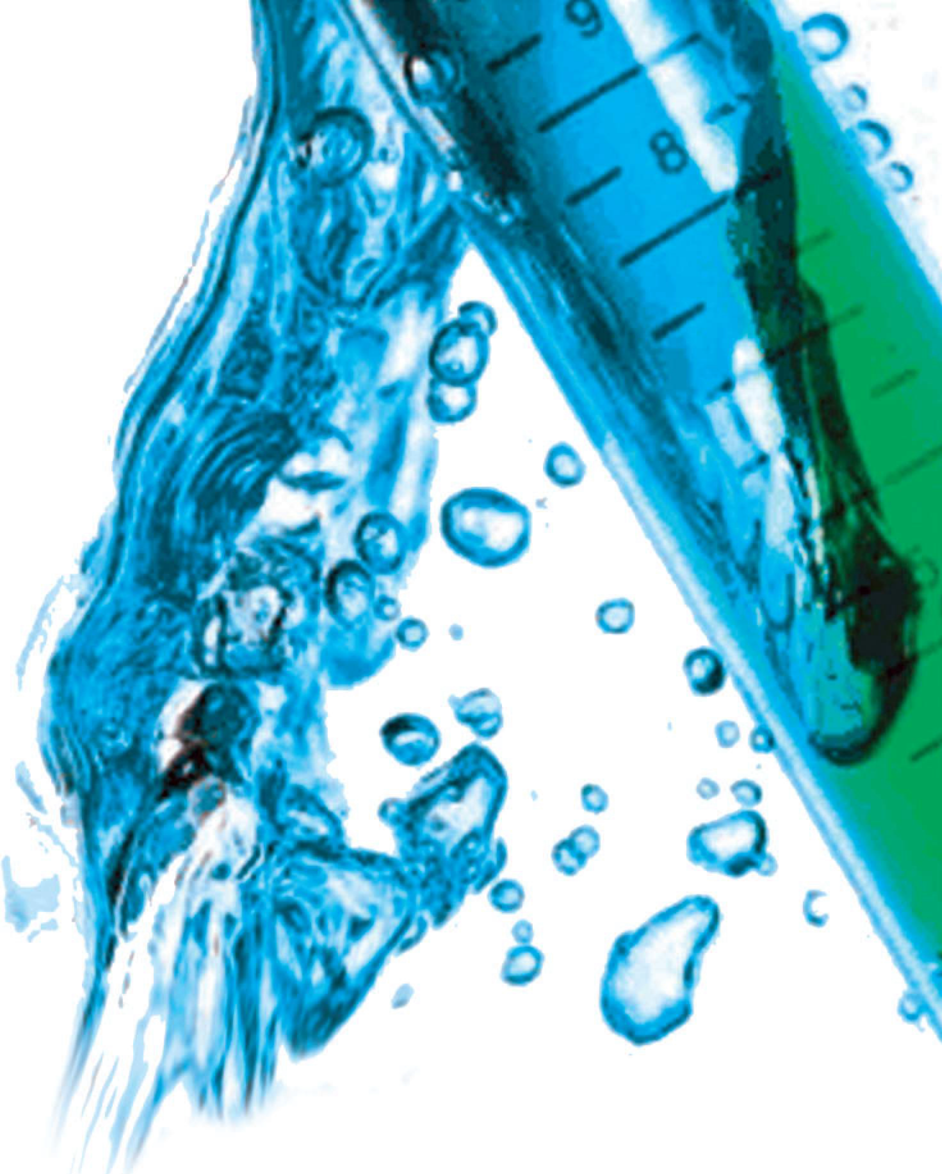
AALBORG UNIVERSITY
STUDENT REPORT



Smart Water

Master degree in oil and gas technology
10th Semester
K10OG-4-F15

Supervisors:

Erik Gydesen Søgaard	Muhammad Adeel Nasser Sohal
Professor	PhD Fellow

Author:

Alireza Pourimani

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Preface

This project is the core of the 10th semester for the students studying MSc Oil and Gas Technology in Aalborg University Esbjerg and is about Smart water or waterflooding in enhance oil recovery and also investigate this issue that Smart water will change wettability and surfactant will decrease IFT (may also change wettability) in this way both effects will play a role to recover additional oil.

This project has divided to three different parts that in first part attempts to investigate, analyze and evaluate Smart water method and different surfactants.

In second part that is data analyzing, has been used data from labratory and evaluate them in order to use them in process simulation.

The third part is about Process simulating and using UTCHEM software for simulation of smart water system.

In this project tried to explain all process and definitions in simple way and everybody with having general knowledge about engineering, could understand that.

All calculations and units are based on SI system.

Title of project: Smart water;

Study field: Master Degree in Oil and Gas Technology, 10th semester;

Supervisors: Professor Erik Gydesen Søgaard ;

Ass. Professor Naser Muhammad AdeelSohail

Submission date: 15th of June 2015

Alireza Pourimani

……………………………….

Acknowledgement

I kindly express my gratitude towards my supervisors Erik and Adeel for their professional advices and guidance through the whole semester as well as their helpful lectures in chemical science and reservoir management.

Special thanks to Dorte from Aalborg university’s laboratory for her helpful guidance and descriptions.

And at the end, my regards to my family and my classmates for their helps and their kindly supports.

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1.1 Project introduction

The project is about introducing Smart water technology by investigating the method of enhance oil recovery. The ultimate objectivity in the project is to use Smart water method with a surfactant and changing wettability and IFT to recover maximum oil.

Smart water or water flooding is an interesting solution in oil and gas field, as companies are making research about it - whether it is a suitable way or not. The most important factor in this topic is the price of this technology, as companies want the cheapest solution when using surfactants and injections in reservoirs.

This project is a master thesis for a student studying MSc Oil and Gas Technology at Aalborg University in Esbjerg. The composition of the well describes its function, as well as the pressure, temperature, and mass flow. All written numbers and data is from the laboratory or from books. While working in the laboratory all calculations are in realistic conditions.

The learning objectives are as follows:

- To understand the Smart water process and Surfactants
- The ability to analyze and simulate the system

1.2 Problem definition

At the beginning, the main problem has to be considered and how it can be solved. What is Smart water and how can it be used in oil recovery, as well as, which types of surfactants are suitable and to analyze the final result.

In Enhance Oil Recovery (EOR) the main goal is to increase oil extraction from reservoirs, where there are several and different methods that can be functional, which are under investigation. EOR uses Smart water or water flooding to replace oil between rocks and stones by injecting one chemical liquid called surfactants in the oil field, which mixes together with water. The used surfactants in this method are different, as they have different parameters, and the selected surfactants have to be evaluated, whether it is suitable or not, and is it logical or not. To answering these questions, different kind of surfactants will be investigated based on the projects condition.

Different factors will be analyzed when the theoretical and practical investigation is done with the result from the laboratory and different experiments. This project will simulate and evaluate the UTCHEM software.

Other key aspects are:

- To investigate Smart water and surfactants
- Analysis of data (data is given from experiments)
- Modeling of process in UTCHEM program.

The aim in this project is to answer above questions and investigate Smart water technology in the best condition.

2. Enhanced Oil Recovery (EOR)

Enhanced oil recovery (curtailed EOR) is the use of a few strategies for expanding the measure of unrefined oil from an oil field.

As indicated by the US Department of Energy, there are three essential systems for EOR that are chemical injection, gas injection and thermal recovery.

Infrequently the term quaternary recovery is utilized to indicate to more theoretical, progressed, EOR systems. Utilizing EOR, 30 to 60 percent, or more, of the supply's unique oil can be extracted, in comparison with 20 percentage using primary recovery and 40-percentage secondary recovery. [Ref 1]

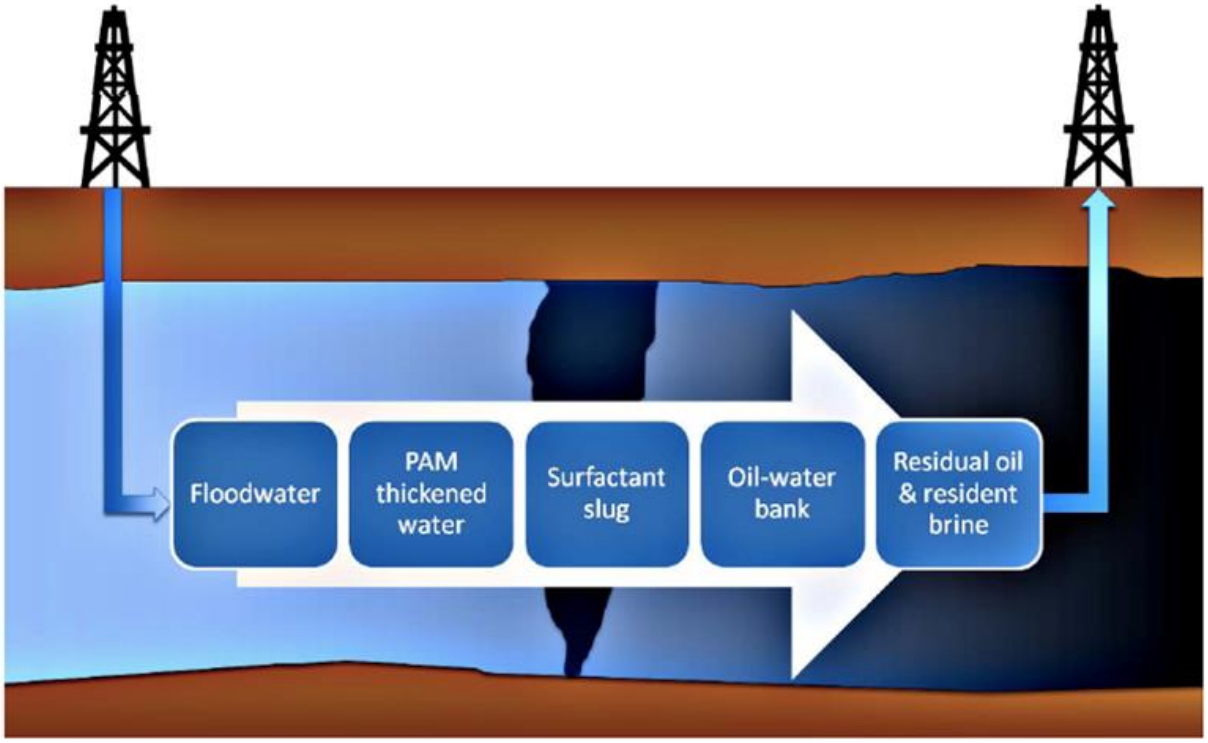


Figure 1 Enhanced Oil Recovery [Ref 2]

2.1 Techniques

As specified some time recently, there are three essential systems of EOR: chemical injection, gas injection and thermal recovery. Chemical injection, that can include the utilization of long-chained molecules titled polymers to rise the efficiency of waterfloods, can increment around one percent of EOR creation in the United States.

Gas injection, that uses gasses, for example, nitrogen, common gas or carbon dioxide (CO2), can build oil recovery producing almost 60 percent and Thermal recovery, that includes the presentation of warmth, expand oil recovery producing 40 percent.

In 2013, a strategy called Plasma-Pulse innovation was demonstrated into the United States from Russia. This procedure can rise oil recovery around 50 percent.

2.1.1 Chemical injection

This technique typically use for decline surface tension and release mobility and for applying, different chemicals and usually with dilute solutions.

With adding a dilute solution of a water-soluble polymer that can increase the viscosity of the injected water, we can increase the amount of oil recovery in some structure. Dilute solutions of bio surfactants such as rhamnolipids of surfactants such as petroleum sulfonates can be injected to lower the interfacial tension or capillary pressure that postponements oil droplets from moving through a reservoir.

Special constructions of water, oil, and surfactant, micro emulsions may be predominantly effective in this.

Generally, the critical factor in this application is cost. Each reservoir based on their formation and properties, have different absorption and this factor can play an important role in absorb or retain of surfactant. This problem cause to increase using of surfactants and it is not economy and suitable for companies. [Ref 1]

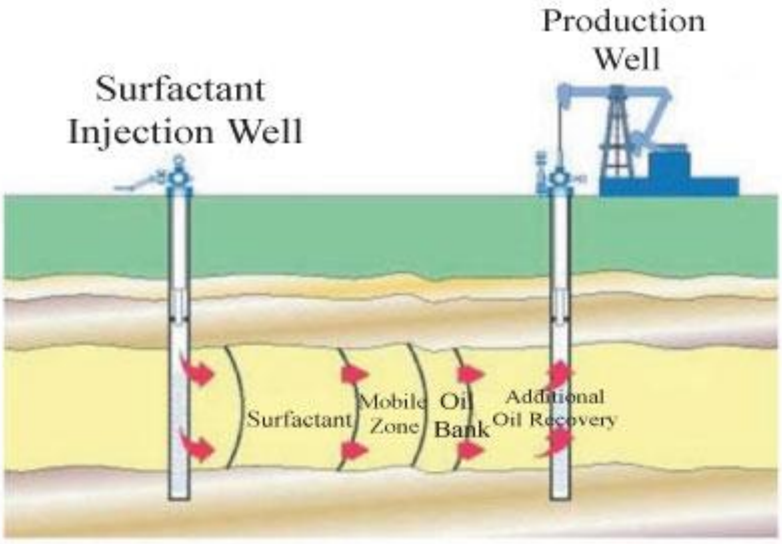


Figure 2 Chemical injection [Ref 3]

3. Waterflooding

This technology refer to use of water injection for increase of oil producing from reservoirs. This method also call secondary recovery and usually come after primary production and it done due to produce oil with use natural energy of reservoir (solution-gas drive, aquifer influx fluid, rock expansion, and gravity drainage). [Ref 4]

3.1 Rationale for waterflooding

As said before, the main reason of using water flooding is to increase of oil production. This is complete by "voidage substitution"—inject of water to expand the pressure to its starting level and keep up it close to that pressure. This water displaces oil from the pore spaces, but the effectiveness of this displacement is related to several parameters such as rock formation and structure and viscosity.

In oil fields (this project =North Sea), voidage replacement additionally has been utilized to direct extra surface diving. [Ref 4]

3.2 History

Salty water or brine was in the beginning of oil industry often produced from a well together with oil, the oil production decreased, as the rate of water production would grow. Usually, the water was set by putting it into nearby streams or rivers. The practice began in the 1920's by reinjections of the made water into porous and permeable subsurface formations, as well as the reservoir interval where the oil and water in the beginning came from. Reinjections of produced water had become a common oilfield practice by the 1930's.

The first reinjection of water happened in the Bradford oil field of Pennsylvania, Us, where the ''circle-flood'' was replaced with a ''line flood,'' and besides the ''line flood'' a ''five-spot'' well layout was used as well in the 1920's. In the production of wells, the two rows that were put on both sides of an equally spaced row of water-injection wells.

Water flooding technology and common practice is mostly established in America by 1940 and 1970. The onshore American oil industry was maturing by the 1940's, where the main production from its reservoirs had weakened severely, however, anywhere else in the world most reservoirs were in an early stage of main production. In America, drilling of closely spaced wells had been made too, to make the effects of water injections more significant.

The need of positioning the produced salty water alongside with oil, made water flooding a method that is reasonable and economical for growing recovery from oil fields. It was early noticed, that in most reservoirs the original oil in place (OOIP) was recovered in small percentage due to the main production period, which is caused by the depletion of the reservoirs' natural energy. The large quantity of oil that remained needed to be produced by a recovery method. The early success of water injections helped improve the oil-production period, as water flooding became the natural way to regain additional oil from reservoirs.

By water flooding's development, water becomes low-priced, as water is available from streams, rivers, oceans, and from wells drilled into aquifers. It is scientifically proved, that water has viscosity, density, and wetting properties because of the success by water flooding. As water flooding was the logical recovery process for most onshore oil fields in America, Russia, and China, some American offshore oil fields, as elsewhere in the world, were getting water injection. From the 1970's, many significant water-injection projects have been applied to oil reservoirs all over the world. [Ref 4]

3.3 Waterflooding considerations

Water displaces oil by unit displacement efficiency from a porous and permeable rock on a microscopic scale. At this level of analysis, it is most functional when water, oil, and flow measurements are made in laboratory on a small core-plug samples. To determine how good the water flooding will work, calculations of the effects of geology, gravity, and geometry must be included. The formula for complete water flood oil-recovery efficiency, where E_R is the product of three independent terms: [Ref 4]

$$E_R = E_D E_I E_A.$$

That

- E_D = the unit-displacement efficiency,
- E_I = the vertical-displacement efficiency,
- E_A = the areal-displacement efficiency.

However, the independence of these factors assumes not to be valid for real oil reservoirs.

The importance of technical and financial success of a water flood are oil properties, where the properties are viscosity and density. In a permeable medium, the fluids mobility is defined by its endpoint that is relative permeability divided by its viscosity. Therefore, a fluid with a low viscosity (≤ 1 cp) has a high mobility, though, if its relative permeability is very low. Likewise, a low-API crude oil (≤ 20°API) has a high viscosity and a very low mobility unless it is heated to high temperatures.

The temperature of waters viscosity is usually much lower or equal to the oil reservoir, where the ratio of water and oil viscosity is usually greater than 1:1. The ratio of water and oil mobility is important to the efficiency of the water/oil displacement process, as the recovery efficiency increases, the water/oil mobility ratio decreases.

More details about oil replacement by water injection are:

- Vertical displacement in a waterflood
- Macroscopic displacement efficiency of a linear waterflood
- Microscopic efficiency of waterflooding
- Areal displacement in a waterflood

3.4 Reservoir geology considerations

When evaluating a water flooding project, it is important to understand the reservoir rocks, and to reach this understanding it is by knowing the depositional environment at the pore and reservoir levels, perhaps also levels in between. The determination of the digenetic history of the rocks, then the determination of the structure, and the criticism of the reservoir to understand the interconnectivities among different parts of the reservoir – in particular the injector/producer connectivity. At the end, the characterization of water, oil, and rocks is needed to understand due to their control of wettability, residual oil saturation to water flooding, as well as the relative permeability of oil at higher saturations. Therefore, there should always be in the water flood evaluation team a developmental geologist.

The main geological evaluation in water flooding is to evaluate the nature and degree of heterogeneities that are in an exact oil field, as oil reservoirs are all heterogeneous rock formations, which can take many forms as in shale, anhydrite, or other impermeable layers. Interbedded hydrocarbon-bearing layers that have different rock qualities such as sandstones and carbonates, changing continuity, and environmental or digenetic changes that is caused by directional permeability trends. Fracture trends that developed due to regional tectonic stresses on the rock and the effects of burial and uplift on the particular rock layer. Fault trends that cause the connection of one part of an oil reservoir to adjacent areas, because they are either flow barriers or open conduits that allow unlimited flow along the fault plane. [Ref 4]

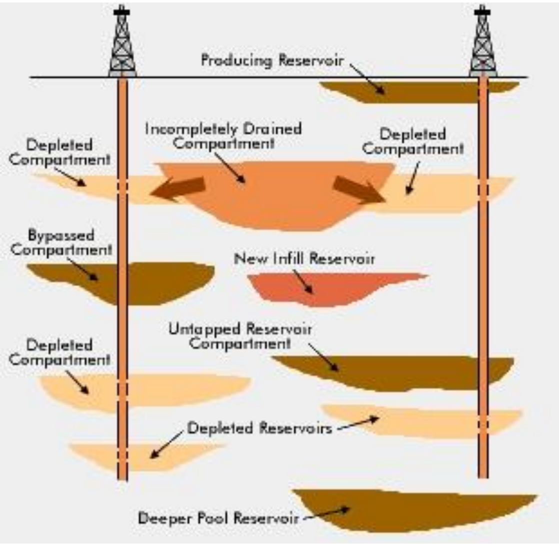


Figure 3 Reservoir geology [Ref 5]

A geological consideration is the structure of the reservoir, as well as how it affects the water flood process, because as the structure creates dipping beds at different angles, the interaction between the bed angle, gravity, and the oil/brine density. Furthermore, it affects the behavior of the relative vertical and horizontal flow. What can also be included is the structural thoughts whether the oil column has a primary aquifer or a covering gas cap – both can affect the probability of success in water flooding.

A technical team such as geologists and geophysicists must take into consideration such geological and structural aspects of a reservoir. To understand depositional environment and post-depositional digenesis, geologists use cores and routine-core-analysis data, where geologists are able to describe the reservoir's internal construction. Geophysicists use seismic data to distinguish between faults and trends in rock quality.

When using water flood, it is required to describe the quantitative evaluation, as well as different approaches may be used. The concept of the ''flow unit'' is how the volume of reservoir rocks affect the fluid flow, whether it is consistent or different from other rock volumes.

The evaluation process starts when a reservoir has been revealed, then a water flood will be initiated. The production and injection data will show the internal features of the rock volume that has been flooded, however, the data is critical, because the data relate to the interwell connectivity within reservoir, which either validates or causes change of the geoscientists' concepts.

Tracers can be injected during water flood to track injector/producer pairs. Other techniques include the use of specially drilled observation wells and 4D-seismic interpretations in order to track the way and shape of the higher-pressure water swept reservoir areas – they are centered on the injection wells.

