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DESIGN & REAL-TIME PROCESS OPTIMISATION OF STEAM ASSISTED GRAVITY DRAINAGE FOR IMPROVED HEAVY OIL RECOVERY

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DESIGN & REAL-TIME PROCESS OPTIMISATION OF STEAM ASSISTED GRAVITY DRAINAGE FOR IMPROVED HEAVY OIL RECOVERY

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A thesis submitted in partial fulfilment of the requirements of the Robert Gordon University for the degree of Doctor of Philosophy

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ABSTRACT

“Introduction to the Canadian Oil Sands”, “Canada’s Oil Sand Industry: An Overview”, “Heavy Oil Technologies”, and so many other topics about heavy oil have become the hotcakes in the oil industry. A number of new projects are in Execute phase for the development of heavy oil assets. This clearly shows the increasing demand for heavy oil. An oil industry is working hard to meet the world oil demand by developing deep water, HPHT, heavy oil, shale sands and all other non-conventional reservoirs but the main challenge is to develop and operate them in a risk free environment.

Understanding the reservoir and fluid properties and developing new technologies help the industry to reduce the risk in developing non-conventional fields. A major problem in heavy oil field is to understand the behaviour of heavy oil. The viscous oil flows sluggishly in the formations and hence it is difficult to transport through unconsolidated formations and is very difficult to produce by conventional methods. Viscous oil recovery entails neatly designed enhanced oil recovery processes like Steam Assisted Gravity Drainage and the success of such technologies are critically dependent on accurate knowledge of reservoir, well and fluid properties of oil under variety of pressure and temperature conditions.

This research project has provided some solutions to the challenges in heavy oil field development and can help the oil industry to optimise heavy oil production. Detailed experimental understanding of PVT properties has allowed this project to contribute to the knowledge. Reservoir, well and fluid properties were studied thoroughly and demonstrated the criticality of each parameter on the efficiency of Steam Assisted Gravity Drainage.

An user friendly SAGD simulator is a big output of this research which allows the user to optimise the heavy oil recovery and enables to do risk assessments quickly during design phase of SAGD. A SAGD simulator is developed

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ACRONYMS

SAGD	Steam Assisted Gravity Drainage
EOR	Enhanced Oil Recovery
ESP	Electrical Submersible Pump
UCS	Unconfined Compressive Strength
API	American Petroleum Institute
CHOP	Cold Heavy Oil Production
GOR	Gas Oil Ratio
TEOR	Thermal Enhanced Oil Recovery
X-SAGD	Cross-SAGD
F-SAGD	Fast-SAGD
SW-SAGD	Single Well SAGD
ES-SAGD	Expanding Solvent SAGD
NCG	Non Condensable Gas
PVT	Pressure Volume Temperature
EOS	Equation Of State
OFVF	Oil Formation Volume Factor
HW	Horizontal Well
QAQC	Quality Assurance & Quality Control
CU	Control Unit
PC	Personal Computer
CP	Centipoise
HPC	High Pressure Cylinder
BP	Bingham Plastic
PL	Power Law
HB	Herschel Bulkley
BKC	Blake-Kozeny-Carman
PI	Productivity Index
FF	Friction Factor
OD	Outer Diameter
ID	Inner Diameter

LIST OF VARIABLES

Symbol	Description
K	Relative permeability
μ	Oil viscosity
mV_s	Butler's constant
Q	Oil rate
ø	Porosity
ΔS_o	Saturation difference between initial and residual
G	Specific gravity
α	Thermal diffusivity
v	Kinematic viscosity
T	Temperature
L	Well length
P	Pressure
B_o	Oil formation volume factor
H	Paythickness
γ_o	Specific gravity of oil
ρ	Density of fluid
C	Isothermal compressibility
V	Volume
R_s	Solution gas oil ratio
J	Productivity index
M	Mass of fluid
R^2	Pearson product moment correlation coefficient
P_b	Bubble point pressure
τ	Shear stress
γ	Shear rate
K, n	Rheological constants
V_{pore}	Pore velocity
D	Diameter
r_w	Wellbore radius
Re	Reynolds number
S	Fluid Saturation
E_o	Oil permeability exponent
FF	Friction factor

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CHAPTER 1: GENERAL INTRODUCTION

1.1 Unconventional oil

The demand for hydrocarbon especially oil is outstripping supply. Conventional oil is filling some of the gap and some of the balance is expected to be filled by heavy oil (1). **It has been confirmed that Unconventional oil is set to play an increasingly important role in world oil supply through to 2035, regardless of what governments do to curb demand (1).** Currently with 2.3 million barrels per day production rate of heavy oil, it is contributing about 3 % to world oil demand and by 2035 it will meet about 10% of world oil demand with almost 9.5 million barrels per day rate [Figure 1.1]. Canadian oil sands and Venezuelan extra-heavy oil will be on top of the list to fill the increasing gap between demand and supply of world crude oil (2).

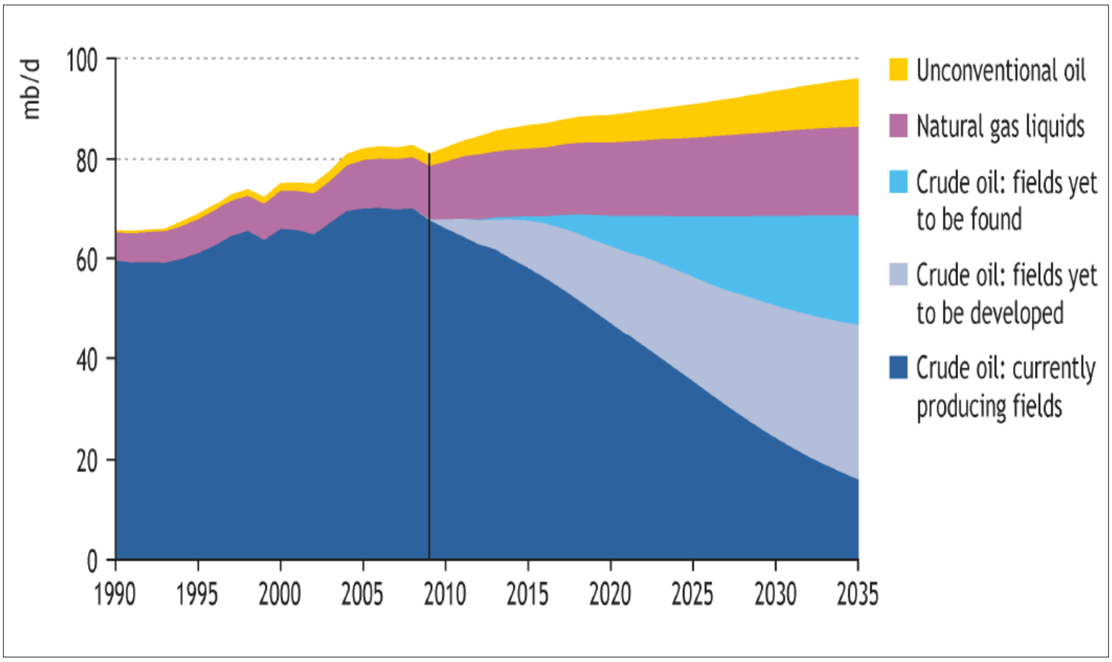


Figure 1.1: World Oil Production

Unconventional oil reserves are not defined strictly and are as diverse as heavy oil and extra-heavy oil, shale oil and bitumen, as well as gas condensate. Bitumen is a black, semisolid degraded form of oil which is found in rock deposits called "oil sands" and "tar sands", which are made of clay and sand particles with water and bitumen in the apertures. Northern Alberta in Canada has the world's largest proven bitumen reserves. Alberta oil sand contains 280 to 300 billion barrels of recoverable bitumen which is almost 85 percent of the total proven bitumen reserves. Surface mining for shallow reserves whereas steam injection with pressure support for deep reserves is commonly used recovery technique for bitumen.

Kerogen is bacterially altered organic plant and animal material, found typically in shale rock, which has not gone through the "oil window" of heat needed to alter it into liquid petroleum (2). Such kerogen can be converted to synthetic crude oil through a heating process called retorting. Synthetic crude oil produced from kerogen is called shale oil. The world's largest reserves of shale oil are in the western United States with the potential of producing one trillion barrels of synthetic crude oil. The shale has to heat up to the 600-650^{o}F to release the kerogen from it and this is main the challenge in developing shale oil reserves. Shallow deposits are mined in open pits and are heated to release the shale oil. In-situ heating is an option for deep shale oil reserves but it is still under development (3).

1.2 Needs for this work

1.2.1 Heavy oil difficult to produce

Dense and viscous remainder of former "conventional oil" from which lighter hydrocarbon components has been degraded away are known as heavy oil. The heavy oil is a type of crude oil which does not flow easily. Heavy oil deposits in Venezuela's Orinoco oil belt are nearly 90 percent of the 300 billion barrels recoverable extra heavy oil reserves in the world. Unconventional Heavy oil reserves are almost 5-6 times than the conventional oil reserves of 1.3 trillion barrels (2). Due to easy access and huge proven reserves, heavy oil is becoming the major contributor towards world oil demand (2). The demand for hydrocarbon especially oil is outstripping supply. Because of its characteristic high density and high viscosity, heavy oil has very low mobility at the reservoir conditions hence the conventional recovery techniques cannot produce heavy oil. There are however field proven cold and thermal heavy oil recovery technologies which are available in the market to develop the heavy oil fields. For deep bitumen and extra-heavy oil reserves, thermal recovery is the most adopted and proven recovery technique. Steam Assisted Gravity Drainage (SAGD) is becoming a very popular thermal method due to its high recovery factor compared to other enhanced oil recovery techniques (EORs) (4).

1.2.2 Optimisation of heavy oil recovery techniques

Steam assisted gravity drainage (SAGD) is one of the thermal recovery techniques for heavy oil and bitumen. The SAGD technique generally requires two vertically aligned horizontal wells. The top one is for the steam injection and the bottom well is for production. Steam chamber develops due to the steam injection around the steam injector and grows with the injection. Steam heats the cold reservoir and the heavy oil. Detailed SAGD illustration is given in Chapter 3. Once the heavy oil becomes mobile, it starts flowing downwards due to the gravity and gets collected in the producer well. If the downhole pressure is insufficient to lift the heavy oil to wellhead then artificial lift such as electrical submersible pump (ESP) is used to produce the heavy oil.

SAGD from the description can be simple but in reality it is a very complex process to manage. SAGD is a dynamic process where different sub processes are happening at the same time such as changes in reservoir temperature, pressure, water saturation, rock composition, fluid behaviour etc. with steam injection and also few more changes in reservoir due to production. SAGD operators have to manage a number of things at optimum level to keep SAGD technique in optimum state. To keep SAGD at optimum level, operators have to manage energy requirements associated with steam production, water quality requirements, minimising heat losses, oil water separation, handling emulsions, pollution prevention, well design, material selection, sand management and operating pressure and temperatures. All the above design and operating parameters need to be correct and optimum for the field where the SAGD is being deployed to produce the heavy oil with high profit margin. This is how one can increase the system efficiency by respecting the field constraints. SAGD can be optimised by managing fluid properly, designing wells correctly and handling reservoir correctly which is the challenge for an operator. To manage SAGD, the fluid understanding is obligatory. The optimum well design is very critical in the SAGD process and understanding the behaviour of reservoir during SAGD also determines the efficiency of the process. Fluid, wells and reservoir management are quite comprehensive challenges and requires number of activities to overcome them.

1.2.3 Needs for better knowledge

In SAGD process, there are still number of black boxes around the fluid properties, wellbore design and reservoir management. Fluid characterisation is must in order to understand the SAGD fluids. Fluid characterisation could be compositional or empirical. In common practice for conventional crude oil and liquids, the black oil empirical approach is being used to understand the liquid whereas for gas and gas condensate, the most common approach is compositional using equation of state. SAGD has both liquid and gas hence it is very necessary to apply both methodologies to understand SAGD fluids. Steam is a standard fluid and huge data have been published for steam properties at various conditions which can be adopted from public domain to understand steam behaviour in SAGD process. But the challenge here is to understand the steam interaction with heavy oil and the behaviour of heavy oil at different pressure and temperature conditions. Previous research work has placed the heavy oil into non-Newtonian fluid group which makes it more complex to understand it. Therefore the current biggest challenge for the heavy oil researcher is to characterise heavy oil correctly for different operating conditions. As pressure and temperature is not steady in the SAGD process hence the fluid characterisation is required at all operating conditions. This has informed **the need for detailed experimental studies to first build huge database of heavy oil fluid properties and then using it to develop empirical correlations for PVT properties (4,5).**

SAGD wells are horizontal and vertically aligned to each other so during well design not only horizontal length but also the vertical spacing is critical here. Vertical spacing along with vertical absolute permeability of formation helps to define the communication between the wells. Therefore the well length and well spacing is case dependent and fluids type with quantity need to be considered during the well design. Horizontal wellbore completion plays an important role in developing the outflow from the injector or inflow to the producer. So the challenge here is to define the optimum well lengths with correct well spacing and accurate well completion.

Steam injection and heavy oil production is a continuous process throughout the life of SAGD. This continuous injection and production causes some changes to fluid and reservoir properties. Fluid properties such as water cut and hence relative permeability are dynamic during SAGD. It also affects the formation strength to hold the grains together which might affect the unconfined compressive strength (UCS) of the formation. UCS needs to be monitored continuously to avoid the sand production. High temperature due to steam injection in the formation could also trigger the grain to grain cementation and affect the absolute porosity which effectively affects the effective permeability. Therefore one cannot assume the constant reservoir properties during the SAGD as in conventional crude oil reservoirs. So the challenge here is to track all above reservoir properties in real time and incorporate them for rate and efficiency calculations.

1.3 Outline of the present work

1.3.1 Objectives

The original idea of this research was to focus more on SAGD operations by simulating in different thermal reservoir simulators and then to optimise the process. It was rapidly realised that very little importance is given to fluid PVT properties in most of the SAGD simulators therefore the PVT properties became the focal point of this research. The objectives of this study were numerous and various. They were to:

1. Identify the critical parameters in Steam Assisted Gravity Drainage
2. analyse and validate the productivity and steam injectivity models for horizontal wells with field data which is one of the critical parameter for SAGD
3. justify the importance of fluid properties on efficiency of SAGD recovery technique
4. analyse the available fluid models for heavy oil and to identify their limitations and then to justify the need for new experiments
5. measure density of different heavy oil samples on two different density cells at different pressures and temperatures
6. develop and validate the empirical model to compute density of heavy oil at higher pressure and temperature
7. develop and validate the compressibility and oil formation volume factor models for low Gas Oil Ratio (GOR) heavy oil

8. measure viscosity of heavy oil samples using viscometers at different temperature
9. do the rheological characterisation for available heavy oil samples and then to develop the database for it
10. define the new strategy for shear viscosity calculations
11. develop the real time shear stress and shear rate models
12. show the improvement of using the in-house density and viscosity models over the traditional conventional black oil PVT models
13. define the process for real time relative permeability calculations in SAGD
14. Use the REVEAL simulation cases of SAGD to track the growth of steam chamber and inflow pattern and then optimise the wellbore parameters like wellbore diameter, well spacing and well lengths.
15. use REVEAL and published models to track the reservoir parameters and if possible then to develop or recommend the models to calculate the real time reservoir parameters like absolute permeability, porosity, grain to grain cementation and fluid mobility.
16. develop a real time PVT simulator for heavy oil PVT properties like compressibility, oil formation volume factor, density, bubble pressure, shear stress, shear rate and viscosity using in-house developed models
17. build an overall SAGD simulator using the developed PVT simulator and shortlisted horizontal productivity and injectivity models
18. Validate the developed SAGD simulator with published data or industry SAGD simulators.
19. Conclude and suggest some further work

1.3.2 Methodology

An appropriate approach was required to fulfil the identified technical gaps in SAGD within the timeframe of this research project. Firstly the technical issues were grouped into reservoir, wellbore and fluid category. Then different phases namely literature survey, experimental studies, data analysis, model development, result validating and simulator development were defined.

Most of the phases were able to run in parallel so it was not easy to define the methodology which follows phases in steps.

Literature survey:

It was a continuously on-going phase. Here the different available literature had reviewed to get the latest published information on the identified technical challenges. In this phase mainly the literature survey was done on following topics.

- Heavy oil recovery techniques
- SAGD process and it's simulators
- Horizontal well productivity models
- PVT properties models for heavy oil
- Rheological models for non-Newtonian fluids
- Viscosity models for heavy oil
- Relative permeability models
- Rock porosity, hardness models
- Pressure drop models for non-Newtonian fluids
- Data collection for validation

The other objective of this phase was also to validate the available data or models on heavy oil and then to explain the need for experimental study.

Experimental studies:

The purpose of the experimental phase was to build appropriate dataset required to develop the different PVT properties models like compressibility, density, oil formation volume factor, viscosity and shear stress models for heavy oil and mixture of heavy oil and steam condensate.

In this project the different experiments were performed on following equipment to generate a huge database for different heavy oil samples.

1. Micro-PVT
2. Density Cell
3. Brookfield rheometer
4. Fann-35 rheometer

Model Development:

In this phase, first the published analytical models were tested against experimental values and then new models were developed where necessary, for PVT properties of heavy oil with the help of Minitab, Mat lab, Crystal Ball and Microsoft excel software.

Also in this phase the screening of horizontal well productivity models was done by benchmarking against results from Eclipse and REVEAL reservoir simulator.

Validation of developed models was thereafter implemented with the use of independent data available in public domain.

Uniting Phase:

All the developed and adopted fluid, flow, well and reservoir models are interlinked with each other to form the SAGD Simulator developed purposely as part of the overall project objectives as they all contribute to the SAGD. It is explained thoroughly in chapter 7 (figure 7.2).

Improvement by new developed models was demonstrated by SAGD process simulation on REVEAL with and without new models.

Excel based SAGD simulator was developed using adopted and developed models. The sensitivity analysis of different parameters was done using Crystal Ball simulator and was validated them against available industry simulators and published data.

1.3.3 Outline of the thesis

This section presents an overview of the contents of the thesis. The main idea for each chapter is briefly given. First, Chapter 1 presented a general background of the problem and gave the objectives of the thesis. Detailed information was also available to understand the relevant heavy oil and its recovery techniques. The needs for the present work are stated to emphasise the numerous applications of the present results.

Chapter 2 describes the heavy oil and its recovery techniques. It also briefly explains the SAGD technique. Cold and thermal recovery techniques are presented, along with a brief analysis. The detailed description about SAGD is in chapter 3. Mechanism of SAGD with key PVT fluid properties is also explained thoroughly in the chapter 3. Gaps of current fluid models for PVT properties are also demonstrated in this chapter with the need for experimental studies. Different types of equipment and experimental studies are presented in the next chapter 4. Operating procedures for all used equipment are also given the same chapter. Experimental results are then demonstrated at the end of the chapter 4.

A huge experimental database built in experimental studies was used to develop new empirical fluid models for density and viscosity which is given in chapter 5. New methodology to handle non-Newtonian behaviour is also in the same chapter. All the developed fluid models are presented in chapter 5 and also validated with external data. Chapter 6 talks about the horizontal well flow models and demonstrates the need for screening. Industry numerical simulator results were used to shortlist the horizontal well flow models for SAGD which is given in chapter 6. Flow efficiency with flow pattern is also demonstrated in the same chapter. Chapter 7 unites all the work done in this research project like developed fluid models for PVT properties, shortlisted horizontal well flow models and reservoir properties models. Then it describes each and every section of the developed in-house SAGD simulator. Validation of SAGD simulator with industry simulator is also mentioned in this chapter. Chapter 8 summarises the contribution to knowledge from this research work with some recommendations for future work. References and appendix A are given after chapter 8. All the coding and logics used in SAGD simulator are given in appendix A.

1.3.4 Contribution to knowledge

There are number of contribution to knowledge can be concluded from this research work. Direct contribution includes the new model development, new process and strategy development. Indirect contribution means improving the applicability of available models which are in public domain for the recovery of heavy oil.

Contributions to knowledge are.

1. Development of the compressibility model for dead and live heavy oil
2. Development of density model for heavy oil
3. Development of PVT properties models for Gas Oil Ratio, Oil formation volume factor for live heavy oil
4. Development of shear stress model for heavy oil
5. Development of unique strategy to calculate shear viscosity of heavy oil
6. Development of real time SAGD simulator which allows engineers to do the risk assessment in heavy oil recovery
7. Development of real time rock hardness model for different temperature and water saturation

8. Development of the analysis program in Microsoft Excel for rheological characterisation of Non-Newtonian fluids
9. Recommending the productivity models for horizontal wells for infinite and finite heavy oil reservoirs
10. Proving the dependency of shear viscosity on drawdown, production rate, drainage profile and fluid behaviour
11. Identified the new research area for researcher

Real time simulator developed during this research work will help engineers to get real time data and to do real time risk analysis. Developed unique fluid models now can be used to understand non-Newtonian fluid correctly. This is the unique real time SAGD simulator which is one of the biggest contributions to knowledge. This work has also discovered new area for academic researcher.

CHAPTER 2: HEAVY OIL AND ITS RECOVERY TECHNIQUES

2.1 Introduction

This chapter presents the definition of heavy oil and its classifications, the proven reserves around the world and its different recovery methods. Heavy oil, which has been considered as a potential hydrocarbon, is needed to fill the increasing gap between future demand and supply of hydrocarbons (1,2). The questions that remain unanswered are: (i) what is heavy oil? (ii) Why is it different from conventional crude oil? (iii) How can one achieve maximum recovery from heavy oil reservoirs? Answers to such questions will be given in subsequent sections of this chapter.

2.2 Definition of Heavy Oil

Heavy crude oil is a type of crude oil whose density and specific gravity are higher than those of light crude oil. American Petroleum Institute (API) have defined heavy crude oil as any liquid petroleum which has API gravity below 20^0, which means that its specific gravity is greater than 0.933. The molecular weight of heavy oil is also high in comparison to conventional crude oil. The viscosity of heavy oil is greater than 100 cp at reservoir conditions of pressure and temperature, which means that the heavy crude oil does not flow naturally (5,6).

However, heavy oil can also have high API gravity above 20^0 with high viscosity above 100 cp at reservoir conditions pressure and temperature or can have low viscosity at low API gravity. But this is not the commonly observed behaviour of heavy oil (7).

Heavy oil gets degraded by bacteria and by constant weathering, which results in the loss of its lighter hydrocarbon fractions leaving behind heavier fractions of carbon, sulphur, and heavy metal content. Heavy oil has a high proportion of low-volatility compounds of high molecular weights and relatively low proportion of high-volatile compounds (6); the high molecular weight low-volatile compounds include long chain alkanes, aromatic compounds and asphaltenes. They have high melting and pour points which are responsible for the relatively high pour point of heavy crude oil compared to conventional crude oil. Therefore, the mobility of heavy oil is low in comparison to conventional crude oil. The fluid mobility is defined as the ratio of effective permeability to effective shear viscosity (8).

$$Mobility_{effective} = {}^{k}/_{\mu} \quad [2.1]$$

Mobility is a critical parameter that determines the recovery rates. The low mobility of heavy crude oil due to high viscosity results in low recovery rates (9). However, it cannot be generalised that the paraffins or aromatic compounds or even asphaltenes are responsible for the low API gravity because different fluids have different fluid composition. Heavy oils with the same API gravity may have different compositions (6,9). The common characteristic properties of heavy oil are low API, high viscosity, low hydrogen to carbon ratio, high specific gravity, high carbon residues, heavy metal, sulphur and nitrogen. [Table 2.1]

Table2.1: Classification of petroleum [6-8]

Fluid Type /Properties	Natural Gas	Gas Condensate	Conventional crude oil	Light heavy oil (viscous)	Medium heavy oil	Extra heavy oil	Tar sands/Bitumen
API specific gravity, ^{0}API	>45	>40	>25	20-25	10-20	<10	<10
Fluid viscosity at reservoir, cp	<0.1 cp	<1 cp	<10 cp	<100 cp	>100 cp	<10000 cp	>10000 cp
Molecular weight of reservoir fluid, g/mol	<50	<150	<200	<350	<600	>600	>1200
Gas Oil Ratio, scf/STB	NA	>1000	>300	<300	<100	<10	NA
Formation volume	<0.1	>2	>1.2	1.1-1.2	<1.1	<1.1	NA

factor, RB/STB							
Reservoir fluid composition, mol%	C1=95 % C2=3% C3=1% C4=1% C5+=1 %	C1=60 % C2=8% C3=6% C4=7% C5=6% C6=5% C7=4% C8=2% C9=1% C10+= 1%	C1=40% C2=4% C3=3% C4=3% C5-C10=20% C11-C15=15% C15-C20=9% C20+=6%	C1=20% C2=3% C3=2% C4=1% C5-C10=15% C11-C15=20% C15-C20=15% C20-C25=10% C25-C35=10% C35+=4%	C1=8% C2=4% C3=2% C4=2% C5-C10=4% C11-C15=10% C15-C20=30% C20-C25=10% C25-C35=10% C35+=20%	C1-C5=3% C5-C10=4% C11-C15=3% C15-C20=10% C20-C25=10% C25-C35=30% C35+=40%	C5-C10=3% C11-C15=4% C15-C20=3% C20-C25=15% C25-C35=25% C35+=50%

2.3 Heavy Oil Reserves

Table 2.2 illustrates that the proven heavy oil reserves worldwide are much greater than conventional crude oil reserves (10). This also explains the huge amount of development taking place in unconventional oil fields.

Table 2.2: Total World oil reserves (10)

Crude oil type	**Proven reserve**	**Percentage**
Conventional crude oil	1.3 TB	30%
Light and Medium heavy oil	0.65 TB	15%
Extra heavy oil	1.08 TB	25%
Tar sands/Bitumen	1.3 TB	30%
Total	**4.3 TB**	**100%**

Figure 2.1 and Table 2.3 show the worldwide distribution of heavy oil reserves (3,6). Large resources of heavy oil are found in Canada, Venezuela, Russia, United States and in other parts of the world, which could be exploited, to meet the linearly increasing demand of crude oil worldwide (10).

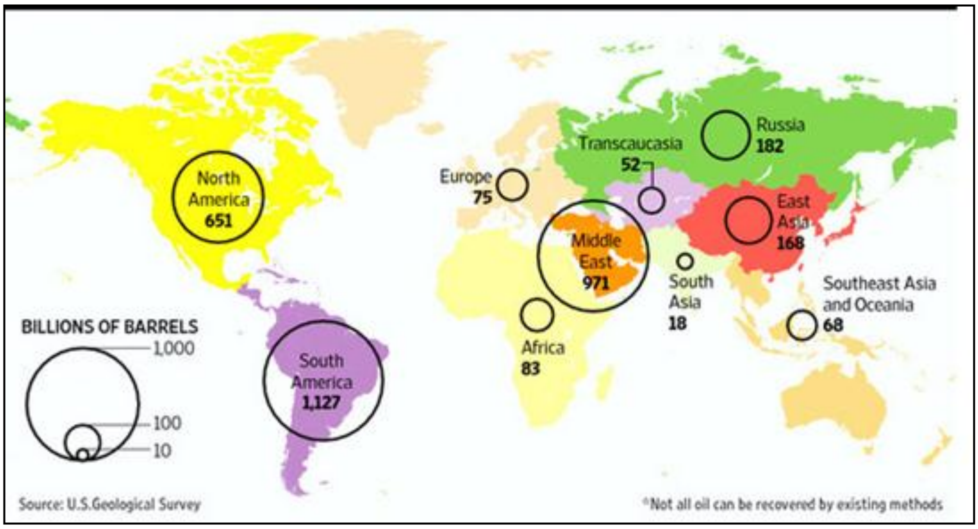


Figure 2.1: Mapping Heavy Oil reserves [10]

Initially, there have been low uptakes in heavy oil field development due to high production cost and difficulty in managing the complex fluid properties. But, with the increasing demand of fossil fuel, new investments are pouring in for heavy oil field developments (5). New technologies are now in place to lower the production cost of heavy oil.

Table 2.3: Heavy oil deposits by region (10)

Region	Heavy oil deposits in billions of barrels
South America	1127
North America	651
Middle East	971
Africa	83
Europe	75
South Asia	18
East Asia	168
Russia	182
Transcaucasia	52
Southeast Asia	68

2.4 Heavy oil recovery techniques

There are mainly two types of heavy oil recovery techniques (11): (i) Cold heavy oil production techniques, and (ii) Thermal recovery techniques.

Each of the above techniques, also known as unconventional recovery methods, adopts different practices and has been classified further on the basis of their deployment procedure.

2.4.1 Cold Heavy Oil Production (CHOP) techniques

Depending upon the method of production there are different types of CHOP techniques: (i) Oil mining, (ii) Solution gas drives, (iii) Solvent injection, and (iv) Electrical Submersible Pump for heavy oil (ESP).

2.4.1.1 Oil Mining

Figure 2.2: Oil mining technique (2)

Similar to other mining operations, the extraction of heavy oil from the earth surface by this technique involves using huge cutting machines to remove the oil saturated rock from the surface. High volumes of oil can be recovered by heating or shaking the cuttings. Oil recovery can also be achieved by washing, flotation or retorting treatments. The recorded recovery factor by this technique is up to 80%. This technique is applicable, where the heavy oil saturated rocks are shallow.

Major limitation of this technique is that, it can’t be deployed beyond around 70 m depth because the operation cost increases with increasing depth. Disposal of tailing streams containing clay and bitumen into river raises environmental concerns. The technique is field proven and has been widely used in Canada (2).

2.4.1.2 Solution gas drive

The traditional recovery techniques for natural production of oil are done by creating an internal energy in the formation. Use of solution gas drive (Figure 2.3) is one such technique in which fluid mobility is achieved by applying differential pressure drop on the formation. Internal energy within the formation is dependent upon the pressure and gas oil ratio (GOR) of heavy oil. This is very good for light heavy oil, but can't be used for medium and extra heavy oil reservoirs.

Downhole sand management is also the pitfall of this technique. Loss of fluid mobility, wellbore collapse, water breakouts from warmholes (high permeable zones) and the facility erosion are some of the concern areas in this technique. Due to high drawdown, the formations can break which increase the potential for sand production. Topside sand handling is also another limitation of this technique.

Sand production can be controlled by lowering the drawdown, but such lowering results in lower production rates and recovery factor. The highest recovery reported so far for this technique is around 20% of recoverable oil. The solution gas drive technique has been used in FAJA field in Venezuela, Elk point and Lindberg fields in Canada (6).

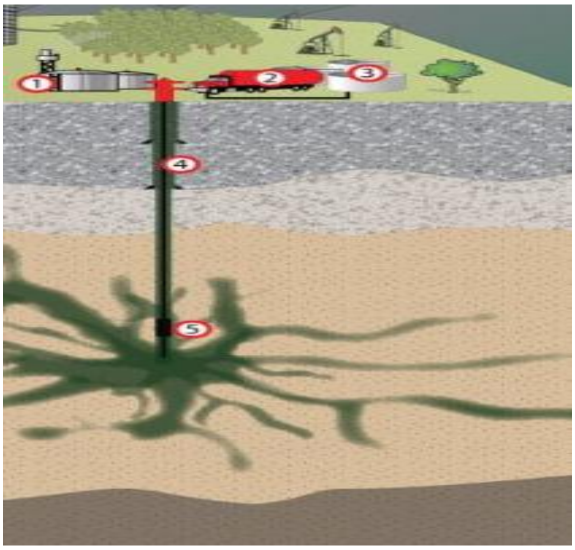


Figure 2.3: Solution gas drive technique (6)

2.4.1.3 Solvent injection

Reducing the viscosity of heavy oil by adding solvent is the main principle of this technology. A number of liquids such as fatty acids and water, and gas phase solvents like light hydrocarbons and carbon dioxide, available in the market, can be used. VAPEX is the process of Injection of vaporised solvent for reducing viscosity of heavy oil is done by VAPEX process. Performance of each solvent is different, but a combination of different solvents has shown better performance in comparison to single solvent. Figure 2.4 compares the relative recovery factor by different solvent injection. Solvent injection also helps to boost the sweep efficiency.

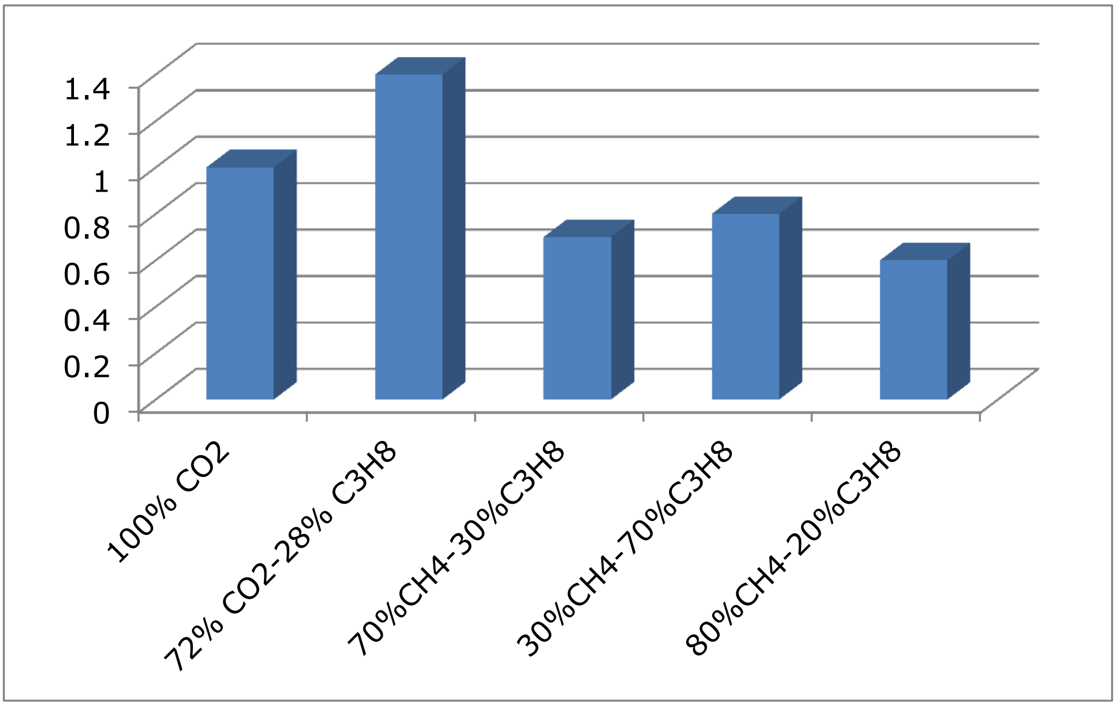


Figure 2.4: Relative recovery factor for different solvents (12)

Problems related to solvent recovery are the major drawback of this technology. Solvent management can make this process expensive and complex to operate. Water flooding has been implemented on Captain Field in North Sea.

2.4.1.4 Electrical Submersible Pump for heavy oil (ESP)

In this recovery technique, electrical submersible pumps (ESP) are used to lift the heavy oil and also to apply the drawdown on formation (Figure 2.5). Oil recovery factor of naturally driven fields can be increased by deploying ESP. Limitation of using ESP is integrity management. Pump maintenance and solid management are the main activities of this technique (11). ESP can only be used where the fluid has mobility at reservoir conditions. High recovery can be achieved by combining ESP with any other recovery technique instead of using ESP alone. The maximum recorded recovery factor achieved by ESP technique is up to 20%.

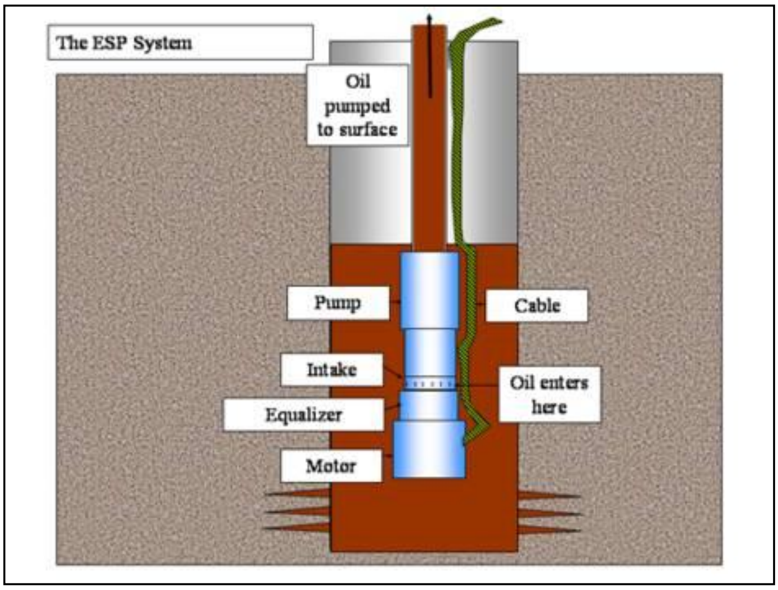


Figure 2.5: ESP recovery technique (11)

2.4.2 Thermal heavy oil recovery techniques

The steam-based processes are the most advanced of all enhanced oil recovery methods in terms of field experience and thus have the least uncertainty in estimating performance. Thermal enhanced oil recovery (TEOR) methods have gained substantial importance in heavy oil field development over other methods by achieving high recovery (13).

There are three major thermal recovery techniques for heavy oil: (i) In-situ combustion, (ii) Huff and puff, and (iii) Steam assisted gravity drainage (SAGD).

2.4.2.1 In-situ Combustion

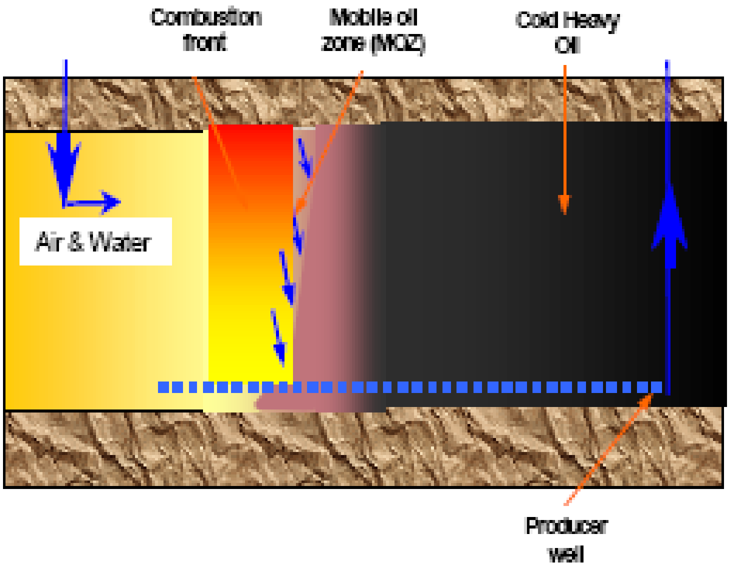


Figure 2.6: In-Situ combustion technique (14)

Controlled downhole combustion is the main mechanism behind this recovery technique. Heating method is same as mining except that the heating is downhole. This process has been tested on light oils, but low success rate was recorded. The drawback of this technique is the increased operational risk because of heavy oil heating caused by the combustion of coke (14).

