of parameters that were represented in form of one number (RRFT) is usual modus operandi, challenge was how to do randomization of tables (relative permeabilities, mixing functions, shear tab). Putting every number in table as a parameter would need restrictions in values so the overlap of the parameters would not happen. Even after putting restrictions there was possibility of unphysical curves due to randomization.

One of the solutions was creating multiple include files with different realizations of tables and giving chance of occurring for every one of them. In this way all curves would be physical but only some cases would be included and that would cause aggrupation of solutions.

After exploring possibilities of CMG software package CEDIT was used to create simple algorithm for generation of random tables inside of master file. In this study, following algorithm based on interpolation between worst, base and best case was introduced in masters file. MC generates parameter x, which is representing curve in range between worst and best case and based on the value of x, curve is generated with interpolation.

IF x < 1

THEN worst_case_value· (1-x) + base_case_value·x

ELSE base_case_value· (2-x) + best_case_value· (x-1)

On this way new tables are generated in every new experiment, tables are physically valid and are within given ranges. Normal distribution was given for parameter x for range 0 to 2. 0 is representing worst case curve, 1 is base case curve and 2 is best case curve. In case that number is less than 1 interpolation would be between worst and base case and in case of number bigger than 1 interpolation would be between base and best case.

Due to insufficient data statistical distribution was based on experience. Probabilities for curve occurrence between worst and base case (interval 0-1) and between base and best case (interval 1-2) were given quantitatively (e.g. 60 % that will go to best case side, 40 % that will go to worst case side). Mean value and standard deviation are then adjusted by the ratio of probability in interval 1 – 2 to interval 0 – 1 with limitation on normal distribution truncation of 10 %. By changing mean value and standard deviation distribution is shifted to objective side (Figure 6-1).

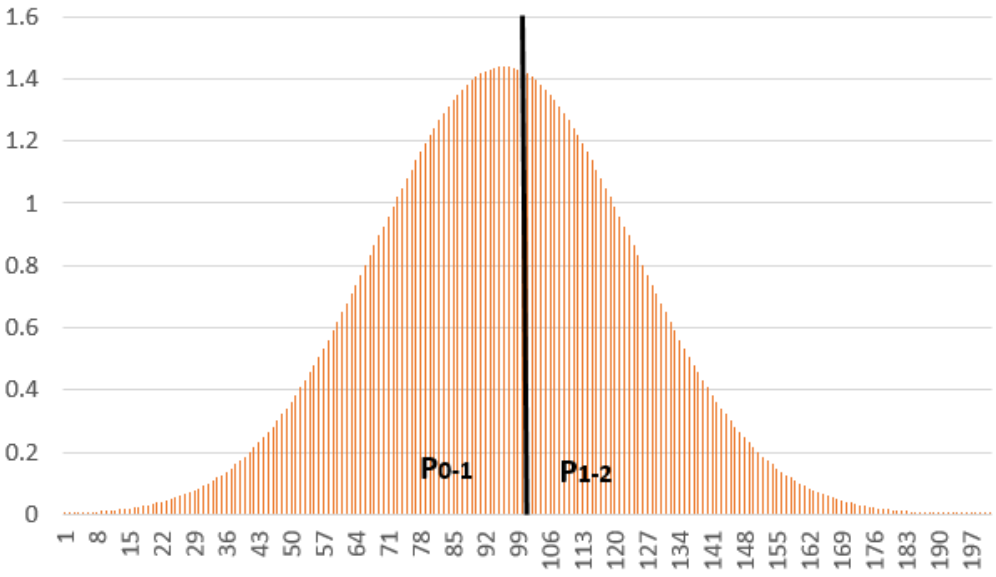


Figure 6-1 Example of normal distribution for interpolation parameter

Probabilities are read from Z – table (Figure 6-2). Where Z is given by formula:

$$Z = \frac{x-\psi}{\sigma} \tag{6-1}$$

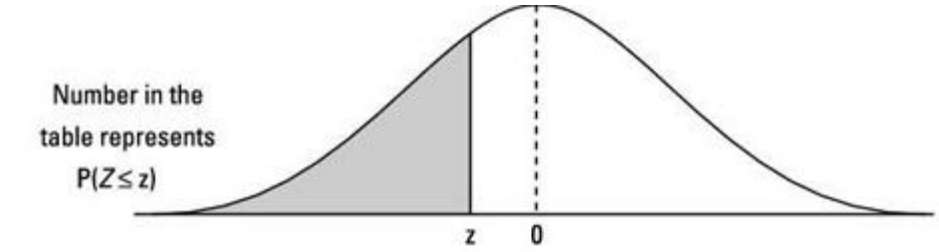
Where

Z – z value (-)

x – value (-)

