Sudan University of Science and Technology

College of Petroleum Engineering an d Technology

Department of Petroleum Enginerring

Project of:

Feasibility Study of commingled steam injection for heavy oil production in FNE Oil Fields

دراسة استقصائية للحقن بالبخار فى عدة طبقات للزيت الثقيل لحقل الفولة شمال شرق

Graduation project submitted to college of petroleum Engineering and Technology at Sudan University of Science and Technology

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الاستهلال

بسم الله الرحمن الرحيم

قال تعالى:

{قالوا سبحانك لا علم لنا إلا ما علمتنا انك انت العليم الحكيم}

,,,,,,, صدق الله العظيم ,,,,,,,

سورة البقرة :(32)

Dedication:-

To our mothers and fathers, beloved family for always supporting, helping, and standing by us

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 throughout the process

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Abstract:-

Thermal methods are the most commonly used Enhanced Oil Recovery methods around the world, one of them is the cyclic steam stimulation process, which had been implemented in FNE field; the well HHH-61 and HHH-38. After the execution the well had low oil rate .

Fula North East (FNE) Oilfield is geographically located in the southwest of Sudan, about 700 km from the capital, Khartoum. Bentiu reservoir is subdivided into four sand units named as B1a, B1b, B1c and B1d with barriers among those four units. Average net pay thickness of B reservoir is 30 to 40 m and average Net to Gross (NTG) is 0.8. Bentiu reservoir is the main hydrocarbon accumulation formation and 263 MMSTB OOIP with 17 API

In this thesis a list of challenges has been recorded in Sudanese heavy oil field and evaluation of current development strategy was done in FNE field

In addition to that a detailed analysis has been done to determine the effect of non uniform steam distribution in commingle well in FNE heavy oil production in HHH-61_inj and HHH-38 also It has been found that top layer get nearly 70% the assumed amount of steam furthermore optimizing of injection rate in HHH-61 well has been while in well HHH-38 the result found that the top layer in the third cycle get nearly 60% compared with designed .

The study recommend to avoid steam injection in multi layers semi tenuously , unless using separate layer technology for injection/production from multi layers.

التجريد :

الطرق الحرارية هي من اكثر الطرقة المستخدمة في الاستخلاص المعزز لزيادة استخلاص النفط ومنها الحقن الدوري بالبخار **Cyclic Steam Stimulation** التي استخدمت في حقل الفولة شمال شرق ووجد عدم توزيع البخار في الابار **HHH**61 و **HHH**38 المصمم لها مما ادى الي انخفاض انتاج الزيت

يقع حقل الفولة شمال شرق في الجنوب الغربي للسودان على بعد 700 كم من العاصمة الخرطوم , يحتوي الحقل على مكمن بانتيو الذي ينقسم الي اربعة طبقات B1a, B1b, B1c و B1d مع وجود طبقات غير نافذة في الوسط و يتراوح سمك المكمن ما بين 30-40 متر وهو من اكبر المكامن التي تحتوي على هيدروكربونات ثقيلة تقدرب 263 MMSTP وكثافة تقدر بي 17 API

في هذا البحث تم تحديد الصعوبات التي تواجه تطبيق عملية ال **CSS** في حقول الزيت الثقيل بالسودان وتقييم الاستراتيجية المتبعة حاليا في حقل **FNE**

زيادة علي ذالك تم دراسة التوزيع غير المنتظم للبخار في ابار متعددة الطبقات في حقل **FNE** في البئر**HHH** 61 و **HHH-38** فوجد ان الطبقات العليا تحصلت على اكثر من 70% من كمية البخار المصمم وأيضا تم ايجاد معدل الحقن الامثل للبئر **HHH-61** بينما في البئر **HHH-38** وجد ان الطبقات العليا في الدورة الثالثة من الحقن قد اخذت ما يقارب 60% من البخار .

الدراسة توصي بتجنب ضخ البخار في المكامن متعددة الطبقات توافقياً واستخدام التقنية المنفصلة لكل طبقة في الحقن والإنتاج

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NOMENCLATURE:-

EOR	: Enhanced Oil Recovery
IOR	: Improved Oil Recovery
CSS	: Cyclic Steam Stimulation
SAGD	: Steam Assisted Gravity Drainage
EUR	: Enhanced Ultimate Recovery
OOIP	: Original Oil in Place
FNE	: Fula North East
CMG	: Computer Modeling Group
API	: American Petroleum Institute
CSI	: cyclic steam injection
PE	: petro energy
FCM	: first contact miscible
MCM	: multiple contact miscible
ISC	: In-situ combustion
CHOPS	: Cold Heavy Oil Production With Sand
NP	: Produced Oil
RF	: Recovery Factor
MMSTB	: Million Stock Tank Barrel
STB	: Stock Tank Barrel
CP	: Centipoises

MD	: Milidarcy
H2	: Hydrogen Gases
CO	: Carbon Oxides
CH4	: Methane Gases
CO2	: Carbon Dioxides
H2S	: Hydrogen Sulfide
BBL	: Barrel

Chapter One

Introduction

Chapter One

Introduction

1.1.Development Sequences :

Petroleum industry considered one of the largest contribution in world energy by 40% and natural gas by 22.5% and rest by less than 35%.

In the U.S., transportation accounted for 28% of all energy use and 70% of petroleum use in 2001; 97% of transportation fuel was petroleum.

Hubert peak Conservative predictions are that conventional oil production will peak in 2007. There are many other predictions, one example is that the world conventional oil production will peak somewhere between 2020 and 2050, but that the output is likely to increase at a substantially slower rate after 2020 (Greene, 2003).

So the unconventional oil become targeted by petroleum industry using recovery methods ,the oil reservoir production life has been consisting of three stages theses stages begin with primary recovery.

During primary recovery the natural energy of the reservoir is used to transport hydrocarbons towards and out of the production wells. There are several different energy sources, and each gives rise to a drive mechanism. Early in the history of a reservoir the drive mechanism will not be known. It is determined by analysis of production data (reservoir pressure and fluid production ratios). The earliest possible determination of the drive mechanism is a primary goal in the early life of the reservoir, as its knowledge can greatly improve the management and recovery of reserves from the reservoir in its middle and later life.

Primary recovery under natural producing mechanism leaves behind 50% to 80% of the original oil in place , consequently a vast amount of oil remain un recoverable according to the decline in pressure and primary recovery .(Ahmed T., 1946)

Petroleum engineers have long realized that another fraction of the remaining oil can be forced out by fluid injection. The process of fluid injection involves the drilling of a second hole into the reservoir at some distance from the first hole through which oil is removed. They use secondary recovery.

the term secondary recovery technique or(IOR) refers to any method for removing oil from a reservoir after all natural recovery methods have been exhausted. The term has slightly different meanings depending on the stage of recovery at which such methods are used, it has been legally 1921 and its applied in wide spread 1950 as water flooding .(Willhite , 1986).

since the end of world war II when operator who owned reservoir withdecling reserve recognize that significant quantities of oil remained in their reservoir after primary and secondary well recovery , research and field activity increased and discover of major new reservoir become infrequently , intense interest in EOR(enhanced oil recovery , tertiary oil recovery).(Green and Willhite ,1998).

Tertiary oil recovery EOR its objective is to increase oil recovery from reservoir depleted by secondary recovery it has three major categories will be discussed .First was stimulated in response to oil Embargo 1973 and flowing energy , the period of high activity lasted until the collapse of worldwide oil pieces in 1986 over years interest in EOR has been tempered by the increase in oil reserve and production , , the discovery of major oil filed in North slop of Alaska ,North sea and other region added large volume of oil to the worldwide market , Although large volume of oil remain in mature reservoir ,the oil will not be produced in large quantities by EOR process unless these process can compete economically with the cost to oil production from conventional sources , thus as reservoir age dichotomy exists between desire to pressure well for potential EOR process and lack of economic incentive .(Green and Willhite ,1998).

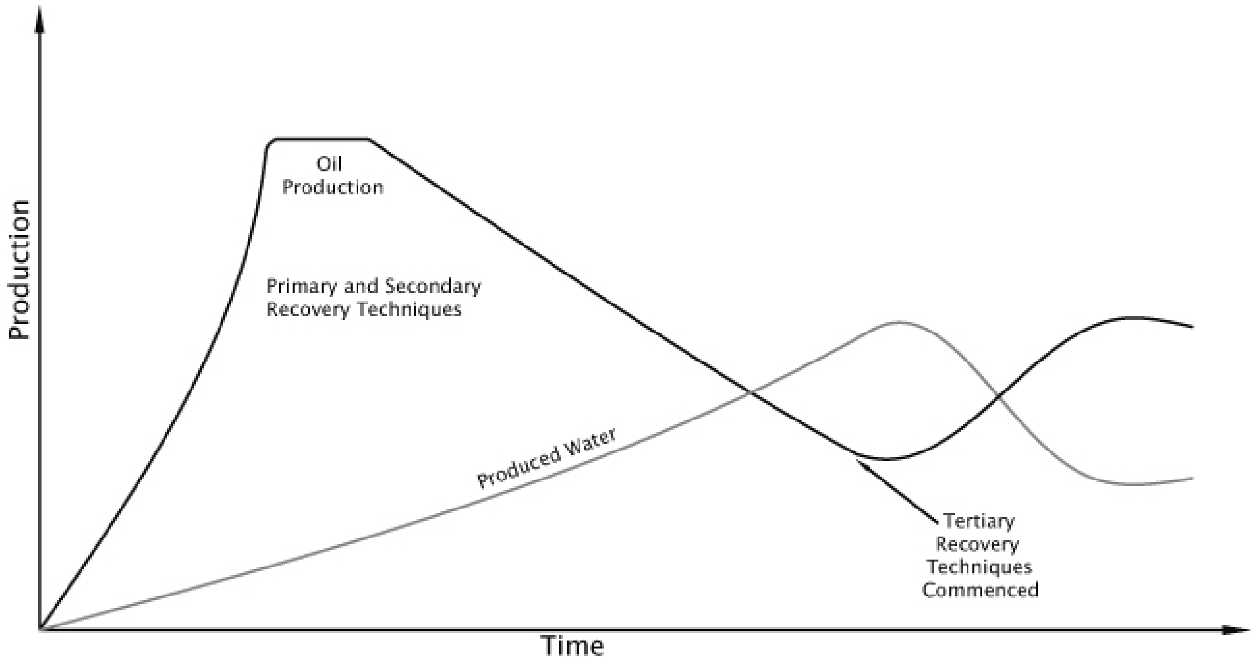


Figure (1.1): Stages of Recovery. (Ahmed T., 1946)

1.2. Recovery Mechanism:-

There are three type of recovery mechanism

- Primary Recovery
- Secondary Recovery
- Tertiary Recovery

1.2.1 Primary Recovery:

The recovery of oil by any of the natural drive mechanisms. The term refers to the production of hydrocarbons from a reservoir without the use of any process to supplement the natural energy of the reservoir. For a proper understanding of reservoir behavior and predicting future performance, it is necessary to have knowledge of the driving mechanisms that control the behavior of fluids within reservoirs. The overall performance of oil reservoirs is largely determined by the nature of the energy, i.e., driving mechanism, available for moving the oil to the well- bore(Ahmad,2010).

There are basically six driving mechanisms that provide the natural energy necessary for oil recovery:

- Rock and liquid expansion drive
- Depletion drive
- Gas-cap drive
- Water drive
- Gravity drainage drive
- Combination drive

1.2.2.Secondary Recovery:

Secondary recovery used when the reservoir pressure is fall ,and the oil in reservoir cannot recovered by primary mechanism. Secondary recovery techniques increase the reservoir's pressure by gas and water injection(Speight,2009).

1.2.3.Tertiary Recovery (EOR):

EOR is the processes that used to improve the recovery of hydrocarbon from reservoir after primary and secondary recovery, and include all methods that use external sources of energy or materials to recover oil that cannot be produced economically by conventional means(Alvarado and Manrique,2010).

EOR Processes Can Classified To:

- miscible process
- thermal process-
- chemical process

1.2.3.1. Miscible Processes:

A miscible process is to displace oil with a fluid that is miscible with the oil at the conditions existing at the interface between the injected fluid and the oil bank being displaced. Displacement fluid such as hydrocarbon solvent, carbon dioxide, flue gas and nitrogen(Green and Willhite,1998).

There Are Two Major Variations In This Process:

- first-contact-miscible (FCM) process.
- multiple contact miscible(MCM) process.

FCM: the injected fluid is directly miscible with the reservoir oil at the conditions of pressure and temperature existing in the reservoir.

MCM: the injected fluid is not miscible with the reservoir oil on first contact. Rather, the process depends on the modification of composition of the injected phase, or oil phase.(Green and Willhite, 1998).

Improved Oil Recovery(IOR):

any of various methods designed to improve the flow of hydrocarbons from the reservoir to the wellbore or to recover more oil after the primary and secondary methods that are uneconomic(Alvarado and Manrique,2010).

1.2.4.2.Thermal Processes :

Thermal processes is heated the reservoir to reduce the viscosity of oil or vaporize the oil to make it more mobile and more effectively to recovered. Thermal processes provide pressure to move the oil to producing wells(Speight,2009).

Thermal Recovery Methods:

- Cycle steam stimulation (CSS).
- Steam drive (steam flooding).
- Hot water flooding.
- In situ combustion.

1.2.4.3.Chemical Process

Chemical process is the injection of specific chemicals liquid that effectively displace oil to producing wells(Green and Willhite,1998).

Chemical Methods:

- Polymer flooding.
- Surfactants flooding.
- Alkaline flooding.

1.3.Thermal EOR :

Thermal recovery processes rely on the use of thermal energy in some from both to increase the reservoir temperature, thereby reducing oil viscosity by mean of heat and also provide the force to increase the flow rates of the oil to the production well that is why thermal drives .in the thermal stimulation techniques ,only the reservoir near the production well is heated.

Stimulation techniques can also be combined with thermal drive ,and in this case the driving force are both natural and imposed ,most thermal oil production is the result of cyclic steam injection and steam drive.(Green and Willhite,1998)

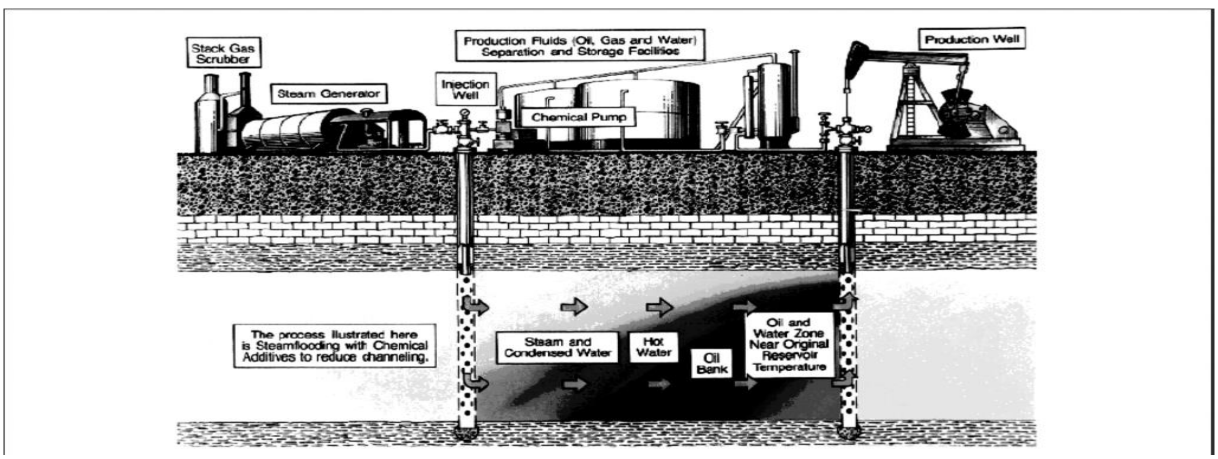


Figure (1.2) Oil Recovery by Thermal Methods,(Tomas,2008)

Thermal recovery processes are applicable to a wide range of reservoir ,the table below summarizes the criteria for thermal recovery processes .these criteria are to be used as a guide in selection candidates for thermal recovery processes.

Table (1.1): Screening Parameters For Thermal Recovery Process (Green and Willhite , 1998)

Screening parameter	Steam	In-situ composition
Oil gravity, API	10 to 34	10 to 35
Viscosity,cp	≤15000	≤5000
Depth, ft	≤3000	≤11500
Thickness, h	≥20	≥20
Reservoir temperature, f	-	-
Porosity	≥0.20	≥0.20
Permeability, k	200	35
Reservoir pressure	≤1500	≤2000
Rock type	Sand stone or carbonate	Sand stone or carbonate

The Thermal Recovery Processes Used Today Fall Into Two Classes:

Those in which a hot fluid is injected into the reservoir and those in which heat is generated within the reservoir itself..an example of which is in-situ combustion or fire flooding.

The Thermal EOR Method Include:

- In- situ combustion(fire flood)
- Steam flooding.
- Cyclic steam stimulation.
- Steam assisted gravity drainage(SAGD).
- Thermal stimulation(thermal recovery).

1.3.1.In-Situ Combustion (ISC):

In-situ combustion or fire flooding is a process in which an oxygen containing gas is injected into a reservoir where it reacts with the oil contained within the pore space to create a high temperature self-sustaining combustion front that is propagated through the reservoir. The heat from the combustion thins out the oil around it, causes gas to vaporize from it, and vaporizes the water in the reservoir to steam. Steam, hot water, and gas ,all act to drive oil in front of the fire to production wells. In-situ combustion is possible if the crude-oil/rock combination produces enough fuel to sustain the combustion front.

Severe corrosion and increased sand oil production are some of the problems that encountered by implementation of this technique(Romero-zeron,2012).

1.3.2.Steam Flooding:-

In steam flooding methods the preheated fluids are injected into the relatively cold reservoir as shown in figure below . The fluids range from water (both liquid and vapor) and air to others, such as natural gas, carbon dioxide ,exhaust gases, and even solvents.

In every hot fluid injection there are heat losses in the well bore from the injection wellbore to the over burden formations as a result of poor insulation of the injected wells and low injected rates. When the heat approaches the formation there is a temperature difference between the wellhead and the formation as a result of heat loss(Dietz,1953).

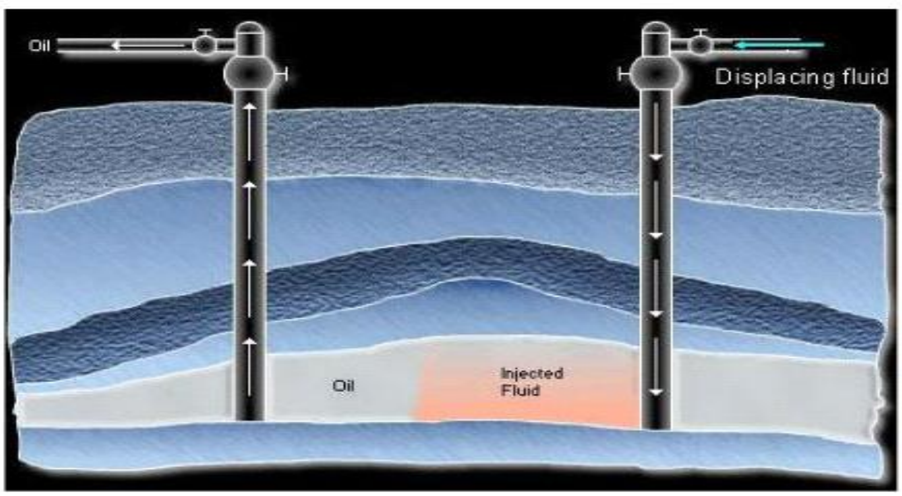


Figure (1.3):Steam Flooding Process (Tandem-Terminal.ru)

1.3.3. CYCLIC STEAM INJECTION:

Cyclic steam injection is the process in which steam is injected in variable intervals followed by a period of production. This is the alternating injection of steam and oil production with condensed steam. Same well is used for production and injection.

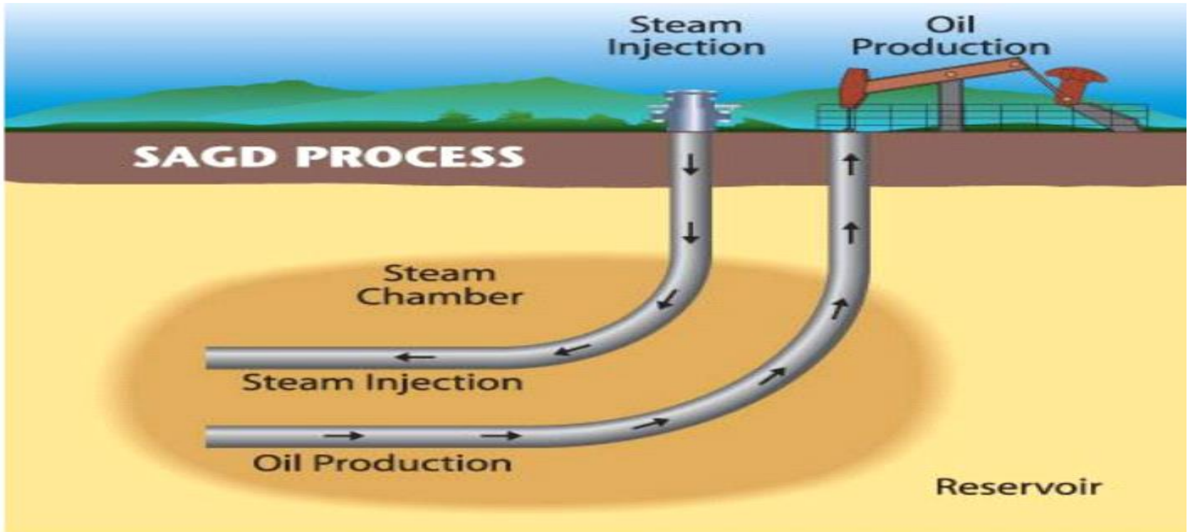
Cyclic steam injection consists of the injection of a modest amount of steam into a well, followed by a period of production from the same well. The process is repeated as and when required, hence the process name cyclic steam injection.

Cyclic steam injection is suitable for the reservoirs with the following characteristics:

- Depth**:** the minimum depth for applying cyclic steam stimulation is on the order of 1,000feet.
- Porosity**:** should be no less than 30%
- Permeability**:** good horizontal permeability (at least 1 Darcy or greater) is important for production.
- Thick pay zone**:** This process is economical on reservoirs that contain pay zones of 10meters and above.(sayedata abbas,2012).

1.3.4.STEAM-ASSISTED GRAVITY DRAINAGE (SAGD):

This method involves drilling of two parallel horizontal wells (shown in figure-), one above the other, along the reservoir itself. Hot steam is introduced from the top well which reduces the viscosity of the heavy oil (like all other thermal methods). The key to this method is the two parallel and horizontal wells, and this has only become possible due to the directional drilling technology, the mechanism causes the steam saturated zone, known as the steam chamber, to rise on the top of the reservoir. The distance between the pair of horizontal wells vertically separated by each other is15-20 feet. The SAGD process, like all gravity driven processes, is extremely stable because the processes zone progresses by means of gravity segregation, and there are no pressure driven instabilities such as conning, fracturing, or channeling (Shin, 2004).



Figure(1.4): SAGD Process(Shin and Polikar,2004)

1.3.5. Thermal stimulation:

In thermal stimulation, the reduction in flow resistance is achieved by heating the wellbore and the reservoir near it. one mechanism that is always in force in thermal stimulation is a reduction in the viscosity of the crude and of the water; reducing the viscosities tend to reduce the flow resistance. A second mechanism is wellbore cleanup, in which the following might occur:

- Organic solids near a wellbore may be melted or dissolved ; clays may be stabilized; the absolute permeability may be increased by the high temperatures.
- Wellbore cleanup usually has a rather minor effect after the first stimulation cycle.
- Thermal stimulation currently is the only effective treatment for viscous oil reservoir with poor lateral continuity. Because the effects are confined to the neighborhood of the wellbore, thermal stimulation improves oil production rates rather quickly. In drive, on the other hand, no significant sustained increase in production rates can be expected until an oil bank or heat (or both) reaches a production well. (hennery,2013).

1.4. Comparison Between The Thermal Method: -

The method is quite effective, especially in the first few cycles providing quick payout. However, ultimate recovery by cyclic steam injection is low (10-40% of Original Oil in Place, OOIP), compared to that of steam flooding and Steam Assisted Gravity Drainage (SAGD) which are over 50% of OOIP as shown in Table(1.3). Therefore, it is quite common for wells to be produced in the cyclic steam manner for a few cycles before put on a steam flooding regime with other wells. (Alikhlalov, Dindoruk ,2011).