2.4.2.2 Huff and Puff

Cyclic steam injection is known as huff and puff process. Here, a single well is used for both steam injection as well as for producing heavy oil. The first step of this process is to inject steam into the reservoir. In the second step, the injected hot steam and condensed water soaks the heavy oil, which reduces its viscosity, resulting in increased mobility. In the last step, which is also known as the production stage, the heated heavy oil with condensed water is pumped to the surface. This is a field proven process with low operating cost.

The main disadvantage of this process is low recovery factor. As steam injection is not continuous and is directed only at one point, it cannot interact with the inner layer of formation. Steam generation is also an expensive procedure; hence achieving high recovery can only make this process feasible (13,15).

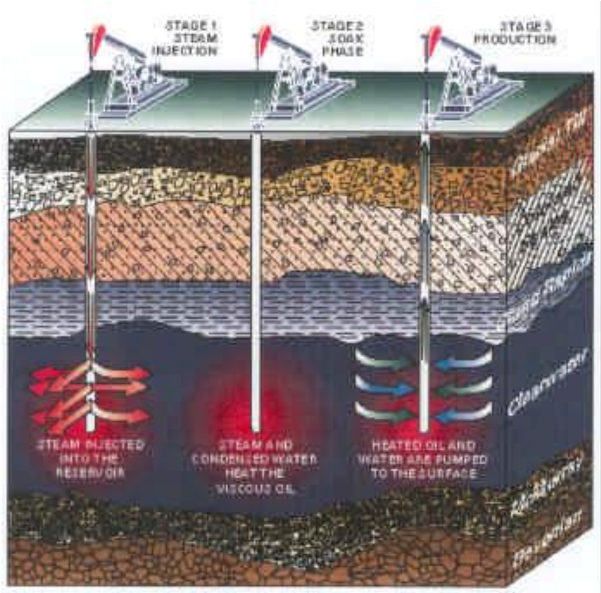


Figure 2.7: Huff and Puff process (15)

2.4.2.3 Steam Assisted Gravity Drainage (SAGD)

Introduced first by Roger Butler and his co-workers (16) in 1970s, the Steam Assisted Gravity Drainage (SAGD) process is one of the popular field proven thermal heavy oil recovery technique with around 65% recovery factor (9). Over 40 years of successful commercialization and use of SAGD has led many researchers to believe SAGD to be a standard technique for heavy oil recovery (17,18). The technique introduced by Butler et al. (16) involves continuous injection of steam into the reservoir via an injection well.

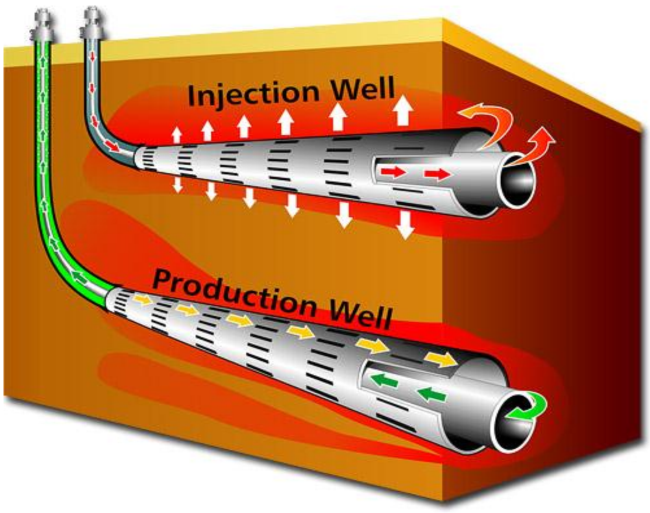


Figure 2.8: Steam Assisted Gravity Drainage (17)

A steam saturated zone is formed, where the temperature is almost same as that of the injected steam. Heat is transferred from the steam to the surrounding reservoir by thermal conduction. Steam condensate and heated oil flow by gravity to the production well located below the injection well. Steam rises in reservoir due to buoyancy to enhance the chamber. Growth of the steam chamber is also due to the oil mobilization at the steam-oil interface (19). As the heated oil flows away, the steam chamber expands both upwards and sideways. Oil has no mobility within steam chamber because oil saturation is below or near to residual oil saturation. Steam injection pressure is assumed constant in SAGD process (16). Due to such dynamic behaviour, two types of flow exist in SAGD: (i) ceiling drainage, which is from the ceiling of steam chamber, and (ii) slope drainage, which is along the slopes of the steam chamber (18,20,21). Detailed SAGD mechanism is presented in chapter 3.

CHAPTER 3: STEAM ASSISTED GRAVITY DRAINAGE (SAGD)

3.1 Introduction

In this chapter, the background and mechanism of SAGD is covered in the first section. In the second section, different approaches for improving the efficiency of SAGD are explained. Key parameters for success of SAGD with their sensitivity on productivity are also explained. In the last section, the technology gaps in SAGD are identified which formed the critical key drivers for this research.

3.2 Background of SAGD Process

The SAGD theory has been modified several times by different authors (9). The initial SAGD theory was developed using a steady state heat equation for temperature profile, viscosity-temperature relation for heavy oil viscosity prediction, Darcy's law for flow rate prediction and a material balance equation for tracking the position of steam-oil interface. Finally, a non-steady state equation was considered by Butler (16) for monitoring the growth of steam chamber. SAGD based on horizontal wells and gravity drainage is becoming very popular in the heavy oil industry as one of the thermal viscosity reduction technique. This is because of its high recovery factor, especially for deep onshore and offshore reservoirs (17). This new SAGD uses two multilateral horizontal wells drilled into the reservoir, which are parallel and vertically aligned on top of each other (Figure 3.1). The upper well acts as the "Injection Well" for the steam.As new reservoir surfaces are heated and the oil viscosity decreases, the oil flows downward along the boundaries of the steam chamber and facilitates the gravity drainage of the lighter oil into the lower lateral well which is the "Production Well". There can be vertical-horizontal or vertical-vertical well pair for SAGD but the most efficient is seen the horizontal-horizontal. SAGD has the potential to generate a heavy oil recovery factor of up to 65% (22).

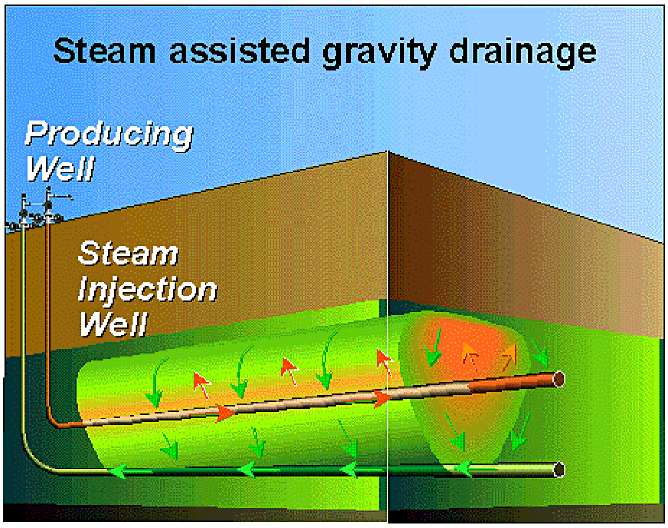


Figure 3.1: Steam Assisted Gravity Drainage technique (23)

3.3 Process for SAGD improvements

SAGD recovery factor mainly depends on the growth of steam chamber, distribution of heat in formation, understanding fluid properties and well length. Different strategies (24,25) can be adopted to improve the efficiency of SAGD process. These can be classified into two main categories: (1) geometrical attempts and (2) chemical attempts.

3.3.1 Geometrical attempts

This approach attempts to improve the heat distribution into formation by accelerating growth of steam chamber.

3.3.1.1 Cross-SAGD (X-SAGD)

The main feature of X-SAGD is to create a mesh of injection and production wells. During operation, production and injection points are altered to minimize steam breakthrough. Stalder (26) concluded the two main concerns about X-SAGD: (i) the initial establishment of steam chamber is due to the crossing points of wells, and not by entire well length, and (ii) the well plugging is an expensive and a challenging operation, which increases the initial risk of project.

3.3.1.2 Fast-SAGD (F-SAGD)

In this attempt, an additional horizontal well is placed alongside the well pair and is operated by huff and puff method. This attempt is to improve the steam chamber growth. Shin and Polikar (22) concluded that the F-SAGD has lower cumulative steam oil ratio and 34% more efficiency than classical SAGD operation.

3.3.1.3 Single Well SAGD (SW-SAGD)

SW-SAGD has the same recovery mechanism as that of the conventional SAGD process. In this attempt, a single horizontal well is used for both injection and production. Steam is injected at the toe of the well and heated fluid is produced from the heel of the horizontal well. This method has been tested successfully in thin reservoirs such as Cactus Lake Field, Alberta, Canada (25). Akin et al. (22) performed different experiments for SW-SAGD and concluded that the principle mechanism in SW-SAGD is "steam chamber formation". They also confirmed that the cyclic steam injection in SW-SAGD has better efficiency than steam circulation.

3.3.1.4 Vertical Injector and horizontal producer in SAGD

Rose et al. (24,27,28) presented different SAGD algorithms for injectors and producers. Vertical Injector-vertical producer, Vertical injector- horizontal producer and conventional SAGD horizontal wells were the combinations used for analysis. They also concluded that the best combination for SAGD wells is the horizontal injector and horizontal producer. Their results are summarized in Figure 3.2 (18).

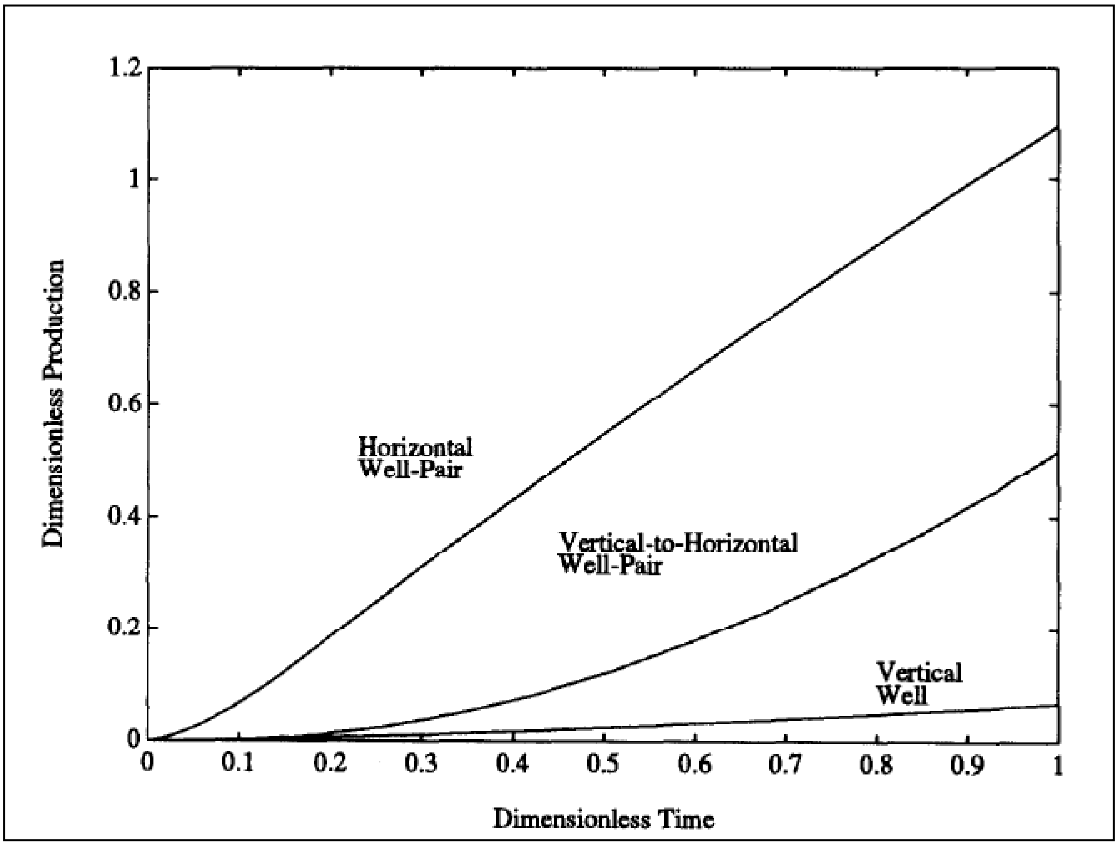


Fig 3.2: Analysis for different well combinations by Rose et al. (24)

3.3.2 Chemical attempts

Chemical approach aims at improving the heating efficiency and reduces the oil water interfacial tension in order to maximize oil production.

3.3.2.1 Expanding Solvent SAGD (ES-SAGD)

Nasr et al. (29) developed the concept of injecting solvent with steam at low concentration. This process was tested in Burnt Lake and Firebag fields in Canada. They reported that only 50% viscosity of heavy oil can be reduced by using steam whereas, 95% viscosity can be reduced by using a combination of solvent and steam.

3.3.2.2 Non Condensable Gas (NCG) or SAGP

In this process, NCG was allowed to flow inside the steam chamber, during steam injection. The shape and growth rate of steam chamber gets affected by the additional inflow of NCG in the steam chamber (11,30,31). Jiang et al. (11)

reported that the quantity of heavy oil produced by using SAGP process was low in comparison to conventional SAGD process. Accumulation of NCG at the boundary of steam chamber may reduce steam temperature, thereby posing serious threat to the process (13).

3.4 Mechanism of SAGD

SAGD is a dynamic process, whose mechanism can be described by following activities:

1. Steam chamber rise
   In SAGD, the oil is produced from the heated steam-oil interface; hence, monitoring and analysing the steam chamber development is important. But due to the dynamic nature of the process, the complete picture of chamber development is not clear. It is a challenge for the scientists to monitor and analyse the steam chamber and track the development of steam chamber during steam injection

2. Steam fingering theory
   Butler (32) who introduced the SAGD process first, also described the steam fingering theory, based on his laboratory experiments. Initially the steam is introduced via injection well, and then at the interface, the steam fingers heats up the cold oil and rock through conduction. The heated oil then drains into the production well. The velocity of oil displacement is equivalent to the velocity of steam chamber rise.

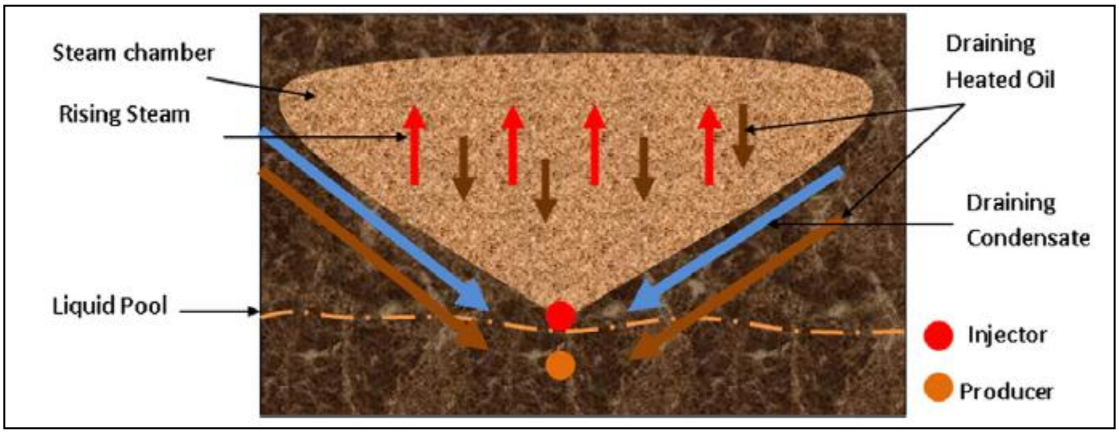


Figure 3.3: Steam fingering and growth of steam chamber (32)

3. Co-current and counter-current displacement

   Nasr et al. (27) stated that the recovery of SAGD depends on the counter-current flows and shape of steam chamber. At the top of the steam chamber, counter-current flow occurs between heated heavy oil and cold bitumen. They developed a numerical model to simulate SAGD counter-current flow. They also proved by history matching that there is a significant difference between counter-current and co-current relative permeabilities for steam and water.

4. Emulsification

   Chung and Butler (33) stated that the production of heavy oil using thermal method always occurs in the form of water in oil emulsion. Viscosity prediction for emulsions is much more complex than for single fluid heavy oil. They proved that when steam chamber grows sideways, the heated heavy oil flows downward. These flow directions of steam and heated oil form the two face stratified flow, which drastically reduces the water in oil emulsion ratio.

5. Residual oil saturation in steam chamber

   Butler (34) observed that the major oil flows sideways on the chamber rather than through the steam chamber. He also supported this observation with two hypotheses:

   (i) Residual oil saturation inside steam chamber is too low to cause any oil movement.
   (ii) Water imbibition and interfacial tension due to water condensate between steam and oil helps the heated oil to flow laterally.

   Walls et al. (35) studied the oil relative permeability within steam chamber, and they concluded that oil and water relative permeability within steam chamber are the main factors, which determines the magnitude and shape of the oil saturation curve as a function of time.

6. Heat transfer and distribution through steam chamber

   Butler (36), in his theory, assumed that the major mode of heat transfer in SAGD is by thermal conduction. Farouq-Ali , Edmunds and Ito and Suzuki (37-39) criticized Butler’s assumption of heat transfer and concluded from their numerical simulations that the main mechanism of heat transfer in SAGD process is by thermal convection. Ghasemi (40) stated that the steam rises in formation due to buoyancy and forms steam chamber. At the edge of the chamber, significant latent heat of steam transfers to oil.

7. Analytical modeling of SAGD for planning and risk assessment

   For planning of SAGD process, doing a risk assessment of critical parameters is very necessary. It can be done by analytically modeling SAGD process. Butler (32) described a mathematical model for steady state conditions. He considered different theories, including Darcy's law of rate prediction and equation of state for viscosity prediction with temperature, for analytical modeling of SAGD process. Temperature was assumed to be constant in the steam chamber. Based on these theories and assumptions, Butler (32) derived the following equations for illustrating the volumetric rate of drainage per unit length.

$$q = 2\sqrt{\frac{2\emptyset \Delta S_o K g \alpha (h-Z)}{m v_s}} \frac{bbl}{day\ per\ length} \qquad [3.1]$$

$$\frac{1}{m v_s} = \left[\frac{1}{v} - \frac{1}{v_r}\right] \log(T_s - T_r) \qquad [3.2]$$

$$q_T = 2\sqrt{\frac{2\emptyset \Delta S_o K g \alpha h}{\left[\frac{1}{v} - \frac{1}{v_r}\right] \log(T_s - T_r)}} \times \frac{L}{B_o} \frac{STB}{day} \qquad [3.3]$$

$\Delta S_o = (Initial - Residual) oil\ saturation$

$\alpha = Thermal\ Diffusivity, sq.ft/day$

$v = kinematic\ viscosity\ of\ oil\ at\ desired\ temperature$

$v_r = kinematic\ viscosity\ of\ oil\ at\ reservoir\ temperature$

$T_s = steam\ temperature$

$T_r = Reservoir\ temperature$

$L = Well\ length, ft$

$B_o = Oil\ formation\ volume\ factor, STB/RB$

$q = rate, K = permeability, g = specific\ gravity, h = paythickness,$

$q_T = total\ rate, z = distance\ of\ producer\ from\ bottom$

3.5 SAGD Element of Success

Success of SAGD project depends upon a number of critical factors such as: (i) accurate knowledge of reservoir, (ii) accurate knowledge of heavy oil, (iii) knowledge of fluid interaction, (iv) efficient utilisation of heat energy injected into reservoir, (v) understanding flow of steam condensate and oil in different direction, (vi) understanding fluid interaction with rock, (vii) impact of steam injection on rock properties (14).

Several authors (4,5,17,19,23,25,41) suggested different ways to ensure success of SAGD. Llaguno et al. (17) after screening more than 1000 reservoirs of Venezuela, classified the elements of success in two subgroups using different prediction models like Butler's original model. The first group was about accumulative properties namely porosity, pay thickness and oil saturation, and the second group was about flow properties such as fluid density, viscosity and relative permeability.

The economics of SAGD process is assessed mainly by the Cumulative Steam-Oil Ratio (CSOR). Steam Oil Ratio is defined as the amount of steam required to produce one barrel of oil (17). Edmunds and Chhina (37) concluded that economics of SAGD is more sensitive to SOR than to oil production rate due to availability of natural gas and price of gas. Some authors (5,36,42,43) also stated that the Recovery Factor (RF), Calendar Day Oil Rate (CDOR) and CSOR decide the economics of SAGD. Ghasemi (40) concluded that initially the economics of SAGD is mainly influenced by the natural gas, which is responsible for steam generation and secondly, by the water treatment and recycling process.

Cumulative steam oil ratio (CSOR) measures the thermal efficiency of SAGD process (40). Gates and Chakrabarty (18) found that the high economic efficiency of the SAGD process can be achieved by optimising the steam injection pressure during the entire life of SAGD process. They also concluded that during the initial phase of SAGD process, the steam injection pressure should be high in order to develop the steam chamber vertically. Later on the pressure should be reduced to minimise the heat loss to overburden.

3.5.1 Key parameters involved in SAGD process

A number of parameters are involved during steam injection into the formation and heated oil production in SAGD process. They include reservoir parameters such as porosity, permeability, thickness, gas saturation, wettability and heterogeneity alter, as well as fluid properties like viscosity, composition, density, oil formation volume factor, relative permeability and thermal coefficient.

It is very important to analyze the behaviour of each involved parameter in order to understand the SAGD process. SAGD process is not a steady state process; hence these parameters are also not constant during the steam injection and oil production. In depth understanding of each key parameter will help in understanding the complex nature of steam chamber growth. Optimization of each and every parameter involved in the process is necessary to optimize SAGD process..

Most of the reservoir and fluid parameters are controlled by operating parameters like steam temperature, steam injection pressure, injection and production rate, spacing and placement of the injector and producer, well length and well pattern. In other words, optimization of the SAGD process can be done by controlling and optimizing the above key parameters.

By reviewing the Butler's analytical model, key parameters involved in SAGD process can be further diagnosed to prioritize their criticality on SAGD process.
It is very clear from analytical equation 3.1 that porosity, permeability, height of reservoir, thermal diffusivity, oil saturation and well length are directly proportional to production rate, whereas, kinematic viscosity (which is the ratio of effective viscosity and density) has indirect relation with the production rate. Achieving high mobility of fluid is the main agenda of any enhanced oil recovery process. Mobility, which is defined as the ratio of effective permeability to effective viscosity (31), can be improved either by reducing effective viscosity or by increasing effective permeability. When it comes to horizontal well, the effective well length also needs to consider equation 3.4:

$$Mobility_{effective} = \frac{K_{effective} l_{effective}}{\mu}$$

[3.4]

In order to have a clear understanding of fluid mobility, one should have a clear understanding about certain fluid properties like viscosity and permeability. The rate predicted by any method is dependent of fluid properties.

Real time knowledge of fluid properties is very crucial in taking decisions about system optimization and well intervention. Uncertainties in the fluid properties result in the low recovery factor due to wrongly optimized recovery process.
Reservoir fluid properties provide key input to (i) simulators used to evaluate reservoir development strategy, and (ii) to daily surveillance tools. Accurate PVT (Pressure-Volume-Temperature) properties are required for interpretation of well test data and the design of surface facilities and processing plants. Fluid characterization and distribution within the reservoir help in defining the continuity and communication within various zones (39). Reliable quantification of fluid phase behaviour entails the measurement of reservoir fluid properties at varying thermodynamic conditions of pressure and temperature. However, it is time consuming and expensive to measure the fluid phase properties at different conditions; thus EOS (Equation of State) or Black oil models are used to predict these properties. The predictions of an EOS cannot be relied upon directly as it cannot accurately simulate the interactions between numerous hydrocarbon and non-hydrocarbon components present in petroleum crude oil. In order to have meaningful and accurate estimates of fluid properties and phase behaviour, EOS requires some amount of tuning to match with experimental data. Petroleum is an extremely complex mixture of hydrocarbon compounds with minor proportions of nitrogen, sulphur and oxygen containing compounds.

Compared to conventional crude oil, heavy oil has different physical, chemical and thermal properties which are due to different compositions. All these properties for a fluid are also dependent on pressure, temperature and volume; hence most of them are known as PVT properties. Some of the physical properties like colour and odour may not depend on PVT conditions, but most other properties are dependent on PVT. The main properties of petroleum heavy crude oil are as follows:

(i) Density and specific gravity
(ii) Compressibility
(iii) Viscosity
(iv) Oil Formation volume factor
(v) Bubble point pressure
(vi) Gas-Oil ratio
(vii) Specific heat
(viii) Thermal coefficient
(ix) Heat of combustion
(x) Pour point
(xi) Boiling point

Critical PVT properties, which depend on PVT conditions are density, specific gravity, compressibility, viscosity, oil formation volume factor, bubble point pressure.

3.5.2 Critical PVT properties

3.5.2.1 Oil Specific Gravity or Oil density

Oil Specific Gravity is defined as the ratio of density of oil to the density of water taken at the same temperature and pressure (44).

$$\gamma_0 = \frac{\rho_o}{\rho_w} = \frac{Density\ of\ oil}{Density\ of\ water} \qquad [3.5]$$

The petroleum industry uses another term known as API gravity

$$API = \frac{141.5}{\gamma_o} - 131.5 \qquad [3.6]$$

3.5.2.2 Oil Viscosity

Oil viscosity is a measure of the resistance of oil to flow. Heavy oil has high molecular weight, due to the presence of high fraction of complex hydrocarbon compounds; hence the internal resistance to flow of heavy oil is much high than light crude oil, which explains the huge difference in viscosity of light and heavy crude oil. High viscosity is a major issue in developing heavy oil fields (45).

Internal resistance to flow of liquid petroleum crude shows an indirect relationship with its temperature, which means that as the temperature increases, viscosity of crude oil decreases. But in case of gases, the viscosity increases with increase in temperature (46).

The reciprocal of viscosity is fluidity. Heavy oil has very low fluidity or mobility due to high viscosity (47). The recovery process of fluid from the reservoir in petroleum industry requires the application of a shear stress corresponding to the fluid viscosity because shear viscosity plays a critical role in the recovery process (48). Depending on the shear viscosity behaviour there are two major classes of fluids.

(i) Newtonian fluids

(ii)Non-Newtonian fluids

Newtonian fluids have constant viscosity, which means that their viscosity is independent of shear rate or shear stress. On the other hand, the non-Newtonian shear viscosity depends on shear rate and shear stress (49). Light crude oil shows Newtonian behaviour; hence its viscosity is only temperature dependant and is independent of shear rate or shear stress. Different empirical correlations were developed to predict the viscosity of light crude oil at any temperature. Similar to other PVT correlations, viscosity correlations were also developed from huge data points by different authors. Commonly used viscosity correlations for the light oil have been listed Table 3.1.

3.5.2.3 Oil Compressibility

Isothermal Compressibility is defined as the rate of change of volume with respect to the change in pressure per unit volume at constant temperature (50).

Like the other fluid properties, isothermal compressibility can also be calculated from experiments and also from existing standard correlations. It is defined in units of psi^{-1}.

The formula for isothermal compressibility is given by

$$C = -\frac{1}{V} \times \frac{dV}{dP} \quad [3.7]$$

3.5.2.4 Oil Formation Volume Factor (B_o)

Oil formation volume factor (OFVF) is defined as the volume of oil measured at reservoir conditions to give unit volume of oil at stock tank conditions (51).

$$B_o = \frac{\text{Volume of Oil+Dissolved gas leaving reservoir at reservoir conditions}}{\text{Volume of Oil entering stock tank at standard conditions}} \quad [3.8]$$

It is critical to track OFVF as it is pressure dependent (figure 3.4).

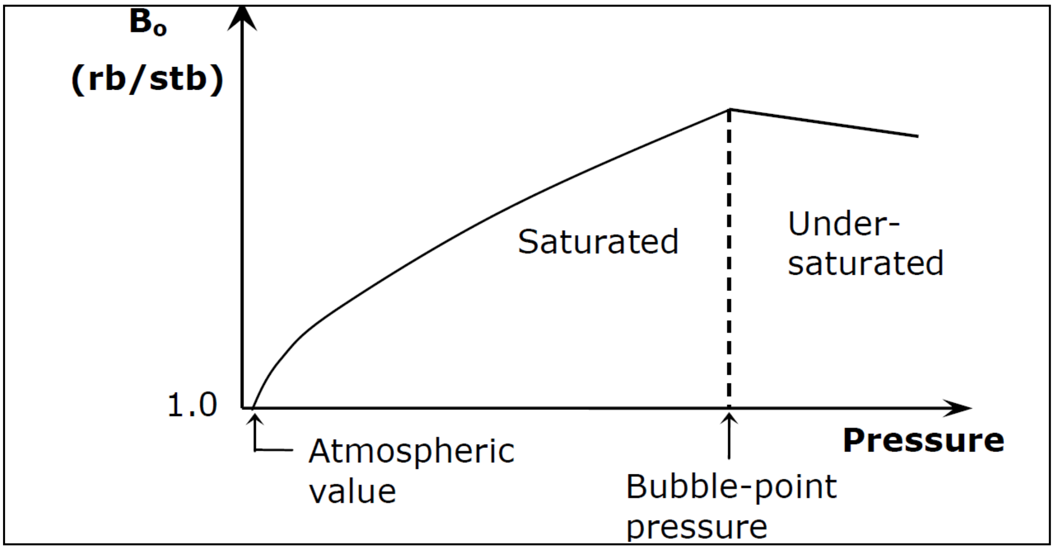


Figure 3.4: OFVF profile with pressure (51)

3.5.2.5 Solution Gas Oil Ratio (GOR)

SGOR can be defined as the amount of gas that gets dissolved in unit volume of crude oil at a specific temperature and pressure (51). This parameter depends on the pressure, temperature, and the API gravity of the oil and the gas. It is expressed in units of scf/STB.

Generally, the GOR increases with pressure until the bubble point. At bubble point, all gas settles in the oil, and the GOR reaches its maximum value. Below the bubble point pressure, gas is liberated and the GOR decreases with pressure.

3.5.3 Prediction Methods for PVT properties

From the reservoir to the separator, the pressure and temperature are not constant; hence it is essential to define the fluid behaviour or PVT properties at those pressure and temperatures for which mainly the following two methods can be used.

3.5.3.1 Equation of State Method

In this method, different Equation-of-State (EOS) can be used to calculate fluid state variables at different conditions. Peng Robinson and Soave Redlich Kwong are two mainly used EOS models (48). Main input parameter for this method is the oil composition. Methods like gas chromatography can be used to identify the fluid composition up to a maximum carbon number limit of 20 (C_{20}), but it cannot be used for higher carbon numbers (C_{20+}) because of very high boiling point of higher carbon number components (48). The higher carbon number components can be categorized into groups like C_{20+} - C_{25+} depending on their boiling point range or average molecular weight. Such components are known as pseudo components. The percentage of pseudo components in heavy crude oil is much higher compared to light crude oil mixtures or natural gas. Hence, it is very difficult to get an accurate composition for heavy crude oil (2,4,6). EOS method is applicable for extracting light crude oil, oils which have high API gravity, gas condensate, and is best suited for the extraction of natural gas, where the major components are methane and short chain alkanes.

3.5.3.2 Black Oil Method

Based on wide range of dataset for PVT properties, different authors have developed empirical equations, known as Black Oil Models, to calculate the PVT properties

Different PVT experiments were performed in different parts of the world on wide range of crude oils and then empirical equations were derived to link the PVT properties at different pressures and temperatures.

In the oil industry, the commonly used correlation for PVT properties like density, oil compressibility, gas-oil ratio, bubble point pressure and oil formation volume factor are tabulated in Table 3.1 (44,51) :

Table 3.1: Commonly used PVT correlations

OFVF Correlation	Equation T in °F
Glaso correlations	$B_{o,Glasq} = 1 + 10^{\left(-6.5811+2.91329logG-0.27683logG^2\right)}$ $G = R_s\left(\rho_g\middle\|\rho_0\right)^{0.526} + 0.968T$
Standing correlations	$B_{o,standing} = 0.9759 + 12 \times 10^{-5}\left[\left(R_s\rho_g\middle\|\rho_0\right)^{0.5} + 1.25T\right]^{1.175}$
Vazquez-Beggs correlations	$B_{o,V\&B} = 1 + 4.677 \times 10^{-4}R_s + 1.751 \times 10^{-5}(T + 60)(API/\rho_g) - 1.811 \times 10^{-8}R_s(T + 60)(API/\rho_g)$
Al-Marhoun correlations	$B_{o,Al-M} = 0.497069 + 0.862963 \times 10^{-3}(T + 459.67) + 0.182594 \times 10^{-2}M + 0.318099 \times 10^{-5}M^2$ $M = {R_s}^{0.74239}{\rho_g}^{0.323294}{\rho_0}^{-1.20204}$
Heavy Oil Viscosity Correlation	
Egbogah-Jack's correlation	$\mu_{Egbogah} = 10^{10^{(2.06492-0.0179API-0.70226logT)}} - 1$
Egbogah-Jack's correlation extra heavy	$\mu_{Egbogah,Extra} = 10^{10^{(1.90296-0.012619API-0.61748logT)}}$
Bennison, >20 API,250 GOR	$\mu_{Bennison,>20API,250GOR} = 10^{(0.10231API^2-3.9464API+46.5037)}T^{(-0.04542API^2+1.70405API-19.18)}$
Bennison, <20 API,250 GOR	$\mu_{Bennison,<20API,250GOR} = 10^{(-0.8021API+23.8765)}T^{(0.31458API-9.21592)}$

A number of black oil correlations are available in the public domain for conventional crude oil. The benefits of such correlations over the EOS method are that

(i) they don't need composition,

(ii) they are less expensive and time saving,

(iii) they can be tuned to experimental data, and

(iv) they require very basic information like oil density and solution GOR

3.5.4 Prioritization of SAGD parameters

HSE risk analysis is a part of decision-making process. During the risk assessment of SAGD process, it is crucial to understand each and every key parameter, which contributes to the success of the SAGD process. Maximum efficiency can be achieved by optimizing the key parameters. Energy losses during SAGD process could be minimized by operating at the optimum point. Due to its dynamic nature, the initial risk assessment of SAGD process is done using different thermal reservoir simulators. Thermal reservoir simulators like Eclipse thermal, Reveal and STARS are normally used to do the planning and risk assessment.

SAGD can be successful, if high recovery factors can be achieved at low cost. Identification or prioritization of critical parameters can be done using the analytical model, which regulates the process. All the parameters have an operating range and each value associates with cost of the project. Parametric study is mandatory for prioritization of different variables, which can be done using any statistical software like Microsoft Excel, Minitab and Oracle Crystal Ball.

In this research, Oracle Crystal Ball was used for parametric and sensitivity analysis. It is a spreadsheet based application, which is used for predictive modeling, forecasting, simulation and optimization. It is based on Monte Carlo simulation principles. "Monte Carlo simulation is a computerized mathematical technique that allows people to account for risk in quantitative analysis and decision making" (31).

When there are more than one operating variable in the system to optimize, then it is very complex to find their optimum values because many different combined interactions between the variables are possible. Hence, in such scenarios, sensitivity analysis is very helpful. The sensitivity and parametric study requires the correlation between objective function and the parameters. Since SAGD has two horizontal wells, it is much better to use the productivity equation of horizontal well than using the Butler's analytical correlation for doing the parametric study. More than 25 productivity equations are available for horizontal well (52,53), but we used the Renard's productivity equation to do the sensitivity analysis as it accounts for all the required parameters (54). Equation 3.9 is the Renard's horizontal well productivity equation for anisotropic reservoir (54).

$$Renard\ Productivity = J = \frac{7.08\times10^{-3}\times K_h\times h}{\mu B_o(Acosh(X)+(I_{ani}{}^{h}/_{L})\times\ln(\frac{\frac{h}{2pir_w(1+I_{ani})}}{2I_{ani}})} \quad [3.9]$$

The reservoir and productivity data (Tables 3.2-3.4) used in the analysis was taken from published literature (55).

Table 3.2: Reservoir and fluid properties (55)

Reservoir thickness	98 ft
Reservoir length	1000 ft
Reservoir Width	1000 ft
Absolute horizontal permeability	5000 md
Absolute vertical permeability	4000 md
Porosity	0.304
Initial reservoir pressure	363 psia
Initial reservoir temperature	80 ^{0}F
Surface oil density	10.1 ^{0}API
Initial oil viscosity	1000 cp
Initial oil saturation	0.87
Initial water saturation	0.13
Oil compressibility	5.03 E-06 psi^{-1}
Oil thermal expansion	4.0E-04 ^{0}F^{-1}
Rock compressibility	3.03 E-06 psi^{-1}
Rock thermal conductivity	24 BTU/(ft-day-^{0}F)
Rock volumetric heat capacity	38.6 BTU/(ft3-^{0}F)

Table3.3: Possible variation in parameters during SAGD (55)

Operating Variables	Operating window
Well spacing	20 – 90 ft

Well length	100-1000 ft
Oil Viscosity (Max. Temp 400 ^{0}F)	1000-5 cp
Oil Density	980-999 Kg/m^3
Porosity	10 %
Water saturation	0.13-0.7
Oil relative permeability	1-0.2
Effective horizontal Permeability	5000-1000 md
Effective horizontal permeability	4000-800 md

Table 3.4: Sensitivity results from Crystal Ball Simulator

Sensitivity Results: Renard PI	
Parameters	Sensitivity
Oil Viscosity	-0.712
Kh effective in X direction	0.162
Well Length	0.112
Kv effective	0.012
Well spacing	0.0003
Oil Formation Volume Factor	4.97E-05
Kh in Y direction	1.26E-05

Sensitivity analysis of the critical parameters simulated on Crystal Ball simulator is presented in Table 3.4. Data from Table 3.3 were used to define the operating window of each parameter in the Crystal Ball simulation. Oil viscosity showed the highest impact on the well productivity of horizontal wells. This is because the oil viscosity parameter has the widest operating window compared to other variables.

The next sensitive parameter was effective permeability of the fluid. In SAGD, due to continuous steam injection, water cut increases with time; hence the oil relative permeability reduces with an increase in water cut, which affects the oil production rate. Well length also has a positive impact on productivity but one has to be careful with well length as the horizontal well flow efficiency reduces after certain well length which is demonstrated in Chapter 6 section 6.4.

Sensitivity analysis showed the three most critical parameters. Hence partial optimization of SAGD process can be achieved by getting optimum values of these three parameters. Oil viscosity has highest negative impact on well productivity, this means as the oil viscosity reduces, horizontal well productivity increases. Reducing oil viscosity to possible lowest value doesn't represent the optimum value, as the relative cost to reduce the oil viscosity by a few percent could be relatively very high. Figure 3.5 shows the variation of well productivity with oil viscosity. Figure 3.6 presents oil viscosity data reported in literature as a function of temperature. But it may not be possible to do such experimental measurements on any heavy oil samples at any required conditions. Hence the correlation of oil viscosity with temperature can help to obtain the optimum solution as there will be constraint on maximum temperature. But if the viscosity correlation has some uncertainties, then the optimum solution cannot be obtained. Hence, getting the accurate oil viscosity correlation for heavy oil is one of the biggest challenges in optimizing heavy oil recovery process.