ψ - mean value (-)

σ - standard deviation (-)



z	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
-3.6	.0002	.0002	.0001	.0001	.0001	.0001	.0001	.0001	.0001	.0001
-3.5	.0002	.0002	.0002	.0002	.0002	.0002	.0002	.0002	.0002	.0002
-3.4	.0003	.0003	.0003	.0003	.0003	.0003	.0003	.0003	.0003	.0002
-3.3	.0005	.0005	.0005	.0004	.0004	.0004	.0004	.0004	.0004	.0003
-3.2	.0007	.0007	.0006	.0006	.0006	.0006	.0006	.0005	.0005	.0005

Figure 6-2 Part of z table (dummies.com)

Another issue was different endpoints of worst, base and best case for relative permeabilities and how much the way of extrapolation would affect final results. Three cases were run, the one that kept original endpoint, the one that had extrapolated trendline until new endpoint and the one that had approximately same relative permeability until new endpoint (Figure 6-3).

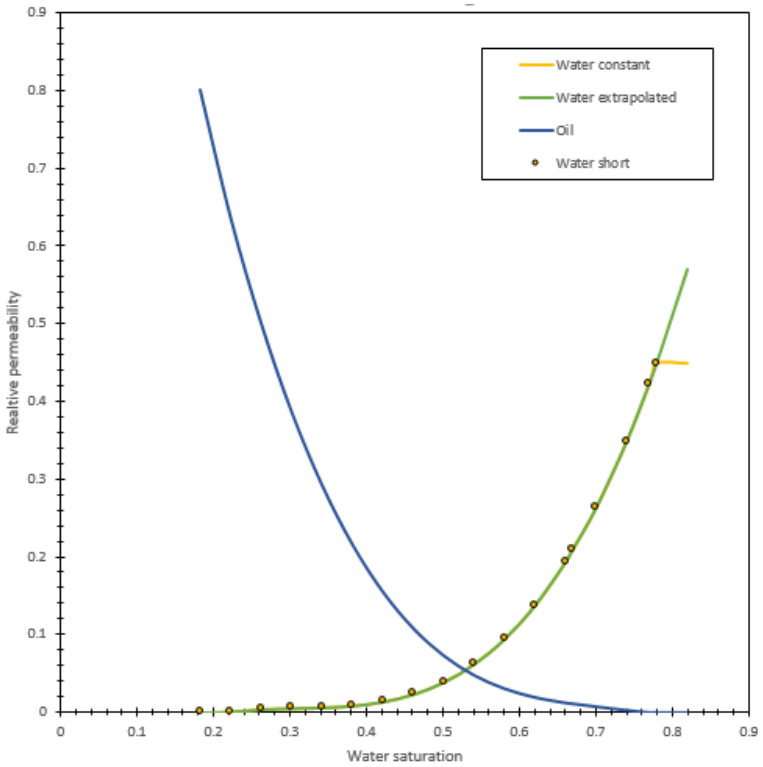


Figure 6-3 Relative permeabilities with different endpoint realization

Simulation results showed that difference in final cumulative oil production for "NEW PRODUCER 1" will be 0.1 % while there will be no difference in "PRODUCER 2" (Figure 6-4). It can be concluded that this part of the curve is reached in simulation due to slight change in simulation cases but is not affecting production a lot due to almost negligible relative permeability for oil in this range of saturations.