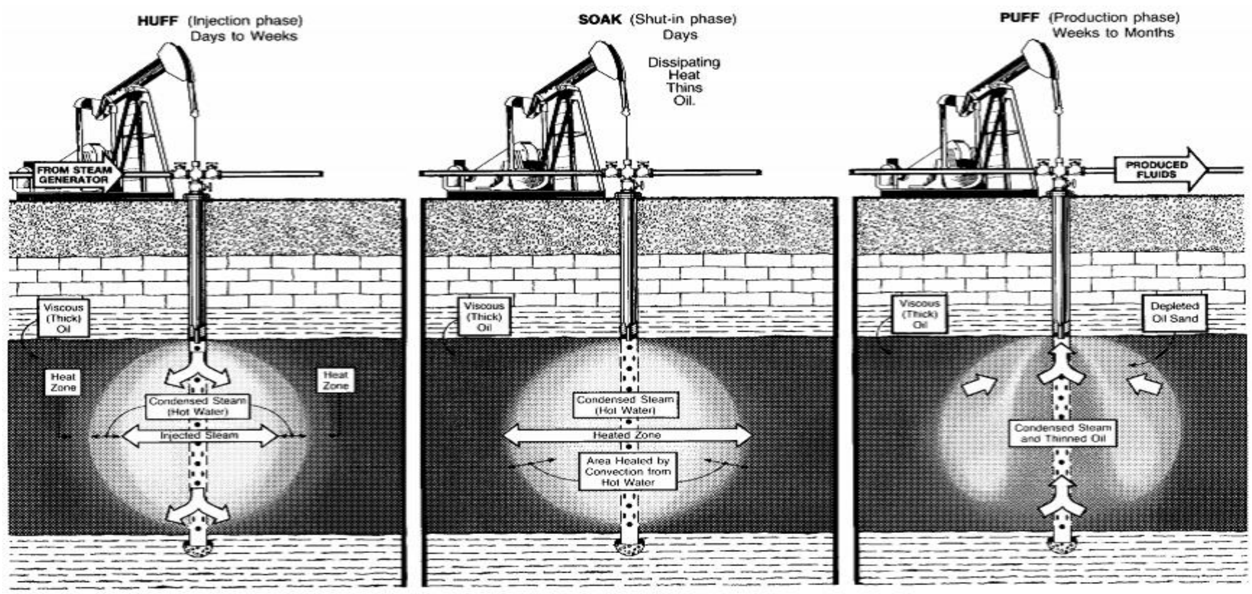
Table (1.2) Oil Recovery Rate of Thermal EOR Method (Castro et al., 2010)

Oil Recovery Factors (successful projects)	
Thermal EOR	% of OOIP
CSI	10 - 40
Steam flooding	50 - 60
SAGD	60 - 70
In-situ Combustion*	70 - 80

1.5. Cyclic Steam Injection Process :

Cyclic Steam Injection , also called Huff n' Puff, is a thermal recovery method which involves periodical injection of steam with purpose of heating the reservoir near wellbore, in which, one well is used as both injector and producer, and a cycle consisting of 3 stages, injection, soaking, and production.(Thomas, 2008)

The well is opened and production stage is triggered by natural flow at first and then by artifici al lift. The reservoir temperature reverts to the level atwhich oil flow rate reduces. Then, another cycle is repeated until the production reaches an economically determined level repeats to enhance the oil production rate as shown in Figure(1.8)



Figure(1.5) : Cyclic Steam Injection Process, (Thomas, 2008)

Typical CSI process is well suited for the formation thickness greater than 30 ft and depth of reservoir less than 3000 ft with high porosity (>0.3) and oil saturation greater than 40%. Near-wellbore geology is critical in CSI for steam distribution as well as capture of the mobilized oil. Unconsolidated sand with low clay content is favorable. Above 10 API gravity and viscosity of oil between 1000 to 4000 cp is considerable while permeability should be at least 100 mD (Thomas, 2008).

CSI includes consists of 3 stages: injection, soaking, and production. Steam is first injected into a well for a certain amount of time to heat the oil in the surrounding reservoir. The mechanism proceeds through cycles of steam injection, soak, and oil production. First, steam is injected into a well at a temperature of(300 to 340°) Celsius for a period of weeks to months. Next, the well is allowed to sit for days to weeks to allow heat to soak into the formation. Finally, the hot oil is pumped out of the well for a period of weeks or months. Once the production rate falls off, the well is put through another cycle of injection, soak and production. This process is repeated until the cost of injecting steam becomes higher than the money made from producing oil. (Butler, Roger ,1991).

Application of CSS, like other EOR methods, targets to reduce viscosity that can be explained by mobility ratio which is the ratio of effective permeability to viscosity.

In addition, during CSI many chemical reactions occur which mainly form gaseous components such as carbon dioxide, hydrogen sulphide, and hydrogen during steam injection

,and these reactions include decarboxylation of the crude, formation of H_2S from sulphur in the crude, formation of H_2, CO, CH_4 and CO_2 from reactions between water and crude and formation of CO_2 by decomposition and reactions of carbonates minerals , The produced gases formed during the CSI create additional driving mechanism which can be named as gas drive. Also, these visbreaking reactions reduce the oil viscosity by increasing the oil mobility (Prats, 1985).

1.5.1. Performance Prediction :

The performance of CSI operation is sensitive to the acting production mechanism, to the reservoir and fluid properties near the well , and to the operating variables.

The applicability of predictive method depends on the proper representation of reservoir and crude properties, one reservoir property affects the reservoir response of CSI operations is the relative permeability to the flowing fluid. Relative permeability's require hysteresis modification (i.e., they are different during injection and back flow) in order to match the performance of a multi cycle operation. (Cline, Basham,2002).

Where CSI production is available, likely values of the reservoir and crude properties can be determined through history matching procedures. These then can be used to predict the behavior of subsequent steam injection cycle in the same well or nearby wells under different operating conditions .The simpler predictive methods are based on specific models of how the CSI works (in contrast with the thermal reservoir numerical simulations , which in principle provide solutions to the differential equations describing conservation of mass and energy in three dimensions). (Cline, Basham,2002).

Because of the average temperature in the heated zone decreases during production the oil rate ratio also decreases with time , so the prediction of the performance of the CSI operation can be calculated by hand using the equations that mentioned above if a few time steps are sufficient to describe the situation **.** (Cline, Basham,2002).

However, the results mention in table 1.2. above can be doubled with Cyclic Steam Injection combined with unconventional technologies such as co-injection with chemical additives, horizontal drilling and hydraulic fracturing have been highly successful, improving its conventional recovery factor up to 40%. Recent studies showed that this can be increased even higher**.** (Alvarez, Han,2010).

1.5.1.1.CSI with Chemical Additives:

- **Solvents:**

The idea of adding solvents to the steam to reduce the oil viscosity has been reported in the literature since 1970s. Previously, solvents and light crudes had been used as diluents to optimize pumping and pipeline transportation of heavy crudes. Both laboratory and field tests later years proved that the use of solvent as an additive to steam during in-situ recovery improved the mobility ratio of displacing and displaced fluid and sweep efficiency.

- **Surfactants:**

Although adding Surfactants to steam can increase production recovery up to 30% upon earlier cycles, high injection volumes are required to reduce the viscosity of oil appreciably thereby necessitating solvent recovery, which leads to high operational cost.

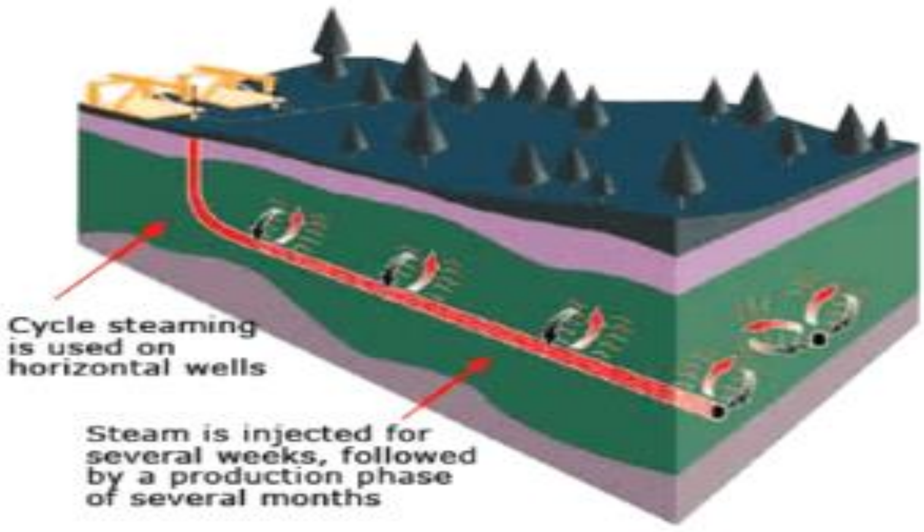
1.5.1.2.CSI with Horizontal Well:

As it shown in figure(1.6). mainly the idea of horizontal well was introduced to the CSI process. The main advantages of the horizontal wells are improved sweep efficiency, increased producible reserves as well as steam infectivity, and decreased number of well required for field development (Joshi, 1991) .

Pilot tests had success on horizontal well application; and indeed, those horizontal producers in comparison to typical vertical ones in each area improved production performance and thermal efficiency as well as operating costs. (Cline, Basham,2002).

Both fields showed about 20 to 50% improvement in production over results from vertical wells and benefited from maximum 45% of directional drilling cost reduction relative to that of a decade ago.

Despite the reduced drilling costs, operating costs for generating steam still remains high due to greater heat loss when steam injection is schemed to horizontal well application. Further investigations inquire possibilities to address the solutions to this problem.



Figure(1.6) :CSI With Horizontal Well From: Cyclic Steam Simulation Thermal Insitu Oil Sands (CNRL,2013)

1.5.1.3. CSI with Hydraulic Fracturing:

Creating fractures allows a more efficient placement of injected steam, heating up larger volume of reservoir and reducing residual oil saturation. This combination is usually considered for low permeability.

Fines and sand production problems are found commonly during cyclic steam injection. The recent study investigated the efficiency of fracturing with viscoelastic surfactant fluid instead of water which worsens the sand and fine production. It was concluded that anionic surfactant fluids minimize gel damage and maintain favorable propane transportation (Gomez et al., 2012).

In many cases, follow up processes after CSI are convenient solutions to increase reservoir ultimate recovery. However, these processes must be evaluated carefully considering reservoir properties and mineralogy and fluid interaction before fully implemented. In addition, in follow up process selection, economic viability is a major issue, so the increase in oil recovery must be sufficient to cover capital cost and maintain the project profitable during the forecasted time.

1.6. Introduction to Case Study:

Fula North East (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.

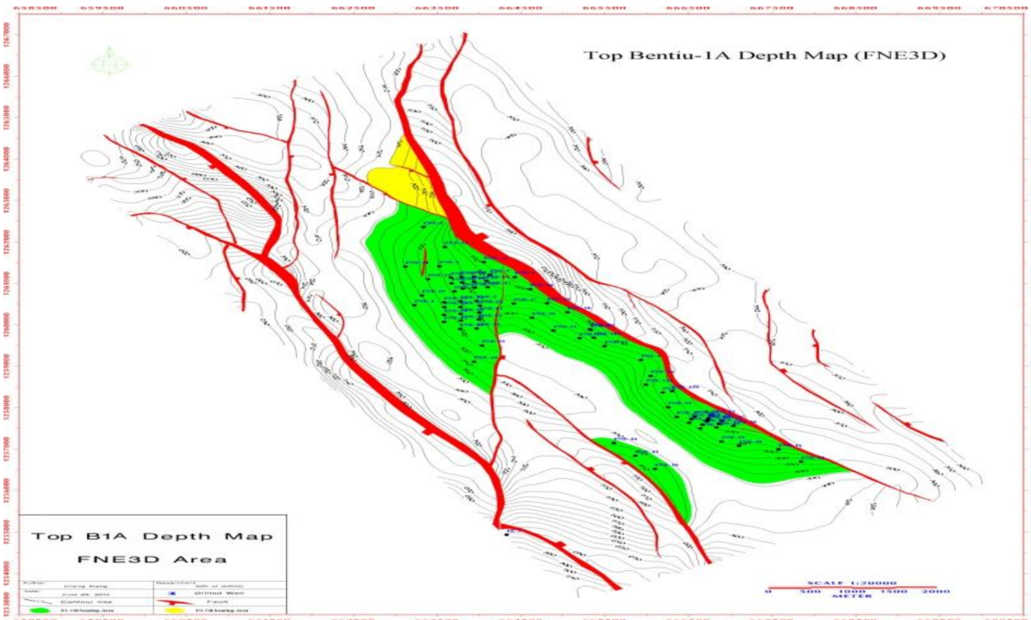


Figure (1-7): FNE Structure Map

FNE Oilfield exploration began in 1989, the first well FNE-1 has been drilled In 2005, it was found one of the largest heavy oil fields in Petroenrgy (PE) block 6 Area.

Then immediately the development and research began. The oilfield development Case was completed by Beijing Research Institute of Petroleum Exploration and Development in May 2008.

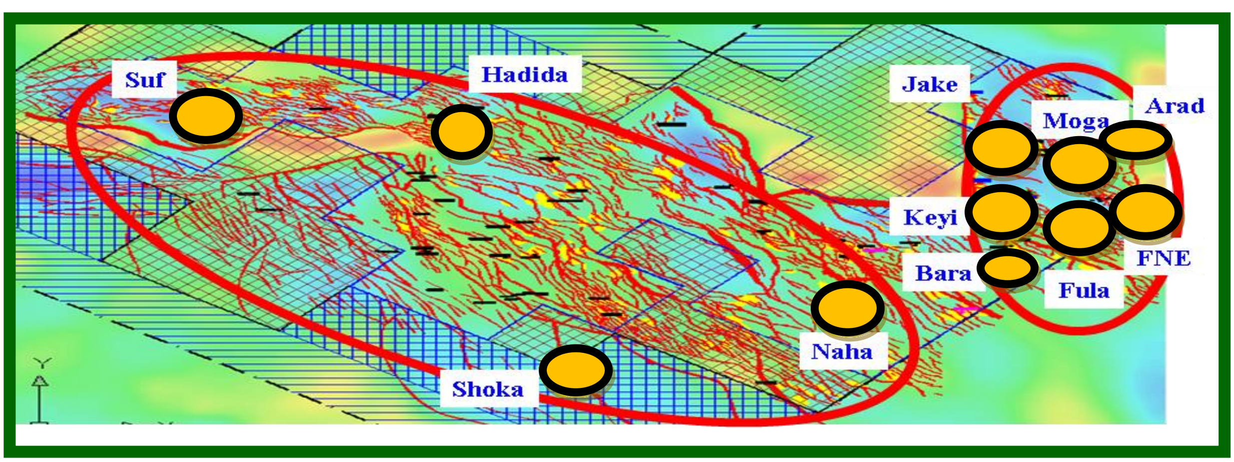


Figure (1-8): Maglad Basin Block 6

The oilfield was put into development in June 2010. By May 2011 before the steam flooding study started, a total of 43 wells had been drilled, including one horizontal well; 36 wells have been put into operation, of which 23 wells are producing as cold, and 13 wells for steam stimulation; 33 wells were opened, with a daily oil production of 5722bbl, a daily fluid production of 6097bbl, a water cut of 6.1%, the total Original Oil In place (OOIP) is 298.7 MM STB, and the up to date recovery factor of reserves is 0.75%. The average daily production for steam stimulation is 2 to 3 times of the cold wells. see Table (1.4) and, Reserve and Cumulative Production. (Elbaloula, et al,2016).

Table (1.3):Reserve And Cumulative Production (Husham Elbaloula,2016)

Item	CHOPS	Thermal	Total
OOIP	298.73	298.7	298.7
EUR(MMSTB)	56	137	137
NP(MMSTB)	3.21	7.54	10.75
Remaining EUR	52.41	131.9	126.3
Up to date EUR	6.41	3.74	6.36
Expected recovery factor %	18.9	45.96	45.96
Up to date recovery factor %	1.07	2.52	3.60

1.7. Problems Statement:

Most of comingle thermal wells has a problem in steam intensity distribution among the layers. When the steam has been injected in more than one layer. Analyze the steam intensity across the comingle injection in order to raise the production rate as high as possible

1.8.Objectives:

- **The General Objectives :**

1. To investigate on Steam comingle Injection and production in FNE Sudanese heavy oil fields.
2. To design the optimum steam injection that can maximize the recovery factor.

- **The Specific Objectives :**

1. Study the main challenges of Heavy oil production in term of comingle injection and production from FNE Sudanese oil fields.
2. Evaluate the current development strategy for comingle steam injection in heavy oil fields at different phases of the pilots including: design, wells selection and analysis, implementation and full field implementation.
3. Analyze and review the actual Steam intensity distribution among each layer for FNE field and compare the actual volume of the steam with the designed volume after that try to calculate the optimum steam adsorption for every single layer.
4. build the modeling to understand the effect of Comingle Injection and production by using the data from single layers.
5. Propose the suitable development strategy and special techniques for Sudanese heavy oil fields that implemented steam flooding.

1.9. 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 Cyclic steam stimulation Mainly and in the commingled as specifically, while chapter three is illustrating the methodology of conducting the analysis of unfair steam distribution and designing the optimum injection parameters using CMG software. Chapter four is summarizing the results and discussion of the work and chapter five is the conclusion and recommendations of the study.

Chapter Two

Literature Review and Theoretical Background

Chapter Two

Literature Review and Theoretical Background

2.1.Theoretical Background

Crude oil classified according viscosity and API to:

Light oil: low viscosity high and API more than 31.1 .

Medium oil: medium viscosity and API between 22.3 and 31.1.

Heavy oil: high viscosity and API less than 22.3 .

Extra heavy oil(bitumen): very high viscosity and API less than 10.

2.1.1. Heavy oil :

Heavy oil is defined as having an API gravity of less than 20 degrees API [greater than 0.93 g/cm3]. Standard practice in the U.S. also uses this gravity definition. The API gravity, however, does not fully describe the flow properties of the crude; this is better represented by the oil viscosity. For instance, some crudes may be heavy (low gravity) but have a relatively low viscosity at reservoir temperature compared with some lighter crudes, nd because the flow rate is a much more important factor in the economic exploitation of the reserve than the oil gravity, it is proposed that heavy oilsand .e., those requiring stimulation by heat or by other meansbe defined as crudes having viscosities greater than 100 cp [greater than 100 mPas] at reservoir conditions heavy oils frequently have high asphalting, sulphur, and metal contents compared with conventional oils. The non hydrocarbon content tends to increase with decreasing API gravity, which, in combination with decreasing quantities of lighter ends, reduces the market value of the crude.(Briggs et al,1988).

Goodarzi et al., (2009) define heavy oil in terms of viscosity as the class of oils ranging from 50 cp to 5000 cp. The high viscosity restricts the easy flow of oil at the reservoir temperature and pressure. Figure2.1 is a graph relating viscosity and API ratings and it can be observed that the heavy oil region lies in the high viscosity range.

Ancheyta and Speight (2007) define heavy oil as a viscous type of petroleum that contains a higher level of sulfur as compared to conventional petroleum that occurs in similar locations.

Meyer et al., (2007) explained that the oil becomes heavy as a result of eradication of light fractions through natural processes after evolution from the natural source materials. A high proportion of asphaltic molecules and with substitution in the carbon network of heteroatom's such as nitrogen, sulfur, and oxygen also play an important role in making the oil heavy. Therefore, heavy oil, regardless of source, always contains the heavy fractions of asphaltenes, heavy metal, sulphur, and nitrogen.

The reservoirs of heavy oil are shallow and have less effective seals (up to 1000 meters below the surface line), which is the reason for the low reservoir temperature (40-60 °C). Low sedimentary overburden tends to ease the biodegradation, and the presence of the bottom aquifers further facilitates the process. As mentioned earlier the less effective seal is due to the low seal pressure, which may cause the dissolved gases to leave the oil, increasing its viscosity. The reservoir lithology is usually sandstones deposited as turbidity with high porosity and permeability; the elevated viscosity is compensated by high permeability.

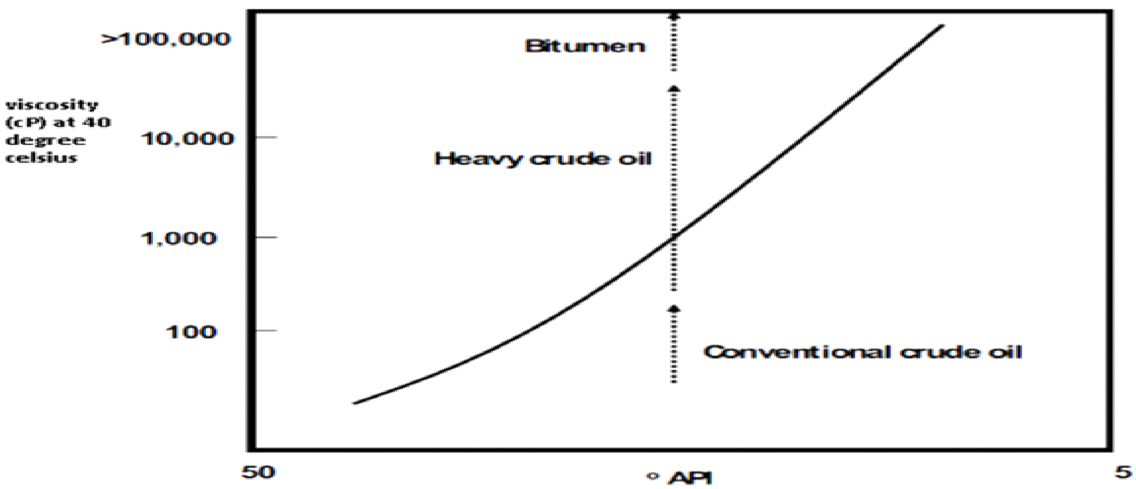


Figure (2.1) : General Relationship of Viscosity to API Gravity (Thomas,2008).

2.1.2. Main Heavy Oil Field In Worldwide:

Hydrocarbon resources of heavy oil and oil sands are nearly three times the conventional oil in place in the world over two trillion barrels of oil is present in the oils sands of Alberta and in Canada the contribution of heavy oil and oil sands resources is 20% of the total oil production. (Farouq Ali and Meldau,1999)

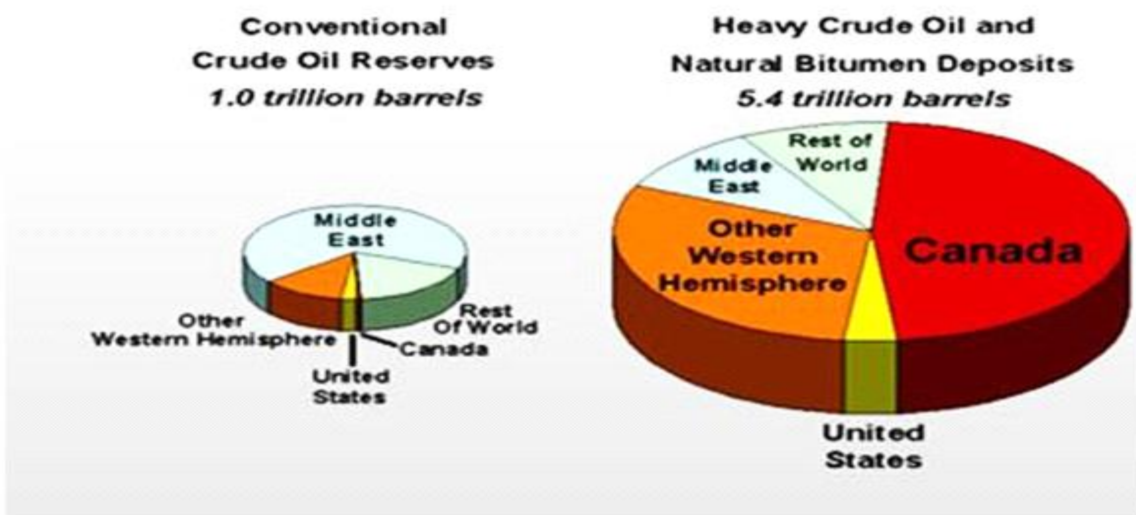


Figure (2.2): Distribution of Conventional Crude Oil and Heavy Hydrocarbon (Herron , 2000)

We have estimated the total discovered heavy oil in place in the world to be 4,600 x bbl [730 x m3]. This should be compared with our estimate of remaining proved and probable conventional oil reserves as of Jan. 1, 1986, of some 700 x bbl [110 X m3].

The largest heavy-oil deposits are located in Canada, Venezuela, and the Soviet Union and represent over 90% of the known heavy oil in place in the world(. Briggs et al,1988).

2.1.3. Heavy Oil Recovery :

5.0 × barrels (0.8 × m3) of heavy oil remain in reservoirs worldwide after conventional recovery methods have been exhausted. Much of this oil would be recovered by EOR methods, which are part of the general scheme of IOR The choice of the method and the expected recovery depends on many considerations, economic as well as technological.(Thomas, 2008).

Many EOR methods have been used in the past, with varying degrees of success, for the recovery of light and heavy oil , as well as tar sands. Thermal methods are primarily intended for heavy oils. (Thomas 2008).

Considering high viscosity of heavy oil, thermal recovery methods seem the right solution for development of shallow heavy oil fields.

several very large projects which produce more than 100,000 barrels per day for heavy oil of approximately 12° API. In the Heavy Oil Belt (FAJA) in Venezuela the recovery yield from primary methods is 8 to 15%. It is expected that the heavy oil production from this belt will last for 35 years at a production rate of 600,000 barrels per day. (Meyer and Attanasi ,2003)

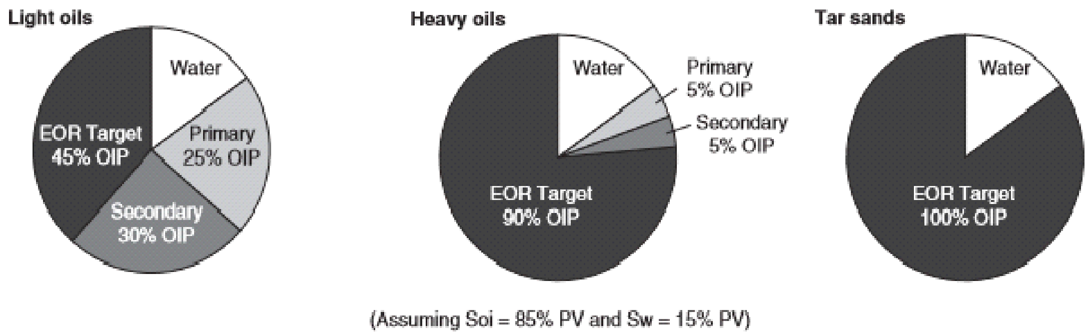


Figure (2.3):EOR Target for Different Hydrocarbons.(Thomas 2008)

2.1.4. Thermal EOR Mechanisms :

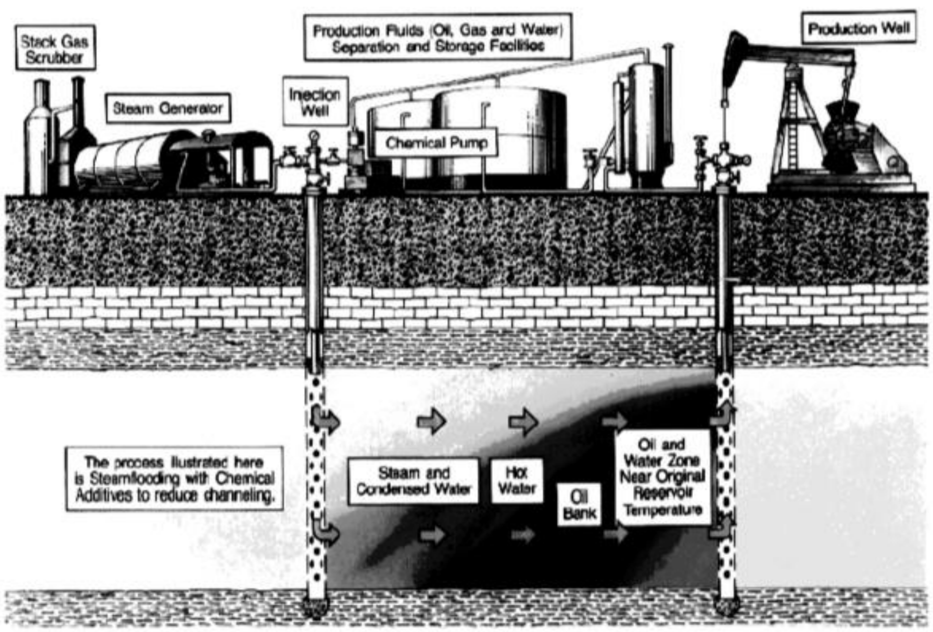


Figure (2.4):Oil Recovery By Thermal Methods. (Thomas, 2008)

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 (≤10° API). Thermal methods supply heat to the reservoir

Its Efficient methods of production require enthalpy input to the reservoir by hot-fluid injection or by creation of heat in the reservoir. Heat losses must be minimized to achieve maximum production efficiency. The widely used thermal EOR (cyclic-steam-injection process) is examined analytically to indicate which parameters govern successful exploitation.(Briggs et al,1988).