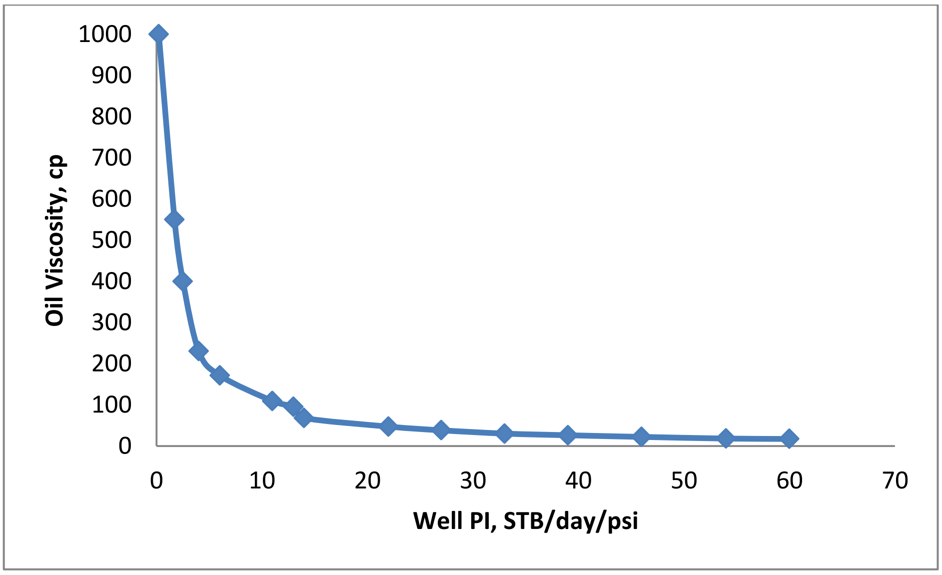


Figure 3.5: Impact of oil viscosity on well productivity

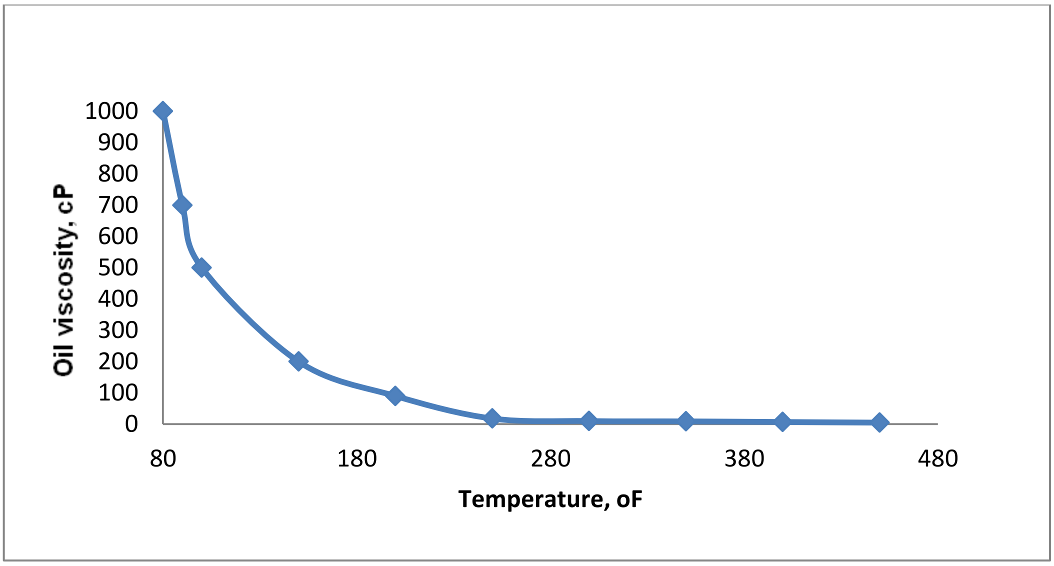


Figure 3.6: Fluid viscosity profile

3.6 Technology gaps in SAGD process

From what has been discussed so far, it is clear that a lot of work has been done on SAGD process by several authors (9,17-19,21,22,24,25,29,31,37,38,40,41,56,57) who tried to minimize the uncertainties in SAGD process. No process is perfect or 100% efficient; there are some technological gaps in SAGD process, which can be grouped into four main categories: (i) Horizontal Well model for SAGD, (ii) Need for controlled PVT experiments, (iii) Effective permeability for oil in SAGD, and (iv) Real time SAGD simulator for risk assessment

3.6.1 Horizontal Well model for SAGD

Although more than 25 horizontal well productivity equations are available in the public domain (52) the choice of equation for risk assessment and planning of SAGD is still unclear. Productivity index is the measure of flow mobility in a reservoir formation. Achieving high productivity index in SAGD process is crucial for both the producer and the injector. Background work proved that all the 25 available horizontal productivity models predict different results at the same operating conditions (31). Hence the uncertainty in choosing the right horizontal productivity equation is denoted as a technology gap in this process. This technology gap can be met, by recommending the apt productivity model for horizontal well in SAGD process, after detailed understanding and screening of each and every equation. The details of this risk assessment are covered in Chapter 6.

3.6.2 Need for controlled PVT experiments

Preliminary studies (49) on different heavy oils have established that they are predominantly non-Newtonian at standard as well as at higher temperatures and pressures [Figure 3.7].

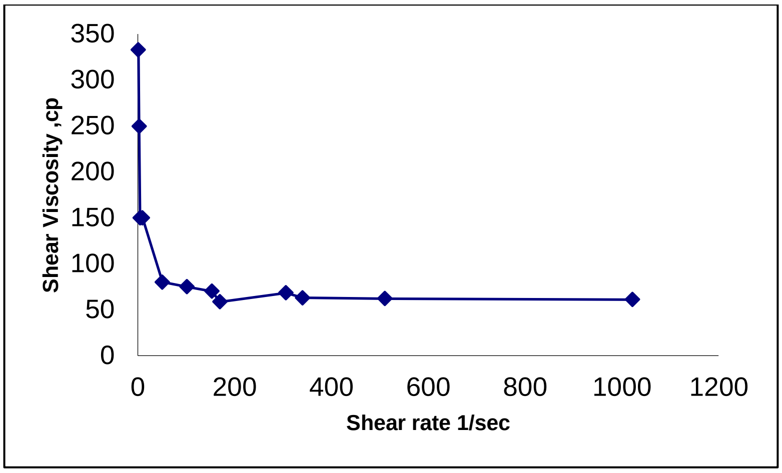


Figure 3.7: Non-Newtonian behaviour of Heavy Oil (31)

Behavior of a Non-Newtonian fluid is different from that of a Newtonian fluid. Few of the reported literature have discussed the Non-Newtonian behaviour of heavy oil. This research gap forms the core of this research. As heavy oil is distinguished from conventional crude oil by its rheology, so it is important to understand the rheology of heavy oil at different conditions. To date, the published work has seldom attempted to track the rheology of heavy oil in SAGD process. Due to the lack of information on its rheology, experimental study is the only option to know the rheology of heavy oil at different temperatures. It is also important to test a large number of samples to cover the whole range of heavy oil. Experimental study should be done not only for rheology, but also for other PVT properties like viscosity and density because some analytical models have also been developed by considering heavy oil as Newtonian fluid (58). The different types of experiments conducted as part of this project study with their observations are presented in Chapter 4.

3.6.3 Effective permeability for oil in SAGD

SAGD process is a multiphase operation. Steam chamber contains steam, water condensate, heated oil, solution gas and formation water. Oil mobility gets affected by the presence of different fluids in the chamber. Oil mobility depends upon the concentration of other fluids. Water cut is an unsteady state variable in the SAGD process. These parameters impact on the effective permeability of the host reservoir. Therefore effective permeability to oil during SAGD process has been identified as one of the critical parameters responsible for success of SAGD. Steam, condensate, formation water and heated oil are the fluids involved in SAGD process; hence getting the relative permeability of oil during SAGD process is also a challenge. Effective permeability is the product of absolute and relative permeability. Getting the real time absolute and relative permeability in SAGD process is also considered as a research gap and will be addressed in Chapter 7.

3.6.4 Real time SAGD simulator for risk assessment

"The process of mimicking the behavior of fluid flow in a petroleum reservoir system through the use of either physical or mathematical models is called reservoir simulation" (59). Thermal reservoir simulators like Eclipse thermal, STARTS and REVEAL are used to do the thermal simulation such as SAGD (55). Every simulator solves different fundamental equations like Darcy's law with energy balance equations, using fluid models for PVT properties. A large body of work (9,17-19,21,22,24,25,29,31,37,38,40,41,56,57,60-62) has been done to understand energy balance equations in order to track the growth of steam chamber to calculate heat losses and to get the shape of steam chamber. These simulators solve a complex reservoir model. High configuration computer system is required to solve the complex reservoir model. Both building and solving reservoir models are a time consuming process. It is impossible to use these simulators in real time to do the quick risk analysis during field development.

Since heavy oil is characterized as a non-Newtonian fluid, the inbuilt fluid models for PVT properties cannot be accurate. The first step to build the real time simulator for SAGD is to build the accurate PVT models for heavy oil. Accurate PVT models for heavy oil are developed using experimental dataset which is given in Chapter 5. The real time SAGD simulator is also presented in Chapter 7 by uniting the developed and adopted models.

3.6.5 The Need for new PVT models

There were main two reasons for conducting the experimental studies on heavy oil.

1. Heavy oil behaviour is Non-Newtonian in nature. Therefore rheology of heavy oil is shear rate and stress dependent. Pressure and temperature are not constant in SAGD process hence there is a need to track the rheology of heavy oil with pressure and temperature for better understanding of fluid behaviour in the SAGD process.
2. There are a number of black oil models available for predicting PVT properties such as oil formation volume factor (OFVF), density and viscosity (58). Using available black oil prediction models from Table 3.1, OFVF and effective viscosity were calculated and plotted in figure 3.8 and figure 3.9. Both figures show the different predictions from different models. Figure 3.7 also explains that the current viscosity models are independent of shear rate which means that they don't consider the Non-Newtonian behaviour of oil. There is therefore a requirement to develop an accurate real time PVT models for heavy oil by considering its Non-Newtonian behaviour which changes with time and compositional phase. For empirical model development, the basic requirement is of actual data measurements. It is a big challenge to get the required data points from the field hence performing controlled PVT experiments and building accurate database is the only solution.

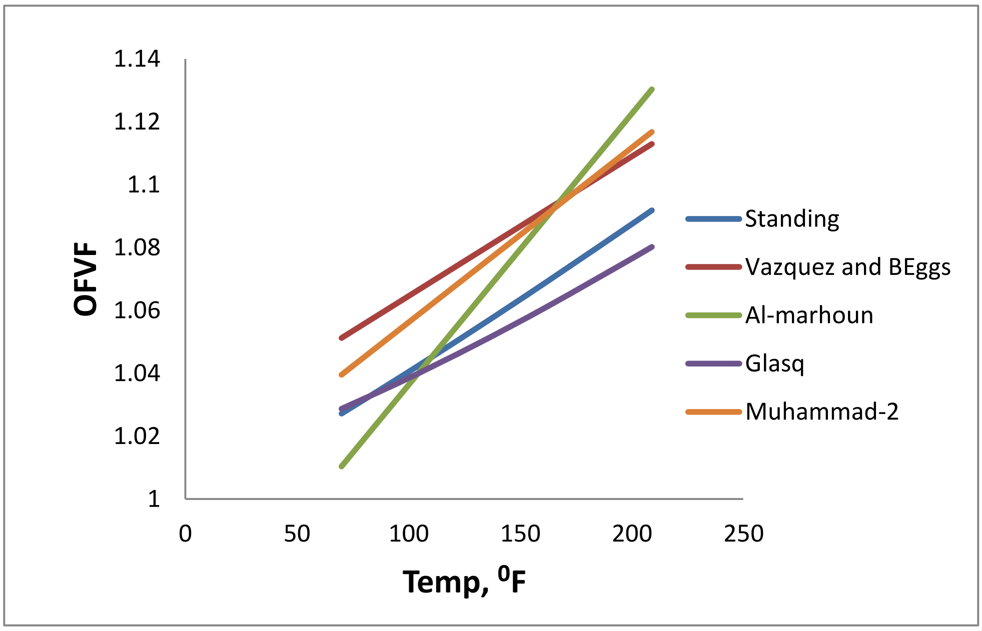


Figure 3.8: OFVF by different correlation for 19.5 API oil with 100 GOR

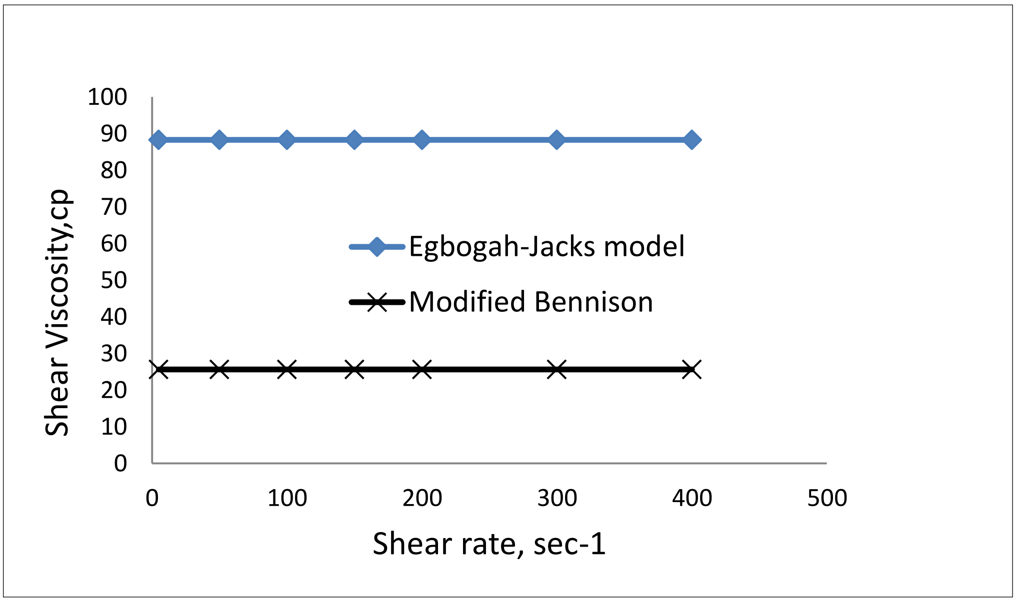


Figure 3.9: Analytical viscosity for heavy oil

CHAPTER 4: EXPERIMENTAL STUDIES FOR PVT PROPERTIES

4.1 Introduction

This chapter presents the experimental studies with different types of experiments. The brief description about the equipment being used in experiments is given prior to the detailed operating procedure for each of the equipment. Quality assurance and quality control (QAQC) is also summarised in this chapter. Experimental results are presented in the last section of this chapter.

4.2 Types of experiments

There was a need for two different types of experiment to build the database.

1. Experiments for PVT analysis
2. Experiments for Rheology analysis

4.2.1 Pressure-Volume-Temperature (PVT) analysis

In these types of experiments the fluid is exposed to different pressure and temperature to understand the fluid behaviour. Different types of PVT cells are available to perform such types of experiments. In this research project, two different types of PVT cells were used and the reason for using the two was to understand the impact of fluid volume on PVT properties and also to validate the dataset. The working principle of major density cells is same but could be slightly differ by types of pressurising system.

4.2.2 Viscosity/ Rheology analysis

For viscosity measurement and rheological characterisation, the fluid is exposed to different shear rates at controlled temperatures and then measure the shear stress or shear viscosity. Rotational Viscometers like Fann-35 rheometer applies different shear rates and allows shear stress measurement whereas viscometer like Brookfield directly measures the shear viscosity directly at specified shear rate. Here also for QAQC, two types of viscometers were used for benchmarking and back-to-back calibration.

4.3 Technical specification of equipment

Four different types of experiments were used in experimental studies and their technical specification is given below.

1. Micro-PVT Density Cell

Micro-PVT system is designed to arrange for experimental studies of dependence of volume and temperature of fluids and crystallizing media on pressure at various loading (compression) and unloading rates. A small electromechanical press is used as a basic tool for these studies (Fig 4.1). In addition to press the instrument consists of control unit (CU) and personal computer (PC). MICRO-PVT system is based on the virtual instrument principle enabling user work in standard environment of physical and chemical experiments, since the computer's display emulates the panel of a virtual instrument. Only concern about Micro-PVT is the small volume which could not represent the whole system correctly.

Figure 4.1: Micro-PVT (63)

Table 4.1: Basic Technical Specification for Micro-PVT (63)

Name	Micro-PVT
Type	Density Cell
Pressure Range	Up to 50000 psi
Temperature Range	Up to 170 ^{0}F
Sample Required	1 ml
Loading-Unloading	From 0.1 rpm onwards
Calibration	All gauges were calibrated

2. In house Density Cell

To overcome the limitation of Micro-PVT of small volume, Density cell was built which can take up to 250 ml of sample. Function of this cell is same as Micro-PVT. This cell needs to run manually such as an oil pump to pressurise the system and pressure, temperature gauges to measure the pressure and temperature of sample. Displacement gauge is to calculate the relative change in volume of the sample.

Figure 4.2: In-house Density Cell

Table 4.2: Basic Technical Specification for In-house density cell

Name	In house density cell
Type	Density Cell
Pressure Range	Up to 5000 psi
Temperature Range	Up to 200 ^{0}F
Sample Required	250 ml
Loading	100 psi per step
Calibration	All gauges were calibrated

3. Fann-35 Viscometer

The test fluid is contained in the annular space or shear gap between the cylinders. Rotation of the outer cylinder at known velocities is accomplished through precision gearing. The viscous drag exerted by the fluid creates a torque on the inner cylinder or bob. This torque is transmitted to a precision spring where its deflection is measured and then related to the test conditions and instrument constants. This system permits the true simulation of most significant flow process conditions encountered in industrial processing.

Table 4.3: Basic Technical Specification for Fann-35 (64)

Name	Fann-35
Type	Viscometer
Pressure Range	Atmospheric pressure
Temperature Range	Up to 200 ^{0}F
Sample Required	100 ml
Shear rate loading	11 rpm steps (0.9 to 300 rpm)
Calibration	All gauges were calibrated

Figure 4.3: Fann-35 (64)

4. Brookfield Viscometer

The Brookfield DV-III Programmable Rheometer measures fluid parameters of Shear Stress and Viscosity at given Shear Rates. The principle of operation of the DV-III is to drive a spindle (which is immersed in the test fluid) through a calibrated spring. The viscous drag of the fluid against the spindle is measured by the spring deflection. Spring deflection is measured with a rotary transducer. The measuring range of a DV-III (in centipoise) is determined by the rotational speed of the spindle, the size and shape of the spindle, the container the spindle is rotating in, and the full scale torque of the calibrated spring.

Figure 4.4: Brookfield (65)

Table 4.4: Basic Technical Specification for Brookfield (65)

Name	Brookfield
Type	Viscometer
Pressure Range	Atmospheric pressure
Temperature Range	Up to 200 ^{0}F
Sample Required	100 ml
Shear rate loading	From 0.1 rpm onwards
Spindles	4 different LV spindles available
Calibration	All gauges were calibrated

4.4 Experimental Procedures

4.4.1 Procedure for Micro-PVT (63)

- Assemble the cylinder on the press, inserting it on the rod and rotating the cylinder by hand , checking alignment and preventing cutting of bushing on the rod. Insert the cylinder until it stops and make 3 or 4 additional rotations aligning fasting holes of the cylinder with those of the arm, and make the cylinder facing the front of the press
- Tighten 6 fastening screws of the cylinder using screw driver from the tool kit.
- Prior to the onset of tests of the substance in High Pressure Cylinder (HPC) it is necessary to calibrate press' volume and pressure to zero.
- Press key V0 on the main interface panel. The mode gets started by pressing button To Low Position
- After volume calibration, press key P0 at the main panel. The regime is being activated by pressing GO button.
- Fill the sample into the HPC using the syringe from the tool kit making sure the syringe and the needle do not contain air. Put the needle down into the aperture of the cylinder until it contacts the rod. It is allowed that some amount of liquid to be tested enters the threaded aperture of the cylinder.
- Close the aperture of the cylinder by sealing stopper (temperature detector with rubber seal) and turn the screw initially by hand and then using two wrenches no 17 from the tool kit.
- Filling of HPC with viscous substance should take place prior to fixing the cylinder on the press and before installation of bushing, fitting rings and nut pressing the test substance through the cylinder hole until it comes from the opposite side of the cylinder.
- After filling HPC establish fitting rings, bushing and nut and mount the cylinder on press.
- In case of necessity compact the viscous substance by push-rod and add it up to the top of cone.
- The process of studying the substance consists of moving a rod relative to HPC with pre-set speed until the pre-set value of pressure (compression) gets achieved. After that the stepper motor reverse

direction and rod moves with the same speed reducing pressure to zero (decompression).

- Before starting operations in the loading-unloading cycle the operator has an opportunity to change values of variables: the maximum pressure of loading, RPM of the shaft of the stepper-motor (through adjusting frequency of generated pulses). Default values of pressure are 500 MPa and RPM = 2 (10 Hz). Automatic reverse can be disengaged (AR Off).
- The regime gets activated by pressing key Go. After that the key transparent start reading Stop. If operator presses this button during operation cycle this will results in shutting down (engine stops and the rod gets immobile). During this phase the pressure in HPC remains the same as it was at the moment of shut down.
- After resuming operation the graph V/V0=f(P) is being displayed in the right hand side of display, digital display depicting current numerical values of process parameters: Detector V, mm indicate position of detector monitoring rod progress in press MT-60; Detector P, mm reflect the output of detector of deformation of measuring spring MT-12; V, mm^3 depict the current value of volume occupied by substance in HPC; Pressure, MPa – yields the current pressure in HPC; Temperature, C^o -- the current temperature inside HPC. The amount of points shows the number of current measurement point.
- When zero pressure achieved in HPC question «Store experimental data?» emerges on display. Pressing key «YES» results in storing the data for further processing in the file having .dat extension and default name consisting of the day, month, hour and minutes (dd_hh_mm.dat) when the file was created. During filing the data the operator can input relevant comments or rename the file. If operator elects pressing «NO» key, the data from a file temp.dat containing the experimental data can be looked through in DATA regime until the next cycle of loading-unloading is accomplished and the contents of file temp.dat is updated.
- Pressing EXIT button results in closing the window of the mode and exiting in the main window of the program.

- Viscous substance should be removed from HPC after the stopper is removed, the cylinder is taken off the press and both the nut and bushing are dismantled. The substance should be forced out of the cylinder by push-rod, o-ring and fitting rings.
- Heating jacket is placed above HPC cell to perform the experiments at constant defined temperature.
- Repeat the procedure at different temperatures.

4.4.2 Procedure for In-house density cell

- Make sure the piston is at top position. If not then push it to top position
- Fill the sample and close the cap
- Use new seal for every sample to avoid the leakage at high pressure
- Connect hand pump to density cell
- Connect temperature sensor
- Put the density cell on hot plate
- Install the displacement gauge to monitor the position of piston
- Start the hot plate and achieve the required temperature
- Heat the cell slowly to avoid overheating.
- Prior to start experiment it is necessary to take piston to fluid level.
- Start pressurising the cell slowly using hand pump and monitor the pressure in pressure gauge. Keep pressurising until the pressure gauge reads the lowest pressure in pressure gauge
- Note down the displacement gauge reading. This is the starting point of experiments.
- Note down the temperature, displacement gauge and pressure readings from hand pump for each step change in pressure gauge installed on density cell
- Load the system up to maximum 5000 psi and then start unloading. Take readings while unloading as well.
- Repeat the experiment at different temperatures.

4.4.3 Procedure for Fann-35 viscometer (64)

- Make sure the main switch is off
- Attach rotor and bob to the spring
- Fill the sample to the sample heating cup
- Put sample holder on base of Fann-35 and make sure it sits properly on base
- Connect sample cup to the heating circuit
- Put the spindle inside sample fluid up to the mark on spindle by lifting the base
- Make sure that the gearbox is set to the low mode and then start the motor at low rpm
- Note down the shear stress from the dial gauge
- Change the rpm to higher value and note down the shear stress. During changing the rpm don't switch off the motor
- After taking readings for all RPMs, switch off the motor and shift the gearbox to high mode
- Start the motor and note down the shear stress readings for different RPMs
- Change the temperature using heating circulation system and repeat the above steps

4.4.4 Procedure for Brookfield viscometer (65)

- Turn power switch on.
- After a short pause the display will read ***"REMOVE SPINDLE, LEVEL RHEOMETER AND PRESS THE MOTOR ON/OFF KEY TO: AUTOZERO."***
- Press Motor ON/OFF key
- After 15 seconds the display reads ***"AUTOZERO IS COMPLETE REPLACE SPINDLE AND PRESS NEXT KEY."*** Press the NEXT key
- Enter the two digit code for the spindle you intend to use. Spindle Entry Code numbers are found in Brookfield Manual in Appendix A. Pressing the SELECT SPDL key once more accepts the spindle entered.
- Insure the motor is on.
- Insure the correct spindle number is shown on the screen

- Enter the required RPM by pressing the appropriate numbers
- Press NEXT to accept the speed
- Note down the viscosity displayed on the screen
- Note down the viscosities at different RPMs
- Repeat the experiment at different temperatures.

4.5 QAQC analysis for experimental studies

The first step in experimental studies is to do the preliminary analysis on experimental procedure, safety guidelines, window of operating parameters, data collection, error elimination, data formatting and template for data analysis. It is also important to understand the operating variables and the output variables. These variables might change with the type of experiment. To decide the step change in operating variable it is also necessary to understand the sensitivity of each operating variables on output measured variable by considering an equipment constraints. Sensitivity analysis is only possible if there is any correlation available between operating and measured variable or it can also be done if there is already previous experimental database available. To minimise uncertainties and to build a good experimental database it is useful to take a smallest step change for operating variables. When there are more than one operating variables then it is also important to perform the experiments by varying only one of them at a time and keeping all others constant. Repeating tests is a good option to minimize the human and instrument errors. Repeating experiments also give a confidence on measured data points. Validation of data points can also be done by performing same type of experiments on different equipment.

4.5.1 Number of samples

Experimental studies were all about to understand the fluid behaviour of heavy oil by generating accurate database for heavy oil. It was important to define the range of heavy oil samples to be tested on different equipment. As discussed in chapter 2, Heavy oil is defined as oil having an API gravity of less than 20^0 API or oil having viscosity above 100 cp (Centipoises) at reservoir conditions. Oil having API gravity below 10 is known as extra heavy oil or tar sands depending on oil viscosity. Therefore the range of API for Heavy oil considered in this research project was from 10-22^0 API. Dead heavy oil samples were collected from different part of the world (North Sea, Alaska, Venezuela) to cover this range. There were in total six heavy oil samples from different fields. Their API specific gravity and volume have been summarised in Table 4.5.

Table 4.5: Summery of API specific gravity for heavy oil samples

Sample Number and Name	API specific gravity at standard room temp.	Volume, mL
1 (Old A)	20.6	5000
2 (Old B)	19.5	4800
3 (Old C)	22.3	4500
4 (Sudan A)	11.4	4900
5 (Exite B)	10	5000
6 (New C)	11.5	5000

4.5.2 HSE study for experiments

After considering the safety of personnel and environment, each of the equipment was tested under health and safety regulations and then defined the operating range for different variables. Mainly the concern variables were fluid, pressure and temperature. Issues and preventive measures against each of the variable are summarised below.

1. Fluid

   Three different types of fluids were handled during the whole set of experiments which were water, heavy oil and toluene. Water was used as a heating fluid and a deep fryer was used to heat the water. Six different types of heavy oil samples were tested on different equipment. Toluene solvent was used to clean the equipment. As heavy oil is very sticky and difficult to remove from metal surface using normal detergents hence toluene solvent was used to clean the tools being used during the experiments. Fumes and smell of toluene was the main concern and to overcome this problem face mask and safety goggle were used while performing experiments and also used while cleaning the utensils.

2. Pressure

   This was the most critical operating variable during the density cell experiments. As mentioned above two different density cells were used to generate large database for heavy oil. One of those density cells were fabricated in-house hence it was essential to define the maximum operating pressure range for it. The cell was designed by considering the safety factor of 2 hence the safety margin was 200%. Design pressure for in-house cell was 10000 psi and maximum operating pressure was set to 5000 psi. Manual hydraulic hand pump was used to pressurise the cell hence the limitation on maximum operating pressure was from hand pump. The manufacturer of the other density cell which is Micro-PVT has provided the maximum operating pressure of 75000 psi but again to remain on safe side it was decided to go up to 50000 psi on Micro-PVT. All the parts of Micro-PVT which were exposed to high pressure were handled carefully and also it was made sure that the seals and joints were placed correctly during every experiment.

3. Temperature

   Temperature constraint was due to the flexible hoses used to circulate the hot water. Plastic tubes were expanding at higher temperature and risk of leakage was increasing with increase in temperature hence the maximum limit on temperature was set to 175 ^{0}F. For in-house density cell where hot plate was used to heat the sample, leakage from temperature sensor was observed above 220 ^{0}F hence the maximum operating temperature for in-house density cell was set to 200 ^{0}F.

4.5.3 Step change in operating variables

In total for both types of experiments there were three main operating variables. For density cell type of experiments the operating variables were pressure and temperature where as for Rheology analysis operating variables were speed of shearing and step change in temperature. By knowing the upper limit of each operating variable, to obtain large database it was essential to have small step change in each operating variables. Fann-35 has fixed twelve rpm options hence here only step change in temperature is possible. From 75 to 175 ^{0}F, step change of 10-20 ^{0}F was adopted. Similarly on Brookfield and Micro-PVT step change in temperature was 10-20 ^{0}F as the same heating system was used for all of them. For in-house density cell, upper limit was slightly higher than others but to maintain consistency the step change in temperature was kept same.

When it comes to pressure step change, in Micro-PVT rate of pressurisation is defined by rpm of motor which rotates the piston. To maintain the isothermal condition it is necessary to rotate the piston at lower speed to avoid dynamic condition. Micro-PVT was tested for different RPMs starting from 0.1 rpm to 12 rpm and then analysed for temperature profile during pressurisation. It was observed that at lower rpm large numbers of data points were recorded compared to one at high rpm hence to have substantial data points for analysis it was decided to perform experiments at 2 rpm to get the isothermal compression as well. For in-house density cell, pressurisation was using manual hydraulic hand pump and lowest recordable step change on pressure gauge was of 10 bar and the maximum operating limit was 400 bar hence step change of 20 bar was adopted during pressurisation.

4.5.4 Minimising experimental errors

Potentially there were two major types of error could be occurred during experimental studies and they were human errors and instrumental errors. Human errors were minimised by repeating the experiments at least three times with fresh samples and then by comparing them against each other. Few experiments performed by different personal were also used to calibrate the data points. Standard operating procedures from section 4.4 were followed during all types of experiments.

For controlling instrumental errors, all transducers were calibrated first against standard fluid and also the whole experimental assembly were calibrated against standard fluid. Two different backup of whole database were maintained to minimise the risk of data loss due to hardware failure.

Uncertainties in measured variables was minimised by repeating the experiments for same conditions and then by comparing each parameter with previous case. Difference in measured values was noted and uncertainty for that variable on that equipment was calculated which is summarised in table 4.6.

Table 4.6: Uncertainty table for measured variables

Measured Parameter	Uncertainty	Unit of Measure	Type of Equipment
Pressure	0.02	MPa	MicroPVT
Temperature	1	°C	
Volume	0.01	mm^3	
Pressure	10	Psi	In-house Density Cell
Temperature	2	°F	
Displacement	0.1	mm	
Temperature	2	°F	Fann-35
Dial reading	2	-	Fann-35
Temperature	2	°F	Brookfield
Viscosity	5	cp	Brookfield

Significance of above measured parameters on derived variables like density, compressibility and viscosity is covered in the chapter 5 by doing the sensitivity analysis for each parameter.

4.6 Experimental Results

4.6.1 PVT Experiments

It was now important to process the collected experimental data points to get required measured parameters. There were different measured or desired parameters for each type of experiments. Compressibility and density were the desired parameters in density cell experiments where as shear rate, shear stress and shear viscosity were the desired parameters in viscosity analysis experiments. Following basic equations and conversion factors were used to convert the raw experimental data points to desired parameters.

Isothermal compressibility is a measure of the relative volume change of a fluid as a response to the pressure change at constant temperature (50).

$$C_o = -\frac{1}{V}\frac{dV}{dP} \qquad [4.1]$$

V *is fluid volume*

dV *is change in volume*

dP *is change in pressure*

Step change in pressure and volume had been measured during the PVT experiments hence using above co-relation fluid isothermal compressibility was determined.

Density of fluid is mass per unit volume (58).

$$\rho = \frac{Mass}{Volume} = \frac{M}{V} \qquad [4.2]$$

All the PVT experiments were carried out in closed environment hence there was no loss of mass.

M *is constant*

$$\rho v = \rho_1 v_1 \qquad [4.3]$$

Initial density or specific gravity of fluid and initial volume were measured hence by knowing the new volume at different pressure above equation was used to calculate fluid isothermal density at different pressure.

Using all above respective correlation and experimental raw data, fluid compressibility and density has been predicted as tabulated in table 4.7.

Compressibility trends also have been built using Microsoft Excel for huge database to understand the behaviour of fluid at higher pressure. Trends have also used to do the comparison of PVT properties at different operating conditions. Isothermal compressibility behaviour for heavy oil has described by figure 4.5. Similarly figure 4.6 has plotted to show the experimental trend for heavy oil density.

Table 4.7: Data processing template for in-house density cell

Change in displacement (inch)	Change in volume (inch^3)	Change in volume (ml)	final volume (ml)	Compressibility per bar	Density g/cc
0.000	0.000	0.000	220.00		

0.015	0.048	0.786	219.21	2.591E-04	933.64
0.019	0.059	0.972	219.03	1.602E-04	934.44
0.021	0.068	1.117	218.88	1.227E-04	935.06
0.024	0.076	1.241	218.76	1.023E-04	935.59
0.026	0.083	1.365	218.64	8.999E-05	936.12
0.029	0.092	1.510	218.49	8.295E-05	936.74
0.031	0.101	1.654	218.35	7.792E-05	937.36
0.040	0.129	2.109	217.89	7.727E-05	939.32
0.048	0.153	2.502	217.50	7.500E-05	941.01

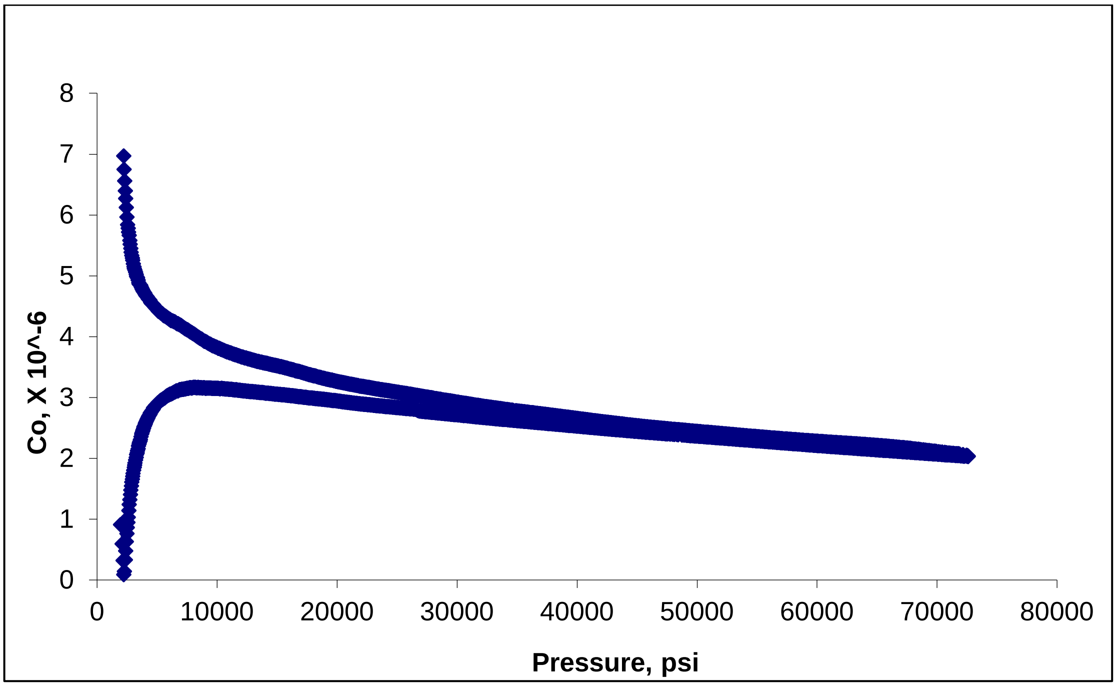


Figure 4.5: Compressibility profile from Micro-PVT for sample 2

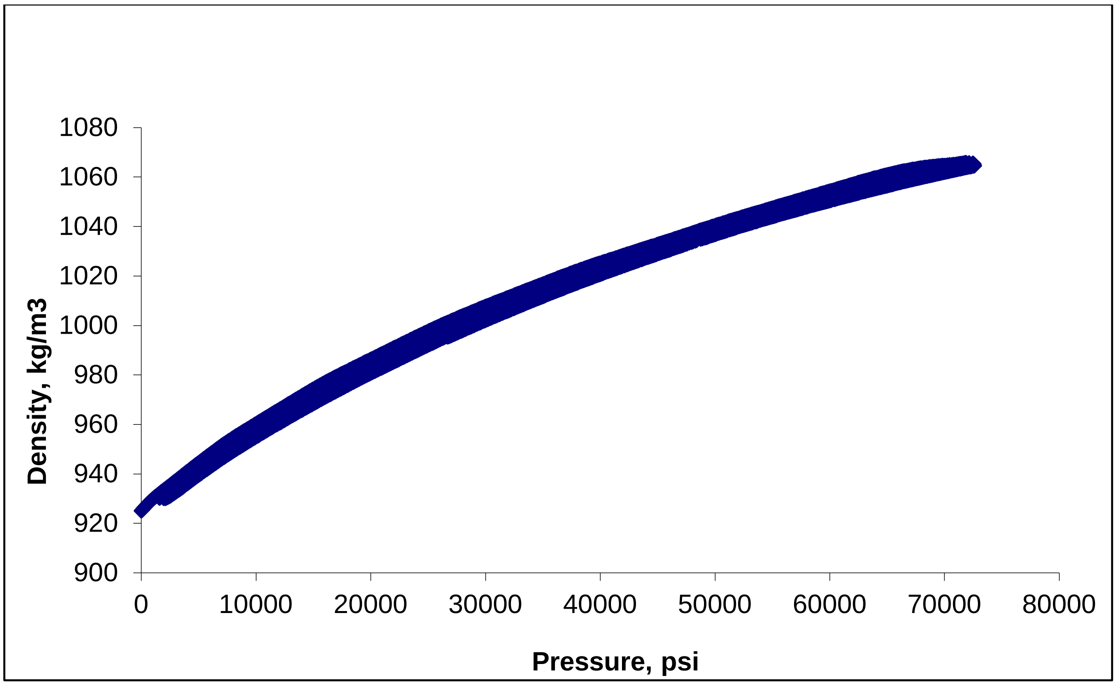


Figure 4.6: Density profile from Micro-PVT for sample 2

Huge experimental database was built using both density cell systems for six different heavy oil samples. Below is the summary for experimental database.