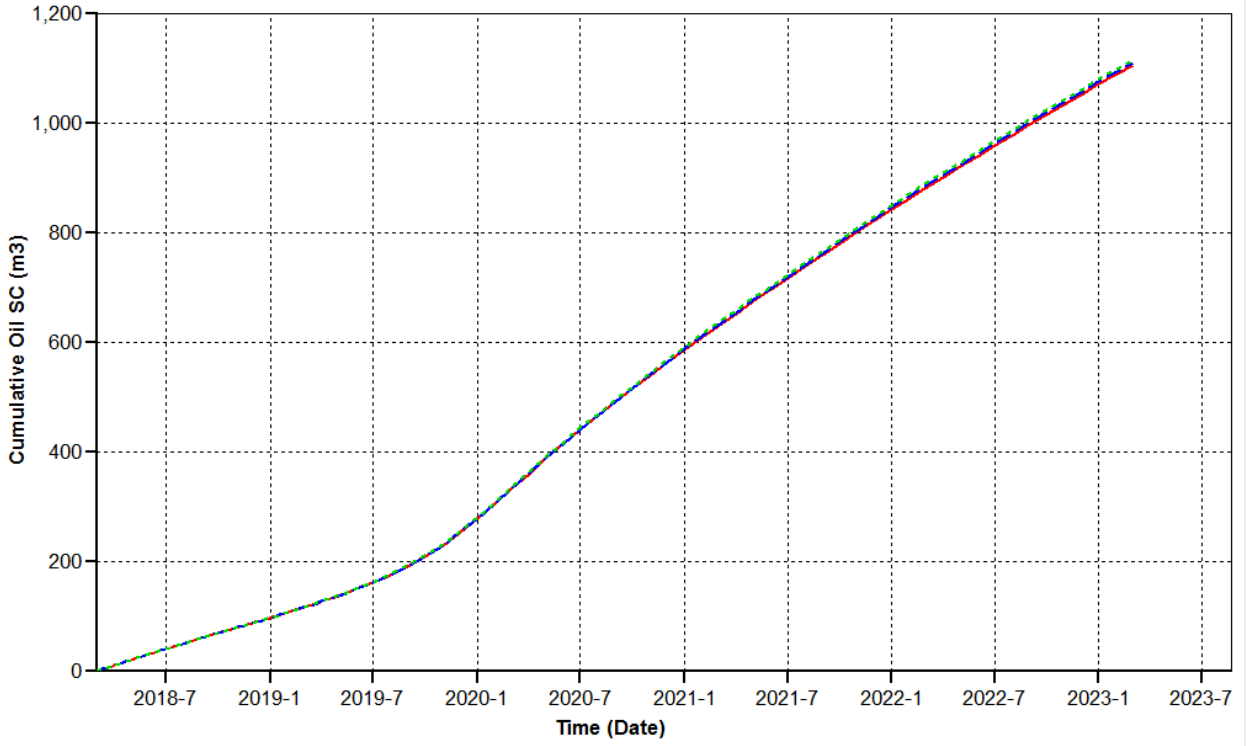


Figure 6-4 Cumulative oil production for different realizations of water relative permeability

After solving all related technical challenges uncertainty assessment was run. Relative permeabilities, water viscosity in dependence of shear rate, rock resistivity factor and CO_2 viscosity mixing functions were parameters used in uncertainty assessment. Best, base and worst case were given, and statistical distributions were adjusted based on experience (Table 6-1).

Table 6-1 Uncertainty assessment parameters

Effect	Min	Max	Mean	Standard deviation	Probability ratio P12/P01
Wettability alteration (varC)	0	2	0.927	0.4	0.67
Water viscosity increase (varB)	0	2	1	0.5	1
Oil viscosity reduction (varA)	0	2	1.07	0.4	1.5
Permeability reduction (RRFT 3, 4, 5)	1.33 2 2.51	2.27 3.5 4.57	2 3 4	0.18 0.32 0.3	X X X

Obtained results showed that cumulative oil in "NEW PRODUCER 1" could be in interval between 675.99 and 1248 m3 (Figure 6-5).