3.5 Limitations of waterflood technology

By using water flooding, it can increase the volume of oil recovered from a reservoir, but it is not always the best solution, which can lead to confusing factors such as compatibility of the planned injected water with the reservoir's connate water, interaction between injected water and reservoir rock, removed oxygen, bacteria, and undesirable chemicals, and occurrence of radioactive materials. When producing a best oil reservoir, a petroleum engineer should take into consideration, that the water flooding should be analyzed in various ways such as technically and economically. [Ref 4]

3.6 Key points concerning waterflooding [Ref 4]

- Waterflooding is a common method in oil enhance recovery because water is low-cost and almost available in large volume and based on experiences because water is very effective at substantially, is very suitable for EOR and increase oil recovery.
- The efficiency of waterflooding depend on mobility ratio between water and oil and geology of the oil reservoir. Most of the time Waterflooding is effective and efficient because almost all reservoir rocks are either mixed-wet or water-wet. The depositional and diagenetic characteristics of a reservoir regulate major aspects of the oil/water transposition process. These characteristics can increase waterflood performance or have damaging effects on the WOR during the time. Frequently, the details of a reservoir’s geology are not known till production wells start to produce injected water.
- Gravity effects that interplay between the density and gravity effects and the geologic layering of a reservoir. This parameter is important in waterflood because at reservoir circumstances, oil always is less dense than brine or injected water. This interplay can either hurt or help to waterflood performance comparative to a homogeneous system.
- Waterflooding is a process that characteristically takes several decades to complete. Therefore, continuous, routine field production and pressure data must be taken for analyzing and monitoring waterflood performance. There are opportunities to modify the original waterflood design and operating strategies based on analysis of the actual field production data. Sometimes, more expensive, special-data acquisition programs (3D- or 4D-seismic data) are run to support the evaluation process. A diversity of engineering tools have been established to analyze waterflood performance, extending from simple plots of field production data to full-field numerical-reservoir-simulation models.
- Waterflood can be modify and with the waterflooded intervals, changing the distribution of injection water among the injection wells and drilling additional wells at infill locations, and/or modifying the pattern style.
- Waterflooding can be used in offshore and onshore all over the world in different fields with different sizes.

4. Waterflooding in carbonate reservoirs [Ref 6]

Waterflooding contains the use of water injecting to relocate oil in a reservoir. Usually, oil recovery with refining volumetric sweep productivity via a variety of techniques and practices, containing in-fill drilling, improved reservoir description, high resolution reservoir simulation, advanced surveillance and monitoring and multidimensional wells.

Currently About 50% of world’s known oil reservoirs are carbonate.

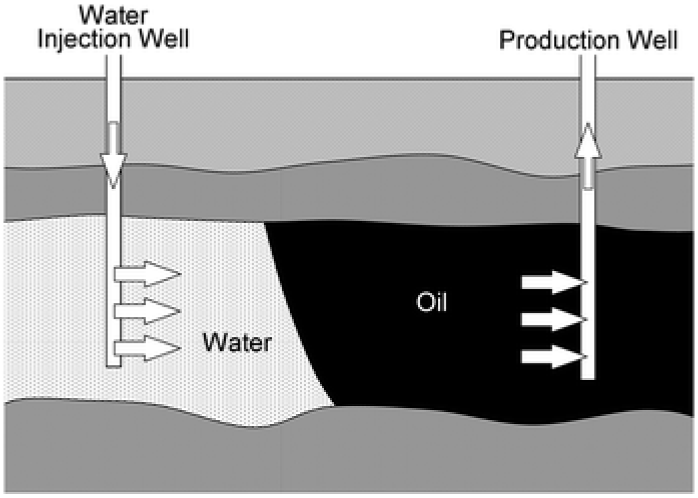


Figure 4 Waterflooding [Ref 7]

4.1 Considerations

In carbonate reservoir, whenever waterflooding is main considerationThe all factors and affected aspects should be evaluate.

Some Factors are constant and some of them are not changeable and also there are some properties that come from formation and structure of them. Those factors include:

- Permeability
- Wettability
- Porosity
- Contact angle
- Rock properties
- Fluid properties
- Fracture Intensity [Ref 6]

4.2 Water Modifications

As mentioned before, In waterflooding the water relocates oil from the pore spaces, but the efficiency of this displacement depends on several parameters such as rock characteristics and oil viscosity.

Since carbonate surfaces have positive charge, the water must be altered, generally by adjusting the salinity, which will affect the concentration of calcium ions (Ca2+), sulfate ions (SO42-), or magnesium ions (Mg2+).[Ref 6]

4.3 Low Salinity

Researches have found that with low salinity of injected water can change wettability of rock and increase oil recovery but it still is not clear why lower salinity water can do this.

For this issue there are three different theories:

- Rock dissolution:

  Initially proposed by Hiorth et al., this theory clarifies the low-salinity effect by hypothesizing that the lower calcium concentration in low-salinity brine causes calcium carbonate from the rock to dissolve and start equilibrium with the brine. The adsorbed oil components are detached and the rock surface is purified more water-wet, whenever the calcium carbonate dissolves.

- Surface ion exchange:

  At usual carbonate reservoir circumstances, rock surfaces have positive charge whereas the acidic components of oil have a negative charge, causing the rock to be mixed-wet or oil-wet.

  If the determining anions in the water (SO42-) have a higher empathy to the rock surface than the acidic oil components, the anions are adsorbed and the oil is desorbed.

  If the rock surface charge is reduced (because of low salinity), desorption of negative charged oily material is also simplified.

- In-situ surfactant formation:

  The potential of in-situ surfactant generation requires a high pH and Hiorth et al. determined it to be a rare mechanism in waterflooding.

4.4 Advantages and Disadvantages

Advantages:

The main reasons that Waterflooding can be a suitable method for oil recovery are:

- Injected water is efficient to replace oil of light to medium gravity;

- water is easy to inject into oil field formations;
- water is cheap and almost available;
- In some aspects, if we compare waterflooding with other EOR methods it is obvious that maybe is an economic way and operation system is not so expensive.

Disadvantages:

Carbonate reservoir approach a badly-behaved in oil recovery, because about 80% of these geologic developments are oil-wet. In addition, Carboxylic acid anions have negative charged and it has to involve for positive charge in carbonate surfaces, hence producing oil-wet surfaces. As we know, because capillary pressure curves is mostly negative waterflooding cannot be successful in oil recovery. Consequently, surfactant/polymer waterflooding is suitable for some in the business to be a more practical alternative. [Ref 6]

5. Definition of theoretical terms

5.1 Porosity

Porosity is a measure of its capacity to hold a liquid. Numerically, porosity is the free space in a rock or stones divided by the total rock volume (Solid + space or openings).

Porosity is typically characterized as a rate of the total rock, which is taken up by pore space. For instance, a sandstone may have 8% porosity, this implies 92 percent is solid rock and 8 percent is open space containing water, oil or gas. and left 8 percent is about the minimum porosity that is obliged to make a proper oil well, however non-economic wells or poorer have less porosity.

In any case, sandstone is hard and seems extremely strong; it is similar to a wipe (a hard, incompressible wipe). Between the grains of sand, enough space exists to trap liquids like oil or normal gas! The gaps in sandstone are called porosity (from "permeable").[Ref 8]

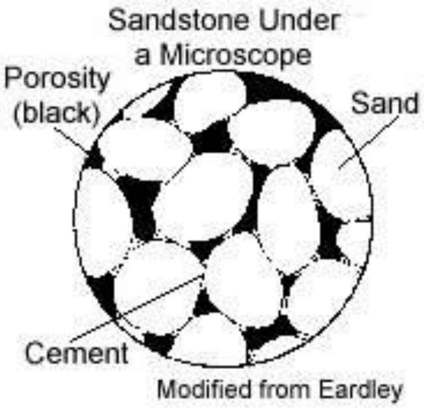


Figure 5 sedimentary-rocks-sandstone-schematic [Ref 9]

The porosity is indicated as dark in the drawing. Gas, water or oil will fill these openings in the rock!

Subsequently, a poor-routed sandstones will have less porosity than a well-rounded one!

A well-rounded sandstone can be more interesting for geologist because these kind of rock can hold more amount of oil and gas!

Porosity (Φ) can be defined:

$$\text{Porosity} = \frac{\text{Pore Volume}}{\text{Total Volume}} = \Phi.$$

Porosity define as a volume proportion so, is dimensionless and is generally reported as a part or percent. To evade disarray, especially when variable or changing porosities are included, it is regularly reported in porosity units (1 PU = 1%).

A few volume definitions are obliged to represent porosity:

Total volume of rock $= V_T$ or V_{rx}
Volume of mineral phase $= V_g$ or V_m
Volume of pores or openings $= V_{\text{por}}$

From these we can characterize the different sorts of porosity experienced:

Total porosity	Φ	$= V_{\text{por}} / V_T$
Effective porosity	Φ_{p-e}	$= V_{p-\text{con}} / V_T$
Ineffective porosity	$\Phi_{p-\text{iso}}$	$= V_{p-\text{iso}} / V_T$
Crack or fracture porosity	Φ_{fx}	$= V_{fx} / V_T$

5.2 Permeability [Ref 10]

The permeability factor in rock is a term that define as resistance to the stream of a liquid through a rock. The rock called low-perm whenever needs lots of pressure for press the fluid through the rock and if liquid goes through the rock effortlessly; its call high-perm or the rock has high permeability.

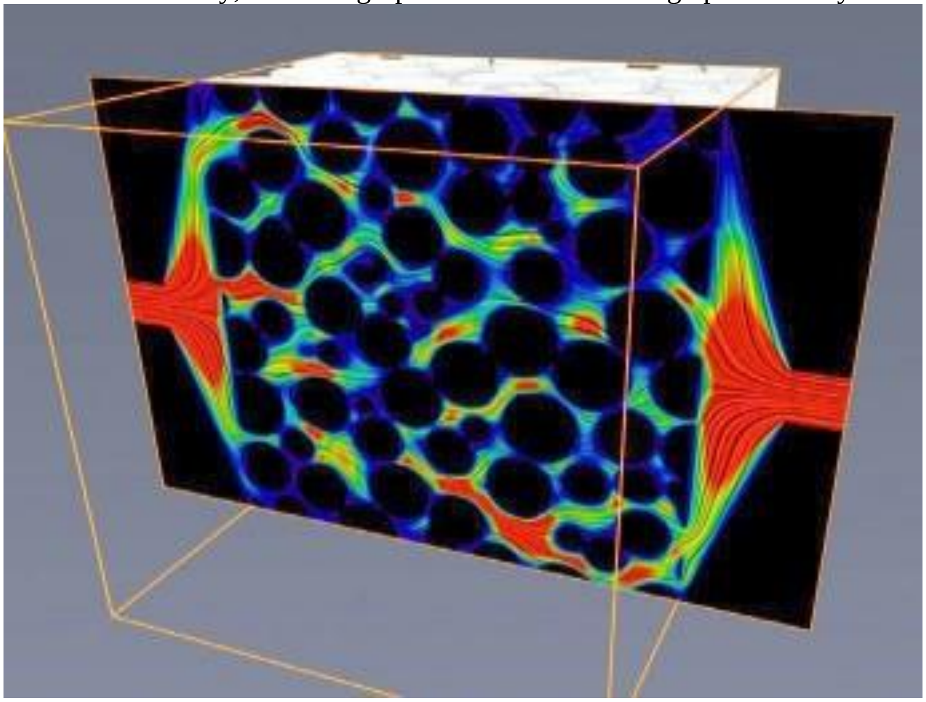


Figure 6 Permeability measures how easily fluid passes through a rock [Ref 11]

In oil production, Permeability expressed by the unit that is millidarcys. One millidarcy is 1/1000 of a Darcy. One Darcy is a high amount of permeability!

Most of reservoirs that can be used for oil and gas production have permeability around ten to several hundred millidarcys.

The increasing amount of US gas production in the last 10 years is coming from shale gas wells that has a big amount of porosity (much more than sandstone), but it has enormously low permeability. Therefore, it means shale is poor producer of hydrocarbons. For over a hundred years, gas has been produced from shale but quantities were small. Allowing for improved shale gas expansion, two things have changed the situation. Based on these concepts, oil and gas companies have been allowed to persuade more permeability into shale gas rock artificially:

- ***Horizontal Drilling*** – The broad adoptance of Horizontal Drilling method, in which the drill bit is made to turn from the vertical to the horizontal (a 90-degree turn), where it can keep to drill horizontally through the structure. The horizontal track can be as much as a mile! [Ref 20]

- ***Advances in Hydraulic Fracturing (fracking)*** – Fracking is not another innovation; it has been around well more than 50 years (regardless of what you may hear on the news). On the other hand, propels in fracking systems in horizontally gaps, especially in shale structure, has prompted a massive increment in shale gas producing. These new methods permit the oil and gas administrator to render low-permeability shale reservoirs more permeable, by artificially bringing little cracks into the structure.

Permeability	Pervious				Semi-Pervious				Impervious				
Unconsolidated Sand & Gravel	Well Sorted Gravel		Well Sorted Sand or Sand & Gravel			Very Fine Sand, Silt, Loess, Loam							
Unconsolidated Clay & Organic					Peat		Layered Clay			Unweathered Clay			
Consolidated Rocks	Highly Fractured Rocks				Oil Reservoir Rocks			Fresh Sandstone		Fresh Limestone, Dolomite		Fresh Granite	
κ (cm^2)	0.001	0.0001	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-10}	10^{-11}	10^{-12}	10^{-13}	10^{-14}	10^{-15}
κ (millidarcy)	10^{+8}	10^{+7}	10^{+6}	10^{+5}	10,000	1,000	100	10	1	0.1	0.01	0.001	0.0001

Source: modified from Bear, 1972

Figure 7 Permeability measures how easily fluid passes through a rock [Ref 12]

Permeability is part of the proportionality constant in Darcy's law. This factor relate to flow rate and physical properties of liquid (viscosity), to a pressure gradient applied to the porous media:

$$v = \frac{\kappa}{\mu}\frac{\Delta P}{\Delta x}$$

Therefore:

$$\kappa = v\frac{\mu \Delta x}{\Delta P}$$

where:

v is the superficial fluid flow velocity through the medium (i.e., the average velocity calculated as if the fluid were the only phase present in the porous medium) (m/s)

κ is the permeability of a medium (m^2)

μ is the dynamic viscosity of the fluid (Pa·s)

ΔP is the applied pressure difference (Pa)

Δx is the thickness of the bed of the porous medium (m)

In normally happening materials, permeability values range over many orders of scale.

5.3 wettability

Wettability can define as tendency of one liquid to spread on, or hold fast to, a solid surface in the vicinity of other immiscible liquids. Wettability refers to the interaction between liquid and solid phases. In a reservoir, solid phase can be the rock mineral accumulation and the fluid phase can be oil, water or gas.

Wettability is all around branded by the contact angle of the liquid with the solid phase.
Interfacial tension (σ) is the energy per unit area (force / distance) at the surface between phases. It is usually expressed in milli Newton / meter or dynes / cm.

Adhesion tension (γ) is expressed as the difference interfacial tensions between two solid and liquid phases.
When γ is negative, that means denser phase (water) better wets the solid surface (and vice versa).
An adhesion tension of 0.0 shows that both phases have equal empathy for the solid surface.

As we know at least 3 groups of forces acting on the fluids whenever 2 or more fluids are present, and it can effect on hydrocarbon recovery.

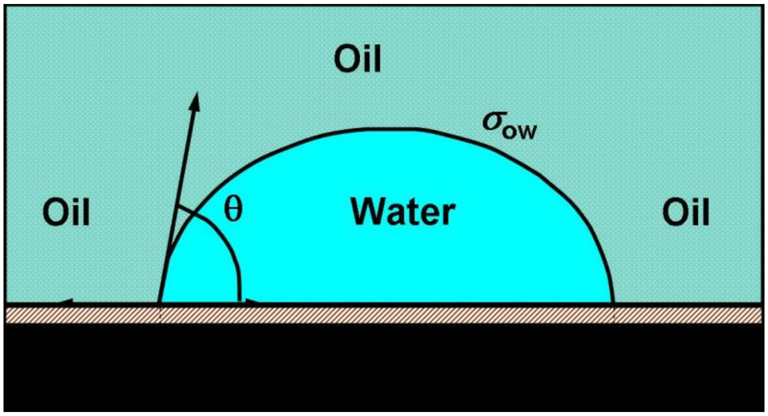


Figure 8 Wettability [Ref 14]

γ = adhesion tension

θ = contact angle between the oil/water/solid interface measured through the water

σ_{OS} = interfacial energy between the oil and solid

σ_{WS} = interfacial energy between the water and solid

σ_{OW} = interfacial energy (interfacial tension) between the oil and water

Attractive forces between fluid and rock draw the wetting phase into slight pores. Wetting phase fluid frequently has low mobility.

Many hydrocarbon reservoirs are either totally or partly water-wet. Attractive forces describe the lower limit to irreducible wetting phase saturation.

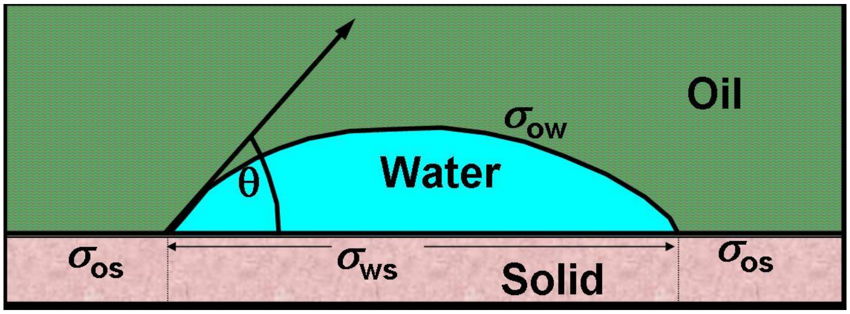


Figure 9 Wettability [Ref 14]

if water better wets the rock surfaces reservoir rock is water wet and The rock is water wet in these conditions:

$$\sigma_{ws} \geq \sigma_{os}$$

$$\gamma < 0 \text{ (adhesion tension is negative)}$$

$$0° \leq \theta \leq 90°$$

When θ is close to 0°, the rock is reflected to be "strongly water wet".

Between fluid and rocks repulsive forces effect nonwetting phase to inhabit largest pores. Nonwetting phase does not better wet the solid rock surface.
In hydrocarbon reservoirs, natural gas is never the wetting phase.
The most mobile fluid is frequently nonwetting phase, especially at large nonwetting phase saturations.

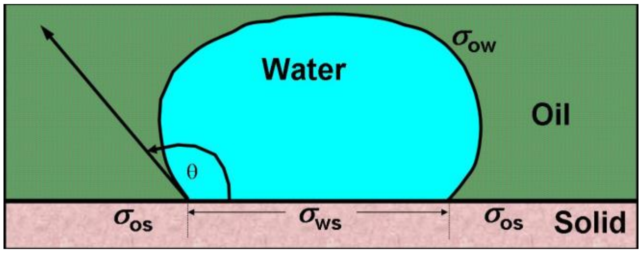


Figure 10 Wettability [Ref 14]

If oil better wets the rock surfaces, reservoir rock is oil-wet. The rock is oil wet in these conditions:

$$\sigma_{os} \geq \sigma_{ws}$$

$$\gamma > 0 \text{ (adhesion tension is positive)}$$

$$90° \leq \theta \leq 180°$$

When θ is close to 180°, the rock is well-thought-out to be "strongly oil wet"

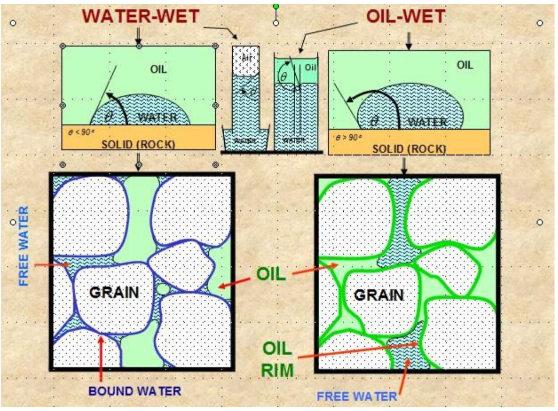


Figure 11 Comparison of water wet and oil wet rocks [Ref 14]

Wettability is categorized by these variations:

- Strongly water or oil wetting.
- Neutral wettability – no better wettability to either oil or water in the pores.
- Fractional wettability – reservoir that has local areas that are strongly oil-wet, while most of the reservoir is strongly water-wet - happens where reservoir rock has changeable mineral composition and surface chemistry.
- Mixed wettability – smaller pores filled with water and are water wet, while larger pores filled with oil and are oil wet. Residual oil saturation is low - happens where oil with polar organic compounds occupies a water-wet rock saturated with brine.
- Wettability differs with surface roughness, so the wettability of a rock will differ with size, grain shape, and rounding.

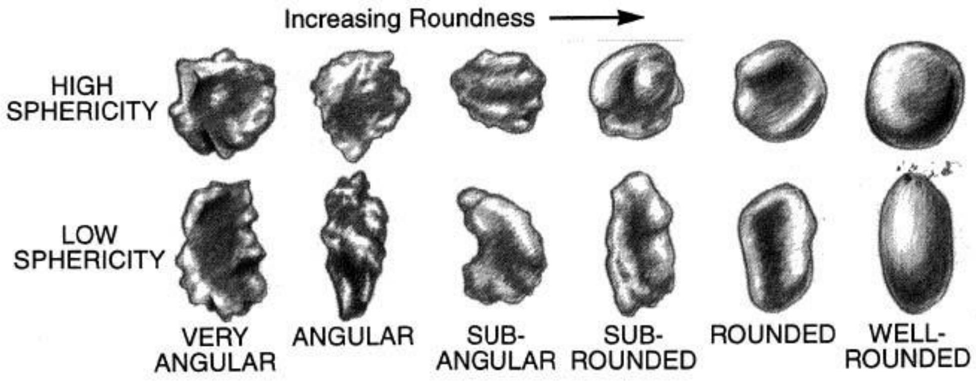


Figure 12 Roughness or angularity of grains affects wettability [Ref 14]

The present measuring technique uses a modern contact angle goniometer and is called the static sessile drop method.
The contact angle goniometer is an optical subsystem which catch the profile of an immaculate fluid on a solid substrate. The angle shaped between the solid and liquid interface and the fluid/vapor interface is the contact angle. More experienced frameworks utilized a magnifying instrument optical framework with a backdrop illumination. Current-era frameworks utilize high determination cameras and programming to catch and investigate the contact angle.

