Sudan University of Science & Technology

College of Petroleum Engineering & Technology

Department of Petroleum Engineering

Designing of Steam Flooding Pilot Test for a Sudanese Oil Field

(FNE Oil Field-Case Study)

تصميم نموذج تجريبي للحقن بالبخار لحقل سوداني

(حقل الفولة (شمال شرق)– دراسة حالة)

Prepared by:

1. Muntasir Mohammed Ali Omar
2. Mohammed TahaDafallaElzain
3. ImanAbdElraheemAlzubairAlbasheer
4. Abdelbagi Dafallah Abdelgabar Dafallah

Supervisor: Husham Awadelsseid Ali

` October, 2016

الإستهلال

قال الله تعالى:

﴿ إقرء بإسم ربك الذي خلق * خلق الإنسان من علق *
إقراء وربك الأكرم * الذي علم بالقلم * علم
الإنسان ما لم يعلم ﴾

صدق الله العظيم

Dedication

To our fathers and mothers, the source of encouragement and inspiration to us throughout our life.

To our supervisor **Husham Awadelsseid Ali** for his guidance and support throughout this study.

To the spirit of **Dr. Mohammed Naeim**

To our brothers and sisters who stand with us, allow us to use their purpose when we need it to complete this research.

To our dear friends who supported us.

For future generations that hold future of the oil industry in Sudan.

To anyone who taught us how to fight life.

Finally, this thesis is dedicated to all those who believe in the richness of learning.

Acknowledgment

Thank to Allah before and after everything.

On a personal note, we would like to thank our parents for their everlasting encouragement, patience, understanding and ability to motivate us. This could not have been done without your support.

We would like to thank our supervisor **Husham Awadelsseid Ali**, for his guidance, direction, feedbacks and offering encouragement precisely when needed and without which it would have been nearly impossible to produce this piece of work.

We wish to express our sincere thanks to **Dr. Tagwa Musa**, Dean of the Faculty, for the continuous encouragement.

Thanks to all our friends for encouragement in many moments Thanks to **College of Petroleum Engineering and Technology**, especially all the members of the petroleum Engineering department.

Abstract

Thermal methods are the most commonly used and most advanced enhanced oil recovery methods around the world. They are best suited for heavy oils (10º-20º) API, and tar sands (≤10 API). One of the thermal EOR method is the steam flooding, which is a pattern drive similar to water flooding; in which the steam is injected continuously with a certain quality (i.e. 80% steam and 20% water) to the reservoir having shallow depth which is preferred. It forms a steam zone which advanced slowly in the reservoir heating the oil and reducing its viscosity. In addition to continuous steam injection, oil is pushed toward the producer.

FNE field is a Sudanese heavy (high viscous) oil field, which need Steam Flooding (SF) to be implemented in the field after the current Cyclic Steam Stimulation (CSS) in the same field and getting low recovery factor (only 3.60%). FNE field consist of three structure units in oil-bearing area: (FNE-1, FNE-3 and FNE-N).

In this report, detail analysis for the current situation of FNE field has been done, then selection of the pilot area in the field (FNE-3), and several simulation models for different development scenarios have been built, each scenario with different steam injection parameters, all this to compare the feasibility of applying steam flooding versus applying the other scenarios like DNC, CSS, Infill wells (cold) and infill wells (css), and to determine the optimum steam flooding parameters to be applied in FNE-3, all this is done by using the thermal simulator of Computer Modeling Group (CMG) software.

From the results obtained after the designing and future forecasting till 2026, it has been found that implementation of (SF) after the current (CSS) in FNE-3 will give high productivity (4.9 MM bbl) as compared with CSS which give only (3.575 MM bbl), and the recovery factor by (SF) will reach up to 20.41% comparing with the current value for the field, which is only 3.60%. Also the optimum steam flooding parameters have been determined as follows: injection rate of 250 m3/day and temperature of 200 (^{0}C) and steam quality equal 80%.

التجريد

تعتبر الطرق الحرارية لاستخلاص النفط هي الأكثر تقدمّاً واستخداماً من بين طرق الاستخلاص المحسّن للنفط في العالم، فهي الأنسب للزيوت الثقيلة (كثافتها 10-20 درجة) و ورمال القطران (كثافتها اقل من 10 درجات). إحدى الطرق الحراريّة للاستخلاص المعزّز للنفط هي الحقن بالبخار، وهو نمط دفع مثل الغمر المائي، يتم حقن البخار باستمرار بجودة معيّنة (80% بخار و20% ماء) الى المكمن ذو العمق الضحل (يفضّل ذلك). وتتشكّل منطقة بخار تتقدّم ببطء في المكمن؛ تسخّن النّفط وتقلّل لزوجته، بالاضافة الى أنّ الحقن المستمر للبخار يقوم بدفع الزيت نحو البئر المنتجة.

حقل الفولة (شمال- شرق) يعتبر من الحقول السودانية ذات الزيت الثقيل (عالي الزوجة)، والذي يحتاج تطبيق الحقن بالبخار بعد تطبيق الحقن المتقطّع للبخار فيه والتحصل على معامل استخلاص منخفض 3.6 %.

في هذا البحث، تم اجراء تحليل مفصّل للوضعية الحالية للحقل، وتمّ اختيار منطقة نموذجية في الحقل، ونمّ بناء نماذج محاكاة لسيناريوهات مختلفة لتحديد المعاملات المثلى للحقن بالبخار، ومقارنة جدوى تطبيق الحقن المستمر بالبخار مع عدم حقن شيء او استخدام الحقن المتقطّع للبخار في الحقل كل هذا باستخدام المحاكي الحراري لبرنامج CMG.

من النتائج التي تمّ الحصول عليها بعد التصميم؛ فقد وُجد أنّ تنفيذ الغمر بالبخار بعد الحقن الحالي المتقطّع للبخار في حقل الفولة (شمال- شرق) يعطي إنتاجيّة عاليّة (4.9 مليون برميل) مقارنة مع (3.575مليون برميل) في حالة الاستمرار بالحقن المتقطّع للبخار؛ ومعامل الاستخلاص يصل إلى 20.41% ، وكذلك تمّ تحديد المعاملات المثلى للحقن بالبخار وهي: معدّل حقن 250 متر مكعّب/يوم، بدرجة حرارة 200 درجة مئوية و جودة بخار 80%.

Table of contents

List of Figures

List of Tables

Nomenclature

AOR	:	Advanced Oil Recovery
API	:	American Petroleum Institute
ASP	:	Alkaline-Surfactant-Polymer
BOPD	:	Barrel Oil per Day
CHOPS	:	Cold Heavy Oil Production with Sand
CMG	:	Computer Modeling Group
CMOST	:	Computer Assisted History Matching , Optimization and Uncertainty Assessment Tool
CO_2	:	Carbon Dioxide
CPF	:	Central Processing Facilities
CSS	:	Cyclic Steam Stimulation
DC	:	Direct Current
DNC	:	Do Nothing Case
DWOC	:	Depth of Water Oil Contact
EEOR	:	Electro Enhanced Oil Recovery
EOR	:	Enhanced Oil Recovery
EPI	:	Electro Petroleum Inc
ES-SAGD	:	Expanding Solvent Steam Assisted Gravity Drainage
EUR	:	Enhanced Ultimate Recovery
FNE	:	Fula North East
FSU	:	Former Soviet Union
HASD	:	Heated Annulus Steam Drive
IFT	:	Interfacial Tension
IMEX	:	Implicit Explicit Black Oil Simulator
IOR	:	Improved Oil Recovery
ISC	:	In-situ Combustion
LASER	:	Liquid Addition to Steam for Enhanced Recovery
MCM	:	Multiple Contact Miscible
NP	:	Cumulative Oil Production
OOIP	:	Original Oil in Place
PE	:	Petro Energy
PSI	:	Pound per Square Inch

REFDEPTH	:	Reference Depth
REFPRESS	:	Reference Pressure
RF	:	Recovery Factor
SA-CSS	:	Solvent Assisted Cyclic Steam Stimulation
SAGD	:	Steam Assisted Gravity Drainage
SATUR	:	Saturation
SCM	:	Single Contact Miscible
SF	:	Steam Flooding
S_{or}	:	Residual Oil Saturation
SOR	:	Steam Oil Ratio
STARS	:	Steam Thermal and Advanced Processes Reservoir Simulator
STB	:	Stock Tank Barrel
S_w	:	Water Saturation, fraction
SWAG	:	Simultaneous Injection of Water and Gas
TAN	:	Total Acid Number
TEMP	:	Temperature
TEOR	:	Thermal Enhanced Oil Recovery
TSX	:	Texas
WAG	:	Water Alternating Gas

Chapter 1

Introduction

Chapter 1: Introduction

1.1 General Introduction

The term "enhanced oil recovery" refers to any method used to recover more oil from a reservoir than would not be obtained by primary recovery. Since the early 1950's, a significant amount of laboratory research and field testing has been undertaken, and some of the resulting findings have been developed on a commercial scale. (Teknica, 2001).

EOR is characterized by injection of special fluids such as: chemicals, miscible gases and /or the injection of thermal energy. (Ronald .E, 2001).

EOR Refers to any method used to recover more oil from a reservoir than would not be obtained by primary recovery. (Teknica, 2001).

EOR refers to the recovery of oil through the injection of fluids and energy not normally present in the reservoir.(Green & Willhite, 1998).

1.2 Development Sequence

The terms primary oil recovery, secondary oil recovery, and tertiary (enhanced) oil recovery are traditionally used to describe hydrocarbons recovered according to the method of production or the time at which they are obtained.(Ronald, 2001).

1.2.1 Primary Oil Recovery:

Describes the production of hydrocarbons under the natural driving mechanisms present in the reservoir without supplementary help from injected fluids such as gas or water. In most cases, the natural driving mechanism is a relatively inefficient process and results in a low overall oil recovery. The lack of sufficient natural drive in most reservoirs has led to the practice of supplementing the natural reservoir energy by introducing some form of artificial drive, the most basic method being the injection of gas or water. (Ronald, 2001).

1.2.2 Secondary Oil Recovery:

Refers to the additional recovery those results from the conventional methods of water injection and immiscible gas injection. Usually, the selected secondary recovery process follows the primary recovery but it can also be conducted concurrently with the primary recovery. However, before undertaking a secondary recovery project, it should be clearly proven that the natural recovery processes are insufficient; otherwise there is a risk that the substantial capital investment required for a secondary recovery project may be wasted. Gas-water combination floods, known as water alternating gas injection (WAG), where slugs of water and gas are injected sequentially. Simultaneous injection of water and gas (SWAG) is also practiced, however the most common fluid injected is water because of its availability, low cost, and high specific gravity which facilitates injection. (Ronald ,2001).

1.2.2.1 Water Injection:

In water injection operation, the injected water is discharged in the aquifer through several injection wells surrounding the production well. The injected water creates a bottom water drive on the oil zone pushing the oil upwards. The water injection is generally carried out when solution gas drive is present or water drive is weak. Therefore for better economy the water injection is carried out when the reservoir pressure is higher than the saturation pressure.

1.2.2.2 Gas Injection:

It is the oldest of the fluid injection processes. This idea of using a gas for the purpose of maintaining reservoir pressure and restoring oil well productivity was suggested as early as 1864 just a few years after the Drake well was drilled. The first gas injection projects were designed to increase the immediate productivity and were more related to pressure maintenance rather to enhanced recovery. Gas may offer economic advantages. Gas injection may be either a miscible or an immiscible displacement process. (Ronald ,2001).

1.2.3 Tertiary (Enhanced) Oil Recovery:

Is that additional recovery over and above what could be recovered by primary and secondary recovery methods. Various methods of enhanced oil recovery (EOR) are essentially designed to recover oil, commonly described as residual oil, left in the reservoir after both primary and secondary recovery methods have been exploited to their respective economic limits. Tarik (2010).

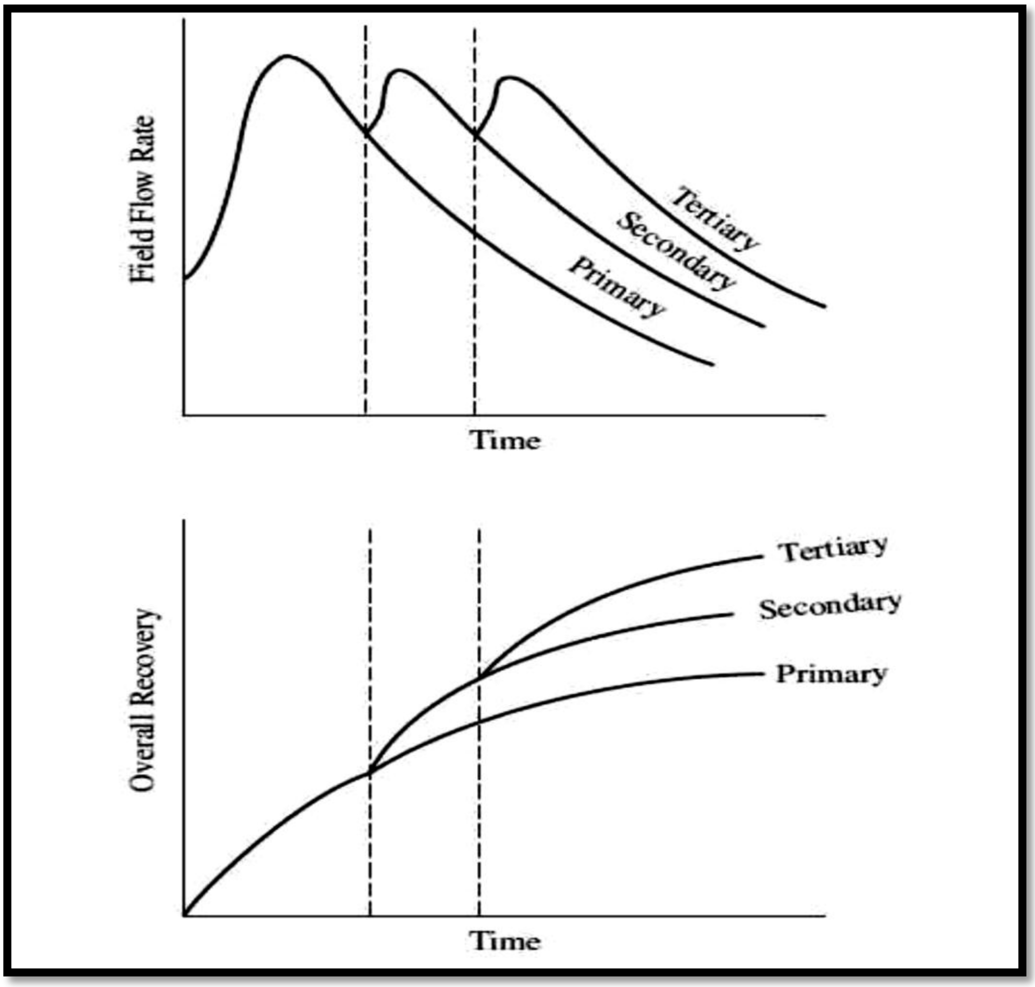


Figure 1-1: Oil Recovery Categories. (Tarik,2010)

During tertiary oil recovery, fluids different than just conventional water and immiscible gas are injected into the formation to effectively boost oil production.

Thus EOR can be implemented as a tertiary process if it follows a water flooding or an immiscible gas injection, or it may be a secondary process if it follows primary recovery directly. Nevertheless, many EOR recovery applications are implemented after water flooding. (Romero-Zerón, 2011).

At this point is important to establish the difference between EOR and Improved Oil Recovery (IOR) to avoid misunderstandings. The term Improved Oil Recovery (IOR) techniques refers to the application of any EOR operation or any other advanced oil-recovery technique that is implemented during any type of ongoing oil recovery process. Examples of IOR applications are any conformance improvement technique that is applied during primary, secondary, or tertiary oil recovery operations. Other examples of IOR applications are: hydraulic fracturing, scale-inhibition treatments, acid-stimulation procedures, infill drilling, and the use of horizontal wells. (S.Thomas,2008).

When to start EOR?

A common procedure for determining the optimum time to start EOR process after water flooding depends on:

- Anticipated oil recovery
- Fluid production rates
- monetary investment
- Costs of water treatment and pumping equipment
- Costs of maintenance and operation of the water installation facilities
- Costs of drilling new injection wells or converting existing production wells into injectors.

The injected fluids must accomplish several objectives (Green & Willhite, 1998). asfollows:-

1- Boost the natural energy in the reservoir
2- Interact with the reservoir rock/oil system to create conditions favorable for residual oil recovery that include among others
    - Reduction of the interfacial tension between the displacing fluid and oil
    - Increase the capillary number
    - Reduce capillary forces
    - Increase the drive water viscosity
    - Provide mobility-control
    - Oil swelling
    - Oil viscosity reduction
    - Alteration of the reservoir rock wettability

The ultimate goal of EOR processes is to increase the overall oil displacement efficiency, which is a function of microscopic and macroscopic displacement efficiency. Microscopic efficiency refers to the displacement or mobilization of oil at the pore scale and measures the effectiveness of the displacing fluid in moving the oil at those places in the rock where the displacing fluid contacts the oil (Green& Willhite, 1998). For instance, microscopic efficiency can be increased by reducing capillary forces or interfacial tension between the displacing fluid and oil or by decreasing the oil viscosity. (Satter et al 2008).

1.3 Enhanced Oil Recovery Classification:

Enhanced oil recovery processes include all methods that use external sources of energy and/or materials to recover oil that cannot be produced economically by conventional means.

EOR processes can be classified broadly as:

- Thermal methods: steam stimulation, steam flooding, hot water drive, and in-situ combustion.
- Chemical methods: polymer, surfactant, caustic (Alkaline), and Alkaline Surfactant Polymer ASP.
- Miscible methods: hydrocarbon gas, CO2, and nitrogen. In addition, flue gas and partial miscible/immiscible gas flood may be also considered. (Tarik 2010)

EOR methods are presented in figure below:-

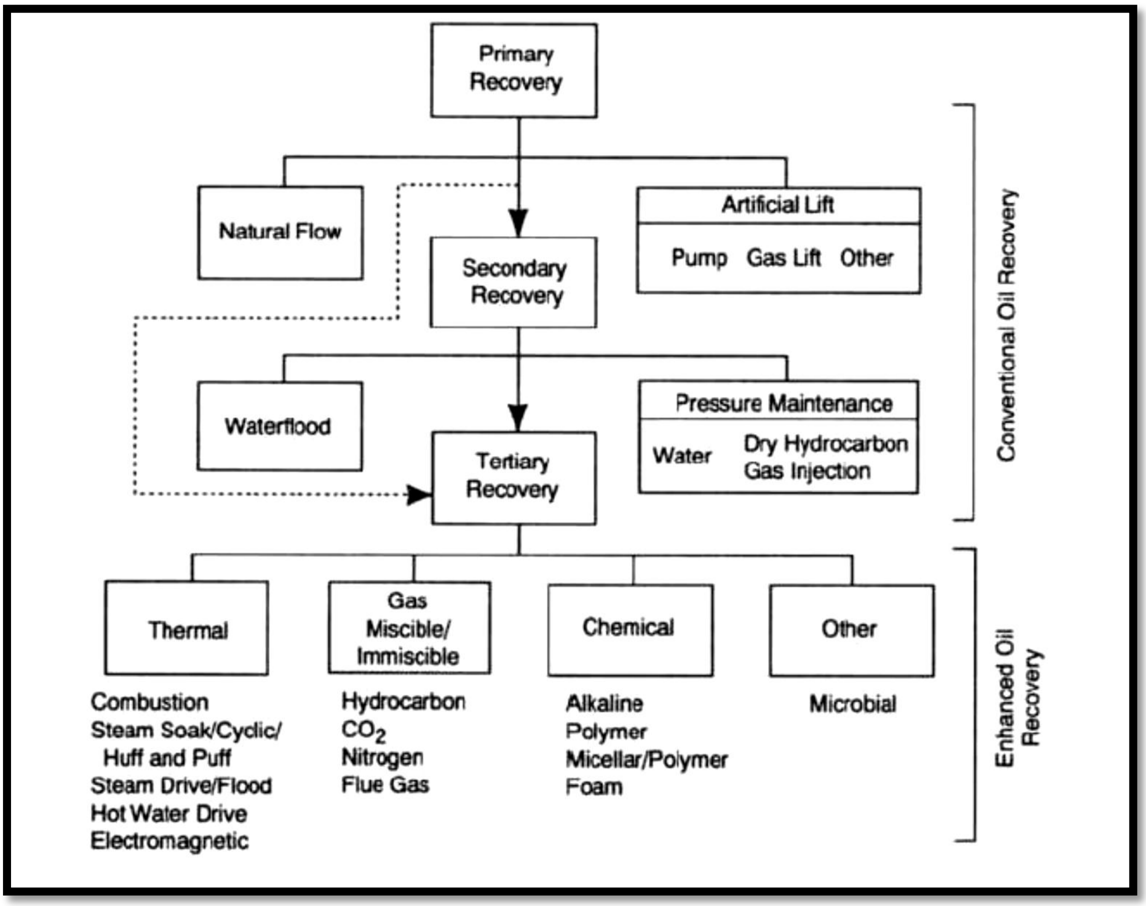


Figure 1-2: EOR Recovery Mechanisms.(From OGJ 1992).

1.3.1 Thermal EOR (TEOR)

Thermal enhanced oil recovery (TEOR) is a family of tertiary processes defined as "any process in which heat is introduced intentionally into a subsurface accumulation of organic compounds for the purpose of recovering fuels through well” (Prats,1982).

Thermal methods of EOR entail the application of heat to the oil well. Thermal methods have been tested since 1950’s, and they are the most advanced among EOR methods, as far as field experience and technology are concerned. They are best suited for heavy oils (10-20° API) and tar sands (≤1-0° API). This acts to lower the viscosity of the oil and thus increase the mobility ratio. These methods are typically employed in relatively shallow oil wells with higher viscosity such as tar sands and heavy oil. Thermal methods of EOR have been highly successful in the US, Canada, Venezuela and Indonesia, and have also been used in China and Brazil. Within the US, Thermal methods account for around 40% of EOR production.

(Prats ,1982).

Thermal EOR (TEOR) consist of a lot methods such as:Steam Flooding (SD), Cyclic Steam Stimulation (CSS), and Steam Assisted Gravity Drainage (SAGD).In-situ Combustion (ISC), Solar EOR, Electro EOR (EEOR). Heated Annulus Steam Drive (HASD), Steam & Solvent Processes.(S. Thomas ,2008).

1.3.1.1 Cyclic Steam Stimulation (CSS)

Cyclic steam stimulation is a “single well” process, and consists of three stages, as shown in figure 1-3. In the initial stage, steam injection is continued for about a month. The well is then shut in for a few days for heat distribution, denoted by soak. Following that, the well is put on production.

Oil rate increases quickly to a high rate, and stays at that Level for a short time, and declines over several months. Cycles are repeated when the oil rate becomes uneconomic. Steam-oil ratio is initially 1-2 or lower, and it increases as the number of cycles increase. Near-well bore geology is important in CSS for heat distribution as well as capture of the mobilized oil. CSS is particularly attractive because it has quick payout, however, recovery factors are low (10-40% OOIP). In a variation, CSS is applied under fracture pressure. The process becomes more complex as communication develops among wells. (S.Thomas ,2008).

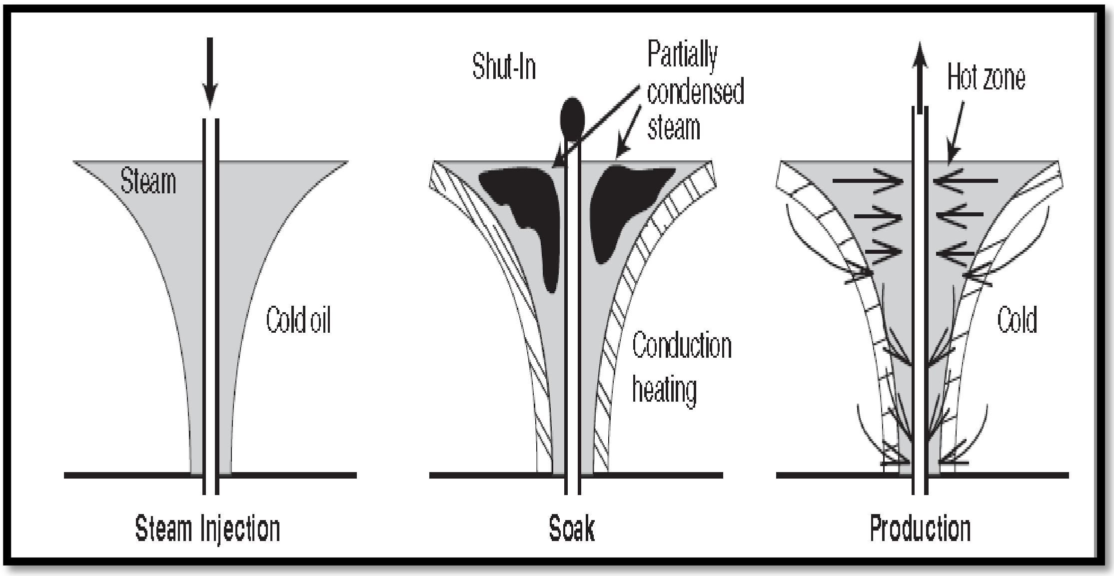


Figure 1-3: Illustrate the CSS Process. (S.Thomas 2008).

1.3.1.2 Steam Assisted Gravity Drainage (SAGD)

SAGD process relies on the gravity segregation of steam, utilizing a pair of parallel horizontal wells, Placed 5 m apart (in the case of tar sands) in the same vertical Plane. The schematic is shown in figure 1-4. The top well is the steam injector, and the bottom well serves as the producer. Steam rises to the top of the formation, forming a steam Chamber. High reduction in viscosity mobilizes the bitumen, which drains down by gravity and is captured by the producer Placed near the bottom of the reservoir. Continuous injection of steam causes the steam chamber to expand and spread laterally in the reservoir. High vertical permeability is crucial for the success of SAGD. The process performs better with Bitumen and oils with low mobility. (S.Thomas, 2008).

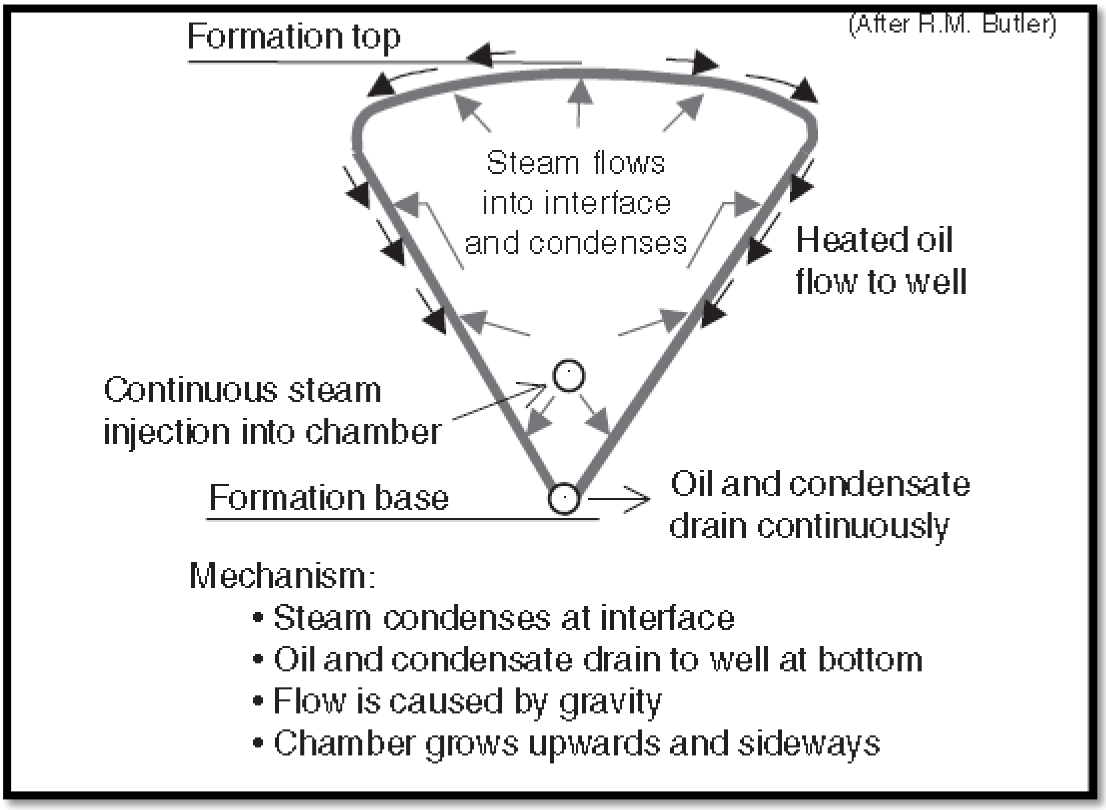


Figure 1-4:Illustrate SAGD Process. (S.Thomas ,2008).

1.3.1.3 In-situ Combustion (ISC)

In this method, also known as fire flooding air or oxygen is injected to burn a portion (~10%) of the in-place oil to generate heat. Very high temperatures, in the range of 450-600°C, are gene-rated in a narrow zone. High reduction in oil viscosity occurs near the combustion zone. The process has high thermal efficiency, since there is relatively small heat loss to the overburden or under burden, and no surface or well bore heat loss. In some cases, additives such as water or a gas is used along with air, mainly to enhance heat recover. See figure 1-5: (S.Thomas 2008).