The major mechanisms include a large reduction in viscosity, and hence mobility ratio. Other mechanisms, such as rock and fluid expansion, compaction, steam distillation and visbreaking may also be present. Thermal methods have been highly successful in Canada, USA, Venezuela, Indonesia and other countries.(Thomas 2008)

Heat application is the most effective means of viscosity reduction. Figure (after Schild) demonstrates the dependence of ,viscosity on temperature for various crude oils. We notice that temperature has a marked effect on Viscosities of low-gravity crudes. The effect is somewhat less on higher gravity oil. To bring the viscosity of heavy oils within the range of ordinary crudes, the oil and rock matrix frequently must be heated to temperatures ranging from 350" to 450;F. This is sometimes both technically and economically feasible by' resorting to well-known thermal recovery methods , Heat transport into or within a formation may be by conduction, convection or a combination of both. Heat conduction will always occur whenever temperature gradients exist within the reservoir. However, heat transport by this mechanism is very slow For example, the conduction rate through 1 square foot of rock surface is only about 1 Btu/hrft a gradient of 1°F/ft. Nevertheless, conduction can be quite effective over large areas and short distances. Convection by means of a fluid carrying sensible or latent heat, or both, is a faster heat transfer mechanism. Heat exchange between the fluid and the formation is also very rapid, and vaporize some of the oil..(SZASZ and THOMAS, 1965)

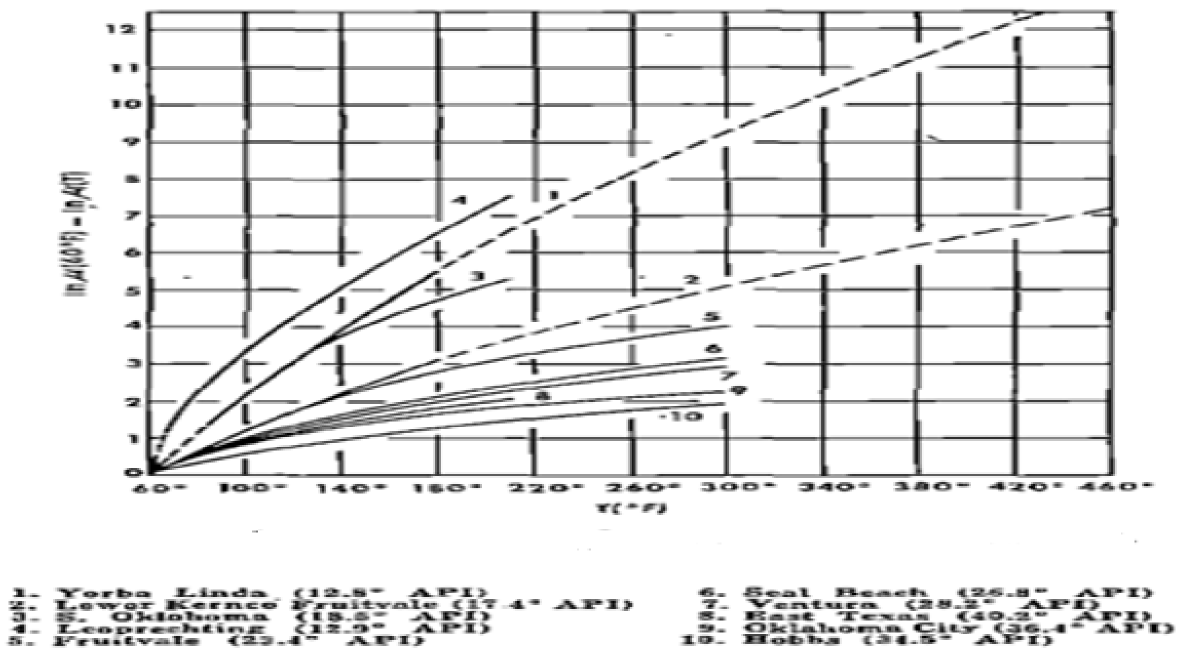


Figure (2.5): Logarithm Of Crude Oil Viscosity Vs. Temperature .(SZASZ And THOMAS, 1965)

The directions of heat and fluid flow may be cocurrent, counter current or perpendicular to each other. In cocurrent flow, the driving fluid is the carrier of both thermal and mechanical energy This means that these two functions cannot be independently controlled and optimized. Counter current flow permits independent control over the injected fluid to some degree. However, heat transport in this case is difficult and inefficient because it relies mostly on conduction Furthermore, the produced fluids carry sensible heat by convection in the opposite direction_ Heat and mass transport in directions perpendicular to each other is possible under specific reservoir conditions. When it is possible mass and heat flow are frequently independent, and conduction is the principal heat transport mechanism within the reservoir. This process has interesting possibilities in viscous oils and will be treated more fully later.(SZASZ and THOMAS, 1965)

Finally ,there are some timing considerations in reservoir heating. The heating phase and the fluid driving phase need not occur simultaneously. They can be sequential or cyclic. This sometimes may result in the most efficient method of heat treatment.(SZASZ and THOMAS, 1965)

Generally There Are Two Thermal Methods Of Recovering Heavy Oil:

1.The process in which heat is injected into the reservoir. Methods include cyclic steam injection, steam flooding

2. The process in which heat is generated within the reservoir itself. include in situ combustion with both type (forward and reverse)

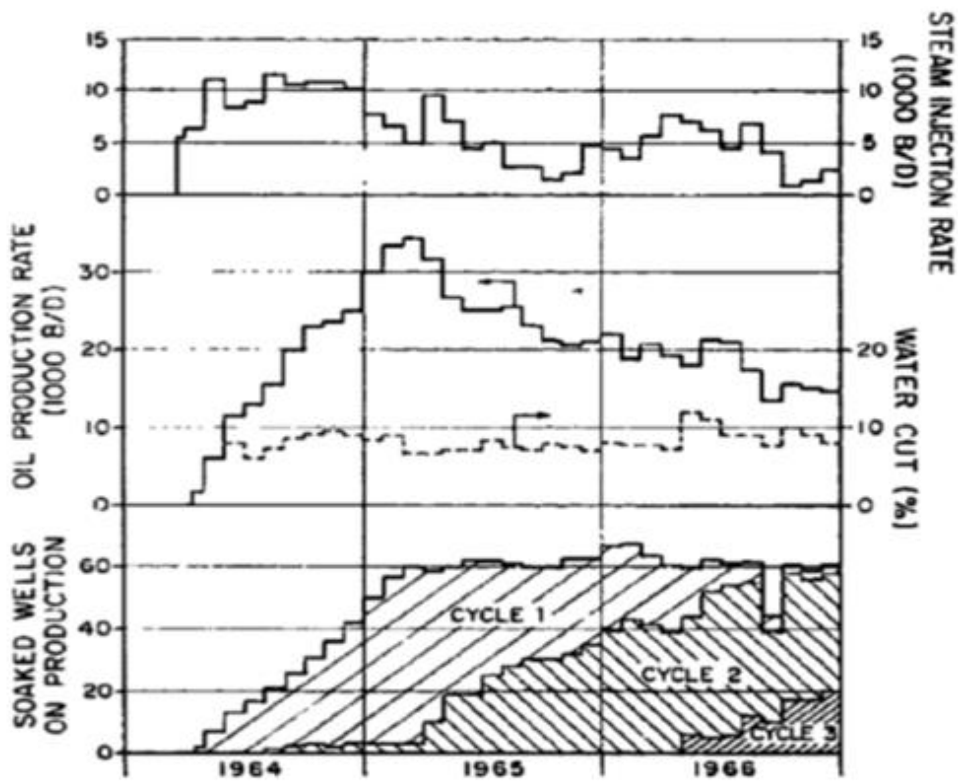


Figure (2-6) : Overall Project Performance , Total Steam Injection and Oil Production Rate for all Soaked Well Vs. Time (Haan And JANUARY, 1969)

2.1.6. Steam Zone Growth:-

Mathematical modeling of the steam zone growth is very important for accurate calculation of the reservoir volume heated by the steam. This is necessary for production, prediction and optimization of steaming/production strategies.(JANKOVIC 1988)

Mandl and Volek have developed a 1-D analytical model for reservoir steam zone growth taking into account conduction heat losses through the base and cap rock, and convective heat flux in the direction of steam zone growth. They also designed an experimental 1-D model "containing unconsolidated sand and fitted with cap and base rocks to simulate heat losses and study the steam zone growth rate and temperature profiles ahead of the steam zone..(JANKOVIC 1988)

The main conclusion of their theory was the existence of a "critical time" denoted by t_c which signified the transition from a predominant contribution by conduction heat losses to convective heat losses on the steam zone growth. Thus for time t>t_c convective heat losses could be neglected and the steam zone growth could ~e described by the Marx and Langenheim analytical model For t<t_c the convective heat losses must be included and the steam zone growth could be adequately described by their approximate analytical solution which they also compared with experimental results..(JANKOVIC 1988)

Quantity must be greater than or equal to zero , and represents the ratio of a generalized enthalpy of the water leaving the steam zone through the condensation front in the direction of the steam zone growth, to the .average enthalpy of the fluids and the rock in the steam zone .(JANKOVIC ,1988).

2.1.7. Steam Zone Growth During Multi-Layer Steam Injection:

The basic mechanisms involved when steam flows through oil-containing porous rock have been reported by Willman et al. The growth of the steam zone when steam enters a single layer at constant injection rate has been developed by Marx and Langenheim. Here considers the steam zone development when a large number of highly permeable paths of equal thickness, separated by arbitrary but equal distances, are available for flow of injected steam.(Closmann, P. J. 1967)

THEORY:

Consider the system with A number of horizontal zones of equal thickness, are separated from each other at distances 1. It is assumed that there are infinitely many layers in the vertical direction. Further, important assumptions of the mathematical model to be employed are as follows. (Closmann, P. J. 1967)

- Steam enters all the layers at constant and equal rates.
- Steam zone temperature remains constant throughout the steam zone at the value of the input steam temperature.
- The heat capacity of the steam zone may be represented by some average value .
- Heat loss occurs normal to the horizontal boundaries of the steam zones.

- No heat is transported by conduction or convection ahead of the steam front. The formation immediately ahead of the steam zone remains at original reservoir temperature. The shape of the temperature distribution will then be that of a step which moves outward.
- At each position in space the fluid and rock temperatures are equal.

2.1.8. CSS Challenges :

Steam was introduced at Kern River around 1970 and immediately had an impressive incremental production rate.(Anna Wegis,2001)

The crude oil produced in California, including that in the Kern River field, is noted for its extremely low gravity number. In 1979, the incremental oil production rate was 199,000B/D due to thermal recovery methods. This was 20% of the state’s total production..(Anna Wegis,2001)

Knowledge of the geology of the Kern River field is essential when attempting to use thermal recovery operations. Many levels of oil-saturated sands exist and are separated by impermeable, non-porous shale layers. These virtually completely impermeable layers present a challenge when trying to achieve steam breakthrough in a certain sand layer. If oil production is desired in more than one layer of sand, it is very difficult to control which layer of sand the steam will enter. This is due to the nature of the steam to take the path of least resistance, The challenge to achieve steam breakthrough is not an issue when it is necessary to steam only one layer of sand, The challenge arises when it is desired to steam two or more layers of sand without needing a steam injector well for each layer..(Anna Wegis,2001)

Casing-limited-entry technology would allow, in theory, the oil company to, steam more than one layer of sand without the need for more than one steam injector well, A portion of the Kern River field was reconfigured to casing limited-entry technology. However, after several years, the reservoir temperature was cold and steam breakthrough (212 degrees Fahrenheit) had not been reached..(Anna Wegis,2001)

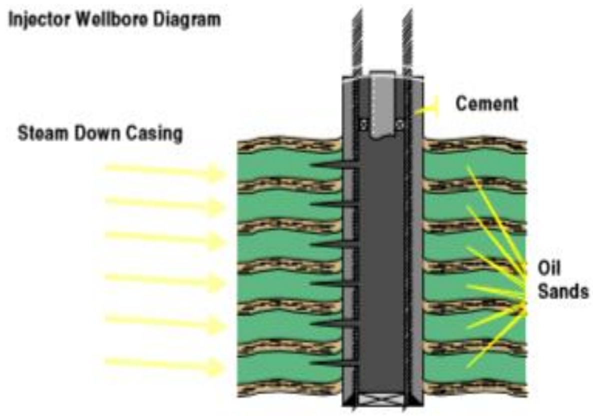


Figure (2.7) :Limited Entry Through Casing.(Anna Wegis,2001)

The only logical explanation for the lack of steam breakthrough is the lack of control of the steam once it was released into the well bore.

The problem of Kern River solved by Limited Entry Injection Through Tubing; Limited entry injection through tubing has proven to be more efficient method for multi-zone flooding. The idea behind steam injection through tubing is to gain more control over the steam once it enters the wellbore, Similar to the steam injection through casing, injection through tubing has perforations in the casing, Packers are then placed in between the casing and the tubing, above and below both level, Once the steam is injected into the tubing, it exits the tubing through the limited-entry holes and enters the casing. The packers above and below the level of desired sand do not allow migration of steam throughout the wellbore, thereby forcing the steam into the desired level of sand..(Anna Wegis,2001)

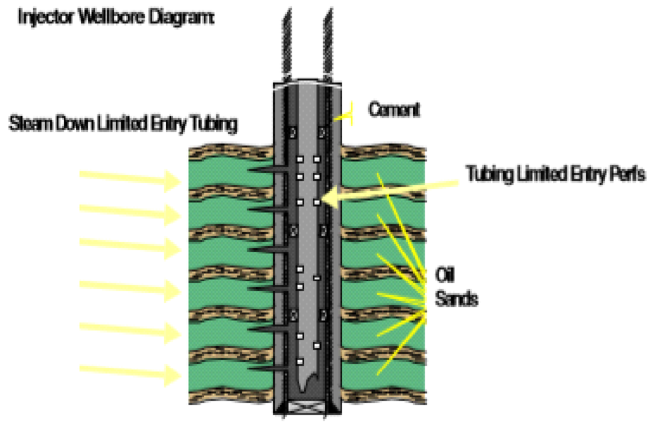


Figure (2-8) :Limited Entry Through Tubing.(Anna Wegis,2001)

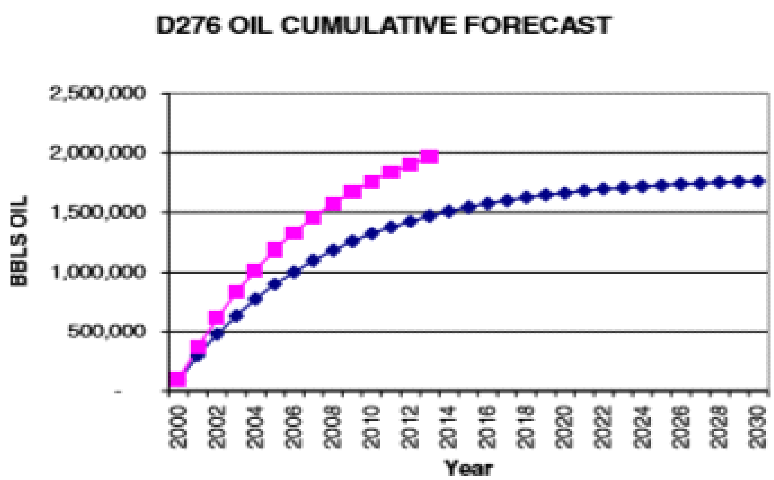


Figure (2-9): Expected Incremental Oil Over Thirty Years For The Field .(Anna Wegis,2001)

In Oman The 'A' East Hardah formation contain a 200 m thick oil column of highly viscous oil , with viscosity range from 200 to 400,000 cp . Due to high viscosity the first production was considered only possible using thermal EOR techniques starting with CSS .(Solenn Bettembourg ,etc 2016)

First CSS injection started in March 2014, in a non-depleted northern part of the field. Initial pressures in this area were high, up to 106 bars, leading to poor or challenging steam injection, first CSS production was very promising, and, within a few months ramped up to 70% of the targeted CSS field peak oil rates. .(Solenn Bettembourg ,etc 2016) shows some examples of CSS wells in A East during their 1st CSS cycle production phase. A high liquid and water cut are observed at the beginning of the production cycle and the difference between the liquid and oil rates is higher initially since the early production consists mainly of the condensed steam. As the well continues producing, the difference between the liquid and oil production reduces with time to be at its minimum at the end of the production phase. .(Bettembourg ,etal 2016)

Steam quality impact in wells performance :

Steam quality has a great impact on CSS wells performance due to the latent heat carried by steam versus hot water. In A East, the steam is generated by once through steam generators (OTSGs) with a discharge steam quality of about 80%. .(Bettembourg ,etal 2016)

The key Elements Changes In Geological Understanding:

- Intra-formational stratigraphy of the Haradh and its impact on reservoir property distribution
- Identification of both flank and intra-field faults.
- A revised structural evaluation for the entire stratigraphic range, including top reservoir.

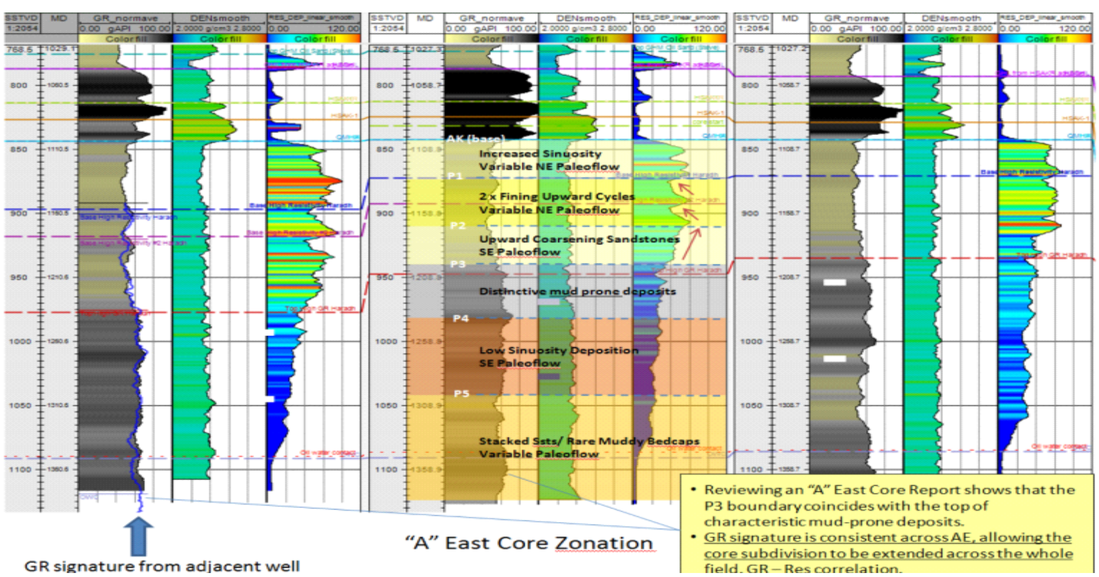


Figure (2-10): East Internal Stratigraphy, Calibrated With Core .(Solenn Bettembourg ,Et Al, 2016)

2.1.9. CSS Challenges In commingle Wells :-

These problems becomes later become big challenges in field industry according to case studies, here we concentrate specifically in the steam distribution in multi zones that separated by impermeable layers and we will back to the models that govern steam and fluid distribution in layers and the

2.1.9.1. Geological Complexity :

- ***Reservoir heterogeneity :***

The CSS recovery method is influenced by complex reservoir geologies, where a CSS well can penetrate multiple layers having significantly different properties, including permeability. It is important to have a solid understanding of the impact of multiple layers on recovery when using CSS, not only to help maximize recovery but also net-present value because of the high cost of steam generation.

The Reservoir heterogeneity according to the depositional of sand layer can be divided into favourable and un favourable stratified reservoir (i.e. the upper layers of the sand sequence have higher permeability's than the lower layers), This stratification of the reservoirs has a significant impact on the sweep efficiency of many displacement processes its affect the steam distribution in layer which tend to higher permeability layers , also gravity segregation the density contrast between the steam and steam condensate leads to the steam override whereby the injected steam rises to the top of the reservoir some short distance from the steam injector leaving a large sand body in the lower part of the reservoir unwept and immobilized, depending on the stratification of the sand body.(Ali, S,etc,1994)

The heterogeneity of formation caused by low permeability zones significantly hinders 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. .(Shijun ,etc,2015)

low permeability zones such as shale layers may act as a flow barrier depending on their size, vertical and horizontal locations, and continuity throughout the reservoir thus making it very important to understand and characterize the effect of shale layers. Shin, H., & Choe, J. (2009, January 1) the presence of intercalated clays and vertical heterogeneity of the sands may lead to different steam injection rates from layer by layer, which results in an early breakthrough of steam in layers with the highest permeability, this affecting process efficiency by decreasing steam flood sweep efficiency .(R. Hoyos Perdomo,etc,2014)

- ***Reservoir thickness :***

For thin reservoir the heating efficiency of injected steam is low because of large heat loss to overburden and under burden

For a 1 m reduction in pay thickness (e.g. from 11 to 10 m), the cumulative oil production/m of pay thickness decreased 6 - 8% when the reservoir pay thickness was less than 11 m, decreased 1 to 2 % when the reservoir pay thickness was between 11 and 17 m, and decreased less than 1% when the reservoir pay thickness was greater than 17 m. Thicker pays had a greater tendency for steam to rise because of an increased gravitational influence resulting in reduced lateral expansion.) (Chang, J. ,2013)

Where α is the thermal diffusivity of the surrounding formation and is the gross reservoir thickness .as can be seen , a factor of one half in the gross reservoir thickness quadruples the value of dimensions less time which reduce the value of significantly for example for t=730 days and = 0.8 sq ft/D the heat efficiency would be 0.51 for a gross reservoir thickness of 40 ft but only 0.33 for one of 20 ft

- ***Geomechanics :***

The CSS recovery method is influenced by complex reservoir geologies, where a CSS well can penetrate multiple layers having significantly different properties, including permeability. It is important to have a solid understanding of the impact of multiple layers on recovery when using CSS, not only to help maximize recovery but also net-present value because of the high cost of steam generation. (Temizel, C,etc ,2015)

Injection and production activities impact the equilibrium stress condition which exist due to pore fluid and in situ formation stress.

Tendency to attain a new equilibrium state initiates the deformation along with the fluid flow due to cyclic steam stimulation. CSS can results in change of in situ stresses, rock properties, porosity, permeability, wettability and capillary pressure (Shafiei et al., 2013).

The variation in pressure and temperature of reservoir can propagate growth of existing fractures, create new fractures or can impact the rock strength which in turn poses risk of fault reactivation and cap rock integrity (Shafiei et al., 2013; Khan et al., 2011; Jamaloei et al., 2015).

Geomechanical understanding of reservoirs subjected to CSS can help in understanding issues like low injectivity, reservoir drive and cap rock integrity. (Temizel, C,etc ,2015)

2.1.9.2 Technical Challenges:

- Several techniques have been applied for selective steam injection in the high-pressure zone(s). So far the best results have been obtained with packers set in blank liner sections. (Butler,1991)
- Casing leaks occurred after steam injection due to corrosion related to the presence of a highly saline water-bearing formation at shallow depth. At present, therefore, all project wells are catholically protected,
- Liner failures due to strongly suggested tension failure and excessive compressive stresses in the other.
- Economic side and are primarily related to cost of the steam, this steam can be used in place of natural gas. This process can be made more economical by generating and selling electricity and using the waste heat for cogeneration

2.2. Case Studies In World Wide

The Css Technology Have Been Implemented In California Field In 8 Zones ,And The Result Was Clearly Worthy, Here We Are Going To Mention Five Of Them And They Are : In Hunting Ton Beach Zone (Tm) The Total Oil Recovered Was 29000,And Oil Recovered Per Barrel Of Steam 6.5 .In Sanardo Field Zone (Lombardy) The Total Oil Recovered Was 50000, And Oil Recovered Per Barrel Of Steam 2.8. While In Kern River Field Zone (China) The Total Oil Recovered Was 11600, And Oil Recovered Per Barrel 2.62. In Mid Way Sunset Field Zone (Tulara) The Total Oil Recovered 4640, And Oil Recovered Per Barrel Of Steam 0.38. And Goalinge Field Zone (Tem Blor) The Total Oil Recovered Was 3000, And Oil Recovered Per Barrel Of Steam 0.48.(Burns,1960).