The dynamic sessile drop system is like the static sessile drop but obliges the drop to be altered. A typical sort of element sessile drop study decides the biggest contact angle conceivable without expanding its liquid and solid interfacial territory by including volume dynamically. This maximum angle is the propelling angle. Volume is removed to deliver the littlest conceivable angle, the retreating angle. The distinction between the progressing and retreating angle is the contact angle hysteresis.

5.4 Surfactants [Ref 15]

A surfactant is fleetingly defined as a material that can greatly reduce the surface tension of water when used in very low concentrations.

Surfactants are usually organic compounds that are amphiphilic, and it means they have both hydrophobic groups (their tails) and hydrophilic groups (their heads). Thus, a surfactant has both parts that are water insoluble (or oil soluble) component and a water-soluble component.

In the mixture of oil and water, surfactants will diffuse in water and adsorb at interfaces between air and water or at the interface between oil and water.
The water-insoluble hydrophobic group can spread out of the bulk water phase, into the oil or into the air phase, whereas the water-soluble head group remains in the water phase.

Reliant on on the nature of the hydrophilic part the surfactants are categorized as Cationic, Anionic, Amphoteric or Nonionic.

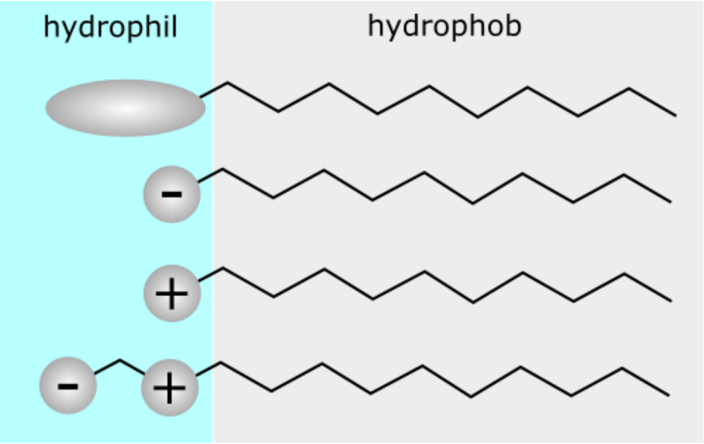


Figure 13 Surfactant classification according to the composition of their head: nonionic, anionic, cationic, amphoteric [Ref 16]

Anionic surfactants

When the hydrophilic part of the surfactant contains of a negatively charged group like a sulphate, sulphonate, or carboxylate the surfactant is named anionic. Basic soaps can be a good example of anionic surfactants. In the last 50 years, many soaps have been replaced with more efficient substances such as Alkyl sulphonates, alkyl sulphates, and alkyl benzene sulphonates.
Anionic surfactants are sensitive for water hardness.

Nonionic surfactants

A surfactant with a non-charged hydrophilic part, for example ethoxylate, is non-ionic. These materials are suitable for cleaning purposes and are not sensitive for water hardness.
They have a extensive use in cleaning detergents and include groups like polyglycosides, fatty alcohol and alcohol ethoxylates.

Cationic surfactants

For this group the hydrophilic part is positively charged for example with a quaternary ammonium ion. This category of surfactants has no wash activity effect, but secures to the surfaces where they might provide antistatic, softening, anti-bacterial, soil repellent or corrosion inhibitory effects.
The most typical applications are for antistatic and softeners.
The cationic surfactant also known by DADMAC.

Amphoteric surfactants

For the amphoteric surfactants the charge of the hydrophilic part is organized by the pH of the solution. It’s means that they can performance as anionic surfactant in an alkalic solution or as cationic surfactant in an acidic solution.regular increase in TMP after each backwash, however, the backwash process cannot always remove accumulation of foulants alone. Chemical cleaning are needed.

5.4.1 Effect of surfactants on wetting

Control of liquid dispersal over solid surfaces require many technological processes. When a drop is located on a surface, it can entirely wet, not wet the surface or partially wet.

By decreasing the surface tension with surfactants, a nonwetting material can become completely or partially wetting. The extra free energy (σ) of a drop on a solid surface is: [Ref 19]

$$\sigma = \gamma S + PV + \pi R^2(\gamma_{\mathrm{SL}} - \gamma_{\mathrm{SV}})$$

That:

- γ = liquid–vapor interfacial tension
- γ_{SL} = solid–liquid interfacial tension
- γ_{SV} = solid–vapor interfacial tension
- S = area of liquid–vapor interface
- P = excess pressure inside liquid
- R = radius of droplet base

Based on this equation, the excess free energy is diminished when γ declines, γ_{SL} declines, or γ_{SV} rises. Surfactants are suck up onto the liquid–vapor solid–liquid, and solid–vapor interfaces, which adjust the wetting behavior of hydrophobic substances to decrease the free energy. When surfactants are suck up onto a hydrophobic surface, the polar head groups expression into the solution with the tail pointing outward.

In more hydrophobic surfaces, surfactants might form a bilayer on the solid, triggering it to become more hydrophilic. The dynamic drop radius can be measured as the drop begins to spread. Therefore, the contact angle changes based on the following equation:

$$\cos\theta(t) = \cos\theta_0 + (\cos\theta_\infty - \cos\theta_0)(1 - \mathrm{e}^{\frac{-t}{\tau}})$$

- θ_0 = initial contact angle
- θ_∞ = final contact angle
- τ = surfactant transfer time scale

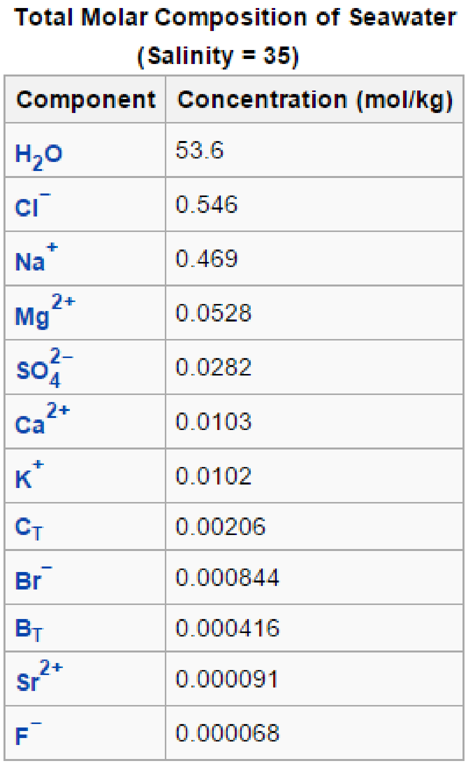
As the surfactants are sucked up, the solid–vapor surface tension increases and the edges of the drop become hydrophilic. Therefore, the drop spreads.

6. Experiments

In this part tried to achieve real results from different experiments in laboratory and use them for analyzing and at the end for project simulation.

For all experiments, synthetic seawater has been used. For making seawater, this followings considered:

- composition of seawater:



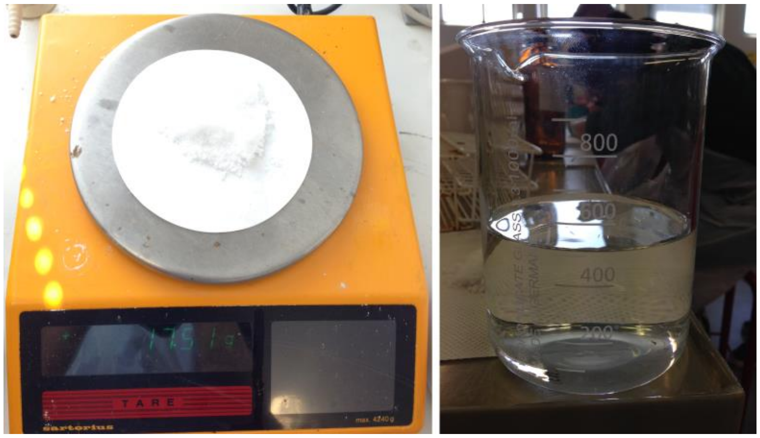
Total Molar Composition of Seawater (Salinity = 35)

Component	Concentration (mol/kg)
H_2O	53.6
Cl^-	0.546
Na^+	0.469
Mg^{2+}	0.0528
SO_4^{2-}	0.0282
Ca^{2+}	0.0103
K^+	0.0102
C_T	0.00206
Br^-	0.000844
B_T	0.000416
Sr^{2+}	0.000091
F^-	0.000068

Figure 14 Seawater compossition [Ref 17]

- Concentration or Salinity of seawater:

On average, seawater in the world's oceans has a salinity of about 3.5% (35 g/L). So base on this concentration, the final mixture is mixture of 500 ml water and 17.5 g sea salt.



6.1 Aqueous stability

The main aim of this experiment is to find a stable surfactant for waterflooding. Due to find a stable surfactant, different kinds of surfactants have been test and finally two surfactants are chose. For finding suitable surfactant, the mixture of seawater and surfactant has to stand on 60 C^0.

In this project, one anionic (SDS) and one cationic (P 50-70) [Appendix 1] surfactants have been chose and for stability test, the mixture of each surfactants and seawater with concentration of 2% stood 2 days on oven with temperature of 60 C^0.

Figure 14 mixture of Seawater and Surfactant in oven on 60 C^0

After 2 days, both surfactant mixtures were stable and homogeneous and could use in other experiments.

6.2 Contact angle for wettability

For this part, different mixtures with different concentrations tested and with camera, contact angle (θ) calculated.

At the beginning, for making chalk surface one simple technique used that with one adhesive tape and $CaCo_3$ powder one thin layer have been made. This method was not functional because surfactant solved the layer and camera was not able to recognize the drop. So One thin layer of chalk ($CaCo_3$) selected as a main surface and for each mixture one drop evaluated separately.

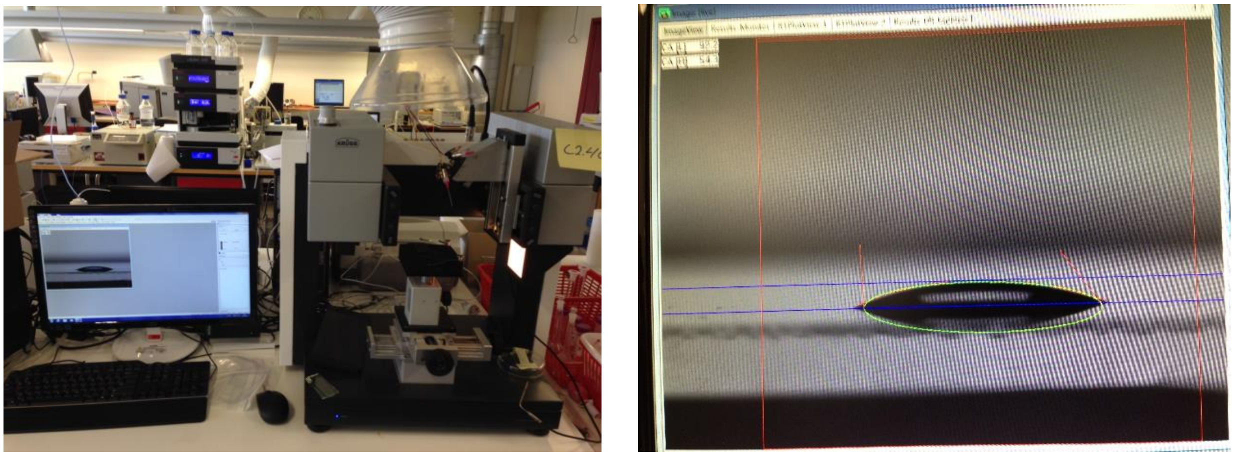


Figure 15 Contact angle measurement

These data will be use in calculation of surface tension.

6.3 Surface Tension

The main goal of this experiment is measuring of Surface Tension due to select a specific concentration of surfactant. This work has been done by Du Nouy ring method with different versions of synthetic seawater (SSW).

The main equation is:

$$\gamma = \frac{m.g.cos\theta}{4\pi.R}$$

That:

γ = Surface tension (N/m)
m = mass (g)
θ = Contact angle
R = Du Nouy-rings radius (m)

For this part, Surface tension in different mixtures with different concentration has calculated.

Seawater

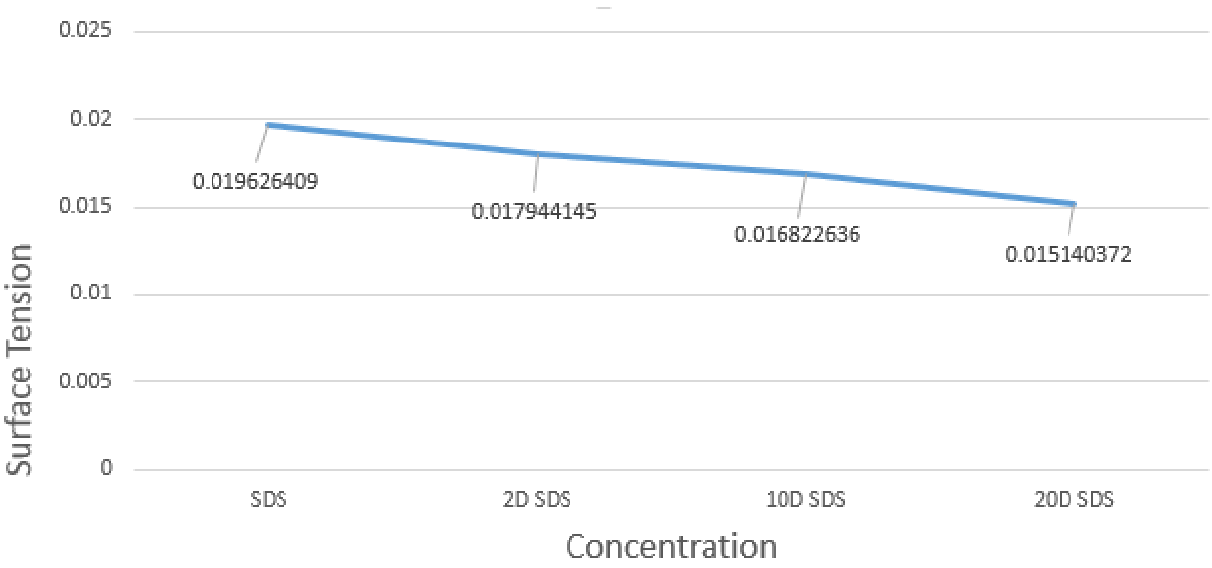
Cos θ for water is 1,

$$\gamma = \frac{0.65*10^{-3}kg*9.81*1}{4\pi*9.75*10^{-3}m} = 0.05207 \text{ N/m}$$

For SDS (Sodium dodecyl sulfate) in different concentration

In mixture of 2% seawater and SDS, $\theta = 45^0$ and if this mixture will be more diluted θ also reduced. In this part for SDS:

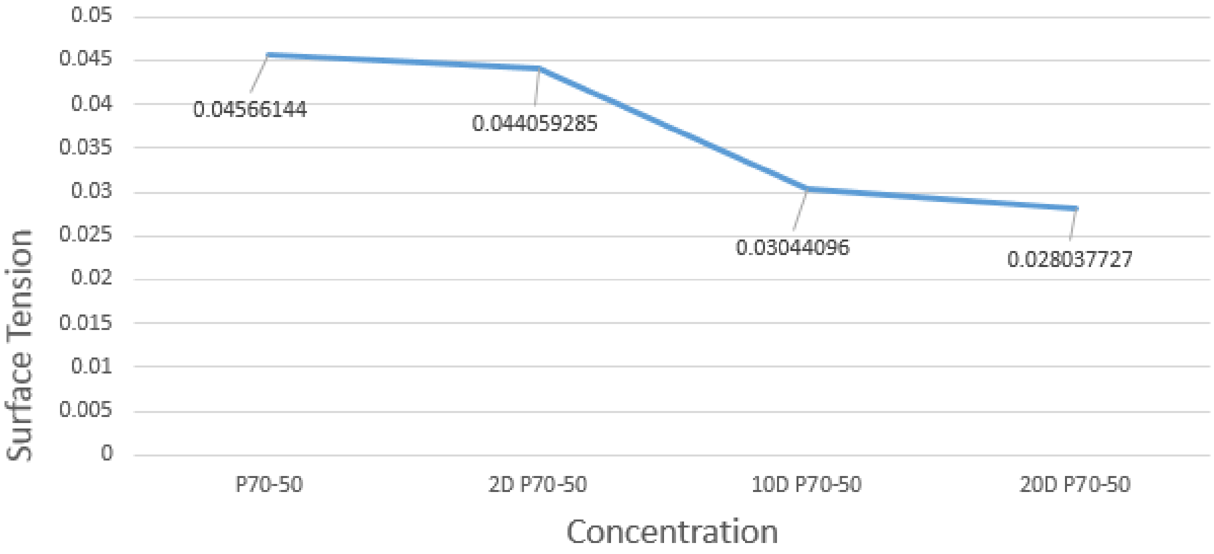
$\theta = 37^{\,0}$ in 2D (two times diluted), $\theta = 29^{\,0}$ 10D (ten times diluted) and $\theta = 20^{\,0}$ 20D (twenty times diluted)



For P 70-50 in different concentration

In mixture of 2% seawater and P 70-50, $\theta = 72.5^0$ and if this mixture will be more diluted θ also reduced. In this part for P 70-50:

$\theta = 65^{\,0}$ in 2D (two times diluted), $\theta = 53^{\,0}$ 10D (ten times diluted) and $\theta = 42^{\,0}$ 20D (twenty times diluted)



6.4 Interfacial tension (IFT)

Interfacial tension is the force that grips the surface of a particular phase together and is normally measured in dynes/cm and this force exists when two phases are present. These phases can be gas/oil, oil/water, or gas/water.
In this part, IFT in different mixture of oil and seawater and 2 different surfactants (SDS and P70-50) has been calculated.

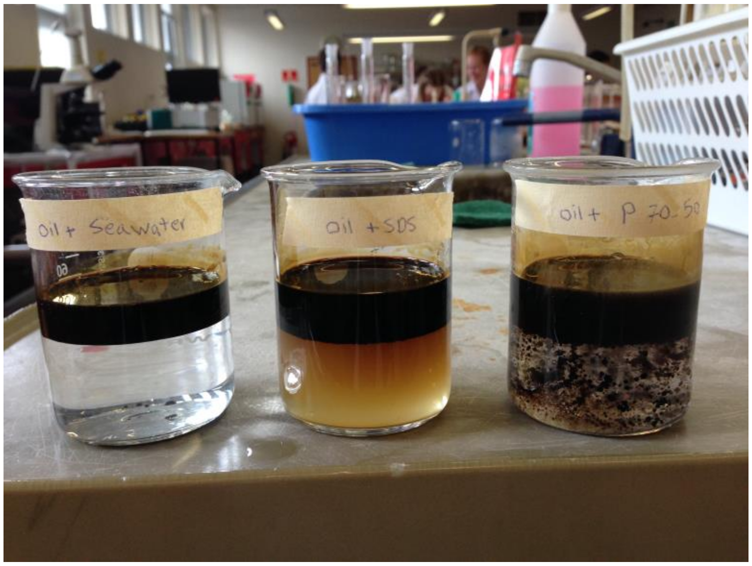
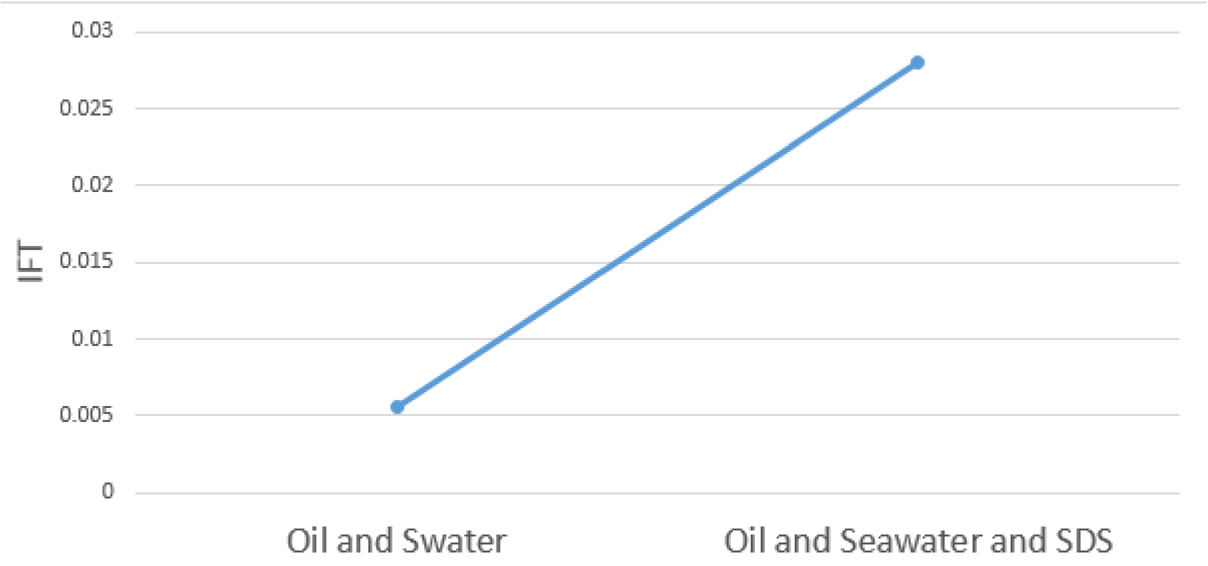
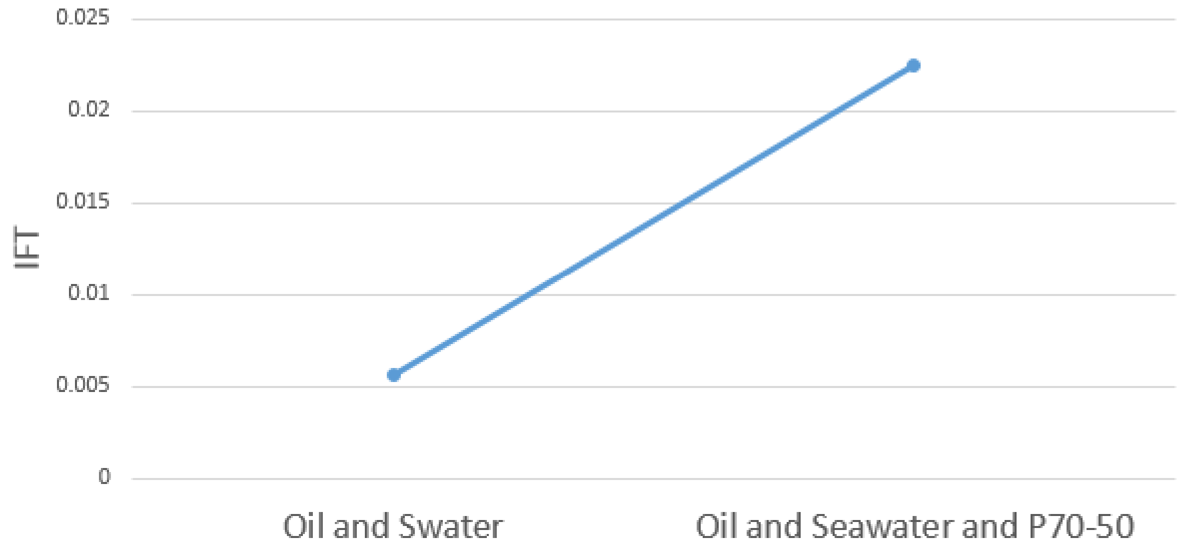


Figure 16 Different mixtures for IFT measurment

The main difference between IFT and surface tension is the places where it occurs. Surface tension is defined to a single liquid surface, whereas the interfacial tension is defined to the interface of two immiscible liquids.