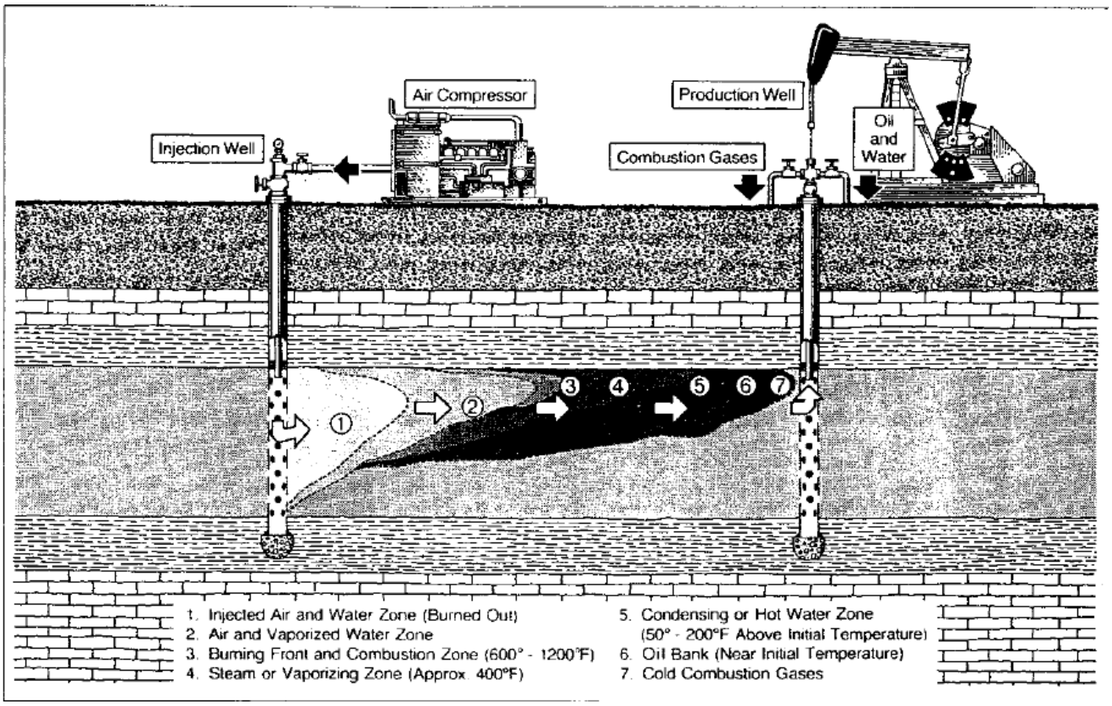


Figure 1-5:Illustrate ISC Process.(Green &Willhite ,1998).

1.3.1.4 Solar EOR

Solar thermal enhanced oil recovery (abbreviated solar EOR) is a form of thermal enhanced oil recovery (EOR), a technique applied by oil producers to extract more oil from maturing oil fields. Solar EOR uses solar thermal arrays to concentrate the sun's energy to heat water and generate steam. The steam is injected into an oil reservoir to reduce the viscosity, or thin, heavy crude thus facilitating its flow to the surface. Thermal recovery processes, also known as steam injection, have traditionally burned natural gas to produce steam. Solar EOR is proving to be a viable alternative to gas-fired steam production for the oil industry. Solar EOR can generate the same quality steam as natural gas, reaching temperatures up to 750˚F (400˚C) and 2,500 PSI. (Van Heel et al ,2010)

1.3.1.5 Electro EOR (EEOR)

Electro-Petroleum, Inc. (EPI) has successfully demonstrated use of DC electrical current for enhanced oil recovery (a process we now call "Electro-Enhanced Oil Recovery or EEOR) at heavy oil fields in the Santa Maria (California) Basin and the Eastern Alberta Plains. They have also conducted large-scale (1 cu-m sample size) laboratory studies to evaluate unexpected results from these field demonstrations. (Donald ,2008).

The EEOR process is based on the concept that by passing an electrical current through a conductive passing an electrical current through a conductive oil bearing formation, resistive heating of the-oil will occur with corresponding reduction in oil viscosity. (Killough &Gonzalez ,1986).

1.3.1.6 Heated Annulus Steam Drive (HASD)

Also called Horizontal Alternating Steam Drive. Used to produce from heavy oil fields by using steam. (Ficocelli et al ,2015).

HASD recovered more oil, though the initial production rate in HASD was low, (compared with SAGD & CSS by using a three dimensional thermal simulator). Sor in HASD was, however, very unfavorable (more than twice that of CSS vertical wells). HASD with offset wells made both SOR and % OOIP recovery more favorable. SAGD had better Sor than HASD; however, it recovered about half the oil recovered by HASD at the end of ten years of the study. (Avik et al ,1993).

1.3.1.7 Thermal & Solvent Processes

Expanding-Solvent Steam-Assisted Gravity Drainage (ES-SAGD) and Solvent-Assisted Cyclic Steam Stimulation (SA-CSS) are in situ steam-solvent recovery process to produce heavy oil and bitumen reservoirs. In ES-SAGD and SA-CSS, steam and solvent are injected into the depletion chamber within the reservoir. At the chamber edge, the steam releases its latent heat heating the oil there and solvent mixes with mobilized bitumen which then flows under gravity to the lower horizontal producer. (Sharma ,2010)

1.3.1.8 Steam Flooding

Steam flooding is an increasingly common method of extracting heavy crude oil. It is considered an enhanced oil recovery (EOR) method and is the main type of thermal stimulation of oil reservoirs (S.Thomas 2008).

In a steam flood, sometimes known as a steam drive, some wells are used as steam injection wells and other wells are used for oil production. Two mechanisms are at work to improve the amount of oil recovered. The first is to heat the oil to higher temperatures and to thereby decrease its viscosity so that it more easily flows through the formation toward the producing wells. A second mechanism is the physical displacement employing in a manner similar to water flooding, in which oil is meant to be pushed to the production wells. While more steam is needed for this method than for the cyclic method, it is typically more effective at recovering a larger portion of the oil. See figure 1-6 below: (Pwage, 2010).

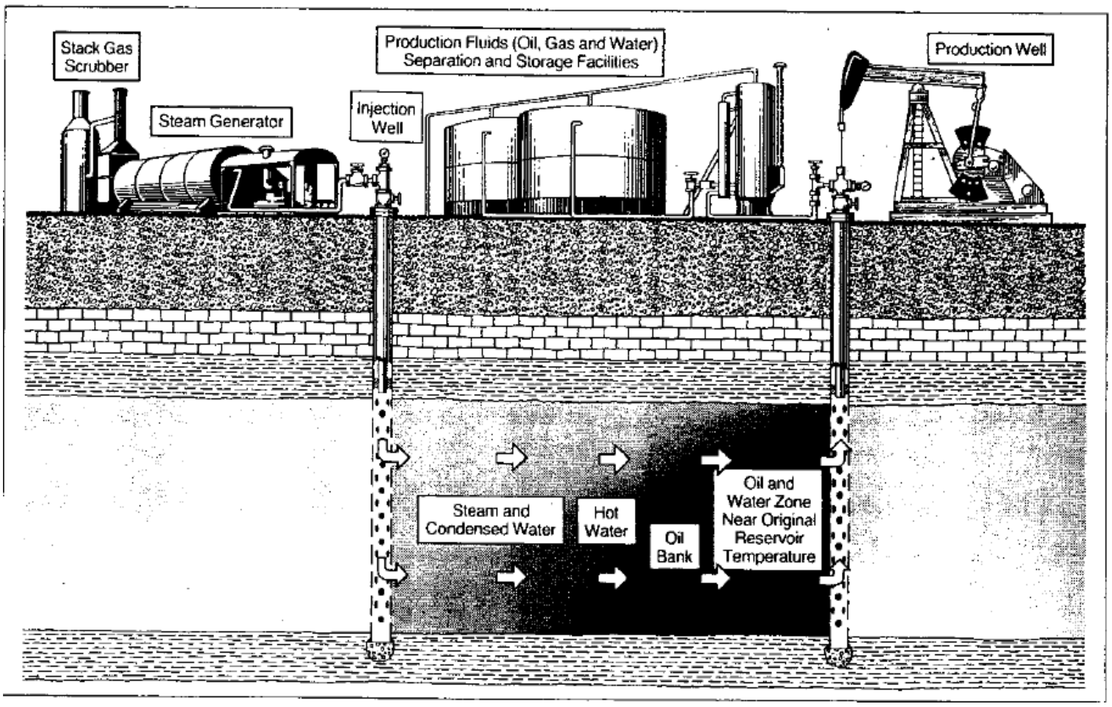


Figure 1-6: Illustrate Steam Flooding Process. (Green &Willhite ,1998)

1.4 Problem Statement

FNE is heavy oil field. The Cyclic Steam Stimulation (CSS) is currently implemented in FNE field,but the up to date recovery factor is only 3.60%, so this field should convert from CSS to steam flooding and need to determine the optimum injection parameters for the steam flooding process to be applied in FNE field.

1.5 Objectives of the Study

The objectives of this thesisare todetermine the feasibility of applying steam flooding in FNE field; by comparing between the results of applying Steam flooding in the field or applying DNC and CSS. Then determine the optimum steam injection parameters (prepare the design) (i.e. steam quality, injection rate, steam temperature), to be applied in the field. Thus increase the productivity and the recovery factor of FNE field.

1.6 Introduction to the Case Study

FNE Oilfield is geographically located in the southwest of Sudan, about 700 km from the capital, Khartoum; structurally located in the northeast of Fula sub-basin of Muglad basin and in the southwest of the Moga Oilfield.

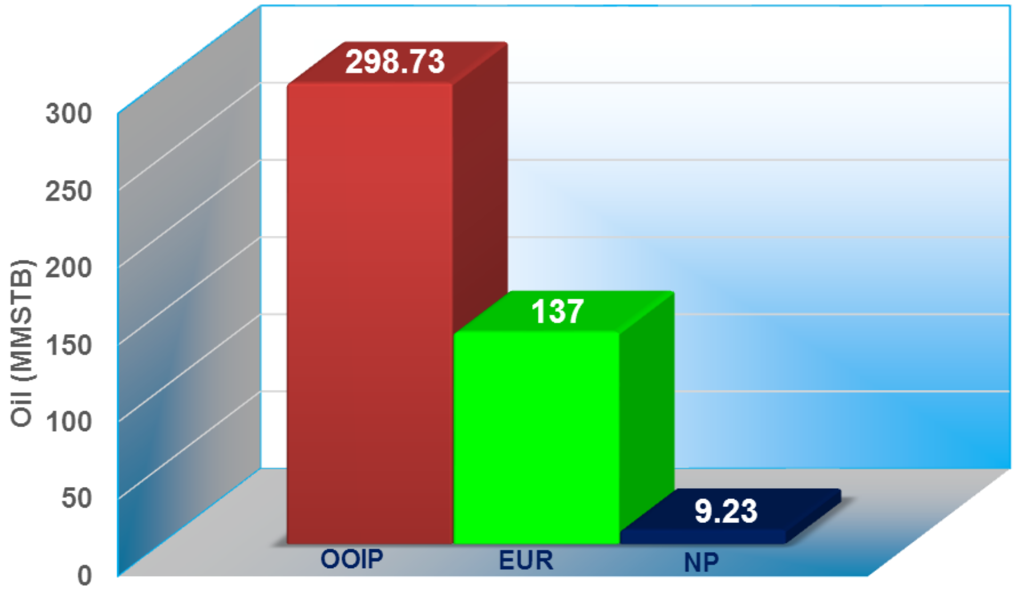


Figure 1-7: OOIP,EUR,and NP of FNE Oil Field. (Husham et al ,2016)

The above figure shows the OOIP, EUR and the cumulative production (NP) of FNE oil field.

FNE reservoirs are highly porous (~30%), permeable (1000-2000 mD) and unconsolidated in nature. the fluid properties include viscous crude with 15 to 17.7 API. Corresponding viscosities are in the range of 250 cp and 500 cp at reservoir conditions. (Husham et al ,2016).

1.7 Thesis Outlines:

In this thesis Chapter one include the general introduction, problem statement, objective of the study and introduction to case study. Chapter two is discussing the literature review and theoretical background of steam flooding, while chapter three is illustrating the methodology startingby analysis and then designing the optimum injection parameters using CMG software. Chapter four is contain the results and discussion of the research and finally chapter five is the conclusion and recommendations of the study.

Chapter 2

Theoretical Background and Literature Review

Chapter 2: Theoretical Background and Literature Review

2.1Theoretical Background

In the background there will be description for the concept and mechanism of EOR and steam flooding.

2.1.1 Steam flooding mechanism

Steam flooding is a pattern drive, similar to water flooding, and performance depends highly on pattern size and geology. Steam drive, also known as steam injection or continuous steam injection, involves generating steam of about 80% quality on the surface and forcing this steam down the injection wells and into the reservoir. When the steam enters the reservoir, it heats up the oil and reduces its viscosity. As the steam flows through the reservoir, it cools down and condenses. The heat from the steam and hot water vaporizes lighter hydrocarbons, or turn them into gases. These gases move ahead of the steam, cool down, and condense back into liquids that dissolve in the oil. In this way, the gases and steam provide additional gas drive. The hot water also moves the thinned oil to production wells, where oil and water are produced (Van Dyke, 1997) cited in (Laura , 2012).

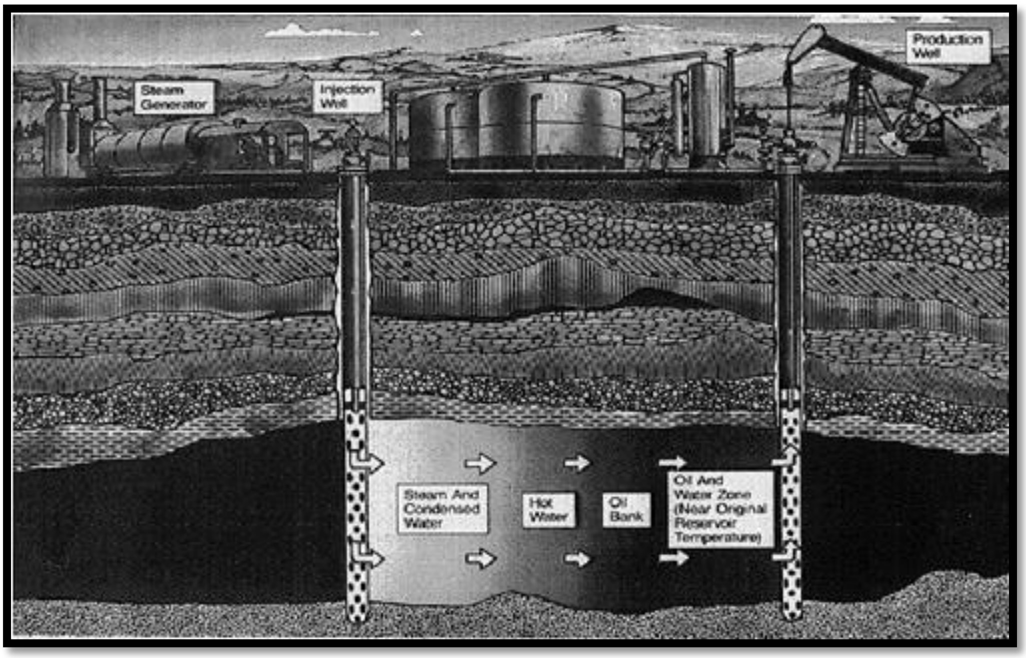


Figure 2-1 : Steam Flooding (SF) (Jelmert,T .et.all ,2010)

2.1.2 Flood patterns

One of the first steps in designing a steam flooding project is flood pattern selection. The objective is to select the proper pattern that will provide the injection fluid with the maximum possible contact with the crude oil system. This selection can be achieved by (1) converting existing production wells into injectors or (2) drilling infill injection wells.

In general, the selection of a suitable flooding pattern for the reservoir depends on the number and location of existing wells. In some cases, producing wells can be converted to injection wells while in other cases it may be necessary or desirable to drill new injection wells. Essentially four types of well arrangements are used in fluid injection projects. (Tarek, 2010):

- Irregular injection patterns
- Peripheral injection patterns
- Regular injection patterns
- Crestal and basal injection patterns

Irregular Injection Patterns

Willhite (1986) points out that surface or subsurface topology and/or the use of slant-hole drilling techniques may result in production or injection wells that are not uniformly located. In these situations, the region affected by the injection well could be different for every injection well. Some small reservoirs are developed for primary production with a limited number of wells and when the economics are marginal, perhaps only a few production wells are converted into injectors in a nonuniform pattern. Faulting and localized variations in porosity or permeability may also lead to irregular patterns(Tarek,2010).

Peripheral Injection Patterns

In peripheral flooding, the injection wells are located at the external boundary of the reservoir and the oil is displaced toward the interior of the reservoir.(Tarek2010).

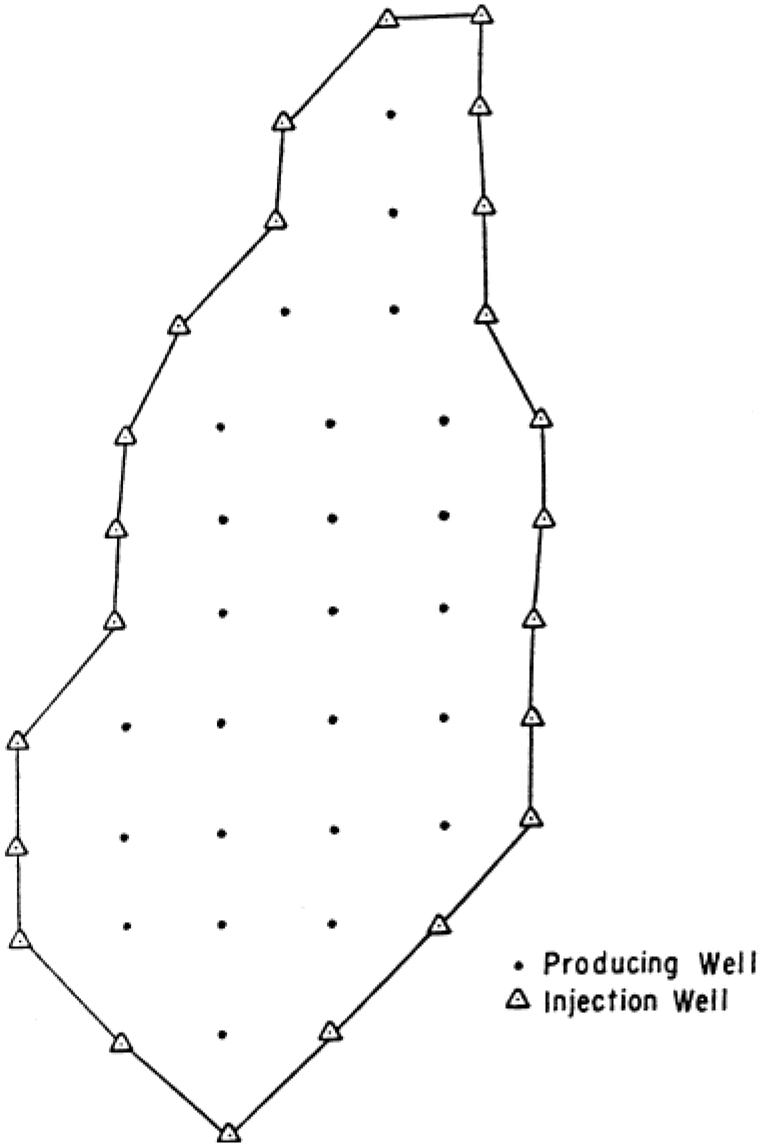


Figure 2.2 : Typical Peripheral Steam Flood(Tarik, 2010).

Regular Injection Patterns

Due to the fact that oil leases are divided into square miles and quarter square miles, fields are developed in a very regular pattern. A wide variety of injection-production well arrangements have been used in injection projects. The most common patterns. (Tarek2010).

- **Direct line drive**.

The lines of injection and production are directly opposed to each other. The pattern is characterized by two parameters ,a= distance between wells of the same type, and d = distance between lines of injectors and producers.

- **Staggered line drive:** the wells are in lines as in the direct line, but the injectors and producers are no longer directly opposed but laterally displaced by a distance of a/2.
- **Five spot:** this is a special case of the staggered line drive in which the distance between all like wells is constant, i.e., a = 2d. Any four injection wells thus form a square with a production well at the center.
- **Seven spot:** the injection wells are located at the corner of a hexagon with a production well at its center.
- **Nine spot:** this pattern is similar to that of the five spot but with an extra injection well drilled at the middle of each side of the square. The pattern essentially contains eight injectors surrounding one producer. The patterns termed **inverted** have only one injection well per pattern. This is the difference between **normal** and **inverted** well arrangements. Note that the four-spot and inverted seven-spot patterns are identical.

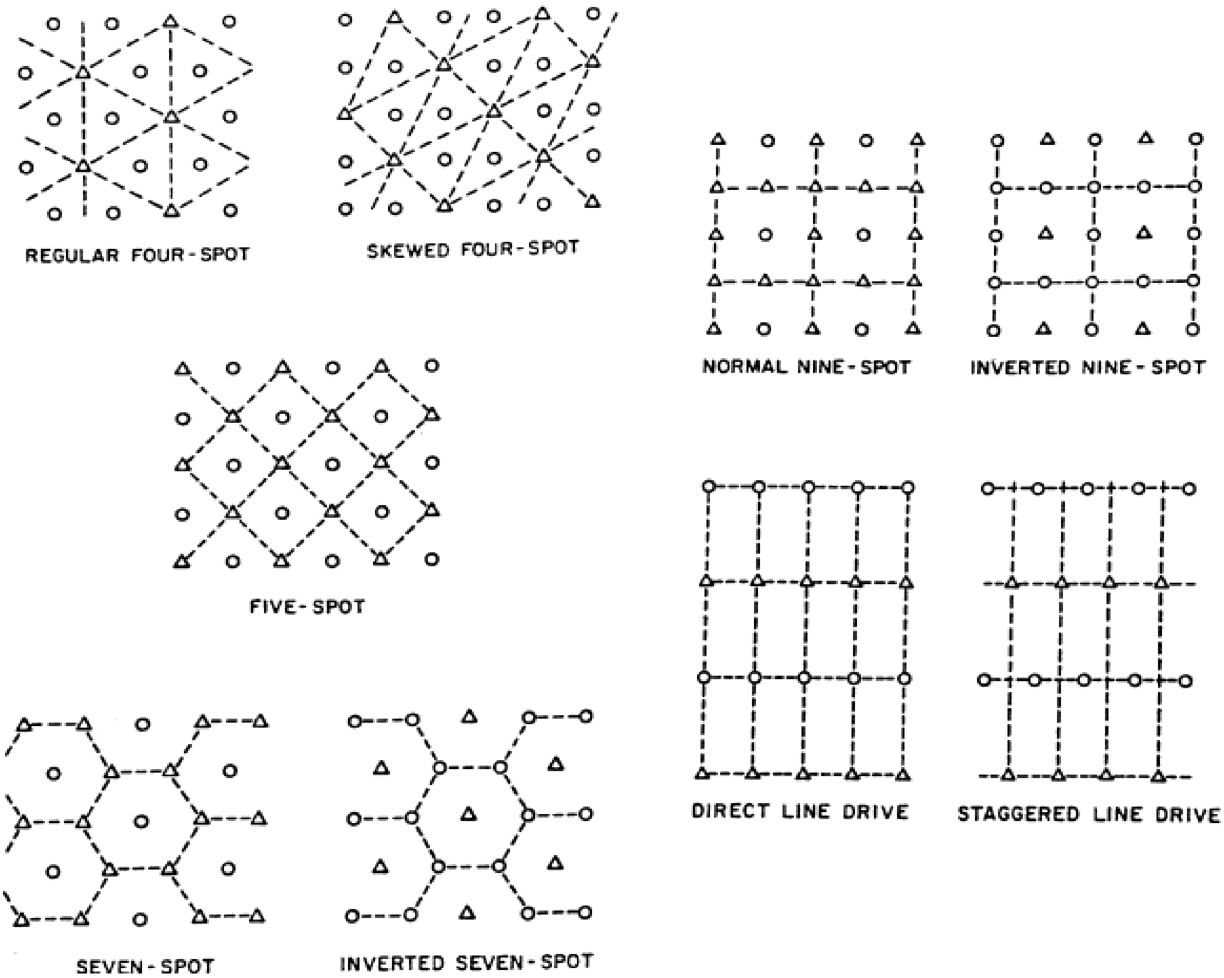


Figure 2.3-: Flood Patterns (Tarik, 2010).

Crestal and Basal Injection Patterns

In crestal injection, as the name implies, the injection is through wells located at the top of the structure. Gas injection projects typically use a crestal injection pattern. In basal injection, the fluid is injected at the bottom of the structure. Many water-injection projects use basal injection patterns with additional benefits being gained from gravity segregation.(Tarik, 2010).

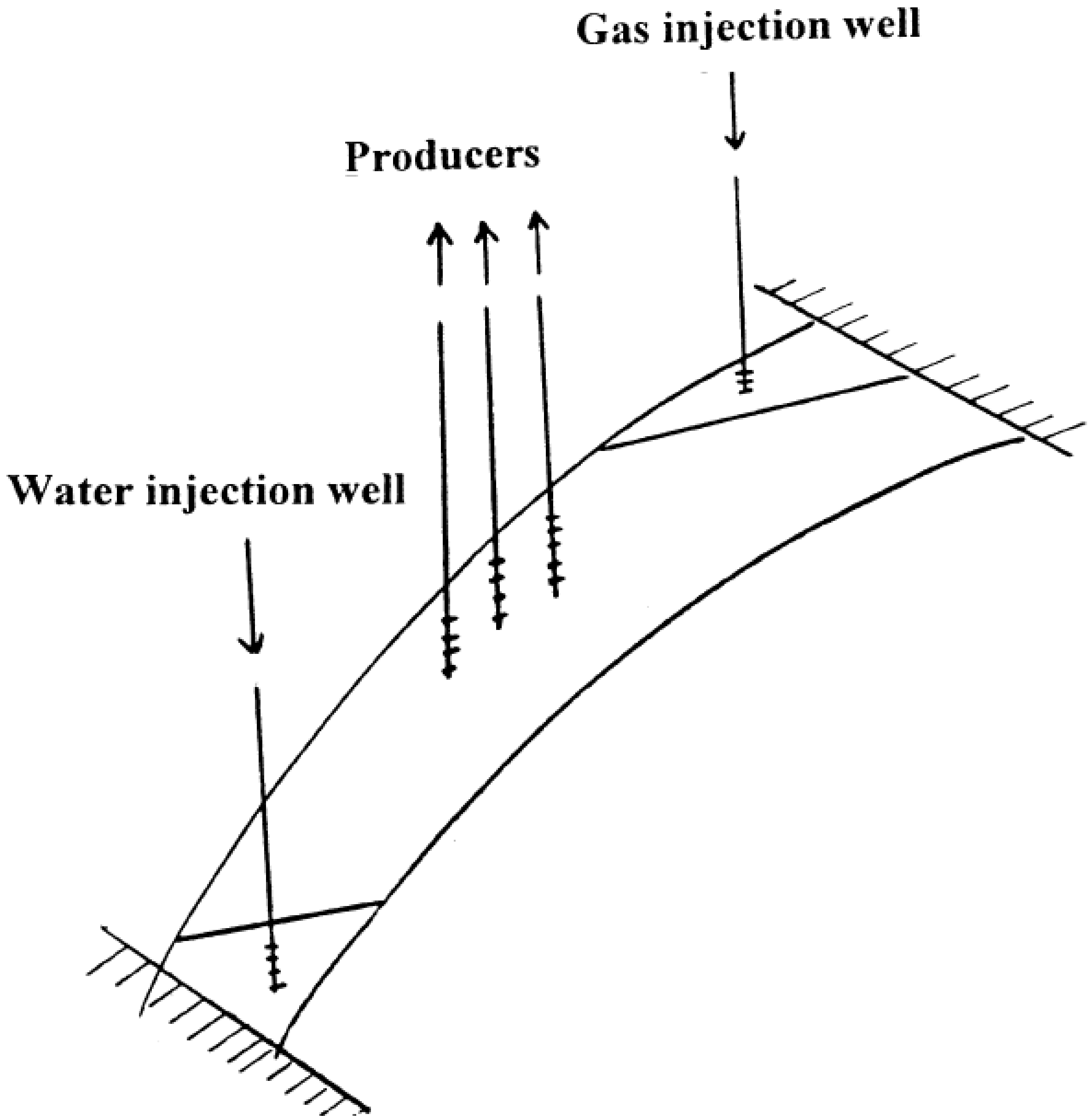


Figure 2.4 : Well Arrangements For Dipping Reservoirs(Tarik, 2010).

2.2 Literature Review

In the literature review their will be illustrate the previous case studies in Sudan and around the world.

2.2.1 World Case Studies

(Pujol, 1972) study the adequacy of scaling methods used for steam-flooding studies in laboratory models of reservoirs containing viscous oils.. For highly viscous oils, it was found that accurate capillary pressure scaling is not required . Model predictions, after adjustment to field conditions to correct for differences between model and field starting oil saturations and injected steam quality, agree closely with numerical two-dimensional, three-phase calculations of the steam drive process. Oil recovery was found to depend mainly on the heat input per unit volume of reservoir sand. Injection rate was found to be a much less important variable.

(Shangqi,1988) describes the development of a fully implicit two-dimensional three-phase numerical simulator for steam flood. The model consists of three phase mass conservation equations for oil ,steam and water, an energy conservation equation. The results will be useful to steam flood project design in this and other oil fields.

(Cheng Zan, 2010) Designed a model to simulate steam flooding of an extra-heavy oil reservoir in Xinjiang Oil Field in which the reservoir is shallow and thin. Numerical simulation of steam flooding processes using different well configurations was performed. The CMG-STARS thermal simulator was used to simulate the data from the present steam flooding experiments.The experimental results indicated that the combination of vertical and horizontal wells plays weak roles for improving steam flooding in the experimental model, because of the limited contribution by gravity drainage.

(Yaser, 2011) addresses experimental and numerical simulation of steam injection in fractured rock. The purpose of the work was to investigate the efficiency and feasibility of steam injection in a core sample which is surrounded by fracture. The results show that steam injection process has great performance and efficiency in fractured systems. However, steam processes are not recommended in very high permeable fractured reservoirs due to high steam oil ratio (SOR).

(Seyed, 2011) studied the steam injection including steam flooding and Cyclic Steam Stimulation (CSS) and compared in detail as potential development scenario of a highly fracture heavy oil reservoir in Iran. The oil gravity is 8-12 API with about 2700 cp viscosity at surface condition. The results show that steam flooding could improve the recovery factor from almost zero to about 12 % while CSS will give about 37 % of recovery factor in the studied sector model which makes it more attractive method as development scenario.. Furthermore the results illustrated that the injection strategies, well spacing, well type, pattern type and size are among the important parameters for designing the steam injection.

(Mehdi, 2012) prepared two separate numerical models to investigate steam flooding performance for the recovery of light and heavy oil. The heavy oil model is a Cartesian hypothesis model with properties of Cold Lake heavy oil reservoir in Canada and light oil model is a sector of an Iranian fractured light oil reservoir. Also, operational parameters such as steam quality, steam flow rate and well perforation were optimized for both reservoirs.Results show heavy oil reservoirs do not response fast to steam compared to the light oil reservoirs. Furthermore, viscosity reduction is a main recovery mechanism in recovery of heavy oil and contribute to 80% of total recovery, while in recovery of light oil all three main recovery mechanisms have the same contribution to total recovery. It was also found that the optimized operational parameters are different for each reservoir.