- From Micro-PVT Cell
  - For one temperature & one rpm case: 2000 data sets
  - Tested 5 Heavy oil samples
  - For five different temperature (70,100,120,140,160 F)
  - For two different RPM (2 & 6 rpm)
  - For 1 sample: almost 15000 data sets
  - Total Micro-PVT data sets: 75000
- From Density Cell
  - Tested 6 Heavy oil samples
  - 30 data sets for each sample

4.6.2 Rheology Experiments

It was important to have a look on raw experimental data points before processing it or before doing further analysis. Here the raw experimental data for sample 1 (old sample A) with initial API of 20.6 was tabulated below. Table 4.8 is the template for Fann-35 rheometer where as table 4.9 is for Brookfield.

Table 4.8: Raw data from Fann-35 rheometer

Temp ^{0}C	70	80	100	110	130	140	150
RPM	Dial Reading						
0.9	8	5	2	2	1	1	2
1.8	16	11	5	4	2	2	4
3	27	18	8	7	3	3	6
6	54	35	16	14	6	6	12
30	265	173	81	66	34	31	55
60			162	131	66	62	105
90			240	195	98	88	96
100			265	214	110	102	110
180					194	175	180
200					215	198	250
300						285	260

Viscosity computation for Fann-35 was done using following procedures (64)

1. Calculate shear rate from RPM using conversion factor of 1.7023. Unit for shear rate is Per second
2. Calculate shear stress from dial reading using 5.11 conversion factor. Shear stress is in dynes/cm2
3. Calculate shear viscosity by taking ratio of shear stress to shear rate. Multiply by 100 to convert it into cp

$$Shear\ viscosity, cP = \frac{5.11 \times Dial\ Reading}{1.7023 \times RPM} \times 100 \qquad [4.4]$$

Same method was adopted to back calculate the shear stress for Brookfield viscometer.

Table 4.9: Raw data from Brookfield viscometer

Temperature	70	Temperature	90	Temperature	105
RPM	Viscosity	RPM	Viscosity	RPM	Viscosity
0.9	3999	1	1200	10	900
1.8	4666	5	1320	25	888
3	4799	10	1380	50	900
6	4799	25	1440	75	904
10	4919	50	1428	100	918
30	4979	75	1368	125	907
50	5015	100	1332	150	908
60	5019	125	1296	175	908
75	5031	150	1264	200	903
100	5027	175	1237	230	905
110	5039	200	1215	250	902
115	5028	230	1200		
		250	1190		

CHAPTER 5: PVT ANALYTICAL MODEL DEVELOPMENT

5.1 Introduction

This chapter explains the need for new PVT models for heavy oil. Step by step procedure towards new model development for shear stress and oil compressibility is also explained in this chapter. Limitations of current models, sensitivity of different parameters and validation of new models are also covered in the last section of this chapter.

5.2 Current state of Black Oil PVT Models

To understand the pitfalls of current PVT models, it is important to do the background study about their development data and assumptions. As explained in chapter 3, commonly used correlation for PVT properties like density, oil compressibility, gas-oil ratio, bubble point pressure and oil formation volume factor are tabulated below from Table 3.1 (44).

Copy of Table 3.1: Commonly used PVT correlations

OFVF Correlation	Equation T in °F
Glaso correlations	$B_{o,Glasq} = 1 + 10^{\left(-6.5811 + 2.91329 logG - 0.27683 logG^2\right)}$ $G = R_s\left(\rho_g \middle| \rho_0\right)^{0.526} + 0.968T$
Standing correlations	$B_{o,standing} = 0.9759 + 12 \times 10^{-5}\left[\left(R_s\rho_g \middle| \rho_0\right)^{0.5} + 1.25T\right]^{1.175}$
Vazquez-Beggs correlations	$B_{o,V\&B} = 1 + 4.677 \times 10^{-4} R_s + 1.751 \times 10^{-5}(T + 60)(API/\rho_g) - 1.811 \times 10^{-8} R_s (T + 60)(API/\rho_g)$
Al-Marhoun correlations	$B_{o,Al-M} = 0.497069 + 0.862963 \times 10^{-3}(T + 459.67) + 0.182594 \times 10^{-2} M + 0.318099 \times 10^{-5} M^2$ $M = {R_s}^{0.74239} {\rho_g}^{0.323294} {\rho_0}^{-1.20204}$
Heavy Oil Viscosity Correlation	
Egbogah-Jack's correlation	$\mu_{Egbogah} = 10^{10^{(2.06492 - 0.0179 API - 0.70226 logT)}} - 1$
Egbogah-Jack's correlation extra heavy	$\mu_{Egbogah,Extra} = 10^{10^{(1.90296 - 0.012619 API - 0.61748 logT)}}$

Bennison, >20 API,250 GOR	$\mu_{Bennison,>20API,250GOR} = 10^{(0.10231API^2-3.9464API+46.5037)}T^{(-0.04542API^2+1.70405API-19.18)}$
Bennison, <20 API,250 GOR	$\mu_{Bennison,<20API,250GOR} = 10^{(-0.8021API+23.8765)}T^{(0.31458API-9.21592)}$

All the above correlations have been developed from empirical database and following tables (Table 5.1 & 5.2) summarised the data points used by different authors (44,50).

Table 5.1: Summary of different PVT correlation data points

PVT correlation	Number of data points	Number of crude samples	Region
Standing	105	22	California fields
Vazquez and Beggs	6004	-	All over the world
Glaso	41	-	North Sea
Al-Marhoun for OFVF	160	69	Middle East
Al-Marhoun for OFVF at bubble point	4012	700	Middle East and North America
Al-Marhoun for OFVF above bubble point	3711	700	Middle East and North America
Al-Marhoun for OFVF below bubble point	4005	700	Middle East and North America
McCain for below bubble point	2097	195	All over the world

Table 5.2: Range of data by Al-Marhoun (44)

Property	Range of data for correlation of		
	FVF at bubble point	FVF above bubble point	FVF below bubble point
Number of data points	4012	3711	4005

FVF above Pb (RB/STB)	-	1.012-2.826	-
Total FVF (RB/STB)	-	-	1.031-254.713
Bubble point FVF (RB/STB)	1.010-2.960	1.020-2.838	1.023-2.838
Pressure, psia	-	115-6015	20-4458
Bubble point pressure, psia	15.6641	24-4475	90-4475
Temperature, ^{0}F	75-300	75-240	75-240
Gas-oil ratio (SCF/STB)	0-3285	1-3113	7-3113
Gas relative density, Air=1	0.575-2.510	0.657-1.588	0.740-1.588
Oil density, ^{0}API	9.5-55.9	10.4-49.2	10.4-49.2

Al-Marhoun (44) validated the commonly used PVT correlations of crude oil on heavy oil and published their accuracy on heavy oil. (Table 5.3)

Table 5.3: Al-Marhoun (44) accuracy table for oil below 25 ^{0}API

Statistical accuracy for Oil FVF (Average absolute relative error, %)			
	API Ranges	<20	20-25
1	At Bubble point pressure grouped by oil ^{0}API gravity		
	Number of data points	103	240
	Standing	0.93	0.60
	Vazquez and Beggs	1.60	2.12
	Glaso	2.28	2.29
	Al-Marhoun old	1.96	0.85
	Al-Marhoun new	0.71	0.56
2	Above Bubble point pressure grouped by oil ^{0}API gravity		
	Number of data points	128	334
	Calhoun	1.16	1.49
	Vazquez and Beggs	1.23	1.24
	Al-Marhoun new	0.40	0.49
3	Below Bubble point pressure grouped by oil ^{0}API gravity		
	Number of data points	94	235

	Glaso	21.53	14.17
	Al-Marhoun old	8.04	5.88
	Al-Marhoun new	1.85	1.99

Similarly for viscosity prediction of heavy oil the current correlations were developed from empirical database which is summarised in Table 5.4.

Table 5.4: Range of Data used for Dead oil viscosity correlations (66)

Author	No. of data points	T range (^{0}F)	^{0}API Range
Beal 1	753	98-250	10.1-52.5
Beggs& Robinson	460	70-295	16-58
Glaso	29	50-300	20.1-48.1
Labedi	29	104-221	25.5-45.5
Egbogah& Ng	394	59-176	5-58
Twu	563	100-210	-4 to 93.1
Kaye	-	143-282	6.6-41.1
Al-Khafaji	350	60-300	15-51
Petrosky	118	114-288	25.4-46.1
Kartoatmodjo & Schmidt	661	80-320	14.4-59
De Ghetto	195	81-342	6-56.8
Fitzgerald	7267	-30 to 500	-2 to 71.5
Bennison	16	39-300	11.1-19.7
Elsharkawy	254	100-300	19.9-48
Bergman	454	40-400	12-60
Dindoruk & Christman	95	121-276	17.4-40
Hossain	184	32-215	7.1-22.3
Naseri	250	105-295	17-44

5.3 Need for accurate models

It is clear from the above experimental dataset that there is very limited data available on heavy oil as compared to light crude oil and also most of the empirical models are not developed using heavy oil samples hence the available PVT models could not be accurate for heavy oil PVT prediction. Validation of available models for heavy oil has been carried out by comparing experimental data from chapter 4 to the prediction of current PVT models. Section one of chapter 4 describes that all these models predict differently for the same input parameters. Hence it is also important to compare the few experimental data points with multiple correlations.

Experimental compressibility data for 21 API oil was compared with the analytical prediction in Figure 5.4. Result presented in Figure 5.4 and Figure 5.5 which is for dead oil viscosity does confirm that the current available crude oil PVT models are not accurate for heavy oil.

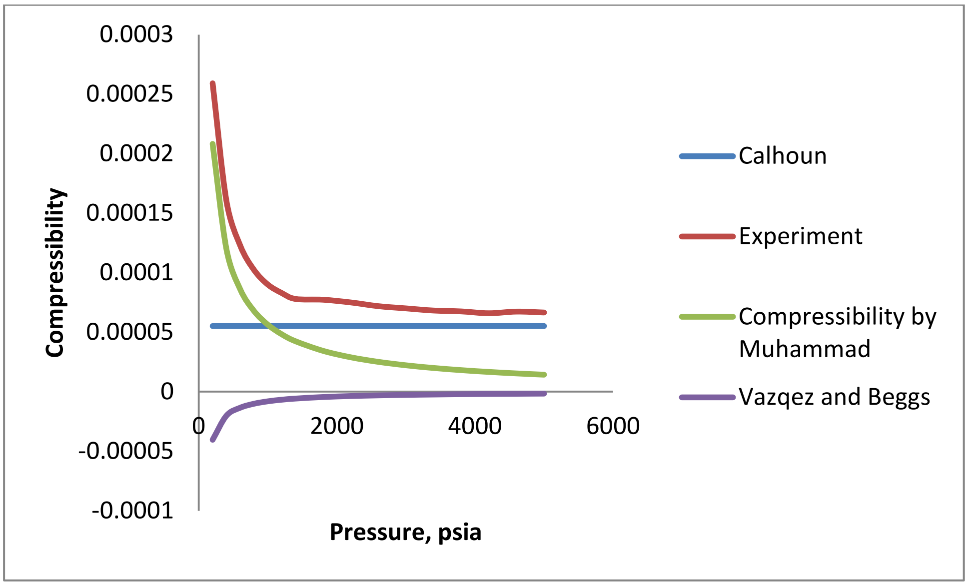


Figure 5.1: Comparison between analytical model predictions and Density cell data

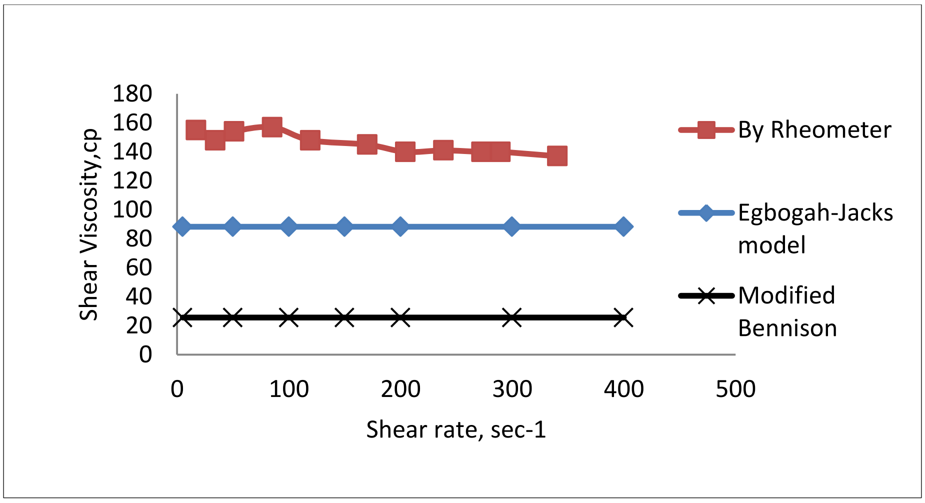


Figure 5.2: analytical vs. Experimental rheology data for heavy oil

5.4 Heavy Oil Compressibility Model

5.4.1 Experimental database for compressibility

A comprehensive experimental database with large number of data sets was built using two density cell systems[the MicoPVT and Density cell] for six different heavy oil samples. Below is the summary for experimental database with 75180 data sets.

- From Micro-PVT Cell
  - For one temp & one rpm case: **2000 data sets**
  - Tested 5 Heavy oil samples
  - For five different temp (70,100,120,140,160 ^{0}F)
  - For two different RPM (2 & 6 rpm)
  - For 1 sample: almost **15000 data sets**
  - Total Micro-PVT data sets: **75000**
- From Density Cell
  - Tested 6 Heavy oil samples
  - 30 data sets for each sample

Procedure from section 4.6.1 was followed with the calculation of compressibility from measured PVT data points. Experimental compressibility from MicroPVT and Density cell are presented in Figure 5.3 for 21 API oil.

Experiments were performed at five different temperatures (70,100,120,140,160 ^{0}F). M represents Micro-PVT and D represents density cell.

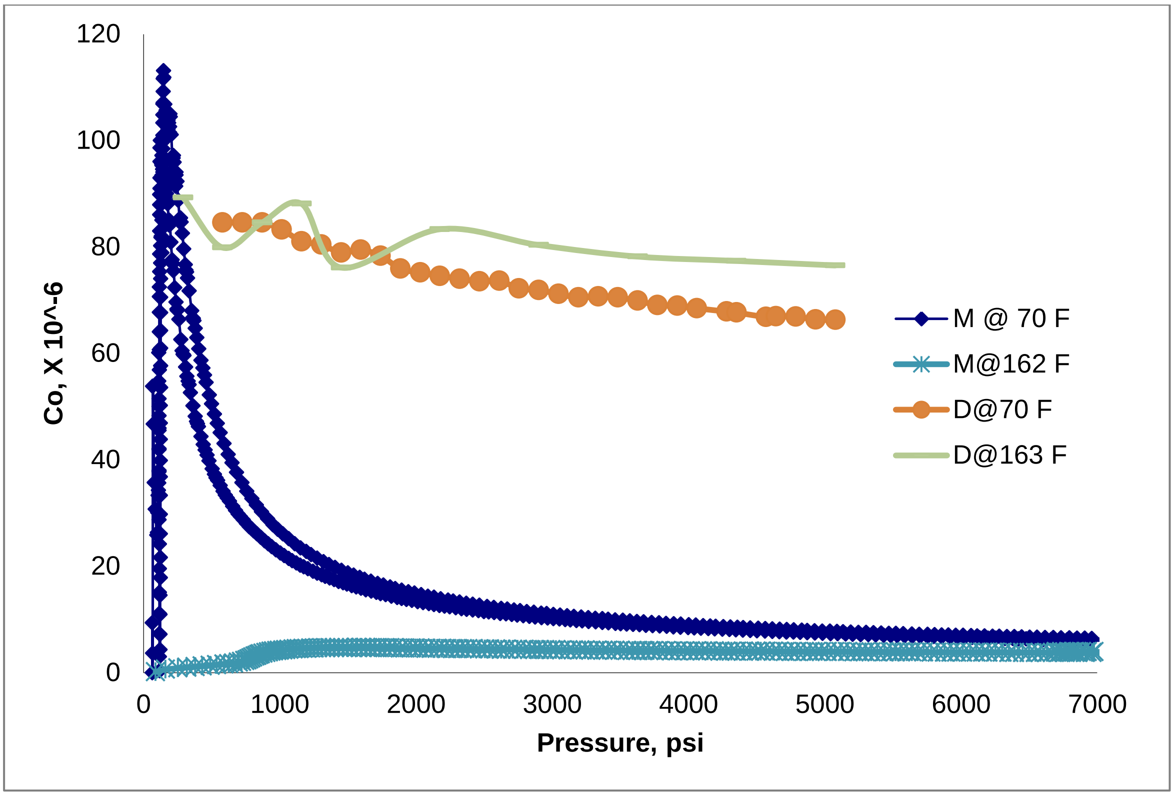


Figure 5.3: Data sets for 21 API oil

5.4.2 Visual Comparison between available models and experimental data

Calhoun, Muhammad and Vazqez & Beggs (58) compressibility models have been used to estimate the compressibility of heavy oil. Basis of selecting these models was

- Heavy oil database were used in development of these models
- Realistic GOR and bubble pressure data was used
- These models were giving close match with experimental data

Figure 5.1 justifies the necessity of new compressibility model for heavy oil as all of them are predicting differently for same input conditions.

Experimental data points were plotted with analytical prediction. Density cell compressibility was compared to analytical prediction in Figure 5.1 whereas Micro-PVT compressibility was compared to analytical models such as in Figure 5.4.

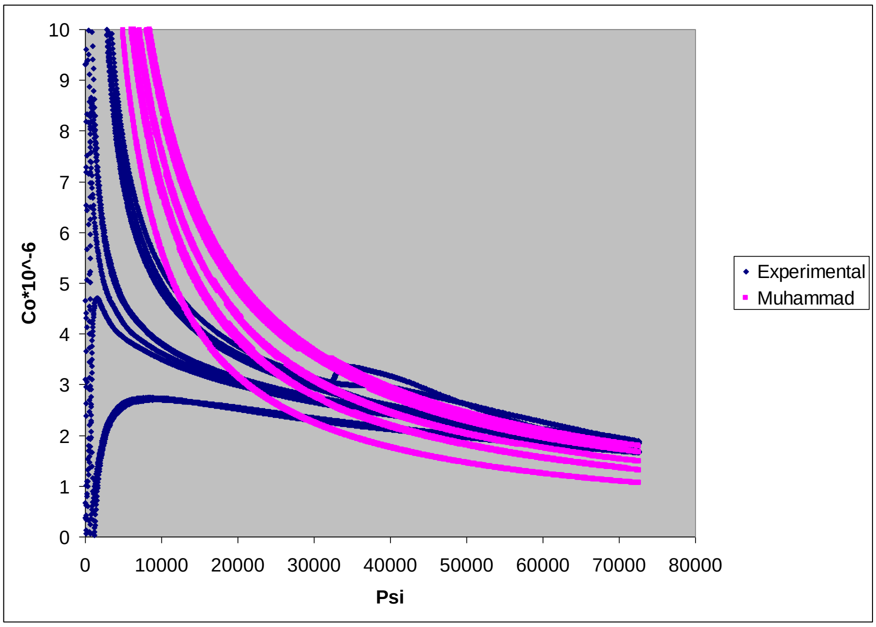


Figure 5.4: Comparison between analytical Muhammad model and Micro-PVT data

5.4.3 Error and Sensitivity analysis of available models

Pearson Product Moment Correlation Coefficient (R^2) and error percentage (% Error) were used to shortlist the analytical models to adopt. Sensitivity of each parameter was also performed on Crystal Ball tool which perform the probability analysis for output variable based on Monte Carlo simulation.

$$R^2 = \frac{1}{n-1}\sum_{i=1}^{n}\left(\frac{X_i - X_{av}}{S_X}\right)\left(\frac{Y_i - Y_{av}}{S_Y}\right) \quad [5.1]$$

$$S = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(X_i - X_{av})^2} \quad [5.2]$$

$$X_{av} = \frac{1}{n}\sum_{i=1}^{n}X_i \quad [5.3]$$

$$\%Error = \left(\frac{Exp - Model}{Exp}\right) \times 100 \quad [5.4]$$

An error analysis was done on 19.5 ^{0}API heavy oil sample using equations 5.1 to 5.4. Three different analytical correlations were validated against experimental data points and the results are tabulated in Table 5.5. The Vazqez and Beggs showed the good match with experimental data at higher temperature but at low temperature Calhoun was good for heavy oil.

Similarly the sensitivity analysis was done on the above three compressibility correlations to understand the sensitivity of different parameters. Sensitivity results are shown in Figure 5.5 and Table 5.6.

Table 5.5: Error analysis for compressibility models

Oil ^{0}API	Model	Data set	Temperature range, 0F	Max Pressure , psi	Average % error	Correlation coefficient	R^2 (Pearson Product Moment Correlation Coefficient)
19.5	Calhoun	103	70-200	up to 6000	-2.11	-0.379	0.143
19.5	Muhammad	103	70-200	up to 6000	-54.3	0.0665	0.0044
19.5	Vazqez and Beggs	103	70-200	up to 6000	89.05	-0.6954	0.483

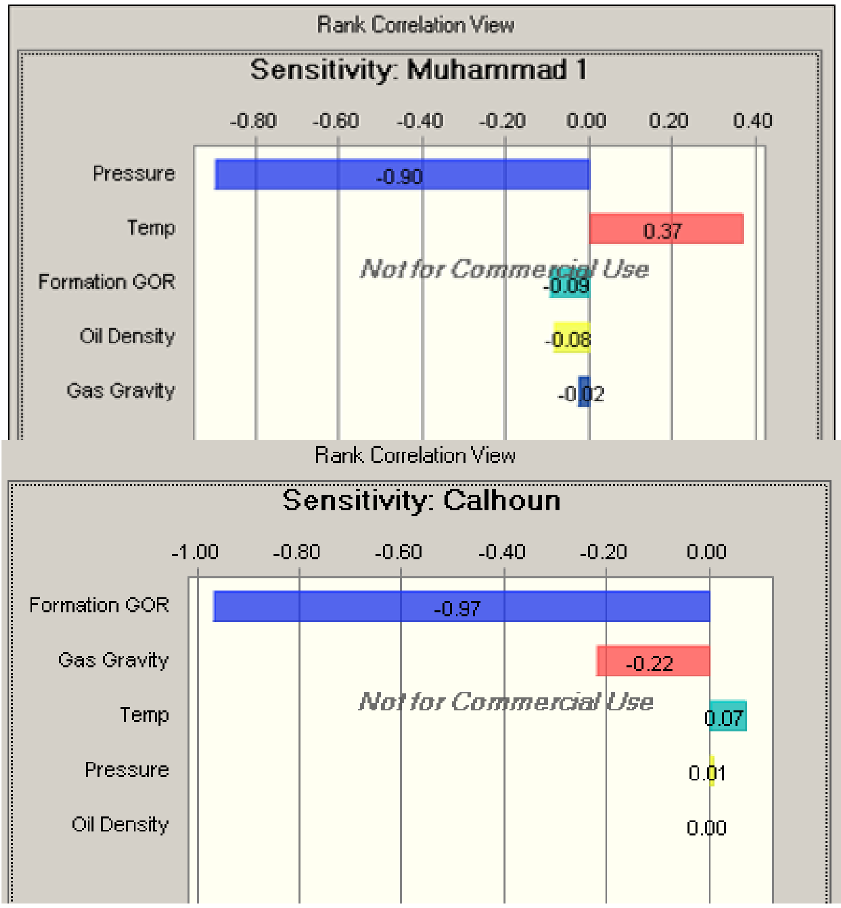


Figure 5.5: Sensitivity analysis for analytical models

Table 5.6: Sensitivity data for compressibility models

Assumptions	Calhoun	Muhammad	V & B 1	V & B 2
Formation GOR	-0.966988777	-0.896502611	-0.8118	0.716283
Gas Gravity	-0.220442672	0.369777137	0.373349	-0.59367
Temp	0.071040674	-0.0922386	0.36896	0.134506
Pressure	0.007987188	-0.083503958	-0.04286	-0.05233
Oil Density	0.000879226	-0.023342299	-0.0145	-0.03036

Conclusions drawn from sensitivity and error analysis are :

(i) Calhoun equation is independent of pressure

(ii) Muhammad prediction follows the experimental trend but the error is higher than Calhoun

(iii) Vazqez and Beggs model is valid above certain temperature which was 120 ^{o}F for tested sample

(iv) Calhoun model is highly sensitive to gas-oil ratio[200-400 scf/bbl]

5.4.4 New compressibility model for Heavy Oil

After doing the sensitivity and error analysis of all available compressibility models, experimental datasets and models base frames have been used to develop the new compressibility model for heavy oil.

The base frame equation was developed by reviewing Calhoun and Muhammad's compressibility equations. Sensitivity figures also helped to consider new parameters to the base frame (Equation 5.5).

Base frame developed for model development

$$C_{o\,Amol} = \frac{A \times \ln\left[{B \times {\gamma_g}^{E} \times (P + C)} \Big/ {{R_s}^{F} {\gamma_o}^{G} {T_F}^{H}} \right]}{(P + D)}$$

[5.5]

Where A to H are imperial constants

P is pressure in psia

Y_g is gas specific gravity

Y_o is oil specific gravity

Rs is solution GOR in scf/STB

T_F is fluid temperature in ^{0}F

Sensitivity analysis has helped in deciding the number of critical input parameters and then using multiple iteration method, the variable coefficients were determined. Critical variables decided after sensitivity analysis for heavy oil compressibility model are listed below.

- Pressure
- Oil specific gravity
- GOR

- Gas specific gravity
- Fluid temperature

After doing multiple iterations in Microsoft Excel, SPSS and also using Goal Seek from excel following empirical equation developed for compressibility of heavy oil (Equation 5.6).

$$C_{o\ Amol} = \frac{0.01 \times ln\left[0.2 \times 10^{-3} \times {\gamma_g}^{1.88} \times (P + 2000) \big/ {R_s}^{0.72}{\gamma_o}^{3.14}{T_F}^{1.33}\right]}{(P + 2200)}$$

[5.6]

Figure 5.6 defines the confidence levels for derived coefficients values. Over 9000 data sets were used to get the variable coefficients. Wide range of input parameters was also considered to resemblance the real scenario. Pressure range was from 100 to 60000 psia whereas temperature range was from 70 to 200 ^{0}F.

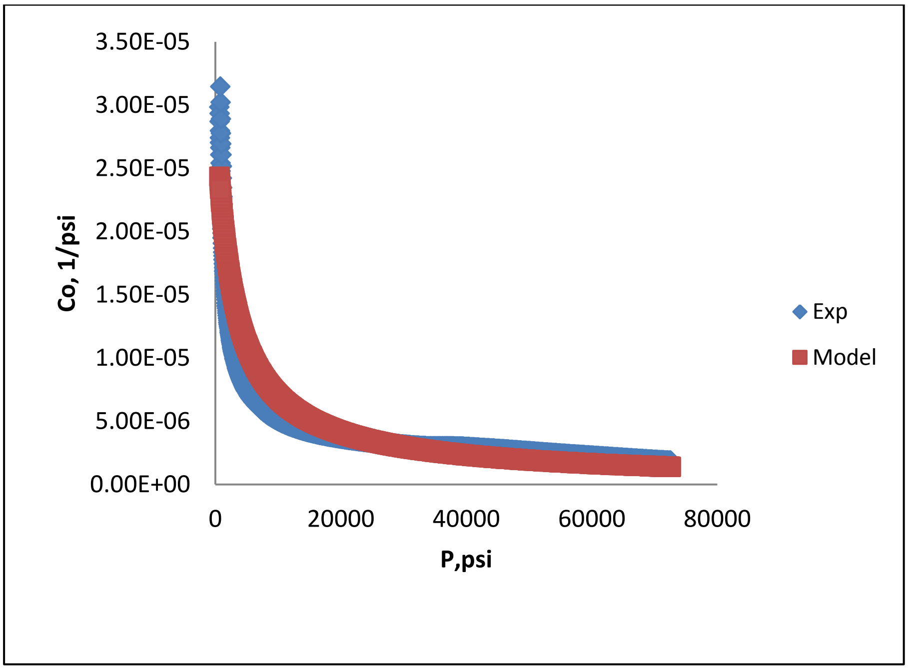


Figure 5.6: Comparison between new model prediction and experimental measurement

From Table 5.7, average R^2 (Pearson Product Moment Correlation Coefficient) for 9138 data sets was 0.84 which means the developed model is good representative for experimental data points. R^2 on higher end went to 0.98 which means the model was 98% accurate. Model showed more accuracy towards MicroPVT data sets than density cell and which confirmed the more uncertainties on density cell data points over MicroPVT.

Table 5.7: Data used in compressibility model development

PVT Cell	Sample	Temp, F	Pressure range	Data sets	R^2
Micro-PVT	1	70	100 to 60000 psia	1800	**0.91**
	2	100		1727	**0.87**
	3	122		1640	**0.82**
	4	144		1930	**0.98**
	5	165		1977	**0.83**
Density Cell	6	70	500 to 5000 psia	32	**0.98**
	7	160		8	**0.93**
	8	203		8	**0.65**
	9	69		16	**0.62**
Total/Avg				9138	**0.84**

Sensitivity analysis of each critical parameter considered during the model development has been done using Crystal Ball and results are displayed in Figure 5.7. Pressure is the most sensitive parameter to compressibility followed by temperature and GOR of heavy oil.

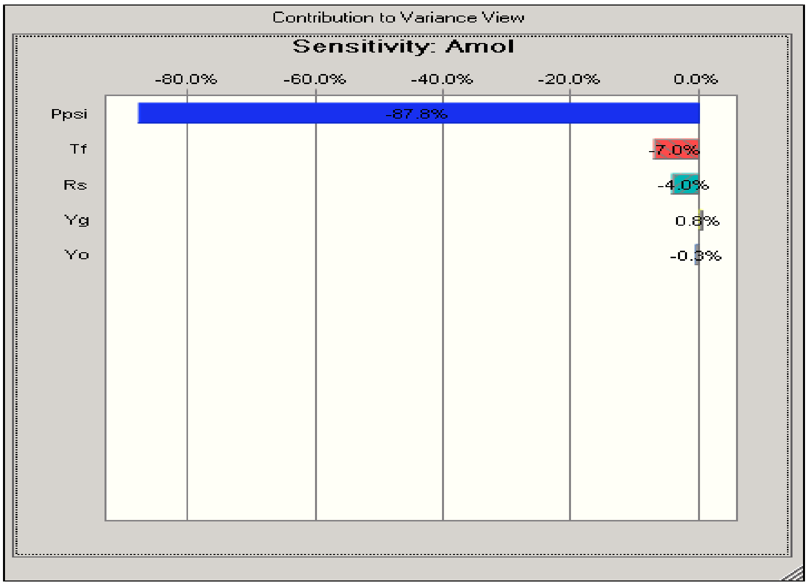


Figure 5.7: Sensitivity analysis on new Amol's compressibility model

5.4.5 Validation of developed model

Validation with independent data gives a confidence for user to use developed models to predict the output close to reality. Without validation the developed models don't have a physical value. Independent data should be used to do the validation. More than 9000 data sets have been used to develop the compressibility model of heavy oil. Similarly more than 25000 different data sets have been used to validate the developed model and the model has given the average R^2 of 0.86 which is within acceptable range. The developed model has improved prediction by as much as 60% over the current available compressibility models for heavy oil. Table 5.8 summarised the results for three different heavy oil fluids over the wide range of temperature and pressure.

Table 5.8: Validation table for compressibility model

Old B with 0.93 specific gravity					
Sample	Temp, F	Pressure Range	Data sets	R^2	Average % error
10	70	300-60000 psi	1572	0.95	8.8
11	86		1647	0.85	-35
12	104		1730	0.74	-55
13	122		1757	0.81	-61
14	150		1770	0.76	-30
15	70-150		8476	0.66	-35
New A with 0.99 specific gravity					
Sample	Temp, F	Pressure Range	Data sets	R^2	
16	83	300-60000 psi	1489	0.9	16.6
17	90		996	0.85	19.9
18	105		1599	0.87	22.8

19	130		1702	0.85	21.8
20	145		1748	0.85	22.4
21	80-145		7534	0.86	20.9
New B with 1.0 specific gravity					
Sample	Temp, F	Pressure Range	Data sets	R^2	
22	72	300-60000 psi	1471	0.9	31.06
23	88		1620	0.85	36.57
24	105		1618	0.87	33.76
25	130		1657	0.85	33.71
26	146		1721	0.85	34.69
27	70-150		8087	0.86	34.02

5.5 Recommended bubble point and GOR model for heavy oil

Analysing the wide range of live heavy oil field data has helped to reduce the uncertainties and also increases the confidence level on the initial prediction for bubble pressure and GOR of heavy oil. All the live heavy oil field data from different part of the world have been analysed and plotted in Figure 5.8 (67,68). The data have also been used to screen the bubble point and GOR prediction model.

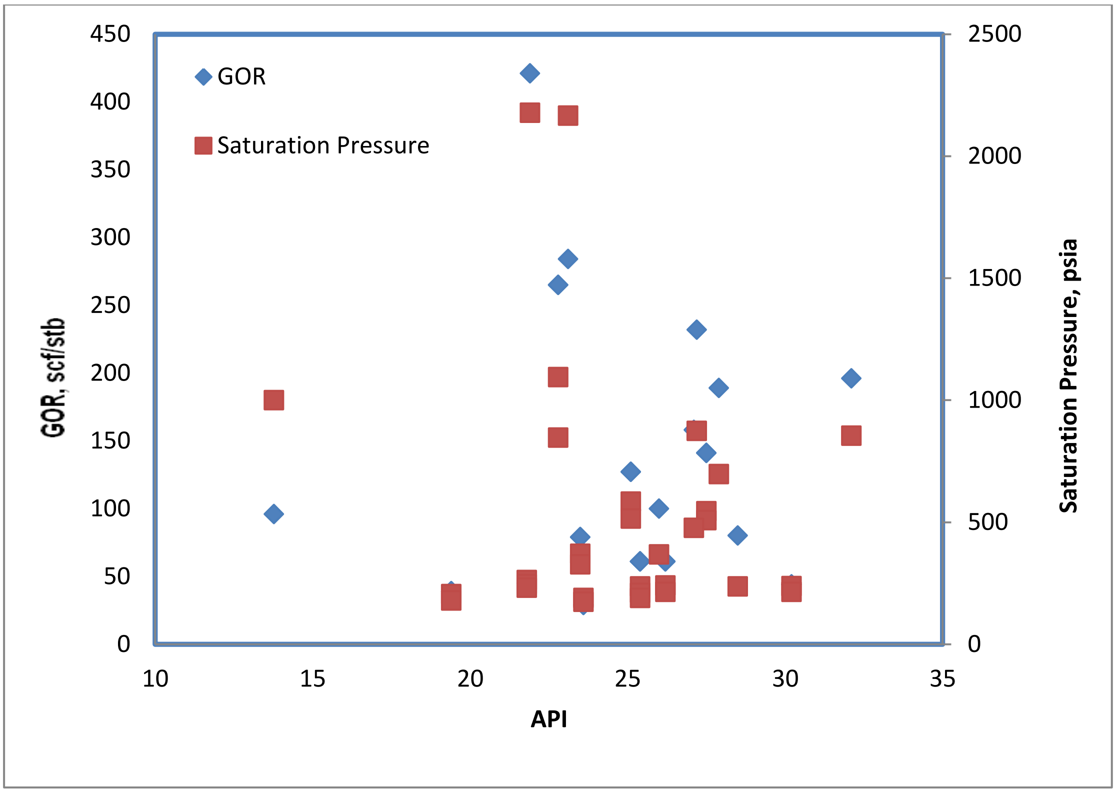


Figure 5.8: Live heavy oil sample envelope

Data points from Figure 5.8 was used to understand the range of GOR and the saturation pressure of heavy oil samples and then the models which predicts close to reality were shortlisted to predict the bubble point and GOR of heavy oil. The following models (Equations 5.7 to 5.13) on the basis of error analysis have been recommended to predict bubble point pressure and GOR below bubble point for heavy oil.

1. Bubble point by Al-Marhoun

   $$P_b = 5.38088 \times 10^{-3} \times R_s^{0.715082} \times \gamma_g^{-1.87784} \times \gamma_{oil}^{3.1437} \times T_F^{1.32657} \qquad [5.7]$$

2. Velarde & Mccain Model for GOR

   Below Bubble point by J.Velarde (51)

$$GOR\ below\ BP = Solution\ GOR \times R_{sr} \qquad [5.8]$$

$$R_{sr} = a_1 p_r^{a_2} + (1 - a_1) p_r^{a_3} \qquad [5.9]$$

$$p_r = {P_{below\ BP}}/{P_b} \qquad [5.10]$$

$$a_1 = 9.73 \times 10^{-7} \times \gamma_g^{1.672608} \times \gamma_{API}^{0.92987} \times T_F^{0.247235} \times P_b^{1.056052} \qquad [5.11]$$

$$a_2 = 0.022339 \times \gamma_g^{-1.00475} \times \gamma_{API}^{0.337711} \times T_F^{0.132795} \times P_b^{0.302065}$$

[5.12]

$$a_3 = 0.725167 \times \gamma_g^{-1.48548} \times \gamma_{API}^{-0.164741} \times T_F^{-0.09133} \times P_b^{0.047094}$$ [5.13]

5.6 Summary of the developed PVT models for Heavy Oil

1. Compressibility model above bubble point

$$C_o = \frac{0.01 \times ln\left[{0.2 \times 10^{-3} \times \gamma_g^{1.88} \times (P+2000)} \Big/ {R_s^{0.72} \gamma_o^{3.14} T_F^{1.33}}\right]}{(P+2200)}$$ [5.14]

2. Compressibility model at bubble point

Bubble point pressure is by Al-Marhoun

$$C_{o@BP} = \frac{0.01 \times ln\left[{0.2 \times 10^{-3} \times \gamma_g^{1.88} \times (P+2000)} \Big/ {R_s^{0.72} \gamma_o^{3.14} T_F^{1.33}}\right]}{(P_B+2200)}$$ [5.15]

3. Compressibility model below bubble point

GOR below bubble point is by Velarde & Mccain model

$$C_{obelowbp} = \frac{0.01 \times ln\left[{0.2 \times 10^{-3} \times \gamma_g^{1.88} \times (P+2000)} \Big/ {R_{sbelowbp}^{0.72} \gamma_o^{3.14} T_F^{1.33}}\right]}{(P+2200)}$$ [5.16]

4. Density model for below, at and above bubble point pressure

By taking corresponding compressibility with pressure gives the density at respective pressure.

$$\rho = \rho_{initial}\left(\frac{1}{1-C_o(P_{psi}-14)}\right) \quad [5.17]$$

Above equation has been derived from basic equation of state and density equation.