The Emeraude Field Is Estimated To Contain Several Hundred Million Tonnes Of Viscous (100-Mpa.S) Original Oil In Place (Ooip). After 14 Years Of Production (1972 To 1986), Only 22 Million Tonnes Had Been Recovered, About 3 % Ooip. Couderc Et Al In 1990 Designed And Development The Emeraude Steam Drive Pilot To Recover A Larger Amount Of Ooip Than Could Be Recovered By Primary Production Despite Difficult Conditions. (Couderc Et,1990)

In 1994 Ail Provides Study Of Steam Flood Performance In Stratified Reservoir, Titis Stratification Of The Reservoirs Has A Significant Impact On The Sweep Efficiency Of Many Displacement Processes, Particularly In The Case Of Thermal Recovery Processes Such As Steam Flooding, Cyclic Steam Stimulation And In-Situ Combustion. Altogether Seven Experiments Are Carried Out For This Investigation Of The Effect Of Reservoir Stratification On Steam Flooding Recovery Performance, These Experiments Are Divided Into Three Groups 115 (Homogenous Reservoir) 120 And 163 (Stratified Reservoir) The Stratification For Experiment 120 Unfavourable While In 163 The Is Favourable. Stratification Promotes Steam Override Reducing Oil Recovery, While Favourable Stratification Lead To Steam Underride In The Lower Regions Of The Model As Sweep Efficiency Enhanced. And For Case Of Un Favourable Utilizing Horizontal Steam Injector Has Negligible Impact On Sweep Efficiency, It Create Preferential Flow Channel In Certain Region. (Ali, S, Etc,1994).

A Benchmarking Study On 43 Steam Flood Of Light/Medium Crude Oils Was Performed, To Find Attractive Reservoir Characteristics And Successful Operational Practices That Are Used Worldwide, We Selected The La Salina Reservoir (La Rosa Formation, Lake Maracaibo, Western Venezuela) As A Potentially Successful Reservoir To Apply Steam Flood Technology. In Addition, Unsuccessful Projects From Two Different Reservoirs (The Naval Petroleum Reserve No. 1, And Buena Vista Hills, Both In The Usa) Were Analysed. Several Reasons Were Identified, Such As: Poor Reservoir Characterization, Thief Zones And Carbon Dioxide Formation By Decomposition Of Reservoir Minerals.(Alfredo,2001).

Also Anna Wegis ,2001 studied the effect of Multi-Zone Injection by Limited-Entry Through Tubing and result shows that these strategy is more effective, economical, and environmentally safe answer than multi-zone injection by limited entry through casing. (Wegis,2001)

The Ondeh field is located in the north east of Syria , its contains 5.1 billion bbls of 12-16 API crude oil and the primary recovery factors is estimated to be only 5 to 7% of the original oil in place. CSS was selected for a pilot test, it was implemented in September 2006 and suspended from 2 to 24 wells. low steam quality at the bottom of the well proved to be the most prominent challenge duo to a combination of heat loss in the wellbore and relatively low steam injectivity , injection into tubing improved steam quality.(minglin li,2010)

. Waterflood Began In 1990 And Suffered From Low Injectivity, Poor Sweep, And Injector To Producer Linkage. The Response To Steam Steam Injection Is Prompt And Significant. The Injectivity Is Doubled And Productivity Is Almost Tripled. The Oil Steam Ratio Is Around 0.3. The Incremental Recovery Is Predicated To Be Over 10%.(Shuhong Wu,2010).

Wu Yongbin, 2010 studied the effect of applying Superheated Steam Injection in Shallow Heavy Oil Reservoir in North KHAZKHSTAN oil field and the results shows that the average cyclic oil production in cyclic superheated stimulation is 61.73% higher than that in cyclic wet steam stimulation for the previous cycles, and the average water cut is reduced for more than 10% . (Yongbin, et al., 2010)

In Heavy Oil Field Of Sudan, This Field Contain Heavy Oil In Multiple Reservoir Of Bentiu Formation. This Primary Recovery Around 18-20%, Plan Is Made For Thermal Enhanced Oil Recovery Application Early To Maximize The Recovery. (Tewari, Et Al, 2011).

Melibur Field Discovered In June 1984, Located In Indonesia, The Main Formation In This Field Is Sihapas Formation Which Is Consist Of Upper Sihapas And Lower Sihapas, The Recovery Factor Of Melibur Field About 29%. (Putra, 2011).

In 2012 Daniel Higuera, Et Provides Study About Optimization Of Cyclic Steam Stimulation In Highly Stratified Oil Reservoir Of Middle Magdalena Basin: Moriche Field. Moriche Is A

Heavy Oil Field Operated By Mansarovar Energy Colombia Limited (Mecl), Which Were The First Fields That Applied Css As Enhanced Recovery Method In Colombia. For Moriche Field To Be An Economically Attractive Development It Was Necessary To Use Thermal Methods To Enhance Oil Recovery. The Moriche Oil Production Comes From A Multilayer Reservoir Called B Zone. To Date The Cumulative Production Is 7 Mmbls With A Recovery Factor Of 2%. The Well Spacing Is 10 Acres. The Oil-Steam Ratio (Osr) Was Less Than 1 Bbl / Mmbtu Which Was Not Economically Feasible For The Exploitation Of The Moriche Field Using Css As A Method Of Recovery (Daniel,2012)

In 2012 Dennis Has Estimated The Number Of Enhanced Oil Recovery (Eor) Projects In The Middle East (Me) Has Increased Over The Past Decade, There Are 11 Eor Projects Kicked Off, On Pilot, Or At Commercial Scale In The Me.Oman Is Taking The Lead In The Implementation Of Eor Projects Because Of Its Declining Oil Production. The Urgency Of Eor Implementation In The Me Is A Function Of Declining Oil Production Rates, Availability Of Remaining "Easy Oil," Impending Momentum To Contain Co2 (Starting Early With The Long Lead Times For Such Projects), And Other Geopolitical Factors. (Dennis Denney,2012).

Blocks 97 and 98 in Karamayfield , china first CSS in September 1980 , the cumulative oil production was 2195 tons ,and in 97 Block in 2004 The producing oil in place was 19.73 million tons with a recovery factor of 8.8% . (Sheng, 2013)

Da66 Block in the liaoshuguang field China , in June 2003 hotwater or steam flooding the recovery factor was 19.76 % and increased to 55.14% . (Sheng, 2013).

Gudao field in china the CSS starting in 4 to 27 August 1991 , the intial oil rate was 23.5 tons/day.(Sheng, 2013).

In cold lake in Alberta, Canada in April 1970 the recovery factor was 20% with a well production rate of 80 bbl/day over an average of 6 years. (Sheng, 2013).

237%32%3%237%32%3%%237%32%3Wu, Yongbin In 2013 Established 3d Geologic Model According To The Petro Physical Properties And Geologic Characteristics To Study The Real Performance With The Real Geological Properties. The Development Zone, The Perforation Strategies, The Cylic Steam Injection Quantity, The Steam Injection Rate, Soak Time, And Cyclic Period Are Optimized For Css. The Simulation Results Indicate That The Thermal Recovery Technique Especially 4 Cycles Of Css Followed By Sf Can Acquire Satisfied Performance(Wu, Yongbin,2013)

In 2014 Maria G. Aguilar Described Css Performance In Sands Of The Samaria Tertiary Field, Which That Extra-Heavy Oil Field Produces From Three Sands A-1, A-4 And A-6. Css Is Implemented As A Result Of The Pilot Project, During The Injection Stage The Average Injecting Is 240 Tons Of Steam Per Day With 80% Steam Quality, 1,508 Equivalent Cold Water Stb/Day, Heavy Oil Samaria Tertiary Field By Cyclic Steam Stimulation (Css) Along Almost 6 Years The Field Originated In A Fluvial Environment; 4 Sands Was Identified As A-0, A-1, A-4 And A-6; The Depth Sands Are From 600 To 1200 M; Contains Extra Heavy Oil With Range Of Api Gravity Between 6 To 10 °Api; Actually The Recovery Factor Is 2.3; With The Development Plan Has Optimization With The Understanding Of The Css Performance In The Field, With Recovery Factor Increment From 6.93 To 8.8 In The Next Three Years. Is Apparent That Net Thickness For A Successful Of Css Is Influenced By Optimization Of Operation Strategies And The Reservoir Properties Where The Css Is Applied. It's Necessary To Reduce Cycle Time As Decrease Temperature. (Aguilar,Etc, 2014)

Abdulaziz Najaf, 2015 in KUWAIT, create a Tracking System for Steam injection, its implemented to serve the both management and operation sides by integrating all the well data including operation and financial parameters , Briefly its provide an excellent understanding and management for the pilot. (Najaf, et al., 2015)

In Russian Field Css Well Can Penetrate Multiple Layers Having Significantly Different Properties, The Impact Of Multiple Layers On Recovery Factor When Using Css Helps To Increase Recoveries Up To 20 To 25%. (Temizel, 2015).

Korany, S. K. In 2015 Described A Case Study Of Cyclic Group Steaming Of Wells (Cgsw) In A Heavy Oil (10-12 Api) Field Located In Egypt(Issaran), During Cyclic Steam Injection In The Pilot, A Negative Effect Was Noticed During Steam Injection In Some Wells On Surrounding Wells; The Gross Production Rate Increased Accompanied By An Increase In Water Cut And Wellhead Temperature Leading To Loss In Oil Production, Cgsw Was Implemented By Applying Steam Cycles In All The Producers Of The Pilots Simultaneously, Allowing For A Better Distribution Of Heat Around All The Wells.Result Are Shown With Full Description .(Korany, S. K,2015)

In 2016 Alali, Y Etc. Discussed Study For Completion Plan For Steam Flood Pilot,] The Development Of The Viscous Oil Resources Of Kuwait Is Considered A Very Important Strategic Goal Of The Country. The First Phase Of Development Plans Is Under Implementation

To Meet A Target Production Of 60 M Bopd By A Combination Of Cold Flow And Cyclic Steam Stimulation (Css) Followed By Steam Flood To Have Optimum Recovery From This Resource. The Reservoir Appears To Be A Layered One With Pay Zones Varying In Fluid And Rock Property. The 4 Pay Zones Are Seen In The Northern Part Of The Field (Fig-), Namely Zone-Ia, Zone-Ib, Zone- Iia And Zone-Iib: .(Alali, Y, Etc,2016)

In 2016 Studied Actual Field Performances For Each Formation Showing The Cyclic Steam Injection Stage And The Timing Of Conversion To Continuous Steam Strategy. A Lot Of Factors Will Be Presented For The Steam Cycle Stage Including: Voidage Replacement Ratio (Vrr), Steam To Oil Ration (Sor), And The Injectivity Index Performance From Cycle To Cycle. Then The Conversion Time From Cyclic To Continuous Steam Flooding Will Be Discussed Per Each Area (Basta, George Soliman,2016).

232%232%%232Delamaide, Eric In 2017 Reviewed Both Steam Injection And Polymer Flood In Light Of Fundamentals And Field Experience, Results Show That While Steam Injection Can Achieve Much Higher Recovery Than Polymer Flood And Is Also Applicable In Much Higher Oil Viscosity, Polymer Flooding Is Not Limited By Depth Or Reservoir Thickness ,It Has Lower Operating Costs And Is Also Less Capital Intensive. Thus, There Is A Large Opportunity To Develop Heavy Oil Reservoirs Using Polymer Where Steam Injection Is Not Possible(Delamaide, Eric,2017).

2.2.1. Case Studies in Sudan:

CSS have been implemented in SUDAN, the field contain heavy oil in multiple reservoir of Bintiu formation in 8 selected wells spread over the field and its leaded to maximize the recovery factor , the actual result is better than predicted in simulation studies with lower steam intensity of 120 m/m compared to planned 160 m/m. (Abdalla, et al, 2011)

Also Husham Elbaloula , 2016 studied the Designing and Implementation of the First Steam Flooding Pilot Test in SUDANESE Oil Field and Africa and 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. (Elbaloula, et al,2016).

The steam commingle injection and production happened in many countries such as china canda oman venzeula USA and published papers confirm the effect of non uniform distribution of steam in commingle layer ,but there is no published papers discussed this challenged in Sudanese oil field only Similar studies has been done as a graduation research in Sudan University of Science and Technology in 2014 in Bambo field well bb-22 , The analysis has been done to determine main reason of high water cut in well bb22. It has been found that layer B-1b get nearly twice the assumed amount of steam and this large amount of water result in water channeling and that why the well had high water cut. this research will investigate the steam commingled injection and production in FNE oil field and design the optimum steam injection that can maximize the recovery factor.

Chapter Three

Methodology

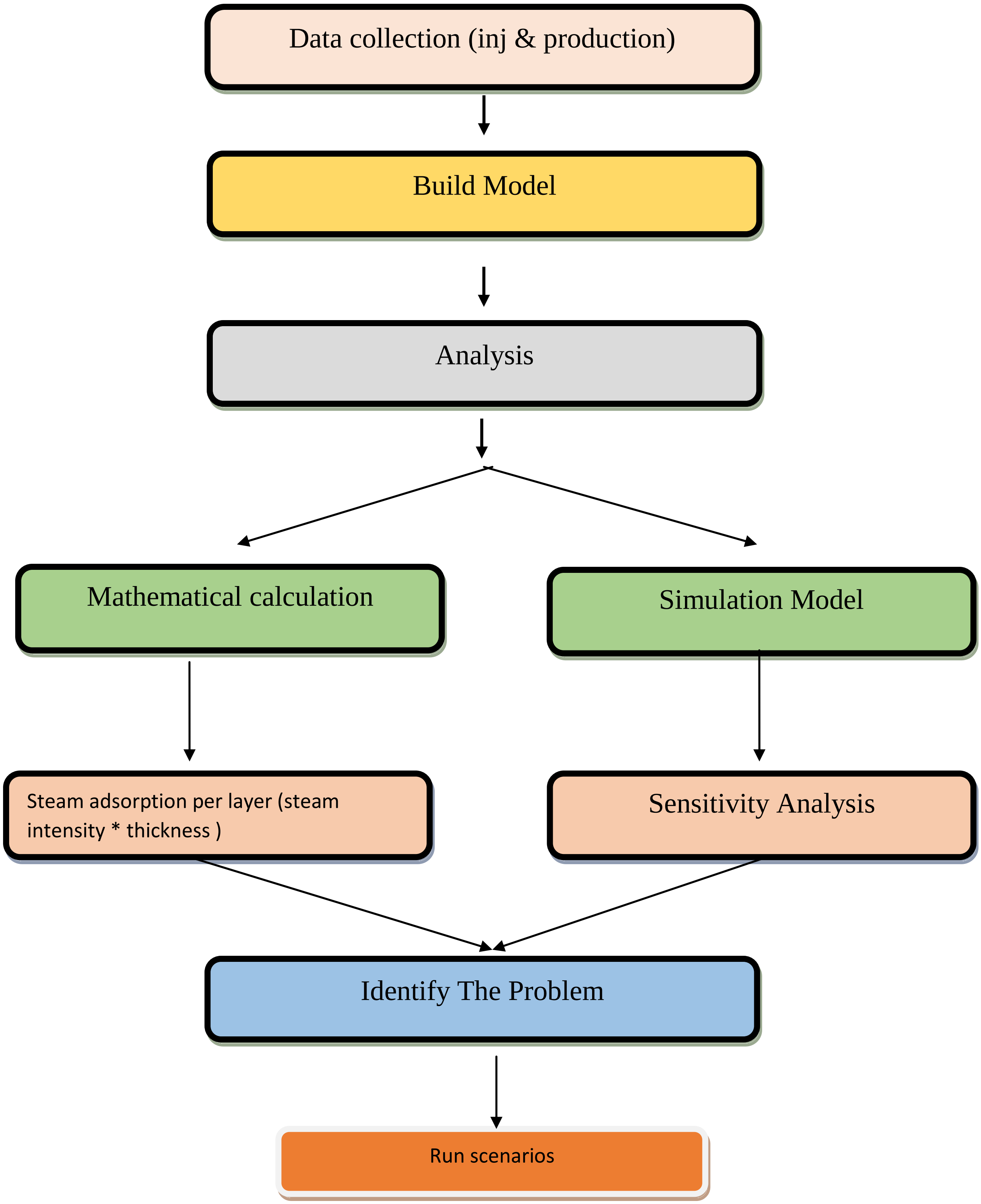
Chapter Three

Methodology

3.1. Introduction :

The Geological data, reservoir data and production data for FNE Oil field has been collected and used for analysis to investigate on Steam comingle Injection and production in FNE field and to design the optimum steam injection that can maximize the recovery factor. The Reservoir Properties (i.e. porosity, permeability, depth, initial formation pressure etc …) has been analyzed.

All these analysis will be implemented and presented in flow chart through steps in order to find the optimum steam injection that can maximize the recovery factor and propose the suitable solution, which will be applied to do the simulation model for the new cycle optimization. The steps below must be followed to get the target of the research, and they are :



Flow Chart (3.1): Steps of Solving The Problem

3.2. Analysis Steps For The Reason Of Insufficient Steam Intensity Distribution Among The Layers :

1) Reading the Interpretation Report of Pressure Decline Survey during Soaking for the reservoir at large. Surveillance (mass and enthalpy) is also needed to evaluate the performance of the steam distribution system.
2) Calculating the amount of steam designed for each zone, using the equation.

   Steam adsorbed for each layer (ton) = steam intensity(ton/m)*thickness(m)

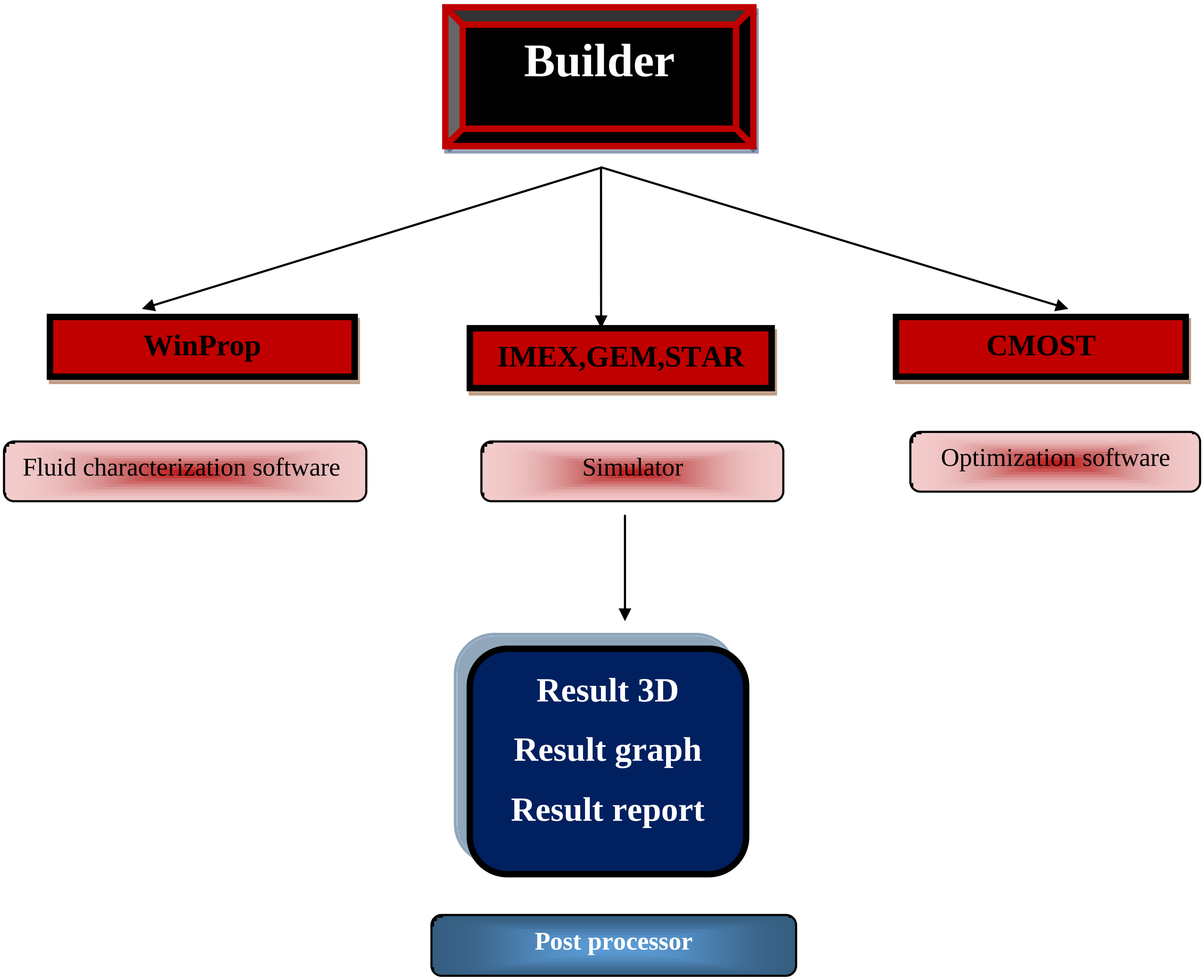
3) Sensitivity analysis for model with designed intensity.
4) Compare the actual calculations with the design calculations and model result for each layer .
5) Suggestion for solution.

3.3. Computer Modeling Group :

Abbreviated as CMG, is a software company that produces reservoir simulation software for the oil and gas industry. offers three simulators, a black oil simulator, called IMEX, a compositional simulator called GEM and a thermal compositional simulator called STARS.

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.

3.4 CMG Components:



Flow chart (3-1): CMG Components

3.4.1 Builder :

Its provide a framework for data integration and workflow management between CMG’s reservoir simulators. Builder is a menu-driven reservoir simulation model creation editing and visualization program for generating input data for all CMG software products –STARS, GEM, IMEX, CMOST and WINDPROP ,Through the use of 2D and 3D visualization, and efficient keyword input, Builder helps reservoir engineers realize immediate time savings by efficiently navigating them through the complex process of building reservoir simulation models.. So builder interface is designed to enhance user productivity .

3.4.2. STARS :

Thermal & Advanced Processes Reservoir Simulator:

STARS , a K-valued (KV) based, advanced process reservoir simulator, can be used to model virtually any recovery process. STARS is especially suited to non-isothermal, light and heavey oil recovery process as well as those that require the modeling of chemical reactions and alkaline-surfactant-polymer (ASP) flooding, foamy heavy oil production and cold heavy oil production. In addition, STARS can model the in-situ formation of emulsion, wax precipitation and thermal desorption. STARS includes a rigorous, iteratively-coupled geomechanics module, as well as, integration with third-party packages for modeling subsidence and related effects that may occur during recovery.

3.4.3 IMEX :

Used when Three-Phase, Black-Oil Reservoir Simulator

IMEX, one of the world's fastest conventional black oil reservoir simulators is used to obtain history-matches and forecasts of primary, secondary and enhanced or improved oil recovery processes. In addition, IMEX models production from conventional sandstone and carbonate reservoirs, including the effects of natural fractures and is widely used to model primary production of gas and liquids from hydraulically fractured shale and tight sand reservoirs.