(Shijunhuang, 2015) present a series of physical experiments investigating the steam flooding using horizontal wells for thin and heterogeneous heavy oil reservoir. The steam chamber sweep efficiency, oil recovery and water cut of homogeneous model and heterogeneous models are compared.The results indicate that the low permeability zones greatly hinder the development of steam chamber.resulting in poorer sweep efficiency, earlier steam breakthrough, more residual oil, as well as lower oil recovery, higher water cut, less liquids and oil production.

(HaoGu, 2015) illustrate that the mathematical model is composed of many sections. The prediction of thermo physical properties of injected steam considering phase change. and, steady-state heat transfer inside the wellbore and transient radial conduction in the formation are coupled at the cement/formation interface, The proposed model is validated by comparing simulated steam pressure, temperature and quality with measured field data from Liaohe Oilfield,. The results indicate that enhancing the wellhead injection rate and using low thermal conductivities of insulation materials can greatly improve the thermal efficiency. But it is not a good choice to achieve this goal by improving the wellhead steam quality.

2.2.2Sudan Case Studies

(Raj deo, 2011) illustrates the successful design, implementation and evaluation of cyclic steam stimulation pilot in heavy oil field of Sudan.This field contains heavy oil in multiple reservoirs of Bentiu formations of late cretaceous age occurring at depths of 550-600m, highly porous (~30%), permeable (1000-2000 mD) ,unconsolidated in nature, API 15 - 17 and corresponding viscosities in the range of 3700 cp and 3000 cp at reservoir conditions.Cyclic steam stimulation has been implemented in eight selected wells spread over the fieldwith Steam quality of 75% was injected for 6-12 days and wells were subjected to soaking of 3-5 days. Putting on production an improvement of three to five foldsActual results are better than predicted in simulation studies with lower steam intensity of 120 m3/m compared to planned 160m3/m.

(Elamin, 2014) illustrate that the problem of excessive water production rate in Bamboo field which are possibly due to the fingering and water conning Currently the field is producing around 9000STB/D with water cut around 75% and keeps increasing. Since the declining production take place for that their strategy to go for implementation of Enhance Oil Recovery (EOR) process . After more study they conclude to use thermal EOR in Bamboo field reservoirs, Feasibility studies shows that steam injection is potentially the most practical and viable option . The Result shows that the thermal EOR projects for bamboo west oil field are very successful and almost reward double production from 280 bbl/day to 500 bbl/day in Bamboo Oil Field.

(Husham, 2016) represent that the optimum pilot area and propose the steam flooding injection parameter, the suitable well spacing as well as the required steam flooding facility for FNE oil field. FNE reservoirs are highly porous (~30%), permeable (1000-2000 mD) and unconsolidated in nature. the fluid properties include viscous crude with 15 to 17.7 API. Corresponding viscosities are in the range of 250 cp and 500 cp at reservoir conditions. the model was designed with six different cases at different well spacing were investigated .Steam temperature of 270 ºC, 5~7 MPa injection pressure, steam quality of 0.6, and steam injection rate of 1.6 m3/d/ha/m; their used as Steam Flooding parameters for all simulation cases while the recovery ratio of 1.2 is also considered. The result showed that converting of Cyclic Steam Stimulation (CSS) to steam flooding after the third cycle could improve the recovery factor of the field up to 43 ~ 50.1%, while CSS only can increase the recovery percent of the suggested well groups by 32.5 - 34.2% of the studied sector model which makes it more attractive method as development scenario for FNE oil field.

After reviewing the history and previous studies in the world and in Sudan, This research aims to do feasibility of applying steam flooding in FNE field as case study in Sudanese oil field using CMG Software and by using actual model and data, and the prediction of the field performance and productivity till 2026.

Chapter 3

Methodology

Chapter 3: Methodology

3.1 Introduction

The Production of heavy oil by conventional methods gave low recovery factor (5%-10%) of the OIIP. FNE oil field is the heavy oil field which has very low recovery factor. The main objective of this task is to find solution to enhance the recovery factor of this oil field.

The Geological data, reservoir data and production data for FNE oil field has been collected and used for analysis to identify the situation of the field and it is suitability for conducting steam flooding.

FNE reservoirs are highly porous (~30%), permeable (1000-2000 mD) and unconsolidated in nature. The fluid properties include viscous crude with 15 to 17.7 API. Corresponding viscosities are in the range of 250 cp and 500 cp at reservoir conditions. (Husham et al, 2016)

The analysis will be done through steps in order to identify the main reason of the problem, and then propose the suitable solution, which will be applied to do the simulation model for the new cycle optimization.

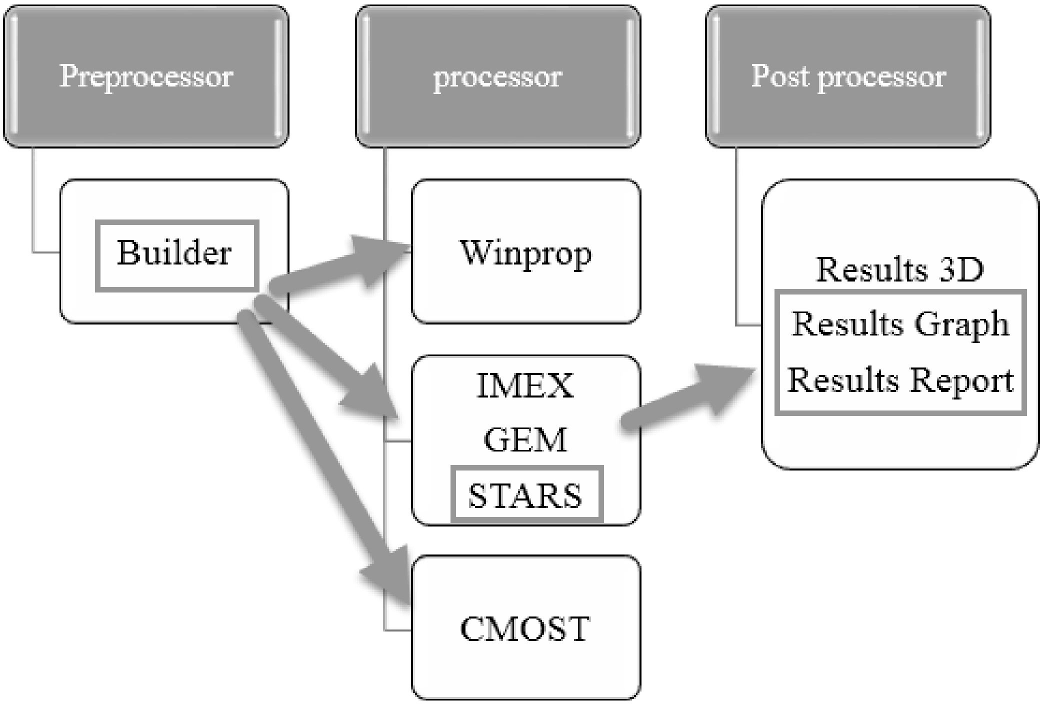
3.2 Computer Modeling Group

Abbreviated as CMG, is a software company that produces reservoir simulation programs for the oil and gas industry. It is based in Calgary, Alberta, Canada with branch offices in Houston, Dubai, Caracas and London. The company is traded on the Toronto Stock Exchange under the symbol CMG. The company offers three simulators, a black oil simulator, called IMEX, a compositional simulator called GEM and a thermal compositional simulator called STARS.

The company began in 1978 as an effort to develop a simulator by Khalid Aziz of the University of Calgary's Chemical Engineering department, with a research grant from the government of Alberta. A commercial product was being sold by the late 1980s. For the first 19 years of the company's history it was a non-profit entity. In 1997 it became a regular public company when it was listed on the TSX. The company now claims over 400 clients in 49 countries.(CMGL ,2016)

Today, CMG remains focused on the development and delivery of reservoir simulation technologies to assist oil and gas companies in determining reservoir capacities and maximizing potential recovery

3.2.1 CMG components



`Figure 3-1 : CMG Components

STARS -Thermal & Advanced Processes Reservoir Simulator

STARS is the undisputed industry standard in thermal and advanced processes reservoir simulation. STARS is a thermal, k-value (KV) compositional, chemical reaction and geomechanics reservoir simulator ideally suited for advanced modelling of recovery processes involving the injection of steam, solvents, air and chemicals. The robust reaction kinetics and geomechanics capabilities make it the most complete and flexible reservoir simulator available.

3.3 Methodology diagram

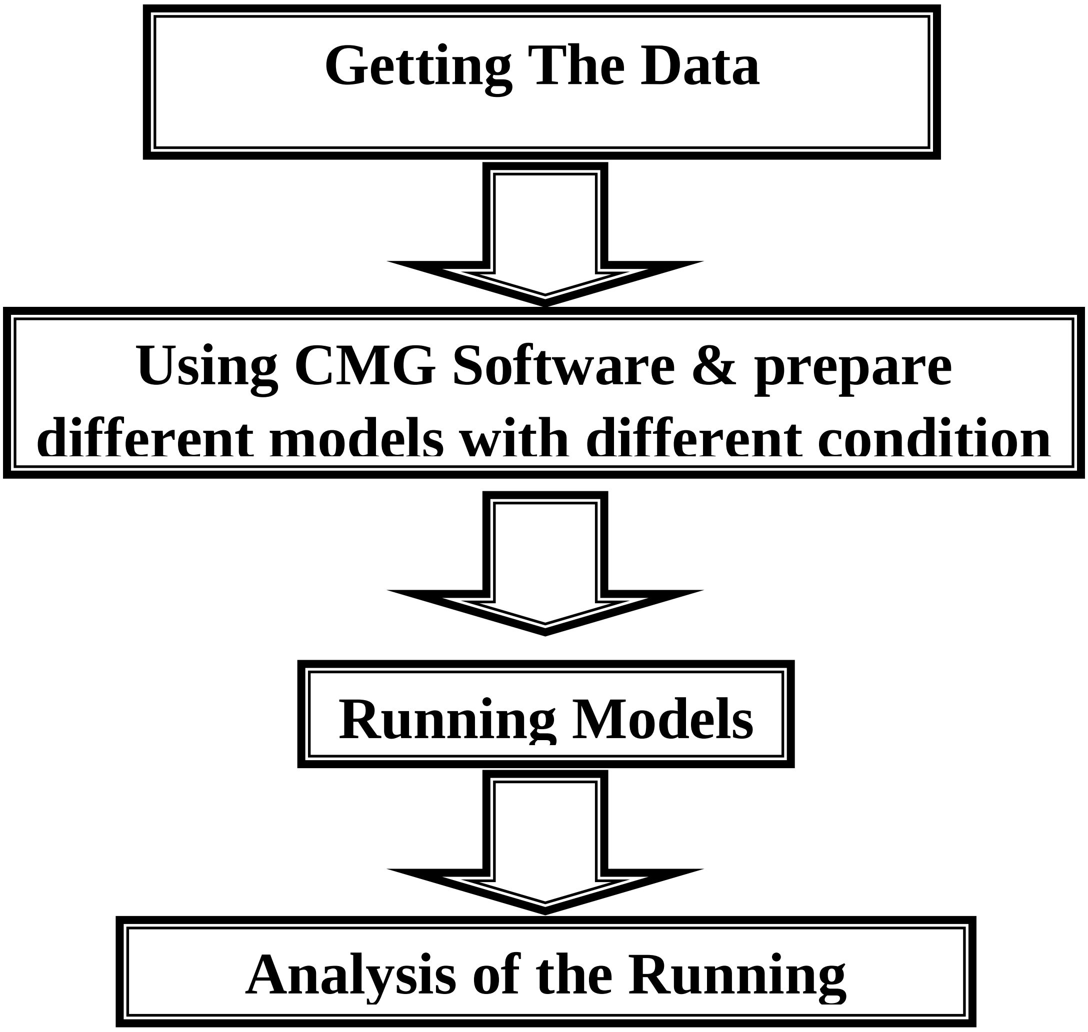


Figure 3-2 :Methodology Diagram

3.4 Steps of Cyclic Steam Simulation Model in STARS

Building the CSS will be by following the flow chart below

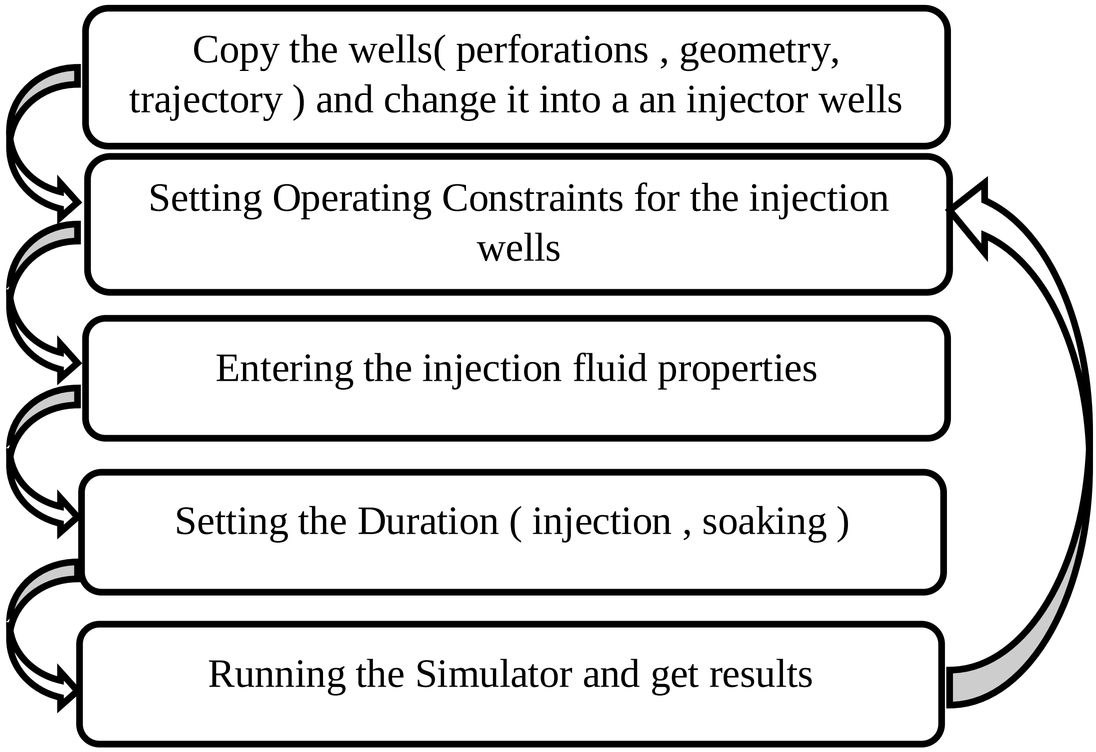


Figure 3-3 : Steps of Cyclic Steam StimulationModel

For cyclic steam injection, there must be an injection well and production well located in the same location. From the wells menu select “Copy well”. Select “producer”. Click next as shown in the figures below.

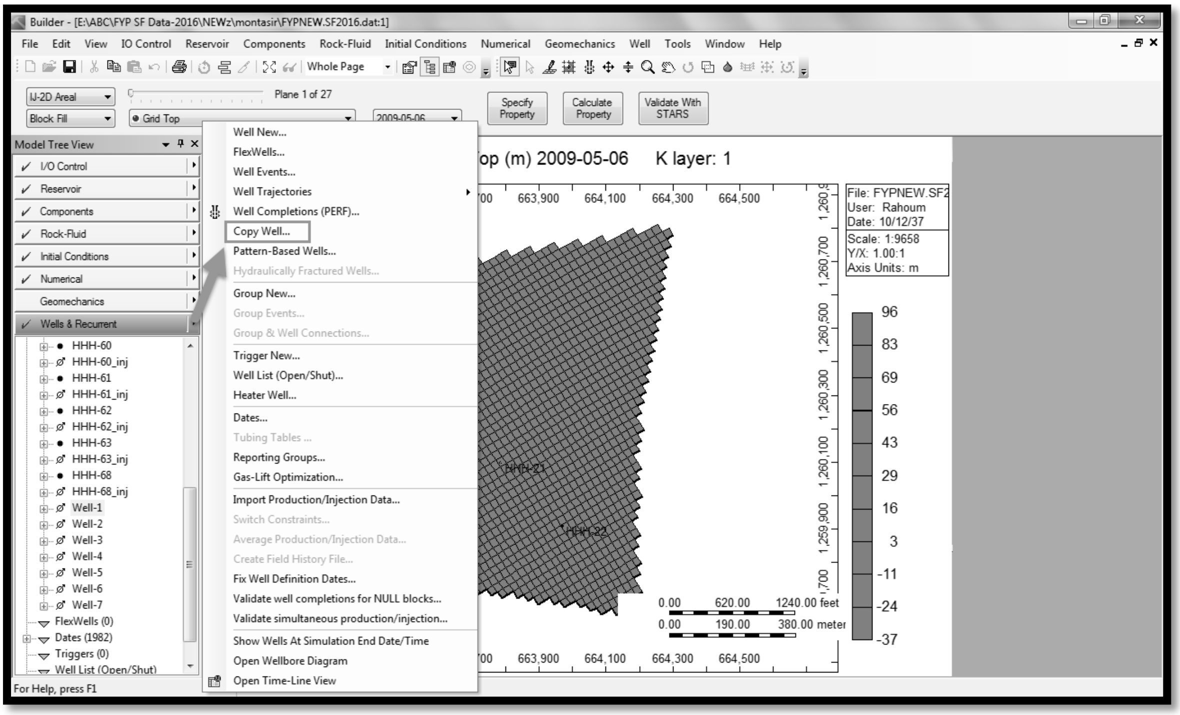


Figure 3-4 :Copy the Well

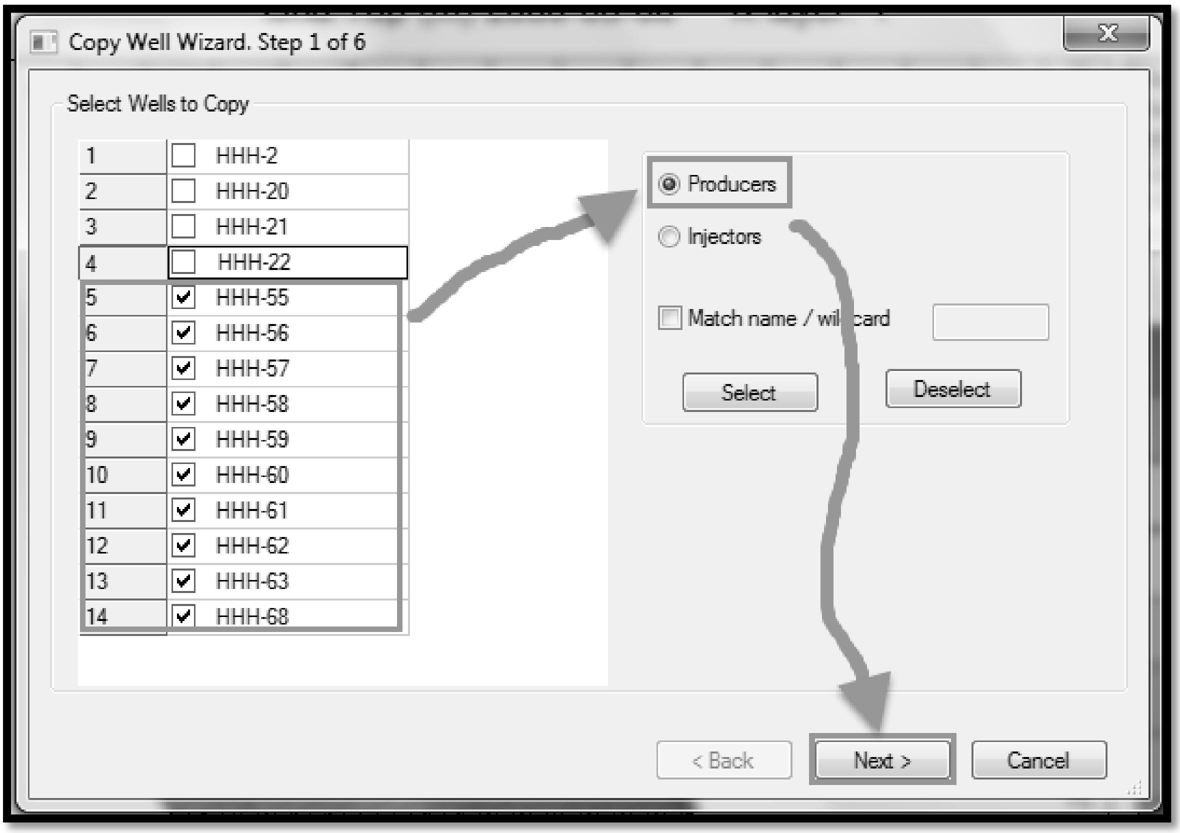


Figure 3-5 : Copying the Wells

and make sure "Copy all perforations" is selected. Click next as shown in the figure below.

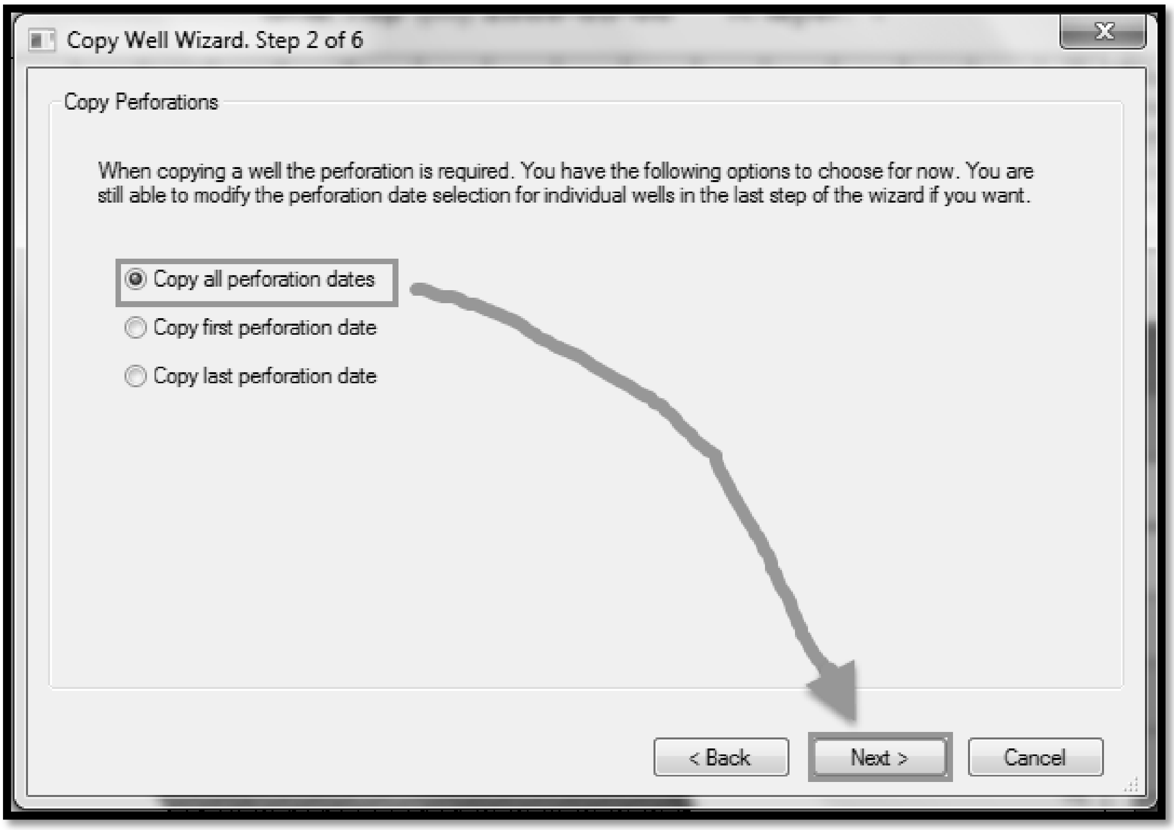


Figure 3-6 : Copying the Perforations

Check the "Copy Geometry" option and click next as shown in below.

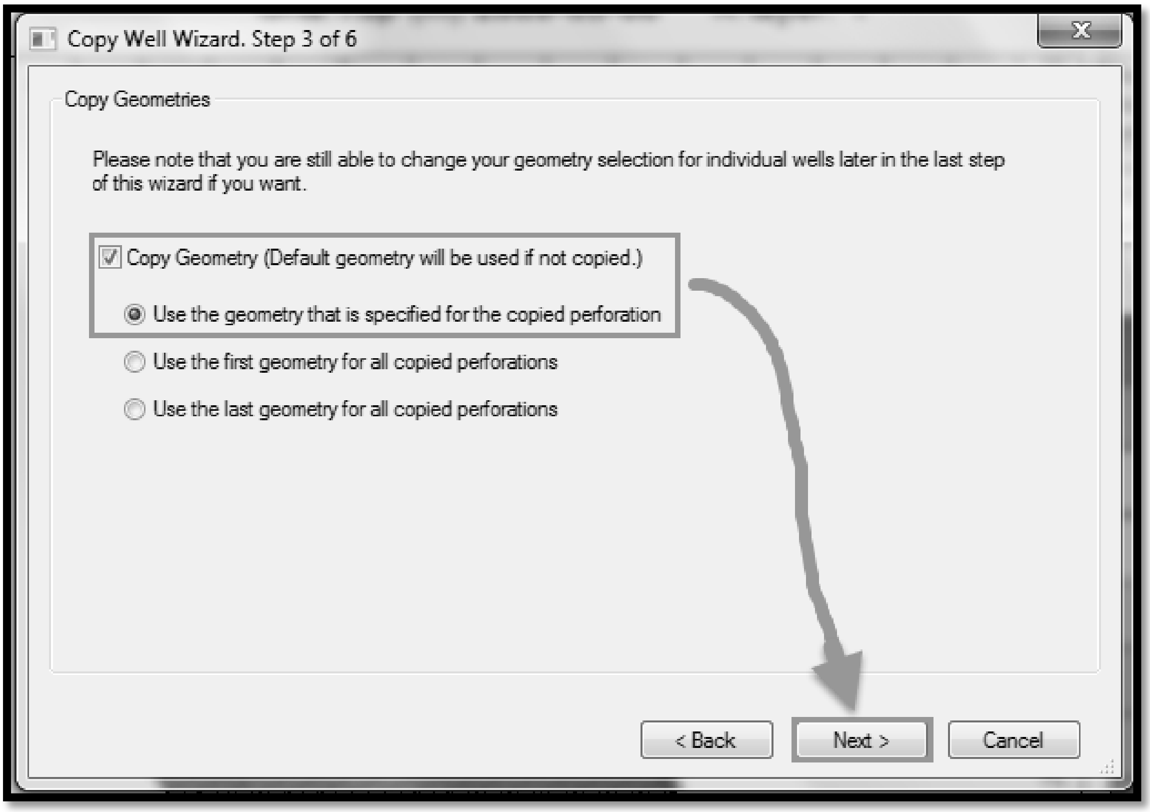


Figure 3-7 : Copying the Geometry

Next again

Figure 3-8 : Copy Trajectories

Select the option “I will manually enter the new well name on the next step”. Then click next as shown below.