Density of fluid is mass per unit volume

$$\rho = \frac{M}{V} \quad [5.18]$$

M is constant for closed experiments

Hence for different volumes,

$$\rho_1 V_1 = \rho_2 V_2 \quad [5.19]$$

Compressibility of fluid from section 4.6.1

$$C_o = -\frac{1}{V_0}\frac{dV}{dP} = \frac{1}{V_0}\frac{(V_0 - V)}{(P - P_0)} \quad [5.20]$$

By rearranging above equation

$$\frac{V}{V_0} = 1 - C_0(P - P_0) \quad [5.21]$$

By combining density and compressibility equations

$$\rho = \left(\frac{\rho_0}{1-C_o(P-P_0)}\right) \quad [5.22]$$

5. Oil Formation Volume Factor Models
    a. OFVF at BP [5.23]

       $B_o = (1 + C_{o@BP} \times P_b)$
    b. OFVF above BP

       $$B_0 = B_{0@BP} \times \exp(-C_0 \times (P - P_b)) \quad [5.24]$$

    c. OFVF below BP

$$B_{0below\ BP} = \exp(C_{obelowBP} \times (P_{below\ BP} - 14.5038)) \quad [5.25]$$

5.7 Rheological Characterisation of Heavy Oil

As defined in previous section, non-Newtonian fluids are those whose viscosity is not constant and it is shear rate or shear stress dependent.

Preliminary studies (31) on different heavy oils have established that they are predominantly non-Newtonian at standard and higher temperatures and pressures [Figure 3.7]. Hence rheological characterisation is required to understand heavy oil behaviour.

5.7.1 Methodology for Rheology classification:

After having experimental shear stress, shear rate and shear viscosity data, it was necessary to do the rheological characterisation to understand the behaviour of the heavy oil at that corresponding temperature.

There are a number of non-Newtonian fluid models available which characterise the flow behaviour of the pure heavy oil and heavy oil-steam mixture from specific gravity and temperature of oil (45,69). The Bingham Plastic, Power law and Herschel Bulkley rheological models have been adopted (70). The following equations (Equation 5.26 to 5.28) were used to define the flow mechanics of these non-Newtonian fluid types through a porous reservoir (45,49,71).

Power Law $\qquad Shear\ stress\ \ \tau = K\gamma^{n}$ $\qquad$ [5.26]

Herschel Bulkley $\qquad Shear\ stress\ \ \tau = \tau_0 + K\gamma^{n}$ $\qquad$ [5.27]

Bingham Plastic $\qquad Shear\ stress\ \ \tau = \tau_y + \mu_p\gamma$ $\qquad$ [5.28]

The Herschel Bulkley model is treated as a modified Power Law fluid defined as :

$$\tau' = K'\gamma^{n'} \quad [5.29]$$

Where $\gamma = Shear\ rate, \mu = shear\ viscosity, K\ and\ n\ are\ rheological\ constants$

$$\tau' = \tau - \tau_o' \quad [5.30]$$

From Fann-35 manual, following conversion factors were used for calculation of shear rate, shear stress and shear viscosity (64).

$$Shear\ rate\ in\ per\ sec = \gamma = RPM \times 1.7032 \quad [5.31]$$

$$Shear\ stress\ in \frac{dynes}{cm2} = \tau = Dial\ reading\ \times 5.1 \quad [5.32]$$

$$Shear\ viscosity\ in\ cP = \mu = \frac{Shear\ stress\ in\ dynes/cm2}{Shear\ rate\ in\ per\ sec} \times 100 \quad [5.33]$$

For Power law and Herschel Bulkley, following procedure has been used to do the rheological characterisation.

1. Power law and Modified Herschel Bulkley fluid models as follows

   $\tau = K\gamma^n \qquad \tau' = K'\gamma^{n'}$

2. Taking natural logarithm on both side will convert them as follows

   $Log(\tau) = LogK + n\log(\gamma\ )$

3. Plot Log (stress) Vs. Log (rate) and note down the Y-intercept and slope of line by adding linear trend line to graph.

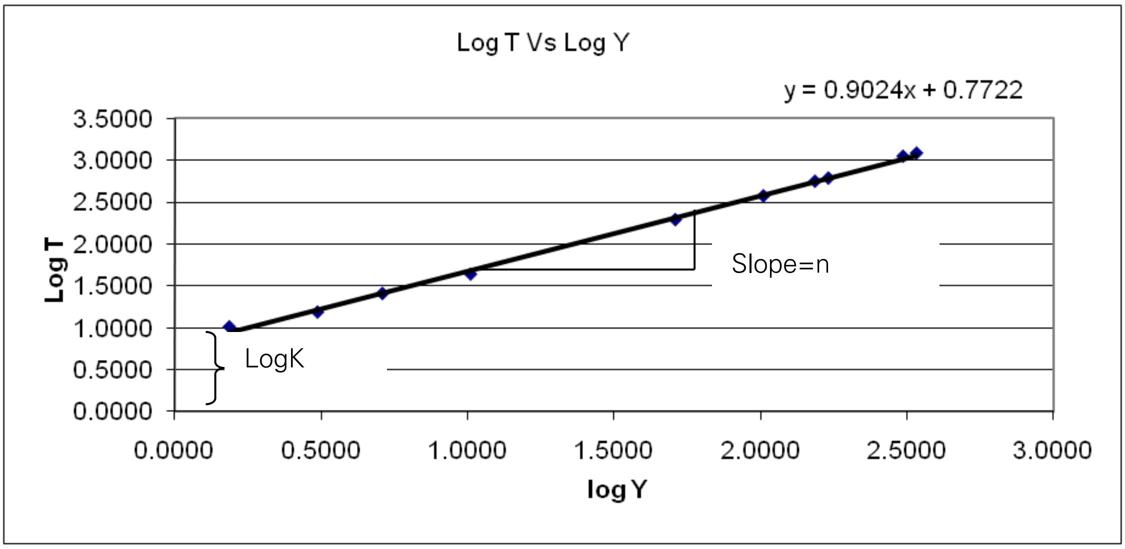


Figure 5.9: Log-Log plot for rheological characterisation

4. From straight line equation, Y-Intercept will represent the Log(K) and slope represents the value for "n"
5. Do the same for exercise for modified Herschel Bulkley model
6. Note down the rheological parameters "K" and "n" for different samples and for different temperatures.

7. Bingham plastic fluid model is already a straight line equation hence there is no need to take natural log. Determine yield stress and plastic viscosity by plotting shear stress and shear rate.

Selection of a fluid model was a challenging step. To do this, the shear stress has been calculated using the fluid model and estimated rheological parameters. Calculated shear stress has been then compared with measured shear stress and the fluid model which has given the good match with measured values has been selected to represent the rheology of fluid at that temperature.

5.8 Analytical model for Effective Shear Viscosity of heavy oil

The non-Newtonian behaviour of heavy oil has made the viscosity prediction complex. It is not like Newtonian fluid where viscosity is independent of shear rate and shear stress. Heavy oil viscosity at a particular temperature depends on applied shear stress on fluid and shear rate. To compute the real time viscosity for heavy oil, knowledge of real time shear rate and shear stress is a necessity.

5.8.1 Real time shear rate for heavy oil viscosity

During SAGD process as the pressure and temperature are not static therefore the heavy oil flow properties are also dynamic . Hence the pore velocity of oil is also unsteady. Fluid velocity determines the shearing rate of fluid so it is critical to determine the real time shear rate during SAGD process and corresponding shear viscosity. Fluid rheology by following procedure from section 5.7.1 and by using experimental data at desired temperature can be determined. Flow rate dependent shear rate is calculated by using equations 5.34 and 5.35.

For Power Law Fluid and Herschel Buckley

$$\gamma = \frac{24 \times V_{pore}}{D_{pore}}\left[3 + \frac{1}{n}\right] \qquad [5.34]$$

$V_{pore} = pore \quad velocity, ft/\sec$

$D_{pore} = pore \quad diameter, in$

For Bingham Plastic fluid

$$\gamma = \frac{96 \times V_{pore}}{D_{pore}} + 160 \times \frac{\tau_y}{\mu_p} \qquad [5.35]$$

Using Blake-Kozeny-Carman equations 5.36 to 5.38 (8,72), calculate diameter of particle. Velocity and pore diameter are derived parameters. Absolute permeability and porosity are the reservoir properties.

$$D_{particle} = \frac{6\times(1-\emptyset)}{S} \qquad [5.36]$$

$$S = Surface\ area\ per\ unit\ volume = \sqrt{\frac{\emptyset^3}{2\times K_a\times(1.8561-0.715\times\emptyset)^2}} \qquad [5.37]$$

$$D_{pore} = \frac{D_{particle}\times\emptyset}{3\times(1-\emptyset)} \qquad [5.38]$$

From known flow rate, by definition of pore velocity

$$Velocity = \frac{Q}{A} = \frac{Flowrate}{Cross.Sec.Area} \qquad [5.39]$$

$$V_{pore} = \frac{Velocity}{\emptyset} \qquad [5.40]$$

Shear viscosity is calculated by rearranging non-Newtonian fluid models (Equations 5.41 to 5.43) for power law, Herschel Buckley and Bingham plastic.

$$\mu_{effective\ for\ PL} = K\gamma^{n-1} \qquad [5.41]$$

$$\mu_{effective\ for\ HB} = \frac{\tau_0}{\gamma} + K\gamma^{n-1} \qquad [5.42]$$

$$\mu_{effective\ for\ BP} = \frac{\tau_y}{\gamma} + \mu_p \qquad [5.43]$$

5.8.2 Real time shear stress model for heavy oil viscosity

During production of heavy oil, the applied drawdown on rock is not always constant. Pressure support due to steam injection and pressure depletion due to production creates the drawdown profile on formation. Similarly well operations such as start up and shut down impacts the drawdown on formation. The drawdown represents the stress applied on rock and fluid. As in reservoir environment shear viscosity is crucial, the stress applied is known as shear stress. Pressure and temperature is also not constant throughout the wellbore hence the shear stress on fluid is also dynamic in nature. It is important to predict the real time shear stress to calculate real time shear viscosity as shear viscosity is ratio of shear stress to shear rate. Shear rate as described above can be calculated by knowing the pore velocity, pore diameter and rheological parameters.

Developing the shear stress model which can predict shear stress at any pressure and temperature then with the help of few experimental data points, the shear viscosity profile at different pressure and temperature can be determined. Experiments performed on Fann-35 and Brookfield viscometers were used to build shear stress database. Some data points from published paper for higher pressure were also used to develop shear stress model (66). Following procedure was adopted to restructure the database.

1. Put all the data points for same shear rate but different temperature together
2. Specified corresponding shear stress separately
3. Plotted shear stress verses temperature for constant shear rate. Figure 5.10 describes the shear stress profile for different shear rates.

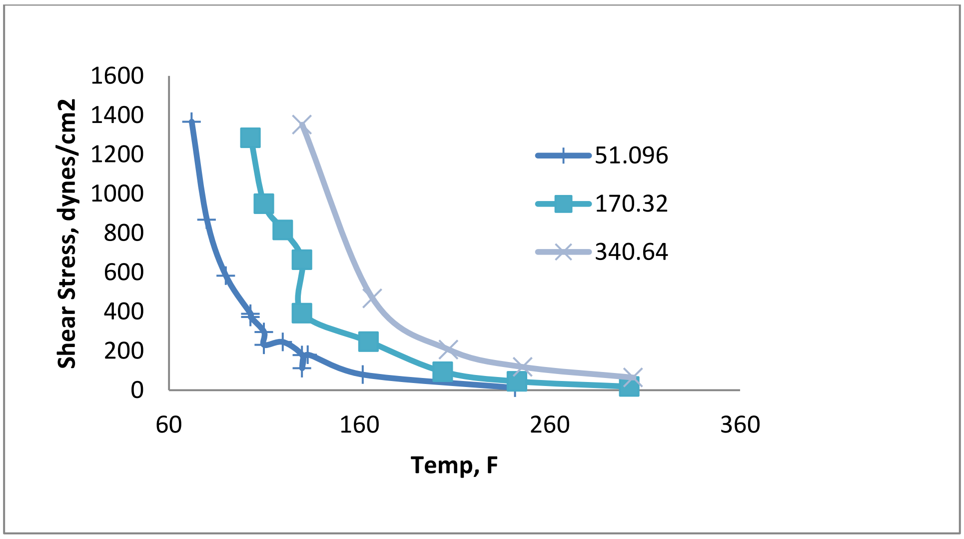


Figure 5.10: Shear stress profile for different shear rates

4. Calculated ratio of shear stress at higher shear rate to initial shear rate

$$\tau_{Ratio} = \frac{Shear\ stress\ at\ higher\ shear\ rate}{Shear\ stress\ at\ lowest\ shear\ rate} = \frac{\tau_{\gamma h}}{\tau_{\gamma l}} \qquad [5.44]$$

5. Similarly calculated ratio for temperature

$$T_{Ratio} = \frac{Temperature\ at\ higher\ shear\ rate}{Temperature\ at\ lowest\ shear\ rate} = \frac{T_{\gamma h}}{T_{\gamma l}} \qquad [5.45]$$

6. Plotted shear stress ratio against temperature ratio to understand the profile for one shear rate. (Figure 5.11)

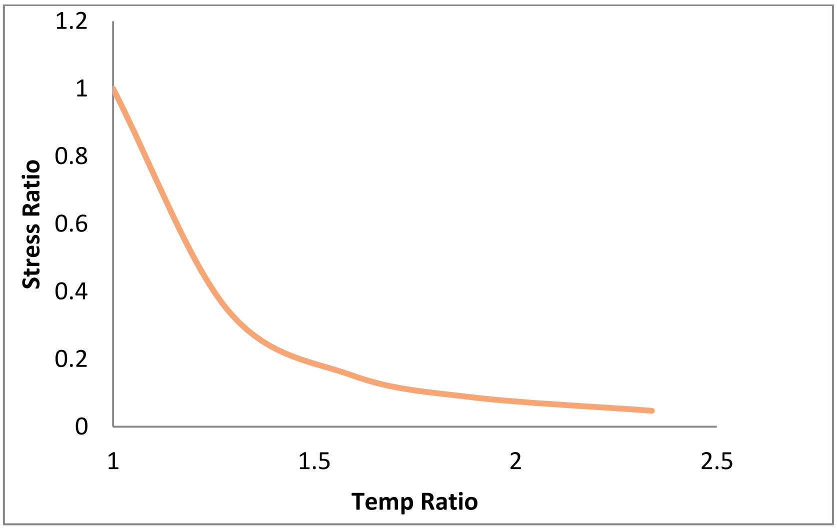


Figure 5.11: Shear Stress ratio profile

7. Plotted the same curve for different shear rates (Figure 5.12)

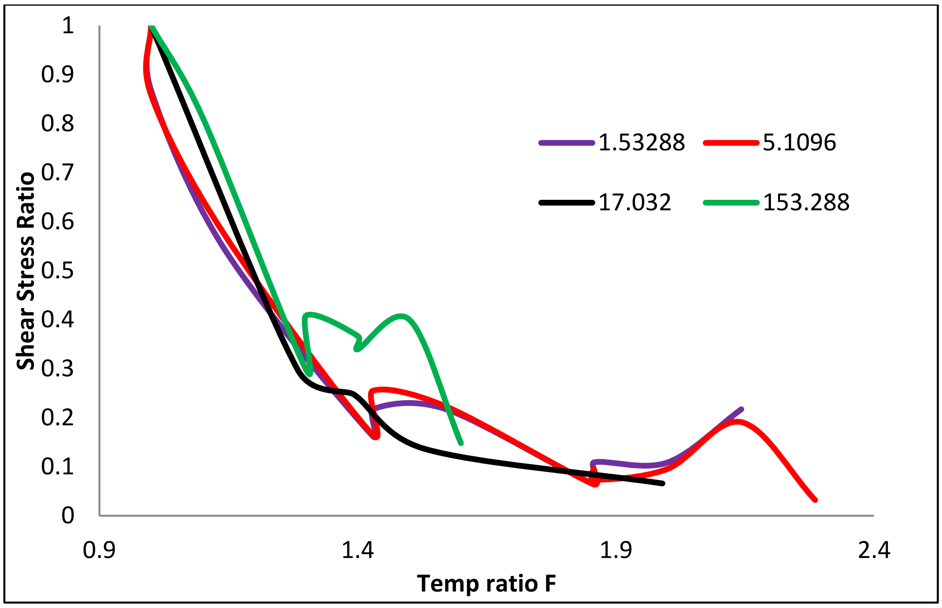


Figure 5.12: Shear stress profile at different shear rates

8. Drilling mud is also a non-Newtonian fluid and during drilling operation the real time mud density and mud viscosity are very crucial to understand the behaviour of drilling mud. The Robert Gordon University has developed a shear stress model for drilling mud (Equation 5.46). After taking the right permission, this model was tested on heavy oil and the

profile is showed in Figure 5.13. The drilling mud model didn't show the good match with experimental data for heavy oil.

$$\tau_{T,P} = \tau_i\left[A \times e^{(B\times T + C\times P)}\right] \quad [5.46]$$

$\tau_{T,P} = Shear\ Stress\ at\ T\ \&\ P\ in\ dynes/cm^2$

$\tau_i = Known\ Initial\ Shear\ Stress\ at\ T_i\ and\ P_i$

$T = Temperature\ in\ °F$

$P = Pressure\ in\ psi$

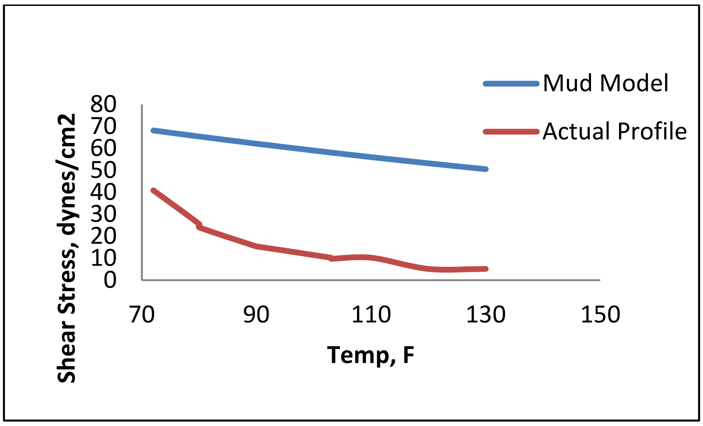


Figure 5.13: Validation of drilling mud model for shear stress

9. The drilling mud model calculates shear stress at any desired pressure and temperature with only input parameter of initial stress. But the model doesn't consider the temperature and pressure at which the initial stress was measured hence the base frame was modified to take care of initial pressure and temperature. Equation 5.47 represents the new base frame for shear stress model.

$$\tau_{T,P} = \tau_i\left[A \times e^{\left(B\times\frac{T}{T_i} + C\times(P-P_i)\right)}\right] \quad [5.47]$$

$\tau_{T,P} = Shear\ Stress\ at\ T\ \&\ P\ in\ dynes/cm^2$

$\tau_i = Known\ Initial\ Shear\ Stress\ at\ T_i\ and\ P_i$

$T_i = Initial\ temperature\ in\ °F$

$P_i = Initial\ Pressure\ in\ psi$

$T = Temperature\ in\ °F$

$P = Pressure\ in\ psi$

10.The multiple iterations were done using different statistical packages to get empirical constants. 150 data points for 19.51 API and 105 data points for 11.42 API oil were used to get empirical constants. Figure 5.14 compares the shear stress prediction by new model and drilling mud model with experimental data points. New model with initial pressure and temperature gives the good match with actual data points as compare to drilling mud model.

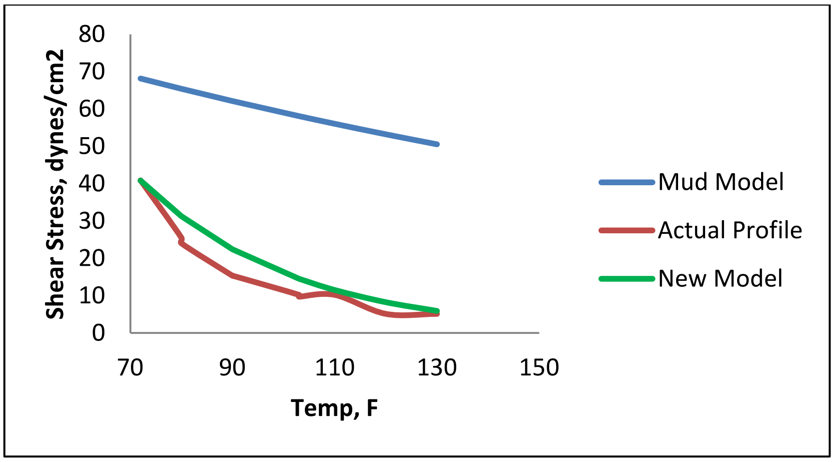


Figure 5.14: Prediction by new stress model and mud model

Pearson Product Moment Correlation Coefficient was calculated by plotting modelled shear stress versus measured shear stress at constant rpm (Figure 5.15). For constant RPM the R^2 is 0.97. In reality as mentioned in section 5.8.1 that the shear rate during SAGD is unsteady so it was important to consider the measurements at different shear rates. Detailed analysis was done to get the empirical constants for different RPMs. It was difficult to get the empirical constants for the whole range of heavy oil density and also for different RPMs hence to simplify this situation, the heavy oil range was divided into two smaller ranges depending on their API density. First group was for up to 15 ^{0}API and second was from 15-23 ^{0}API. All the empirical constants were tabulated in Table 5.9.

Table 5.9: Empirical constants for developed shear stress model

Empirical constants			
Oil API range	A	B	C
9-15 ^{0}API	44.046	-3.785	3×10^{-5}
15-23 ^{0}API	11.046	-2.402	3×10^{-5}

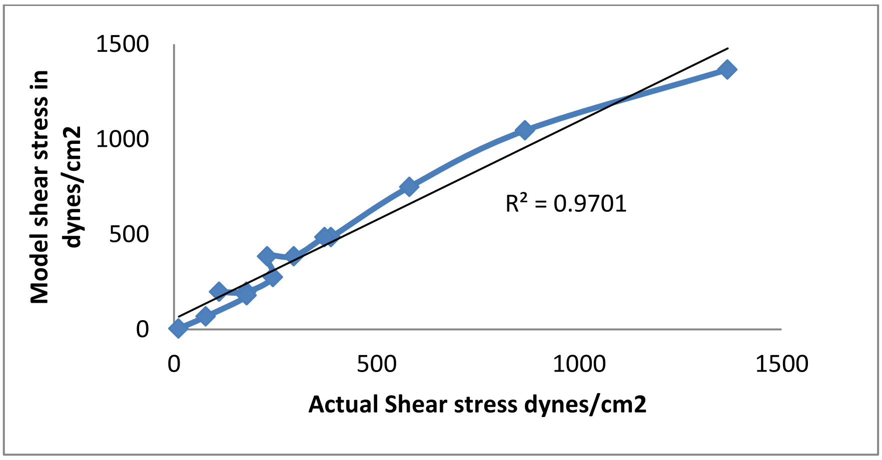


Figure 5.15: Prediction by new shear stress model at fixed shear rate

11. The developed model was validated and tested with independent data set. Overall the model for both ranges of heavy oil showed a good match. Table 5.10 summarises the number of data points used for development, validation and testing with the accuracy.

Table 5.10: Summary for database used for shear stress model

Stage	Number of data points	Sample API	R^2
Development	120	19.51	0.96
	105	11.42	0.93
Validation	145	20.65	0.94
	74	10.7	0.91
Testing	73	22.3	0.95

Figures 5.16 to 5.18 show the accuracy of new shear stress model

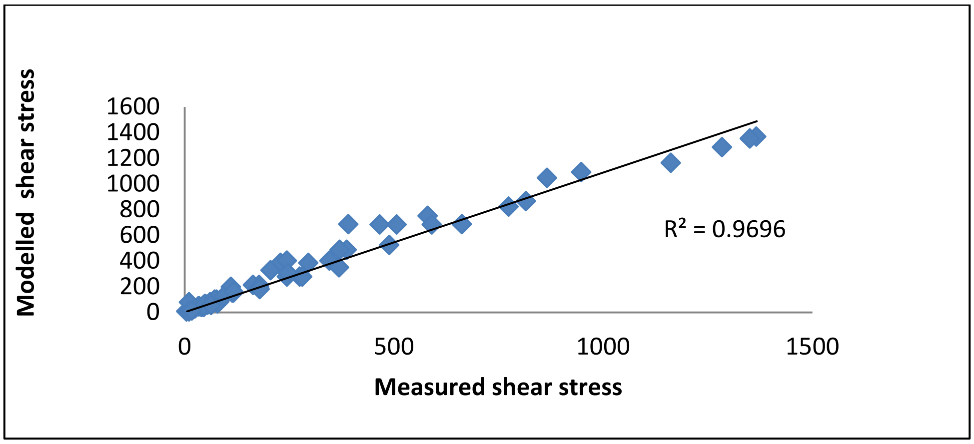


Figure 5.16: Accuracy during development

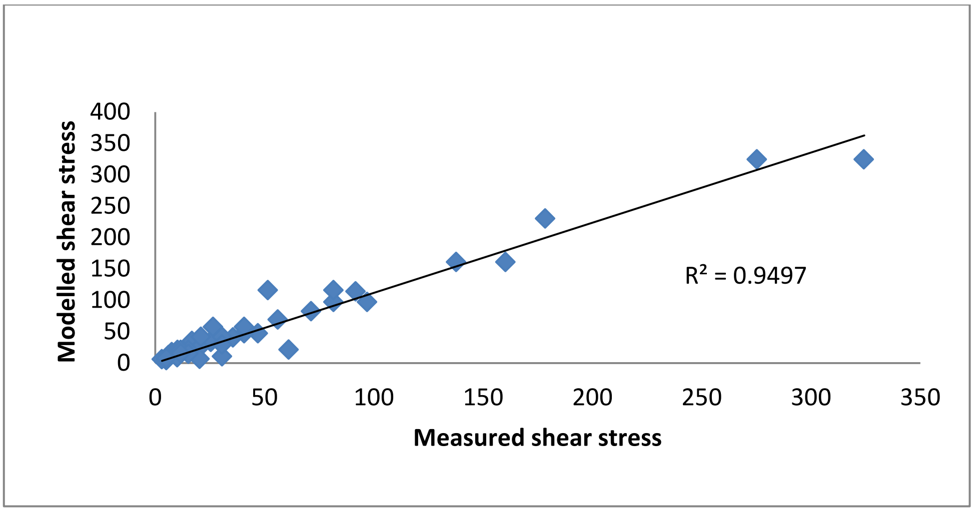


Figure 5.17: Accuracy during validation

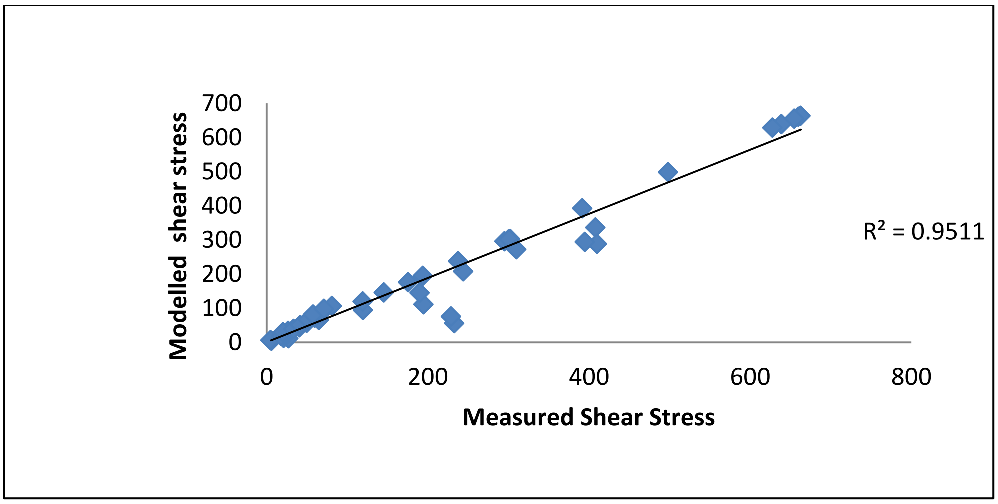


Figure 5.18: Accuracy during testing

CHAPTER 6: WELL MODELS FOR SAGD

6.1 Introduction:

In this chapter the different horizontal well productivity models are being introduced. Need of accurate model for SAGD is also demonstrated. Short listing is done using different simulator results and then recommendations are made for SAGD. Flow efficiency for optimum well length, segmentation for optimum drawdown is also covered in this chapter.

6.2 Flow equations for horizontal well:

The SAGD process has two horizontal wells. The analytical Butler's SAGD model equation 3.1 (34) is for the steady state drainage flow to the horizontal producer well. Butler's SAGD model does not give the productivity index in horizontal well. Productivity index, J, for a well is defined as the ratio of flow rate to pressure drop (q/dP) which means, the volume of produced oil per unit of pressure drop (73,74).

$$Productivity\ index, PI = J = \frac{q}{\Delta P} = \frac{q}{(P_r - P_{BHP})} \qquad [6.1]$$

Traditional horizontal well PI models can be used to determine the productivity of oil producer well and injectivity of steam injector well in SAGD. There are more than 25 horizontal well PI models available. These models have been developed for different reservoir conditions and can be grouped under following categories. In table 6.1, all the flow models for horizontal well are tabulated (75-77).

1. Steady state open flow models for isotropic reservoir
    - Borisov (78)
    - Ginger (79)
    - Renard and Dupuy (54)
    - Joshi (78)
    - Permadi (78)
    - Shedid (80)
    - Escobar (81)
2. Steady state open flow models for anisotropic reservoir
    - Joshi (82)

- Furui (73)
- Economides (73)
- Renard (54)

3. Pseudo-steady state models for infinite boundary
   - Babu and Odeh (83)
   - Donald (84)
   - William (85)
   - Mutalik (83)

Table 6.1: Flow models for horizontal well

Equations	Flow models	Equations
6.2	Borisov	$q_h = \frac{2\pi K_h h\Delta P/(\mu_o B_o)}{[\ln\left(\frac{4r_{eh}}{L}\right) + \left(\frac{h}{L}\right)\ln\left(\frac{h}{2\pi r_w}\right)]}$
6.3	Ginger	$q_h = \frac{2\pi K_h L\Delta P/(\mu_o B_o)}{\left(\frac{L}{h}\right)\ln\left[\frac{1+\sqrt{1-[\frac{L}{2r_{eh}}]^2}}{[\frac{L}{2r_{eh}}]}\right] + \ln\left(\frac{h}{2\pi r_w}\right)}$
6.4	Renard and Dupuy (isotropic)	$q_h = \frac{2\pi K_h h\Delta P/(\mu_o B_o)}{\cosh^{-1}(X) + \left(\frac{h}{L}\right)\ln\left(\frac{h}{2\pi r_w}\right)}$
6.5	Joshi (isotropic)	$q_h = \frac{2\pi K_h h\Delta P/(\mu_o B_o)}{\left[\ln\left(\frac{a+\sqrt{a^2+(\frac{L}{2})^2}}{(\frac{L}{2})}\right) + \left(\frac{h}{L}\right)\ln\left(\frac{h}{2r_w}\right)\right]}$
6.6	Permadi	$q_h = \frac{0.00708 K_h h\Delta P/(\mu_o B_o)}{\left[X_e - Y_e\sqrt{\frac{h}{L}} + \left\{\ln\left(\frac{Y_e}{2r_w}\sqrt{\frac{h}{L}}\right)\right\}\right]}$
6.7	Shedid	$q_h = \frac{0.007078 K_h h\Delta P/(\mu_o B_o)}{\left[\frac{\ln(\frac{h}{2r_w})}{(\frac{L}{h})} + \left(0.25 + \frac{C}{L}\right)\left(\frac{1}{r_w} - \frac{2}{h}\right)\right]}$
6.8	Escobar	$q_h = \frac{0.00708 K_h h\Delta P/(\mu_o B_o)}{\left[ACOSH(1.075X) + \left(\frac{0.874h}{L}\right)\ln(\frac{h}{2\pi r_w})\right]}$

6.9	Joshi (anisotropic)	$q_h = \dfrac{2\pi K_h h \Delta P/(\mu_o B_o)}{\left[\ln\left(\dfrac{a+\sqrt{a^2+(\frac{L}{2})^2}}{(\frac{L}{2})}\right) + (I_{ani})\left(\frac{h}{L}\right)\ln\left(\frac{h}{2r_w}\right)\right]}$
6.10	Joshi (anisotropic and eccentric)	$q_h = \dfrac{2\pi K_h h \Delta P/(\mu_o B_o)}{\left[\ln\left(\dfrac{a+\sqrt{a^2+(\frac{L}{2})^2}}{(\frac{L}{2})}\right) + (I_{ani})\left(\frac{h}{L}\right) ln\left[\left\{\left(\frac{I_{ani}h}{2}\right)^2 + I_{ani}{}^2\left(\frac{h}{2}-Z\right)^2\right\}/\{(I_{ani}\right.\right.}$
6.11	Furui	$q_h = \dfrac{0.00708 K_h L \Delta P/(\mu_o B_o)}{\left[I_{ani} ln\left[\frac{hI_{ani}}{r_w(I_{ani}+1)}\right] + \frac{\pi y_b}{h} - I_{ani}(1.224 - s)\right]}$
6.12	Butler	$q_h = \dfrac{0.00708 K_h L \Delta P/(\mu_o B_o)}{\left[I_{ani} ln\left[\frac{hI_{ani}}{r_w(I_{ani}+1)}\right] + \frac{\pi y_b}{h} - 1.14 I_{ani}\right]}$
6.13	Economides	$q_h = \dfrac{2\pi K_h h \Delta P/(\mu_o B_o)}{\left[\ln\left(\dfrac{a+\sqrt{a^2+(\frac{L}{2})^2}}{(\frac{L}{2})}\right) + \left(\frac{I_{ani}h}{L}\right)\ln\left(\frac{I_{ani}h}{r_w(I_{ani}+1)} + s\right)\right]}$
6.14	Renard (anisotropic)	$q_h = \dfrac{7.08\times10^{-3}\times K_h \times h}{\mu B_o (Acosh(X) + (I_{ani}\, {}^{h}/_{L}) \times \ln(\frac{\frac{h}{2pir_w(1+I_{ani})}}{2I_{ani}})}$
6.15	Babu and Odeh	$q_h = \dfrac{7.08\times10^{-3}\times\sqrt{K_x K_y}\times L}{\mu B_o\left[ln\left(\frac{A^{0.5}}{r_w}\right) + lnC_H - 0.75 + S_R\right]}$
6.16	Donald	$q_h = \dfrac{7.08\times10^{-3}\times\sqrt{K_x K_y}\times L}{\mu B_o\left[ln\left(\frac{(a_1 h)^{0.5}}{r_w}\right) + lnC_{H1} - 0.75 + S_R\right]}$
6.17	William	$q_h = \dfrac{7.08\times10^{-3}\times\sqrt{K_x K_y}\times L}{\mu B_o\left[ln\left(\frac{(a_1 h)^{0.5}}{r_{wwilliam}}\right) + lnC_{H1} - 0.75 + S_R\right]}$
6.18	Mutalik	$q_h = \dfrac{7.08\times10^{-3}\times K_h \times h}{\mu B_o\left[ln\left(\frac{r_{emutalik}}{r_w}\right) - 0.738 + S_f + S_{ca} - 1.386\right]}$

An anisotropic case was considered to compare the prediction of all horizontal well flow models. Table 6.2 and table 6.3 give the assumed reservoir, fluid and wellbore parameters required for calculations.

Table 6.2: Rock and oil properties

Rock Properties		
Absolute Permeability		
in X-direction	200	mD
in Y-direction	100	mD
in Z-direction	100	mD
Porosity	20	%
Reservoir Temperature	75	^{0}C
Reservoir Pressure	2500	psig
Oil Properties		
Oil API	21	^{0}API
Viscosity at reservoir	10	cp
Oil Formation Factor	1.1	rb/STB

Table 6.3: Reservoir and wellbore properties

Reservoir Parameters					
Bounded Reservoir			Infinite reservoir		
Length of reservoir	6000	ft	Hydraulic radius	500	ft
Width of reservoir	545.45	ft	Assumed Length	6000	ft
Pay thickness	480	ft	Eq. Width	545.45	ft
Wellbore Parameters					
			Well Location		

Well Length	700	ft	Xo	272.73	ft
Well bore radius	0.354	ft	Yo	1000	ft
			Zo	240	ft

Equations from Table 6.1 were solved for the above considered case and PI in horizontal well was calculated. PI values by different models were tabulated in Table 6.4 and also graphical comparison was done in Figure 6.1. It is clear from Figure 6.1 that the prediction of each model is different. There are no recommended PI models for SAGD wells. There is a technical gap on using horizontal flow model for SAGD process.

Table 6.4: PI results

Flow Model	PI, J, stb/d-psi
Borisov	13.05
Ginger	50.21
Renard	13.03
Joshi	11.18
Permadi	4.13
Shedid	9.99
Escobar	14.14
Joshi1	6.18
Joshi2	8.01
Economides	0.23
Butler	7.90
Furui	0.23
Renard1	9.62
Babu	12.95
Donald	12.96
William	13.04
Mutalik	13.41

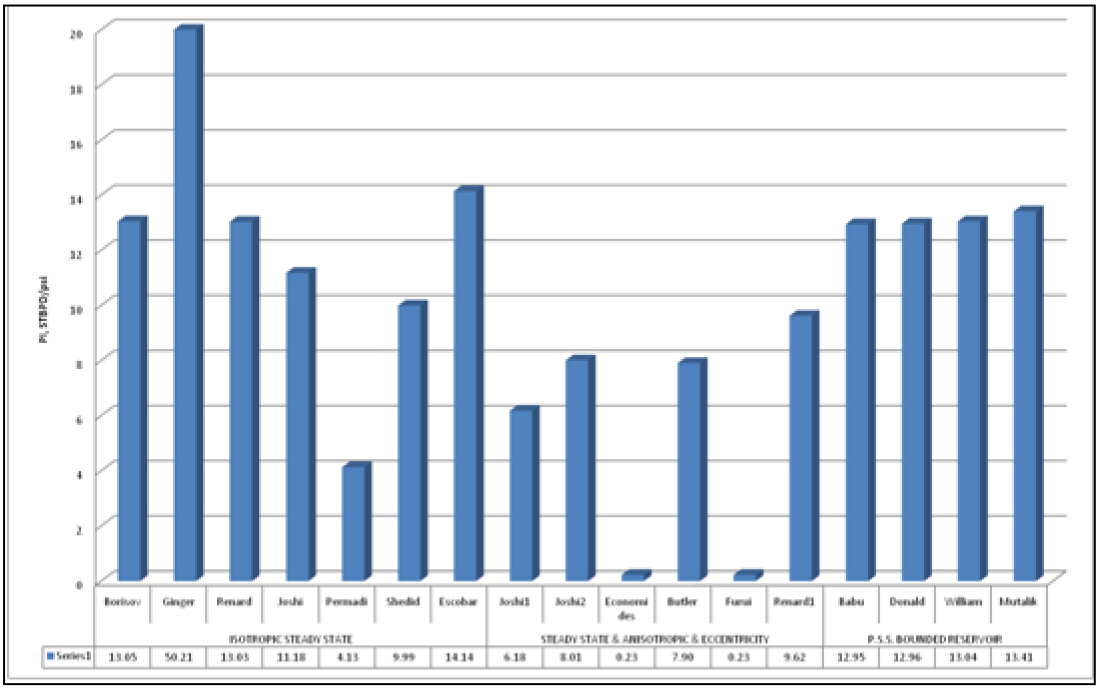


Fig 6.1: PI comparison for heavy oil

6.3 Flow models for SAGD wells

Flow model for SAGD wells was shortlisted by validating the analytical prediction with reservoir and wellbore simulators. Simulator prediction was preferred to validate the models due to lack of field and experimental data. Reservoir simulators are used during initial planning of field development hence it was decided to validate the analytical prediction against the simulators. Reservoir simulators REVEAL and ECLIPSE100 were used and wellbore simulators PROSPER was also used to validate HW PI models (86,87).