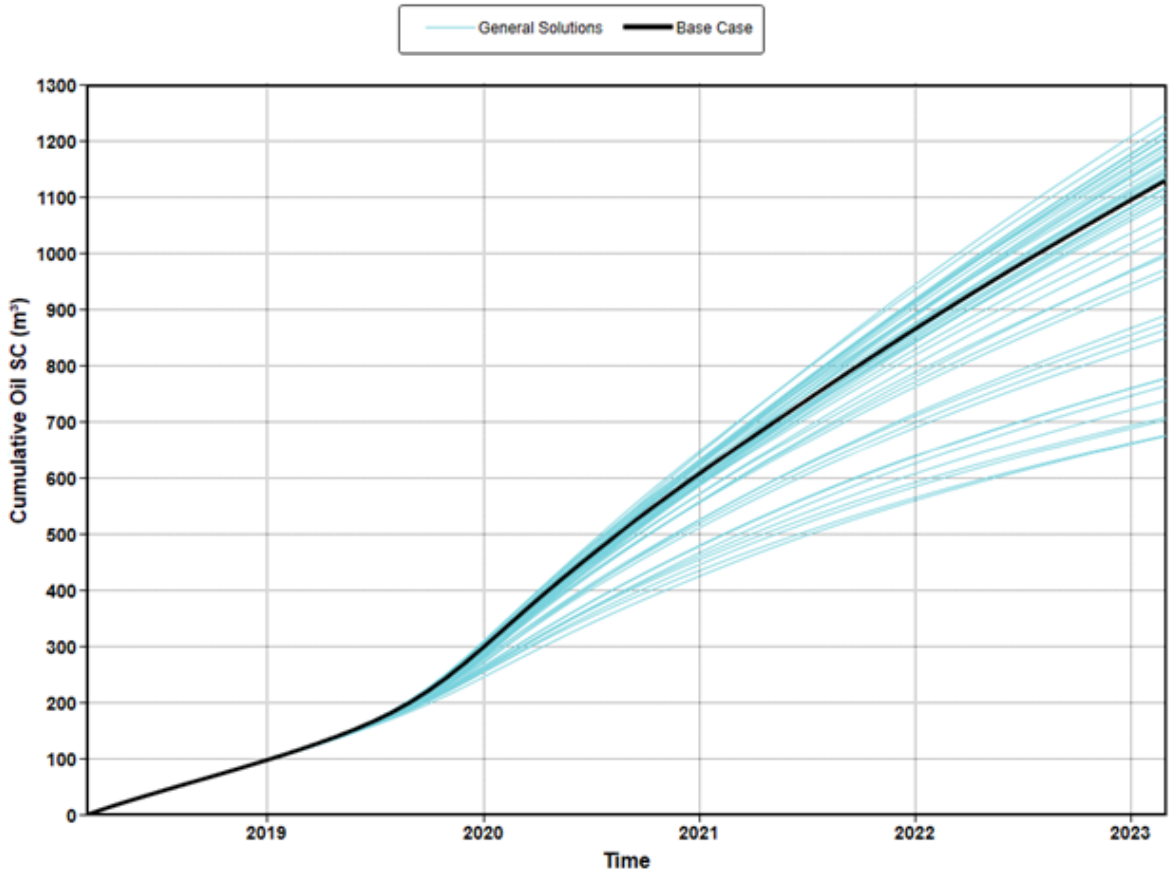


Figure 6-5 Cumulative oil production for "NEW PRODUCER 1"

Based on 65000 cases that were created by proxy analysis it can be seen there is higher probability that result will be closer to higher predictions. P10 percentile is 904 m^3, P50 percentile is 1077 m^3 and P90 percentile is 1181 m^3 (Figure 6-6).