After measurement of IFT in three different scenario base on these two graphs we can say that adding surfactant increase IFT.





Based on IFT calculations, in P70-50 maximum IFT happened in point 20 dynes oer centimeter and this number can be use in our simulation.

As conclusion, based on results and graphs we can say that adding surfactants increased IFT and Wettability and reduced surface tension.

7 Process simulation with UTCHEM software

UTCHEM is a three-dimensional chemical flooding simulator and in this part, tried to simulate the data that have gotten from experiments [Appendix 4] and evaluate adding P50-70 surfactant with 2% concentration.

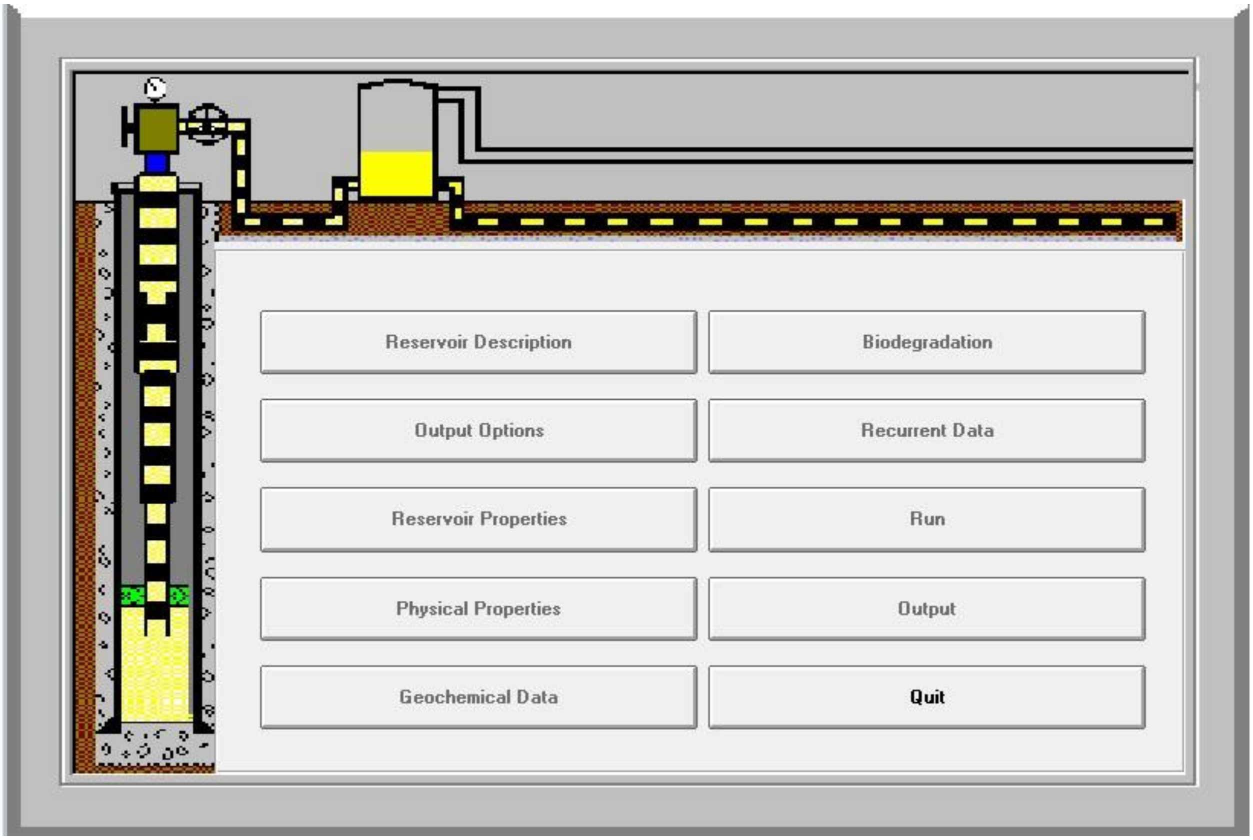
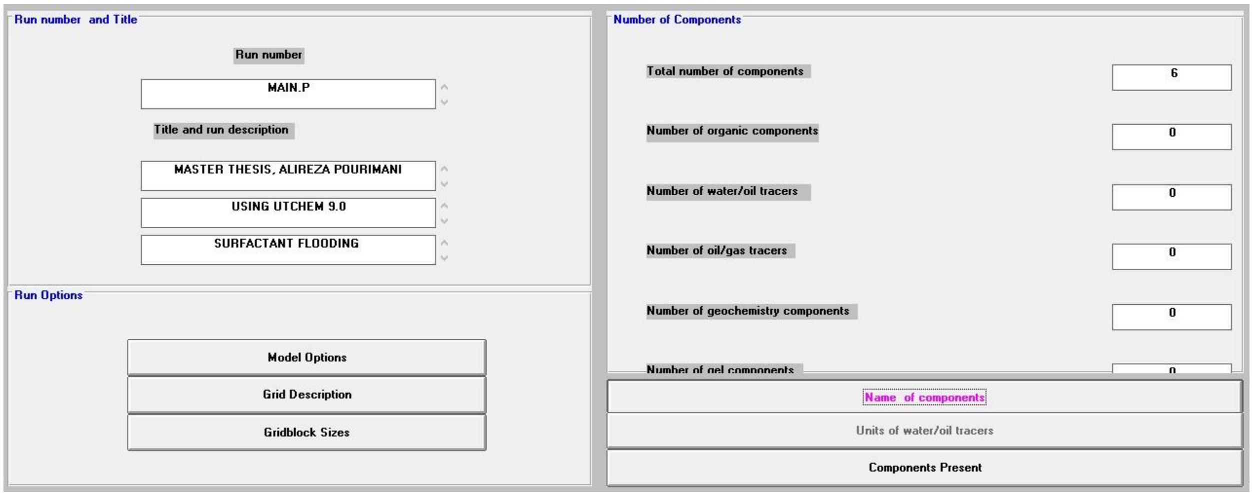


Figure 17 UTCHEM's main window

7.1 Reservoir description

In the first step in this program, reservoir description should be consider.



Run number and Title

Run number: MAIN.P

Title and run description:
MASTER THESIS, ALIREZA POURIMANI
USING UTCHEM 9.0
SURFACTANT FLOODING

Run Options

Model Options
Grid Description
Gridblock Sizes

Number of Components

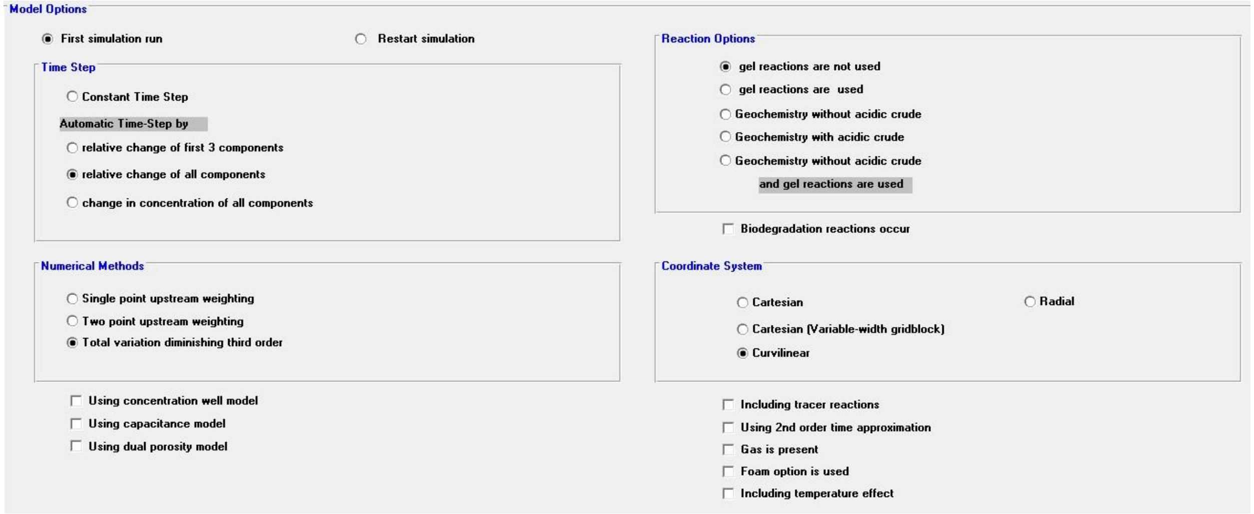
Total number of components: 6
Number of organic components: 0
Number of water/oil tracers: 0
Number of oil/gas tracers: 0
Number of geochemistry components: 0
Number of gel components: 0

Name of components
Units of water/oil tracers
Components Present

Figure 18 Reservoir Description

The title of project and number of components have to write here. As you can see for components part, 6 components considered that 3 of them (Oil, Water, Surfactant) are our main components, two components are from reservoir (Chloride and Calcium) and other component is an option for other surfactant or polymer.

Other important adjustment in this part is Model Option.



Model Options

● First simulation run ○ Restart simulation

Time Step

○ Constant Time Step
Automatic Time-Step by
○ relative change of first 3 components
● relative change of all components
○ change in concentration of all components

Numerical Methods

○ Single point upstream weighting
○ Two point upstream weighting
● Total variation diminishing third order

☐ Using concentration well model
☐ Using capacitance model
☐ Using dual porosity model

Reaction Options

● gel reactions are not used
○ gel reactions are used
○ Geochemistry without acidic crude
○ Geochemistry with acidic crude
○ Geochemistry without acidic crude and gel reactions are used

☐ Biodegradation reactions occur

Coordinate System

○ Cartesian ○ Radial
○ Cartesian (Variable-width gridblock)
● Curvilinear

☐ Including tracer reactions
☐ Using 2nd order time approximation
☐ Gas is present
☐ Foam option is used
☐ Including temperature effect

Figure 19 Model Option

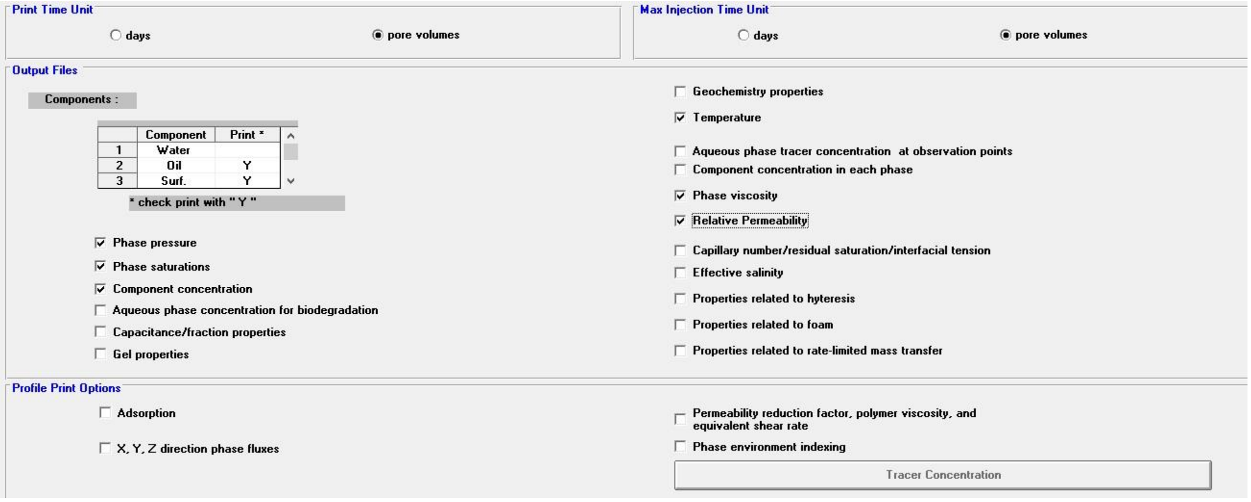
As you can see in Figure 19:

FIRST SIMULATION RUN have been chose and for TIME STEP part, all components selected. For NUMERICAL METHOD, total variation diminishing third order has been chose.

For REACTION OPTION, the first option has been chose because in this project, using gel did not consider and or COORDINATE SYSTEM curvilinear condition has been chose.

7.2 Output Option

For this part, the final data the want to export from UTCHEM has to be consider.



Print Time Unit
○ days ● pore volumes

Max Injection Time Unit
○ days ● pore volumes

Output Files

Components :

	Component	Print *
1	Water	
2	Oil	Y
3	Surf.	Y

* check print with " Y "

☑ Phase pressure
☑ Phase saturations
☑ Component concentration
☐ Aqueous phase concentration for biodegradation
☐ Capacitance/fraction properties
☐ Gel properties

☐ Geochemistry properties
☑ Temperature
☐ Aqueous phase tracer concentration at observation points
☐ Component concentration in each phase
☑ Phase viscosity
☑ Relative Permeability
☐ Capillary number/residual saturation/interfacial tension
☐ Effective salinity
☐ Properties related to hyteresis
☐ Properties related to foam
☐ Properties related to rate-limited mass transfer

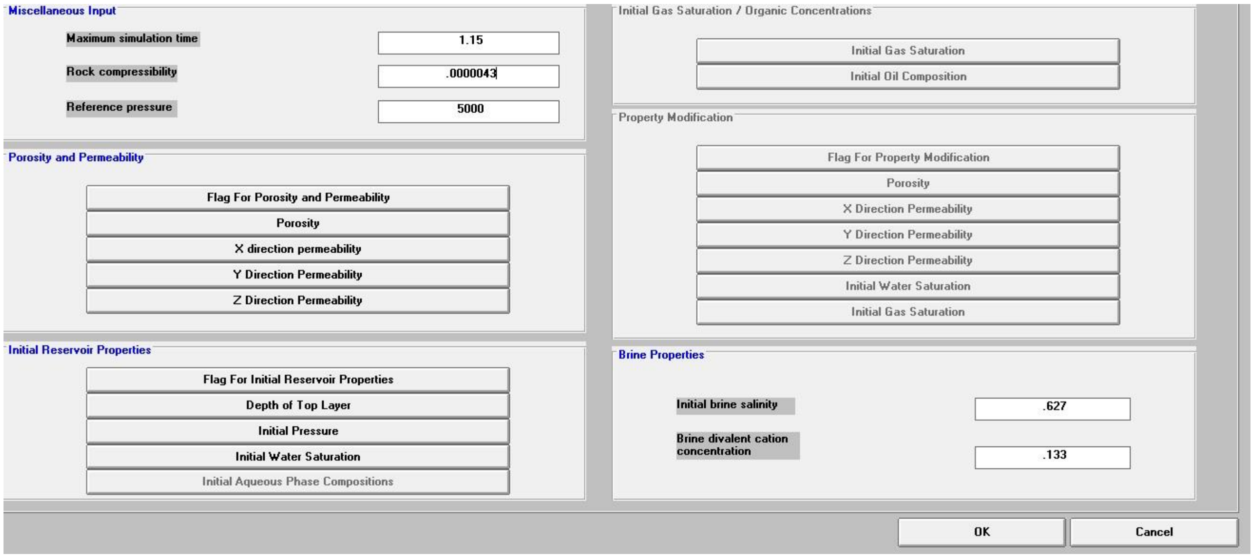
Profile Print Options
☐ Adsorption
☐ X, Y, Z direction phase fluxes
☐ Permeability reduction factor, polymer viscosity, and equivalent shear rate
☐ Phase environment indexing

Figure 20 Output Option

As you can see in Figure 20, after simulation we can extract Phase pressure, Phase saturations and component concentrations and for Maximum injection time, we can export temperature, phase viscosity and relative permeability.

7.3 Reservoir properties

In this part, the reservoir details have to be consider.



Maximum simulation time 1.15

Rock compressibility .0000043

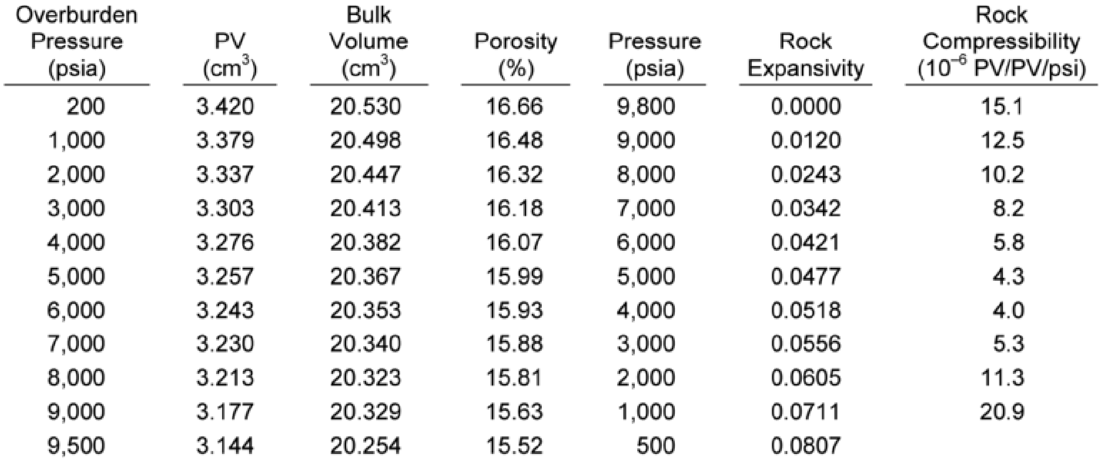
Reference pressure 5000

Initial brine salinity .627

Brine divalent cation concentration .133

Figure 21 Reservoir properties

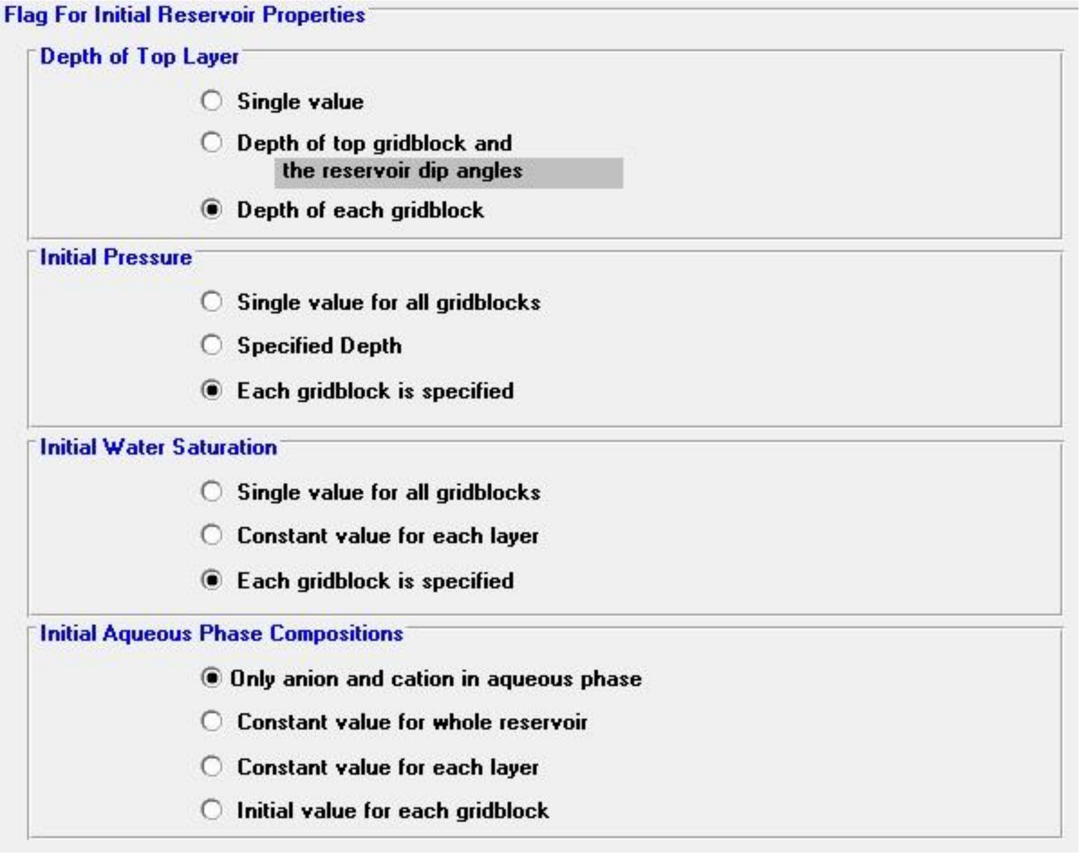
As you can see in Figure 21, maximum simulation time set on 1.15 days or 30 hours. For Rock compressibility and pressure, Figure 22 can be use that 4.3 and 5000 has been chose.