In SAGD process there could be an isotropic or an anisotropic formation. Also there could be finite and infinite reservoir boundaries. There is also a possibility of partial and full penetration in finite reservoir. There could be more uncertainties as well but in this research project six different cases were considered for short listing the HW flow models for SAGD wells which are as follows.

1. Full penetration in isotropic reservoir
2. Partial penetration in isotropic reservoir
3. Infinite isotropic reservoir
4. Full penetration in anisotropic reservoir

5. Partial penetration in anisotropic reservoir
6. Infinite anisotropic reservoir

Case1: Isotropic and full penetration

Table 6.5: Case1 parameters

Rock Properties					
Absolute Permeability					
in X-direction	500	mD			
in Y-direction	500	mD			
in Z-direction	500	mD			
Porosity	20	%			
Reservoir Temperature	75	^{0}C			
Reservoir Pressure	2500	psig			
Oil Properties					
Oil API	21	^{0}API			
Viscosity at reservoir	9.21	cp			
Oil Formation Factor	1.1	rb/STB			
Reservoir Parameters					
Bounded Reservoir			Infinite reservoir		
Length of reservoir	3000	ft	Hydraulic radius	500	ft
Width of reservoir	600	ft	Assumed Length	3000	ft
Pay thickness	480	ft	Eq. Width	545.45	ft

Wellbore Parameters					
			Well Location		
Well Length	3000	ft	Xo	300	ft
Well bore radius	0.354	ft	Yo	0	ft
			Zo	240	ft

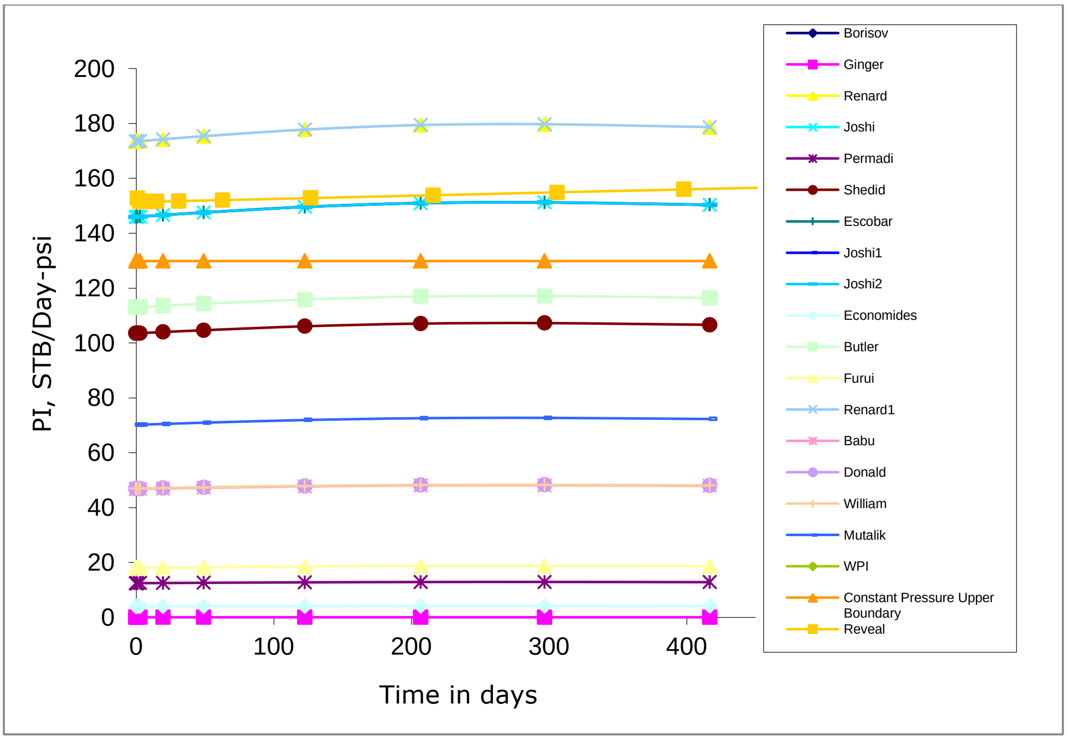


Fig 6.2: Isotropic and full penetration case

Case2: Isotropic, partial penetration 33%

Table6.6: Case2 parameters

Reservoir Parameters					
Bounded Reservoir			Infinite reservoir		
Length of reservoir	3000	ft	Hydraulic radius	500	ft
Width of reservoir	600	ft	Assumed Length	3000	ft
Pay thickness	480	ft	Eq. Width	600	ft
Wellbore Parameters					
			Well Location		
Well Length	1000	ft	Xo	300	ft
Well bore radius	0.354	ft	Yo	1000	ft
			Zo	240	ft

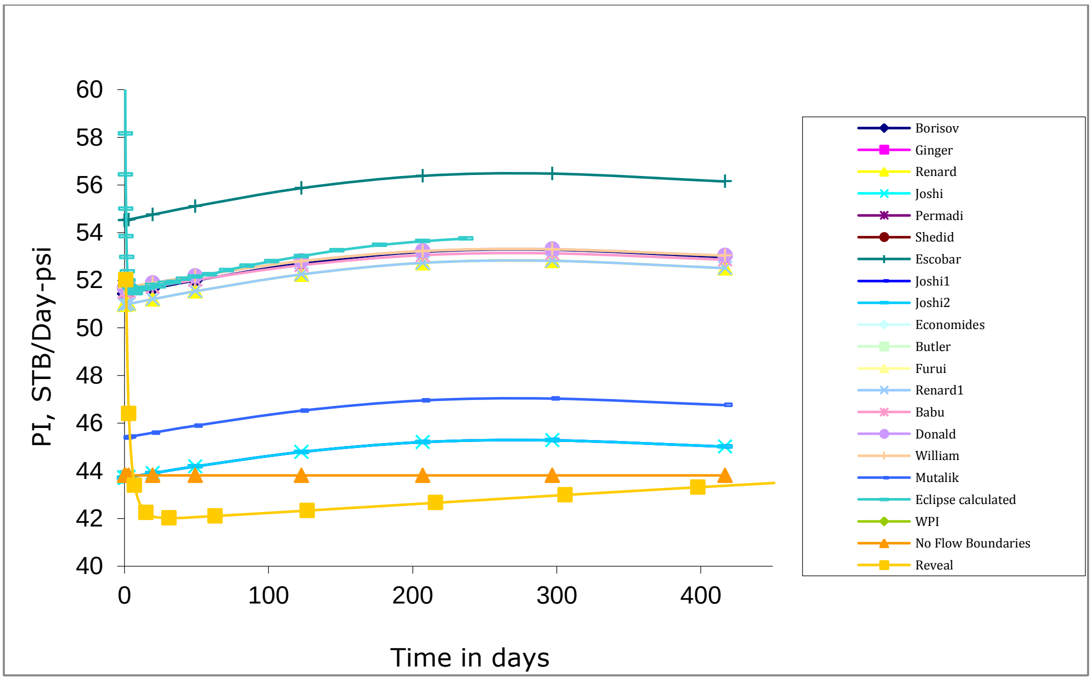


Fig 6.3: Isotropic and partial penetration case

Case 3: Isotropic, infinite reservoir

Table6.7: Case3 parameters

Reservoir Parameters					
Bounded Reservoir			Infinite reservoir		
Length of reservoir	10000	ft	Hydraulic radius	-	ft
Width of reservoir	1000	ft	Assumed Length	-	ft
Pay thickness	480	ft	Eq. Width	-	ft
Wellbore Parameters					
			Well Location		
Well Length	1000	ft	Xo	5000	ft
Well bore radius	0.354	ft	Yo	4500	ft
			Zo	240	ft

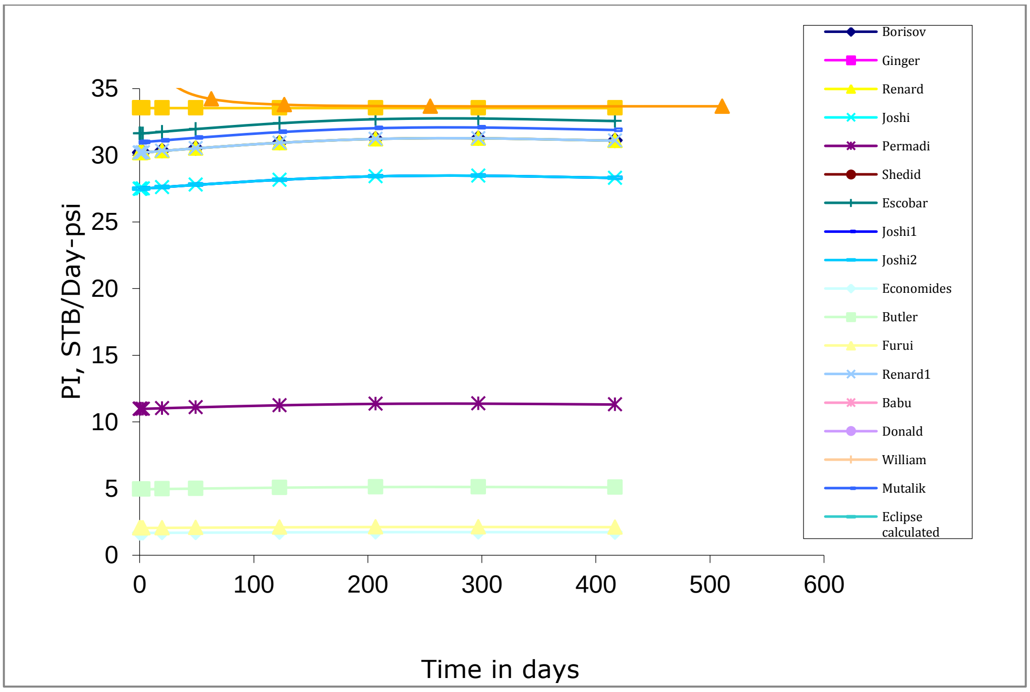


Fig 6.4: Isotropic and infinite reservoir case

Case 4: Anisotropic, full penetration

Table 6.8: Case4 parameters

Rock Properties		
Absolute Permeability		
in X-direction	500	mD
in Y-direction	500	mD
in Z-direction	50	mD

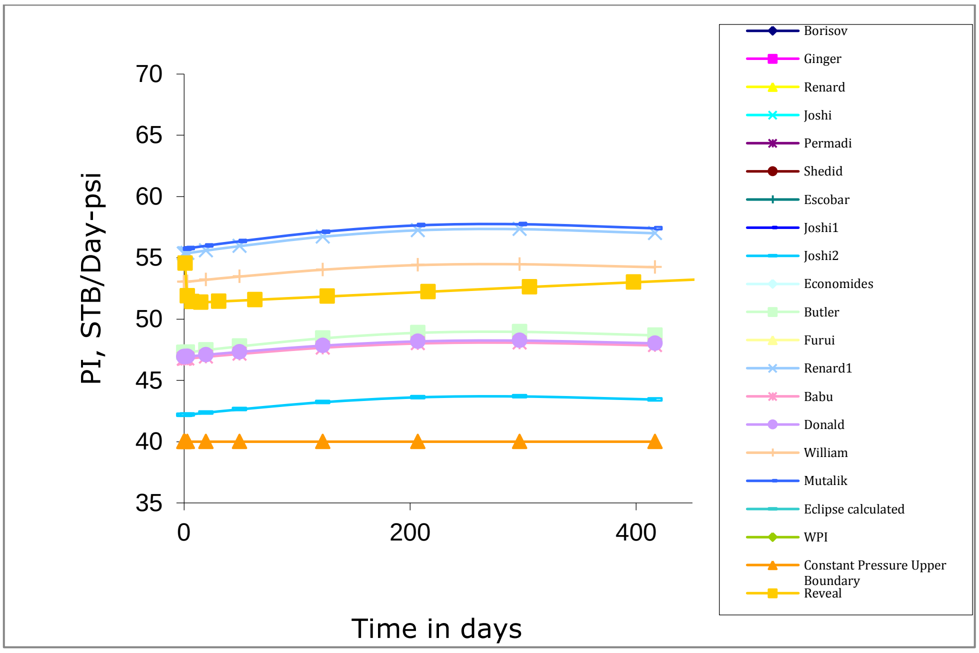


Fig 6.5: Anisotropic and full penetration case

Case 5: Anisotropic, partial penetration 33%

Table 6.9: Case5 parameters

Wellbore Parameters					
			Well Location		

Well Length	1000	ft	Xo	300	ft
Well bore radius	0.354	ft	Yo	1000	ft
			Zo	240	ft

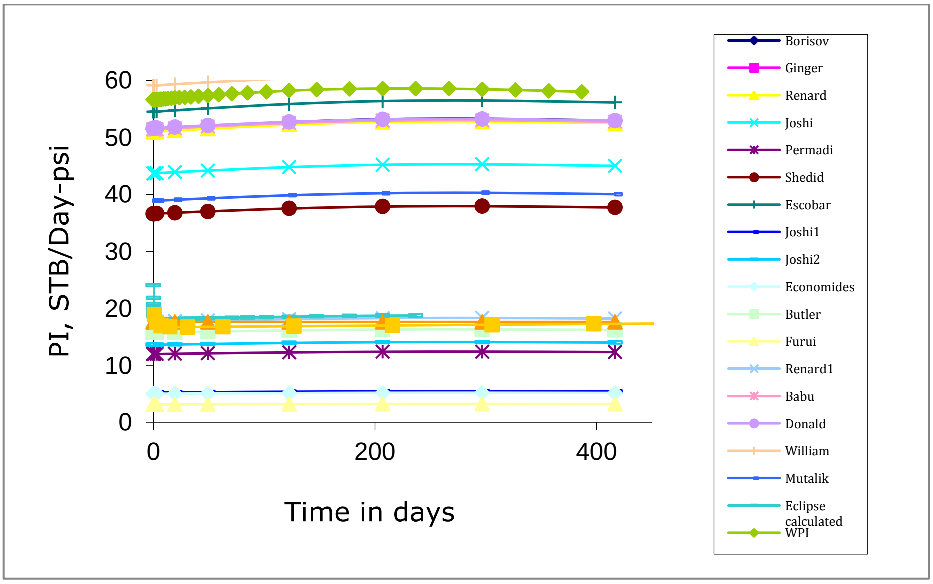


Fig 6.6: Anisotropic and partial penetration case

Case 6: Anisotropic, infinite reservoir

Table 6.10: Case6 parameters

Reservoir Parameters					
Bounded Reservoir			Infinite reservoir		
Length of reservoir	10000	ft	Hydraulic radius	-	ft
Width of reservoir	1000	ft	Assumed Length	-	ft
Pay thickness	480	ft	Eq. Width	-	ft
Wellbore Parameters					
			Well Location		
Well Length	1000	ft	Xo	5000	ft

Well bore radius	0.354	ft	Yo	4500	ft
			Zo	240	ft

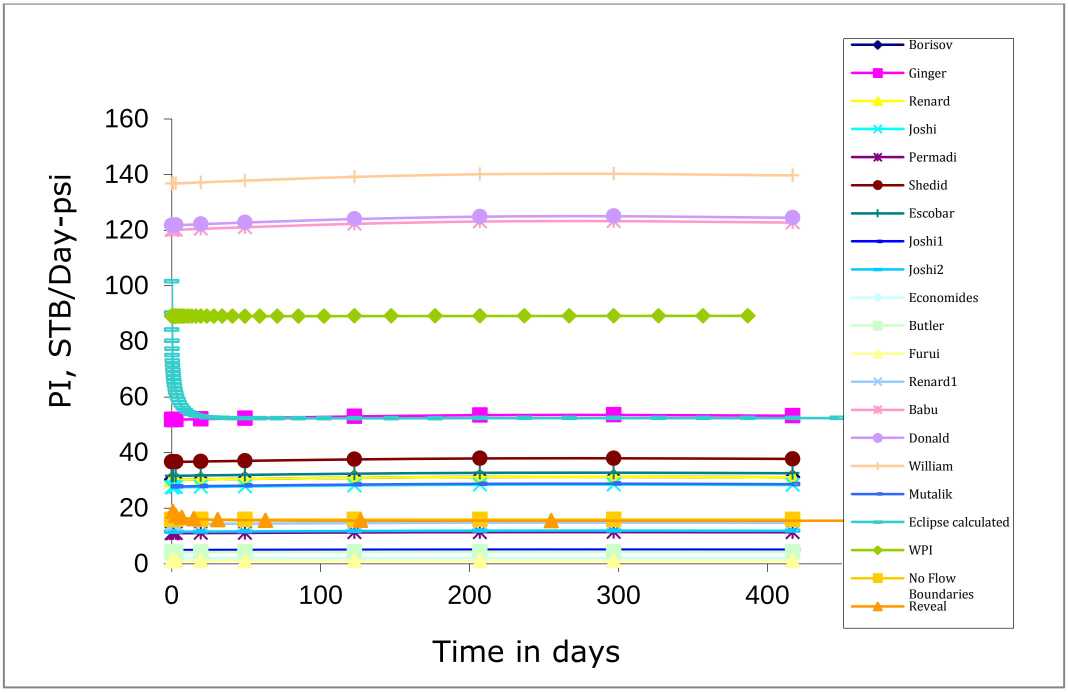


Fig 6.7: Anisotropic and infinite reservoir case

Summary:

After doing the simulation for different six cases, following four HW flow models were shortlisted for SAGD wells. These models have showed a good match with simulator results.

Table6.11: Shortlisted HW flow models

	Isotropic	Anisotropic
Full Penetration	**Joshi2**	**Renard1**
Partial Penetration	**Mutalik**	
Infinite reservoir	**Escobar**	

6.4 Flow efficiency of HW

Getting optimum horizontal well length is a very critical decision during designing and field development plan. As identified in chapter 3, the well length has direct impact on recovery and also the well length according to Butler's SAGD equation is directly proportional to oil rate. Optimum flow rate can be achieved by achieving highest flow efficiency. Equation 6.6 were used to calculate the flow efficiency of horizontal well (54,88).

$$E_h = \frac{J_{Actual}}{J_{ideal}} = \frac{\frac{L}{h\beta}Acosh(X)+ln\left(\frac{h}{2\pi r_w'}\right)}{\frac{L}{h\beta}Acosh(X)+ln\left(\frac{h}{2\pi r_w'}\right)+S_V} \qquad [6.19]$$

$$\beta = \sqrt{\frac{K_h}{K_V}}$$

$$r_w' = \left(\frac{1+\beta}{2\times\beta}\right) \times r_w$$

The productivity index of horizontal well is also dependent on wellbore skin. By knowing the wellbore skin, above equation can be solved for different well lengths and wellbore diameters to optimise the well length and tubing diameter. Equation 6.19 was solved for case 6 for wide range of well length and flow efficiency was plotted in Figure 6.8. For this case 1000 ft lateral length was giving the optimum flow efficiency. Above 1000 ft the flow efficiency is constant so drilling longer lateral section above 1000 ft doesn't add extra production but only increases the drilling and completion cost.

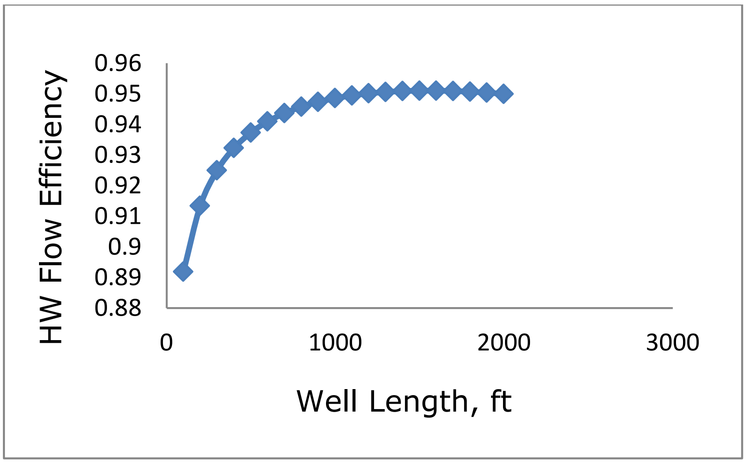


Fig 6.8: HW flow efficiency for different well length

Similarly for 1000 ft lateral length wellbore, same case was solved for different tubing sizes. It is clear from figure 6.9 that the tubing size doesn't have huge impact on flow efficiency.

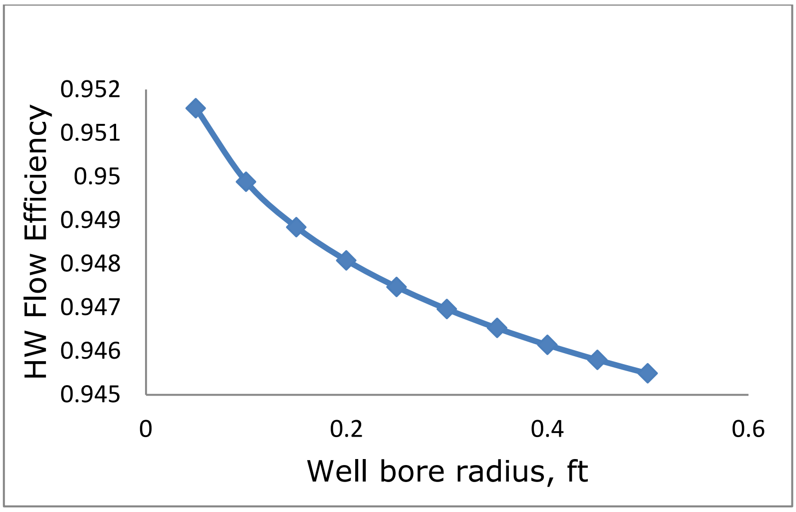


Fig 6.9: HW flow efficiency for different tubing sizes

6.5 Flow pattern for horizontal well

In horizontal wellbore, flow can only initiate when the pressure at toe and heel is different. Drawdown on formation is the pressure difference between reservoir and wellbore pressure. Pressure in horizontal well could not be same along the horizontal length hence the applied drawdown on formation along horizontal length is also different. Different drawdown will give different inflow or outflow rates which results in different inflow or outflow patterns along horizontal well. The shape of flow pattern depends on number of parameters such as wellbore completion, reservoir horizontal and vertical absolute permeability, well length, flow rates and pressure drop in wellbore.

Basically three different types of pattern can be achieved in horizontal well by monitoring the design and operating parameters.

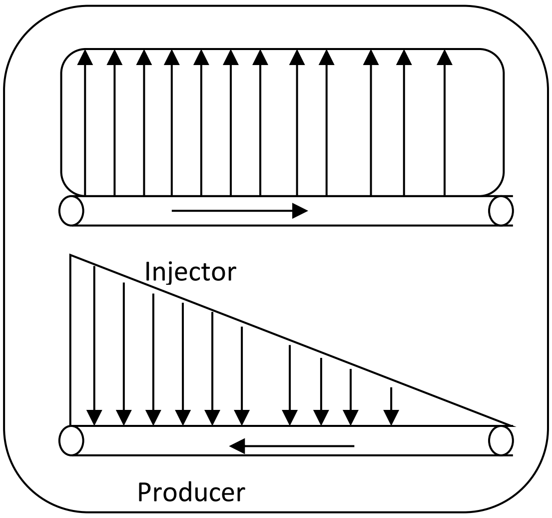
- Triangular pattern
- Trapezoidal pattern
- Rectangular pattern

With the help of smart completion such as inflow control devices, the flow pattern can be optimised to achieve maximum recovery.

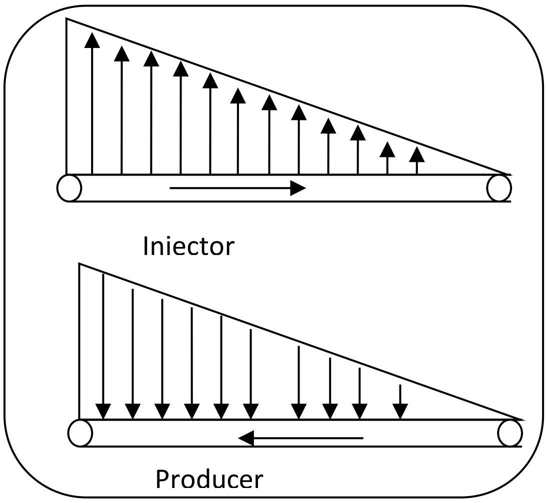
In Steam Assisted Gravity Drainage, depending on injection, production and reservoir parameters the different combinations of outflow and inflow are possible. If steam injection is at one point which is heel of injector then the outflow at heel of injector is higher than at toe of injector. Below are the possible drainage profiles which could see in SAGD.

T= Triangular, U= Uniform, Z= Trapezoidal, O= Outflow for injector, I=inflow for producer

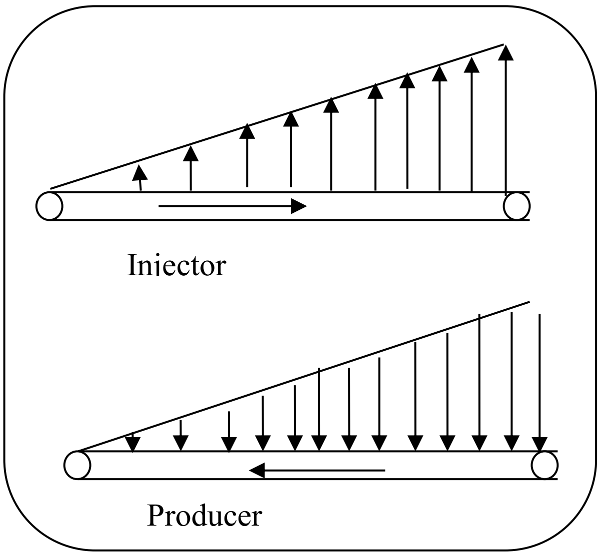
U-O,T-I



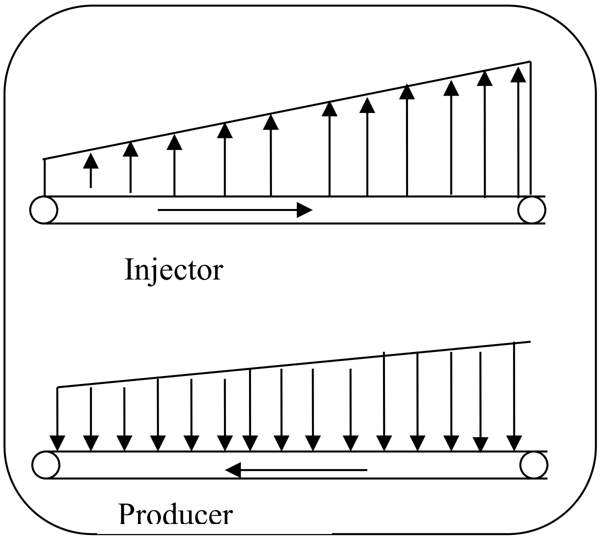
T-O,T-I



T-O,T-I



Z-O,Z-I



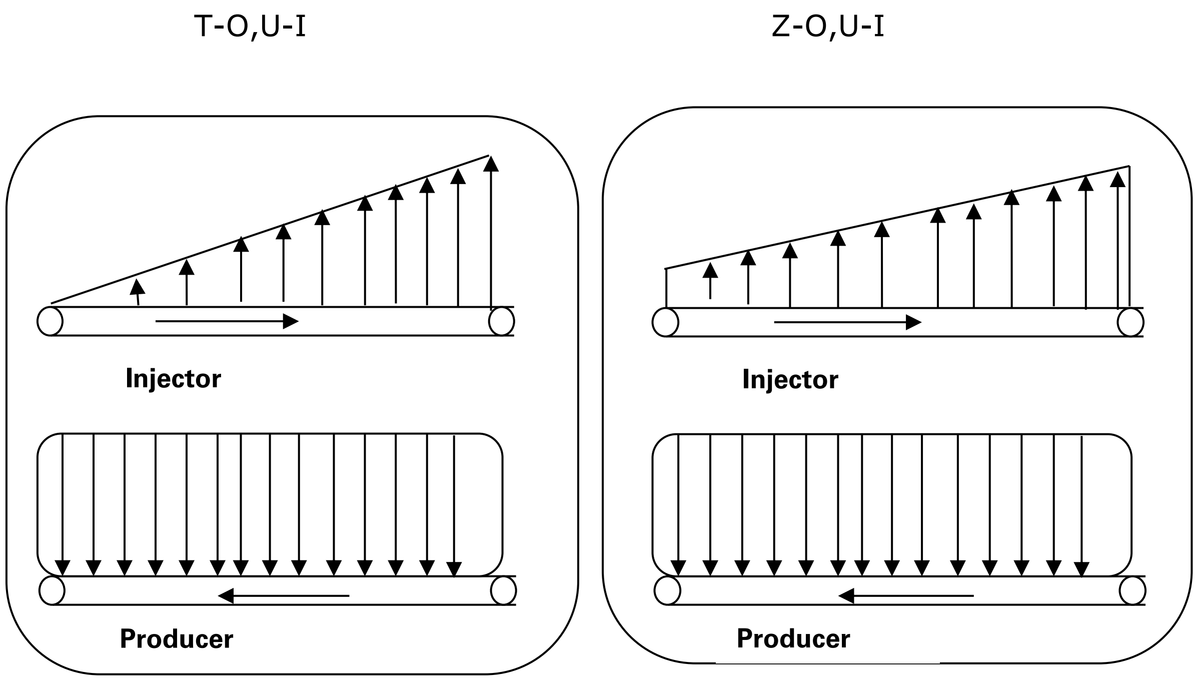


Fig 6.10: Different drainage profiles in SAGD

The reservoir simulation results were used to demonstrate the different flow patterns and same approached can be used while designing the SAGD wells.

6.6 Segmentation of horizontal well

In an ideal SAGD process, the aim is to get uniform inflow and outflow profiles for maximum recovery. An optimum drawdown on injection and production well could give an optimum drainage for both the wells. To apply the optimum drawdown it is important to understand the pressure profile along the wells (89,90). In injectors the pressure profile is not that critical as only steam is flowing through it. There is a multiphase flow through the producer hence it becomes crucial to get pressure profile along the horizontal producer. In Figure 6.11, the schematic for inflow to the horizontal producer well is explained. The oil flow is from toe to heel. After dividing the lateral section to small segments and then calculating pressure drop for each segment by considering cumulative flow through them can give the pressure profile for the horizontal well. The calculation starts from toe. First calculate the inflow to first segment and then using that flow determines the pressure loss in small segment. This gives the inlet pressure to adjacent segment towards heel. Repeat the process for all the segments to determine the pressure profile along the wellbore.

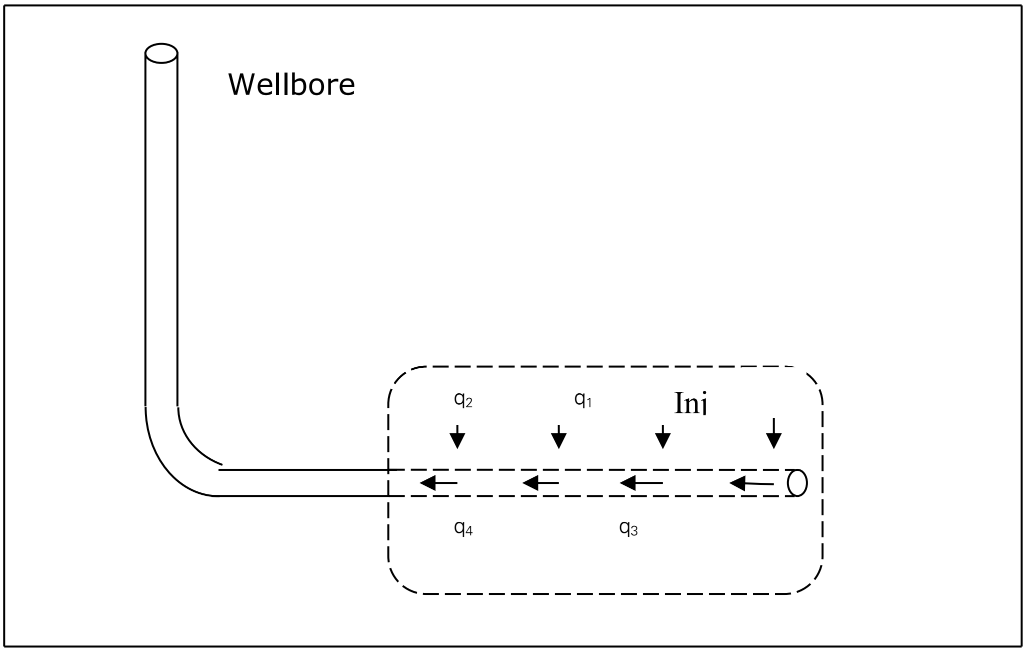


Fig 6.11: Schematic for inflow to the horizontal producer well

A case was built in Reveal reservoir simulator and results were illustrated in detail to get the pressure profile along the horizontal well. Tubing pressure data was analysed after the SAGD process reaches to steady state. In this case data points were taken after 2 months from injection date. The horizontal well was divided into 60 segments of equal length of 50 feet and the initial reservoir pressure was 3200 psig. In Figure 6.12, the reservoir and tubing pressure were plotted for a particular timestamp which was after 2 months after injection. It is obvious to get high pressure at toe and low pressure at heel.

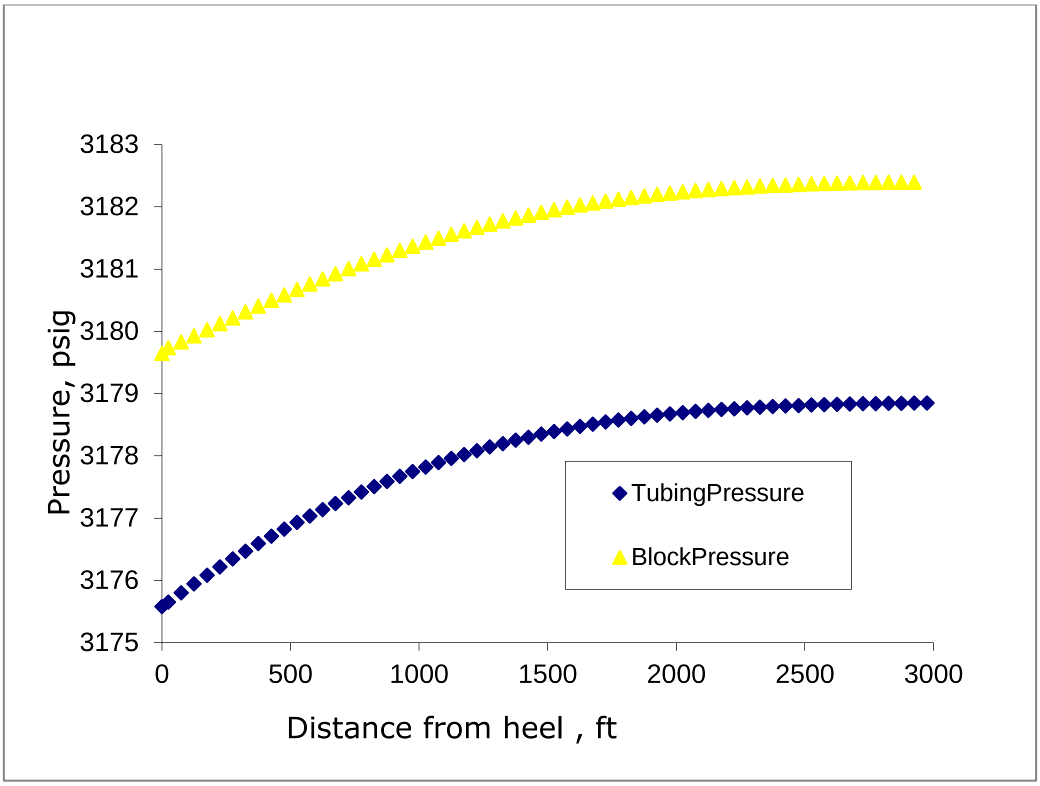


Fig 6.12: Pressure profile along the horizontal well

The above pressure profiles were then used to get the real time drawdown on each segment of the horizontal well. There were 60 segments hence the analytical PI was calculated for each segment using shortlisted HW flow models. Knowing the PI and drawdown for each segment, the inflow rate was calculated. Following the principle from Figure 6.11, the cumulative rate was derived from each segment rates. In figure 6.13, the cumulative rates by analytical and numerical models were compared. Apart from Mutalik, other analytical models predicted low compare to reservoir simulators. The different prediction by REVEAL and ECLIPSE as compare to analytical models was because of different oil viscosity used in calculations. Reservoir simulators had used the internal models to predict the 8.5 cp viscosity where as the analytical models had used 9.2 cp. This comparison increased the confidence on analytical models.