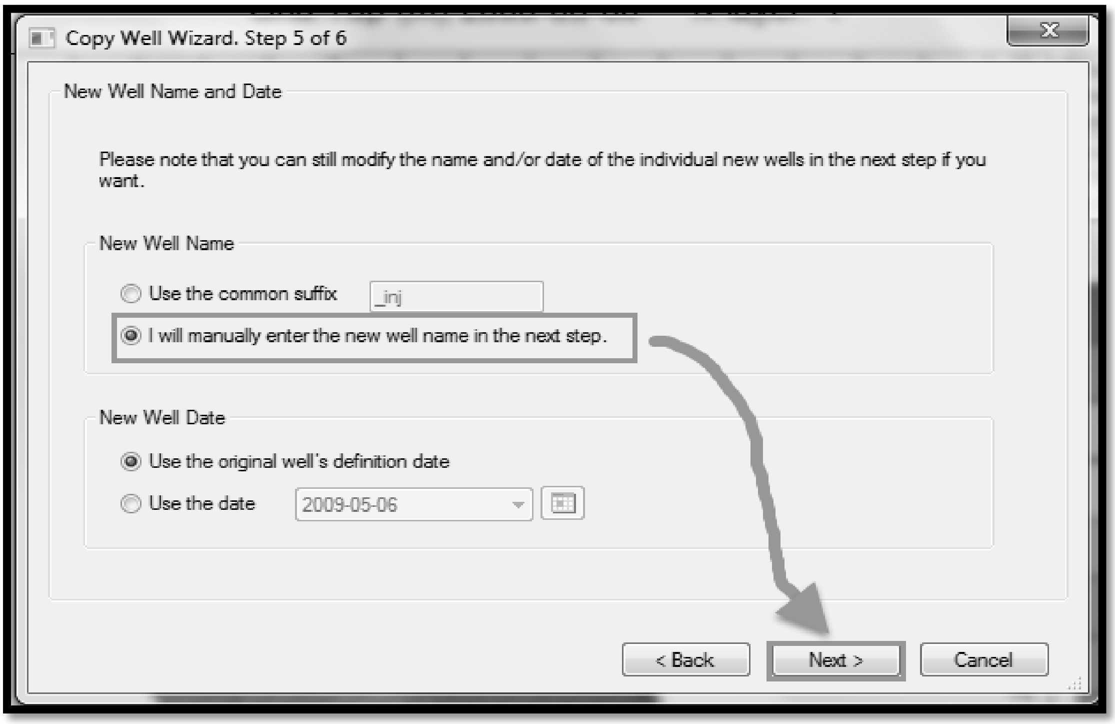


Figure 3-9 : Entering the Injection Wells Names 1

Enter the name " HHH-55_inj, HHH-56_inj, HHH-57_inj, HHH-58_inj, HHH-59_inj, HHH-60_inj, HHH-61_inj, HHH-62_inj, HHH-63_inj, HHH-68_inj " in the wells names as shown below and click finish

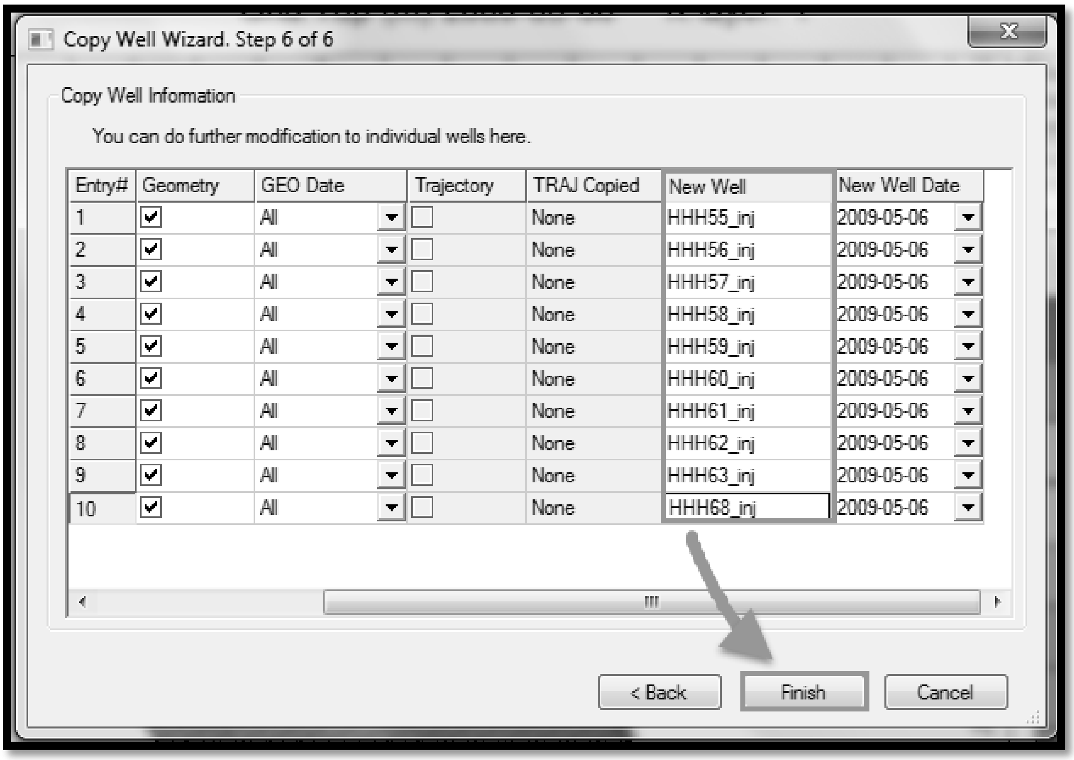


Figure 3-10 : Entering the Injection Wells Names 2

Then setting the constraints for the injection well as shown in figure below

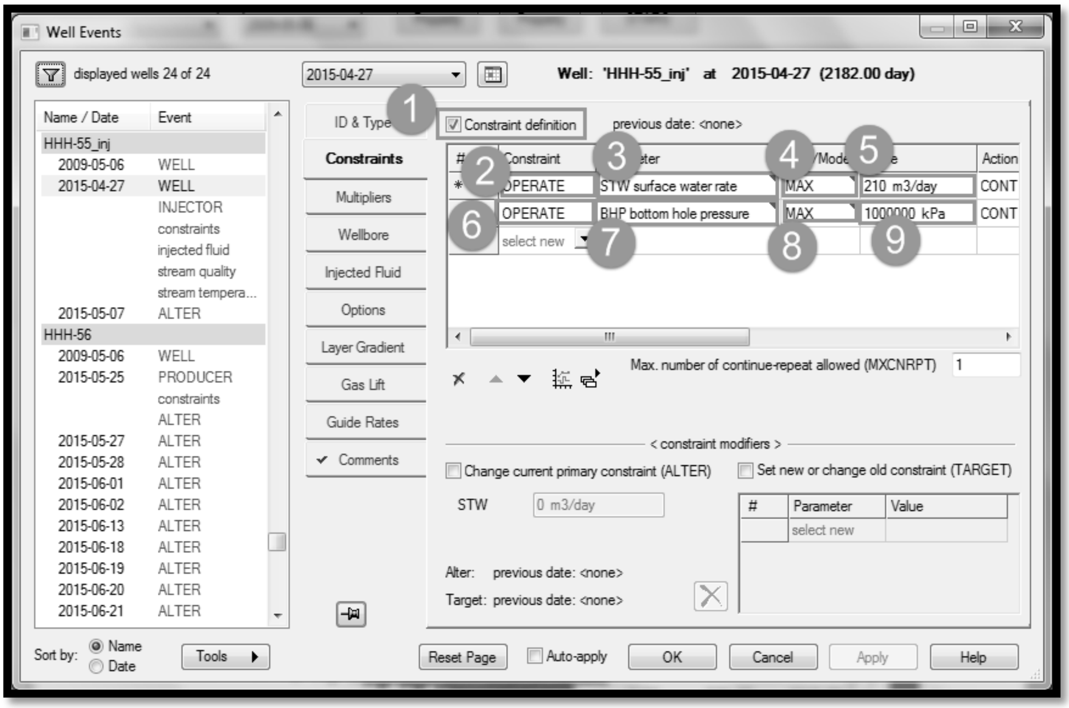


Figure 3-11: Adjusting the Constraints for the Injection Well

Then entering the injection fluid properties as shown in figure below.

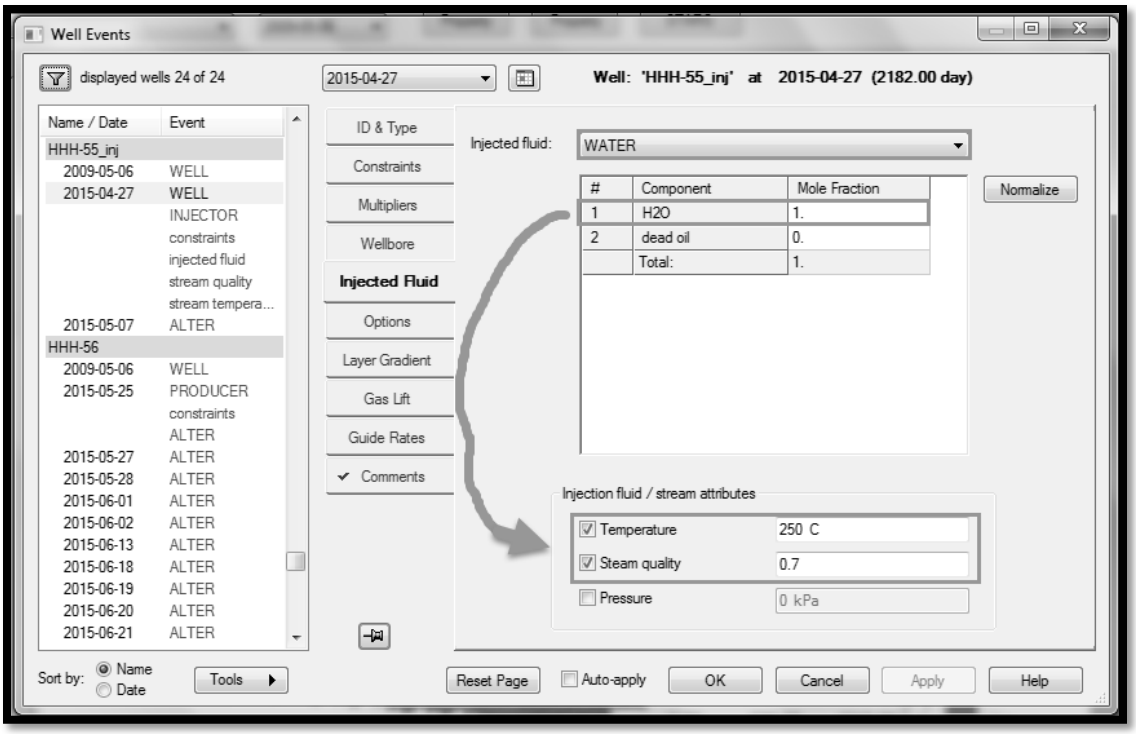


Figure 3-12 : Entering the Injection Fluid Properties

After that we will add seven new wells and work for the purpose of steam injection into the field and working the field into steam flooding and before that the field is run in two cases (infill wells cold and infill wells CSS).

3.5 Steps of Steam Flooding Model in STARS

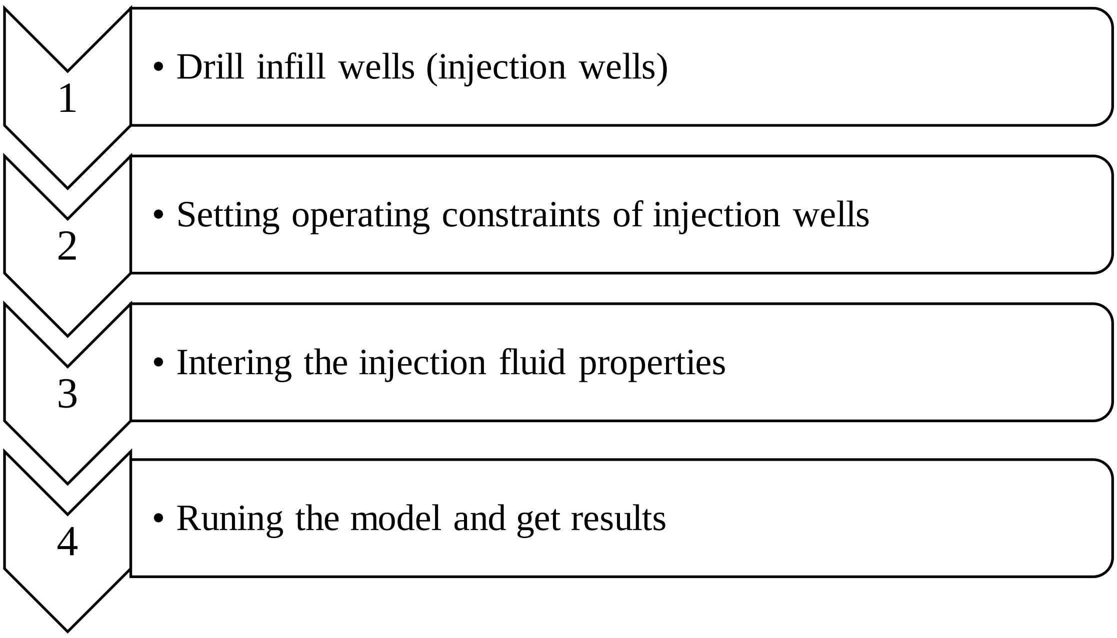


Figure 3-13 :Stepsof Steam Flooding Model

Infill wells

At this stage, it will add seven new wells, any well in the middle of the four wells and to the work of the steam injection case as shown in figures below .

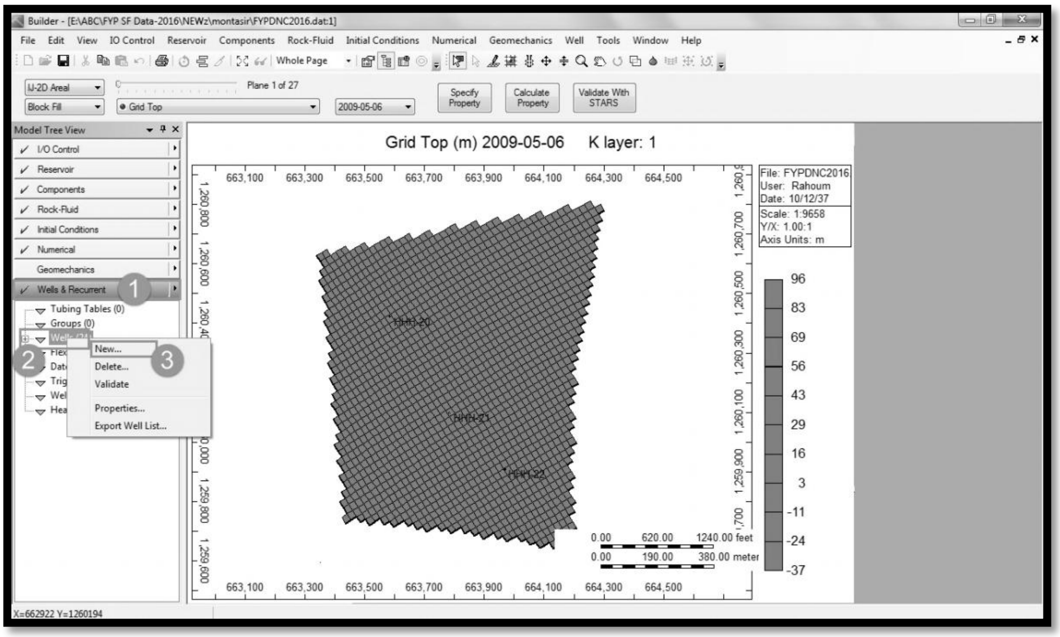


Figure 3-14: Adding New Well

After that we will define the well and identify the type of well as shown in figure 3.15.

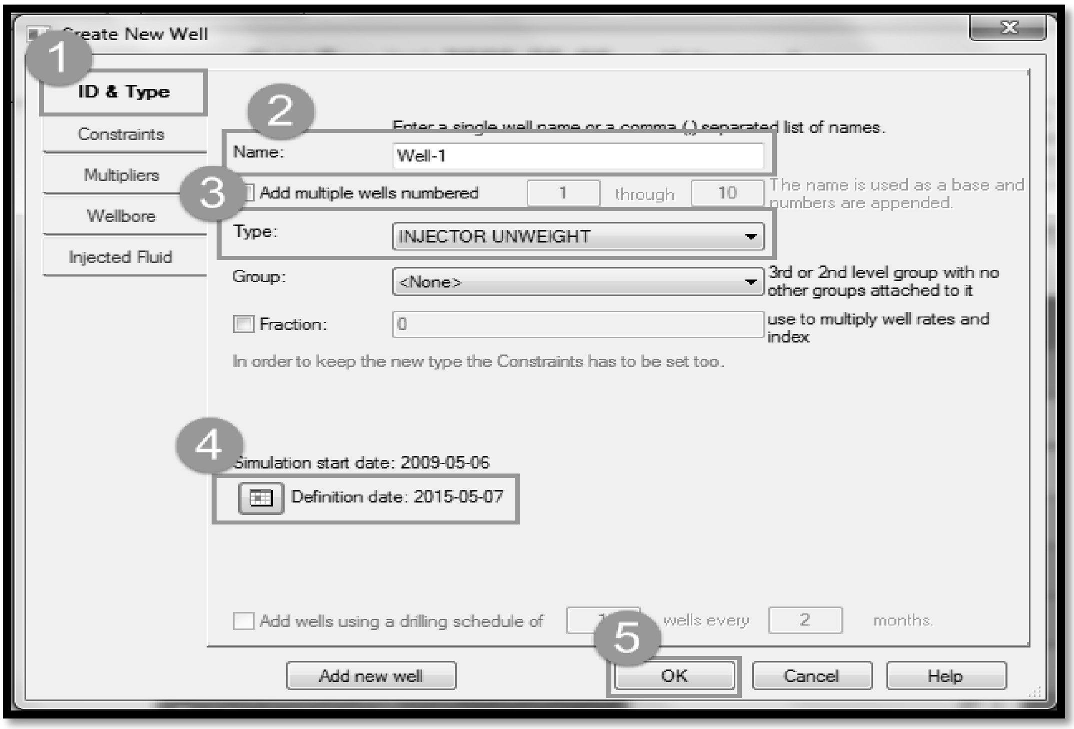


Figure 3-15: Defining the Well

After defining the well we will entering the constraints as shown in figure 3-16

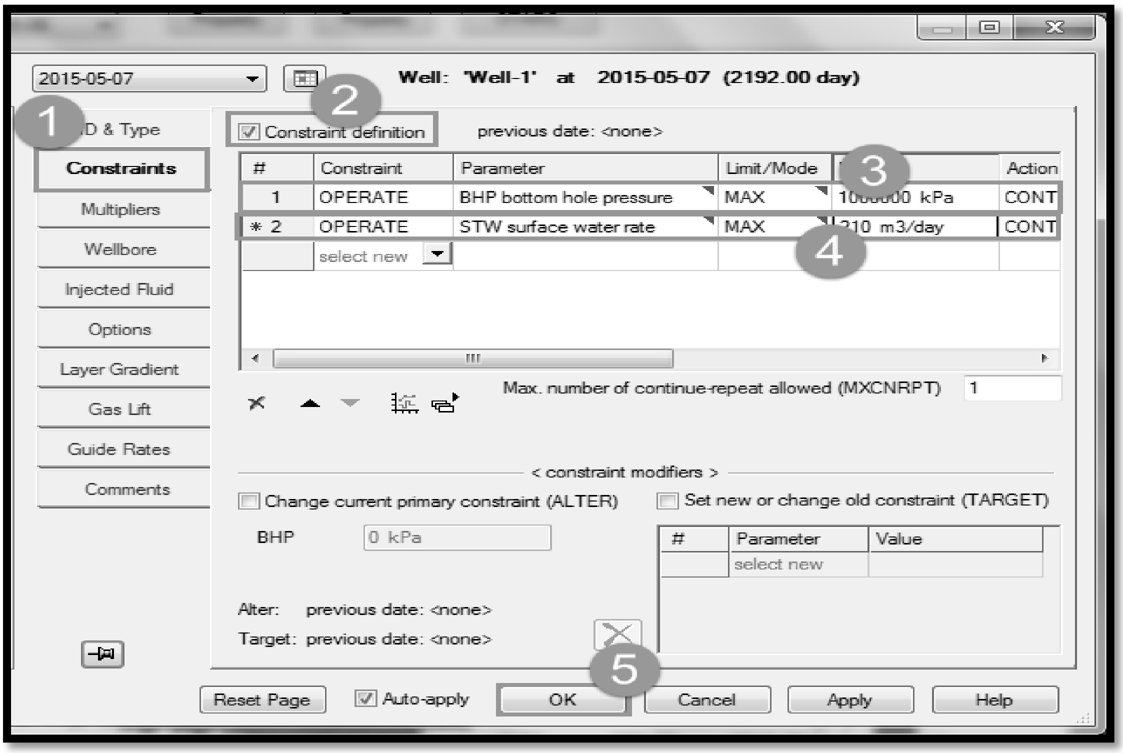


Figure 3-16: Entering the Constraints To The Well

After that we will entering the injection fluid , fluid temperature , and steam quality.as shown in figure 3-17

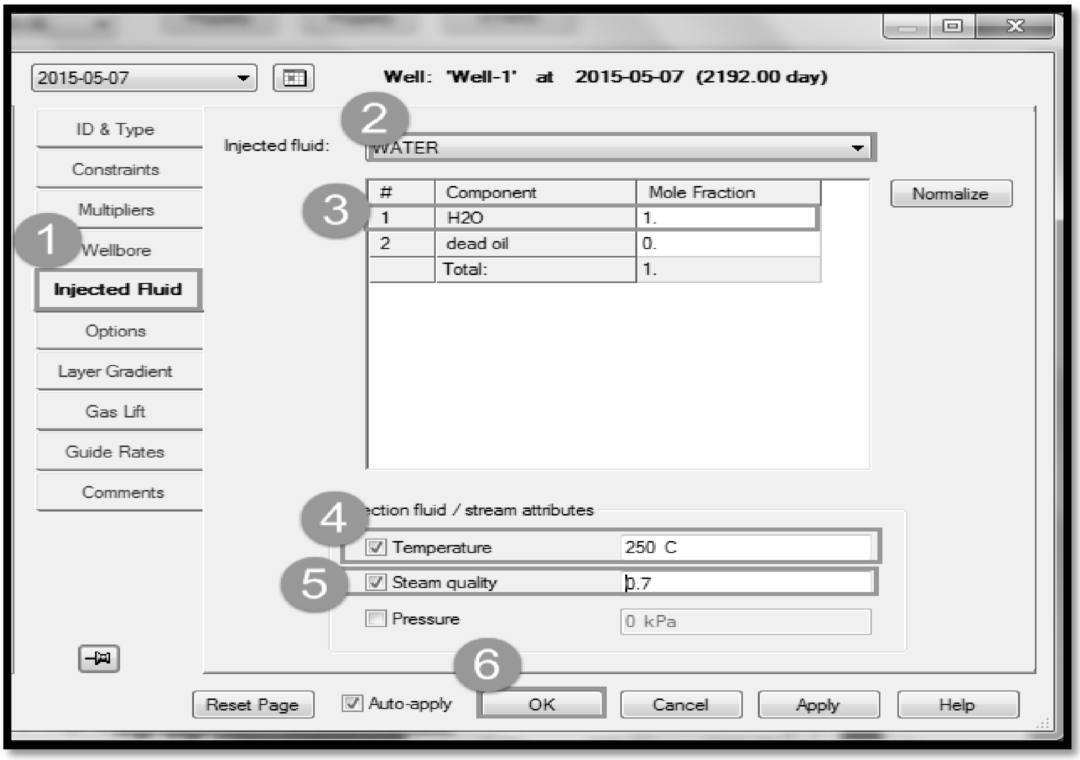


Figure 3-17: Entering the Injection Fluid , Temperature , and Steam Quality

After that we will select the layers to be perforated as shown in figure 3-18

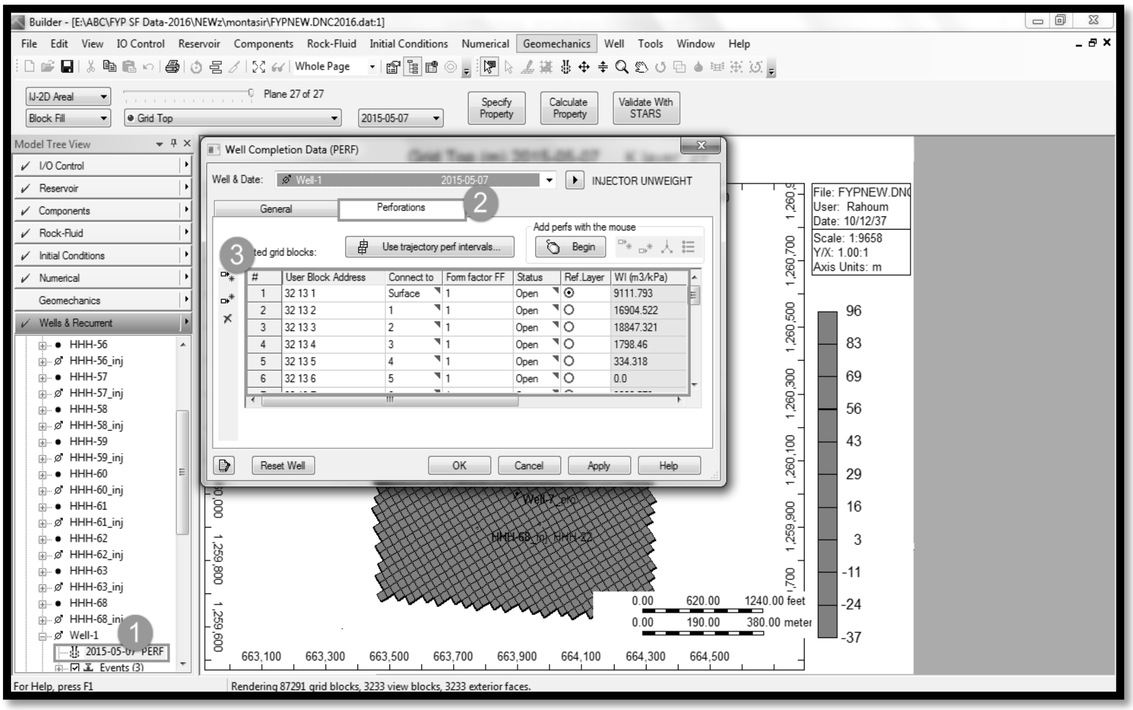


Figure 3-18 :Perforations of the Well

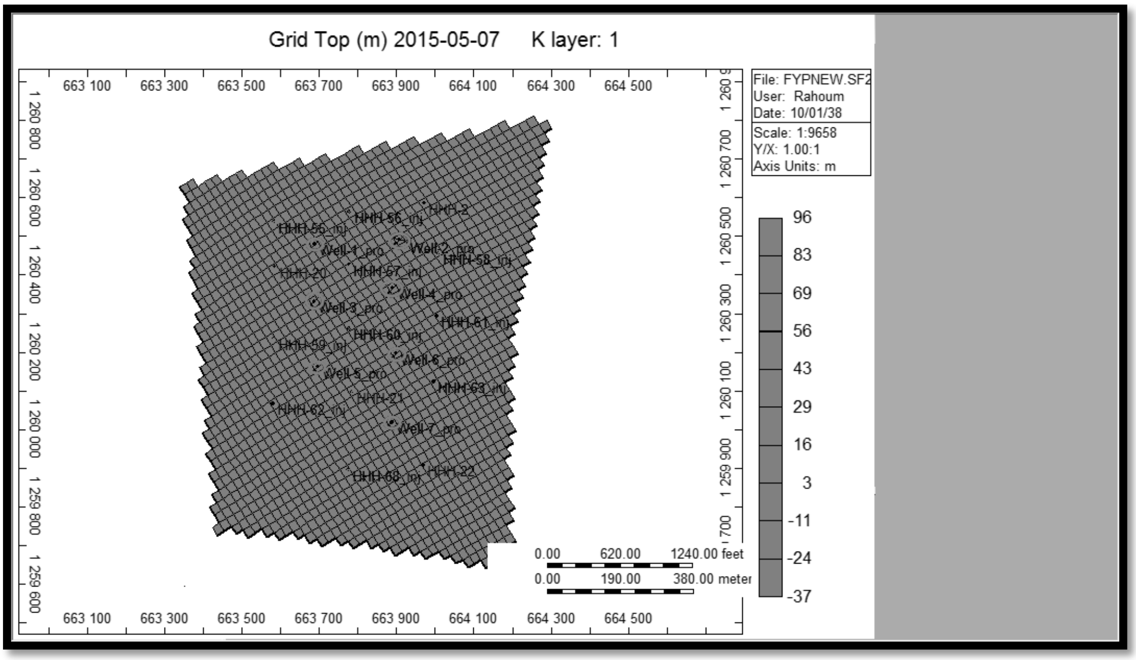


Figure 3-19 :Infill Wells

To do CSS we will need to Copy the wells with the same previous steps of CSS to the wells from 1 to 7 as shown in figures bellow