Overburden Pressure (psia)	PV (cm^3)	Bulk Volume (cm^3)	Porosity (%)	Pressure (psia)	Rock Expansivity	Rock Compressibility (10^{-6} PV/PV/psi)
200	3.420	20.530	16.66	9,800	0.0000	15.1
1,000	3.379	20.498	16.48	9,000	0.0120	12.5
2,000	3.337	20.447	16.32	8,000	0.0243	10.2
3,000	3.303	20.413	16.18	7,000	0.0342	8.2
4,000	3.276	20.382	16.07	6,000	0.0421	5.8
5,000	3.257	20.367	15.99	5,000	0.0477	4.3
6,000	3.243	20.353	15.93	4,000	0.0518	4.0
7,000	3.230	20.340	15.88	3,000	0.0556	5.3
8,000	3.213	20.323	15.81	2,000	0.0605	11.3
9,000	3.177	20.329	15.63	1,000	0.0711	20.9
9,500	3.144	20.254	15.52	500	0.0807	

Figure 21 North sea's reservoir conditions [Ref 18]

For porosity and permeability, variable condition has been chose. For initial reservoir properties, the data that come from North sea reservoir properties has been used. [Appendix 2]



Flag For Initial Reservoir Properties

Depth of Top Layer
- ○ Single value
- ○ Depth of top gridblock and the reservoir dip angles
- ● Depth of each gridblock

Initial Pressure
- ○ Single value for all gridblocks
- ○ Specified Depth
- ● Each gridblock is specified

Initial Water Saturation
- ○ Single value for all gridblocks
- ○ Constant value for each layer
- ● Each gridblock is specified

Initial Aqueous Phase Compositions
- ● Only anion and cation in aqueous phase
- ○ Constant value for whole reservoir
- ○ Constant value for each layer
- ○ Initial value for each gridblock

Figure 22 Initial reservoir properties

And for brine properties 2 parameters have to consider that are salinity and concentration

Brine Properties

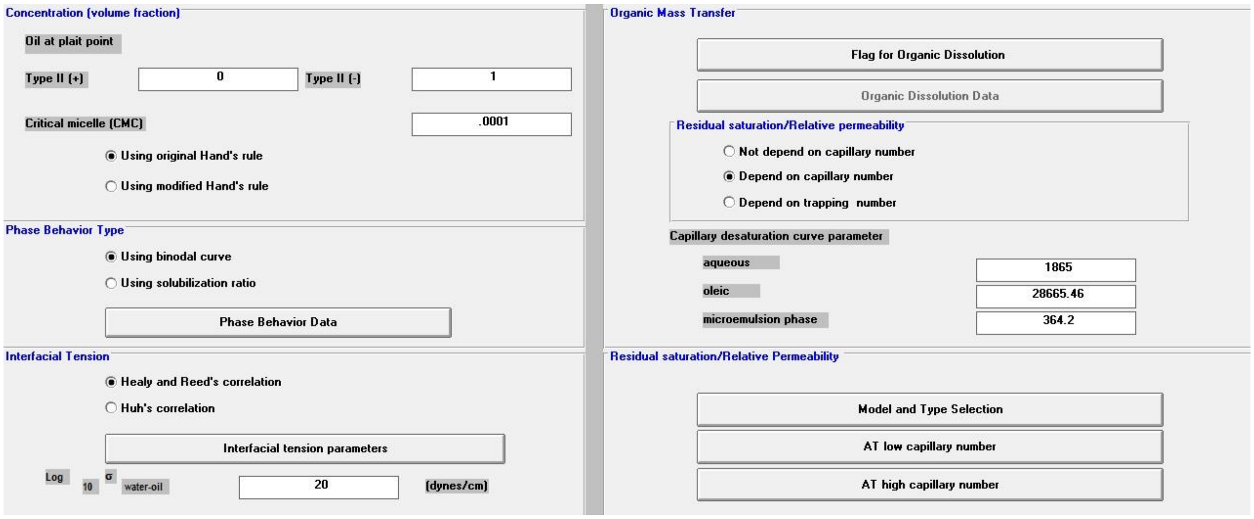
Initial brine salinity	.630
Brine divalent cation concentration	.140

Figure 23 Brine properties

The unit of those number is meq/ml of water.

7.4 Phisical properties

The most important part In this section is IFT or interfacial tension that calculated in experiments and other parameters set by data sheet that come from Surfactant description and components description.



Concentration (volume fraction)
Oil at plait point
Type II (+) 0
Type II (-) 1
Critical micelle (CMC) .0001
● Using original Hand's rule
○ Using modified Hand's rule

Phase Behavior Type
● Using binodal curve
○ Using solubilization ratio

Interfacial Tension
● Healy and Reed's correlation
○ Huh's correlation
$\log_{10} \sigma_{water\text{-}oil}$ 20 (dynes/cm)

Organic Mass Transfer

Residual saturation/Relative permeability
○ Not depend on capillary number
● Depend on capillary number
○ Depend on trapping number

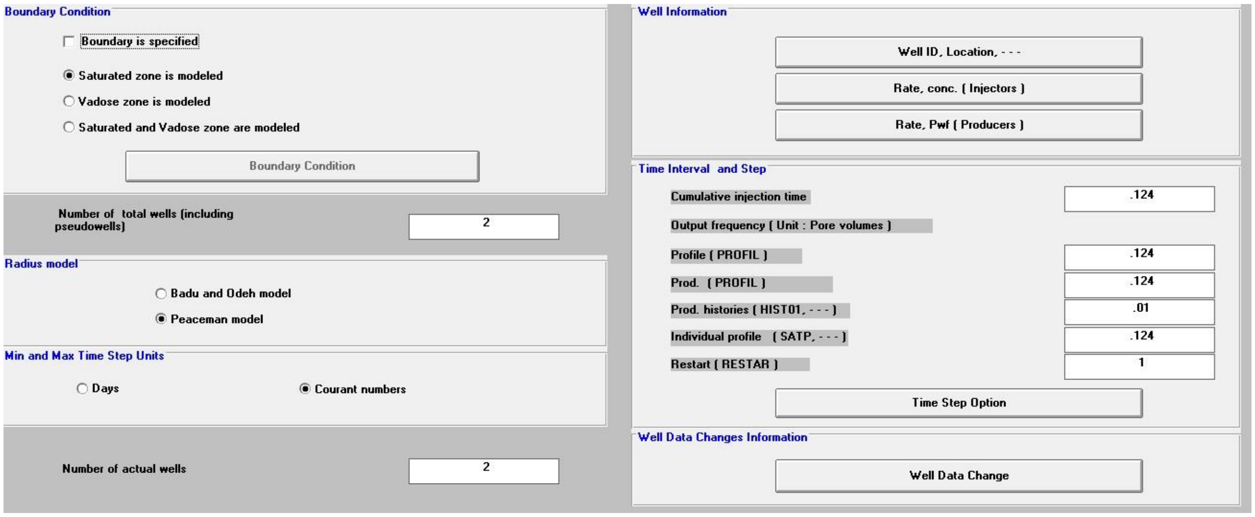
Capillary desaturation curve parameter
aqueous 1865
oleic 28665.46
microemulsion phase 364.2

Residual saturation/Relative Permeability

Figure 24 Phisical properties

7.5 Recurrent data

In this part, data about Well and boundary condition has to be consider.



Boundary Condition
☐ Boundary is specified
● Saturated zone is modeled
○ Vadose zone is modeled
○ Saturated and Vadose zone are modeled

Number of total wells (including pseudowells) 2

Radius model
○ Badu and Odeh model
● Peaceman model

Min and Max Time Step Units
○ Days
● Courant numbers

Number of actual wells 2

Well Information

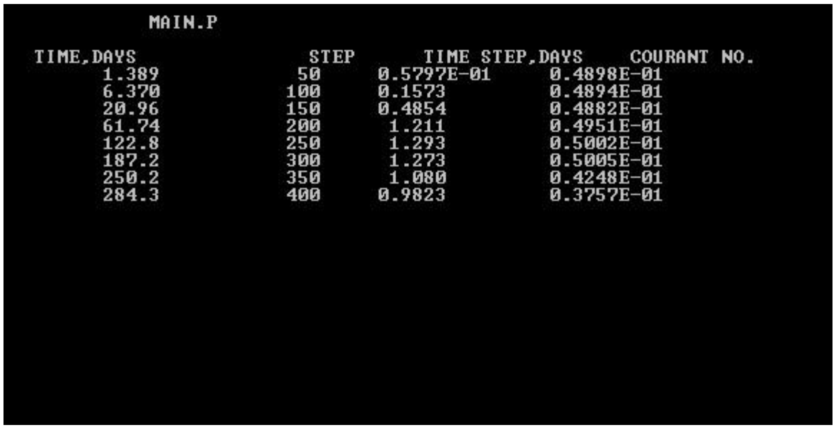
Time Interval and Step
Cumulative injection time .124
Output frequency (Unit : Pore volumes)
Profile (PROFIL) .124
Prod. (PROFIL) .124
Prod. histories (HIST01, - - -) .01
Individual profile (SATP, - - -) .124
Restart (RESTAR) 1

Well Data Changes Information

Figure 25 Recurrent data

7.6 Run

After all calculation and data analyzing, with press of RUN button, all tables and plots are accessible.



```
          MAIN.P

TIME,DAYS               STEP      TIME STEP,DAYS     COURANT NO.
      1.389              50     0.5797E-01     0.4898E-01
      6.370             100     0.1573         0.4894E-01
      20.96             150     0.4854         0.4882E-01
      61.74             200      1.211         0.4951E-01
      122.8             250      1.293         0.5002E-01
      187.2             300      1.273         0.5005E-01
      250.2             350      1.080         0.4248E-01
      284.3             400     0.9823         0.3757E-01
```

Figure 26 Runing

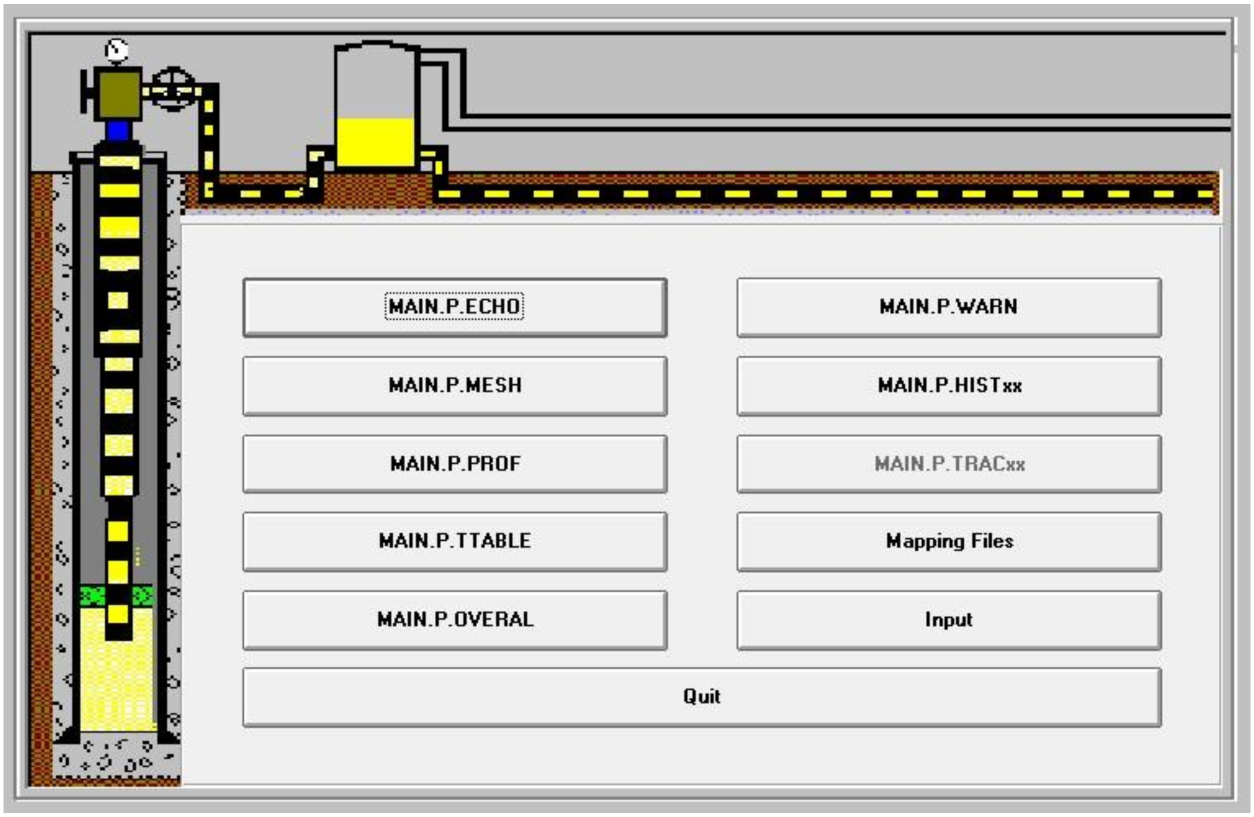
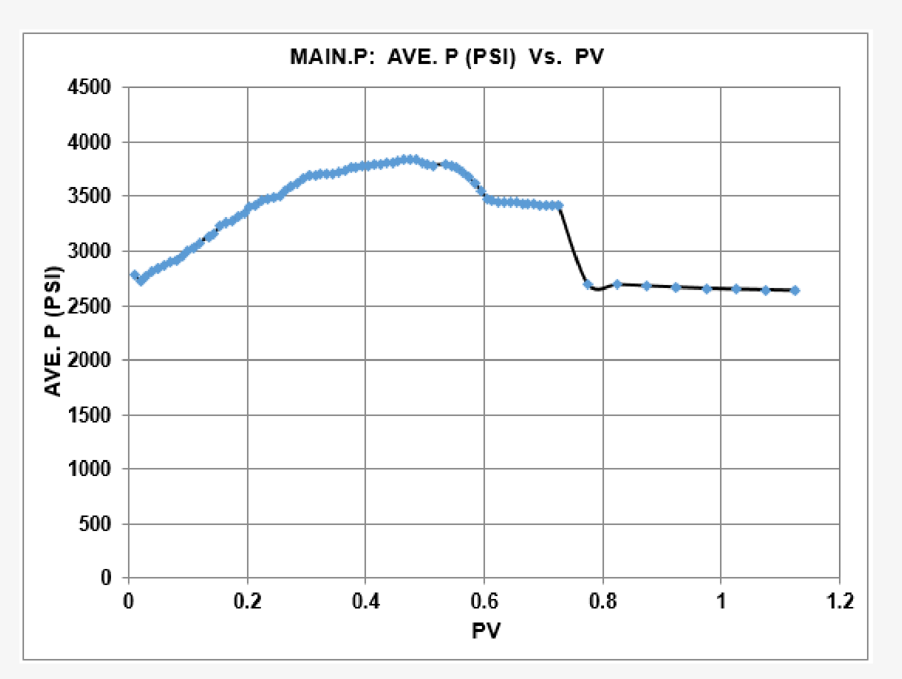


Figure 27 Output files

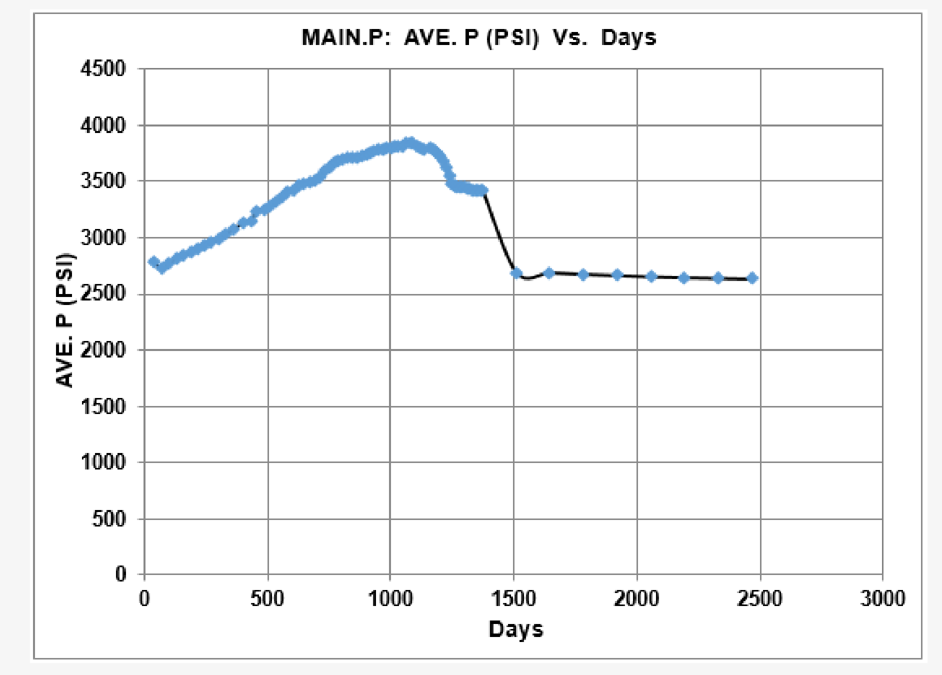
As you can see in Figur 27 after running of data some file will export and these files are our final data about our simulation.

In overal section, all well’s data and final calculation about running ti,e exist. Also in this section we can extract our data as an exle file or plot them [Appendix 3].

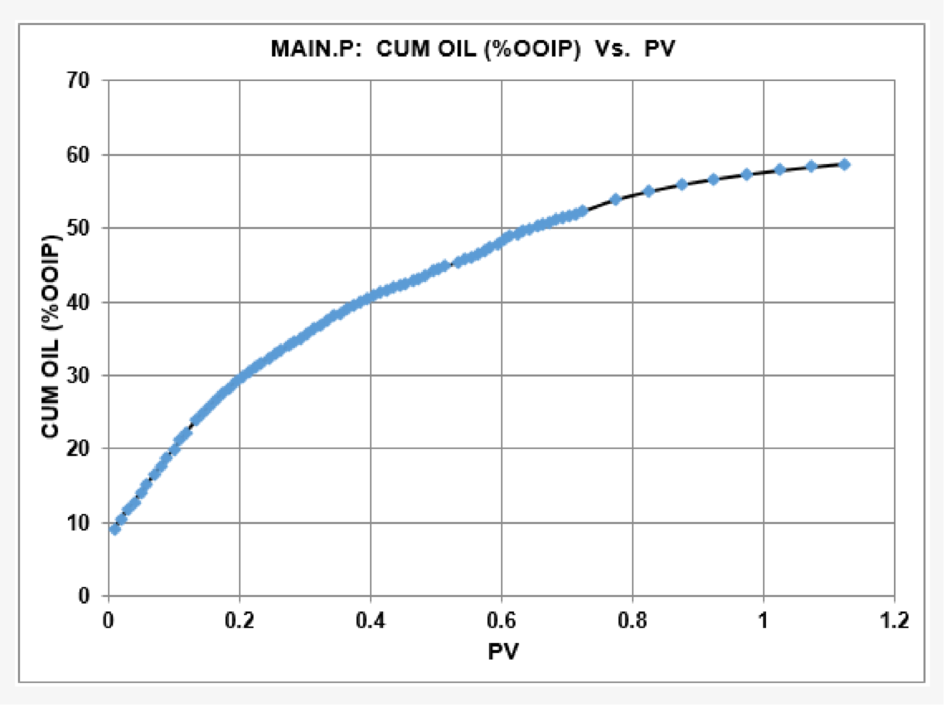
The Plots are :

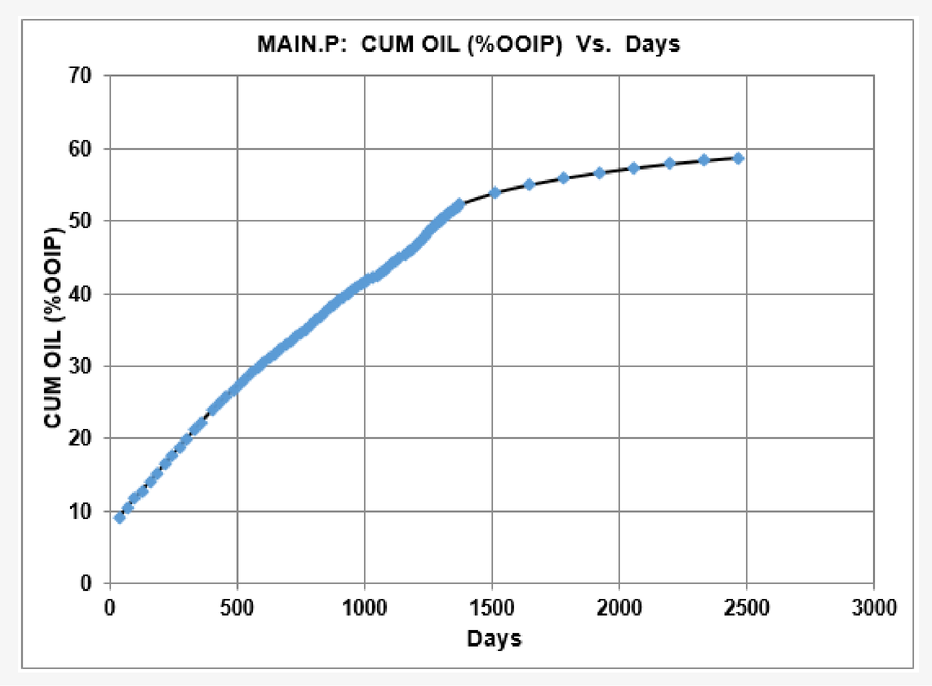


This graph shows the variation of Pressure in different volumes of surfactant and it pressents adding surfactand cause to rise of pressure and after the point (0,6), the rate of pressure will be steady and It means the reservoir is in saturation condition and adding more surfactant can not increase the pressure.