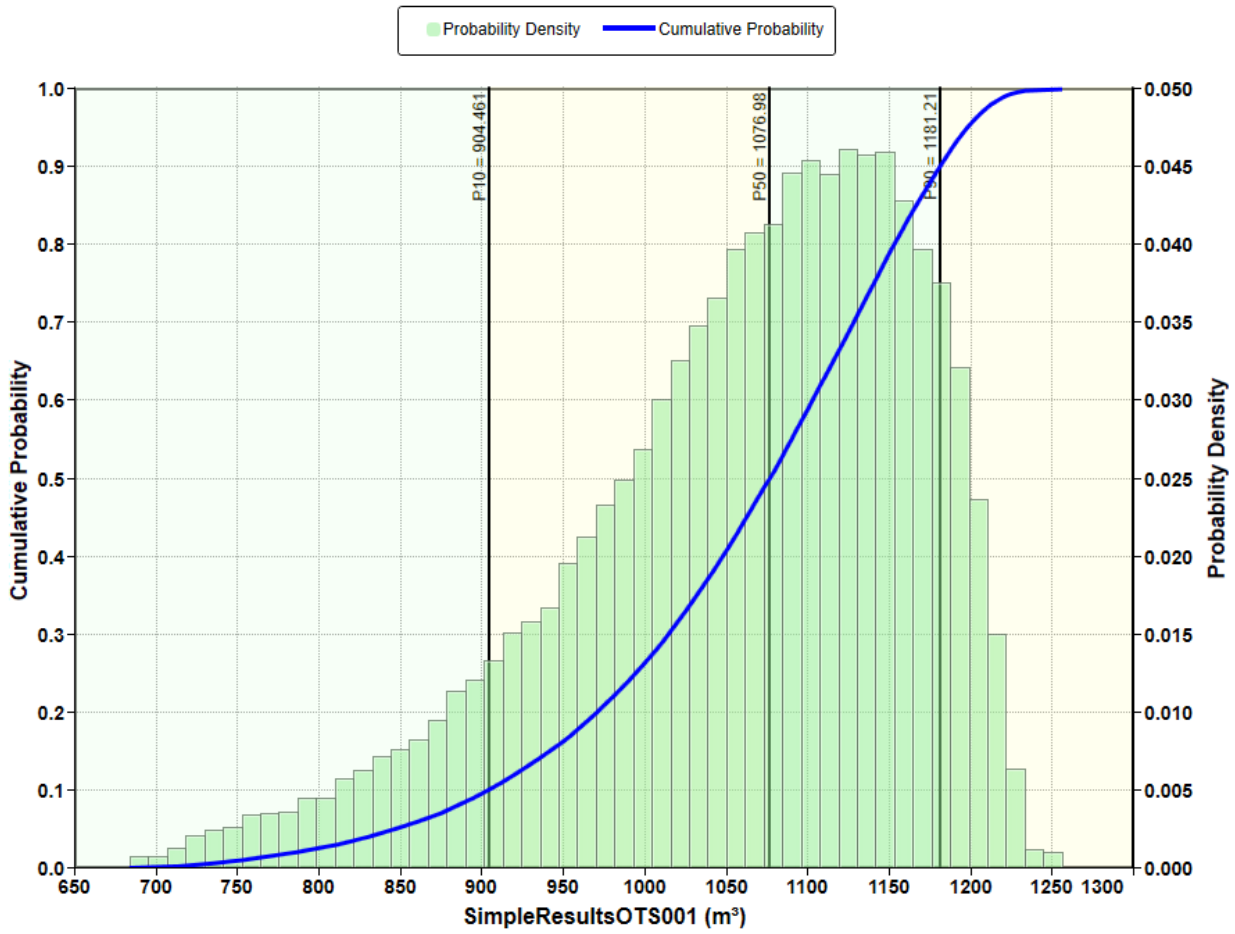


Figure 6-6 Statistical distribution of cumulative oil production for "NEW PRODUCER 1"

Also, the results for "PRODUCER 2" were obtained, cumulative production was between 4913, 6 and 5061.77 m^3. P10 percentile is 5017 m^3, P50 percentile is 5037 m^3 and P90 percentile is 5052 m^3 (Figure 6-7 and 6-8).