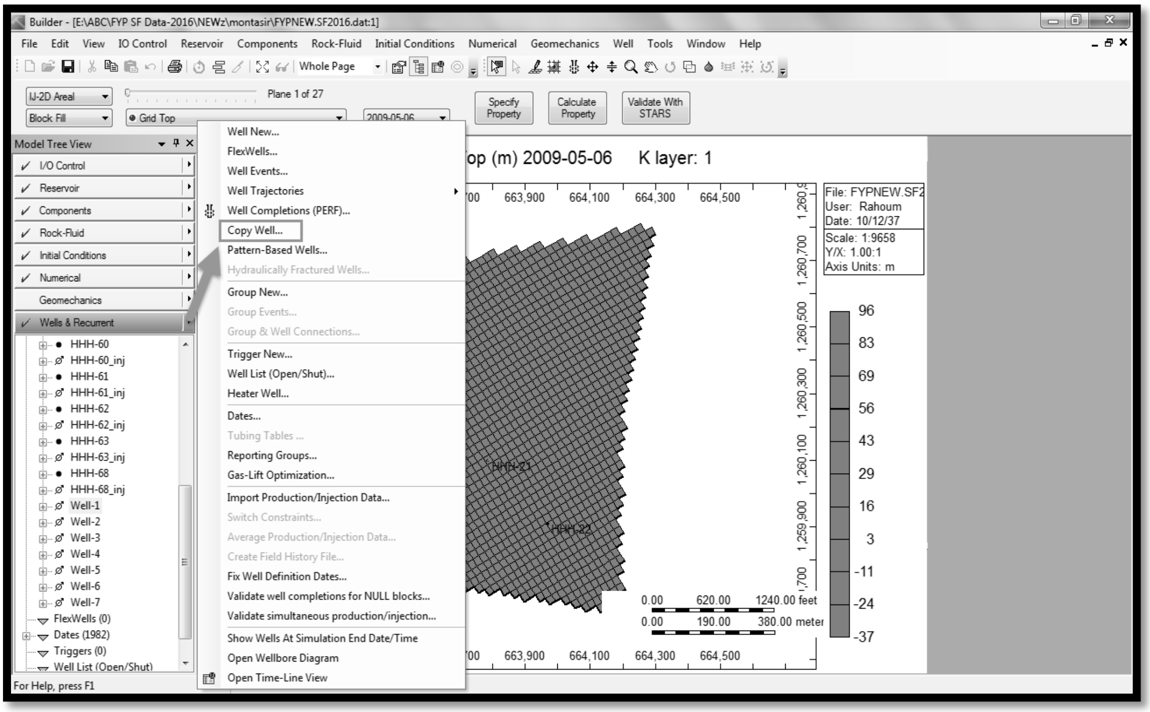


Figure 3-20 :Copy the Well

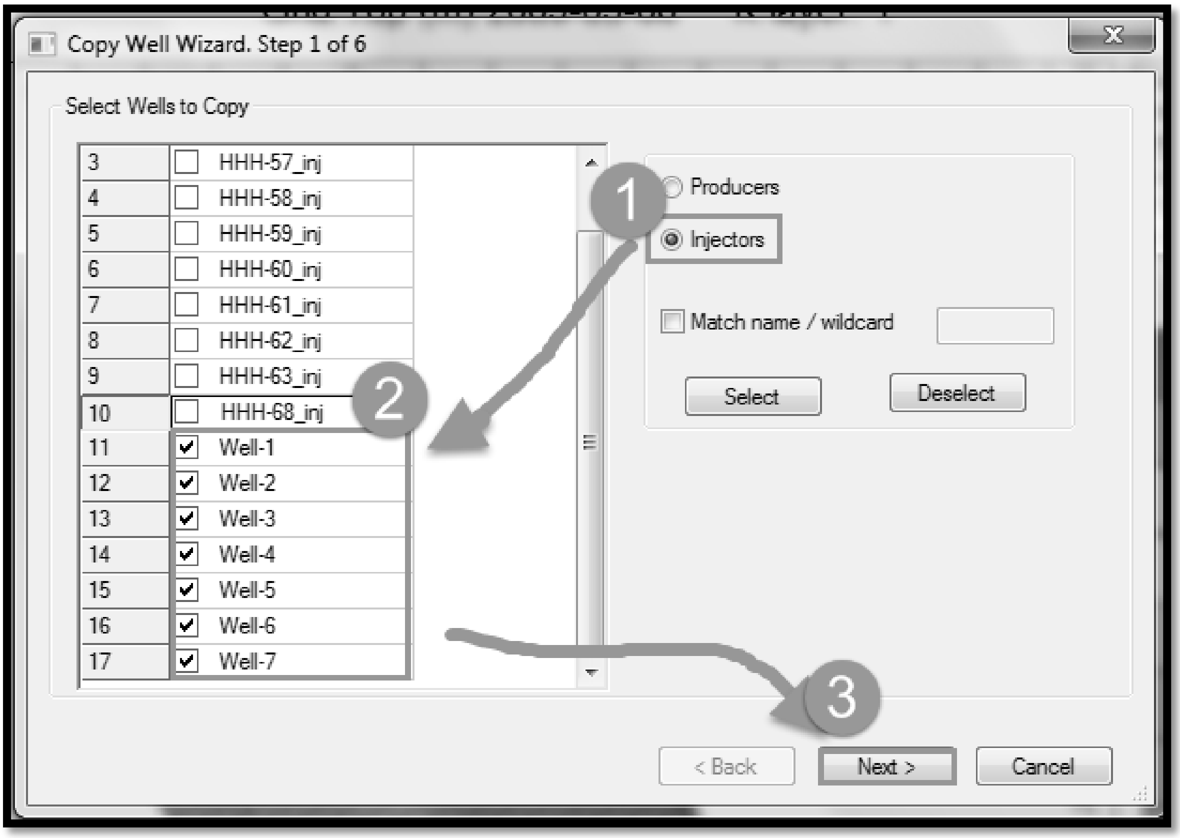


Figure 3-21 :Copy the Injection Wells To Producers

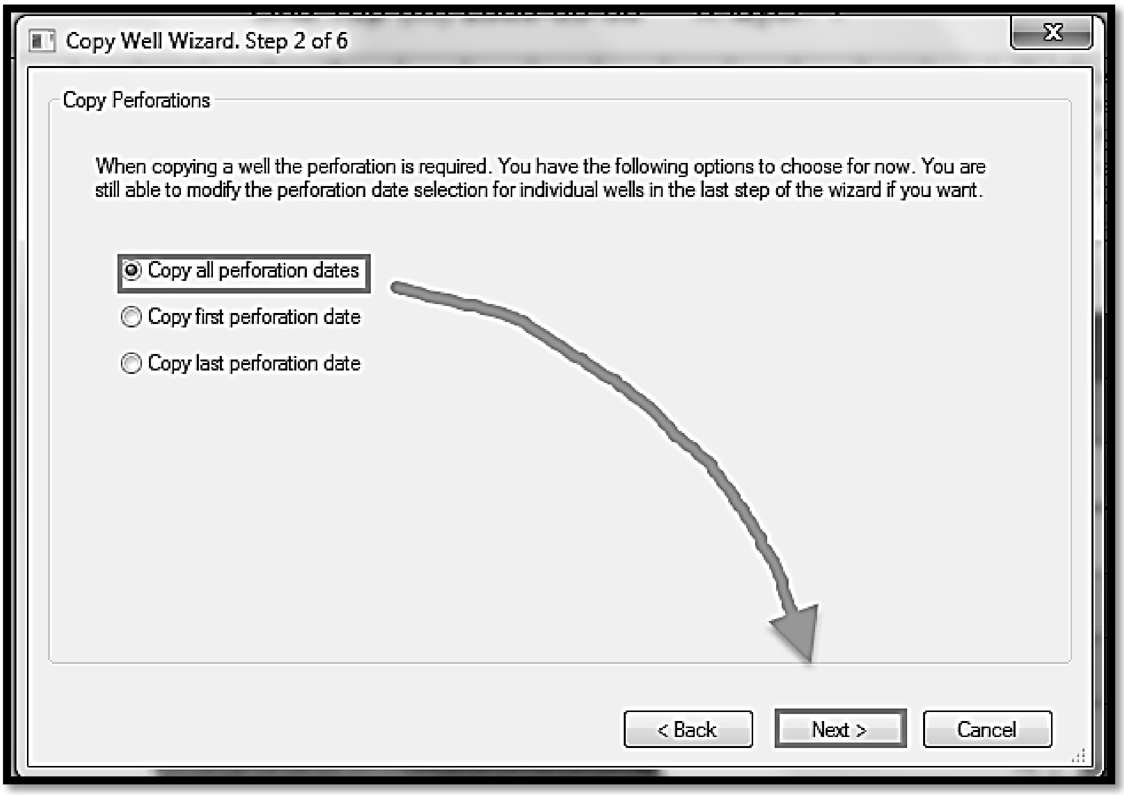


Figure 3-22 :Copying All Perforations

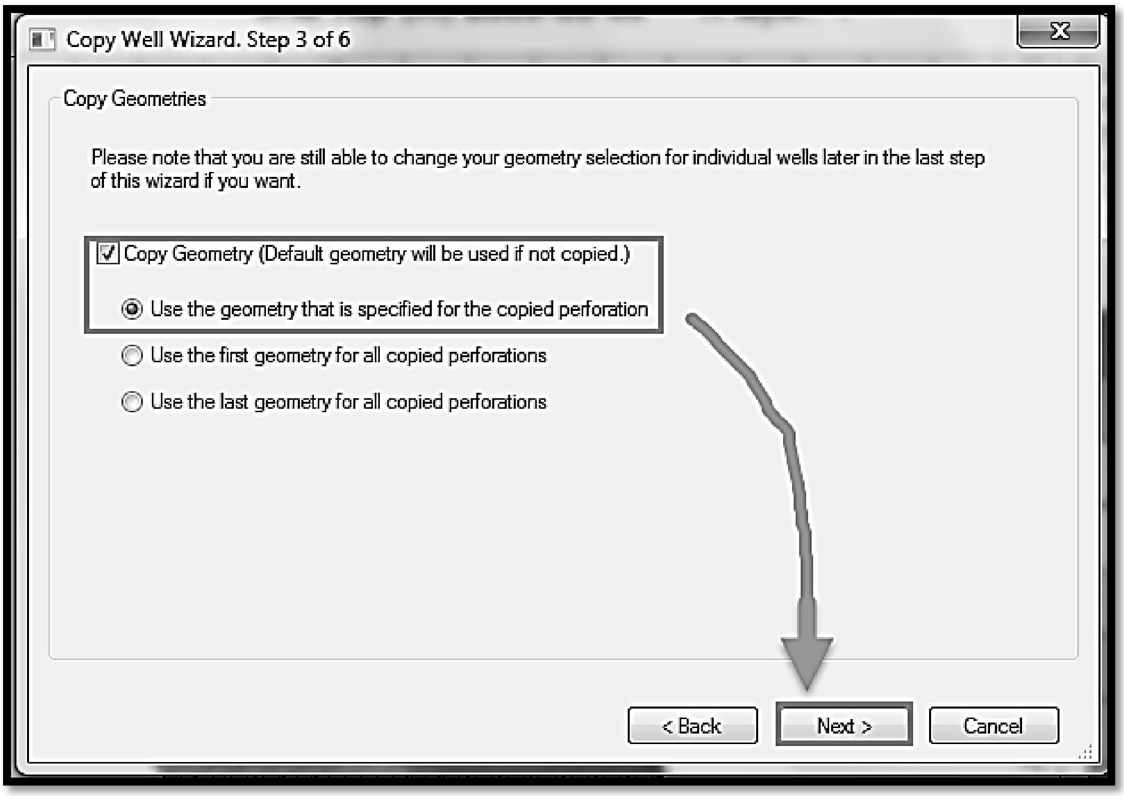


Figure 3-23 :Copying the Geometry

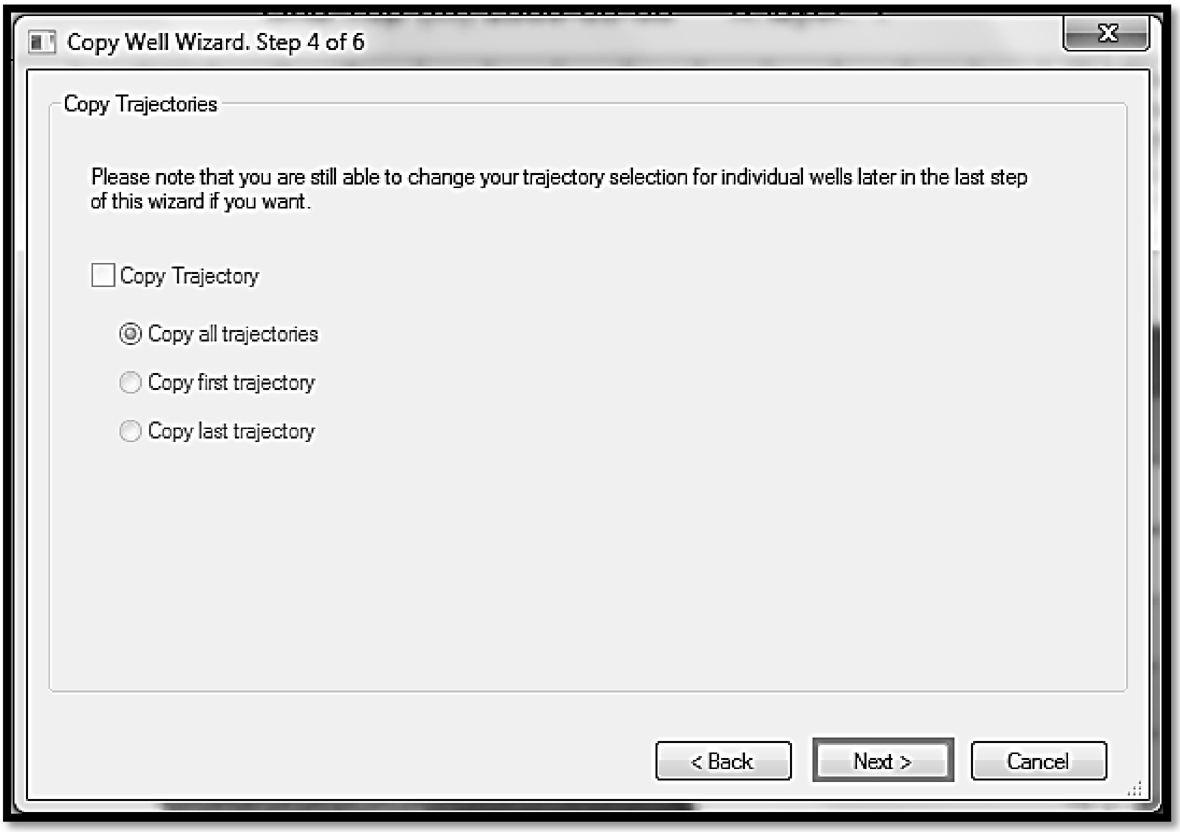


Figure 3-24 :Copying the Trajectory

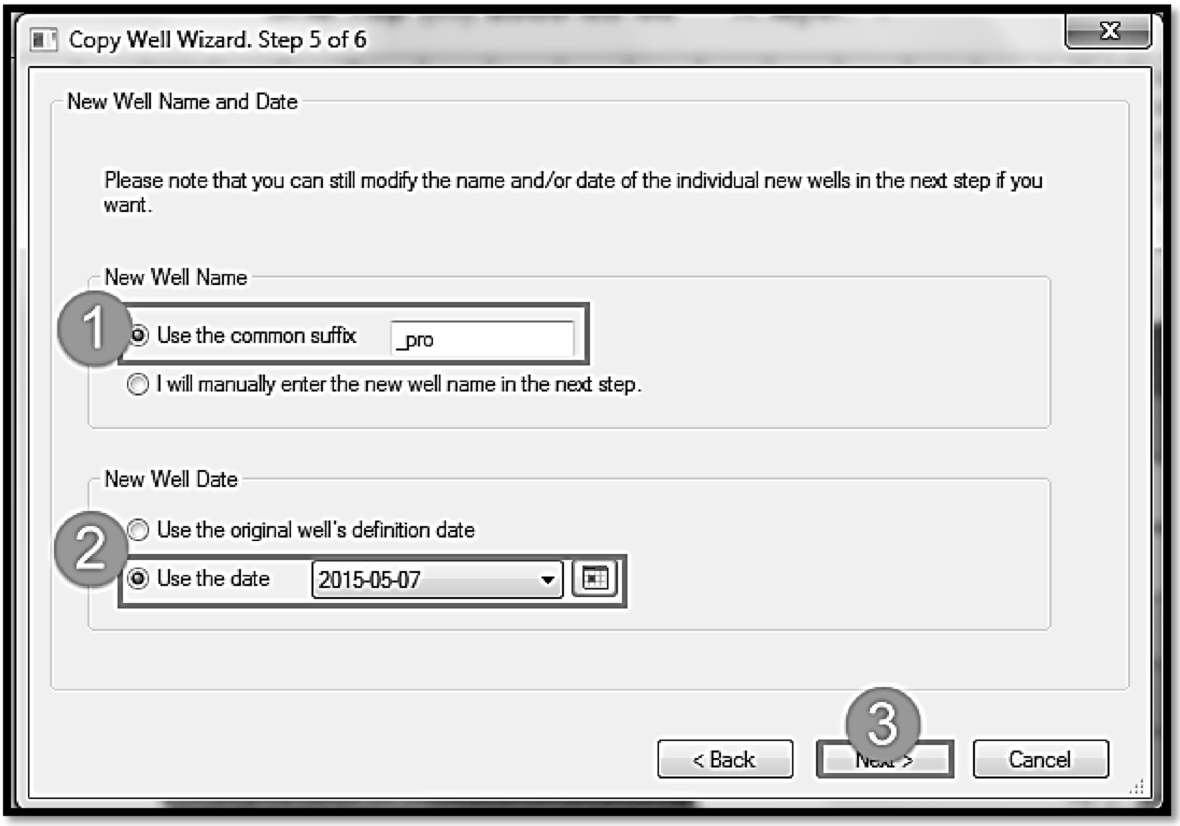


Figure 3-25 : Entering the Production Wells Names 1

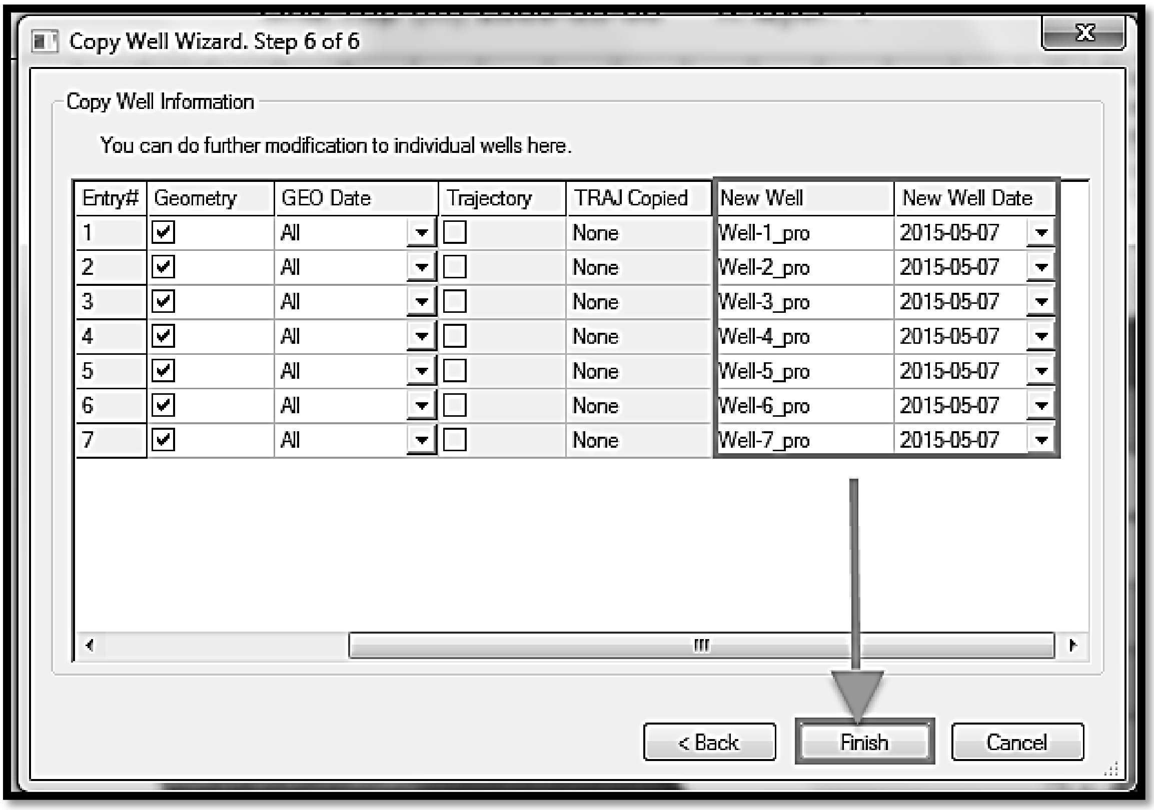


Figure 3-26 : Entering the Production Wells Names 2

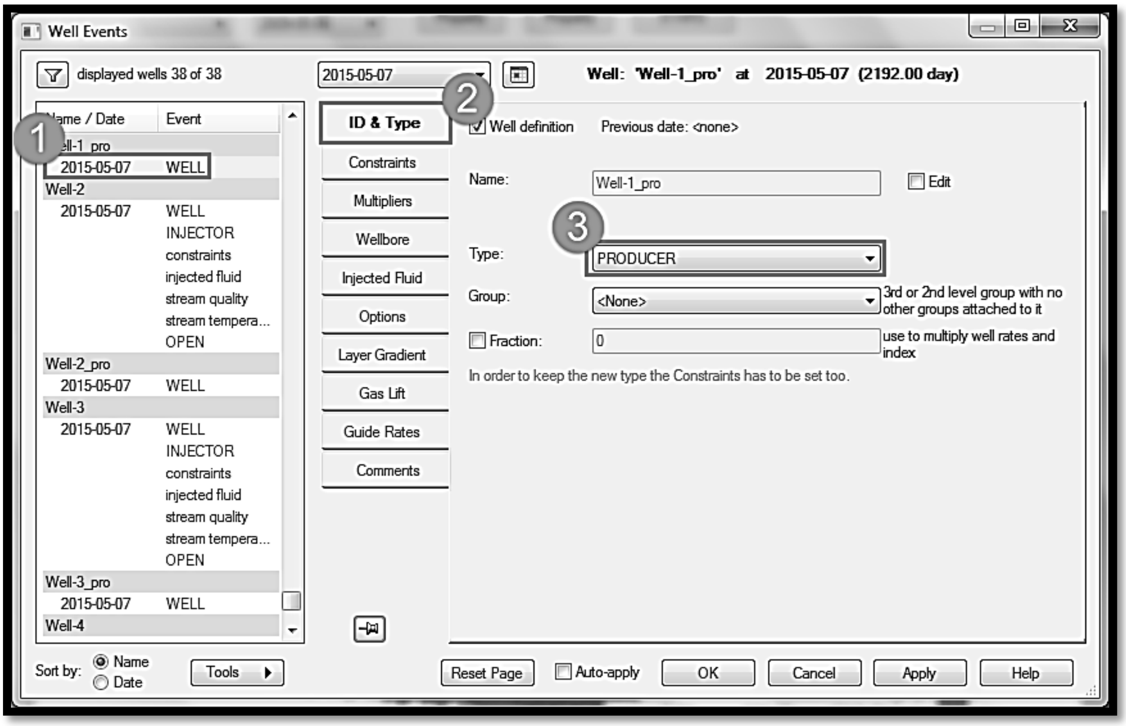


Figure 3-27 :Production Well Definition

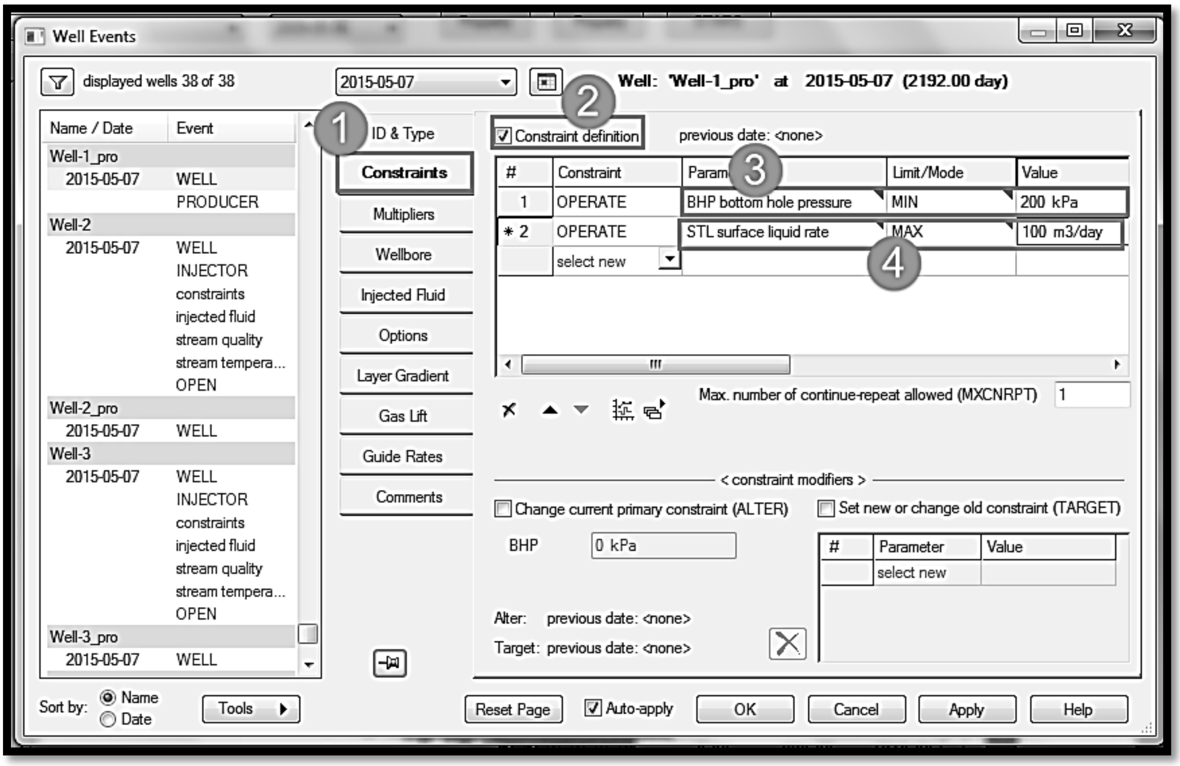


Figure 3-28 : Entering the Constraints

Chapter 4

Results & Discussion

Chapter 4: Results & Discussion

4.1 Introduction

The development of enhanced-oil-recovery (EOR) processes has been ongoing since the end of World War II**,**when operators who owned reservoirs with declining reserves recognized that significant quantities of oilremained in their reservoirs after primary and secondary recovery (primarily waterflooding). Research andfield activity increased as production from major reservoirs declined, worldwide consumption of oilincreased, and discoveries of major new reservoirs became infrequent. Intense interest in EOR processes wasstimulated in response to the oil embargo of 1973 and the following energy "crisis." The period of highactivity lasted until the collapse of worldwide oil prices in 1986.(Green & Willhite, 1998).

Over the years, interest in EOR has been tempered by the increase in oil reserves and production. The discovery of major oil fields in the North Slope of Alaska, the North Sea, and other regions (such asIndonesia and South America) added large volumes of oil to the worldwide market. In addition, estimates ofreserves from reservoirs in the Middle East increased significantly, leading to the expectation that the oilsupply will be plentiful and that the oil price will remain in the vicinity of U.S. $20 to $25lbbl. (constantdollars) for many years.(Green & Willhite,1998).

Although large volumes of oil remain in mature reservoirs, the oil will not be produced in large quantities by EOR processes unless these processes can compete economically with the cost of oil production fromconventional sources. Thus, as reservoirs age, a dichotomy exists between the desire to preserve wells forpotential EOR processes and the lack of economic incentive because of the existence oflarge reserves of oil inthe world.

Thermal recovery processes rely on the use of thermal energy in some form both to increase the reservoir temperature, thereby reducing oil viscosity, and to displace oil to a producing well.

One of the Thermal recovery processes is CSS, in cyclic steam stimulation, steam is injected into a productionwell for a period of 2 to 4 weeks. The well is shut in and allowed to"soak" before returning to production. The initial oil rate is high because of the reduced oil viscosities at the increased reservoir temperatures. There is also some acceleration from increased reservoir pressure near the well bore. With time, the heated-zone temperature declines as a result of heat removed with the produced fluids and conduction losses to over- and underlying formations. Oil rates decline as the heated-zone temperature and oil viscosity decrease.

When the production declines to a predetermined level, another cycle of steam injection is initiated. In some reservoirs, up to 20 cycles have been carried out.

- **Importance of CSS:**
  - Prepare the field for future steam flooding by heating a part of the reservoir.
  - Reduced oil viscosity and there for change the wettability around the well bore from oil to water wet in addition to mobility ratio reduction.
  - Reduces S_{or} (remaining oil in the reservoir).
  - Quick increment in oil rate once the production phase is started.

(Green & Willhite, 1998).

4.1.1 Field Introduction

Fula North East FNE oil field is located in the Northeast of Fula sub basin, 9 Km from Fula CPF 3D Area: 72 km^2. Structure units in oil-bearing area: (FNE-1, FNE-3 & FNE-N).

FNE consist of 23wells on CHOPS, 8wells have been converted from CHOPS to CSS 4wells (3^{rd} cycle) 4wells (4^{th} cycle) 25wells started with CSS: 3wells (1^{st} cycle) 12wells (3^{rd} cycle) 8wells (4^{th} cycle) 2wells (5^{th} cycle), Then the total number of wells is 56. It has two main Pay Zones are:

Aradeiba (d)

- ✓ OIIP: 33.23 MMSTB
- ✓ Weak edge water

Bentiu (a, b & c)

- ✓ OIIP: 265.5 MMSTB
- ✓ Massive sand
- ✓ Burial Depth (460~580 m)
- ✓ Bottom water support

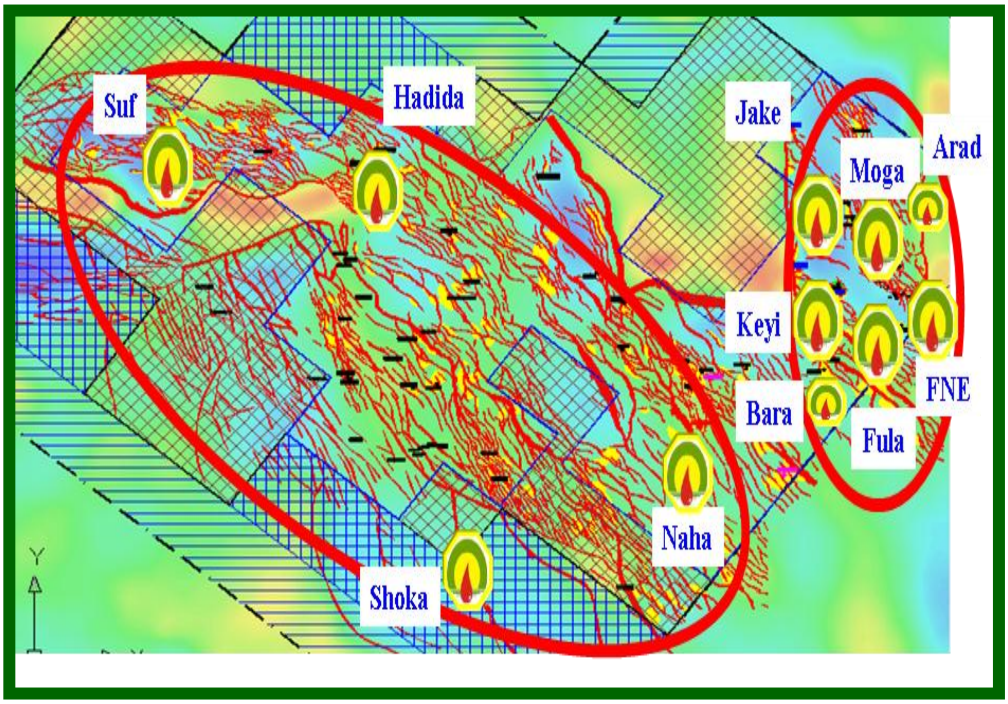


Figure 4-1: FNE Oilfield Location Map (OEPA, 2015)

4.1.1.1 Pressure and temperature system

At 529 m depth the average pressure is 576 psi and the average temperature is 43.9^0c.

4.1.1.2 Reservoir Fluid Properties

Conventional heavy oil in both Aradeiba & Bentiu, see table 4-1 of crude oil properties and water properties of FNE oil field.

Table 4-1: Crude Oil Properties and Water Properties of FNE Oil Field

Crude properties	
API	17.7
TAN(mgKOH/l)	5.4
Pour point(^{0}c)	4
Viscosity @29^{0}c(cp)	3800
Viscosity @50^{0}c(cp)	727.33
Water properties	
Water type	$NaHCO_3$
PH value	7.64
Salinity (mg/L)	1067.82
Chloride content (mg/L)	524.66

4.1.1.3 Reservoir Characterization

See table 4-2 of reservoir characterization for the producing layers of FNE oil field.

Table 4-2: Reservoir Characterization of FNE Oil Field

Formation	Aradeiba	Bentiu
Φ(%)	25 to 30	29 to 34
K(md)	100 to 5000	1000 to 10000
Net pay	3.3	31.5

Table 4-3 show the originaloil in place division of FNE productive formations (Aradeiba & Bentiu).

Table 4-3: Original Oil In Place (OOIP) Of Aradeiba and Bentiu Formations

Formation	OOIP(MMSTB)
AD	33.23
B	265.5
Total	298.73

FNE reservoirs are highly porous (~30%), permeable (1000-2000 mD) and unconsolidated in nature. the fluid properties include viscous crude with 15 to 17.7 API. Corresponding viscosities are in the range of 250 cp and 500 cp at reservoir conditions. (Husham et al, 2016).

4.1.2 Selection of Steam Flooding pilot Area

According to FNE oilfield geological and reservoir characteristics, combined with reservoir production performance, determine the main factors should be considered for the selection test area, as follows:

- Abundance of reserves.
- Reservoir properties can represent the general level of the oilfield.
- Oil reservoir thickness>9m:
- Most wells should be thermal recovery completion; there are relatively more existing wells with stimulation effect.

- Located in the high parts of the local structure; with good cross-hole connectivity and a unified oil-water system. See table 4-4 of screening criteria for thermal recovery.