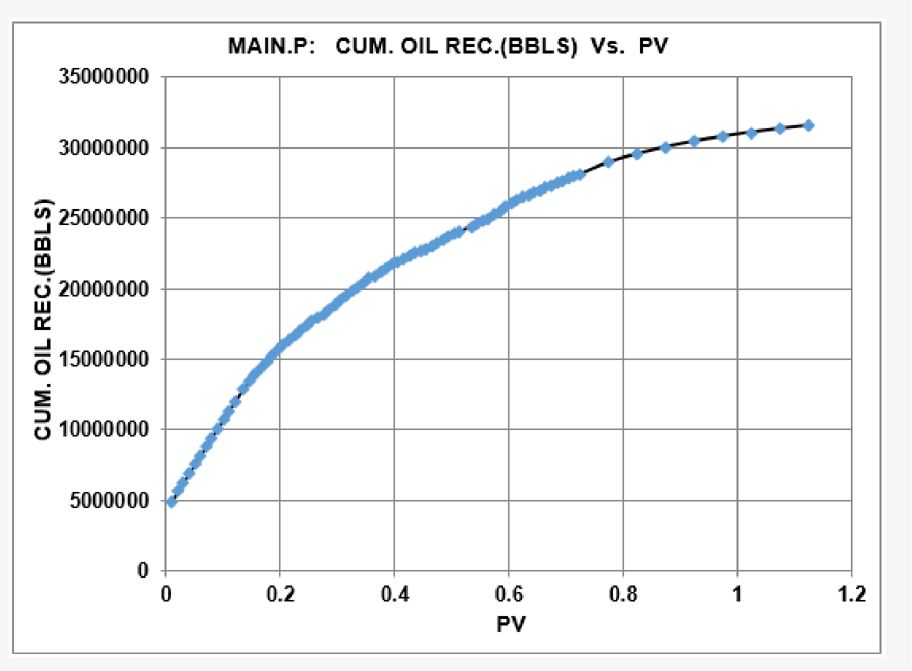
This graph also is about variation of pressure but during the times and different days and similar to previous graph presents how pressure change in different days.

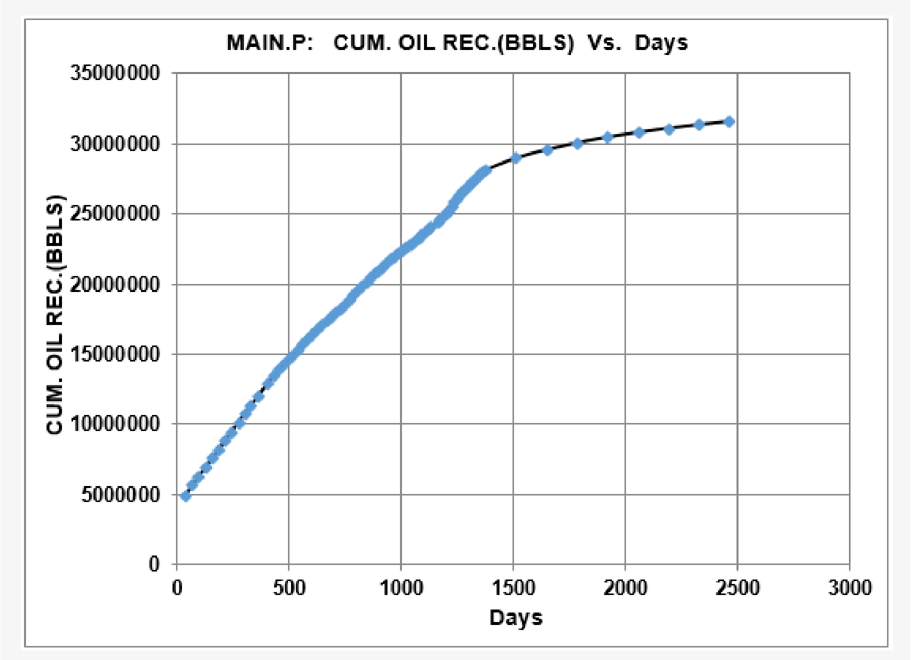




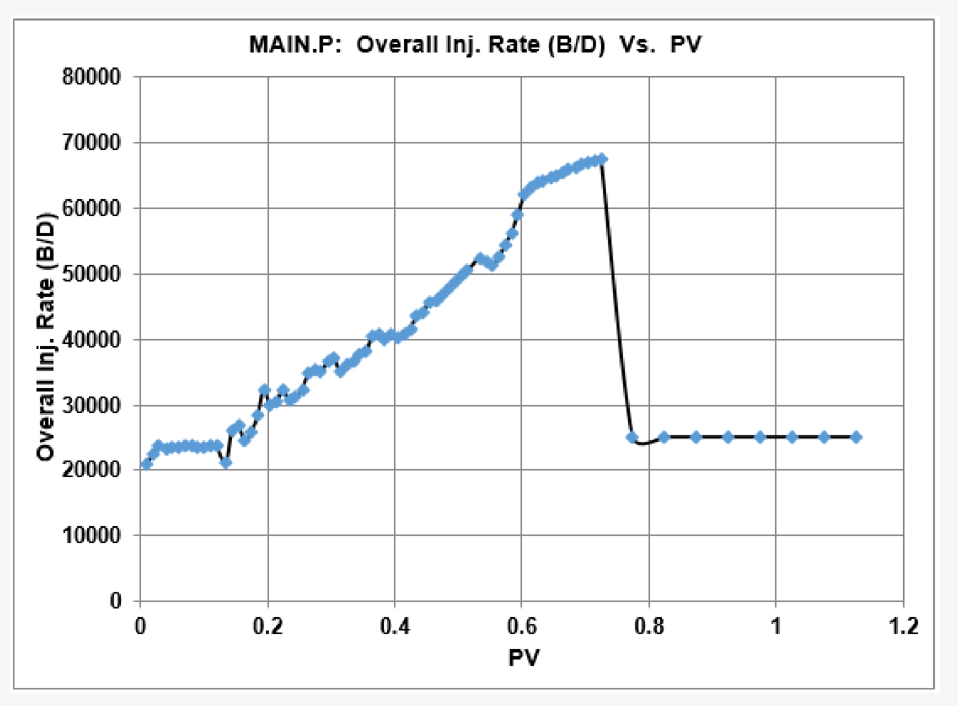
These two graphs show variation of cumulative oil per volumes (PV) and per days. Based on this calculation, adding surfactant increas amount of oil production.

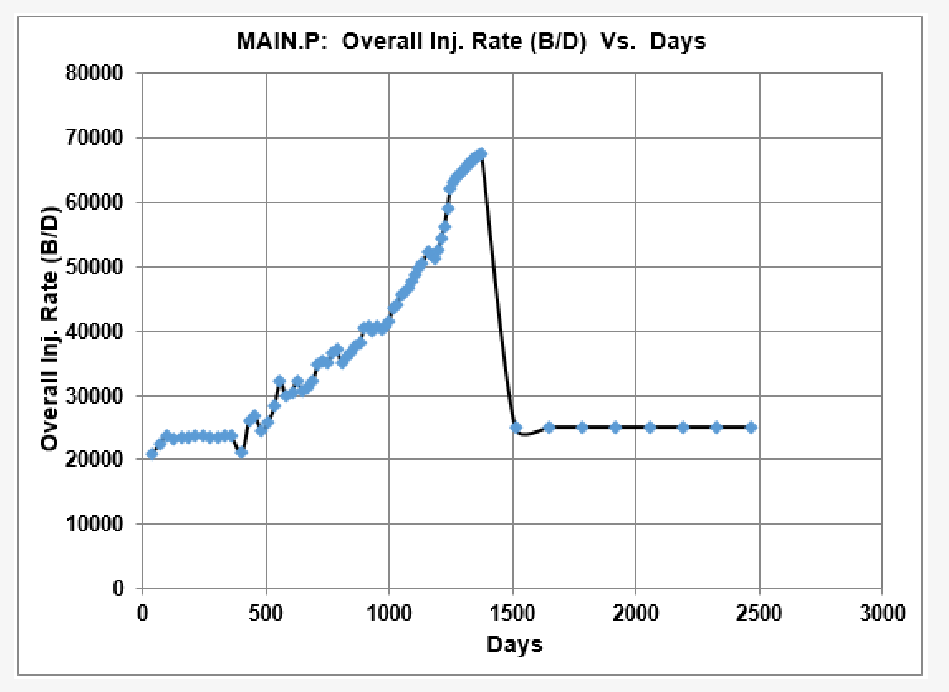
The numbers of vertical axes present percentage of OOIP (Orginal oil in place).



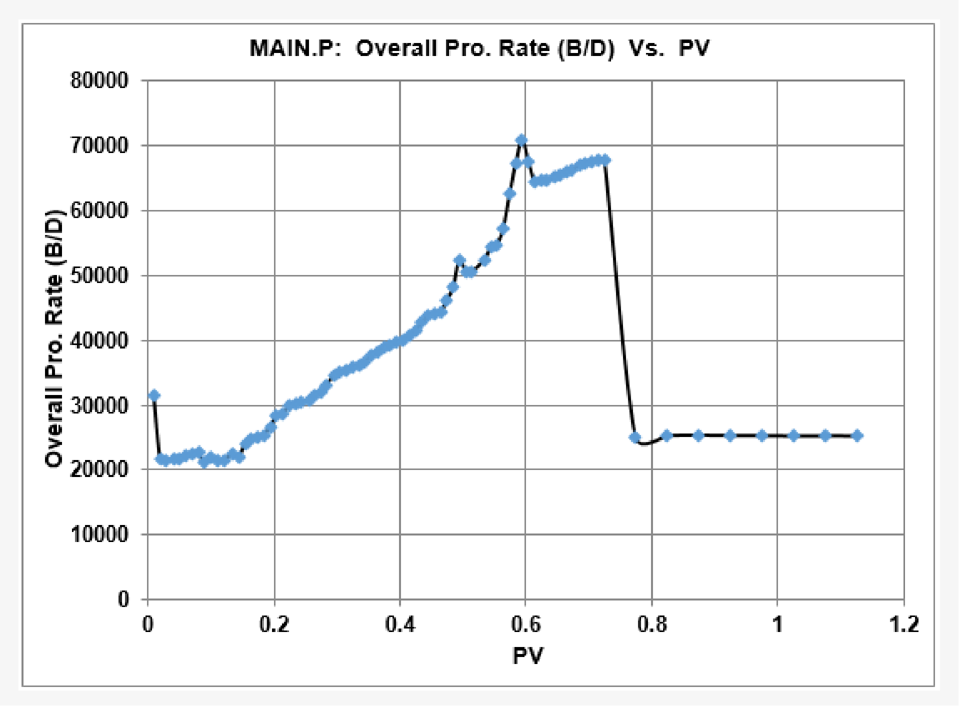


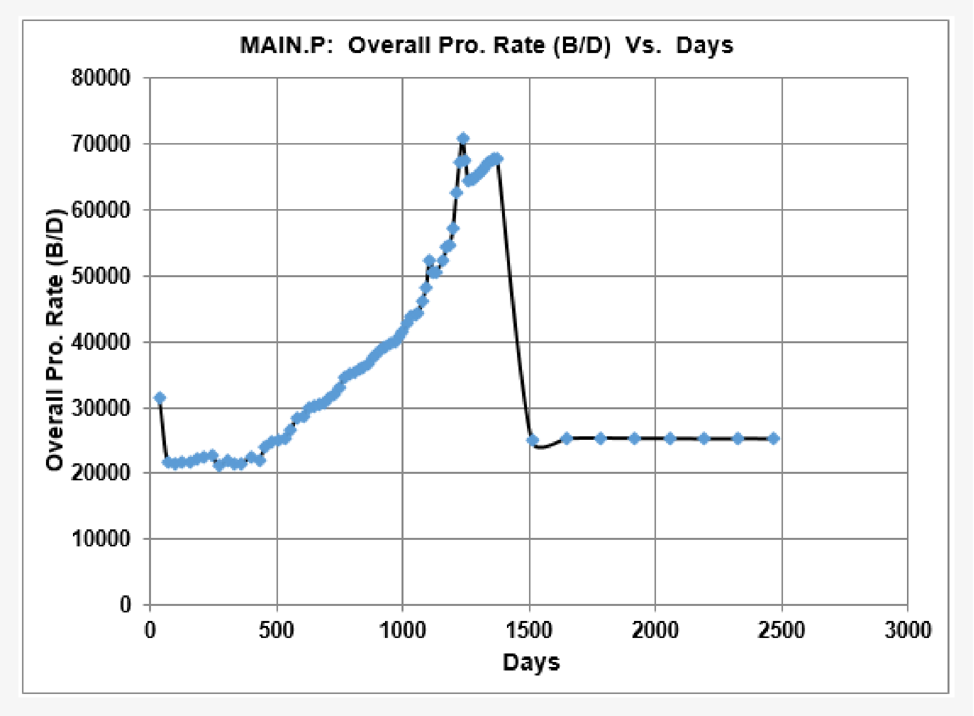
These two graphs also show variation of cumulative oil per volumes (PV) and per days but in different unit that is BBLs (barrels).





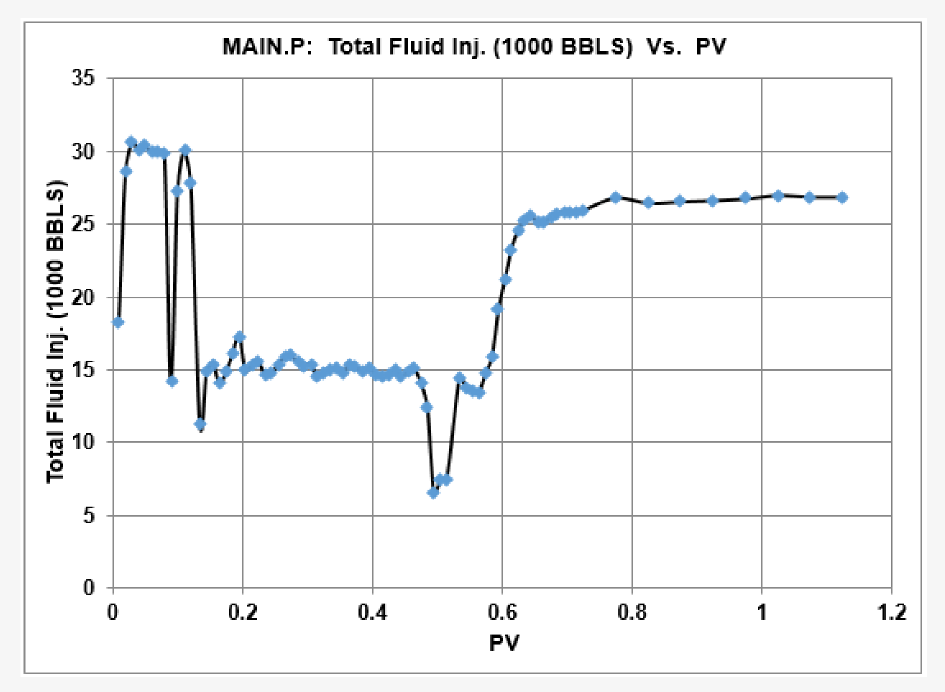
These two graphs show overal rate of injection per volumes (PV) and per days and it is clear during the time, this rate will be increase.

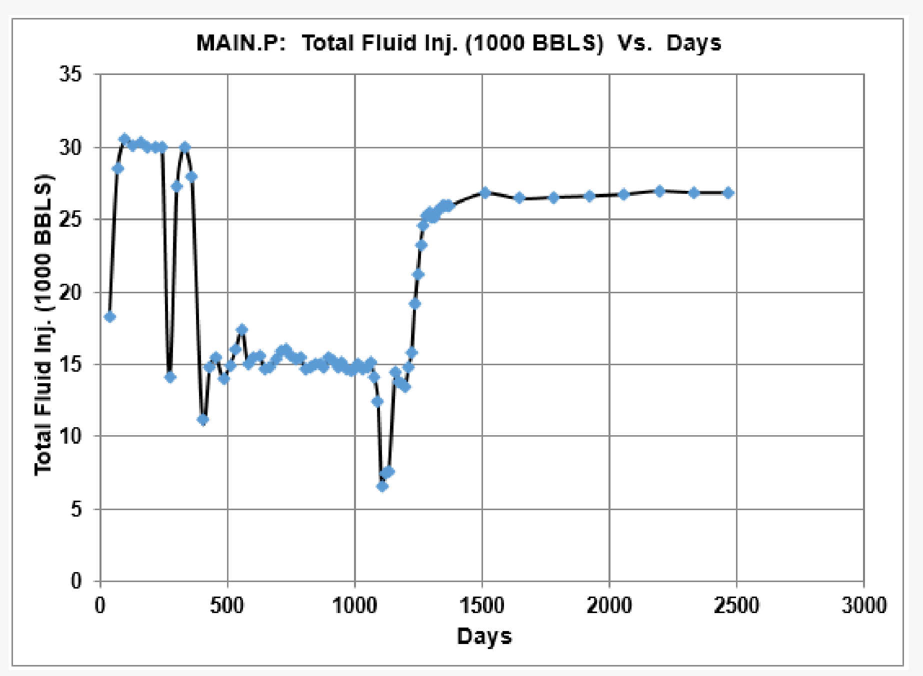




These two graphs show overal rate of production (barrel per day) in different volumes (PV) and also different days.

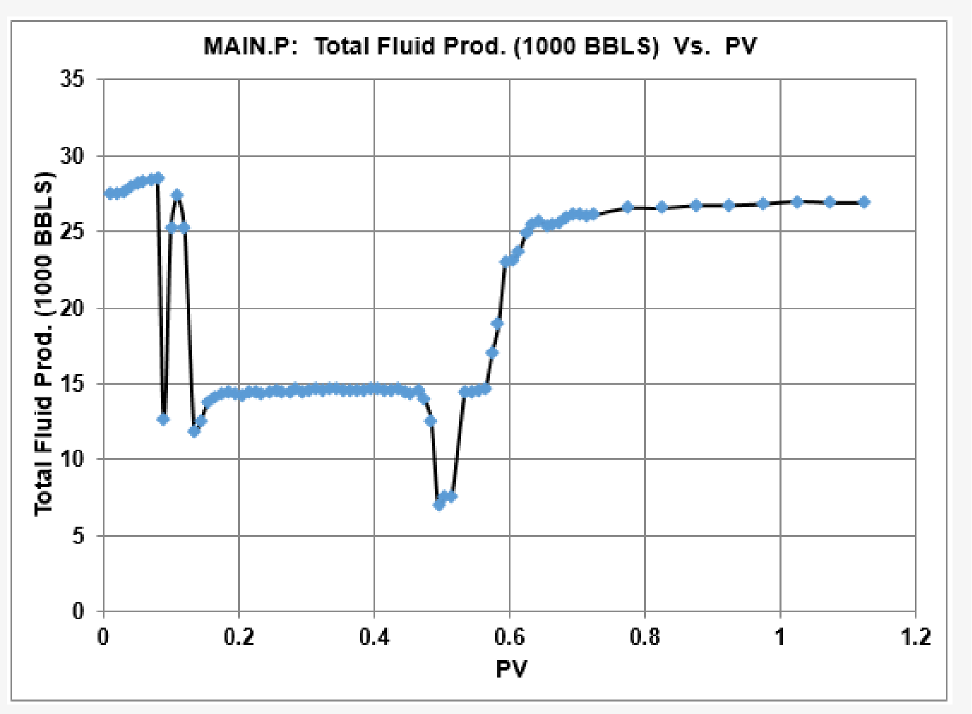
Based on these two graphs, overal production rate is constant but after some days this rate will increase.