3.4.4. GEM :

Used when Compositional & Unconventional Oil & Gas Reservoir Simulator

GEM is the world’s leading reservoir simulation software for compositional and unconventional modelling. GEM is an advanced general Equation-of-State (EOS)compositional simulator that models the flow of three-phase, multi-component fluids. GEM can model any type of recovery process where effective fluid composition is important

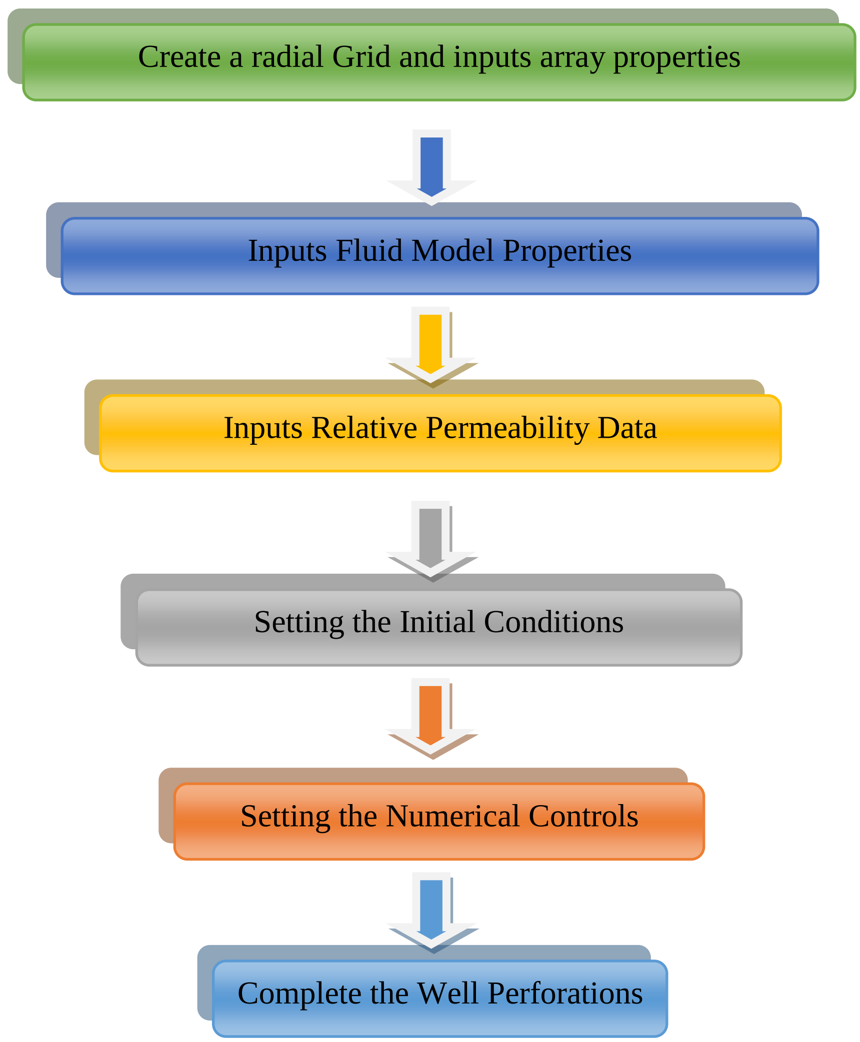
3.4.5. RESULTS :

Visualization & Analysis

Through industry-leading visualization capabilities, results allows engineers to enhance productivity, gain new understanding and insight into recovery processes and improve Net Present Value (NPV). Results, a set of post-processing applications, is designed to visualize and report CMG software – STARS, GEM, IMEX – input and output data into 2D aerial maps, 2D cross-sections, 3D perspectives, stereoscopic 3D formats and tabular reports. Results is comprised of three modules , Results 3D,Results Graph, and Results Report

3.5. Building a Cyclic Steam Simulation Model in STARS:

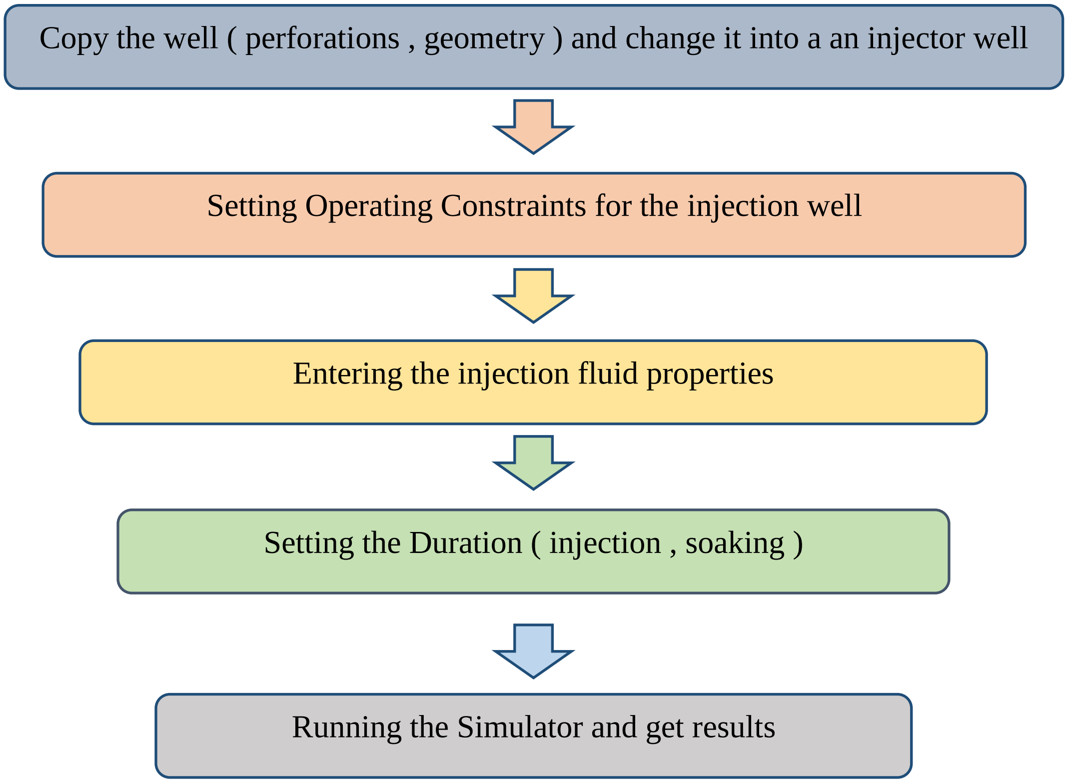
Flow chart below represent the steps of creating the numerical model through the use of CMG software



Flow chart 3-3:Steps Building Model

Flow Chart 3-2 : Steps Of Building The Numerical Model

Building the CSS will be by following the flow chart below :-



Flow Chart 3-3 : Steps of Building Cyclic Steam Stimulation

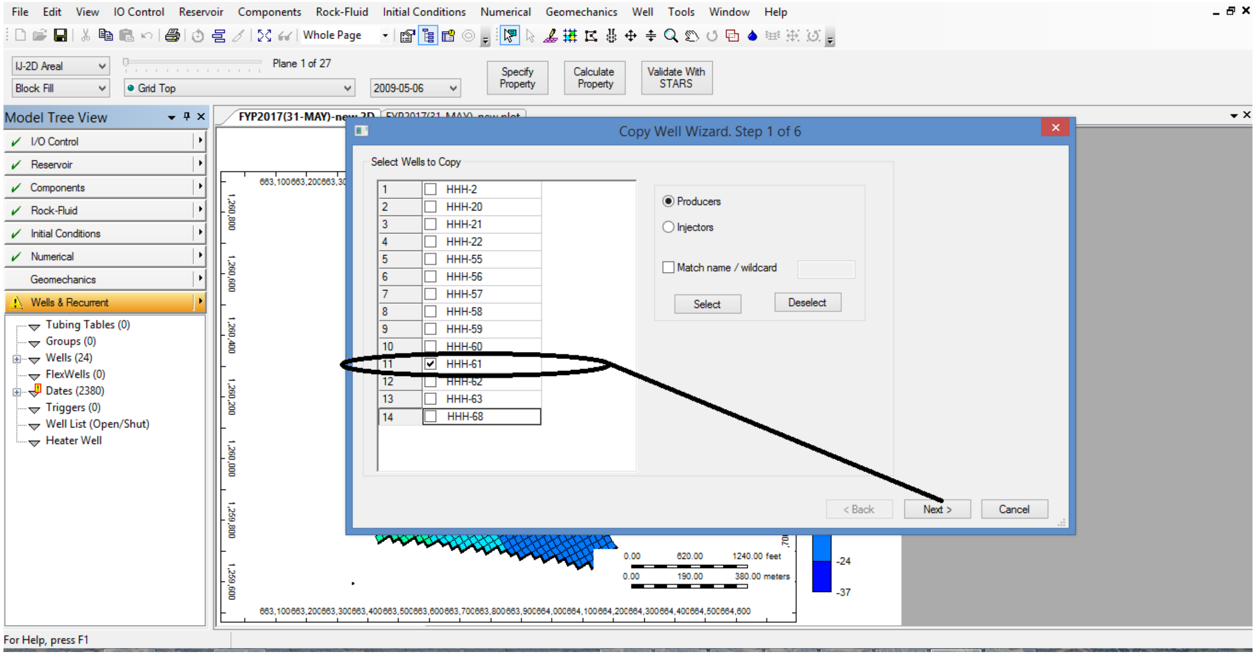


Figure (3-1) : Copying The Well

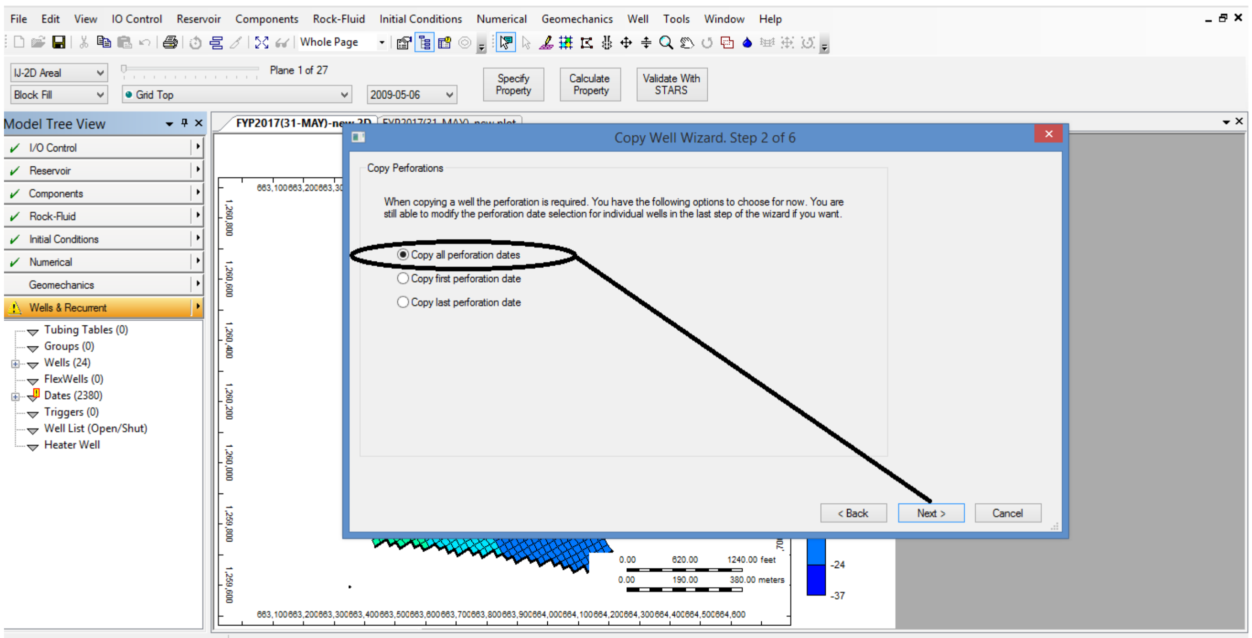


Figure (3-2) : Copying The Perforation

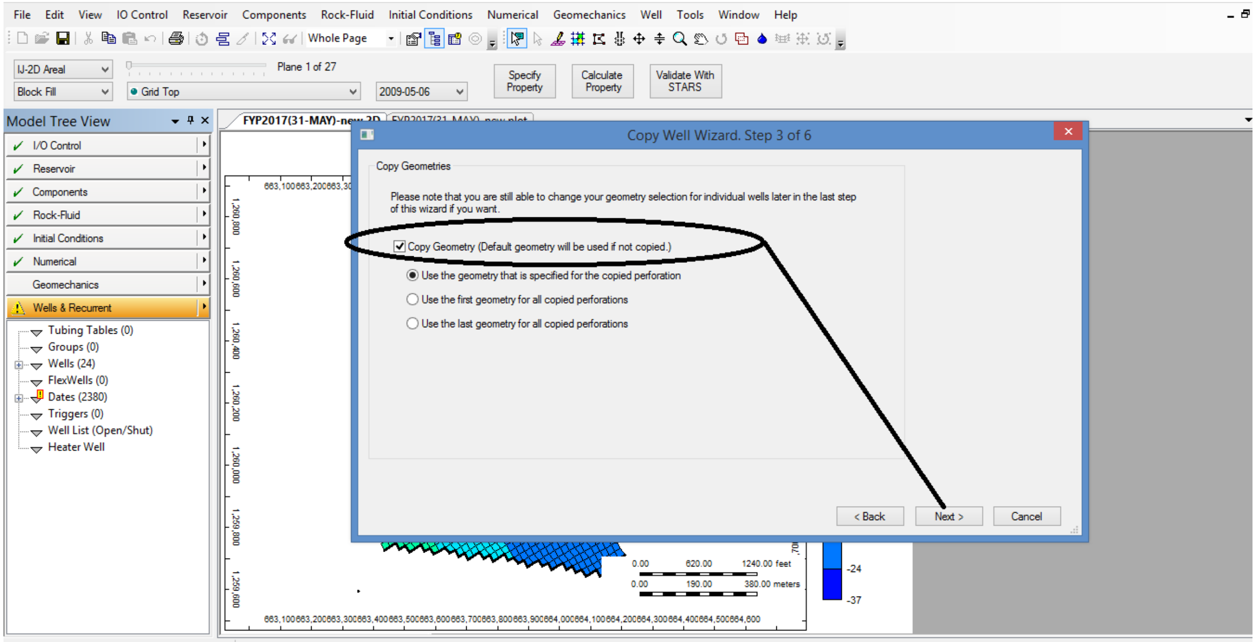


Figure (3-3): Copying The Geometry

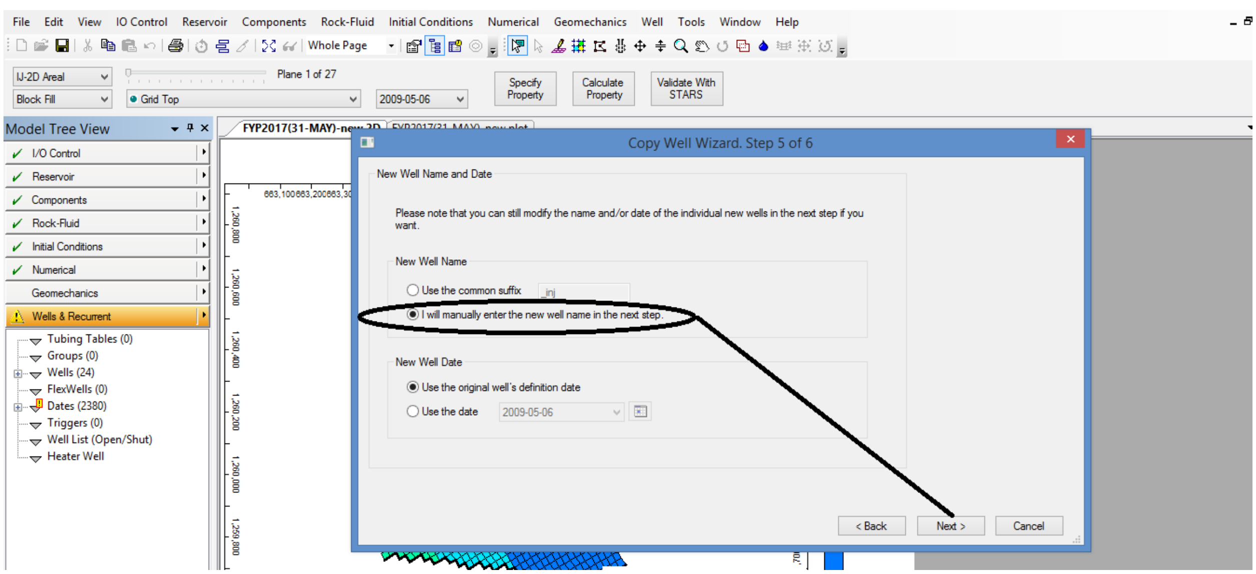


Figure (3-4) : Entering The Injection Well Name-1

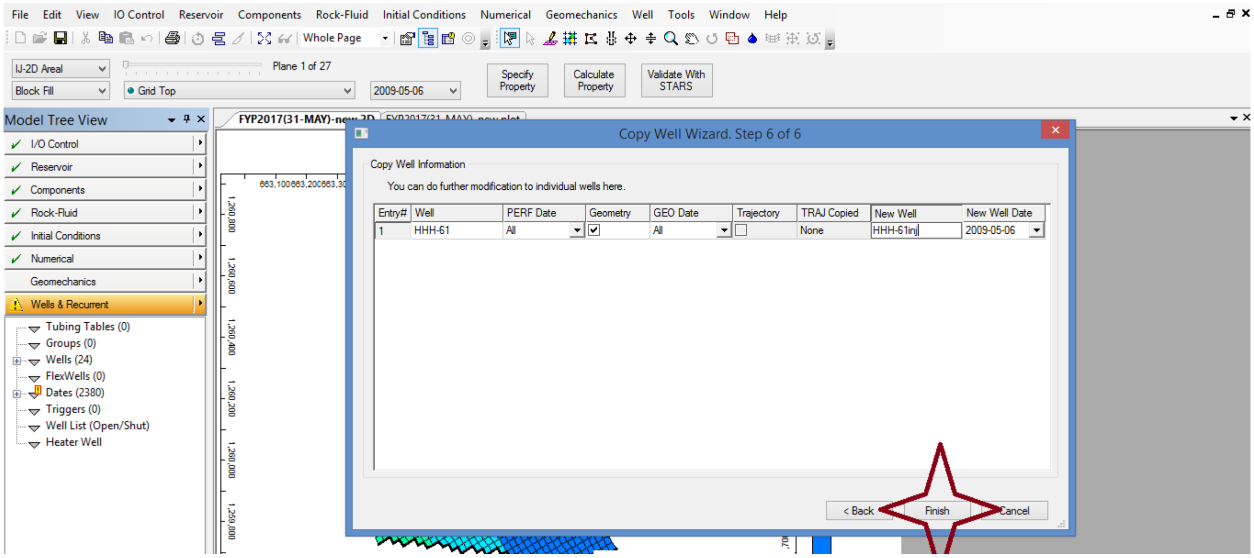


Figure (3-5) : Entering The Injection Well Name-2

Chapter four

Results and Discussion

Chapter four

Results and Discussion

4.1. CSS Challenges in Heavy Oil Sudanese Fields.

1. Depth limitation (more than 1400m)
2. Horizontal wells
3. High water cut
4. High potential (good oil rate)
5. Conventional completion wells
6. Production Csg.5/8
7. Commingle injection and production

4.2. Evaluate The current development strategy for comingle steam injection in heavy oil Sudanese fields:

Unfortunately one paper is published in Rabat, Morocco, April 11-13, 2017 evaluate the implementation of steam injection in FNE field .

The development strategy in FNE field by applying thermal EOR using CSS completed by Beijing Research Institute of Petroleum Exploration and Development in May 2008.

3 wells were drilled to delineate structure boundary and tested under CHOPS production

Eight thermal (CSS) well were drilled actual result were convincible and better than predict At of the end of 2011, totally 43 wells have been drilled, Up to 2016 the total CSS wells reach to 67 wells including 37 wells under the first and second cycle, 24 wells under the third and fourth cycle, 6 wells under the fifth cycle.

The compare between performance of the CSS well and CHOP well through four cycle found that oil production rate increases twice in first cycle recorded 319 STB/D and decreased to 256, 249 and 151 for the second, third and fourth cycles respectively for same the same

Original Oil in Place about 298 MM STB and up 2016

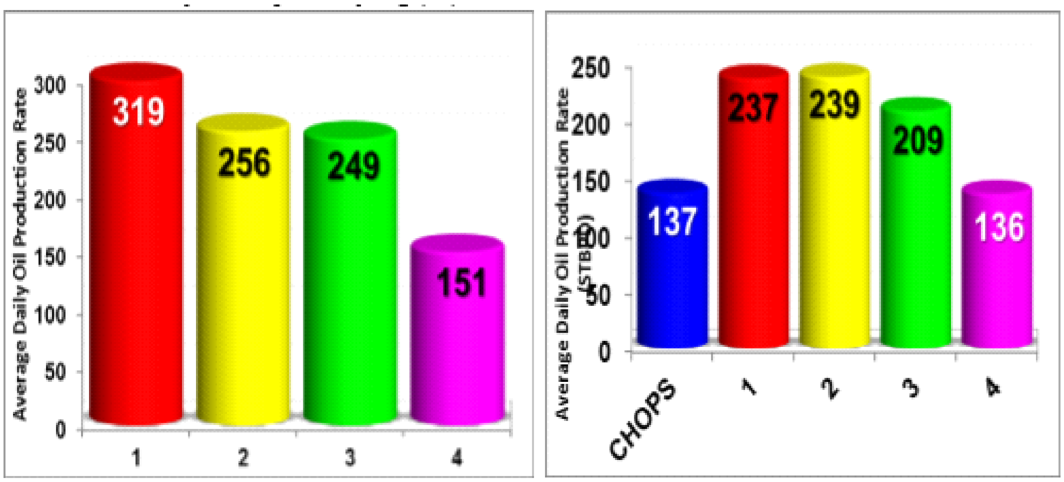


Figure (4-1): The Average Oil Daily Production For Each Cycle(Elbaloula And Musa,2017)

In the table below overall comparison between CHOPS and CSS recording the cumulative oil and cumulative water and SOR

In general The average oil daily production for this field has been increase from 5,300 bbl/d as of Dec. 2014 to 8,300 bbl/d as of Sep., 2016 the peak production has recorded on 2016 as 9000 bbl/d.

Table (4-1): Comparison Between CHOPS And CSS Cycles For All Wells

(Elbaloula And Musa,2017)

Cycle #	Injected Steam Amount (bbl)	Avg. Soaking Time (Days)	Cumulative Oil Production (STB)	Cumulative Water Production (bbl)	Avg. Cycle Duration (Days)	Avg. Uptime (%)	Avg. Oil Rate (STBPD)	Oil/Steam Ratio
CHOPS	--	--	264,006	21,346	309	94	121	--
1	457,470	33	2,830,254	526,414	370	86	211	6.2
2	373,217	19	1,302,752	465,189	268	91	169	3.5
3	406,378	18	1,030,439	782,467	297	96	129	2.5
4	214,618	19	658,455	354,905	302	95	123	3.1
5	54,159	14	47,376	34,982	355	99	172	0.9

The Current daily average oil production rate is 8,000 STBPD (CSS: 130 STBPD/Well, CHOPS: 65 STBPD/well) the CSS recorded good result which motivate to complete the development strategy by completing remaining cycles and converted into steam flooding which had been studied and carried out in 2011

4.3 Analyze and review the actual Steam intensity distribution among each layer for FNE field and compare :

FNE field is located in Northeast of Fula sub basin, 9 Km from Fula CPF 3D Area: 72 km^2 Started production on Oct 1, 2009

4.3.1.1. Formation and structure :

FNE field is a horst structure confined by two major normal faults with uniform oil-water contacts (Fig.1). B reservoir is the major producing series in FN field, taking 85% of total reserves. Burial depth of B reservoir is 1250 m on average. Pressure gradient of B pool is rather low

The main formations in FNE : Aradeiba D, Bentiu-1A, Bentiu-1B, Bentiu-1C, Bentiu-1D.

FNE-1, FNE-2, FNE-10 and FNE North block are regarded as the main blocks.

4.3.1.2. Reservoir characteristics:

Pressure & Temperature System:

- Avg. Press: 567 psi
- Avg. Temp: 43.9 ºC

Reservoir Fluid Properties:

Conventional heavy oil in both Aradeiba & Bentiu

Table No.(4-2) :Crude and Water Properties

Crude Properties	
API	17.7
TAN (mg KOH/L)	5.4
Pour point (ºC)	4
Viscosity@29ºC (cp)	3800
Viscosity@50ºC (cp)	727.33
Water Properties	
Water Type	$NaHCO_3$
PH value	7.64
Salinity (mg/L)	1067.82
Chloride Cont. (mg/L)	524.66

Reservoir Characterization:

- Aradeiba sand average thickness: 5 m
- Bentiu sand average thickness: 86 m

B reservoir is a sequence of massive and continuous sandstones interbedded with shales, deposited in braided river environment, with porosity ranging from 26% to 34% and oil saturation ranging from 61% to 86% with permeability above 3000 md. B reservoir is subdivided into four sand units named as B1a, B1b, B1c and B1d with barriers among those four units. Average net pay thickness of B reservoir is 30 to 40 m and average Net to Gross (NTG) is 0.8. Bentiu reservoir is the main hydrocarbon accumulation formation and 263 MMSTB OOIP is calculated.

- Average porosity: 27%

Field development:

FNE Oilfield exploration began in 1989, the first well FNE-1 has been drilled In 2005, it was found one of the largest heavy oil fields in Petroenrgy (PE) block 6 Area.

Then immediately the development and research began. The oilfield development Case was completed by Beijing Research Institute of Petroleum Exploration and Development in May 2008.

FNE oilfield began production test in Oct 2009, came on line in Jun 2010, kept stable oil production rate 6198STB/D in Oct 2010, peaked 7469STB/D in Jul 2011. As of April 21, 2014 the cumulative oil is 7.3 MMSTB and RF-to-Date is 2.7%. To increase the recovery factor of FNE field, as well as to sustain the production performance of Block-6 and to overcome the issue of small drainage area for each well due to the short heated radius, a new CSS and/or steam flood pattern is proposed composed of 10 new thermal wells to be drilled plus 4 existing wells

The oilfield was put into development in June 2010. By May 2011 before the steam flooding study started, a total of 43 wells had been drilled, including one horizontal well; 36 wells have been put into operation, of which 23 wells are producing as cold, and 13 wells for steam stimulation; 33 wells were opened, with a daily oil production of 5722bbl, a daily fluid production of 6097bbl, a water cut of 6.1%, the total Orignial Oil In place (OOIP) is 298.7 MM STB, and the up to date recovery factor of reserves is 0.75%. The average daily production for steam stimulation is 2 to 3 times of the cold wells.

4.3.1.3. FNE model:

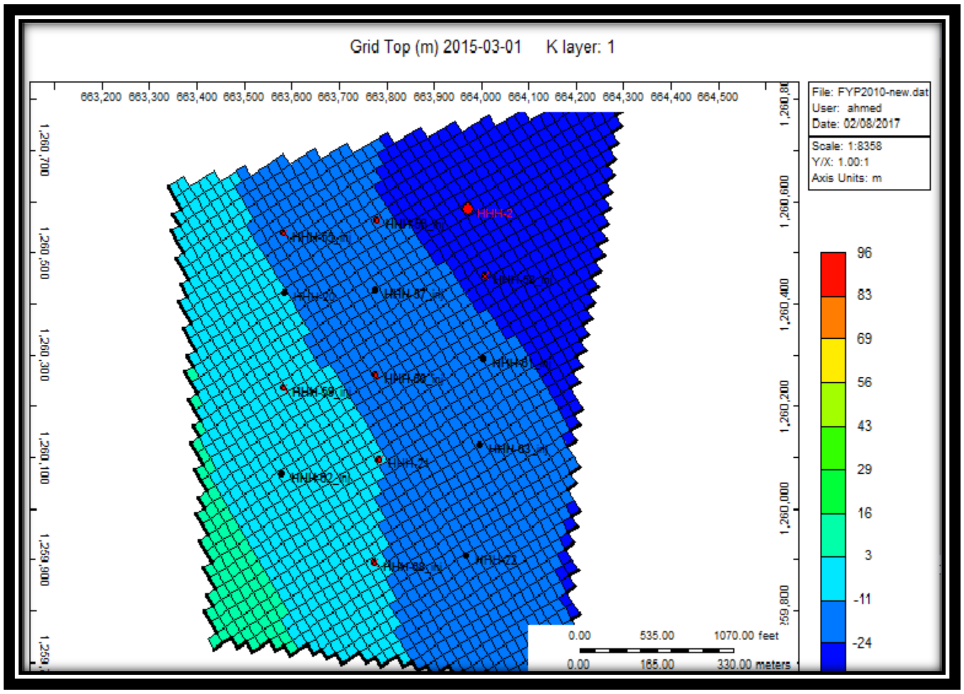


Figure (4-2): FNE Field Model Using CMG-Builder

Figure (4-2) shows the general shape of the CMG software of FNE field thermal model using CSS simulation consist of wells HHH-2.HHH-20.HHH-21.HHH-22,HHH-55,HHH-55_inj,HHH-56,HHH56_inj,HHH-57,HHH-57_inj,HHH-58,HHH-58_inj,HHH-59,HHH-59_inj,HHH-60,HHH-60_inj,HHH-61,HHH-61_inj,HHH-62,HHH-62_inj,HHH-63,HHH-63_inj,HHH-68,HHH-68_inj.