Table 4-4: Screening Criteria ForThermal Recovery

Item	SF	FNE
Pay depth (m)	<1300	550
Pay thickness(m)	7~60	30
NTG	>0.4	0.6
Horizontal perm	>200	4000
Porosity%	>20	32
Oil Saturation%	>45	70
Oil viscosity	<10000	661 @50^0C
Reservoir pressure	<725	610

Considering the abundance of reserves in the test area, reservoir properties can represent the oilfield properties, taking B1a, B1b and B1c oil formation for examples, it can be determined with the porosity, permeability, oil saturation field, the abundance distribution of reserves . Most wells in the selected pilot area are the steam stimulation wells, and the reservoir thicknesses greater than 9m, selected pilot test area is located in the high parts of the local structure; with good cross-holeconnectivity and a unified oil-water system. See figure 4-2: Structural map of FNE

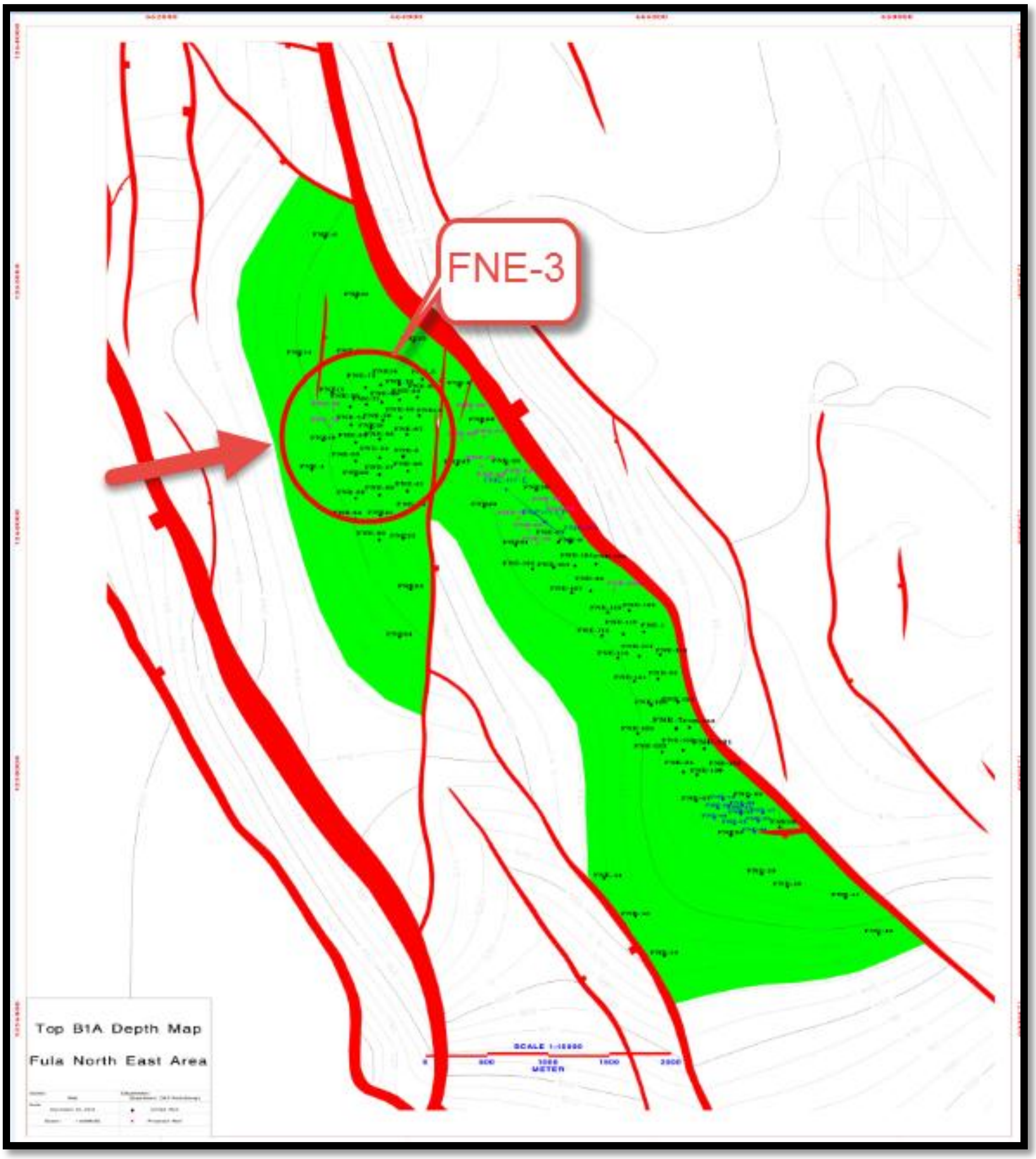


Figure 4-2: Structural Map of FNE Top B1A

By analysis of the reserve, structure, connectivity, oil saturation and other parameters of FNE; the area is in line with the selection principle forsteam injection pilot test area, so it is recommended as the area for SteamFlooding pilot test.
Husham et al. (2016).

4.1.3 Model Introduction

The simulation of this thesis begins from 6-5-2015 to 6-5-2026 as a prediction to the future performance and productivity of the FNE oil field by running the simulation model in different scenarios (DNC, CSS, infill wells cold, infill wells CSS and SF scenario) with different steam parameters to make an optimization between all the scenarios which will be done in this chapter.

The model is Do Nothing Case (DNC) model, its simulation history begins from 6-5-2009 till 1-3-2015 with 2082 dates and 14 wells, 4 of it processing with CHOPS and 10 wells with CSS.

The simulation model consists of 27 layers, Grid Type: Corner Point 61*53*27, Total Blocks = 87291.

Porosity Type: Single, Connection Type: Five Point, Named Faults: 1, Geological Units: 5. the sectors: B1a, B1b, Sector1.

It has 14 wells, 4 wells produce with CHOPS and 10 wells producing by CSS, the Reference Pressure (REFPRES) is 3647.33 kPa, the Reference Depth (REFDEPTH) is 28.4 m, Water Oil Contact Depth (DWOC) is 28.4 m and the First Time Step Size After Well Change (DTWELL) = 10day.

Pressure (PRESS) 500 kPa, Saturation (SATUR) 0.2, Temperature (TEMP) =30 C. The dates are 1982, begins from 6-5-2009 till 6-5-2026 with step=1, per days. Figure 4-3 show the grid top (m) in 2D while figure 4-4 grid top in 3D for the simulation model.

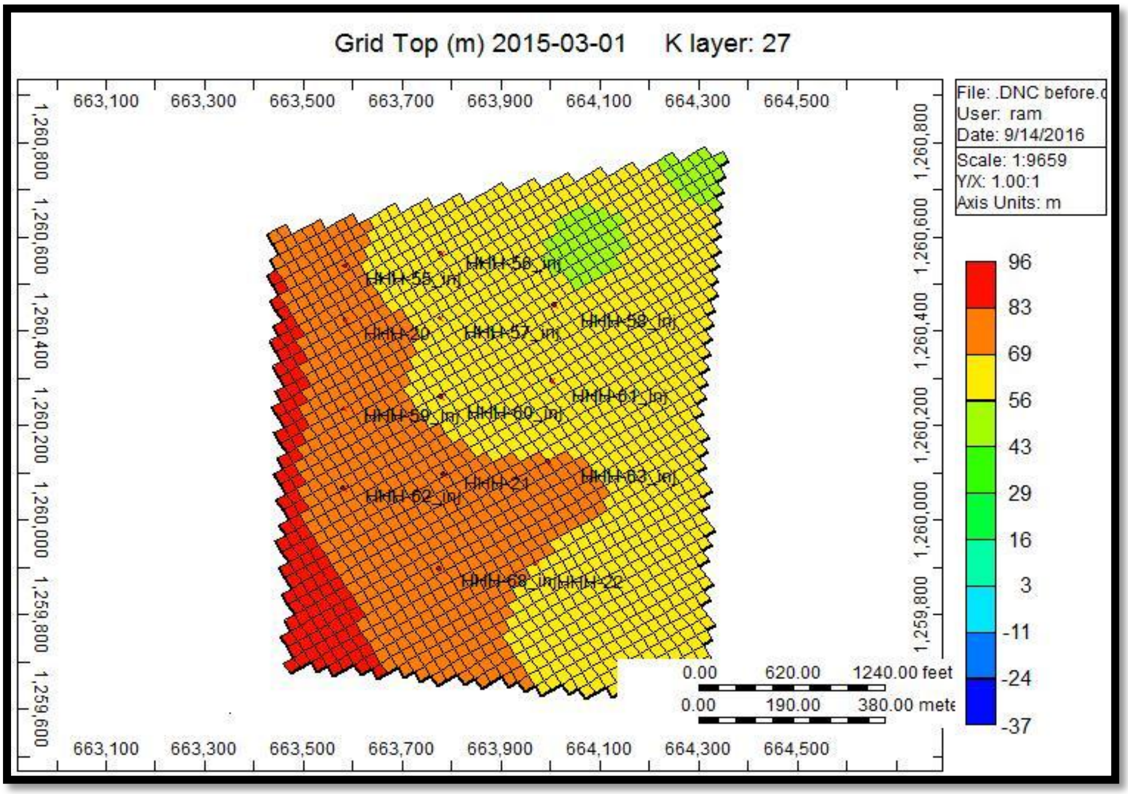


Figure 4-3: GridTop (m) For the Simulation Model

Grid top (m) range from (-37 to 96) m, but the most of grids are above 56 m.

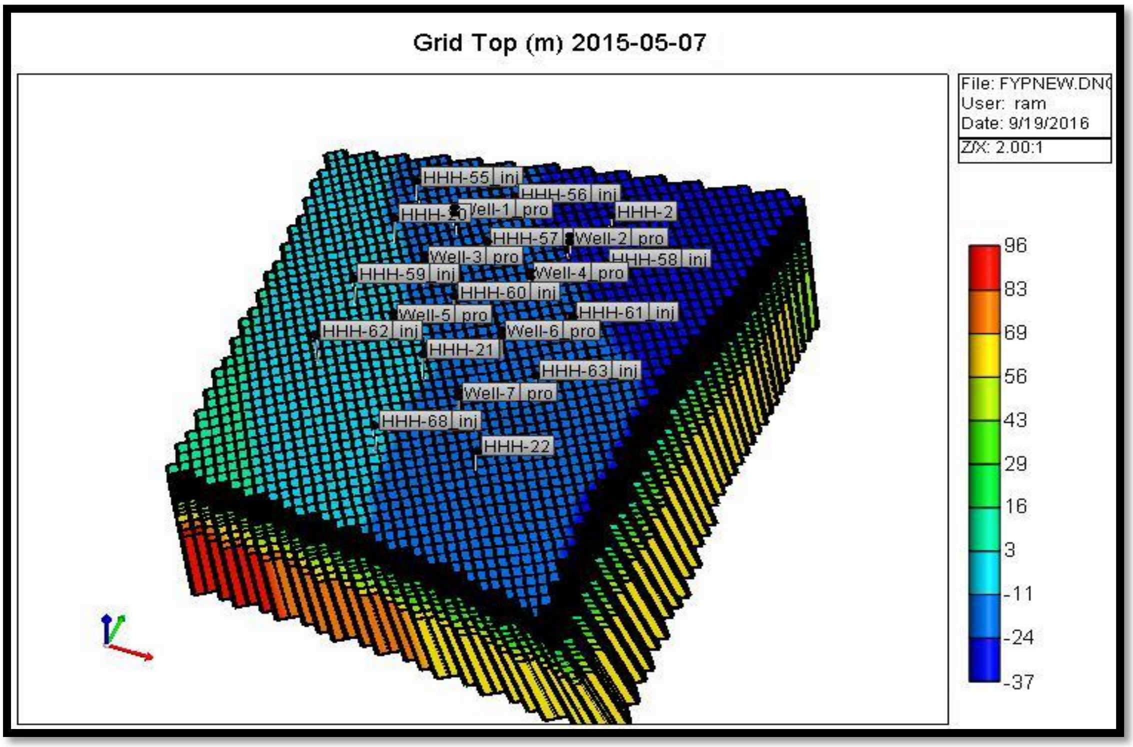


Figure 4-4: Grid Top In3DFor the Simulation Model

At surface the grid top 3D range from (-37 to29) m and then increase with depth till reach 96m as maximum grid top.

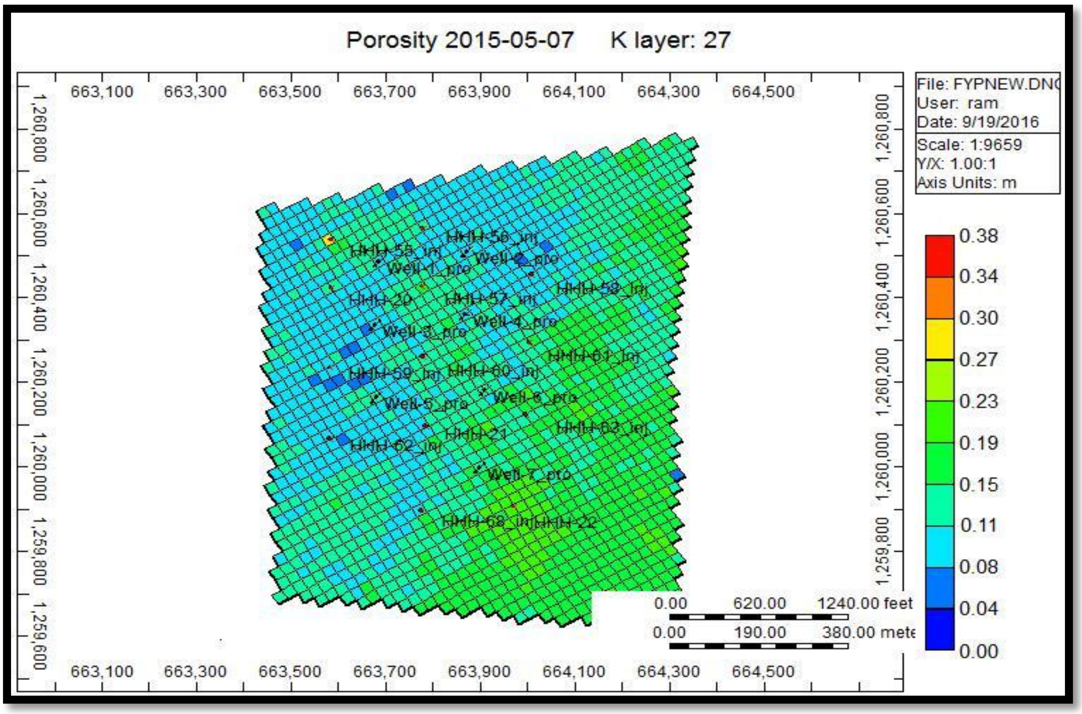


Figure 4-5: Porosity ForPerforations Layerof the Simulation Model

The above figure (4-5) illustrates porosity distribution for perforations layer of the simulation model. Good distribution of porosity, its range from 0.15 to 0.27.

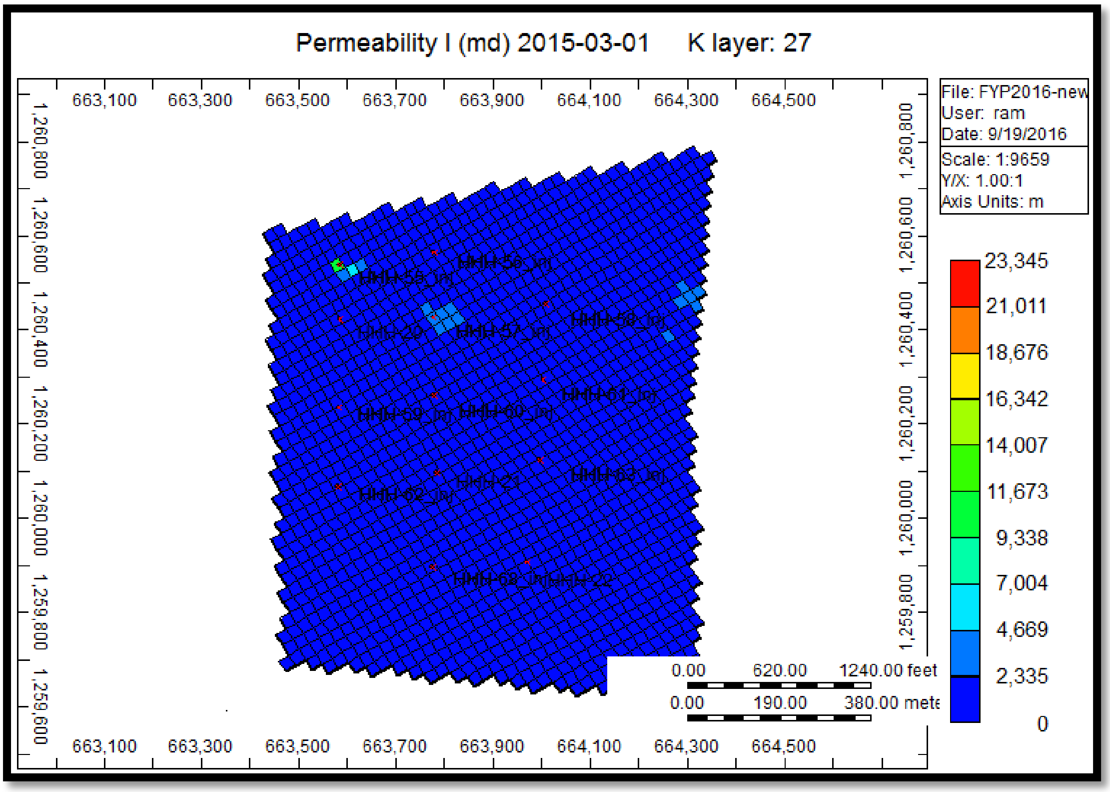


Figure 4-6: PermeabilityForPerforations Layerof The Simulation Model

Figure 4-6show Permeabilitydistribution for perforations layer of the simulation model. High permeability, increase till reach 10000 md.

4.2 Development Scenarios:

This section contains the results, analysis and discussion for the simulation models of the sector of FNE oil field. Discussing of different scenarios: DNC&CSS , infill wells (cold), infill wells (CSS) and steam flooding scenarios, by using different sets of steam injection parameters : (injection rates of 120,180,210,250m3/day &temperatures of 200,250,300,350 ^{0}C& with steam qualities of 0.5,0.6,0.7,0.8) to make optimization to choose the optimum one to be applied in FNE Sudanese oil field.

4.2.1 Case One:Do Nothing Case (DNC)

In DNC: there is no injection wells, just producing from 14 production wells, without using any injection processes and without drilling new seven wells (without doing anything), so it will give almost less oil production results as compared with the other cases which will be discussed later in this chapter.

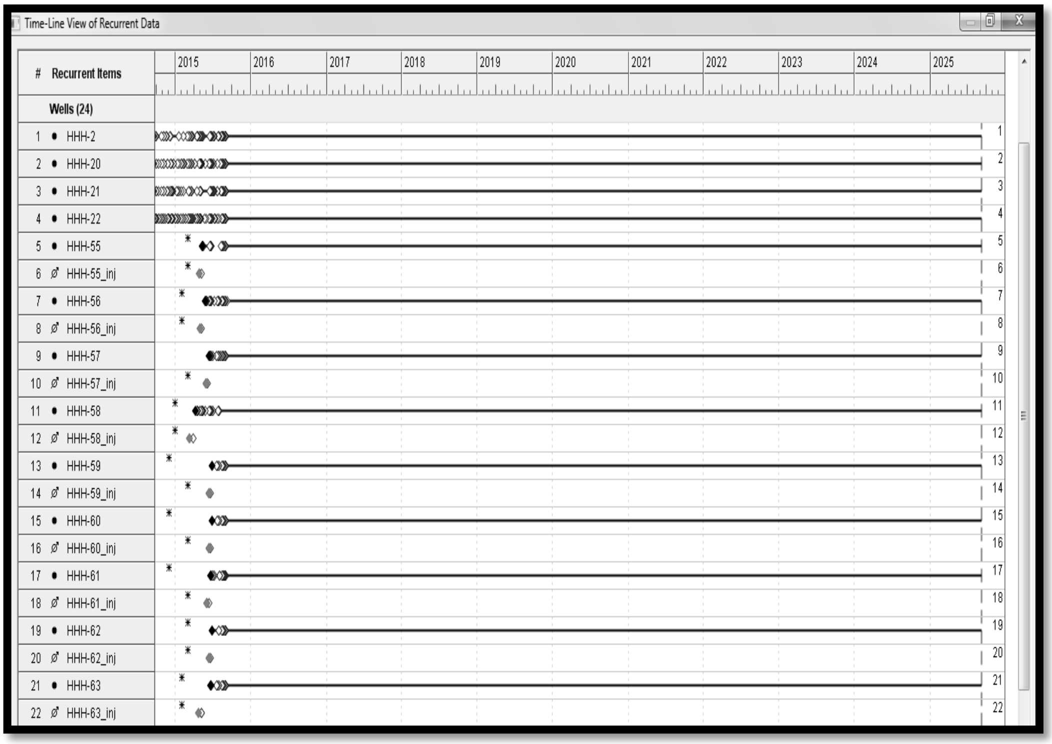


Figure 4-7 : Time Line View of DNC.

The time line view (figure 4-7) show that there is no injection wells working, just produce from the production wells.

DNC scenario had been done by using production parameter as follows:(production rate 100 m3/day and production pressure of 200 kPa), and the injection wells are closed , so the changes in injection parameters will not effect on the DNC performance.

See figure 4-8 below of plotting DNC.

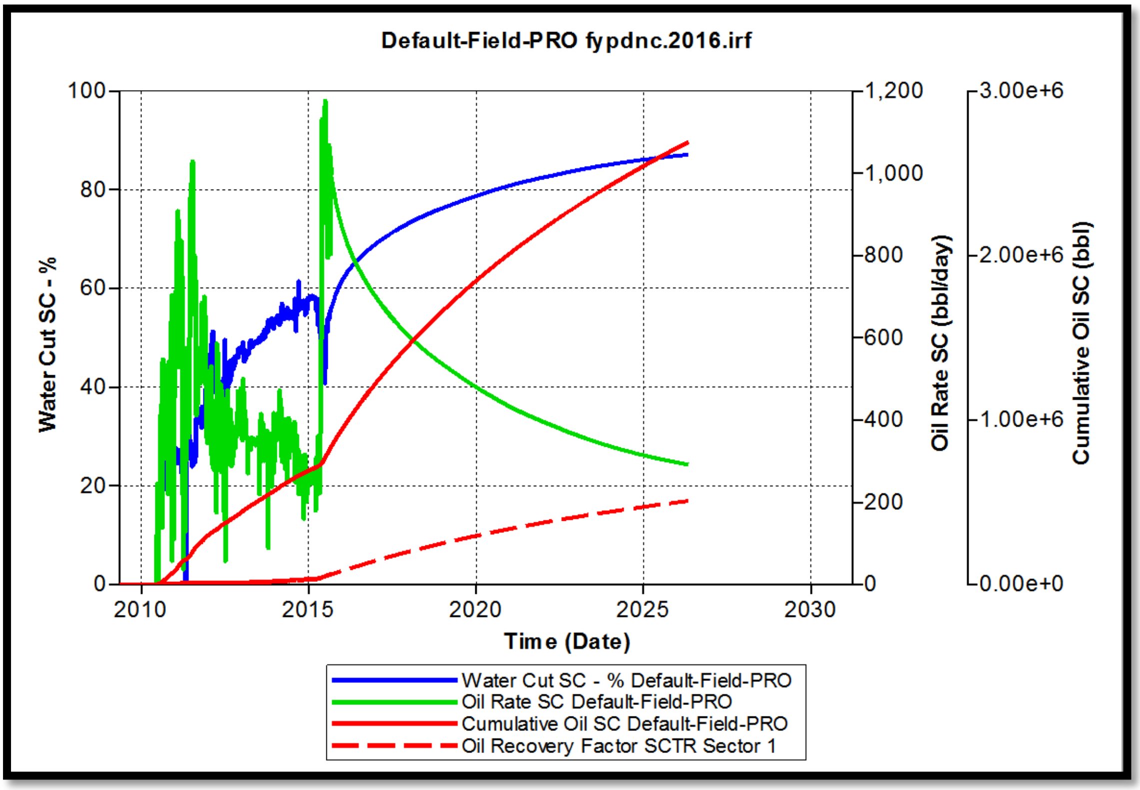


Figure 4-8: Plotting of (Cumulative Oil SC, Oil Rate SC, Water Cut SC %, Recovery Factor) Versus (Time) of DNC.

Figure 4-8 is the DNC scenario which had been done and plotting of the results: cumulative oil sc, oil rate sc, water cut sc %, oil recovery factor) versus (time) as a prediction of the field performance till 2026.

The figure 4-8 shows a significant increase in the value of cumulative oil from 2015 to 2026. It was found that the value of cumulative oil was 728779bbl in 2015 and become 2.69E06 bbl in 2026 and also chart shows the average oil production rate where it was 449.8bbl/day before 2015 and become 523.54 bbl/day from 2015 to 2026 and the water cut in 2026 and it was 87% and the Recovery factor it 1.26 % was in 2015 and become in 11.23 % 2026. See table 4-5 of DNC results:

Table 4-5: Results of DNC Scenario at 2026

Case	Injection rate (m3/day)	Temperature (^{0}C)	Steam quality	Cumulative oil (bbl)	Oil rate (bbl/day)	Wat Cut %	RF (%)
DNC	*	*	*	2.69E06	523.54	87	11.23

4.2.2 Case Two: Cyclic Steam Stimulation (CSS)

CSS means using Cyclic Steam Stimulation on the injection wells as a mechanism to produce oil (CSS consist of: Injection period then soaking period then production period), to better increase the productivity from the production wells. See figure 4-9 time line view.

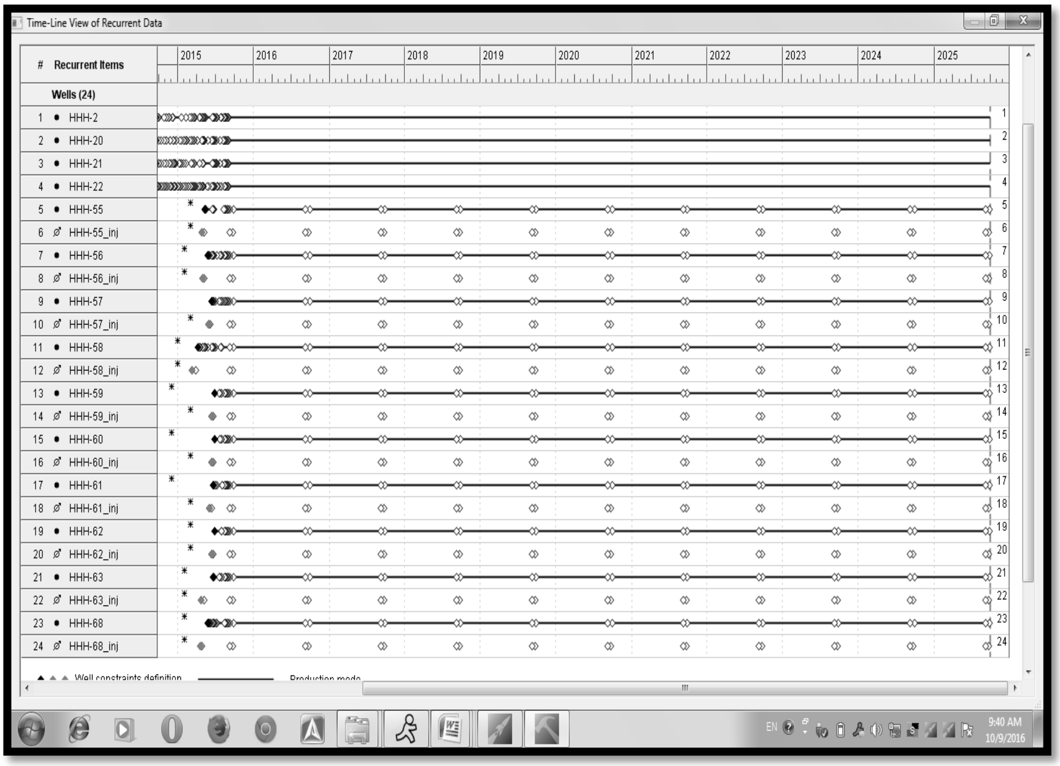


Figure 4-9: Time Line View of CSS.

In this case one cycle with soaking period of 5days, periodic injection of steam for 14 days in 10 injection wells, then produce from 14 production wells with the same production parameters.

Four different scenarios with different parameters had been done for the CSS case. Table 4-6below illustrate the CSS scenarios which had been done.

Table 4-6: CSS Scenarios.

Case	Injection rate (m3/day)	Temperature (^{0}C)	Steam quality (fraction)	Color
CSS	250	200	0.8	Red
	210	250	0.7	Blue
	180	350	0.6	Green
	120	300	0.5	Magenta

There are no significant changes between the results of CSS scenarios, but the scenario of using Injection rate of 210(m3/day), Steam quality of 0.7 and with steam temperature = 250^0C is slightly better than the others. See figure 4-10 of cum oil production of the all scenarios of CSS.

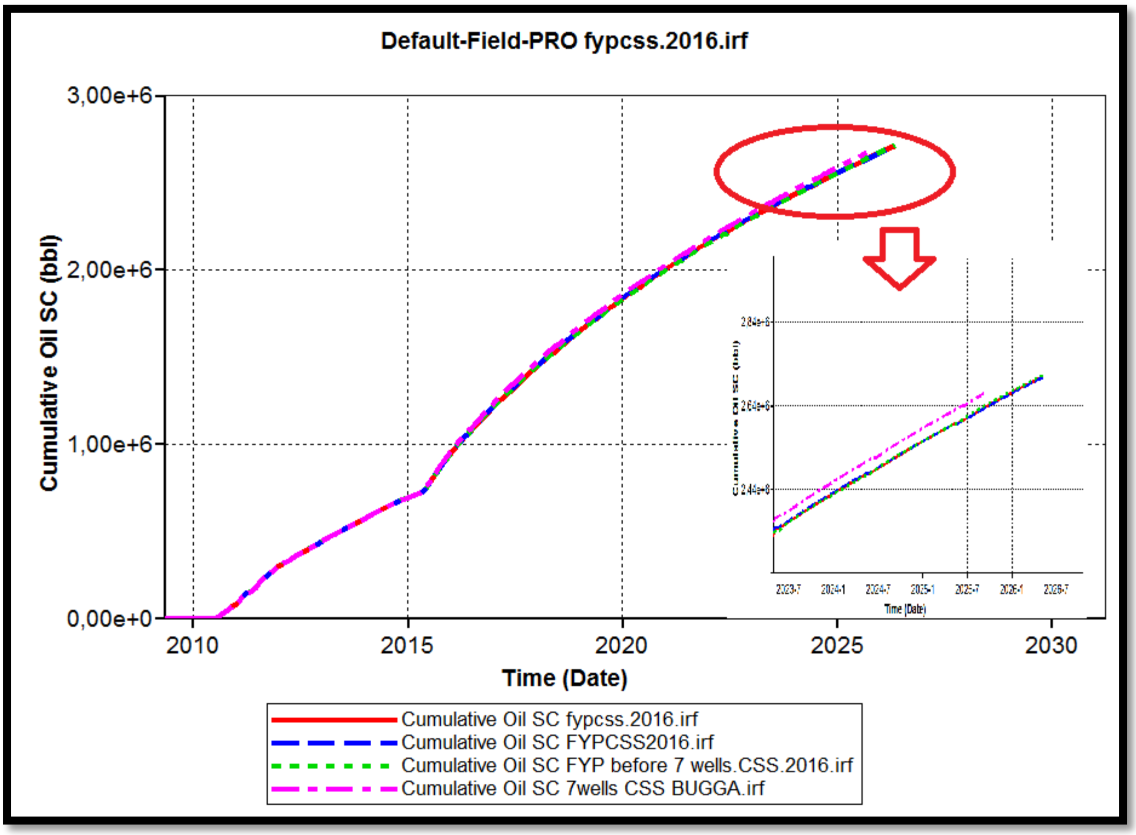


Figure 4-10: Cumulative Oil SC for All Cases of CSS Scenario.