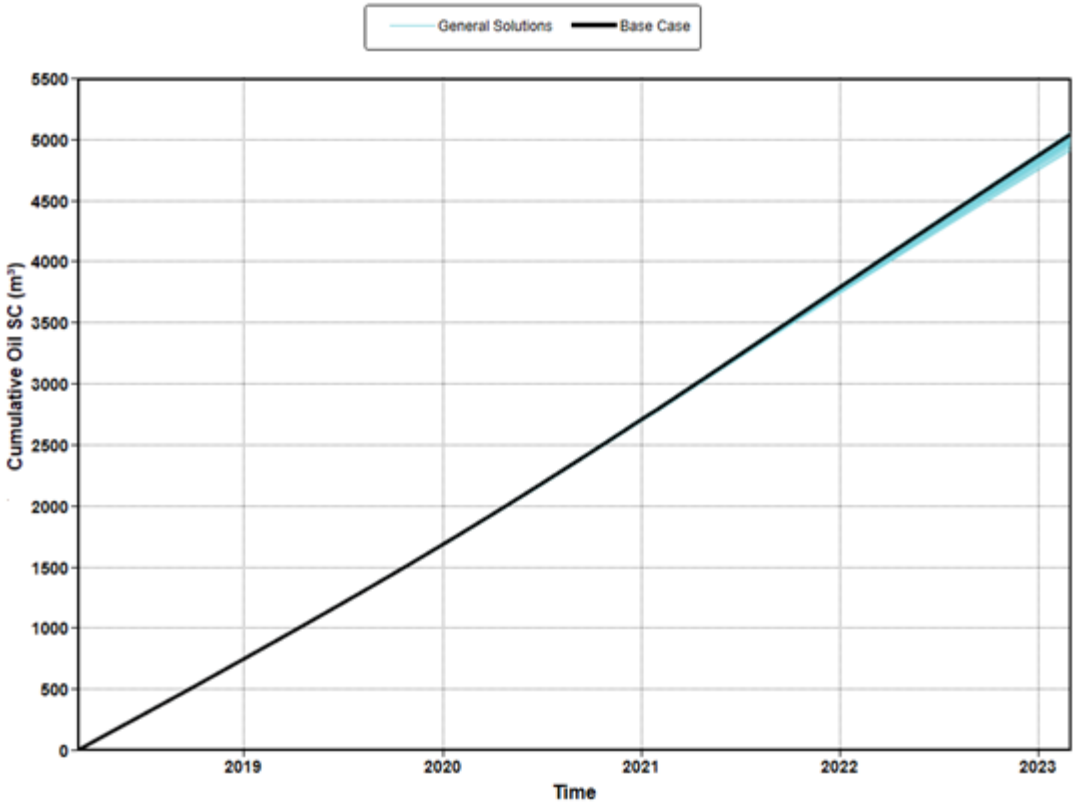


Figure 6-7 Cumulative oil production for "PRODUCER 2"

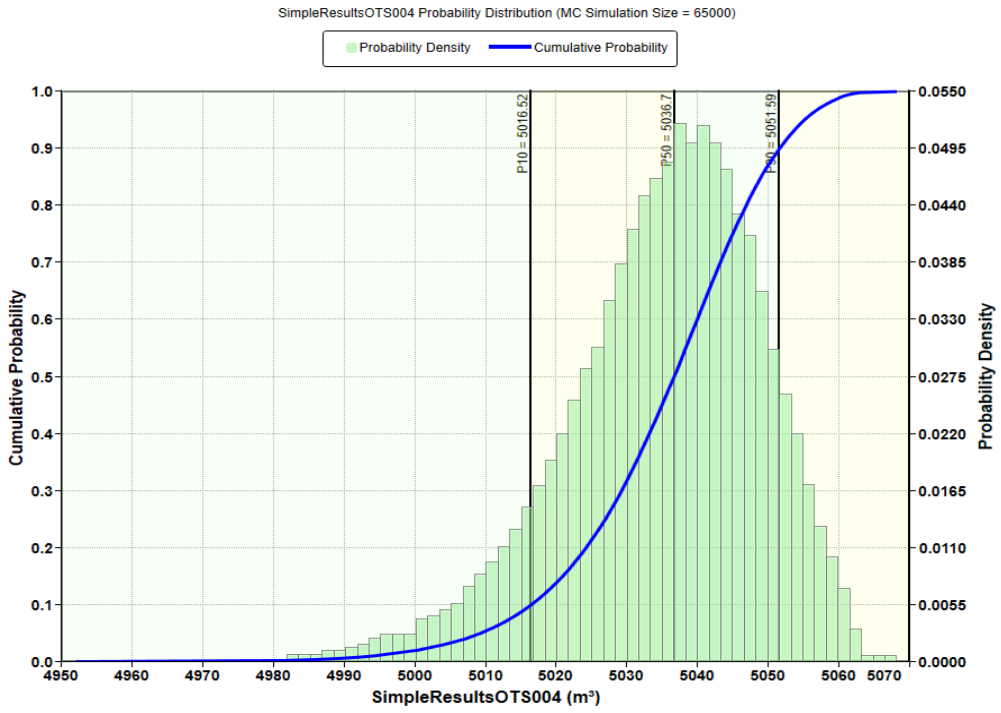


Figure 6-8 Statistical distribution of cumulative oil production for "PRODUCER 2"

As it can be observed variations in cumulative oil are much higher in closer well. This is because of bigger impact of wettability change in this area due to different rock types distribution. To investigate the relevance of each effect a Sobol analysis was conducted. The Sobol method is powerful in quantifying the relative importance of input factors as well as their interactions and effect on output. As it can be seen from Sobol analysis in "PRODUCER 2" dominant effect is permeability reduction while in "NEW PRODUCER 1" main effect was wettability change with over 95 percent of the contribution to incremental oil production (Figure 6-9).