4.3.1.4. Grid Thickness :

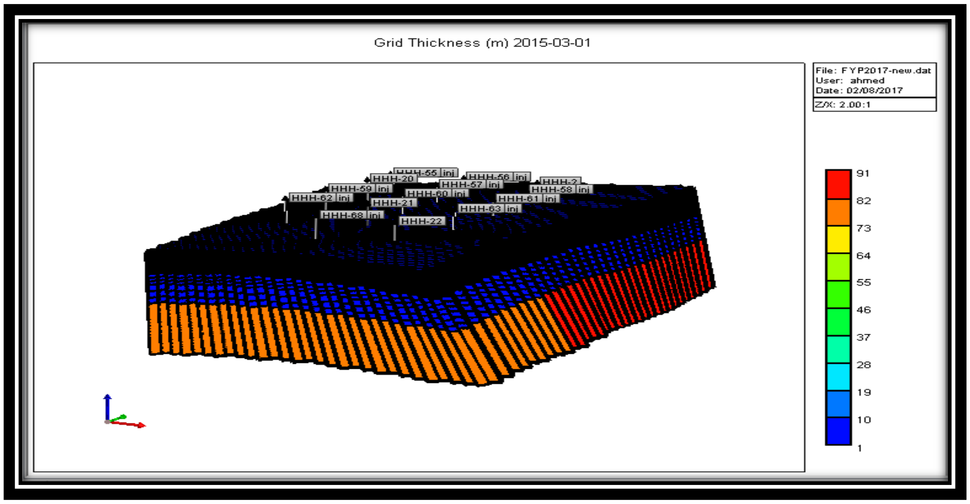


Figure (4-3): Grid Thickness Distribution in the FNE Field

Figure (4-3) shows that the model consist of 87291 grids 61x53x27(I,J,K) with single porosity and grid thickness of different type of formation starting with bantio which divided in three B1a from 1-10 and B1b 10-20 and B1c 21-23 and B1d 24-26

4.3.1.5. Porosity Distribution :

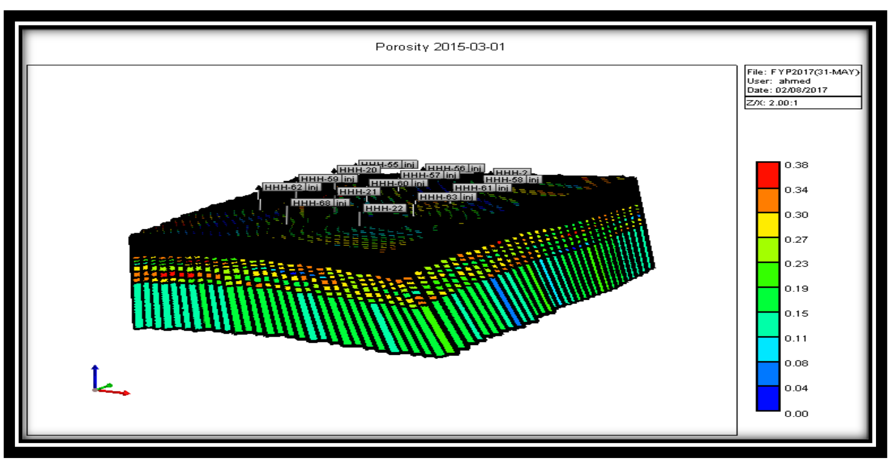


Figure (4-4): The Porosity Distribution

The figure(4-4) represent the porosity distribution among B reservoir which is a sequence of massive and continuous sandstones interceded with shale's , deposited in braided river environment, with porosity ranging from 26% to 34% and oil saturation ranging from 61% to 86%

4.3.1.6. permeability Distribution :

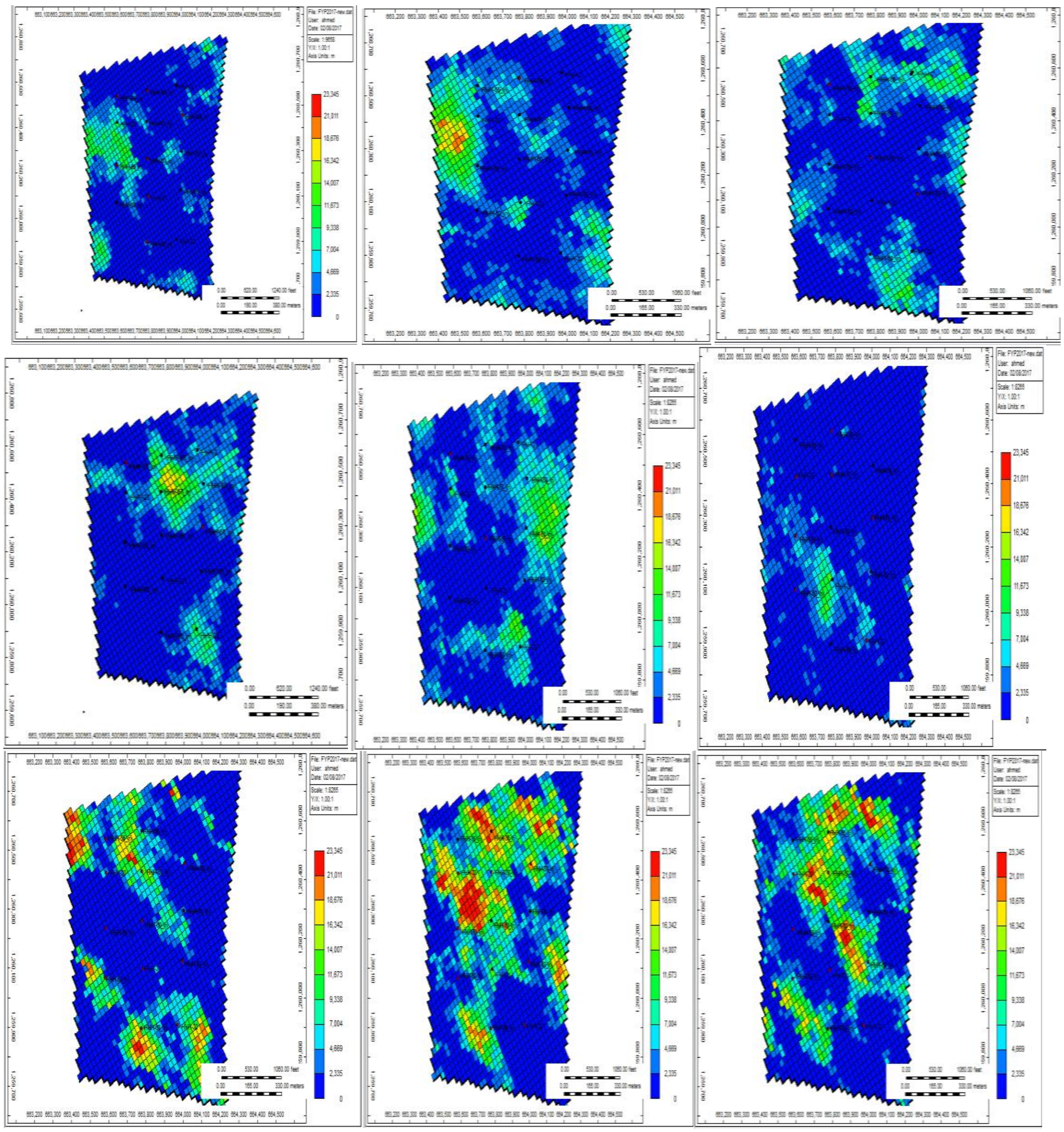


Figure (4-5) : Permeability Distribution Across all the Opened Layers in the HHH-61

These figure above shown the permeability's across different layers: layer 1 sector B1a, layer 3 sector B1a, layer 5 sector B1a, layer 6 sector B1a, layer 7 sector B1a, layer 10 sector B1a, layer 13 sector B1b, layer 14 sector B1b, layer 15 sector B1b, layer 16 sector B1b.

4.3.1.7. Rock Properties :

Click on the " Specify Property " button (top middle of screen) to open the General Property Specification spreadsheet as shown below in Figure (4-6) and enter the data of top grid, grid thickness, permeability (I,J,K), net pay and oil saturation.

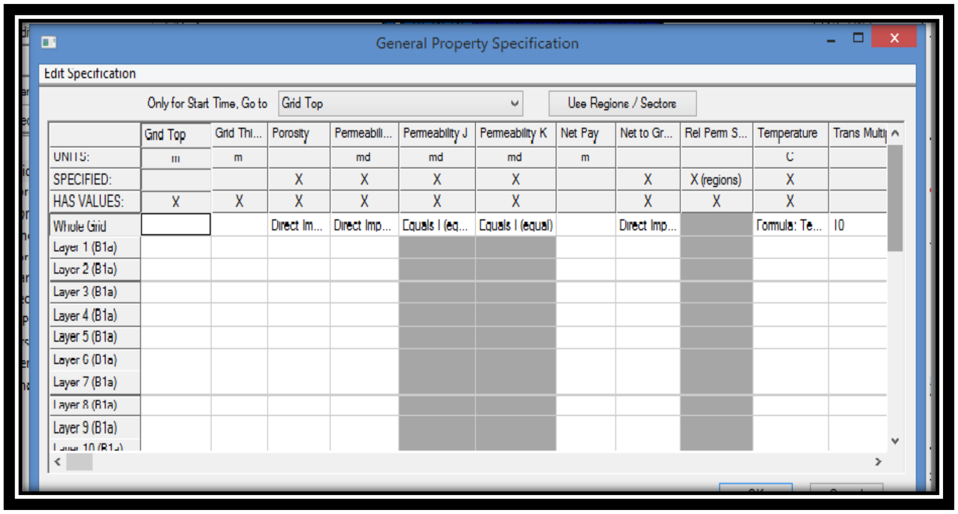


Figure (4-6): General Property Specification Table

4.3.1.8 Relative Permeability:

Click the Rock-Fluid tab in the tree view which located on the left side of the screen. Double click on Rock Fluid Types in the tree view. A window will open. Click on the button and select New Rock Type, then entering the relatives permeability's table as shown in Figure for five types of rocks.

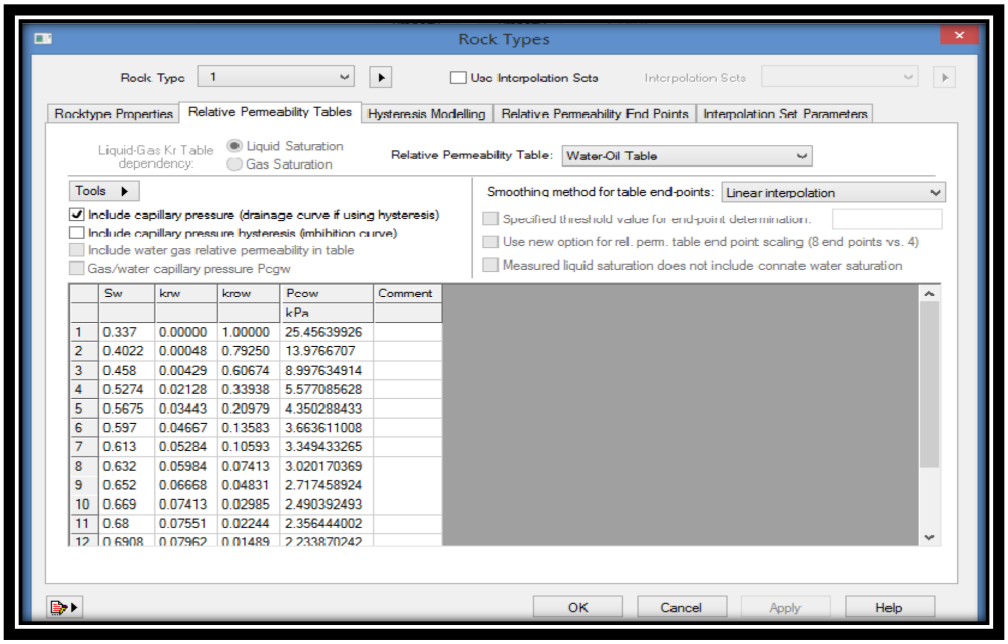


Figure (4-7): Rock Type 1

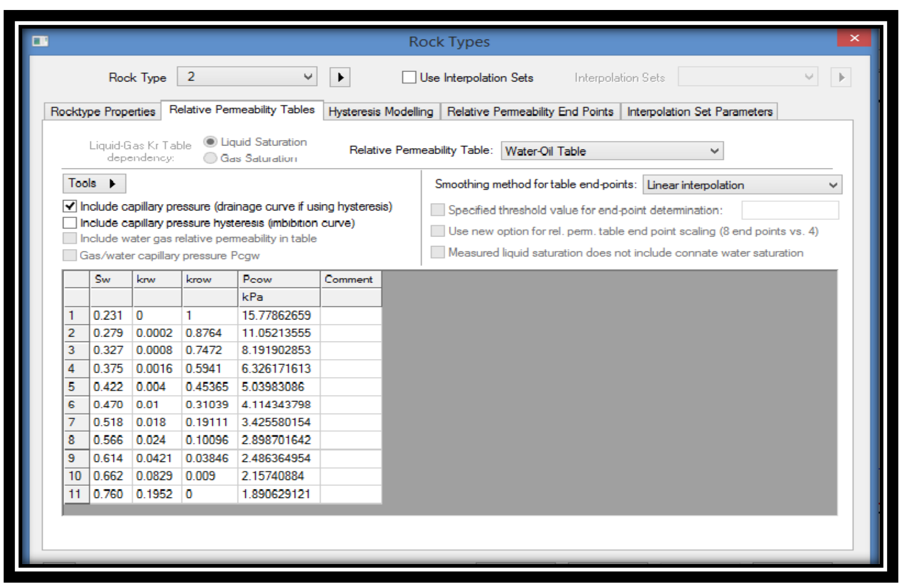
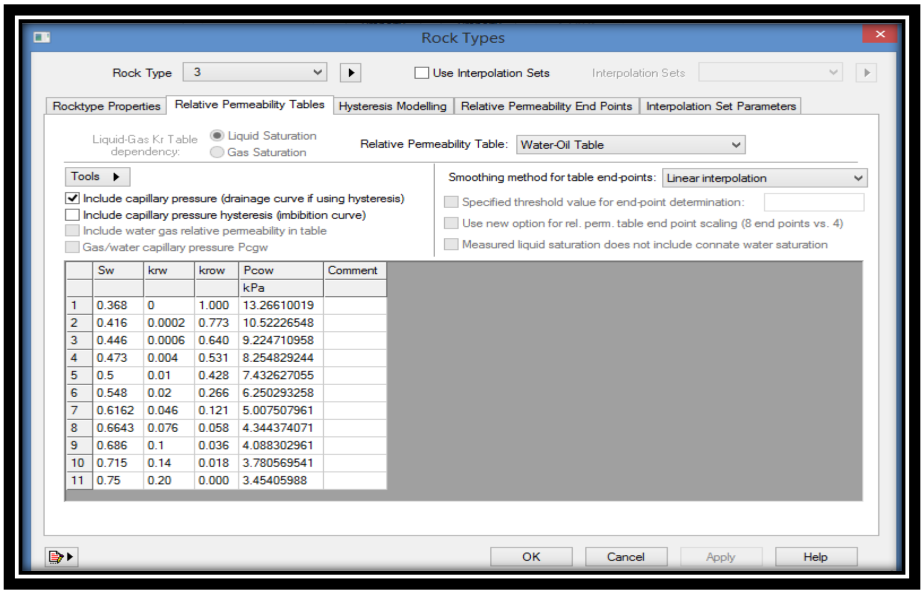
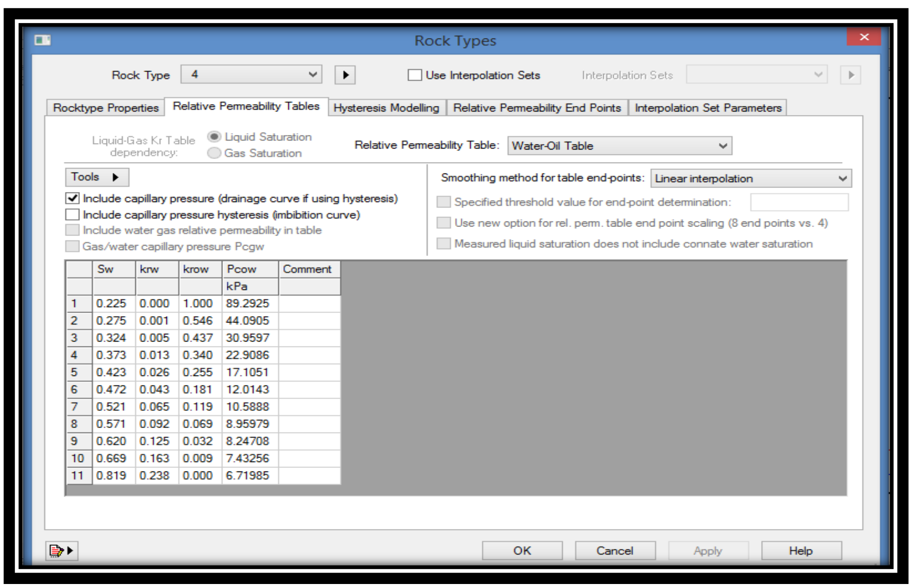


Figure (4-8): Rock Type 2



	Sw	krw	krow	Pcow (kPa)	Comment
1	0.368	0	1.000	13.26610019	
2	0.416	0.0002	0.773	10.52226548	
3	0.446	0.0006	0.640	9.224710958	
4	0.473	0.004	0.531	8.254829244	
5	0.5	0.01	0.428	7.432627055	
6	0.548	0.02	0.266	6.250293258	
7	0.6162	0.046	0.121	5.007507961	
8	0.6643	0.076	0.058	4.344374071	
9	0.686	0.1	0.036	4.088302961	
10	0.715	0.14	0.018	3.780569541	
11	0.75	0.20	0.000	3.45405988	

Figure (4-9): Rock Type 3



	Sw	krw	krow	Pcow (kPa)	Comment
1	0.225	0.000	1.000	89.2925	
2	0.275	0.001	0.546	44.0905	
3	0.324	0.005	0.437	30.9597	
4	0.373	0.013	0.340	22.9086	
5	0.423	0.026	0.255	17.1051	
6	0.472	0.043	0.181	12.0143	
7	0.521	0.065	0.119	10.5888	
8	0.571	0.092	0.069	8.95979	
9	0.620	0.125	0.032	8.24708	
10	0.669	0.163	0.009	7.43256	
11	0.819	0.238	0.000	6.71985	

Figure (4-10): Rock Type 4

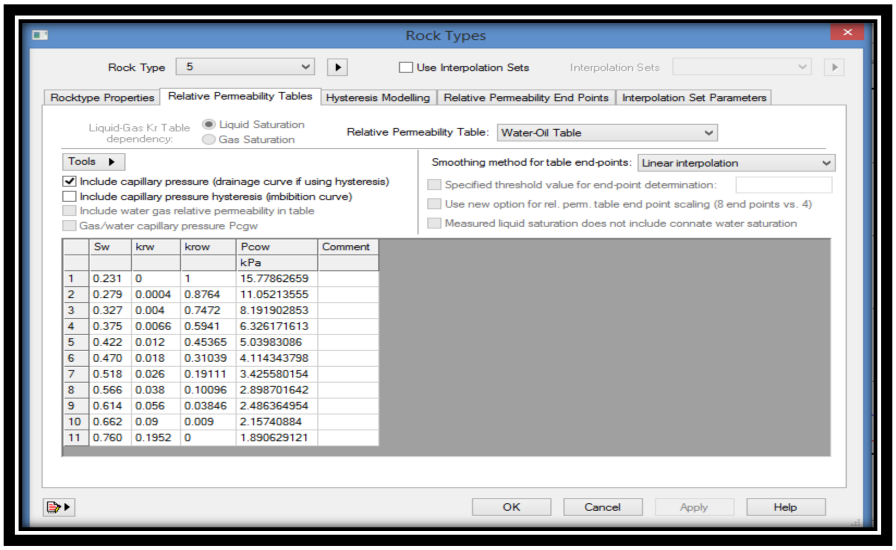


Figure (4-11): Rock Type 5

4.3.1.9. The Initial conditions of the reservoir:

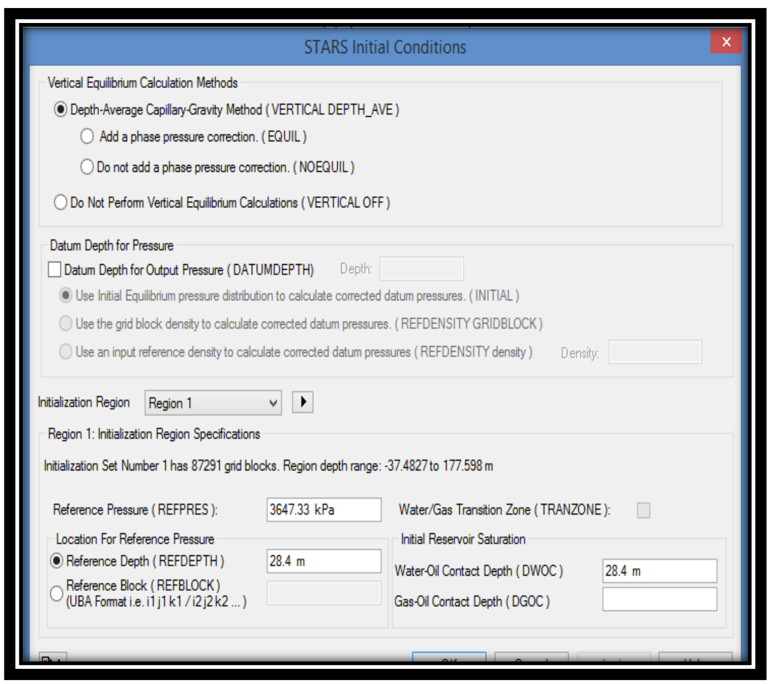


Figure (4-12):STARS Initial Condition

Click the Initial conditions on the tree view of Builder. Double click on Initial Conditions. Then typing the values for reference pressure(3647.33 KPa), reference depth and for water-oil (28.4)contact as shown in Figure (4-12).

4.3.1.10. Injected fluid properties:

Click on the "Well & Recurrent" on the tree view of Builder. And clicking on the "Wells", where there is two wells .Double clicking on the " HHH-55-inj " and then go to "Injected fluid" and choosing Water as injection fluid. Enter the water composition as 1.0 for component Water. Enter the steam Temperature and steam quality as in Figure A – 5, and apply for other injection wells .