From the above figures there is no clear difference between the cases of CSS. See figure 4-11which illustrate the results of the best CSS scenario between the others scenarios.

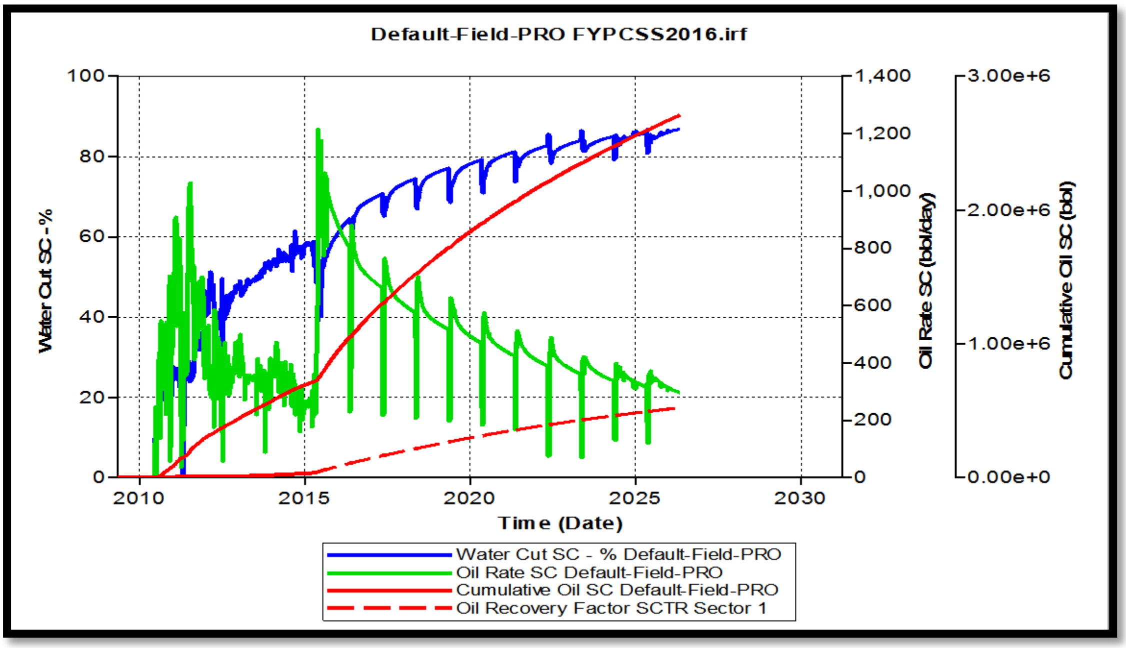


Figure 4-11: Plotting of (Cumulative Oil SC, Oil Rate SC, Water Cut SC %, Oil Recovery Factor) Versus (Time) of The Best CSS Scenario.

The above figure illustrate a significant increase in the value of cumulative oil from 2015 to 2026. It was found that the value of cumulative oil was 728779 bbl. in 2015 and become 2.71E06bbl in 2026 and also chart shows the average oil production rate where it was 446.1 bbl./day before 2015 and become 363.24 bbl/day from 2015 to 2026 and the water cut in 2026 and it was 86.8% and the Recovery factor it was 1.2 % in 2015 and become in 11.31 % 2026 The table below shows the production per well separately and the total of cumulative oil for all wells . See table 4-7 results of CSS scenarios which had been done.

Table 4-7: Results of All CSS Scenarios.

Case	Injection Rate (m3/day)	Temp (^{0}C)	Steam quality (fraction)	Cumulative Oil-SC (bbl)	Oil Rate (bbl/day)	Water Cut-SC (%)	RF (%)
CSS	250	200	0.8	2.7E06	357.3	86.5	11.27
	210	250	0.7	2.71E06	363.24	86.8	11.31
	180	350	0.6	2.69E06	361.12	86.7	11.23
	120	300	0.5	2.696E06	359.5	87.2	11.25

The table of CSS results show that using Injection rate of 210(m3/day), Steam quality of 0.7 and with steam temperature of 250^{0}C is slightly better than the others.

4.2.3 Case Three:Infill wells (Cold)

After that seven new wells was drilled in the middle of each four wells (infill wills), in order to design the main project which is steam injection, the total wells become 21 wells and has also worked on cases infill wells cold and infill wells CSS before applying steam injection into the field.

Infill wells (cold) is like DNC, there is no injection wells, but producing from 21 production wells, without using any injection processes (without doing anything), so it will give almost better oil production results than the DNC scenarios or even if CSS scenarios. See time line view (figure 4-12).

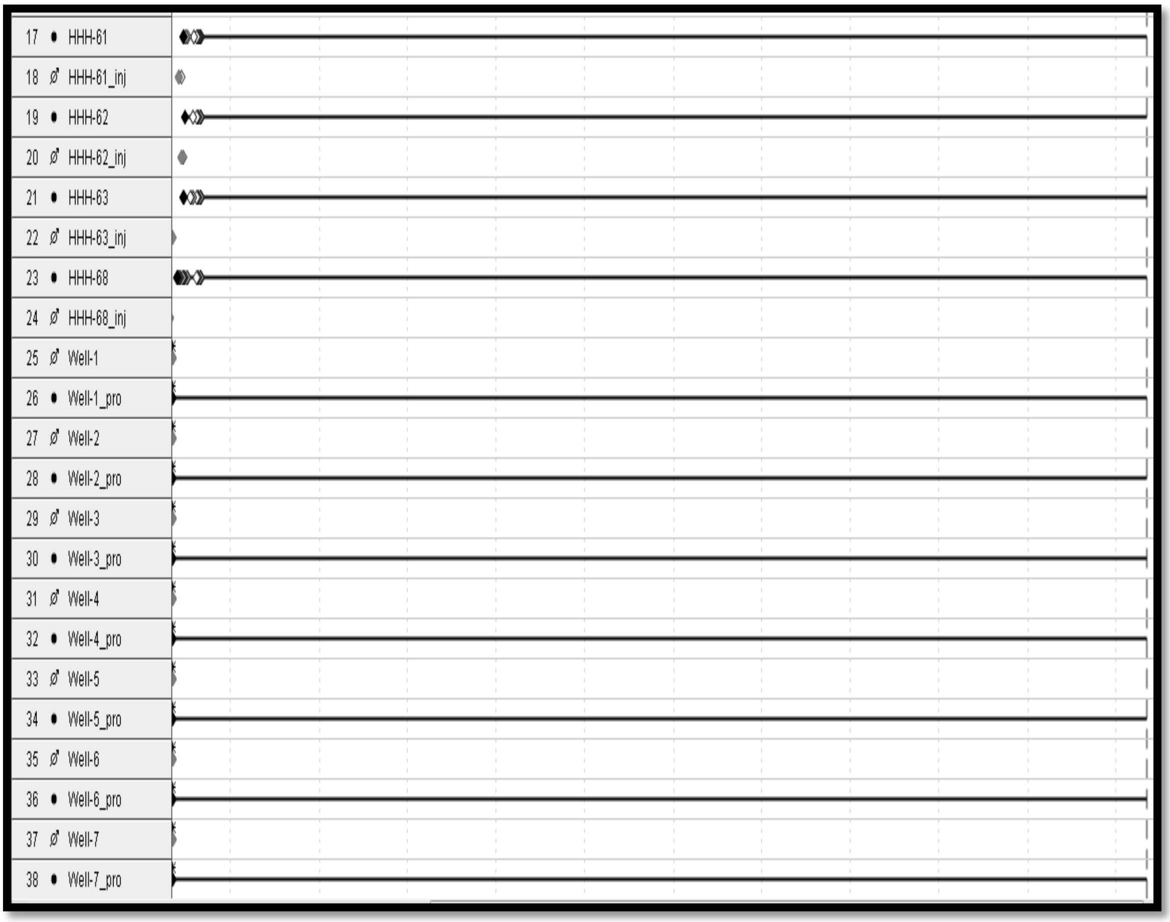


Figure 4-12: Time Line View of Infill Wells DNC

From the time line view it is clear that is there is no injection process, just producing from 14 wells + 7 new wells (infill wells); so the total production in this case is from 21 wells. Scenario had been done with the same production parameters (production rate 100 m3/day and production pressure of 200 kPa). The injection parameters will not effect on the performance of this case, because the injection wells are in shut-in situation, and produce without doing anything (cold production).

Figure 4-13showing theplotting of infill wells (cold) scenario.

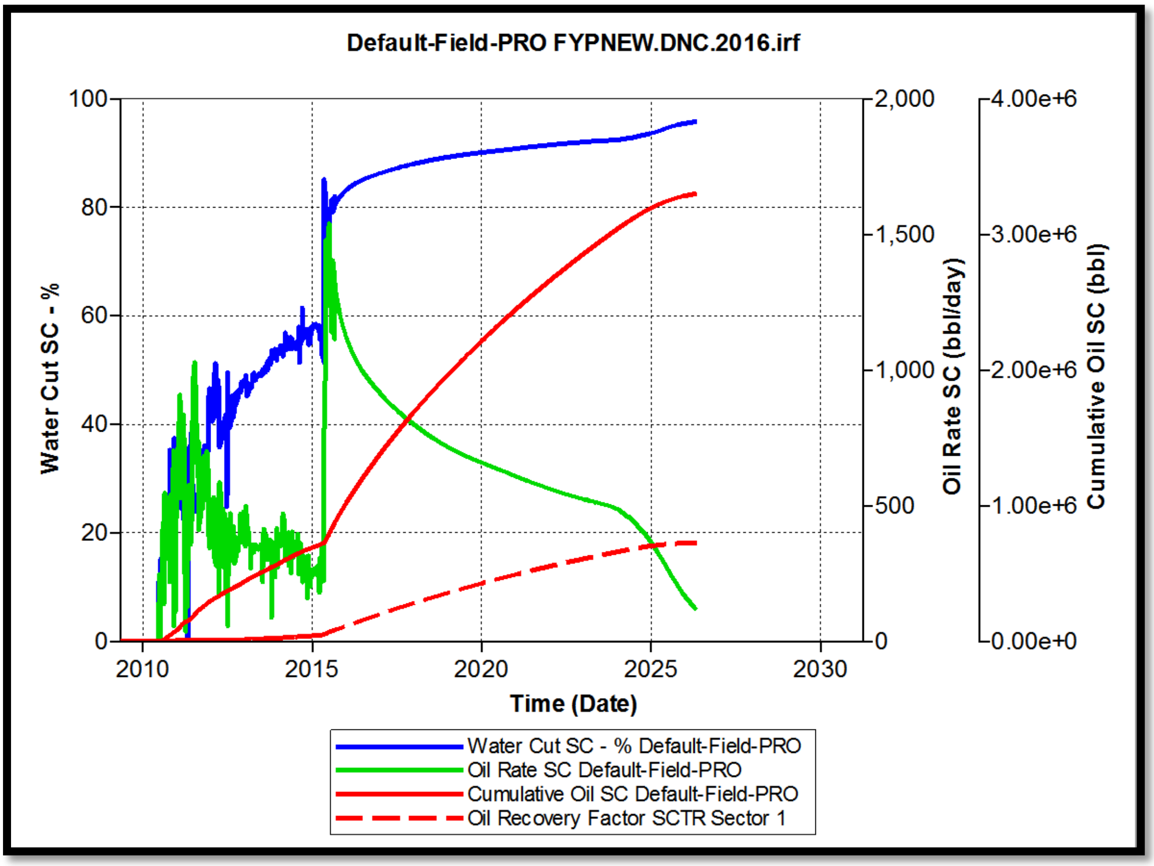


Figure 4-13: Plotting Of (Cumulative Oil SC, Oil Rate SC, Water Cut SC %, Oil Recovery Factor) Versus (Time) Of Infill Wells (Cold) Scenario.

The figure 4-13 shows a significant increase in the value of cumulative oil from 2015 to 2026. It was found that the value of cumulative oil was 728779bbl in 2015 and become 3.3E06bbl in 2026 and also chart shows the average oil production rate where it was 481.4bbl/day before 2015 and become 680.2bbl/day from 2015 to 2026. It is noted from the figure sudden drop in the middle of the year 2024.And the water cut in 2026 and it was 95.72% and the Recovery factor it was 1.2 % in 2015 and become in 13.78 % 2026 .

Table 4-8: Results of Infill Wells (Cold) Scenario

Scenario	Injection Rate (m3/day)	Temp (^{0}C)	Steam quality (fraction)	Cumulative Oil-SC (bbl)	Oil Rate (bbl/day)	Water Cut-SC (%)	RF (%)
Infill wells cold	250	200	0.8	3.3E06	680.2	95.72	13.78

Table 4-8illustrate the results which had been gained from the simulation done for the infill will (cold)

4.2.4 Case Four - Infill wells (CSS)

After infill wells (cold) the field is developed to Cyclic Steam Stimulation (CSS) by the same soaking period 5 days and one cycle per year and using the samedifferent injection parameter, withthe same production parameters said before. See figure 4-14 the time line view. See table 4-9 of the scenarios done in this case

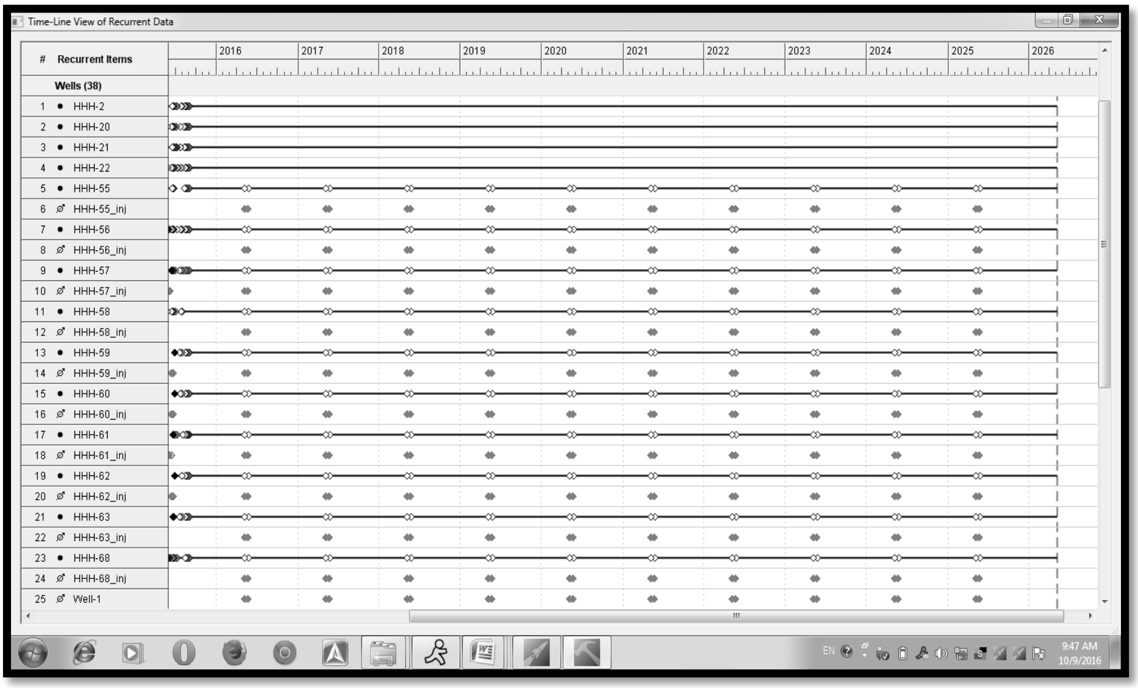


Figure 4-14: Time Line View of Infill Wells CSS

Figure 4-14 show the CSS and producing from 21 well instead of 14 wells

Table 4-9: Infill wells (CSS) scenarios.

Scenario	Injection Rate (m3/day)	Temperature (^{0}C)	Steam quality(fraction)	Color
Infill wells CSS	250	200	0.8	Red
	210	250	0.7	Blue
	180	350	0.6	Green
	120	300	0.5	Magenta

Four different scenarios with different injection parameters (table 4-9) had been done. See figure 4-15 of cumulative oil sc For the Scenarios of Infill Wells (CSS).

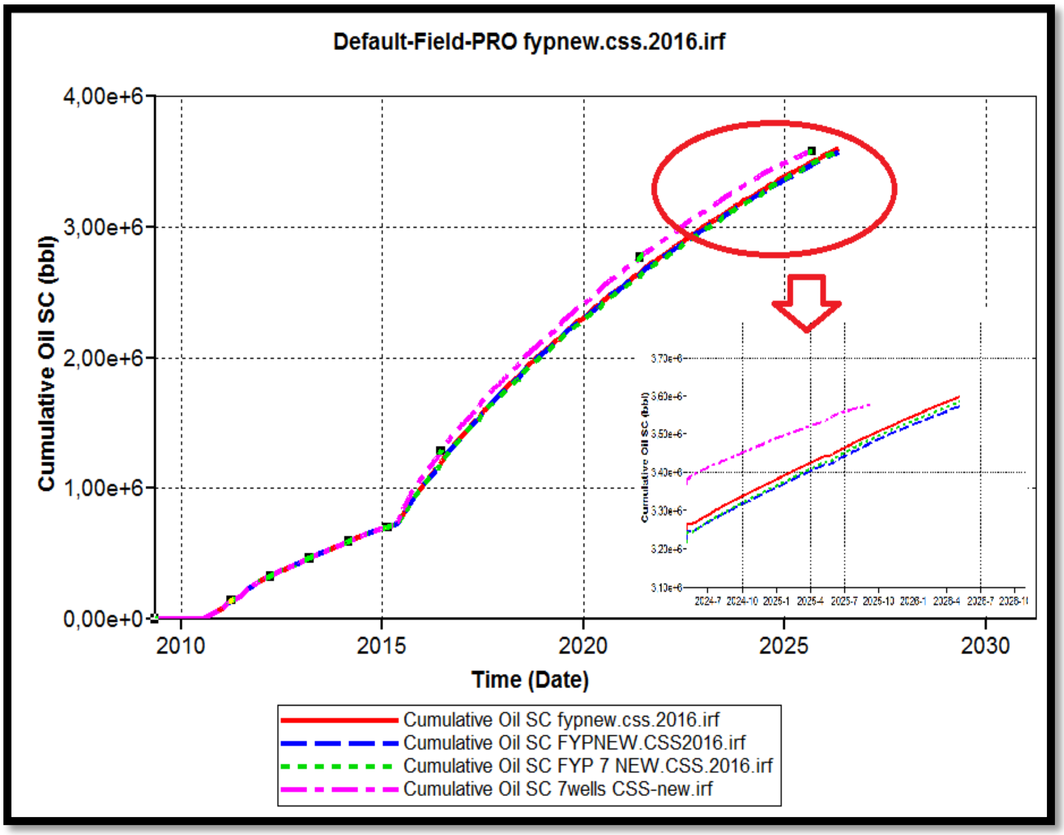


Figure 4-15: Cumulative Oil-SC For the Scenarios of Infill Wells (CSS).

It is clear from figure 4-15 that the Cumulative oil-SC of the 1st case is the optimum one, it is value is 3.6 MM bbl. Figure 4-16 illustrate plotting the results of the best infill wells css scenario.

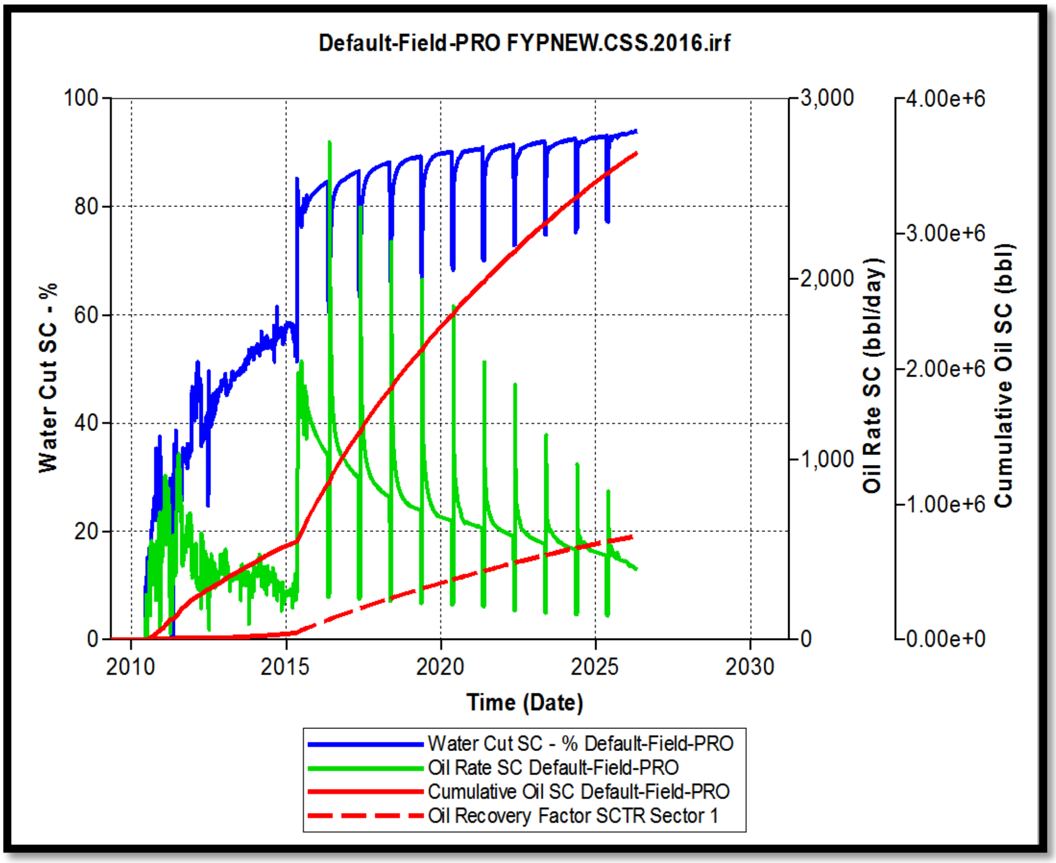


Figure 4-16: Plotting of (Cumulative Oil SC, Oil Rate SC, Water Cut SC %, Oil Recovery Factor) Versus (Time) of Infill Wells (CSS).

Above figure illustrate a significant increase in the value of cumulative oil from 2015 to 2026. It was found that the value of cumulative oil was 728779 bbl in 2015 and become 3.6E06 bbl in 2026 and also chart shows the average oil production rate where it was 481.4 bbl/day before 2015 and become 698.5 bbl/day from 2015 to 2026, and the water cut-sc % in 2026 and it was 94% and the oil recovery factor it was in 1.2 % 2015 and become in 15.03 % 2026.

Table 4-10: Results of Infill Wells (CSS) Scenarios.

Scenario	Injection Rate (m3/day)	Temp (^{0}C)	Steam quality (fraction)	Cumulative Oil-SC (bbl)	Oil Rate (bbl/day)	Water Cut-SC (%)	RF (%)
Infill wells CSS	250	200	0.8	3.6E06	698.5	94	15.03
	210	250	0.7	3.575E06	600.7	94.26	14.92
	180	350	0.6	3.6E06	595.3	94	15.03
	120	300	0.5	3.53E06	597.35	94.5	14.74

It is clear from table 4-10 that the 1st scenario of using injection rateof 250 m3/day, temperature of 200^0C and steam quality of 80%; is the optimum scenario for CSS with infill wells.

4.2.5 Case Five: Steam Flooding (SF)

The injection of steam from injection wells toward the production wells to more decrease for oil high viscosity and thus improve the recovery factor of the field. By using the seven new wells (1-7) as injectors and others as producers.In steam flooding scenario using continuous steam injection instead of cyclic steam injection. See figure 4-17 time line view.

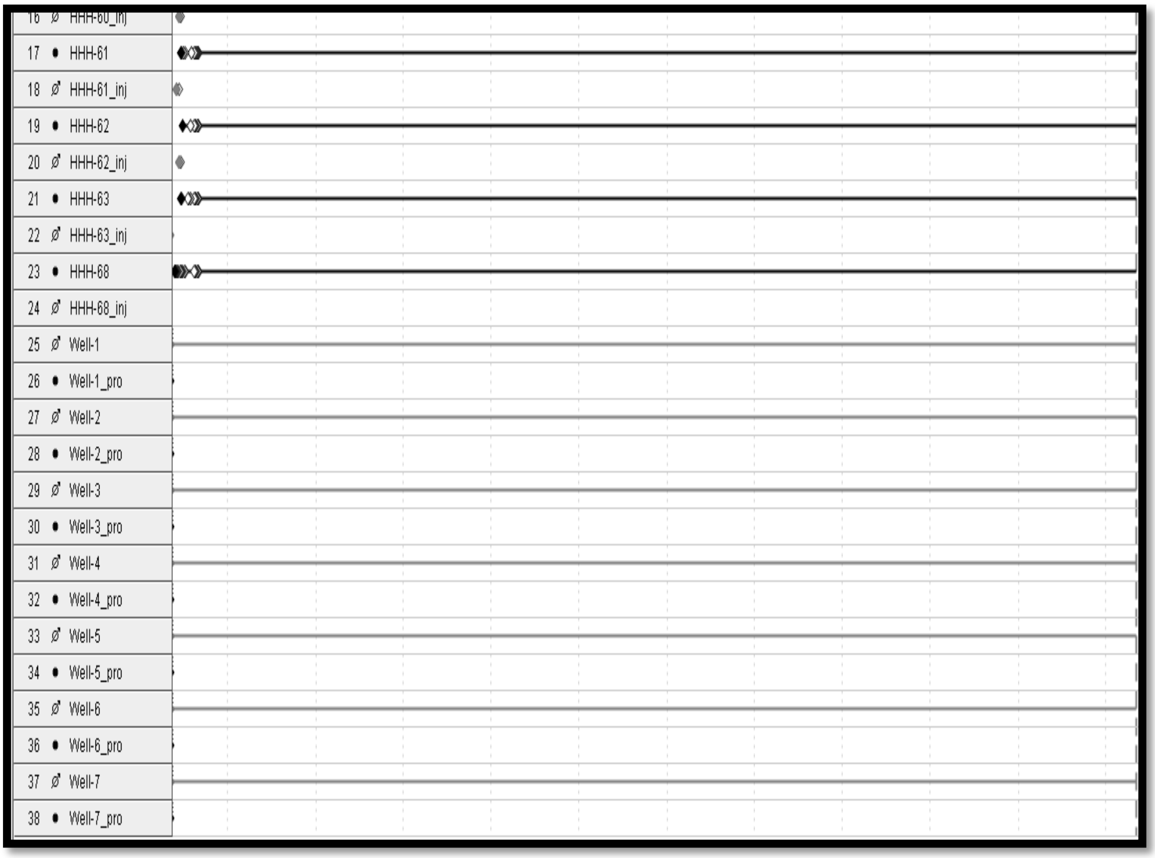


Figure 4-17: Time Line View of SF.

It is clear as shown in the time line view; in SF case using continues steam injection by the seven new wells, and producing from the production wells.

Four different scenarios with various injection parameters of steam flooding have been done, see table 4-11 below of SF scenarios:

Table 4-11: SF scenarios.

Scenario	Injection Rate (m3/day)	Temperature (^{0}C)	Steam quality(fraction)	Color
Steam flooding	250	200	0.8	Red
	210	250	0.7	Blue
	180	350	0.6	Green
	120	300	0.5	Magenta

Table 4-11 shows the 4 scenarios which had been done for SF process, the results of simulation model after built & run it & getting variable results, it had been found that the 1st set of steam injection parameters is the best and get the highest results of: cumulative oil production, oil rate, oil recovery factor and with the lowest water cut % among the other scenarios. See figure 4-18 plotting of cumulative oil of the steam flooding cases.

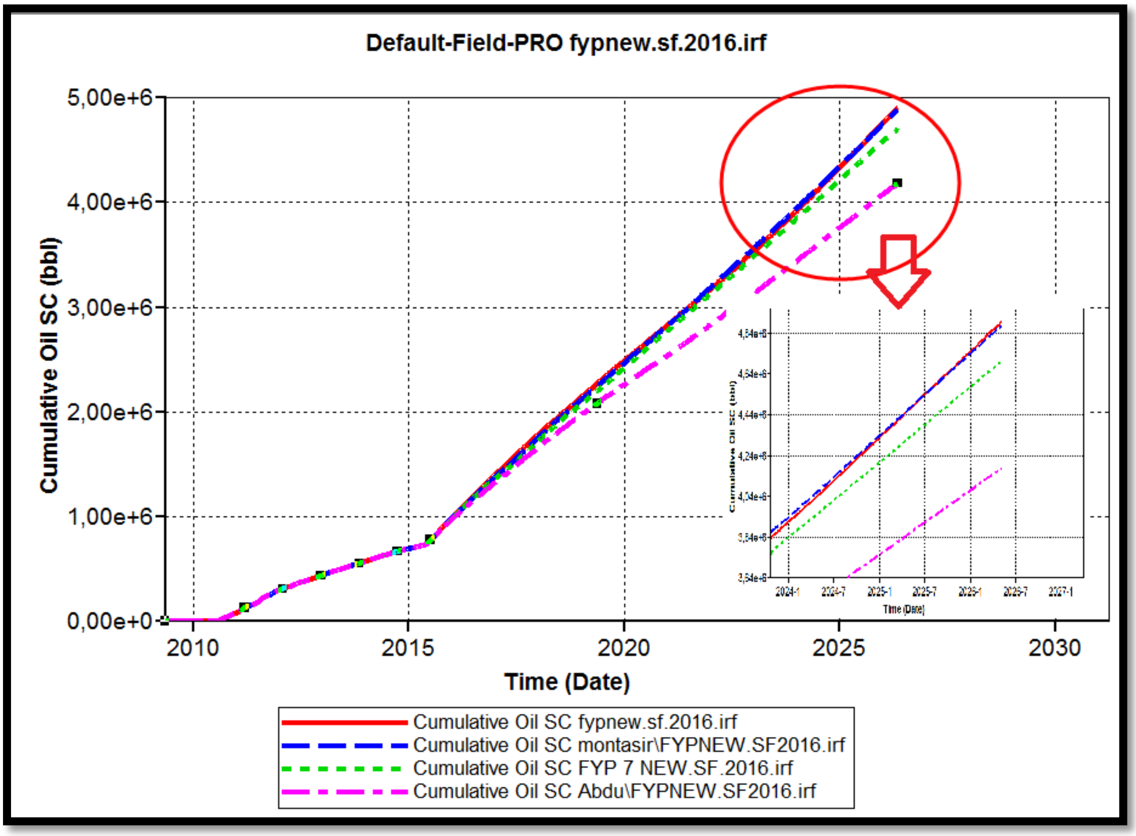


Figure 4-18: Plotting of Cumulative Oil SC forThe Steam Flooding Cases.