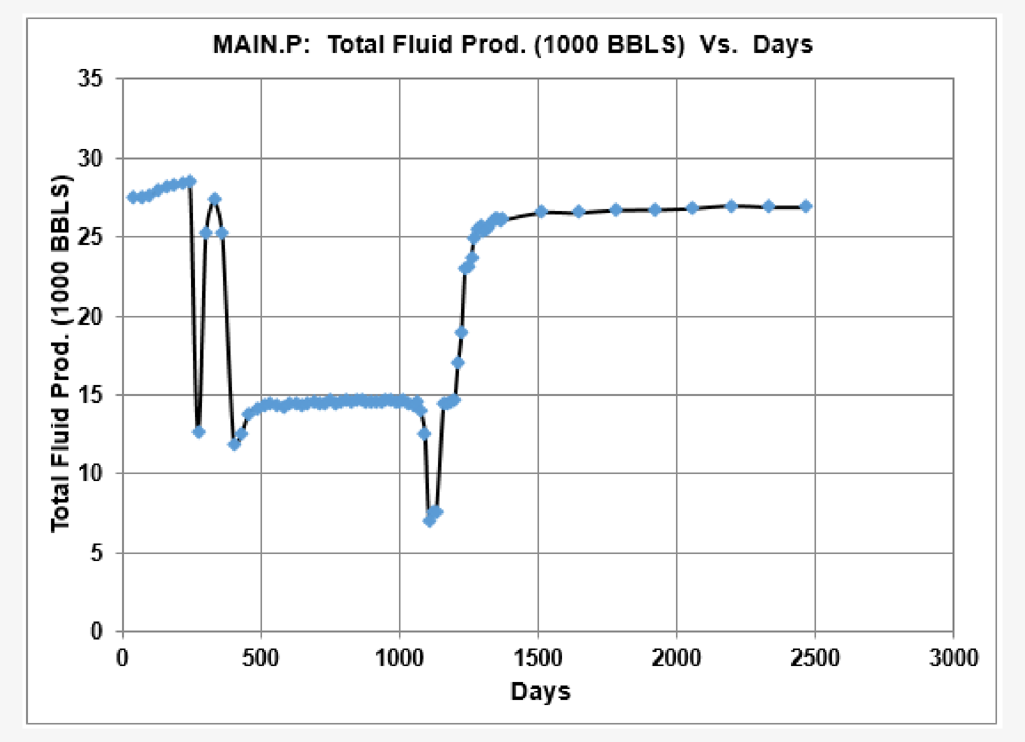




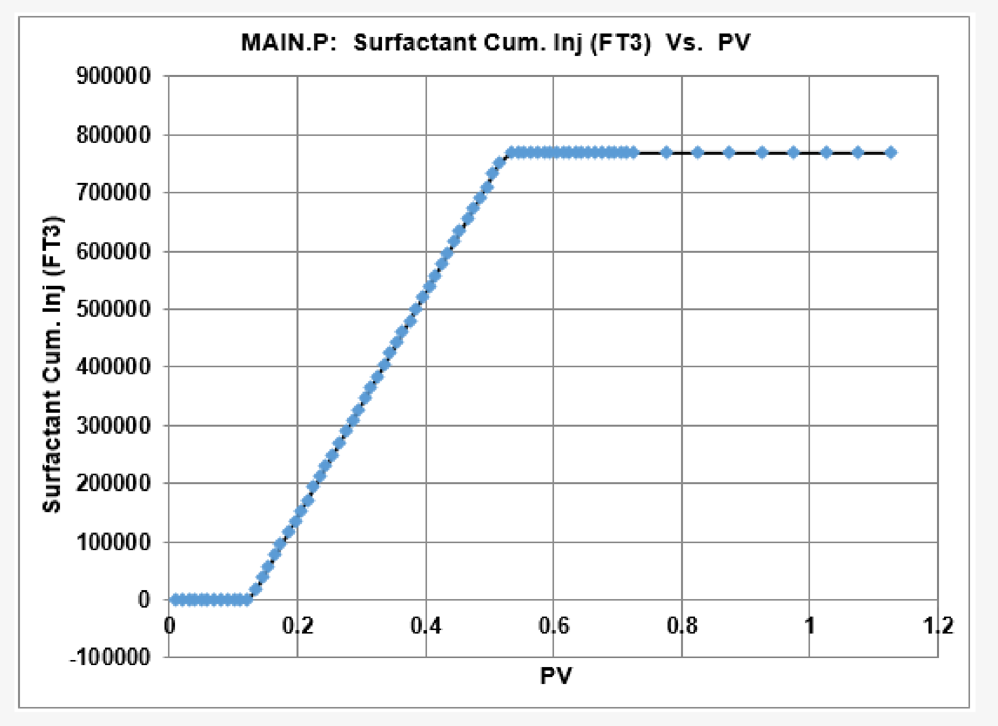
These two graphs presents amount of fluid injection during the time also different volumes.

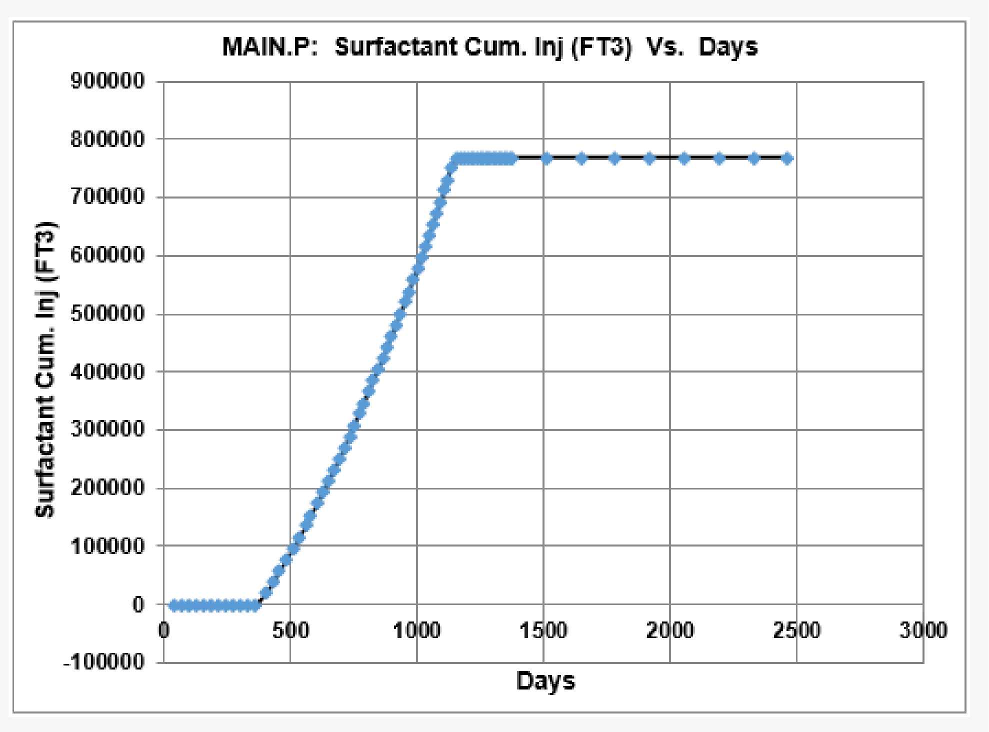
If there are big variation between some points, it is natural because in some points amount of surfactant and injected water are different. In some points because of process pressure this amount should be lass than normal time.



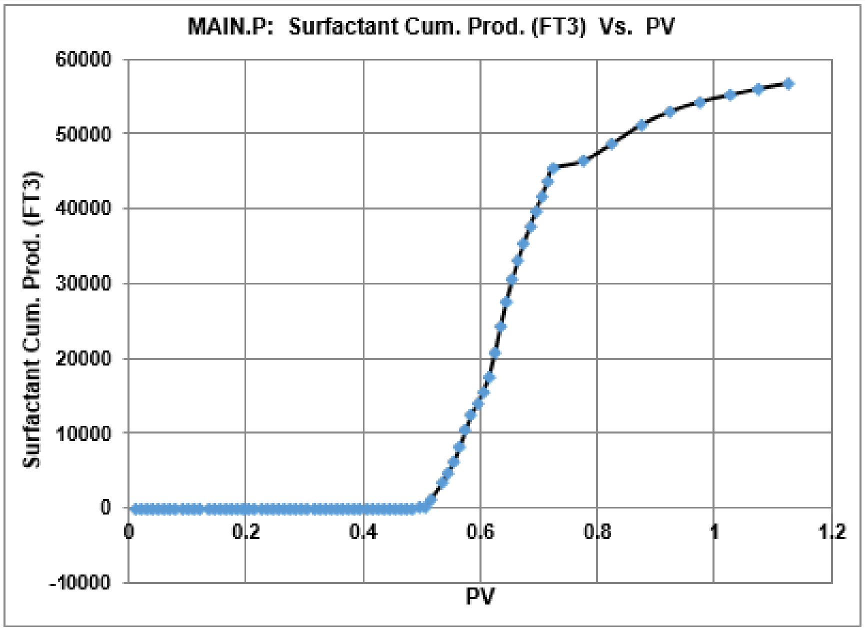


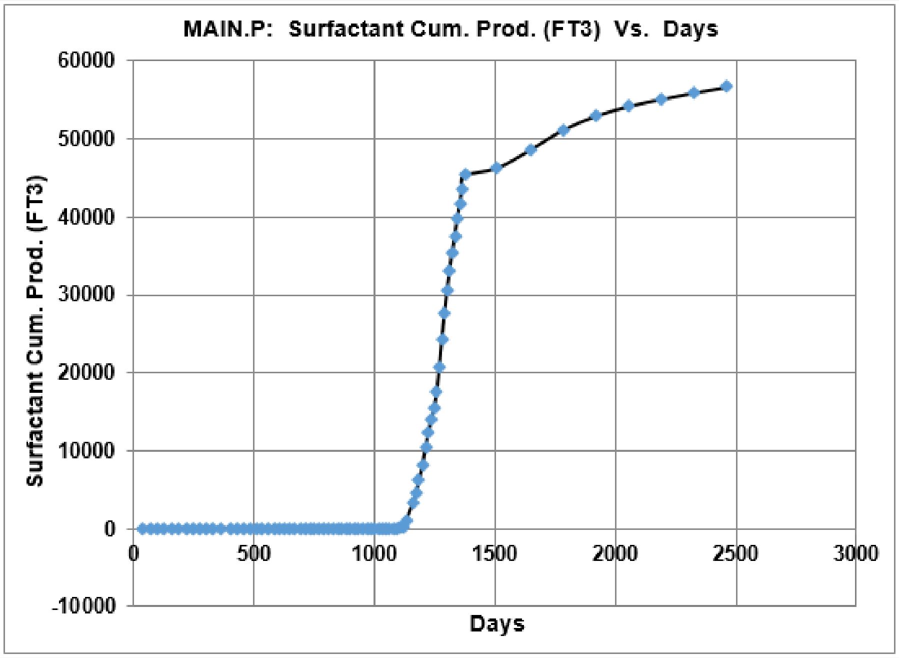
These two graphs shows rate total fluid production after water injection in different volume and different days. Again same previous graphs, there different points that is because of reservoir properties and process conditions.



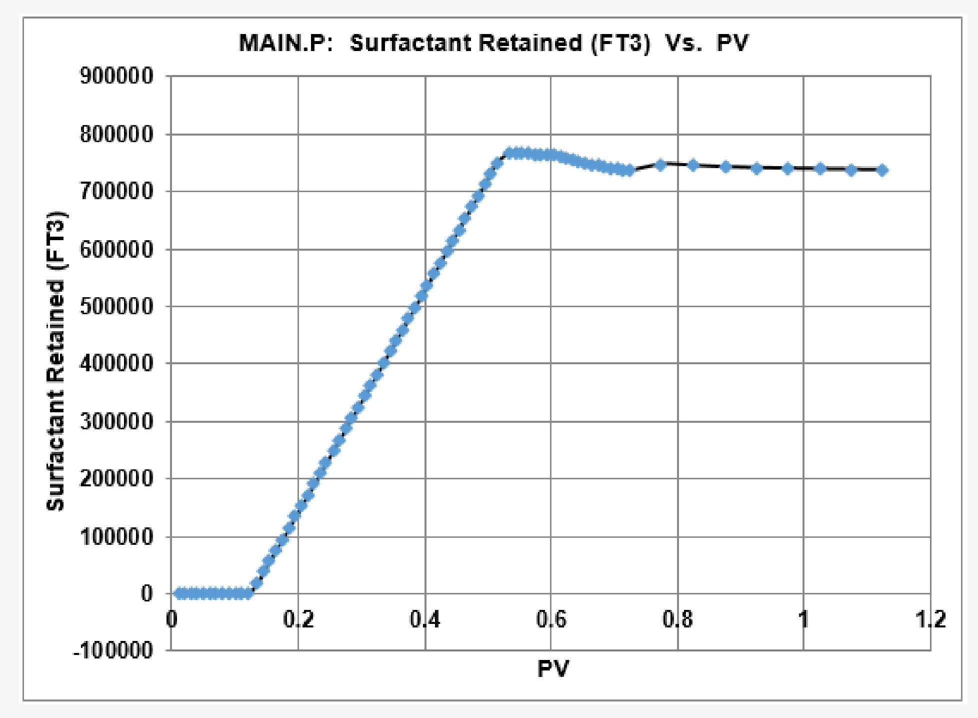


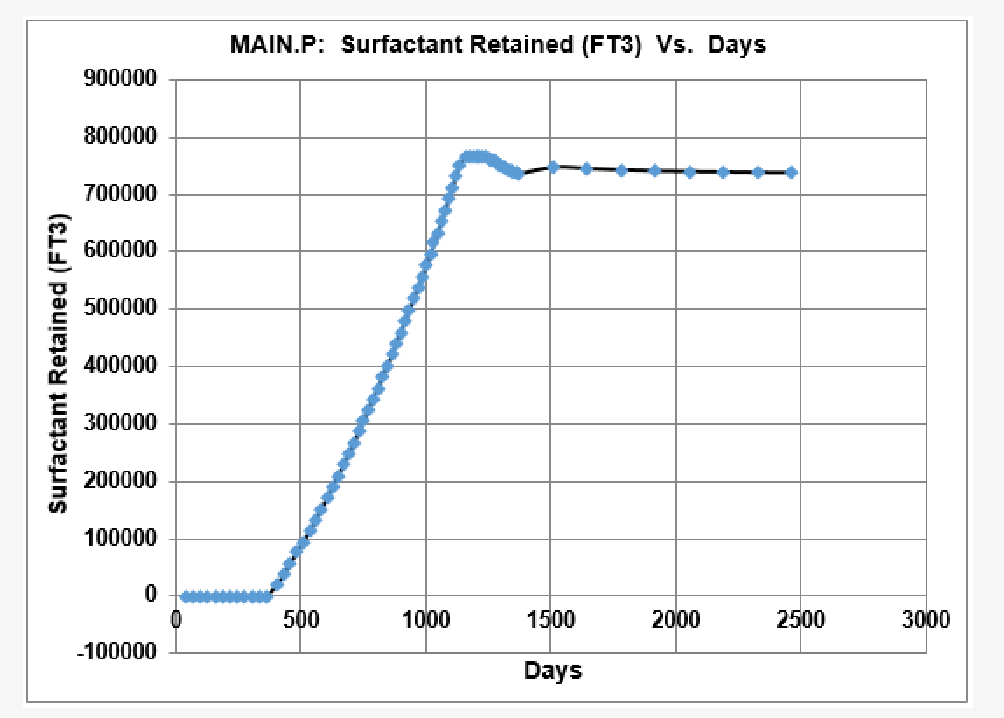
These two graphs shows rate of surfactant cumulative injection per volume and per day. The unit is FT3 or cubic feet and based on graphs, this parameter at the beginning is 0 and during the time with increase of surfactant injection will increase.





These two graphs shows rate of surfactant cumulative in production. As graphs say, at the begginig and after some days there is no surfactant but after one point this this rate suddenlly increase and in durring the time this increase will continue.





These two graphs present amount of surfactant retained after production. This amount also during the time increase and after high rise in peak of production, will change to stady and constant rate.

8 Conclusion

In this project tried to explain main concept of smart water and evaluate different methods in this technology.

After data analyzing that should be based on theory part, some important experiments had been done. These experiments can explain different parameters in order to evaluate water flooding.

For experiments, two different surfactants chose and all calculation done for both of them. The main reason of this selection was comparison between Anionic and Cationic surfactants.

In experiments part, two essential parameters (wettability and Interfacial tension) considered and showed us with adding surfactant these two parameters also changed.

These parameters analyzed in different concentrations and based on surfactant's behavior, all calculations have been done logically.

For simulation part, cationic surfactant was under consideration and according to final simulation, we can estimate rate of injected surfactant, production rate, surfactant retained and other calculations.

Based on simulation graphs, adding surfactant at the beginning cannot increase oil production and after some days with increase pressure in reservoir and becoming saturated, oil recovery will increase.

With data about amount of recovered oil and surfactant this issue should be consider that using this surfactant is functional or not that in this project with using 1% surfactant was acceptable and just related to geology properties. With exact data and details about reservoir properties, this estimate would be more real and functional.

Another important issue is environmental impacts. Using chemical materials and inject to the reservoirs can change many parameters in seabed and effect on animals life. Retained surfactant also has to consider because based on materials and properties can be harmful for ecosystem.

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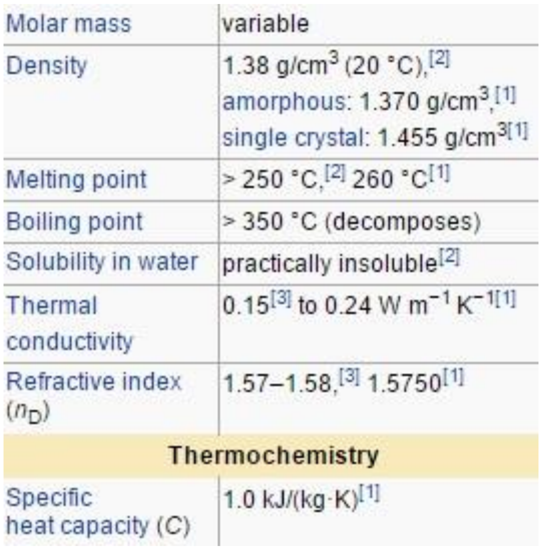
APPENDIX – Data sheets

[Appendix 1] surfactant's properties used from produced company

http://www.accudynetest.com/polytable_03.html?sortby=contact_angle

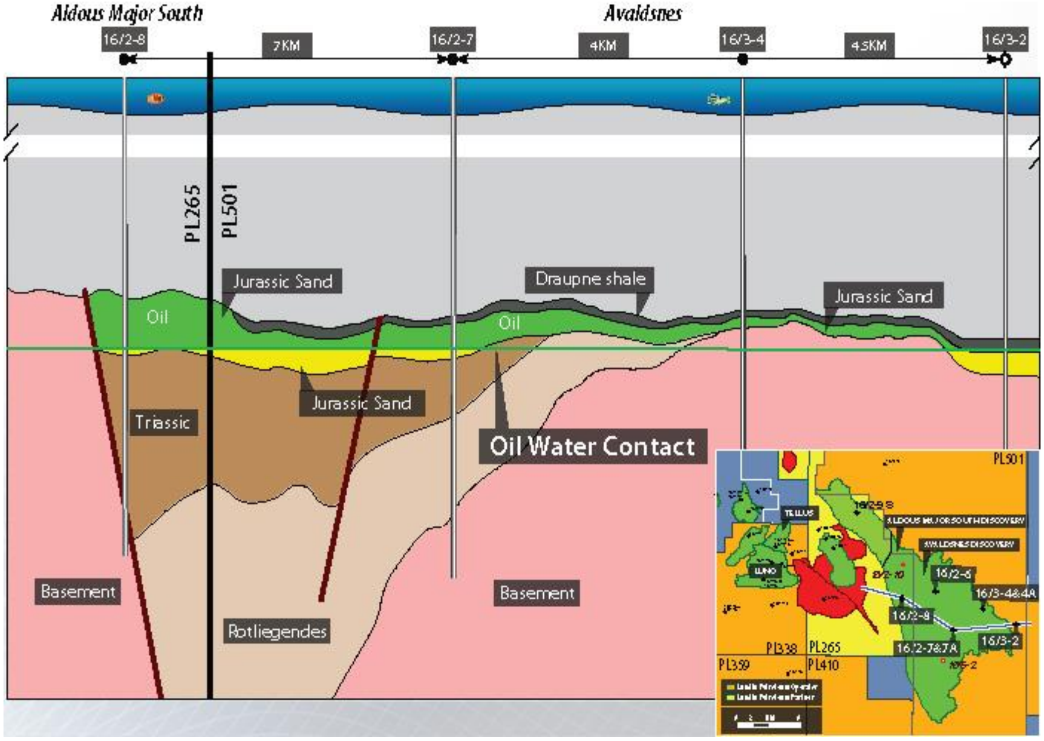


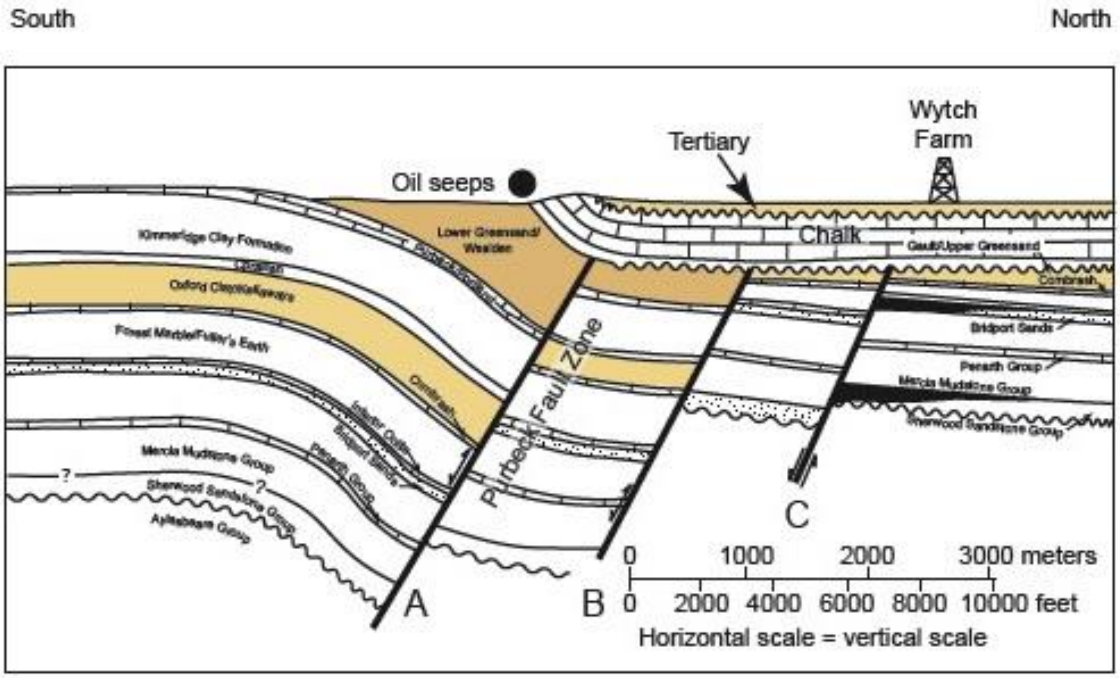
Molar mass	variable
Density	1.38 g/cm^3 (20 °C),[2] amorphous: 1.370 g/cm^3,[1] single crystal: 1.455 g/cm^3[1]
Melting point	> 250 °C,[2] 260 °C[1]
Boiling point	> 350 °C (decomposes)
Solubility in water	practically insoluble[2]
Thermal conductivity	0.15[3] to 0.24 W m^{-1} K^{-1}[1]
Refractive index (n_D)	1.57–1.58,[3] 1.5750[1]
Thermochemistry	
Specific heat capacity (C)	1.0 kJ/(kg·K)[1]