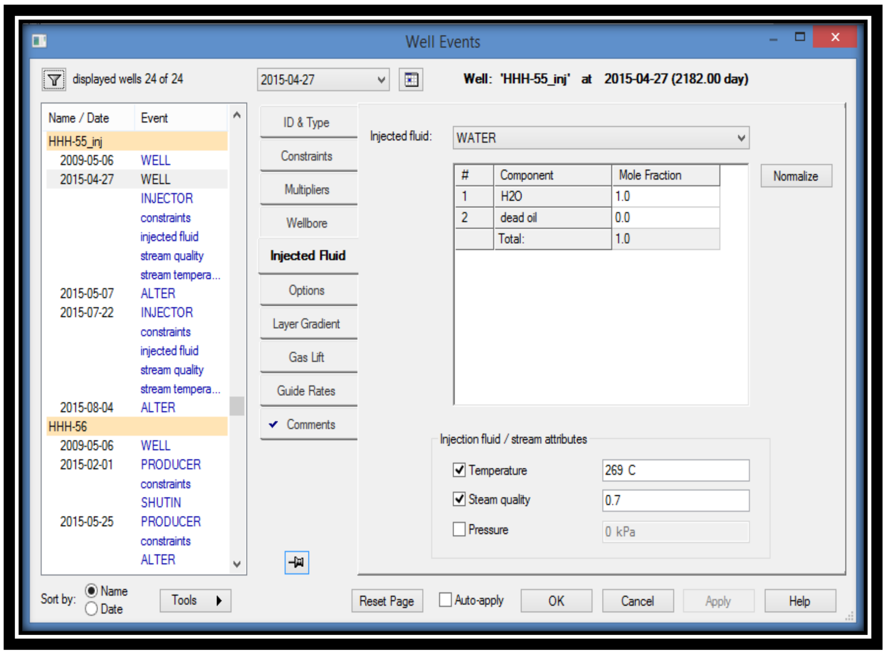


Figure (4-13) : Define the Inject Fluid Properties

` 4.3.1.11.Time line view of recurrent data:

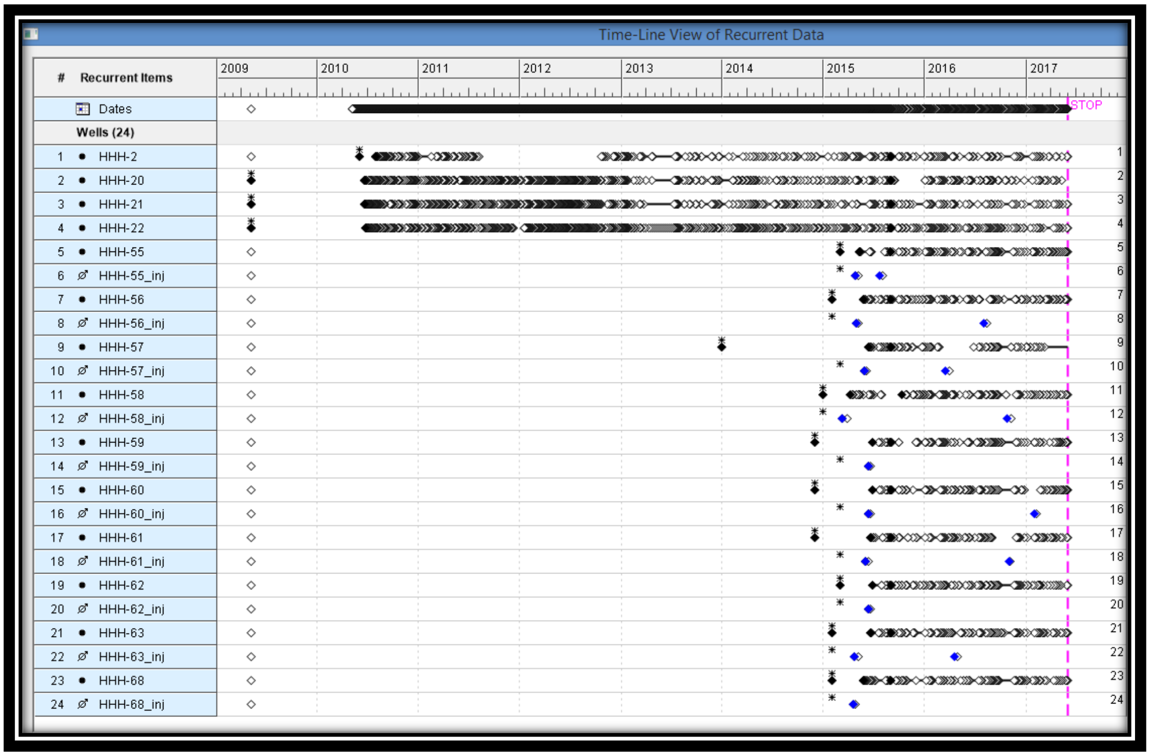


Figure (4-14): The Time - Line View of Recurrent Data

Figure (4-14) represent the time - line view of recurrent data. The model consist of 14 wells, 10 of the wells are hot and the remaining four are cold , The production mainly started at May 2010 HHH-2 HHH-20 HHH-21 HHH-22 were in the production process without applying any CSS yet , The first CSS applied were in well HHH-55_inj at May 2015 and the 2nd CSS were in August 2015, the well HHH-56_inj the first CSS were applied at May 2015 while the 2nd cycle were at August 2016, The first cycle in HHH-57_inj were at June 2015 and the 2nd cycle started at April 2016, Then the well HHH-58_inj the 1st cycle were at March 2015 and the 2nd were at October 2016, and at July 2015 the first and only cycle were applied at HHH-59_inj, The well HHH-60_inj the first CSS applied were at July 2015 and the 2sd at March 2017, At Jun 2015 the first cycle were applid in HHH-61_inj and the 2nd were at Nov. 2016, while the well HHH-62_inj the 1st and only cycle were applied at July 2015, and at May 2015 the 1st cycle were applied in well HHH-63_inj and the 2nd were at May 2016, and lastly the well HHH-68_inj the 1st and only CSS applied on it were at May 2015 . As it showen these time line view represent the data till May 2017.

4.3.2. HHH-61_inj :

FNE-61 is one of the thermal development wells in Fula North East Block targeting Aradeiba and Bentiu reservoirs to exploit heavy oil.

FNE-61 was spaded in on Dec.8.2014 and rig was released on Dec.15.2015.

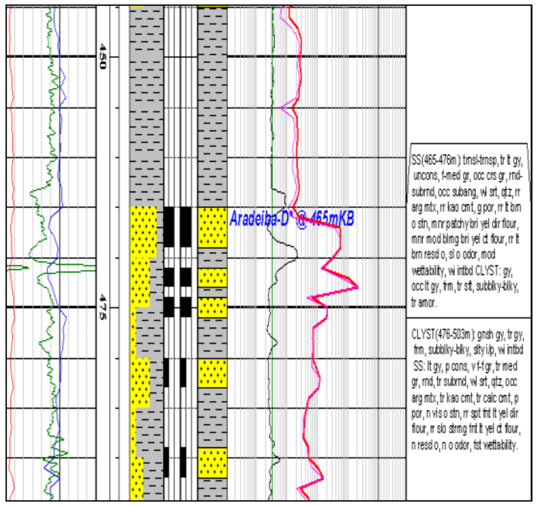


Figure:(4-15): FNE-61 Master Log(Aradeiba)

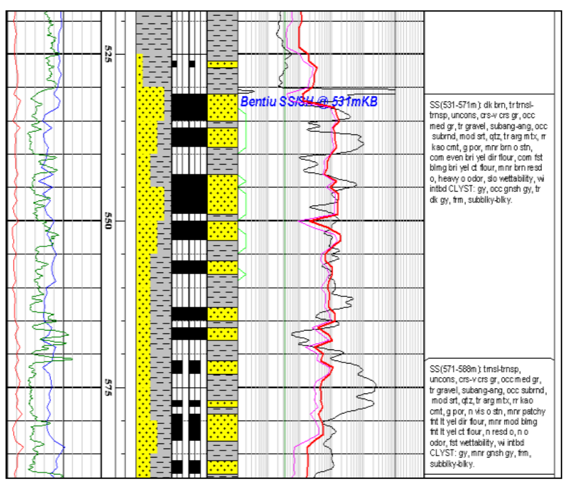


Figure (4-16):FNE-61 Master Log (Bentiu)

4.3.2.1.Well completion and string :

The table below represent the casing data flowed by two figure represent the steam completion string

Table (4-3) Casing Data For Well HHH-61_I

Casing Data:-									
Casing	**OD**		**ID**	**Thick (mm)**	**Grade**	**Weight**		**Casing depth**	**Casing shoe Depth**
	in	**Mm**	**(mm)**			**Kg/m**	**Ib/ft**	**(m)**	**(m)**
Surface	10-3/4"	273.05	255.27	8.89	K55	60.27	40.50	0 - 66.18	66.18
Production	7"	177.80	157.08	10.36	**N80**	43.16	29.00	0-695.01	695.01

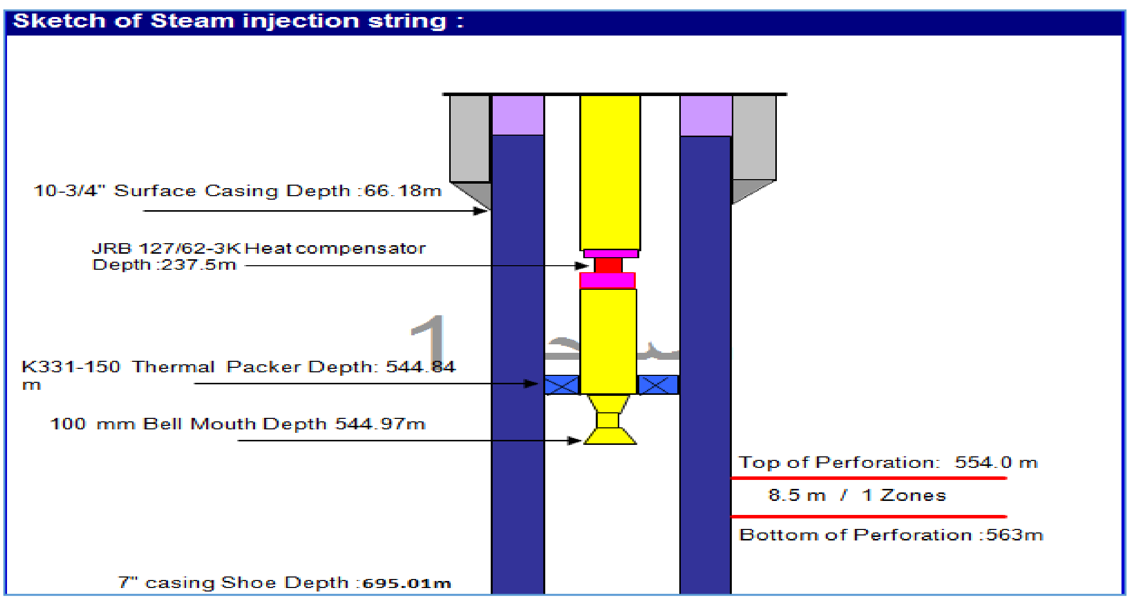


Figure No (4-17) : HHH-61_Inj Steam Injection String

4.3.2.2. Injection Parameters :

1. Injection rate: 192 t/d; (As large as possible under injection capability of boiler).
2. Injection Intensity: 140t/m.
3. Total amount per cycle: 1190 ton. (to be updated by RE).
4. Steam quality at wellhead: >75%.
5. Steam Injection Pressure of wellhead : <1378Psi.
6. Fracture Pressure gradient: 285.56Psi/100m.
7. Formation Fracturing Pressure: 1453.0 -1504 Psi.

4.3.2.3. the perforation :

The tables below represnt the perforation interval for well HHH-61_inj and the technique uesd (Gun)with specification targeting the Bantiu formation.

Table (4-4) Perforation Interval

Zone	**Zone**	**Perforation Intervals**		**Perf. Thickness**	**Net Pay**	**VCL**	**PHIE**	**SW**	**Result**
13	**Bentiu**	554.5	563	8.5	8.76	9	30	27	**Oil**
	Total			8.5					

Table (4-5) Gun Specification.

Formation	Bentiu
Perforation Interval(mKB)	554.5-563.0
Perforate thickness(m)	8.5 m
Gun Type	DP127-32-45
Shot Density	32 shots per meter
Phasing	45^o
Weight of Charge	25g
Charge Name	DP36RDX-3

By using the model entering the

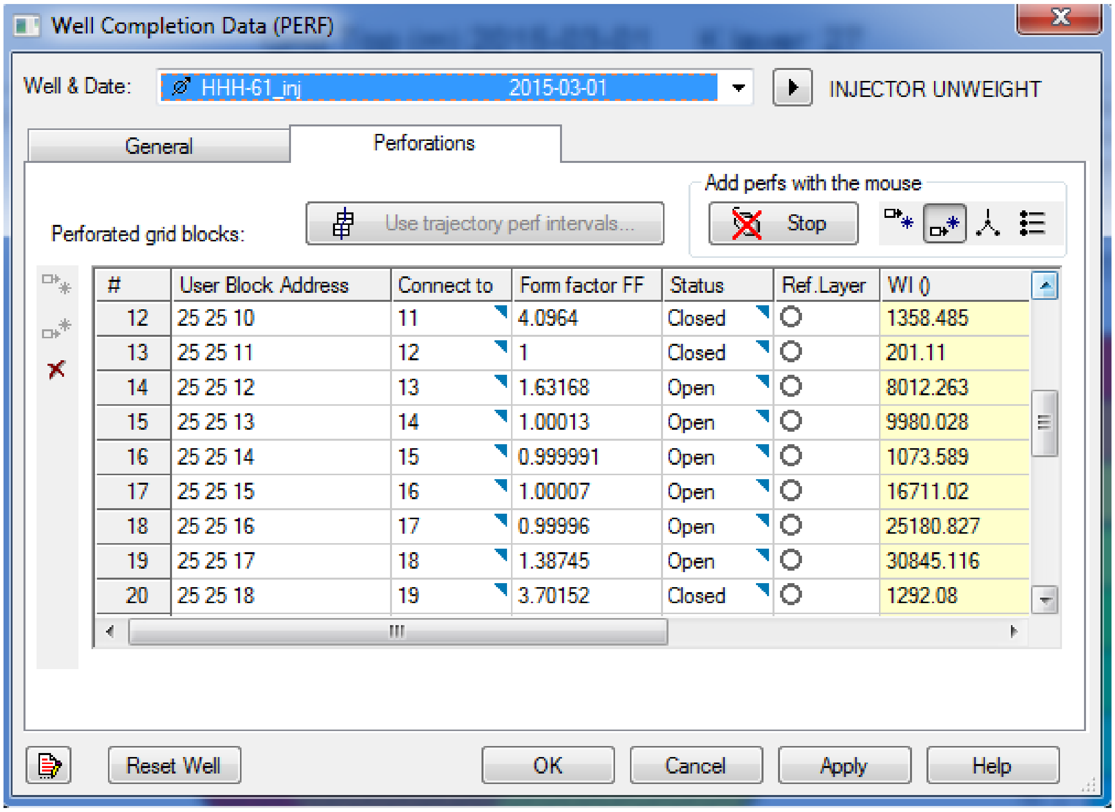


Figure (4-18): The Perforation of Well HHH-61_inj

Figure (4-15) show the perforation of the well which is opened at Block 25 25 12, 25 25 13 , 25 25 14, 25 25 15, 25 25 16, 25 25 17

The model was run according to designed data and sensitivity analysis is done through calculating the amount of steam that injected into the layer and compared with simulator result.

4.3.2.4 Analysis of non uniform steam distribution :

In this analysis we are going to calculate the amount of steam for each zone in actual and be the design and model and then compare the actual calculations with the assumed calculations and find out what is the reason of non uniform steam distribution .

The amount of steam injected in the cycle for well (HHH-61_inj) can be calculated using.

Volume (ton)= injection rate *injection period

This result is used later to calculate the designed steam intensity in table (4-4) and there for the amount of steam injected for each layer ,also by using the model we figure out the amount of steam injected for each layer in figure (4-26) Depending on this relation below:

The total volume (ton) = steam intensity (t/m) * thickness (m)

- Assumed design calculations :-

Table (4-6) :Design Calculation for HHH-61

Iayer	Thickness (m)	Steam Mass (Ton) Cycle 1	Steam Mass (Ton) Cycle 2	Total
25 25 12	0.634	88.76	88.76	177.52
25 25 13	1.784	249.76	249.76	499.52
25 25 14	1.783	249.62	249.62	499.24
25 25 15	1.782	249.48	249.48	498.96
25 25 16	1.782	249.48	249.48	498.96
25 25 17	0.735	102.9	102.9	205.8
	8.5	1190	1190	2380

Table (4-7): Design parameters for HHH-61

	Cycle 1	Cycle 2	total
thickness(m)	8.5	8.5	
inj rate(m3/d)	192	192	
inj volume(m3)	1190	1190	2380
intensity(t/m)	140	140	280
duration(d)	6.197916667	6.197916667	
Temperature	270	276	

- Assume field data calculation :

Table(4-8) : Field Calculation for HHH-61

layer	Thickness (m)	steam mass(Ton)cycle 1	steam mass(Ton)cycle 2	Total
25 25 12	0.634	88.760	71.605	160.365
25 25 13	1.784	249.760	201.487	451.247
25 25 14	1.783	249.620	201.374	450.994
25 25 15	1.782	249.480	201.261	450.741
25 25 16	1.782	249.480	201.261	450.741
25 25 17	0.735	102.900	83.012	185.911
	8.5	1190	960	2150

Table (4-9) : Field Parameters for HHH-61

	cycle 1	cycle 2	total
thickness(m)	8.5	8.5	
inj rate(m3/d)	192	192	
inj volume(m3)	1190	960	2150
intensity(t/m)	140	112.941	252.941
duration(d)	6.198	5	
temperature	272.69	280.39	

- Figure Out The Model Result :

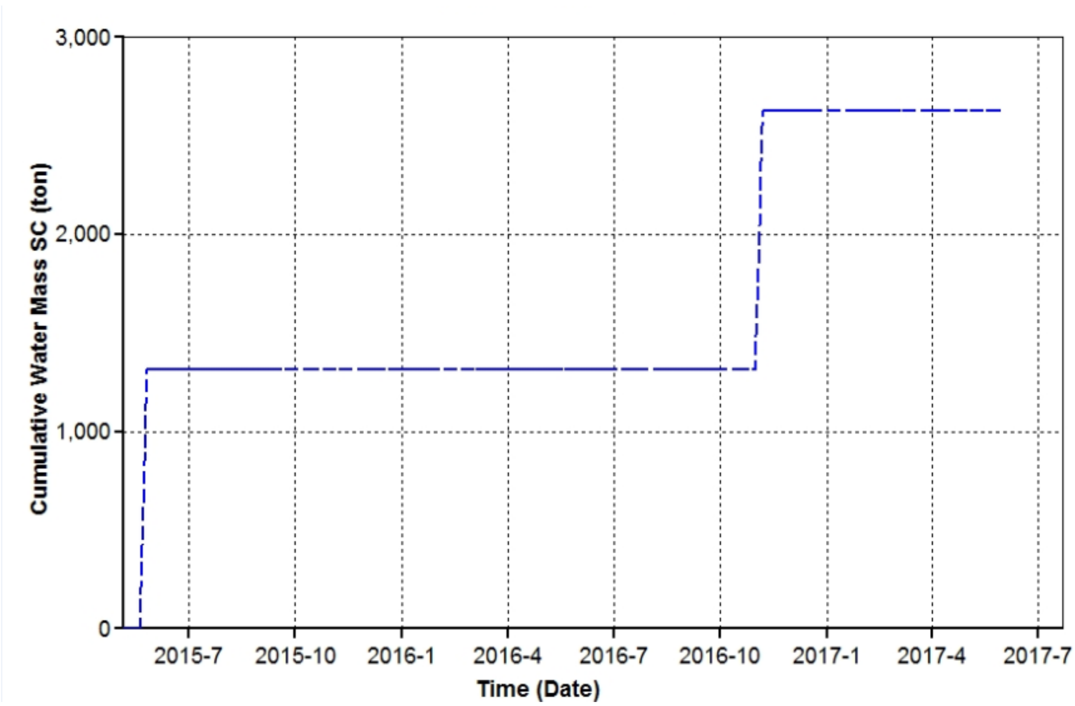


Figure (4-19): Cumulative Water Mass SC (Ton) Injected During the Two Cycle.

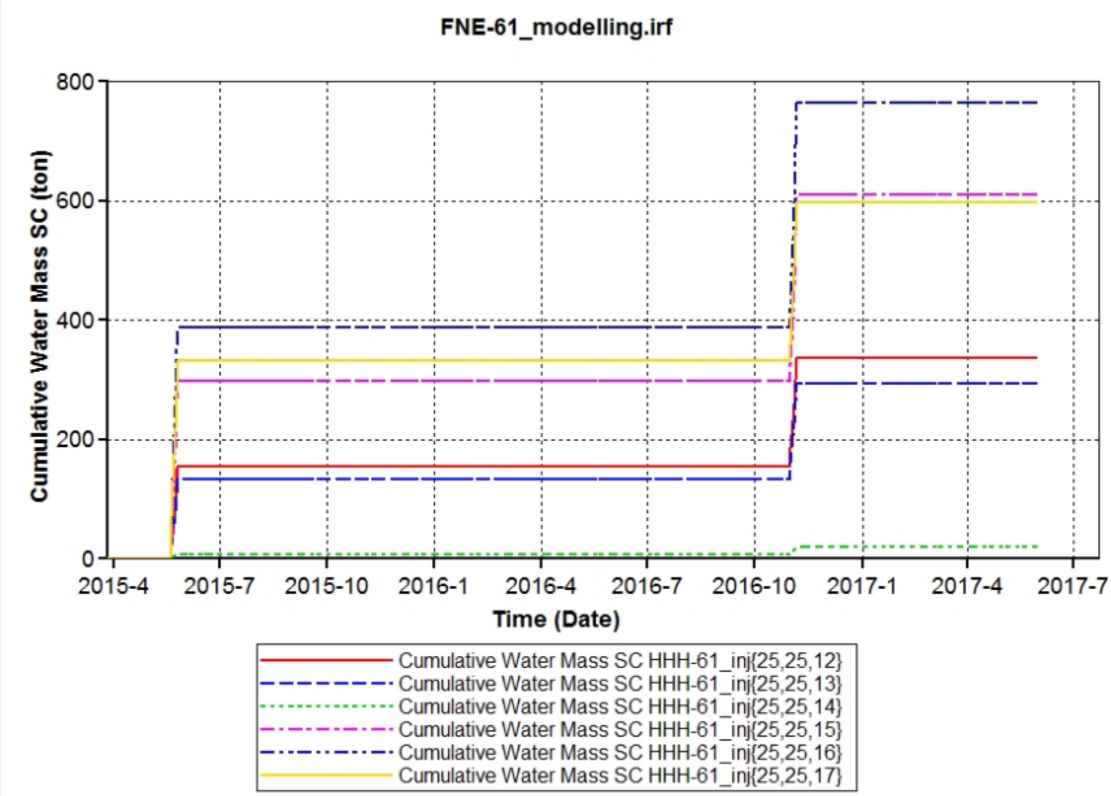


Figure (4-20): Cumulative Water Mass SC (Ton) for Each Layer Alone

Table No.(4-10) : Model result in tabulated form HHH-61

layer	steam mass (Ton) cycle 1	steam mass (Ton) cycle 2	total
25 25 12	140.995	164.506	305.501
25 25 13	120.146	146.466	266.612
25 25 14	6.22115	12.24405	18.4652
25 25 15	269.54	284.676	554.216
25 25 16	351.889	341.826	693.715
25 25 17	301.335	240.407	541.742
	1190.12615	1190.12505	2380.25

Table (4-11) : Model Parameters for HHH-61

	cycle 1	cycle 2	total
inj reat(m3/d)	192	192	
inj volume(m3)	1190.126	1190.125	2380.251
intensity(t/m)	140	140	280
duration(d)	6.198572917	6.198567708	
temperature	270	276	

From CSS test for near well HHH-64_inj it found that the top layer adsorb 72% and considering the same distribution in well HHH-61_inj , so the first two layer adsorbed 72% as (HHH-64_inj) based on this a wide different in steam distribution through layers was observed , by comparing the designed calculation and Modelling with actual and calculating the adsorption percentage the

The design calculation in the tables (4-8) above shows the assumed designed volume per ton for each layer that should be absorbed depending on the intensity , while the figure (4-18) and table (4-10) represent model result using the design parameters and from

Table (4-12) : Compare Between The Model with Actual In first Cycle for HHH-61

First cycle							
		Modelling			actual		
Layer	Thickness(m)	Steam mass (Ton)	Intensity (Ton/m)	Adsorption %	steam mass(Ton) actual	Intensity (Ton/m)	Adsorption %
25 25 12	0.634	140.995	63.643	11.8%	130.5623	205.9343	11.0%
25 25 13	1.784	120.146		10.1%	367.3868		30.9%
25 25 14	1.783	6.22115		0.5%	367.1809		30.9%
25 25 15	1.782	269.54	174.36	22.6%	102.34	57.42985	8.6%
25 25 16	1.782	351.889		29.6%	102.34		8.6%
25 25 17	0.735	301.335	409.98	25.3%	120.19	163.5238	10.1%
total	8.5	1190.126		100.0%	1190		100.0%

Table (4-13) : Compare Between The Model with actual In Second Cycle for HHH-61

Second cycle							
		Model			actual		
layer	Thickness (m)	Steam mass (Ton)	Intensity (Ton/m)	Adsorption %	steam mass(Ton) actual	Intensity (Ton/m)	Adsorption %
25 25 12	0.634	164.51		11.0%	105.3276		25.3%
25 25 13	1.784	146.47	76.938	30.9%	296.3793	166.1319	33.7%
25 25 14	1.783	12.244		30.9%	296.2131		14.6%
25 25 15	1.782	284.68	175.79	8.6%	82.56	46.32997	12.3%
25 25 16	1.782	341.83		8.6%	82.56		2.3%
25 25 17	0.735	240.41	327.08	10.1%	96.96	131.9184	11.7%
total	8.5	1190.1		100.0%	960		100.0%

Table (4-14) Comparing Design with Actual in first cycle HHH-61

First cycle						
		design		Actual		
Layer	Thickness(m)	Steam mass (Ton)	Intensity (Ton/m)	steam mass(Ton) actual	Intensity (Ton/m)	Adsorption %
25 25 12	0.634	88.76	140	130.5623		11.0%
25 25 13	1.784	249.76		367.3868	205.9343	30.9%
First cycle25 25 14	1.783	249.62		367.1809		30.9%
25 25 15	1.782	249.48		102.34	57.42985	8.6%
25 25 16	1.782	249.48		102.34		8.6%
25 25 17	0.735	102.9		120.19	163.5238	10.1%
Total	8.5	1190		1190		100.0%

Table (4-15) Comparing Actual with Design in second cycle HHH-61

Second cycle						
		Design		Actual		
Layer	Thickness(m)	Steam mass (Ton)	Intensity (Ton/m)	steam mass(Ton) actual	Intensity (Ton/m)	Adsorption %
25 25 12	0.634	88.76	140	105.3276		25.3%
25 25 13	1.784	249.76		296.3793		33.7%
25 25 14	1.783	249.62		296.2131	166.1319	14.6%
25 25 15	1.782	249.48		82.56		12.3%
25 25 16	1.782	249.48		82.56	46.32997	2.3%
25 25 17	0.735	102.9		96.96	131.9184	11.7%
Total	8.5	1190		960		100.0%

The effect of non uniform distribution on production can be shows by Modelling the actual field data in the simulator and comparing .Its observed that the volume injected during second cycle in actual is less than the designed (960 ton) lead to decease the intensity to (112.94ton/m) from (140ton/m) ,