It is clear from figure 4-18 that the 1st case of steam flooding of applying injectionof 250 m3/day with steam quality of 80% and temperature of 200^{0}C is the optimum which is equal 4.889E06bbl.

See figure 4-19 of plotting the results of the best SF scenario.

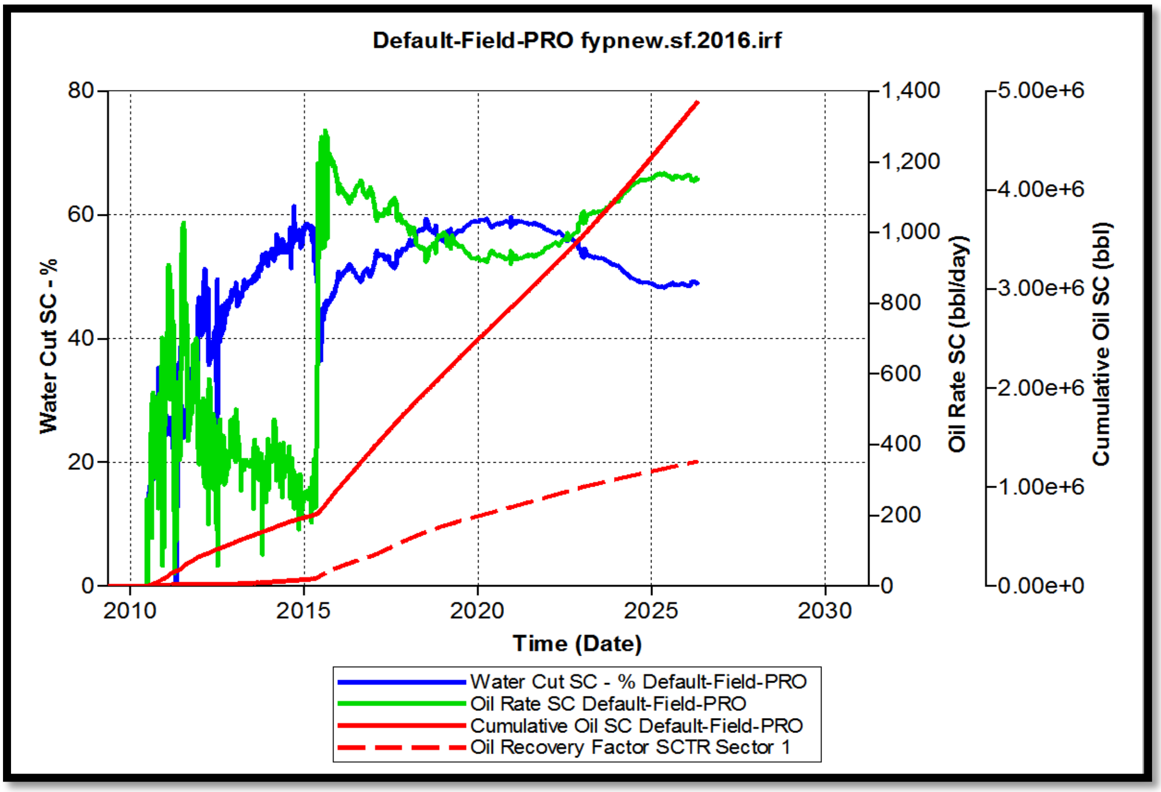


Figure 4-19: Cumulative Oil, Oil Rate, Water Cut and Recovery Factor For Steam Flooding

Above figure illustrate a significant increase in the value of cumulative oil from 2015 to 2026. It was found that the value of cumulative oil was 728779bbl in 2015 and become 4.889E06bbl in 2026 and also the figure shows the average oil production rate where it was 470.34bbl/day before 2015 and become 1053bbl/day from 2015 to 2026.

The water cut-sc % in 2026 is 49% and the Recovery factor it was 1.2 in 2015 and become in 20.41 % 2026.

See table 4-12 cumulative oil production from individual wells of the best SF scenario:

Table 4-12: Cumulative Oil of Wells For Steam Flooding

Well No.	Well name	Cumulative Oil Production (Mbbl)
1	HHH-2	123.3
2	HHH-20	446.32
3	HHH-21	381.8
4	HHH-22	1181.3
5	HHH-55	231.93
6	HHH-56	590.91
7	HHH-57	255.7
8	HHH-58	110.42
9	HHH-59	280.443
10	HHH-60	154.77
11	HHH-61	241.44
12	HHH-62	221.96
13	HHH-63	353.4
14	HHH-68	313.3
Total	14 wells	4889

The above table illustrates the individual production from each well of thebest SF scenario.

See table 4-13 of the overall result of the four SF scenarios which had been done.

Table 4-13: Results of SF scenarios.

Scenario	Injection Rate (m3/day)	Temp (^{0}C)	Steam quality (fraction)	Cumulative Oil-SC (bbl)	Oil Rate (bbl/day)	Water Cut-SC (%)	RF (%)
Steam flooding	250	200	0.8	4.889E06	1053	49	20.41
	210	250	0.7	4.868E06	1038.8	51.6	20.29
	180	350	0.6	4.7E06	997.1	55	19.49
	120	300	0.5	4.17E06	872.7	62	17.45

From the above table it is clear that the scenario of using injectionrate of 250m3/day, steam quality of 80% and with steam temperature 200 ^{0}C; give the best results, so its parameters are the optimum one to be applied in FNE field, also the scenario of using injectionrate of 210m3/day, steam quality of 70% and with steam temperature 250 ^{0}C as it is shown in the table 4-14 has good results, it can be applied to the field. Finally see table 4-14 for final results.

4.3 Final Results

Table 4-14: Summary Table Showing the Overall Results of All Cases Done

Scenario	Injection rate (m3/day)	Temp (^0C)	Steam quality (%)	Cumulative oil (Mbbl)	Oil rate (bbl/day)	Water cut (%)	RF (%)
DNC	-	-	-	2690	520	87	11.23
CSS	250	200	0.8	2700	357.3	86.5	11.27
	210	250	0.7	2710	363.24	86.8	11.31
	180	350	0.6	2690	361.12	86.7	11.23
	120	300	0.5	2696	359.5	87.2	11.25
Infill wells cold	-	-	-	3300	680.2	95.72	13.78
Infill wells CSS	250	200	0.8	3600	698.5	94	15.03
	210	250	0.7	3575	600.7	94.26	14.92
	180	350	0.6	3600	595.3	94	15.03
	120	300	0.5	3530	597.35	94.5	14.74
Steam Flooding	250	200	0.8	4889	1053	49	20.41
	210	250	0.7	4860	1038.8	51.6	20.29
	180	350	0.6	4669	997.1	55	19.49
	120	300	0.5	4181	872.7	62	17.45

Table 4-14 illustrates the overall results from the graph results for each run that have been done in this thesis, and shows that when the injection rate increase the cumulative oil increase, also the water cut (%) increase.

Also when the injection rate increase, the oil rate increase. The production rate of hot fluids starts higher than that of the primary cold production. However, the rate declines with time as heat is removed with produced fluids.

Also it is clear from the table that the optimum steam injection parameters are: injection rate of 250 m3/day and temperature of 200 (^0C) and steam quality equal 80%. To be applied as steam flooding parameters in FNE. It gives the highest cumulative oil (4.889 MM bbl) and the best Oil rate (1053 bbl/day) all that with less water cut 49 % which is favorable and acceptable value. In the next chapter the conclusion and recommendations of this thesis.

Chapter 5

Conclusion & Recommendations

Chapter 5: Conclusion & Recommendations

5.1 Conclusion

- Data has been collected and analysis has been done to select the optimum location (FNE field).
- Simulation models have been built using .
- Different development scenarios have been done such as(steam flooding scenario with : DNC, CSS, infill wells cold and infill wells CSS)
- four different cases has been done.each scenario;
- It has been found that the production with CSS only;the RF can reach 15.03 % while converting the current CSS to steam flooding gives RF up-to 20.41%.
- The optimum injection parameters for steam flooding which have been found are: (Steam injection rate = 250 m^3 / day, steam temperature = 200° C and Steam Injection Quality = 80%.

5.2 Recommendations

- Running economic evaluation for SF project before the implementation.
- Detailed designing for the facilities.
- Detailed study for the environmental effects.
- It is highly recommended to start the implementation of converting the current CSS to SF.

References

Ahmed.T(2001),”Reservoir Engineering HANDBOOK”,2edn,Boston.

Ahmed.T(2010),”Reservoir engineering handbook”. 4th edition.Huston : Gulf Professional Publishing.

BagheripourHaghighi, M., Ayatollahi, S., &Shabaninejad, M. (2012, January 1). Comparing the Performance and Recovery Mechanisms for Steam Flooding in Heavy and Light Oil Reservoirs. Society of Petroleum Engineers.doi:10.2118/144797-MS,AL berta-Canada.

D.W.Green,G.P.Willhite (1998).’Enhanced Oil Recovery’, Societyof petroleum engineering, Richardson ,Texas , USA.

Elamin S. Mohammed, Husham A. Ali (2014, 8–10 December), Design and Implementation of Enhanced Oil Recovery Cyclic Steam Stimulation (CSS) Program in Bamboo West Field-Sudan, Case Study. SPE 172892-MS ,Kuwait.

Elbaloula, H., Pengxiang, H., Elammas, T., Alwad, F., Rdwan, M., & Musa, T. (2016, April 25). Designing and Implementation of the First Steam Flooding Pilot Test in Sudanese Oil Field and Africa.Society of Petroleum Engineers.doi:10.2118/182790-MS, Saudi Arabia.

Gu, H., Li, C., Cheng, L., Huang, S., Lin, M., &Xiong, W. (2015, August 11). A Comprehensive Mathematical Model for Estimating Thermal Efficiency of Steam Injection Wells Considering Phase Change. Society of Petroleum Engineers.doi:10.2118/174669-MS,Kuala lumpur,Malaysia.

Http://www.cmgl.ca, date August 20th, 2016

Huang, S., Huang, C., Cheng, L., Liu, T., Chen, Z., & Mao, W. (2015, November 18). Experiment Investigation of Steam Flooding of Horizontal Wells for Thin and Heterogeneous Heavy Oil Reservoira. Society of Petroleum Engineers.doi:10.2118/177030-MS,port of spain,Trinidad and Tobago .

Liu, S. (1988, January 1). Numerical Simulation Study Of Effects Of Formation Thickness On Steam Flooding Results. Society of Petroleum Engineers.doi:10.2118/17837-MS,Tianjin,China.

Lucia I.B. Gonçalves, GuilhermeBlaitterman, Juliana P. Diniz, Rosângela B.Z.L. Moreno, Osvair Vidal Trevisan, Denis J. Schiozer,(2009),’ Heavy Oil Recovery

By Steam Injection – Numerical Simulation On Production Strategy', State University Of Campinas - UNICAMP, Caixa Postal 6122, Campinas-SP, Brasil, CEP: 13083-970.

MousaviMirkalaei, S. M., Masoudi, R., &Ataei, A. (2011, January 1). Evaluation of Steam Flooding and Cyclic Steam stimulation (CSS) for a Fractured Carbonate Heavy Oil Reservoir.International Petroleum Technology Conference.doi:10.2523/IPTC-15454-MS,Bangkok,Thailand.

Pujol, L., &Boberg, T. C. (1972, January 1). Scaling Accuracy of Laboratory Steam Flooding Models.Society of Petroleum Engineers.doi:10.2118/4191-MS,Bakersield,California.

Pwage.S,Huore.C,Hundseth.O,Juarez.F.P,Usman.M.I(May2010),"Comparative Study of Different EOR Methods.

Romero.L(2012),'Introduction to Enhanced Oil Recovery (EOR) Processes and Bioremediation of Oil-Contaminated Sites', TeodoraSmiljanic, VanaPersen, ISBN 978-953-51-0629-6.

Romero.L.Z(2012),"Advanced in Enhanced Oil Recovery", China : InTech.

Ronald.E.T(2001),"Enhanced Oil Recovery" ,Robert.A.Aed ,3rd edn,Vol18,Academic press(2001,PP:504).

S Thomas, (2008) '*Enhanced Oil Recovery – An Overview'*, Oil & Gas Science and Technology – Rev. IFP, Vol. No. 1**.**

Souraki, Y., Ashrafi, M., Karimaie, H., &Torsaeter, O. (2011, January 1). Experimental Investigation and Numerical Simulation of Steam Flooding in Heavy Oil Fractured Reservoir. Society of Petroleum Engineers.doi:10.2118/144552-MS,Anchorage,Alaska,USA.

Tewari, R. D., Abdalla, F., Lutfi, H. G., Keqiang, Y., Faroug, A., Bakri, H., &Guocheng, L. (2011, July 19). Successful Cyclic Steam Stimulation Pilot in Heavy Oilfield of Sudan.Society of Petroleum Engineers.doi:10.2118/144638-MS, Malaysia.

Zan, C., Ma, D., Wang, H., Li, X. X., Guo, J., Li, M., …Luo, J. (2010, January 1). Experimental and Simulation Studies of Steam Flooding Process in Shallow, Thin Extra-Heavy Oil Reservoirs. Society of Petroleum Engineers.doi:10.2118/131942-MS,Beijing,China.

ZhanghuaLian, Taihe Shi, JianzhengHan(No date)' Thermal-Stress Simulation of a Casing in a Heavy-Oil Recovery Well', Southwest Petroleum Institute, P.R.of China.

Appendix A

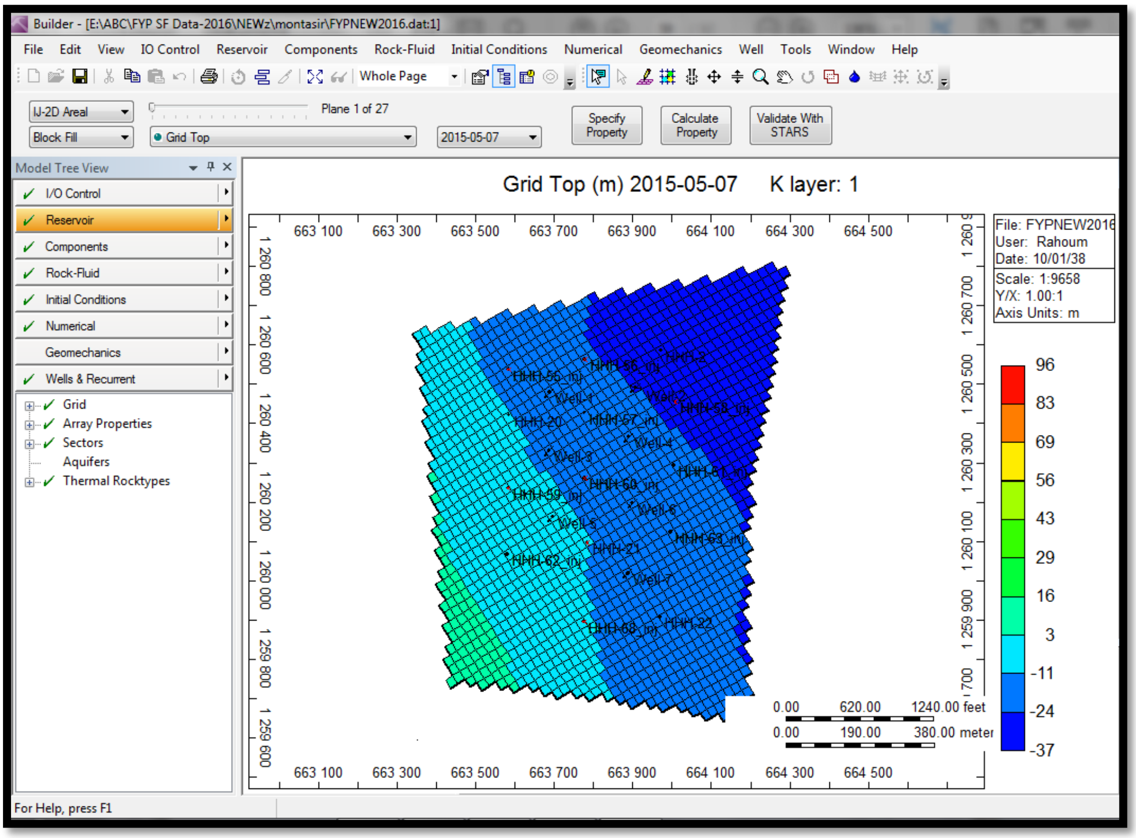


Figure A - 1 : General Shape of the CMG Software

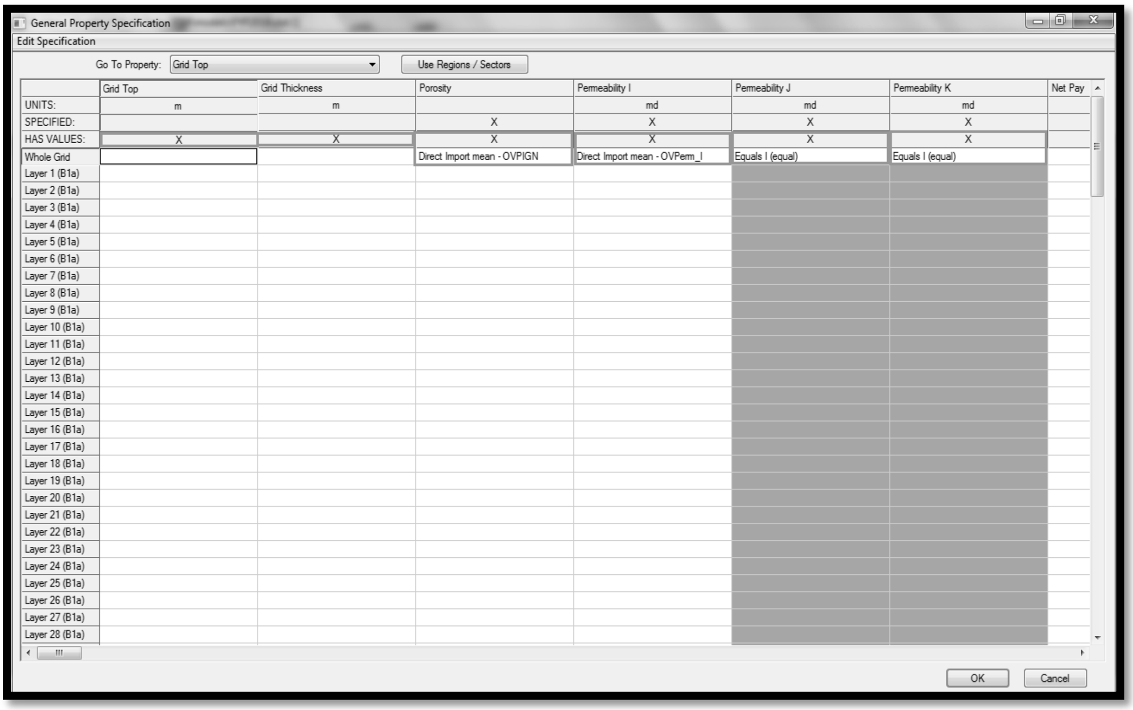
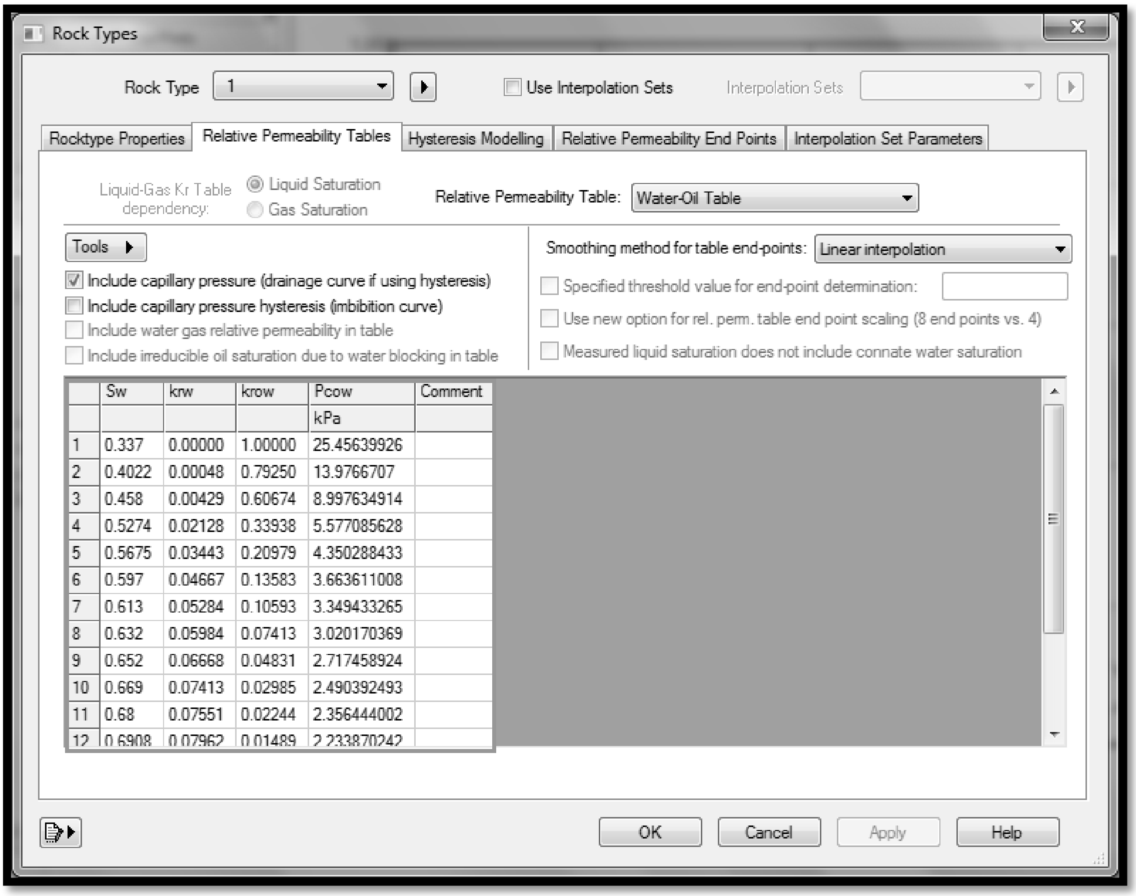


Figure A - 2 : Rock Properties



	Sw	krw	krow	Pcow	Comment
				kPa	
1	0.337	0.00000	1.00000	25.45639926	
2	0.4022	0.00048	0.79250	13.9766707	
3	0.458	0.00429	0.60674	8.997634914	
4	0.5274	0.02128	0.33938	5.577085628	
5	0.5675	0.03443	0.20979	4.350288433	
6	0.597	0.04667	0.13583	3.663611008	
7	0.613	0.05284	0.10593	3.349433265	
8	0.632	0.05984	0.07413	3.020170369	
9	0.652	0.06668	0.04831	2.717458924	
10	0.669	0.07413	0.02985	2.490392493	
11	0.68	0.07551	0.02244	2.356444002	
12	0.6908	0.07962	0.01489	2.233870242	

Figure A - 3 : Relative Permeability Table

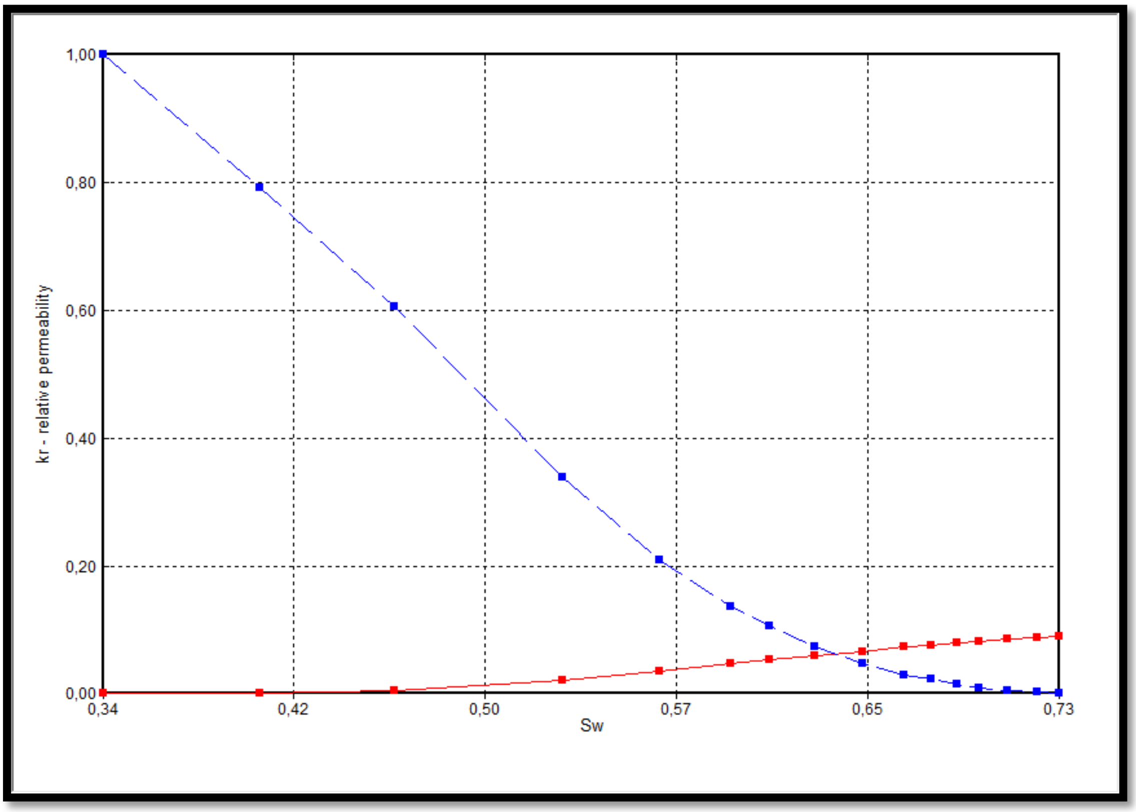


Figure A- 4 : Relative Permeability Curve

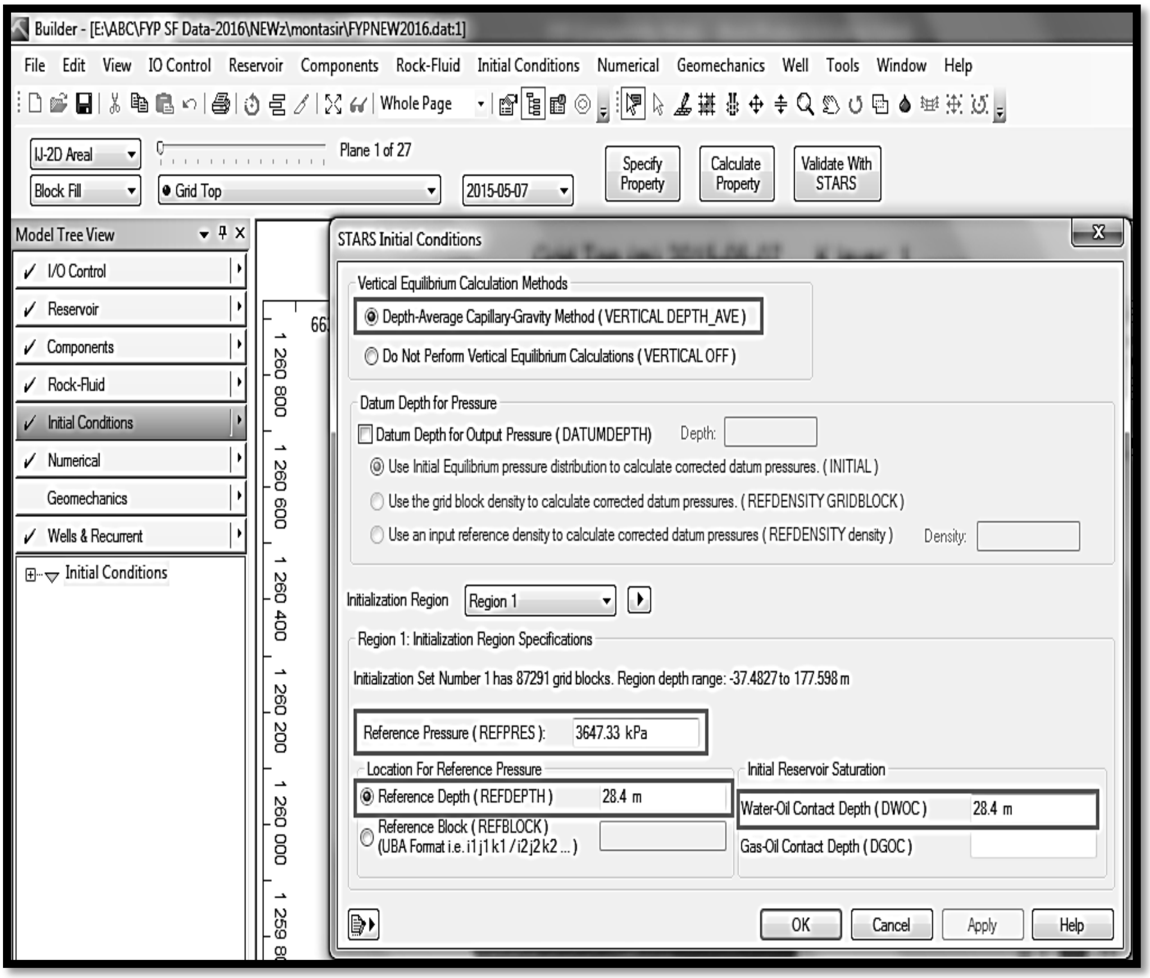


Figure A-5: Initial Condition of the Reservoir