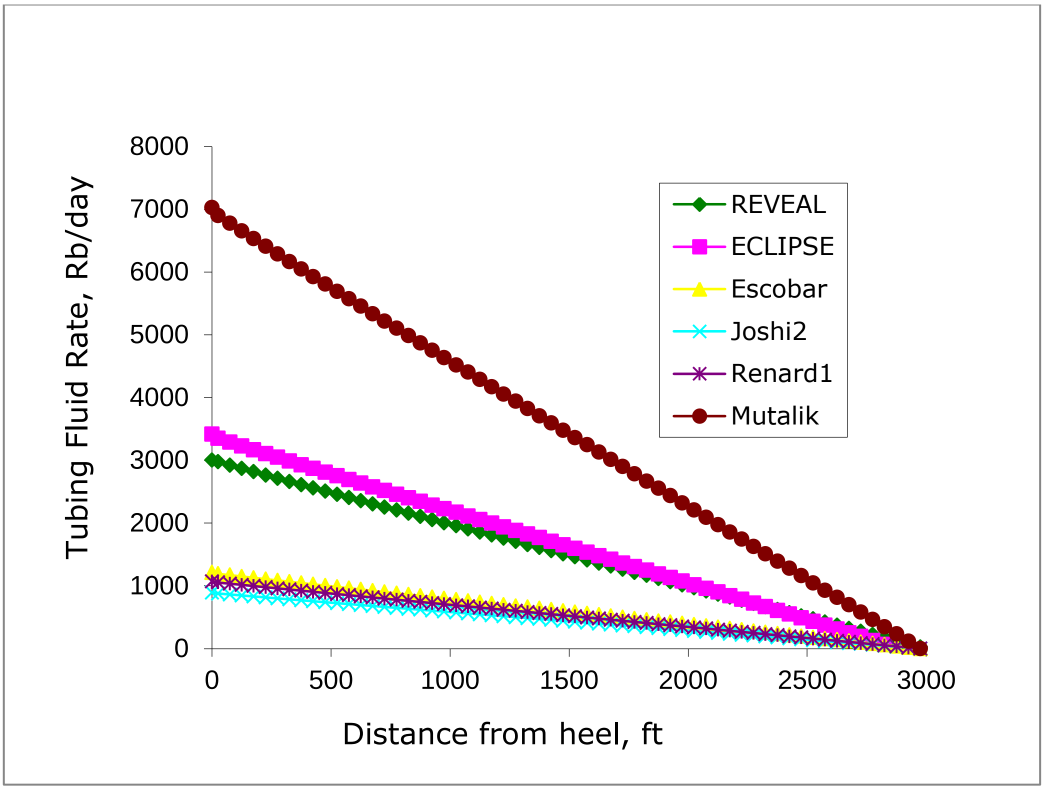


Fig 6.13: Cumulative inflow by different models

The inflow profiles by all analytical models from Figure 6.13 are not uniform. To get uniform inflow profile or to optimise the well length and well diameter, the pressure drop calculations were done using the below equation 6.20 (91,92) and the flow efficiency calculations were done using equations 6.19.

$$\mathrm{Re} = \mathrm{DV}\rho/\mu$$

For Laminar flow (Re<3200), FF=16/Re

For turbulent flow (Re>3200)

$$\text{Friction factor} = \mathrm{FF} = 0.001375\left\{\left[\left(\frac{10^6}{\mathrm{Re}}\right) + 20000\left(\frac{\text{Roughness}}{\text{Pipe ID}}\right)\right]^{0.33} + 1\right\}$$

$$\Delta P_{\text{single phase}} = 4 \times \mathrm{FF} \times \left(\frac{L}{\text{Pipe ID}}\right) \times \left(\frac{\rho V^2}{2}\right) \qquad [6.20]$$

Case study for optimum inflow profile using above mentioned procedure is given in the chapter 8 where the flow of simulators with other outcomes are explained.

CHAPTER 7: THE STEAM ASSISTED GRAVITY DRAINAGE SIMULATOR

7.1: Introduction

Previous chapters have covered the dynamic behaviour of heavy oil. This chapter is to focus on the other dynamic properties such as effective permeability by tracking the relative and absolute permeability. In this chapter the procedure for tracking the growth of steam chamber has also been explained. The excel based simulator has also been introduced in this chapter.

7.2: Effective permeability in Steam Chamber

In SAGD process the water cut, reservoir pressure and formation temperature are dynamic in nature and these affect the effective permeability of oil. Water cut is responsible for change in relative permeability of oil whereas steam chamber's pressure and temperature will affect the porosity of the formation.

Effective permeability is the multiplication of the relative permeability of heavy oil to the absolute permeability of reservoir at desired conditions. To calculate real time effective permeability in steam chamber, one has to determine the real time relative and absolute permeabilities first. Here the tracking of both types of permeabilities is explained separately.

7.2.1: Tracking relative permeability to heavy oil in steam chamber

Two models were shortlisted to calculate the relative permeability of oil. Recommendations were made by testing Stone 1 (equation 7.7) (93,94) and Wang (equation 7.8) (35,95) models on the live data. Live data was collected from one of the producing heavy oil wells from North Sea [well o1]. Production test data over the period of four years was used to explain the recommendations on relative permeability model.

The actual relative permeability of heavy oil was calculated from production test data by the following procedure.

i. Collect the production test data
ii. Calculate the water cut profile from liquid and oil rates

iii. Using Renard's HW flow model, calculate the effective permeability for measured drawdown

iv. Calculate relative permeability of oil by dividing with the absolute permeability of formation

v. Plot the oil relative permeability with water cut. Figure 7.1 shows the measured oil relative permeability with different WC

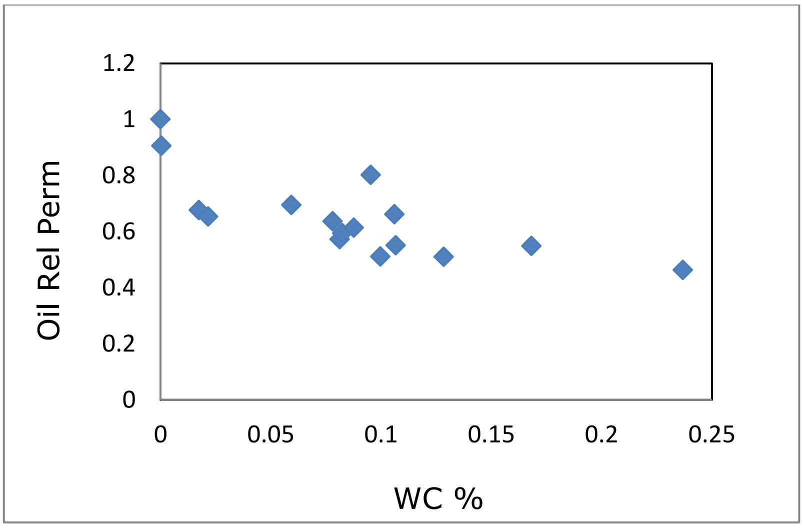


Figure 7.1: Oil relative permeability profile

Analytical oil relative permeability was calculated using Stone 1 and Wang's equations 7.7 and 7.8 respectively. Below is the step by step procedure to calculate the oil relative permeability. From the live heavy oil data from figure 5.10, it is clear that the operating downhole pressure will always be above saturation pressure of heavy oil. This can allow us to make an assumption of no free gas in heavy oil reservoirs. Hence gas saturation can be neglected. Hence Stone's three phase relative permeability model can be simplified to two phase.

The following procedure and models were adopted to calculate the analytical oil relative permeability.

i. Calculate water saturation

$$S_w = S_{wi} + \left[\frac{WC \times B_w}{(1-WC)B_o + WC \times B_W}\right][1 - S_{wi} - S_{orw}] \qquad [7.1]$$

ii. Calculate effective water saturation considering initial water saturation

$$S_{we} = \frac{S_w - S_{wi}}{1 - S_{wi} - S_{orw}} \qquad [7.2]$$

iii. Calculate two phase oil relative permeability for oil/water displacement at initial water saturation

$$K_{ro(wi)} = 0.76067\left[\frac{S_{wi} - S_{orw}}{1 - S_{wi} - S_{orw}}\right]^2 + 2.6318 \times \emptyset \times [1 - S_{orw}][1 - S_{wi} - S_{orw}] \qquad [7.3]$$

iv. Calculate oil saturation

$$S_o = S_{orw} + \left[\frac{(1 - WC)B_o}{(1 - WC)B_o + WC \times B_W}\right][1 - S_{wi} - S_{orw}] \qquad [7.4]$$

v. Calculate effective oil saturation

$$S_{oe} = \frac{S_o - S_{orw}}{1 - S_{wi} - S_{orw}} \qquad [7.5]$$

vi. Calculate two phase oil relative permeability for oil/water displacement at real water saturation

$$K_{ro(w)} = 0.76067\left[\frac{\frac{S_o}{1 - S_{wi}} - S_{orw}}{1 - S_{orw}}\right]^{1.8}\left[\frac{S_0 - S_{orw}}{1 - S_{wi} - S_{orw}}\right]^2 + 2.6318 \times \emptyset \times [1 - S_{orw}][S_o - S_{orw}] \qquad [7.6]$$

vii. Calculate three phase oil relative permeability using simplified Stone's and Wang's equations

Stone 1 simplified three phase equation

$$K_{ro} = \frac{S_{oe}K_{ro(w)}}{K_{ro(wi)}(1 - S_{we})} \qquad [7.7]$$

Wang three phase equation

$$K_{ro} = K_{ro(S_{wi})}\left(\frac{1 - S_{or} - S_w}{1 - S_{wi} - S_{or}}\right)^{E_o} \qquad [7.8]$$

E_0 in Wang's equation is the oil relative permeability equation exponent which is an adjustable parameter. By doing iterative matching the value of E_0 was set to two. Predicted three phase oil relative permeability was plotted against actual in Figure 7.2.The R-squared value for Stone's model was 0.73.

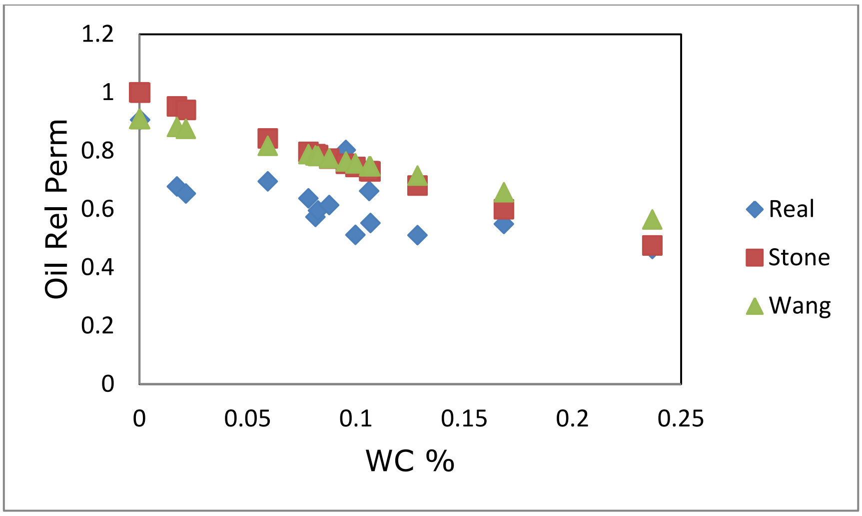


Figure 7.2: Three phase oil relative permeability

7.2.2: Absolute permeability of formation

For absolute permeability prediction, equations 7.9 and 7.10 (35) were adopted to track the relative change in porosity with pressure and temperature.

$$\emptyset = \emptyset_{Ref} exp^{(C_r \Delta P)} \qquad [7.9]$$

$$\emptyset = \emptyset_{Ref}(1 - C_T \Delta T) \qquad [7.10]$$

C_r is the rock compressibility and C_T is the thermal expansion coefficient of formation. Assuming extreme conditions during SAGD, the above equations were solved to understand the sensitivity of absolute permeability to pressure and temperature. Reservoir pressure was assumed to deplete by five times where as temperature was assumed to increase by ten times.

Table 7.1: Case parameters for absolute permeability

Initial Porosity	0.35 %
Uniform rock compressibility	0.000015/psi
Thermal expansion coefficient	0.000015/F

Initial reservoir Pressure	5000 psi
Initial reservoir temperature	100 ^{0}F
Absolute Permeability	1000 mD

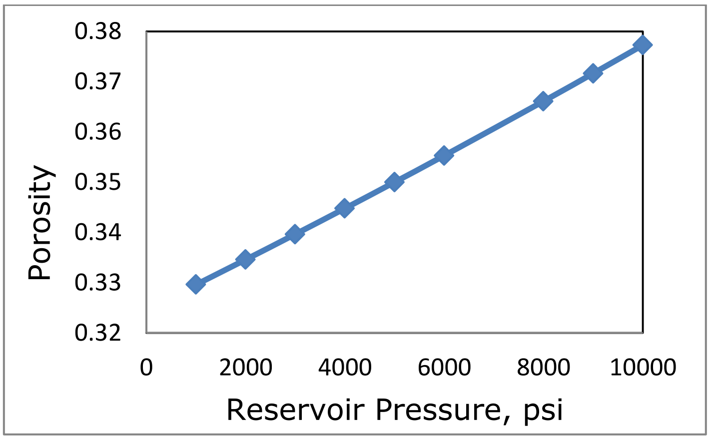


Figure 7.3: Porosity profile with rock pressure

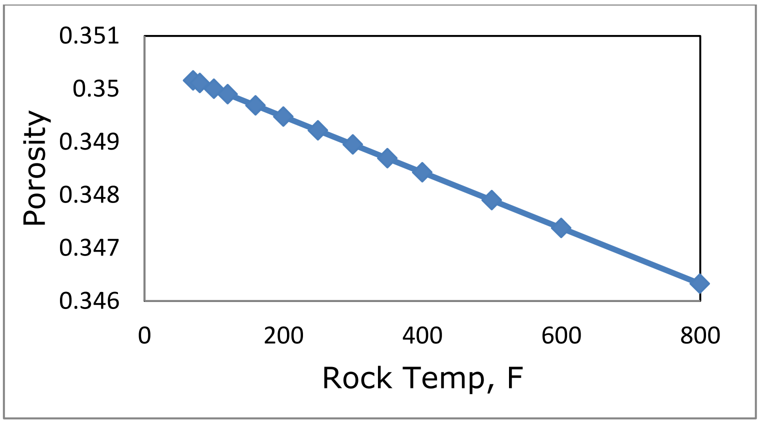


Figure 7.4: Porosity with rock temperature

In Figures 7.3 and 7.4, calculated porosity was plotted against different reservoir pressures and formation temperatures. Using Blake-Kozeny-Carman (BKC) Equation 7.11 (8), the absolute permeability was calculated for different formation porosities. The particle diameter was calculated from initial porosity and absolute permeability using BKC equation 7.11. New absolute permeabilities were calculated by keeping constant particle diameter for different pore diameters and porosities.

$$D_{particle} = \frac{6 \times (1 - \emptyset)}{S_{vol.part}}$$

$$S_{vol.part} = \sqrt{\frac{\emptyset^3}{2 \times k_a \times (1.8561 - 0.715\emptyset)^2}}$$

$$D_{pore} = \frac{D_{particle} \times \emptyset}{3 \times (1 - \emptyset)} \quad [7.11]$$

Absolute permeability for different reservoir pressure is plotted in figure 7.5 where as for different temperature it is in figure 7.6.

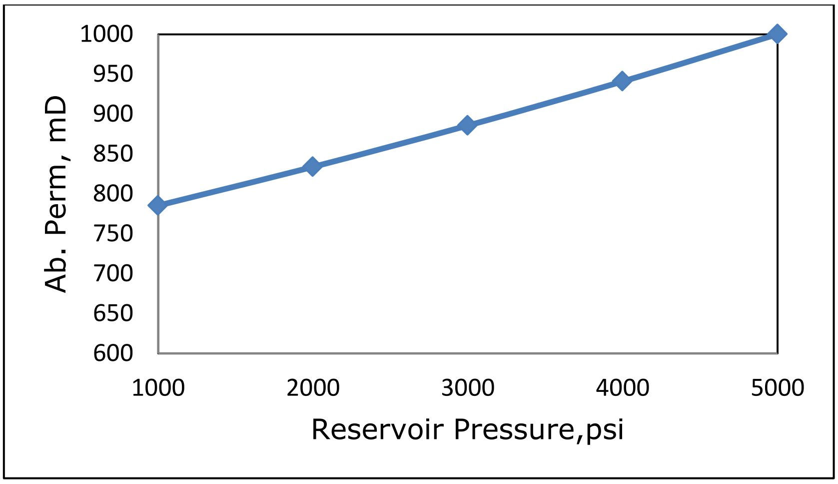


Figure 7.5: Absolute permeability profile with reservoir pressure

After comparing the variation in absolute permeability of formation with pressure and temperature, the reservoir pressure is slightly more sensitive than temperature.

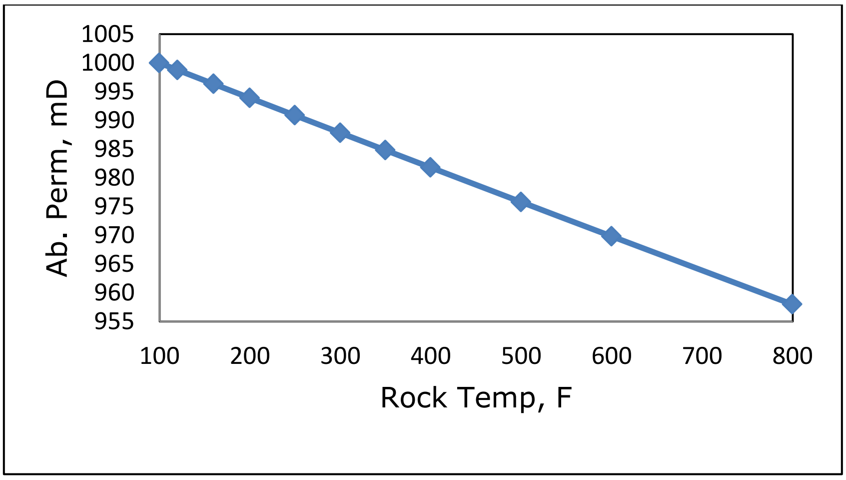


Figure 7.6: Absolute permeability profile with rock temperature

7.3: Tracking the growth of steam chamber

Steam injection in SAGD will develop the steam chamber. As described in the mechanism of SAGD the steam chamber initially will grow vertically and then laterally. Growth in both directions is very dynamic in nature and the shape of steam chamber mainly relies on the reservoir properties such as vertical and lateral absolute permeability. To get an approximate idea about the location of steam-oil interface, Marx's (14) equations and procedure were adopted.

Step by step procedure to calculate heat injection rate, oil displacement rate and economic areal limit for sustained injection is given below with the necessary equations.

i. From specific heat capacities of formation, water and oil, calculate volumetric heat capacity of mixture

$$M = [(1-\emptyset)\rho_r C_r + S_w \emptyset \rho_w C_W + S_o \emptyset \rho_o C_o] \qquad [7.12]$$

ii. Calculate area swept in time t

$$A(t) = \left[\frac{H_o M h D}{4K^2 \Delta T}\right]\left[e^{x^2} erfc\, x + \frac{2x}{\sqrt{\pi}} - 1\right] \qquad [7.13]$$

$$x = \left[\frac{2K}{Mh\sqrt{D}}\right] t^{1/2} \qquad [7.14]$$

iii. Calculate oil displacement rate at time t

$$V_o = 4.273\left[\frac{H_o \emptyset (S_o - S_{or})}{M \Delta T}\right]\left(e^{x^2} erfc\, x\right) \qquad [7.15]$$

iv. Calculate reservoir volume heated in time t

The time there is assumed to be after full vertical growth of steam chamber. During lateral growth of steam chamber for optimum outflow and inflow the shape of steam chamber could be cylindrical. Cylindrical shape is too ideal hence the conical cylinder was assumed as the shape of steam chamber.

$$Reservoir\ volume\ heated_t = \frac{(Volume\ of\ cylinder + Volume\ of\ cone)}{2} \qquad [7.16]$$

v. Calculate economic areal limit for sustained injection

$$\left(e^{x^2} erfc\, x\right)_l = (5.618 \times 10^{-6}) \left[\frac{\$_h M \Delta T}{\$_o \emptyset (S_o - S_{or})}\right] \qquad [7.17]$$

vi. Calculate the time required to reach economic areal limit
- Using goal seek, calculate maximum value for x
- Calculate t from equation 7.14

7.4: Steam Assisted Gravity Drainage (SAGD) simulator

SAGD is a complex process. It is not only all about the heavy oil production by injecting steam into the reservoir. A number of things will happen in the reservoir during SAGD process and each and every small bit is very critical to the optimisation of SAGD. Figure 7.7 tries to demonstrate the linkage of critical parameters with steam injection and oil production. All of the previous sections have explained the importance of these critical parameters and also explained the methodology to calculate them in dynamic environment. But to see the overall impact on oil production of each and every critical parameter, it is important to link them to each other in dynamic environment. To do so the SAGD excel based simulator was built. The flow of the simulator is explained below.

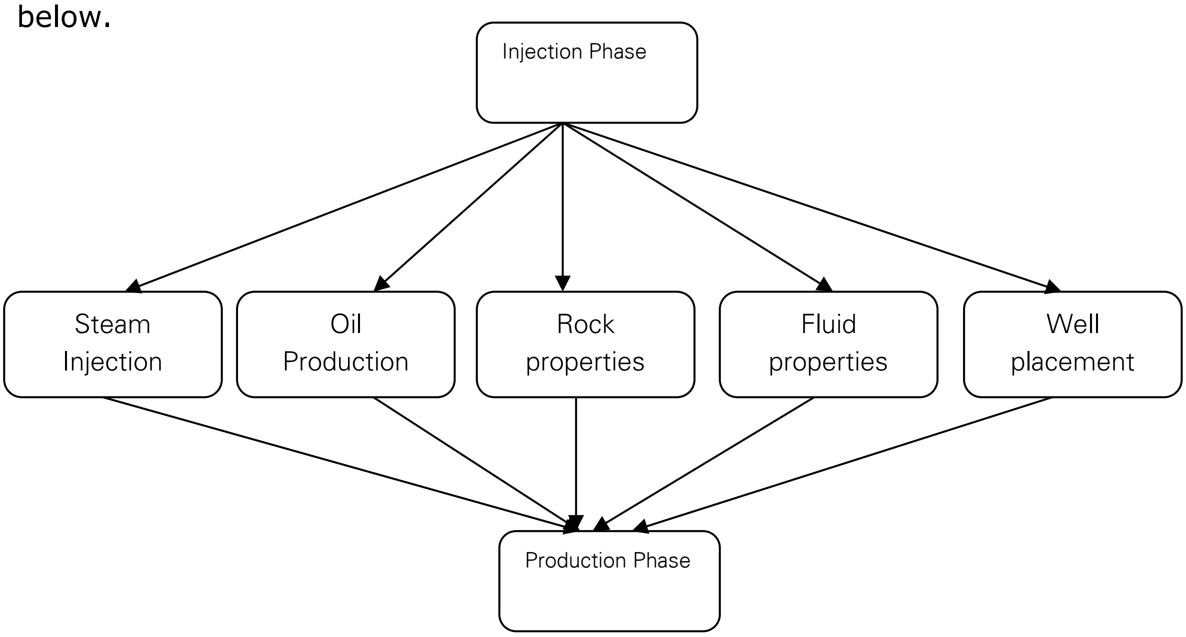


Figure 7.7: Complex nature of SAGD

To maximise the oil production, it is important to consider each and every phase during the recovery process. If the understanding of fluid is wrong then the possibility of completing the wellbore wrongly which might limit the operating envelope of the well. This can affect the oil recovery factor. During the design or operation phase, it is therefore important to consider each and every critical parameter. To achieve the aim of this research project, the real time effect of each and every critical parameter was analysed. After that, wherever required the empirical models were developed from the experimental data and also few were adopted from public domain. Below is the summary table for all the critical parameters which are also being used in SAGD simulator. Reference to the respective chapters is also provided in the Table 7.2.

Table 7.2: Backbone of SAGD simulator

Property/parameter	Developed/Adopted	Equation Number
Oil compressibility	Developed	5.14-5.16
Oil density	Developed	5.17-5.22
Oil formation volume factor	Developed	5.23-5.25
Bubble pressure	Adopted	5.7
GOR prediction	Adopted	5.8
Oil displacement rate	Adopted	3.1
Rheology characterisation	Adopted	5.26-5.33
Shear rate prediction	Adopted	5.34-5.35
Shear stress prediction	Developed	5.47
Shear viscosity prediction	Developed	5.33
Absolute permeability	Adopted	7.9-7.10
Porosity-permeability relation	Adopted	5.36-5.38
Relative permeability to oil	Developed	7.7
Flow models for Horizontal well	Adopted	Table 6.11
HW flow efficiency	Adopted	6.19
Pressure drop in horizontal well	Adopted	6.20
Heat injection rate	Adopted	7.12
Optimum time for steam injection	Adopted	7.16-7.17

7.4.1: SAGD simulator System Architecture

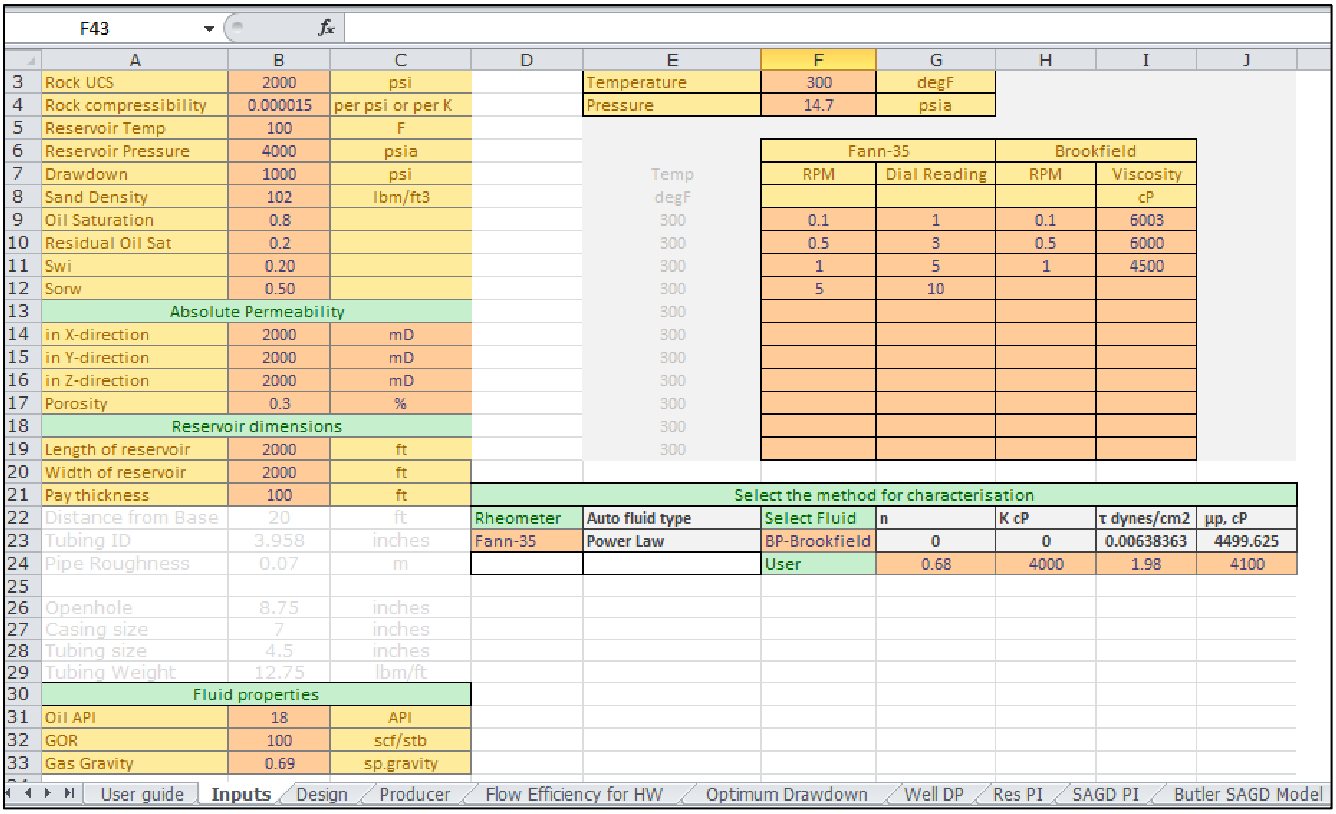
SAGD simulator has around 15 different critical sections to perform all different calculations. Most of them are interlinked with each other and taking inputs for analysis from the other section. Though there is a main input section which provides inputs to almost every other calculation. The main sections of SAGD simulator are described below.

1. Input Section
2. Output section
3. Producer
4. Flow efficiency of HW
5. Optimum drawdown
6. HW productivity models at reservoir conditions
7. HW productivity models at SAGD conditions
8. Butler SAGD model
9. Growth of steam chamber
10. Injector calculations
11. Rheology characterisation section
12. PVT models
13. Viscosity calculation
14. Relative permeability
15. Absolute permeability
16. Wellbore losses
17. Inflow analysis

More information is given in the individual section.

7.4.1.1 Input section

Input section is the first sheet in SAGD simulator. Screenshot for input screen is shown in figure 7.8.



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	A	B	C	D	E	F	G	H	I	J
3	Rock UCS	2000	psi		Temperature	300	degF			
4	Rock compressibility	0.000015	per psi or per K		Pressure	14.7	psia			
5	Reservoir Temp	100	F							
6	Reservoir Pressure	4000	psia			Fann-35		Brookfield		
7	Drawdown	1000	psi		Temp	RPM	Dial Reading	RPM	Viscosity	
8	Sand Density	102	lbm/ft3		degF				cP	
9	Oil Saturation	0.8			300	0.1	1	0.1	6003	
10	Residual Oil Sat	0.2			300	0.5	3	0.5	6000	
11	Swi	0.20			300	1	5	1	4500	
12	Sorw	0.50			300	5	10			
13	Absolute Permeability				300					
14	in X-direction	2000	mD		300					
15	in Y-direction	2000	mD		300					
16	in Z-direction	2000	mD		300					
17	Porosity	0.3	%		300					
18	Reservoir dimensions				300					
19	Length of reservoir	2000	ft		300					
20	Width of reservoir	2000	ft							
21	Pay thickness	100	ft	Select the method for characterisation						
22	Distance from Base	20	ft	Rheometer	Auto fluid type	Select Fluid	n	K cP	τ dynes/cm2	µp, cP
23	Tubing ID	3.958	inches	Fann-35	Power Law	BP-Brookfield	0	0	0.00638363	4499.625
24	Pipe Roughness	0.07	m			User	0.68	4000	1.98	4100
25										
26	Openhole	8.75	inches							
27	Casing size	7	inches							
28	Tubing size	4.5	inches							
29	Tubing Weight	12.75	lbm/ft							
30	Fluid properties									
31	Oil API	18	API							
32	GOR	100	scf/stb							
33	Gas Gravity	0.69	sp.gravity							

User guide | Inputs | Design | Producer | Flow Efficiency for HW | Optimum Drawdown | Well DP | Res PI | SAGD PI | Butler SAGD Model

Figure 7.8: Input section from SAGD simulator

This section will ask for the information about the reservoir such as reservoir pressure, temperature, sand density, porosity, absolute permeability, size and shape of the reservoir. On right hand side of the section, there is an option to enter the viscometer reading or to define the fluid manually. Yellow coloured cells are mandatory inputs.

7.4.1.2 Design section

Design sheet allows an user to select the critical parameters such as tubing size, well length and required oil rate.

This section (figure 7.9) will summarise the results from the different sheets. There are no inputs to this section. This section will give an overall picture for different scenarios. Output section will also give an idea about the heat requirement to reduce the oil viscosity to get required productivity index of the formation. It all has the information about the oil relative permeability for mentioned water cut in input section.

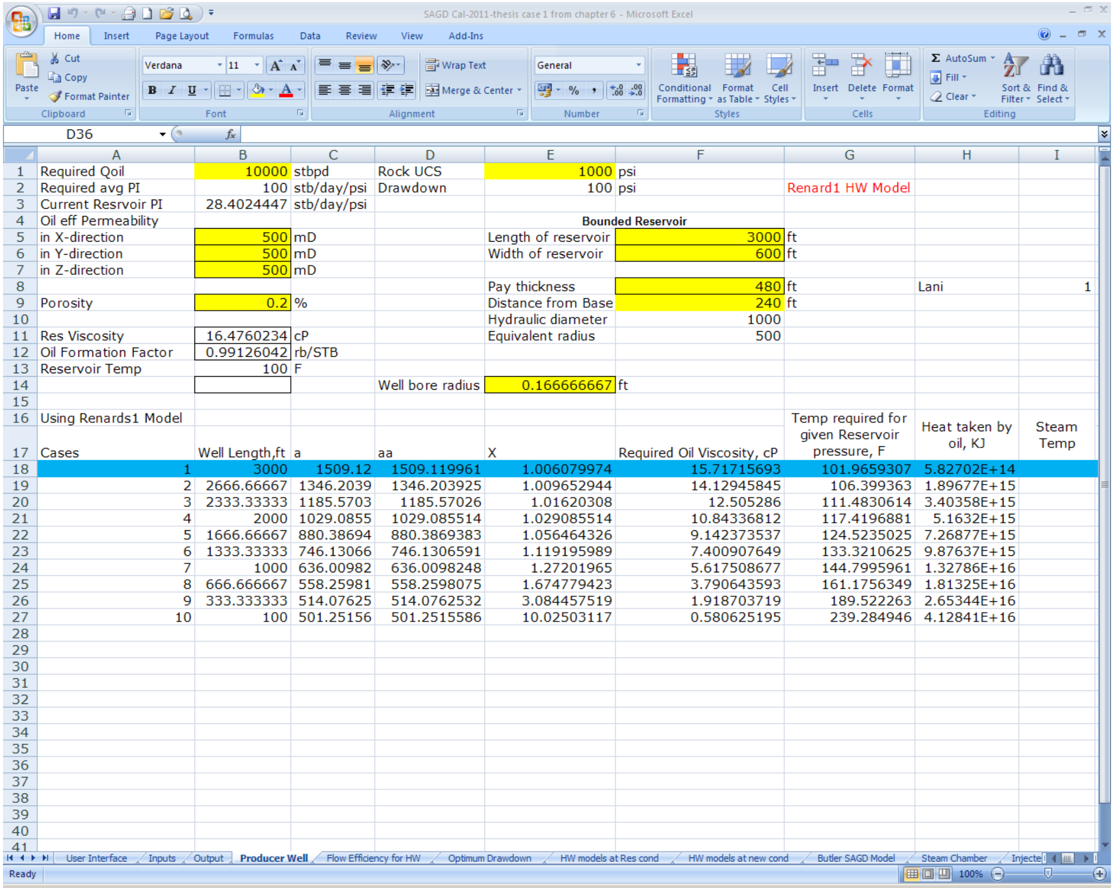
Select		
Open hole	8.75	inches
Casing OD	7	inches
Tubing OD	4.5	inches
Producer horizontal length	1000.00	ft
Injector horizontal length	1000	ft
Required oil rate	5000	bpd
Wellbore/pipe roughness	0.07	m

Output Summary		
At SAGD conditions		
Required reservoir temp	337.04	degF
Oil viscosity	84.87	cp
Oil formation volume factor	0.9998	rb/stb
Saturation pressure	1742.77	psia
Oil density	0.96	rel.density
Oil compressibility	3.90E-06	per psi
New Reservoir PI	4.96	stbpd/psi
HW Flow efficiency	0.95	
Required Well length for maximum flow efficiency	2000.00	ft
Optimum flow rate	4962.68	stbpd
Pressure drop in lateral section of wellbore	13.77	psia
Bottom hole pressure at heel	3000.00	psia
Pressure at toe	3013.77	psia
Oil rate by Butler's model	1272.10	stbpd
Oil relative permeability for defined WC	0.55	
Tubing weight	12.75	lbm/ft
Tubing capacity	0.02	bbl/ft
Tubing ID	3.96	inches
Casing ID	6.46	inches
Casing weight	20.00	lbm/ft
Casing capacity	0.04	bbl/ft
Open hole capacity	0.07	bbl/ft
When reservoir is cold		
Oil formation volume factor	0.9923	rb/stb
Saturation pressure	1096.66	psia
Oil density	0.97	rel.density
Oil compressibility	6.50E-06	per psi
Oil viscosity	25200.28	cp
Cold PI	0.02	stbpd/psi

Figure 7.9: Design section from SAGD simulator

7.4.1.3 Producer Well

This section will perform the required viscosity calculations using recommended horizontal well flow model for possible different horizontal wellbore lengths. Here the horizontal wellbore represents the open lateral wellbore section. It will also source the required temperature to get that oil viscosity from "Heat Calc" section. Figure 7.10 outlines the Producer well section. Downhole well completion is not considered at this point of analysis. An analysis is done for open lateral section of the well.



	A	B	C	D	E	F	G	H	I
1	Required Qoil	10000	stbpd	Rock UCS	1000	psi			
2	Required avg PI	100	stb/day/psi	Drawdown	100	psi	Renard1 HW Model		
3	Current Resrvoir PI	28.4024447	stb/day/psi						
4	Oil eff Permeability				Bounded Reservoir				
5	in X-direction	500	mD		Length of reservoir	3000	ft		
6	in Y-direction	500	mD		Width of reservoir	600	ft		
7	in Z-direction	500	mD						
8					Pay thickness	480	ft	Lani	1
9	Porosity	0.2	%		Distance from Base	240	ft		
10					Hydraulic diameter	1000			
11	Res Viscosity	16.4760234	cP		Equivalent radius	500			
12	Oil Formation Factor	0.99126042	rb/STB						
13	Reservoir Temp	100	F						
14				Well bore radius	0.166666667	ft			
15									
16	Using Renards1 Model								
17	Cases	Well Length,ft	a	aa	X	Required Oil Viscosity, cP	Temp required for given Reservoir pressure, F	Heat taken by oil, KJ	Steam Temp
18	1	3000	1509.12	1509.119961	1.006079974	15.71715693	101.9659307	5.82702E+14	
19	2	2666.66667	1346.2039	1346.203925	1.009652944	14.12945845	106.399363	1.89677E+15	
20	3	2333.33333	1185.5703	1185.57026	1.01620308	12.505286	111.4830614	3.40358E+15	
21	4	2000	1029.0855	1029.085514	1.029085514	10.84336812	117.4196881	5.1632E+15	
22	5	1666.66667	880.38694	880.3869383	1.056464326	9.142373537	124.5235025	7.26877E+15	
23	6	1333.33333	746.13066	746.1306591	1.119195989	7.400907649	133.3210625	9.87637E+15	
24	7	1000	636.00982	636.0098248	1.27201965	5.617508677	144.7995961	1.32786E+16	
25	8	666.666667	558.25981	558.2598075	1.674779423	3.790643593	161.1756349	1.81325E+16	
26	9	333.333333	514.07625	514.0762532	3.084457519	1.918703719	189.522263	2.65344E+16	
27	10	100	501.25156	501.2515586	10.02503117	0.580625195	239.284946	4.12841E+16	

Figure 7.10: Producer well section from SAGD simulator

7.4.1.4 Flow efficiency of HW

This section deals with the flow efficiency of horizontal wellbore. It will plot the well flow efficiency for different wellbore lengths. This also gives the flow efficiency for different tubing sizes. Here the wellbore storage effect is not considered. User has to highlight or choose manually the optimum length for the lateral section and also the optimum tubing size. Tubing size will also affect the frictional pressure loss in lateral section which is then covered in the "Wellbore Losses" section separately.