Young's modulus (E)	2800–3100 MPa
Tensile strength(σ_t)	55–75 MPa
Elastic limit	50–150%
notch test	3.6 kJ/m^2
Glass transition temperature (Tg)	67 to 81 °C
Vicat B	82 °C
linear expansion coefficient (α)	7×10^{-5}/K
Water absorption (ASTM)	0.16
Source[1]	

[Appendix 2]

https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/197333/TR_SEA2_Geology.pdf




South
North
Wytch
Farm
Tertiary
Oil seeps
Chalk
Lower Greensand/
Wealden
Kimmeridge Clay Formation
Corallian
Oxford Clay/Kellaways
Forest Marble/Fuller's Earth
Cornbrash
Inferior Oolite
Bridport Sands
Penarth Group
Mercia Mudstone Group
Sherwood Sandstone Group
Aylesbeare Group
Purbeck Fault Zone
Gault/Upper Greensand
Cornbrash
Bridport Sands
Penarth Group
Mercia Mudstone Group
Sherwood Sandstone Group
?
?
A
B
C
0
1000
2000
3000 meters
0
2000
4000
6000
8000
10000 feet
Horizontal scale = vertical scale

[Appendix 3]

PV	DAYS	AVE. P (PSI	CUM OIL (	CUM. OIL	Overall Inj.	Overall Prc	Total Fluid	Total Fluid	Productior	Productior	Productior	Overall Prc	Overall Prc	Overall Prc	Overall Sat	Overall Sat	Overall Sat	Surfactant	Surfactant	Surfactant	Surfactant	Surfactant Ads.(ML/ML PV)
0.010058	37.777	2787.3	9.0625	4869100	20967	31485	18.31	27.495	186.02	31299	0	0.005908	0.99409	0	0.24724	0.75276	0	0	0	0	0	0
0.020188	69.23	2731	10.506	5644900	22469	21641	28.568	27.516	110.52	21531	0	0.005107	0.99489	0	0.25784	0.74216	0	0	0	0	0	0
0.030063	98.229	2769.2	11.657	6262900	23788	21535	30.569	27.674	102.08	21433	0	0.00474	0.99526	0	0.26778	0.73222	0	0	0	0	0	0
0.040261	127.95	2809.1	12.845	6901200	23327	21648	30.112	27.945	95.753	21552	0	0.004423	0.99558	0	0.27804	0.72196	0	0	0	0	0	0
0.050365	157.54	2842.1	14.039	7542900	23468	21784	30.364	28.186	90.463	21694	0	0.004153	0.99585	0	0.2883	0.7117	0	0	0	0	0	0
0.060075	185.91	2871.9	15.192	8162600	23505	22168	29.96	28.256	87.437	22081	0	0.003944	0.99606	0	0.29818	0.70182	0	0	0	0	0	0
0.070122	215.09	2897.2	16.401	8812000	23676	22422	30.031	28.44	84.453	22337	0	0.003767	0.99623	0	0.30846	0.69154	0	0	0	0	0	0
0.080152	244.04	2920.1	17.614	9463800	23842	22671	29.949	28.479	82.253	22589	0	0.003628	0.99637	0	0.31877	0.68123	0	0	0	0	0	0
0.090121	272.76	2959.5	18.776	10088000	23551	21076	14.141	12.655	71.69	21004	0	0.003402	0.9966	0	0.32886	0.67114	0	0	0	0	0	0
0.10038	302.66	2993.9	19.986	10738000	23635	21894	27.306	25.295	74.074	21820	0	0.003383	0.99662	0	0.33938	0.66062	0	0	0	0	0	0
0.11016	331	3032.6	21.125	11350000	23668	21547	30.078	27.383	75.164	21472	0	0.003488	0.99651	0	0.34935	0.65065	0	0	0	0	0	0
0.12032	360.45	3073.8	22.304	11984000	23659	21438	27.938	25.315	123.31	21315	0	0.005752	0.99425	0	0.35971	0.64029	0	0	0	0	0	0
0.13478	402.28	3128.9	23.916	12850000	21229	22418	11.214	11.842	2515.8	19902	0	0.11223	0.88777	0	0.3737	0.62428	0.002023	19473	4.24E-13	6521.8	19187	1.71E-05
0.14477	431.69	3152.7	24.948	13404000	25983	21983	14.833	12.55	3867	18116	0	0.1759	0.8241	0	0.38231	0.61323	0.00446	38698	4.52E-10	9974.7	38165	2.62E-05
0.15477	456.48	3234	25.795	13859000	26812	24035	15.429	13.831	5388.8	18647	0	0.2242	0.7758	0	0.38993	0.60488	0.005186	57950	1.19E-08	15434	57169	4.05E-05
0.16474	482.93	3256.6	26.701	14346000	24669	24847	14.057	14.159	6792.9	18055	0	0.27338	0.72662	0	0.39713	0.59677	0.006095	77129	1.51E-07	20634	76088	5.42E-05
0.17486	509.87	3273.6	27.584	14820000	25876	24939	14.878	14.34	7680.1	17259	0	0.30795	0.69205	0	0.40398	0.58806	0.007967	96608	8.44E-07	25142	95348	6.6E-05
0.18473	534.47	3315.2	28.359	15237000	28284	25419	16.083	14.454	8703	16716	0	0.34238	0.65762	0	0.41018	0.57981	0.010011	115600	2.51E-06	29709	114150	7.8E-05
0.19476	558.71	3354.7	29.108	15639000	32299	26690	17.34	14.328	10128	16562	0	0.37947	0.62053	0	0.41647	0.5708	0.012736	134910	5.74E-06	35998	133370	9.44E-05
0.20475	580.79	3405.2	29.793	16007000	29863	28358	14.975	14.22	11799	16559	0	0.41608	0.58392	0	0.42239	0.56274	0.014873	154130	1.15E-05	42452	152380	0.000111
0.21466	603.88	3420.4	30.489	16381000	30530	28681	15.422	14.488	12746	15935	0	0.44441	0.55559	0	0.42761	0.55605	0.016333	173200	2.42E-05	48546	171360	0.000127
0.22486	625.74	3461.3	31.131	16726000	32249	29887	15.581	14.44	14279	15608	0	0.47778	0.52222	0	0.42961	0.5488	0.021587	192830	4.66E-05	53861	190890	0.000141
0.23486	647.76	3477	31.757	17062000	30743	30146	14.656	14.371	15233	14913	0	0.5053	0.4947	0	0.4342	0.54232	0.023476	212070	8.7E-05	58618	209930	0.000154
0.24473	669.65	3487.5	32.35	17381000	31115	30465	14.777	14.468	16171	14294	0	0.53081	0.46919	0	0.44182	0.53688	0.021298	231060	0.000146	63143	228860	0.000166
0.25483	691.5	3504.1	32.918	17686000	32429	30665	15.396	14.559	16996	13669	0	0.55425	0.44575	0	0.44466	0.53097	0.024367	250500	0.000234	67907	248250	0.000178
0.26477	711.6	3544.3	33.428	17960000	34809	31575	15.895	14.418	17713	13862	0	0.561	0.439	0	0.44303	0.52391	0.033063	269630	0.00034	73457	267400	0.000193
0.27486	731.2	3592.7	33.95	18241000	35307	31991	16.009	14.506	17236	14755	0	0.53879	0.46121	0	0.44267	0.51614	0.041191	289050	0.000491	79681	286630	0.000209
0.28469	750.53	3624.6	34.499	18536000	35139	33040	15.57	14.64	17289	15751	0	0.52328	0.47672	0	0.45284	0.51059	0.03657	307960	0.001034	85422	305660	0.000224
0.29482	769.32	3663.8	35.066	18840000	36579	34599	15.295	14.467	18049	16551	0	0.52165	0.47835	0	0.45148	0.50431	0.044209	327470	0.002841	92005	325070	0.000241
0.30467	787.62	3689.3	35.636	19147000	37158	35027	15.435	14.549	18039	16987	0	0.51502	0.48498	0	0.454	0.49805	0.04795	346410	0.007015	97815	343830	0.000256
0.31471	806.75	3699.8	36.252	19478000	35069	35282	14.622	14.711	17777	17506	0	0.50384	0.49616	0	0.45786	0.49229	0.049855	365730	0.014617	102390	363090	0.000268
0.32467	825.77	3705.3	36.87	19809000	36204	35760	14.769	14.588	18517	17243	0	0.51781	0.48219	0	0.46211	0.48658	0.051305	384900	0.025621	106590	382350	0.000279
0.33481	844.92	3710	37.466	20130000	36729	36058	14.972	14.698	19857	16201	0	0.55071	0.44929	0	0.46859	0.48096	0.050444	404410	0.041831	111370	401910	0.000292
0.34471	863.45	3712.5	38.008	20421000	37737	36718	15.041	14.635	21517	15201	0	0.586	0.414	0	0.4729	0.47606	0.051039	423470	0.066446	116090	421200	0.000304
0.3548	881.52	3725.1	38.504	20687000	38116	37570	14.804	14.592	23278	14293	0	0.61957	0.38043	0	0.48023	0.4715	0.048275	442880	0.11317	120920	440750	0.000317
0.36474	898.88	3743.1	38.961	20933000	40350	38024	15.429	14.539	23596	14428	0	0.62056	0.37944	0	0.47858	0.46711	0.054305	462010	0.19844	125930	460000	0.00033
0.37467	915.87	3761.3	39.434	21187000	40841	39067	15.262	14.599	23779	15288	0	0.60867	0.39133	0	0.48322	0.46249	0.054294	481120	0.3273	130930	479190	0.000343
0.38472	932.97	3773.7	39.922	21449000	40049	39350	14.858	14.598	23853	15497	0	0.60617	0.39383	0	0.4874	0.45747	0.05513	500470	0.48529	135670	498560	0.000355
0.39472	950.01	3782	40.403	21708000	40884	39690	15.119	14.677	25068	14622	0	0.6316	0.3684	0	0.4885	0.45233	0.059179	519710	0.6497	139880	517810	0.000366
0.40466	966.9	3787.2	40.841	21943000	40315	40127	14.713	14.644	26884	13243	0	0.66998	0.33002	0	0.48918	0.44733	0.063498	538840	0.90304	143710	537000	0.000376
0.41476	983.92	3790.9	41.239	22157000	40811	40669	14.593	14.542	28669	11999	0	0.70495	0.29505	0	0.49569	0.44264	0.061672	558280	1.4138	147550	556550	0.000386
0.42484	1000.6	3795.5	41.596	22349000	41708	41498	14.654	14.58	30424	11073	0	0.73316	0.26684	0	0.49402	0.43841	0.067572	577670	2.34	151730	576100	0.000397
0.43474	1016.2	3809	41.91	22518000	43529	42650	14.972	14.67	32078	10572	0	0.75213	0.24787	0	0.49841	0.43493	0.066659	596720	3.6473	156900	595270	0.000411
0.44484	1032.1	3813.8	42.215	22682000	44114	43769	14.627	14.513	33658	10111	0	0.76898	0.23102	0	0.49616	0.43179	0.072046	616160	5.3688	162730	614930	0.000426
0.45471	1047.2	3820.7	42.499	22834000	45706	44054	14.868	14.331	33525	10529	0	0.76101	0.23899	0	0.5037	0.4288	0.067504	635160	7.2263	168960	634310	0.000442
0.46476	1062.3	3837.8	42.832	23013000	45860	44256	15.088	14.56	30540	13715	0	0.69009	0.30991	0	0.50072	0.42515	0.074121	654500	9.1849	175560	653780	0.00046
0.47468	1077.2	3842.7	43.231	23227000	46719	46222	14.112	13.962	31351	14871	0	0.67827	0.32173	0	0.50481	0.42128	0.073903	673580	11.268	181810	673150	0.000476
0.48471	1091.9	3837.3	43.645	23449000	47846	48080	12.493	12.554	32750	15330	0	0.68115	0.31885	0	0.50584	0.41726	0.076907	692900	14.117	187230	692790	0.00049
0.49475	1106.2	3806.8	44.085	23686000	48741	52459	6.5802	7.082	35032	17427	0	0.6678	0.3322	0	0.50617	0.4133	0.080529	712210	33.939	191960	712480	0.000503
0.50467	1120	3791.5	44.445	23880000	49864	50634	7.4737	7.589	37097	13009	527.81	0.73266	0.25692	0.010424	0.49901	0.40998	0.091002	731290	159.24	195480	731840	0.000512
0.51468	1133.6	3788.6	44.78	24059000	50448	50624	7.568	7.5944	37702	12282	640.25	0.74474	0.24261	0.012647	0.49713	0.4066	0.096269	750560	1148.3	198540	750350	0.00052
0.53434	1159.8	3793	45.393	24389000	52514	52477	14.505	14.495	39444	12282	750.43	0.75165	0.23405	0.0143	0.49167	0.4	0.10833	768750	3358.6	204490	767150	0.000535
0.54414	1172.6	3787.2	45.71	24559000	51831	54283	13.756	14.407	40445	12888	949.29	0.74509	0.23742	0.017488	0.50992	0.39697	0.093107	768750	4648.9	208290	766850	0.000545
0.55421	1185.8	3762.7	46.072	24754000	51291	54779	13.617	14.544	38984	14693	1102.8	0.71165	0.26822	0.020131	0.5254	0.39398	0.080615	768750	6203.1	213030	766610	0.000558
0.56427	1198.9	3728.9	46.487	24976000	52561	57300	13.455	14.668	38582	17394	1324.7	0.67332	0.30356	0.023119	0.542	0.39109	0.06691	768750	8128	218530	765920	0.000572
0.57429	1211.9	3676.6	46.943	25222000	54518	62588	14.794	16.984	39919	21351	1317.6	0.63781	0.34114	0.021052	0.54868	0.38852	0.062804	768750	10365	224300	765030	0.000588
0.58415	1224.1	3619.1	47.432	25484000	56338	67351	15.876	18.979	40188	26019	1143.8	0.5967	0.38631	0.016983	0.55245	0.386	0.061551	768750	12387	230320	764160	0.000604
0.59432	1236.2	3548.4	47.964	25770000	59127	70941	19.179	23.011	44800	25229	911.27	0.63151	0.35564	0.012845	0.55661	0.38334	0.060054	768750	13962	236600	763800	0.00062

0.60424	1247.4	3484.2	48.463	26038000	62058	67646	21.237	23.15	44496	21844	1306.2	0.65778	0.32291	0.01931	0.56394	0.38079	0.055274	768750	15584	242140	763340	0.000635
0.61422	1258.3	3459.4	48.865	26255000	63295	64411	23.287	23.698	47454	15239	1717.4	0.73674	0.2366	0.026663	0.56757	0.37827	0.054163	768750	17602	246480	761950	0.000646
0.62435	1269.2	3454.6	49.205	26437000	63837	64615	24.603	24.902	46991	14679	2944.3	0.72726	0.22718	0.045567	0.57042	0.37604	0.053544	768750	20743	249640	759040	0.000655
0.6342	1279.7	3451.3	49.538	26616000	64252	64787	25.237	25.447	47522	14537	2728.5	0.73351	0.22438	0.042115	0.57312	0.37388	0.053001	768750	24326	252140	755590	0.000661
0.64421	1290.4	3445.9	49.87	26795000	64640	65122	25.533	25.723	48181	14517	2424.3	0.73985	0.22292	0.037227	0.57594	0.37173	0.052334	768750	27652	254330	752420	0.000667
0.65423	1301	3442.8	50.194	26968000	64977	65530	25.195	25.41	48921	14472	2137	0.74655	0.22084	0.03261	0.57854	0.36958	0.051884	768750	30534	256240	749660	0.000672
0.66416	1311.4	3439.2	50.51	27138000	65394	66077	25.204	25.467	49615	14535	1927.5	0.75087	0.21996	0.02917	0.58108	0.36747	0.05145	768750	33116	257860	747210	0.000676
0.67413	1321.8	3435.3	50.821	27305000	65888	66336	25.425	25.598	50100	14427	1808.2	0.75525	0.21749	0.027259	0.58376	0.36539	0.050849	768750	35424	259280	745020	0.00068
0.6842	1332.3	3429.7	51.128	27470000	66307	67092	25.706	26.011	51170	14223	1698.3	0.76269	0.212	0.025313	0.58617	0.36332	0.050513	768750	37594	260560	743000	0.000683
0.69438	1342.8	3425.2	51.432	27634000	66702	67242	25.922	26.132	51565	14008	1669.3	0.76685	0.20832	0.024825	0.58888	0.36127	0.049847	768750	39741	261660	740960	0.000686
0.70421	1352.8	3421.8	51.718	27787000	67028	67498	25.919	26.101	52196	13727	1574.9	0.77329	0.20337	0.023333	0.59113	0.35933	0.049543	768750	41693	262610	739100	0.000689
0.71442	1363.2	3418.6	52.007	27943000	67305	67706	25.896	26.051	52720	13492	1493.5	0.77867	0.19927	0.022059	0.59342	0.35735	0.04923	768750	43596	263520	737270	0.000691
0.72424	1373.2	3415.6	52.28	28089000	67554	67977	25.945	26.108	53204	13342	1431.1	0.78267	0.19627	0.021053	0.5956	0.35546	0.048934	768750	45336	264330	735610	0.000693
0.77449	1509.7	2692.1	53.88	28949000	25159	24935	26.812	26.574	20604	4330.7	2.89E-19	0.82632	0.17368	1.16E-23	0.60151	0.35139	0.047104	768750	46323	262990	746860	0.000692
0.82468	1646.5	2689.8	55.002	29552000	25159	25275	26.443	26.564	21126	3949	199.36	0.83587	0.15624	0.007888	0.61091	0.34244	0.046646	768750	48643	265850	744650	0.000699
0.8747	1782.7	2675.9	55.92	30045000	25159	25346	26.542	26.74	22165	3059.4	121.37	0.87451	0.12071	0.004788	0.61849	0.33538	0.046131	768750	51213	268200	742280	0.000706
0.92461	1918.7	2664.8	56.667	30446000	25159	25296	26.61	26.755	22627	2577.9	91.628	0.89447	0.10191	0.003622	0.62465	0.32964	0.045703	768750	52982	270500	740670	0.000712
0.97488	2055.7	2654.2	57.311	30792000	25159	25253	26.736	26.835	22838	2352.7	62.139	0.90437	0.093166	0.002461	0.62997	0.32471	0.045317	768750	54254	272680	739550	0.000718
1.0247	2191.5	2647.1	57.86	31087000	25159	25209	26.965	27.019	23206	1954.6	48.832	0.92053	0.077534	0.001937	0.63451	0.32044	0.045053	768750	55160	274310	738740	0.000722
1.0746	2327.3	2640.7	58.334	31342000	25159	25222	26.858	26.925	23449	1734.4	38.248	0.92972	0.068765	0.001517	0.63846	0.31676	0.044777	768750	55974	275770	738020	0.000726
1.1247	2463.9	2634.9	58.758	31570000	25159	25215	26.852	26.911	23631	1552.7	30.902	0.9372	0.061577	0.001226	0.64196	0.31346	0.044585	768750	56708	277010	737360	0.000729

[Appendix 4]

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