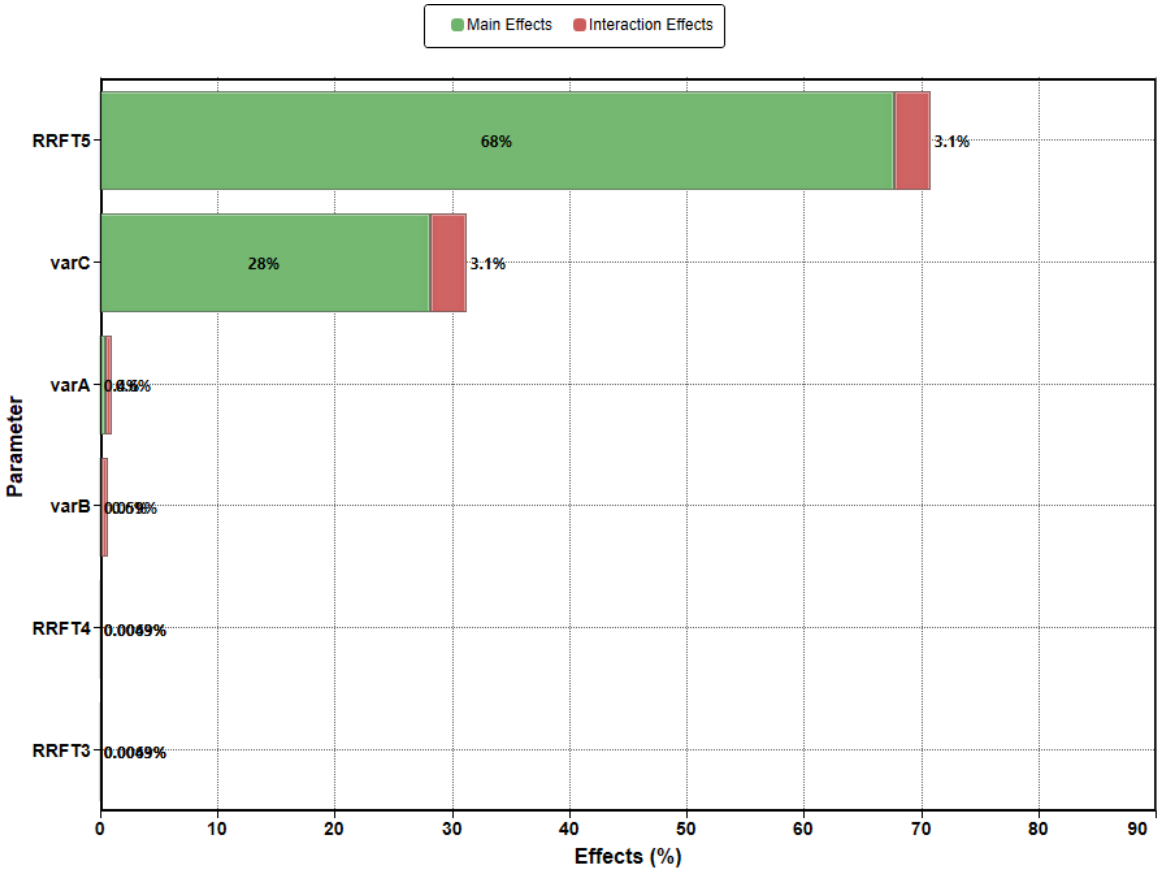


Figure 6-9 Sobol analysis for "PRODUCER 2"

7 CONCLUSION

This work showed that matching bacteria growth, nutrient consumption and metabolite generation at static conditions (batch experiment) with CMG STARS chemical reaction kinetics module is possible and that good match can be obtained.

Regressed matching parameters were used as input data for sand pack experiment and attempts to match components amounts were done. Occurred modelling challenges in terms of kinetics module in combination with bacteria retention and transport were presented, and simplistic approach was introduced.

Theoretical background on MEOR effects was given and modelling of MEOR effects in commercial simulator CMG STARS has been discussed. It is shown that MEOR effects can be modelled in terms of:

- wettability alteration,
- selective plugging,
- oil viscosity reduction and
- water viscosity increase.

Established workflow for generating physically valid random realizations of table parameters in Monte Carlo technique and creating appropriate statistical distribution based on probability ratio was described. After Monte Carlo simulation was performed, probability distributions for objective functions were obtained. Obtained results can be used in further analysis and estimates of project risks assessments for calculating net present value.

Field pilot is currently active and, after obtaining production results, workflows from this thesis and previous ones (Be 2018, Bueltemeier 2014, Gaich 2016) will be evaluated, tuned and implemented.

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IZJAVA

Izjavljujem da sam diplomski rad izradio samostalno na temelju znanja i vještina stečenih na Rudarsko-geološko-naftnom fakultetu Sveučilišta u Zagrebu i uz korištenje navedene literature.

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