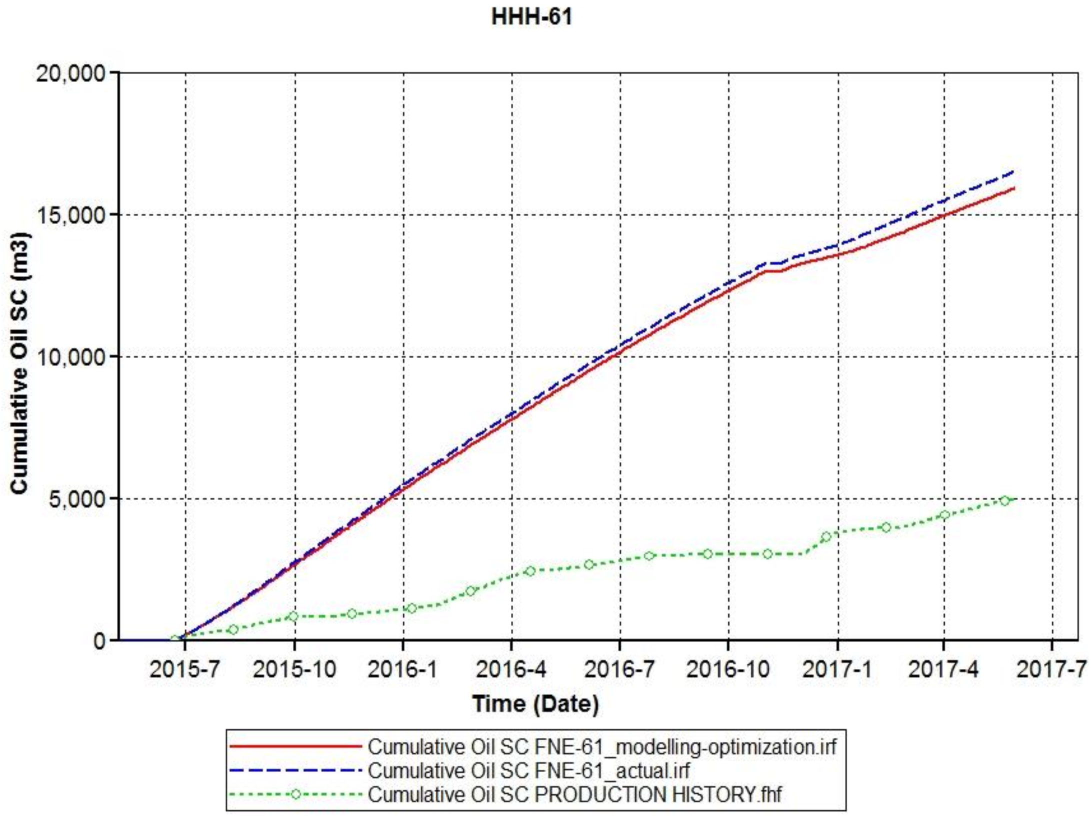


Figure (4-21): Represent Cumulative Production Using Injection Volume (960)and (1190) and History Match Second Cycle for HHH-61

4.3.2.5. Optimizing injection rate :

Different scenarios were constructed to see the effect of injection rate on steam distribution which related to oil rate , the injection rate was increased to 212 and 232 and decreased to 172 and 152 to find the optimum that perform high oil rate

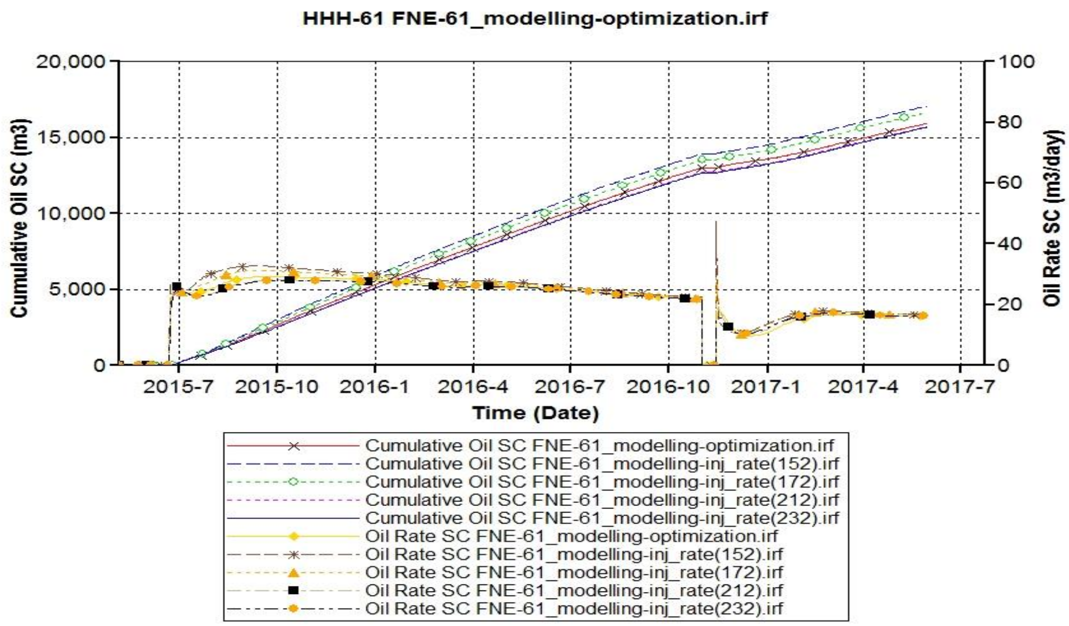


Figure (4-22) :optimum injection rate for HHH-61

4.3.3. HHH-38_inj:-

one of the thermal development wells in Fula North East Block targeting Aradeiba and Bentiu reservoirs to exploit heavy oil.

The first cycle was in 29 august 2009 and start production 1 October 2009 for two years ,the second cycle was in 8 March 2011 and put into production for less than tow years ,the third cycle started 14 December 2012 and put into production for three years ,the fourth cycle was in 1 September 2015 the figure below represent the well timeline view

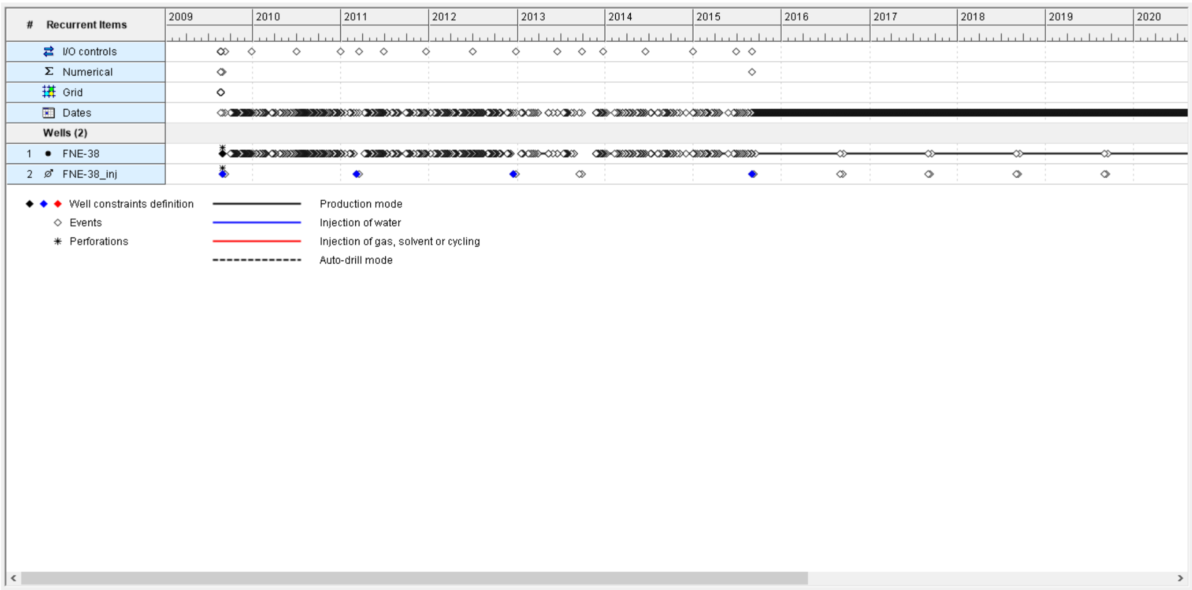


Figure (4-23):Well HHH-38_Inj Time Line View

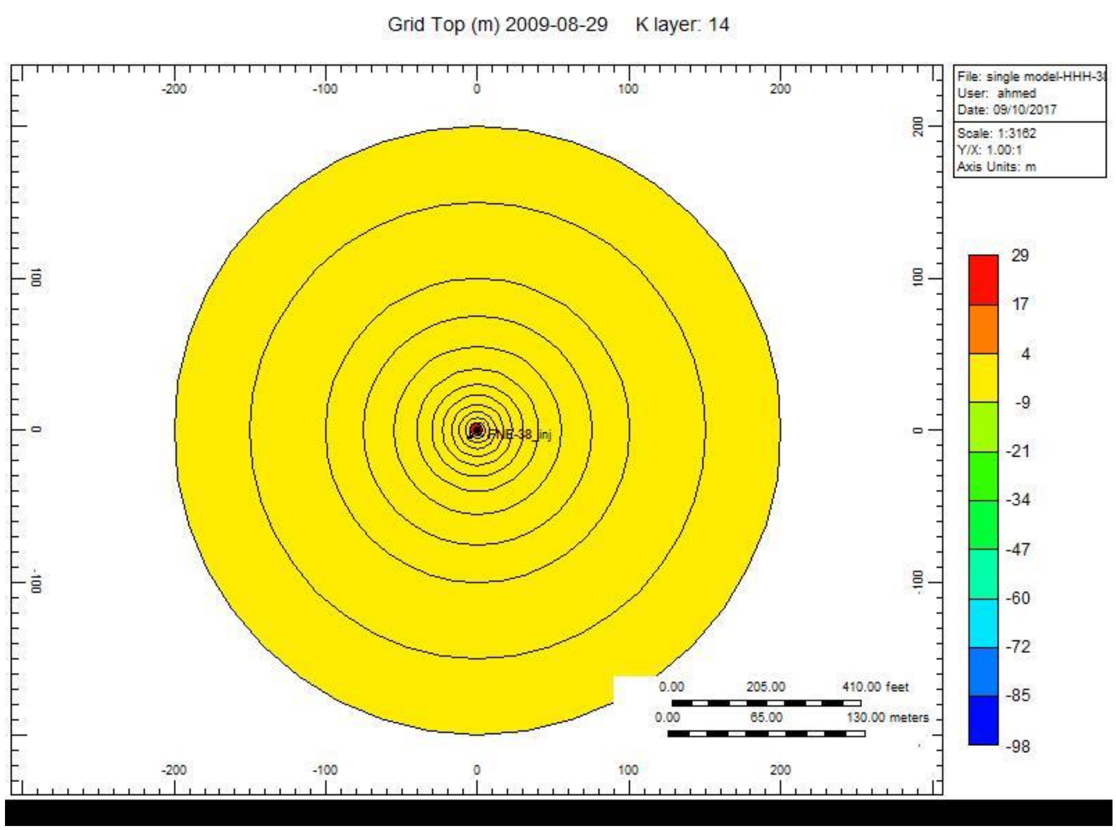


Figure (4-24) : Grid Top for Well HHH-38_Inj

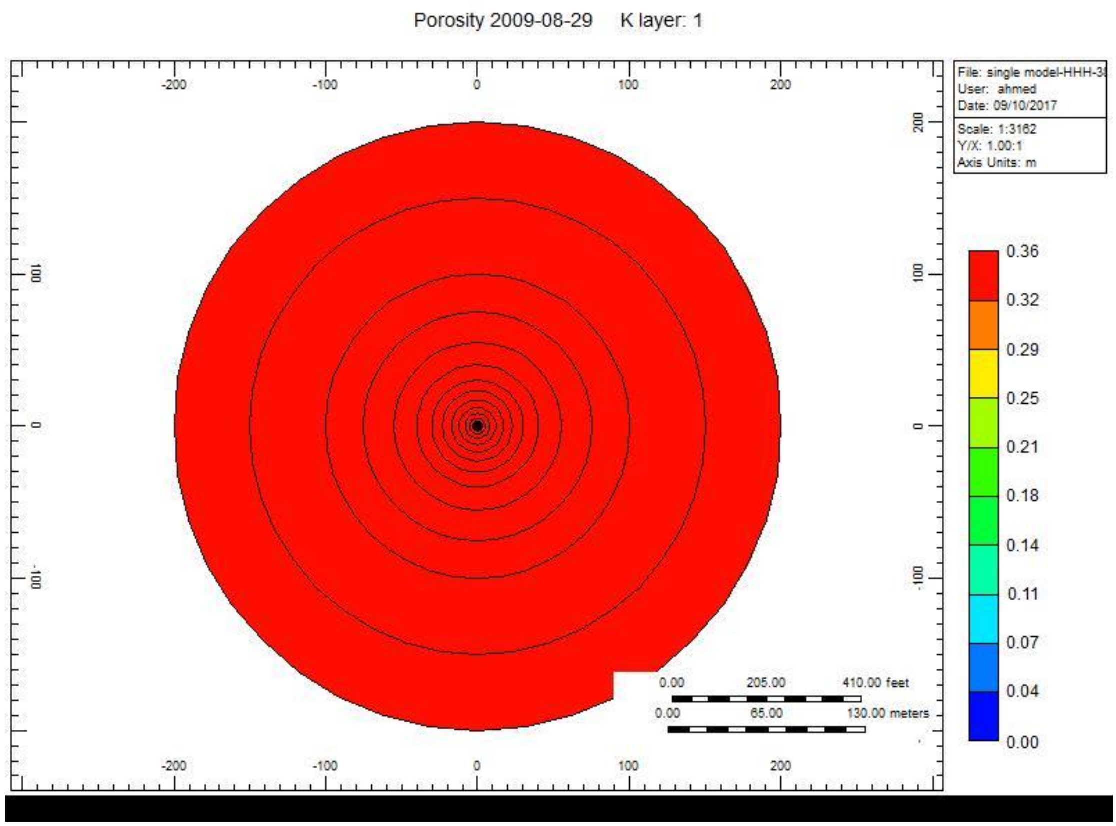
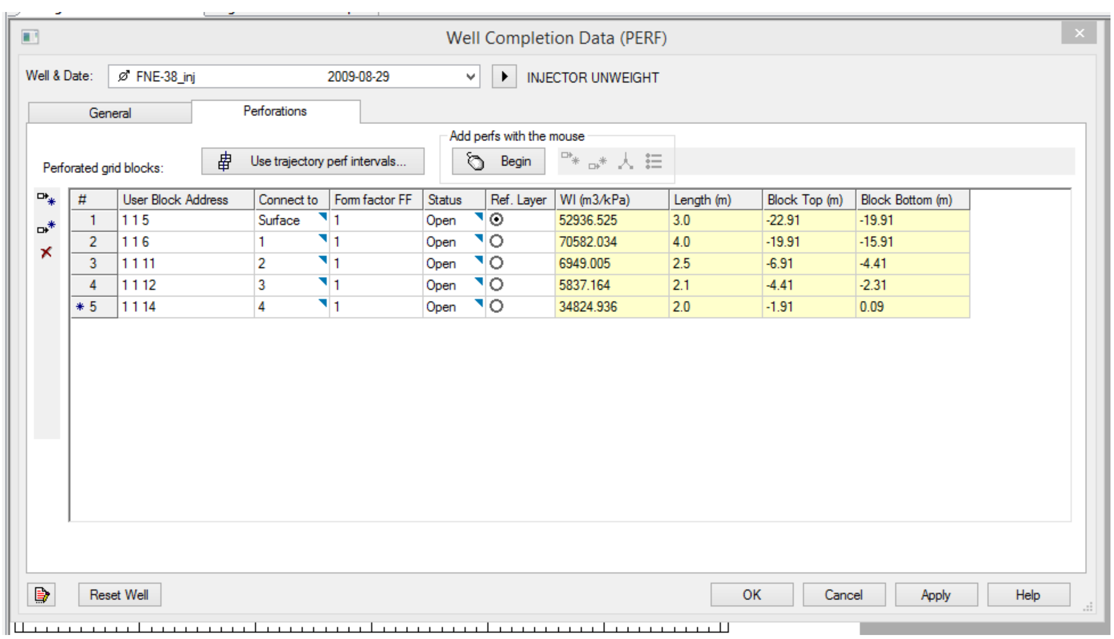


Figure (4-25):Porosity Distribution for Well HHH-38_Inj

Perforation interval :



#	User Block Address	Connect to	Form factor FF	Status	Ref. Layer	WI (m3/kPa)	Length (m)	Block Top (m)	Block Bottom (m)
1	1 1 5	Surface	1	Open	⦿	52936.525	3.0	-22.91	-19.91
2	1 1 6	1	1	Open	○	70582.034	4.0	-19.91	-15.91
3	1 1 11	2	1	Open	○	6949.005	2.5	-6.91	-4.41
4	1 1 12	3	1	Open	○	5837.164	2.1	-4.41	-2.31
* 5	1 1 14	4	1	Open	○	34824.936	2.0	-1.91	0.09

Figure (4-26) : Perforation Interval

Injection Parameters :

Table (4-16): design parameter for HHH-38

	cycle 1	cycle 2	cycle 3
thickness(m)	14	14	14
inj reat(m3/d)	204	192	192
inj volume(m3)	1680	1848	2058
intensity(t/m)	120	132	147
duration(d)	8.235294118	9.625	10.71875
steam quality(%)	68.54	69.8	70.14
temperature	276.4	267	255.22

Assumed design calculation :

Table (4-17): assumed design calculation for HHH-38

layer	length(m)	steam mass(Ton) cycle 1	steam mass(Ton) cycle 2	steam mass(Ton) cycle 3
1 1 5	3	360	396	441
1 1 6	4	480	528	588
1 1 11	2.5	300	330	367.5
1 1 12	2.1	252	277.2	308.7
1 1 13	0.4	48	52.8	58.8
1 1 14	2	240	264	294
	14	1680	1848	2058

Model result :

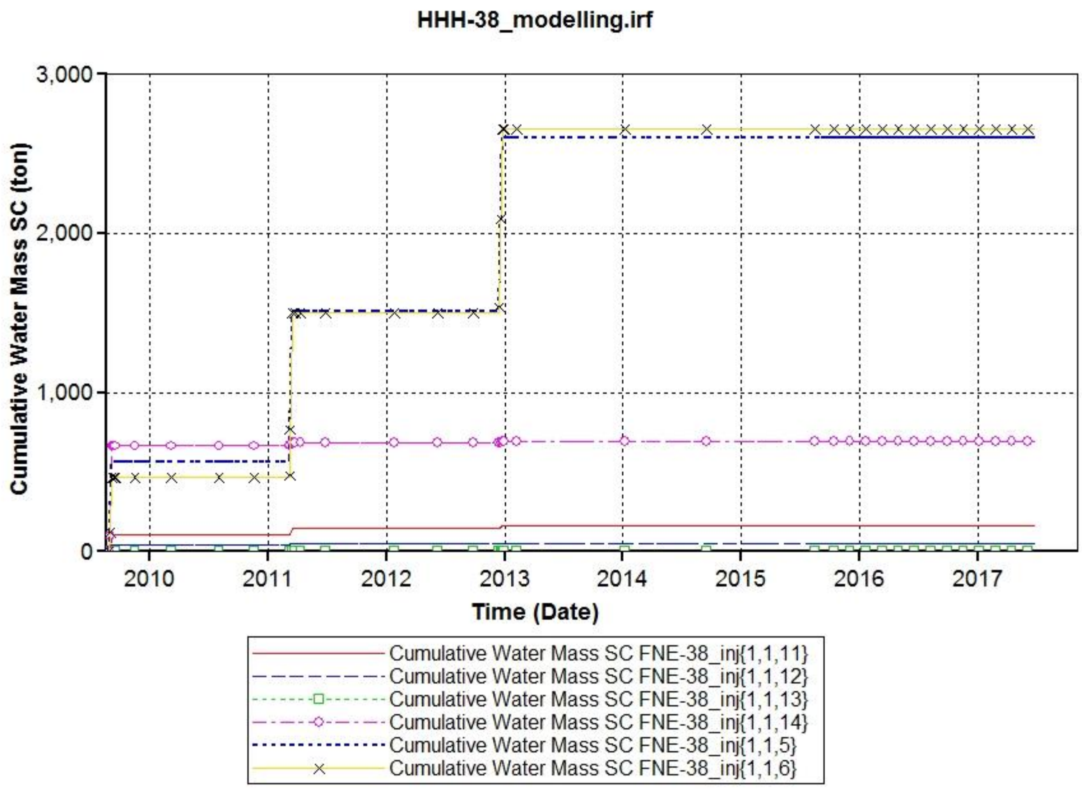


Figure: (4-27) Cumulative Water Mass Per Cycle

Table (4-18): model Result in Tabulated form HHH-38

Layer	steam mass (Ton) cycle 1	steam mass (Ton) cycle 2	steam mass (Ton) cycle 3
1 1 5	511.147	857.063	990.65
1 1 6	425.192	936.018	1047.51
1 1 11	98.062	34.862	16.901
1 1 12	42.417	0.145	0.203
1 1 13	0.006	0.000	0.000
1 1 14	603.080	19.963	2.848
	1679.904	1848.051	2058.112

From CSS test for well 38_inj ,in the first cycle the top layers adsorb 57% while 42% adsorbed for bottom layers accordance to the total steam injected , by repeating cycles the top layer capabilities increase to took more than 60% in the third cycle , the table (4-17) shows the actual adsorption percentage for the layers and comparing with designed calculation , same comparison is done for the actual distribution versus model result.

Comparing design and actual

Table (4-19): steam distribution comparison actual with design for first cycle HHH-38

first cycle						
		Design		Actual		
Layer	Thickness(m)	Steam mass (Ton)	Intensity Ton/m	steam mass(Ton)	Intensity Ton/m	Adsorption %
1 1 5	3	360	120	415.3714	138.5	24.7
1 1 6	4	480		553.8286		32.9
1 1 11	2.5	300		254.7857	101.9	15.1
1 1 12	2.1	252		214.02		12.7
1 1 13	0.4	48		40.76571		2.4
1 1 14	2	240		203.8286		12.1
Total	14	1680		1682.6		100.0

Table (4.20) : steam distribution comparison design with actual for second cycle HHH-38

second cycle						
		Design		Actual		
Layer	Thickness(m)	Steam mass (Ton)	Intensity Ton/m	steam mass(Ton) actual	Intensity Ton/m	Adsorption %
1 1 5	3	396	132	467.7857	155.9	25.3
1 1 6	4	528		623.7143		33.7
1 1 11	2.5	330		270.8929	108.4	14.6
1 1 12	2.1	277.2		227.55		12.3
1 1 13	0.4	52.8		43.34286		2.3
1 1 14	2	264		216.7143		11.7
Total	14	1848		1850		100.0

Table(4.21) : steam distribution comparison design with actual for third cycle HHH38

third cycle						
Layer	Thickness(m)	Design		actual		
		Steam mass (Ton)	Intensity Ton/m	steam mass(Ton)	Intensity Ton/m	Adsorption %
1 1 5	3	441	147	546.3	182.1	26.6
1 1 6	4	588		728.4		35.4
1 1 11	2.5	367.5		279.0357	111.6	13.6
1 1 12	2.1	308.7		234.39		11.4
1 1 13	0.4	58.8		44.64571		2.2
1 1 14	2	294		223.2286		10.9
Total	14	2058		2056		100.0

Comparing actual and model

Table (4-22) comparing actual with model first cycle HHH-38

first cycle							
layer	Thickness (m)	Modelling			actual		
		Steam mass (Ton)	Intensity (Ton/m)	Adsorption %	steam mass(Ton) actual	Intensity (Ton/m)	Adsorption %
1 1 5	3	511.147	133.76	30.43	415.37	138.5	24.7
1 1 6	4	425.192		25.31	553.83		32.9
1 1 11	2.5	98.062	106.22	5.84	254.79	101.9	15.1
1 1 12	2.1	42.417		2.52	214.02		12.7
1 1 13	0.4	0.006		0.00	40.766		2.4
1 1 14	2	603.080		35.90	203.83		12.1
total	14	1679.904		100	1682.6		100.0

Table (4-23) comparing actual with model second cycle HHH-38

second cycle							
layer	Thickness(m)	Modelling			actual		
		Steam mass (Ton)	Intensity (Ton/m)	Adsorption %	steam mass(Ton) actual	Intensity (Ton/m)	Adsorption %
1 1 5	3	857.06	256.15	46.38	467.79	155.9	25.3
1 1 6	4	936.02		50.65	623.71		33.7
1 1 11	2.5	34.862	7.8529	1.89	270.89	108.4	14.6
1 1 12	2.1	0.1446		0.01	227.55		12.3
1 1 13	0.4	0.000		0.00	43.343		2.3
1 1 14	2	19.963		1.08	216.71		11.7
total	14	1848.1		100.00	1850		100.0

Table (4-24) comparing actual with model third cycle HHH-38

third cycle							
layer	Thickness(m)	Modelling			Actual		
		Steam mass (Ton)	Intensity (Ton/m)	Adsorption %	steam mass (Ton)	Intensity (Ton/m)	Adsorption %
1 1 5	3	990.65	291.17	48.13	546.3	182.1	26.6
1 1 6	4	1047.5		50.90	728.4		35.4
1 1 11	2.5	16.901	2.8502	0.82	279.04	111.6	13.6
1 1 12	2.1	0.2025		0.01	234.39		11.4
1 1 13	0.4	0.00		0.00	44.646		2.2
1 1 14	2	2.848		0.14	223.23		10.9
total	14	2058.1		100.0%	2056		100.0

Chapter Five

Conclusion and Recommendations

Chapter Five

Conclusion and Recommendations

5.1 Conclusion:

- a list of challenges were recorded in Sudanese heavy oil field
- evaluation of current development strategy was done in FNE field
- The analysis has been done in HHH-61 it found that the amount of steam injected in second cycle was less than the designed which result decrease in oil production also It has been found that top layer get nearly 70% of the assumed amount of steam
- The optimum injection rate in HHH-61_inj well recorded cross pond ding oil rate
- The optimal injection rate is 152 with approximately 182 stb/day

5.2 Recommendations

- Avoid steam injection stimulation in multi layers, unless using separate layer technology for injection/production from multi layers.
- Conduct the technology analysis for separate layer technology.
- Conduct laboratory study to understand the effect of commingled well.
- The injection must be doing as a same of the modelling method to achieved the better production

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