7.4.1.5 Horizontal well flow models

There are two different sections to calculate the productivity for the lateral section of the wellbore at the initial reservoir conditions and also at the heated conditions. In heated case, it will use the temperature and oil viscosity in correspondence with the optimum wellbore length. In both the sections the calculation is done for 17 different horizontal well flow models. This is done intentionally to get an idea about their wide range of predictions so that user can use them carefully in other wellbore software. Productivity calculations at reservoir conditions are showed in figure 7.11.

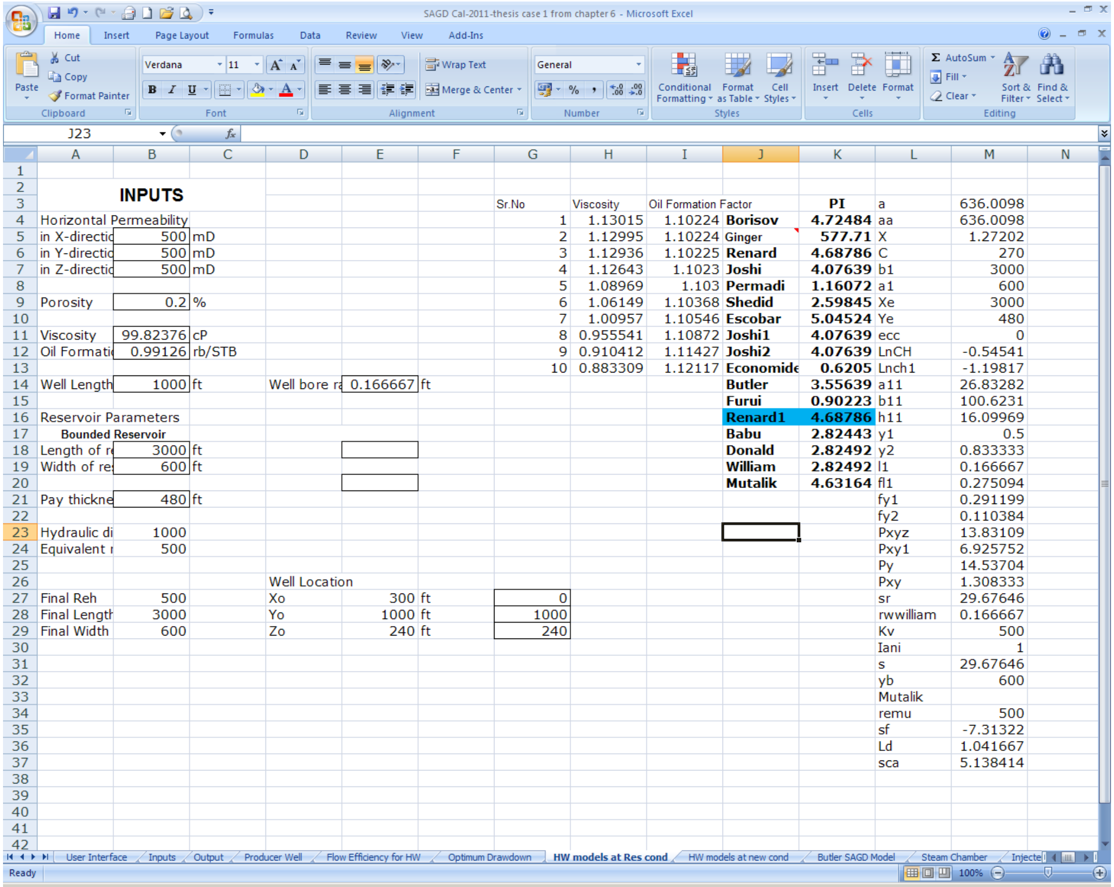


Figure 7.11: HW productivity models from SAGD simulator

7.4.1.6 Injector Well

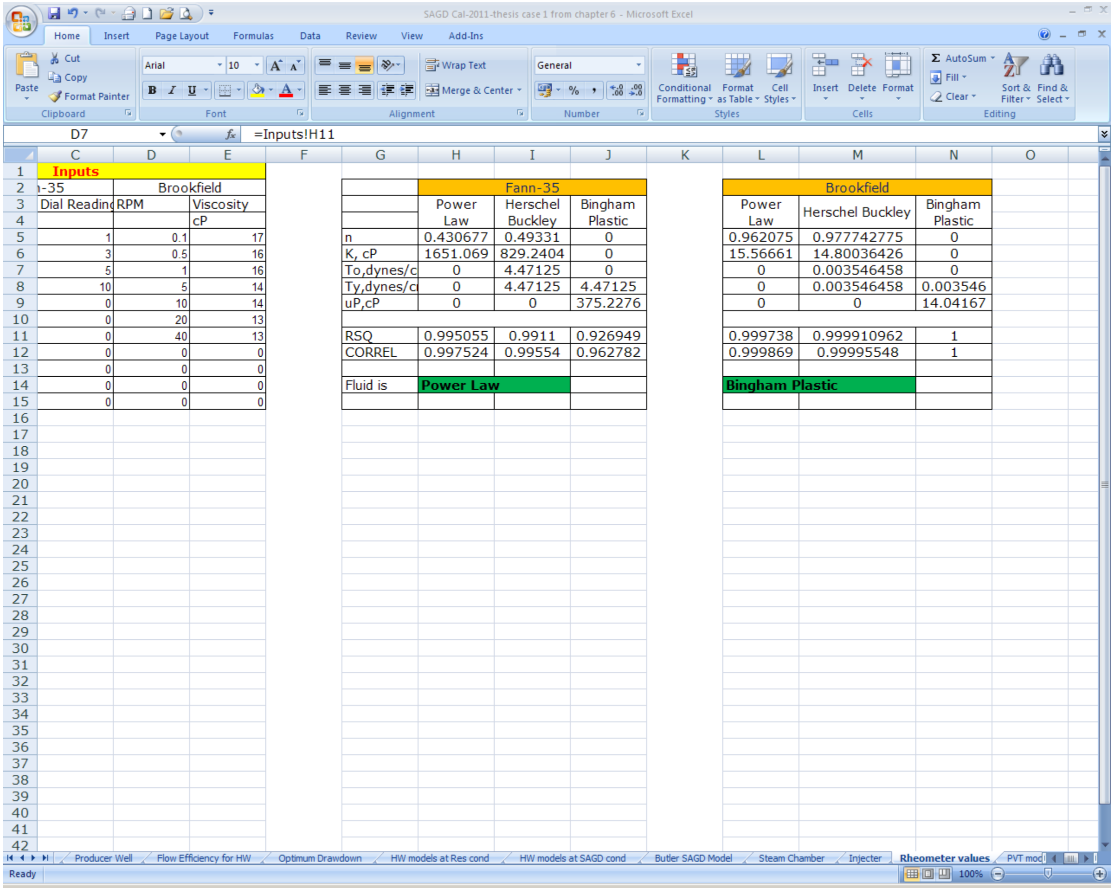
All the calculations related to economic areal limit to sustained steam injection and time required to reach economic areal limit are done in this section showed in figure 7.12. This also gives an idea about the position of steam-oil interface at the specified timestamp.

Required Fluid Temp	333.29	F		Specific Heat			
Initial Reservoir Temp	200.00	F		Rock	0.200	BTU/lb-F	
				Water	1.048	BTU/lb-F	
Steam Saturation Pressure at required fluid temp	70.00	psia		Oil	0.549	BTU/lb-F	
Saturated Steam Density	2.55	Kg/m3		Density			
Saturated Steam Injection at wellbore	5000.00	lb/hr		Rock	102.00	lb/ft3	
	342.31	bbl/day		Water	56.19	lb/ft3	
Allowable injection Pressure	5818.18	psia		Oil	60.00	lb/ft3	
				Overburden thermal conductivity	K	1.5	BTU/ft-hr F
Saturation Pressure at injection pressure at well	554	F		Overburden thermal diffusivity	D	0.07353026	ft2/hr
Available heat of steam at injection P,T	2000	BTU/lb					
DT	354.00	F		Steam Energy cost	3	$/million BTU	
Volumetric Heat capacity of mixture	25.71	BTU/ft3-F		Displaced oil Value	10	$/bbl	
x/t^(1/2)	1.08E-02						
Ho	1.00E+07	BTU/hr					
Steam Injection in Days	100.00	Days					
	2400.00	hr					
x after 100 days	0.53						
exp(x2)*erfc(x)	0.60						
exp(x2)*erfc(x)+2x/sqrt(PI)-1	0.20		dA/dt	11.03	ft2/hr		
				264.60	ft2/day		
Area Swept Out in 100 days	46701.67	ft2					
Oil Displacement Rate at given days	508.79	bbl/day					
				377.00			
Radial Distance	185.82	ft					
Temp. Distribution DT/dr	85.95	F/ft					
Economic Limits			x	5.35			
[exp(x2)*erfc(x)]t	0.09		exp(x2)*erfc(	0.10			
Using Goal Seek, calculate x	5.35						
			exp(x2)*erfc(	5.14			
Economic areal limit for sustained injection	1830282.34	ft2					
	42.02	Acres					
Time Required to reach economic areal limit	10306.63	Days					
	28.24	Years					

Figure 7.12: Injector well

7.4.1.7 Rheological Characterisation

Figure 7.13 gives the summary of the detailed rheological characterisation done on the provided rheometer data. This section uses the rheometer data from input section and runs the comprehensive analysis to understand the rheology of the fluid. There are two sub sheets for this section to do the characterisation for different types of rheometer. Using the defined logic, it will also define the fluid type with the rheological parameters. In summary display the parameter values are for all types of fluid which gives a confidence to user on other type of fluid. Logics and formulas for characterisation are given in the appendix [A]



Inputs		
ı-35	Brookfield	
Dial Readinc	RPM	Viscosity
		cP
1	0.1	17
3	0.5	16
5	1	16
10	5	14
0	10	14
0	20	13
0	40	13
0	0	0
0	0	0
0	0	0
0	0	0

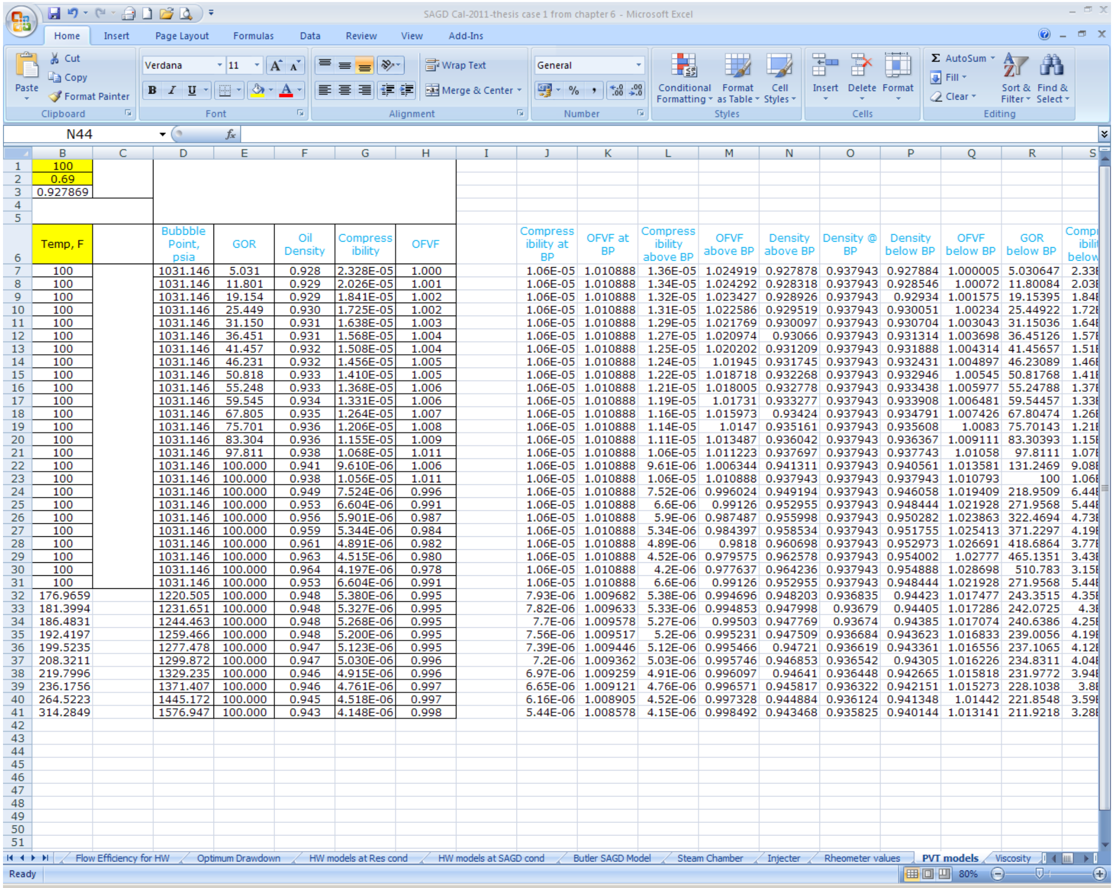
	Fann-35		
	Power Law	Herschel Buckley	Bingham Plastic
n	0.430677	0.49331	0
K, cP	1651.069	829.2404	0
To,dynes/c	0	4.47125	0
Ty,dynes/c	0	4.47125	4.47125
uP,cP	0	0	375.2276
RSQ	0.995055	0.9911	0.926949
CORREL	0.997524	0.99554	0.962782
Fluid is	Power Law		

Brookfield		
Power Law	Herschel Buckley	Bingham Plastic
0.962075	0.977742775	0
15.56661	14.80036426	0
0	0.003546458	0
0	0.003546458	0.003546
0	0	14.04167
0.999738	0.999910962	1
0.999869	0.99995548	1
Bingham Plastic		

Figure 7.13: Rheological characterisation

7.4.1.8 PVT models

This is also an important section where the developed and adopted PVT models used to calculate the PVT properties of fluid for defined pressure and temperature conditions. There are also different logics for selecting PVT properties according to the operating pressure which are provided in appendix [A]. In-build logics will split the pressure and temperature from reservoir conditions to SAGD conditions and also allows user to define any particular pressure and temperature conditions as seen in Figure 7.14. It will do the bubble point pressure, gas-oil ratio, density, compressibility and oil formation volume factor for all pressure and temperature conditions.



	B	D: Bubbble Point, psia	E: GOR	F: Oil Density	G: Compress ibility	H: OFVF
1	100					
2	0.69					
3	0.927869					
6	Temp, F	Bubbble Point, psia	GOR	Oil Density	Compress ibility	OFVF
7	100	1031.146	5.031	0.928	2.328E-05	1.000
8	100	1031.146	11.801	0.929	2.026E-05	1.001
9	100	1031.146	19.154	0.929	1.841E-05	1.002
10	100	1031.146	25.449	0.930	1.725E-05	1.002
11	100	1031.146	31.150	0.931	1.638E-05	1.003
12	100	1031.146	36.451	0.931	1.568E-05	1.004
13	100	1031.146	41.457	0.932	1.508E-05	1.004
14	100	1031.146	46.231	0.932	1.456E-05	1.005
15	100	1031.146	50.818	0.933	1.410E-05	1.005
16	100	1031.146	55.248	0.933	1.368E-05	1.006
17	100	1031.146	59.545	0.934	1.331E-05	1.006
18	100	1031.146	67.805	0.935	1.264E-05	1.007
19	100	1031.146	75.701	0.936	1.206E-05	1.008
20	100	1031.146	83.304	0.936	1.155E-05	1.009
21	100	1031.146	97.811	0.938	1.068E-05	1.011
22	100	1031.146	100.000	0.941	9.610E-06	1.006
23	100	1031.146	100.000	0.938	1.056E-05	1.011
24	100	1031.146	100.000	0.949	7.524E-06	0.996
25	100	1031.146	100.000	0.953	6.604E-06	0.991
26	100	1031.146	100.000	0.956	5.901E-06	0.987
27	100	1031.146	100.000	0.959	5.344E-06	0.984
28	100	1031.146	100.000	0.961	4.891E-06	0.982
29	100	1031.146	100.000	0.963	4.515E-06	0.980
30	100	1031.146	100.000	0.964	4.197E-06	0.978
31	100	1031.146	100.000	0.953	6.604E-06	0.991
32	176.9659	1220.505	100.000	0.948	5.380E-06	0.995
33	181.3994	1231.651	100.000	0.948	5.327E-06	0.995
34	186.4831	1244.463	100.000	0.948	5.268E-06	0.995
35	192.4197	1259.466	100.000	0.948	5.200E-06	0.995
36	199.5235	1277.478	100.000	0.947	5.123E-06	0.995
37	208.3211	1299.872	100.000	0.947	5.030E-06	0.996
38	219.7996	1329.235	100.000	0.946	4.915E-06	0.996
39	236.1756	1371.407	100.000	0.946	4.761E-06	0.997
40	264.5223	1445.172	100.000	0.945	4.518E-06	0.997
41	314.2849	1576.947	100.000	0.943	4.148E-06	0.998

	J: Compress ibility at BP	K: OFVF at BP	L: Compress ibility above BP	M: OFVF above BP	N: Density above BP	O: Density @ BP	P: Density below BP	Q: OFVF below BP	R: GOR below BP	S: Compr ibili below
7	1.06E-05	1.010888	1.36E-05	1.024919	0.927878	0.937943	0.927884	1.000005	5.030647	2.33E
8	1.06E-05	1.010888	1.34E-05	1.024292	0.928318	0.937943	0.928546	1.00072	11.80084	2.03E
9	1.06E-05	1.010888	1.32E-05	1.023427	0.928926	0.937943	0.92934	1.001575	19.15395	1.84E
10	1.06E-05	1.010888	1.31E-05	1.022586	0.929519	0.937943	0.930051	1.00234	25.44922	1.72E
11	1.06E-05	1.010888	1.29E-05	1.021769	0.930097	0.937943	0.930704	1.003043	31.15036	1.64E
12	1.06E-05	1.010888	1.27E-05	1.020974	0.93066	0.937943	0.931314	1.003698	36.45126	1.57E
13	1.06E-05	1.010888	1.25E-05	1.020202	0.931209	0.937943	0.931888	1.004314	41.45657	1.51E
14	1.06E-05	1.010888	1.24E-05	1.01945	0.931745	0.937943	0.932431	1.004897	46.23089	1.46E
15	1.06E-05	1.010888	1.22E-05	1.018718	0.932268	0.937943	0.932946	1.00545	50.81768	1.41E
16	1.06E-05	1.010888	1.21E-05	1.018005	0.932778	0.937943	0.933438	1.005977	55.24788	1.37E
17	1.06E-05	1.010888	1.19E-05	1.01731	0.933277	0.937943	0.933908	1.006481	59.54457	1.33E
18	1.06E-05	1.010888	1.16E-05	1.015973	0.93424	0.937943	0.934791	1.007426	67.80474	1.26E
19	1.06E-05	1.010888	1.14E-05	1.0147	0.935161	0.937943	0.935608	1.0083	75.70143	1.21E
20	1.06E-05	1.010888	1.11E-05	1.013487	0.936042	0.937943	0.936367	1.009111	83.30393	1.15E
21	1.06E-05	1.010888	1.06E-05	1.011223	0.937697	0.937943	0.937743	1.01058	97.8111	1.07E
22	1.06E-05	1.010888	9.61E-06	1.006344	0.941311	0.937943	0.940561	1.013581	131.2469	9.08E
23	1.06E-05	1.010888	1.06E-05	1.010888	0.937943	0.937943	0.937943	1.010793	100	1.06E
24	1.06E-05	1.010888	7.52E-06	0.996024	0.949194	0.937943	0.946058	1.019409	218.9509	6.44E
25	1.06E-05	1.010888	6.6E-06	0.99126	0.952955	0.937943	0.948444	1.021928	271.9568	5.44E
26	1.06E-05	1.010888	5.9E-06	0.987487	0.955998	0.937943	0.950282	1.023863	322.4694	4.73E
27	1.06E-05	1.010888	5.34E-06	0.984397	0.958534	0.937943	0.951755	1.025413	371.2297	4.19E
28	1.06E-05	1.010888	4.89E-06	0.9818	0.960698	0.937943	0.952973	1.026691	418.6864	3.77E
29	1.06E-05	1.010888	4.52E-06	0.979575	0.962578	0.937943	0.954002	1.02777	465.1351	3.43E
30	1.06E-05	1.010888	4.2E-06	0.977637	0.964236	0.937943	0.954888	1.028698	510.783	3.15E
31	1.06E-05	1.010888	6.6E-06	0.99126	0.952955	0.937943	0.948444	1.021928	271.9568	5.44E
32	7.93E-06	1.009682	5.38E-06	0.994696	0.948203	0.936835	0.94423	1.017477	243.3515	4.35E
33	7.82E-06	1.009633	5.33E-06	0.994853	0.947998	0.93679	0.94405	1.017286	242.0725	4.3E
34	7.7E-06	1.009578	5.27E-06	0.99503	0.947769	0.93674	0.94385	1.017074	240.6386	4.25E
35	7.56E-06	1.009517	5.2E-06	0.995231	0.947509	0.936684	0.943623	1.016833	239.0056	4.19E
36	7.39E-06	1.009446	5.12E-06	0.995466	0.94721	0.936619	0.943361	1.016556	237.1065	4.12E
37	7.2E-06	1.009362	5.03E-06	0.995746	0.946853	0.936542	0.94305	1.016226	234.8311	4.04E
38	6.97E-06	1.009259	4.91E-06	0.996097	0.94641	0.936448	0.942665	1.015818	231.9772	3.94E
39	6.65E-06	1.009121	4.76E-06	0.996571	0.945817	0.936322	0.942151	1.015273	228.1038	3.8E
40	6.16E-06	1.008905	4.52E-06	0.997328	0.944884	0.936124	0.941348	1.01442	221.8548	3.59E
41	5.44E-06	1.008578	4.15E-06	0.998492	0.943468	0.935825	0.940144	1.013141	211.9218	3.28E

Figure 7.14: PVT properties for defined conditions

7.4.1.9 Viscosity calculations

Unique method for viscosity calculation by considering fluid rheology is demonstrated in this section. Real time shear rate and shear stress calculation is performed for all different types of fluid and then the respective values are used in shear viscosity calculation to determine real time fluid viscosity at desired conditions. This real time viscosity is then used in other sections of the SAGD simulator. Logic flow is shown in figure 7.15.

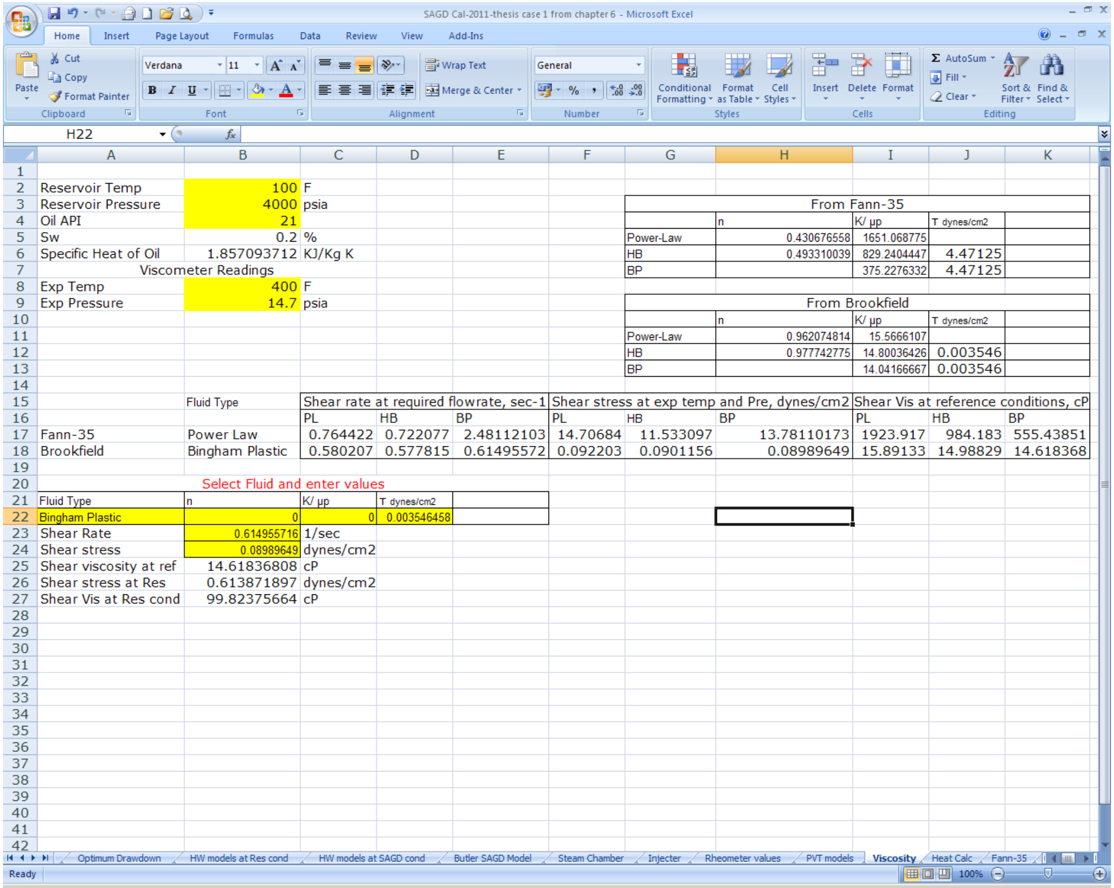


Figure 7.15: Viscosity calculation

The outcomes of the SAGD simulator are presented in the next chapter with some case studies. Validation of SAGD simulator is also done in the next chapter.

7.4.2.SAGD Case study

An example for the demonstration of SAGD simulator is given in this section. Table 7.3 summarises all the inputs required to SAGD simulator.

Table 7.3: Inputs to SAGD simulator

Reservoir inputs		
Rock UCS	2000	psi
Rock compressibility	0.000015	per psi or per K
Reservoir Temp	100	F
Reservoir Pressure	4000	psia

Drawdown	1000	psi
Sand Density	102	lbm/ft3
Oil Saturation	0.8	
Residual Oil Sat	0.2	
Swi	0.20	
Sorw	0.50	
Absolute Permeability		
in X-direction	2000	mD
in Y-direction	2000	mD
in Z-direction	2000	mD
Porosity	0.3	%
Reservoir dimensions		
Length of reservoir	2000	ft
Width of reservoir	2000	ft
Pay thickness	100	ft
Fluid properties		
Oil API	18	API
GOR	100	scf/stb
Gas Gravity	0.69	sp.gravity

Viscometer readings			
Experimental Data			
Temperature		300	degF
Pressure		14.7	psia
Fann-35		Brookfield	
RPM	Dial Reading	RPM	Viscosity
			cp
0.1	1	0.1	6003
0.5	3	0.5	6000
1	5	1	4500
5	10		

Next stage is to select the type of fluid. SAGD simulator will do the rheological characterisation for the inserted experimental data or it can also take the user defined rheological parameters. The fluid select option is on the Inputs sheet only.

Once the reservoir and fluid is defined, next stage is to design the SAGD case. In Design sheet, an user have options to select the tubing size, casing size, lateral length for producer and the design oil rate. SAGD simulator will solve the case for defined inputs and will display critical output parameters in Output summary table. This way user can very quickly run the different case studies and note down the output parameters. An user can also run the sensitivity of tubing size, lateral well length and oil rates on output parameters and can optimise the design within the constraints. Table 7.4 is a snapshot of results. Detailed results can be found in respective sheets.

Table 7.4: Output Summary from SAGD simulator

Output Summary		
At SAGD conditions		
Required reservoir temp	337.04	degF
Oil viscosity	84.87	cp
Oil formation volume factor	0.9998	rb/stb
Saturation pressure	1742.77	psia
Oil density	0.96	rel.density
Oil compressibility	3.90E-06	per psi
New Reservoir PI	4.96	stbpd/psi
HW Flow efficiency	0.95	
Required Well length for maximum flow efficiency	2000.00	ft
Optimum flow rate	4962.68	stbpd
Pressure drop in lateral section of wellbore	13.77	psia
Bottom hole pressure at heel	3000.00	psia
Pressure at toe	3013.77	psia
Oil rate by Butler's model	1272.10	stbpd
Oil relative permeability for defined WC	0.55	
Tubing weight	12.75	lbm/ft
Tubing capacity	0.02	bbl/ft
Tubing ID	3.96	inches
Casing ID	6.46	inches
Casing weight	20.00	lbm/ft
Casing capacity	0.04	bbl/ft
Open hole capacity	0.07	bbl/ft
When reservoir is cold		
Oil formation volume factor	0.9923	rb/stb
Saturation pressure	1096.66	psia
Oil density	0.97	rel.density
Oil compressibility	6.50E-06	per psi
Oil viscosity	25200.28	cp
Cold PI	0.02	stbpd/psi

CHAPTER 8: RESULTS & RECOMMENDATIONS

8.1 Introduction

The need & development strategy for SAGD simulator has been explained so far in this thesis. This is the time to discuss some of its applications and highlight results. Also the further development required to SAGD simulator is also given in this chapter.

8.2 SAGD Simulator Results

The whole idea behind developing such analytical simulator was to do the same level of analysis as by using numerical simulators. As explained in chapter 7, numeric simulators are very expensive and time consuming to run. This simulator can do the similar depth analysis very quickly and the user can also run the sensitivity analysis very quickly. Numerical simulation requires number of inputs, modelling tools, solvers and expertise to run it where as SAGD simulator is very easy and self-explanatory analytical simulator which is quick, fast and reliable. It can be used real time during SAGD operation to do risk assessment and can also help to take quick critical decision.

Only to run for different timestamp, the user has to input pressure and temperature for that timestamp manually. Figure 8.1 gives the confidence on SAGD simulator as it gives the good match with numeric simulator outputs.

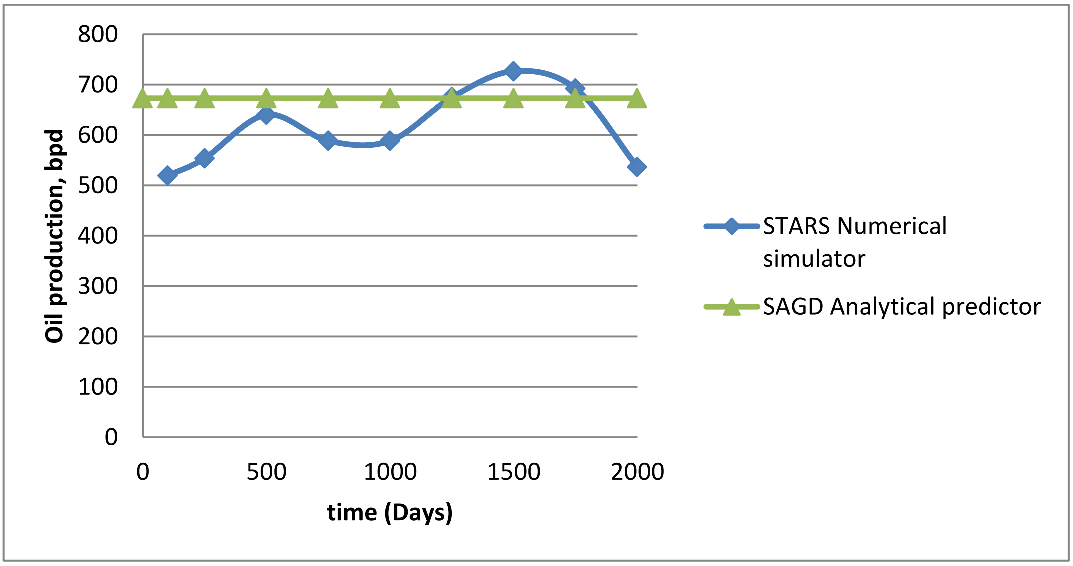


Figure 8.1: Numerical and Analytical SAGD simulator prediction

8.3 Other Applications Of SAGD simulator

An user can also use the SAGD simulator for number of other applications. Some of them are described in this section. The SAGD simulator is very robust and self-explanatory so that the user can easily play with it and get more familiarise with it.

8.3.1 Real Time Viscosity Prediction

There is no any analytical simulator or model which can predict the oil viscosity for any pressure and temperature. Current models don't take care of pressure and they are mainly temperature parameter focus. As the oil viscosity is pressure dependent as well, this simulator takes care of pressure and temperature at the same time. Figure 8.2 clearly explains the value addition by this simulator as the oil viscosity can be calculated for any pressure and temperature using this SAGD simulator .

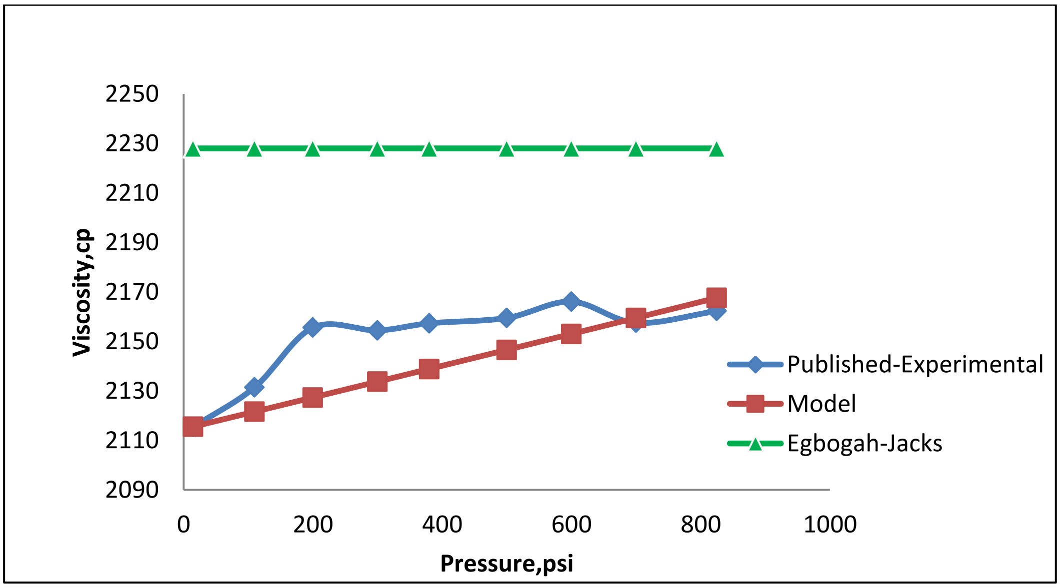


Figure 8.2: Real time Viscosity prediction

8.3.2 Real Time Rheology Prediction

Processing the experimental data from different rheometers is also a challenge and doing it in offshore laboratory in real time could be time consuming and chances of error are pretty high. This simulator has the fixed template for both Fann-35 and Brookfield type of rheometers. It can also handle the readings from other viscometers. Normally in oil industry, the user has an tendency to the fluid characterisation only for Bingham plastic type of fluid but this simulator can do it for Bingham plastic, Power law and Herschel buckley type of fluids as seen in figure 8.3. Simulator will also show the detailed rheological characterisation and gives user a confidence on SAGD simulator process of viscosity calculation.

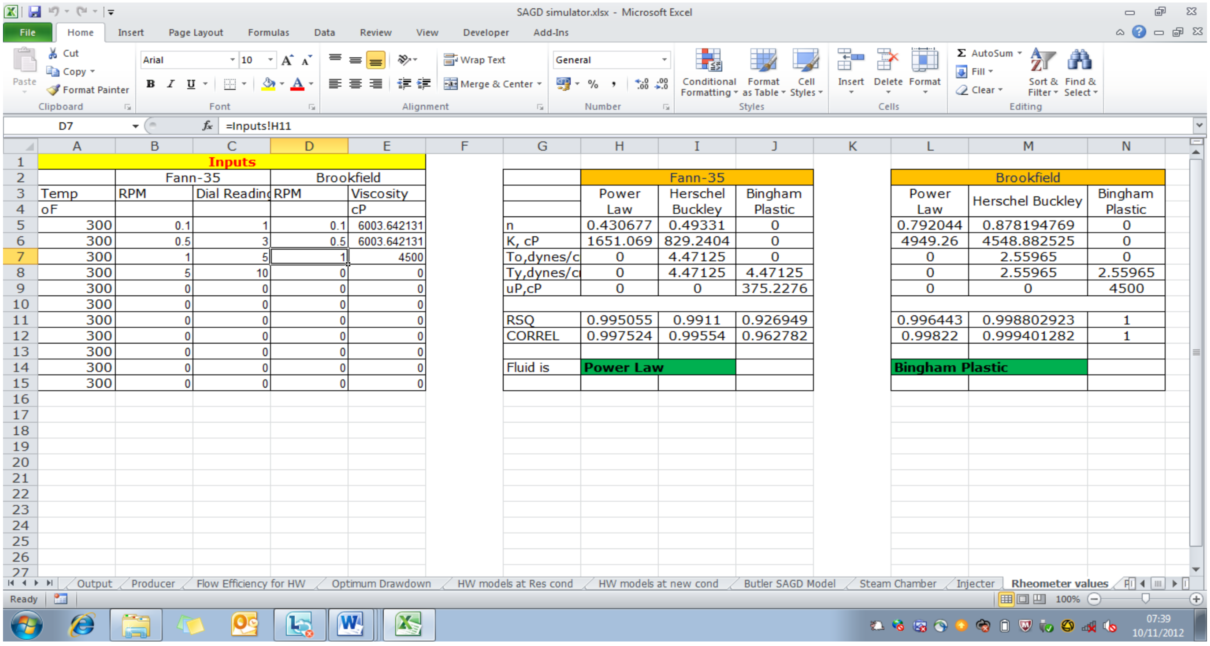


Figure 8.3: Rheological characterisation

Instead of doing analysis for only one type of fluid, user can quickly see the fluid rheology for other types. SAGD simulator has the facility to select the fluid type for rheological characterisation and also can take user override values for shear stress calculation. As shown in figure 8.4, an user only has to select the fluid type and the SAGD simulator will pull the respective rheological characterisation for that type of fluid. There is also a recommendation by the simulator about the fluid type. An user can also go with the manual entry if they are available.

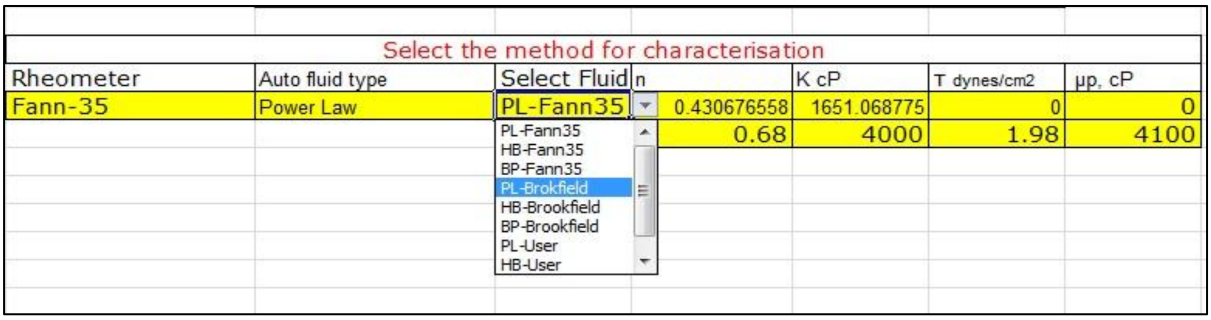
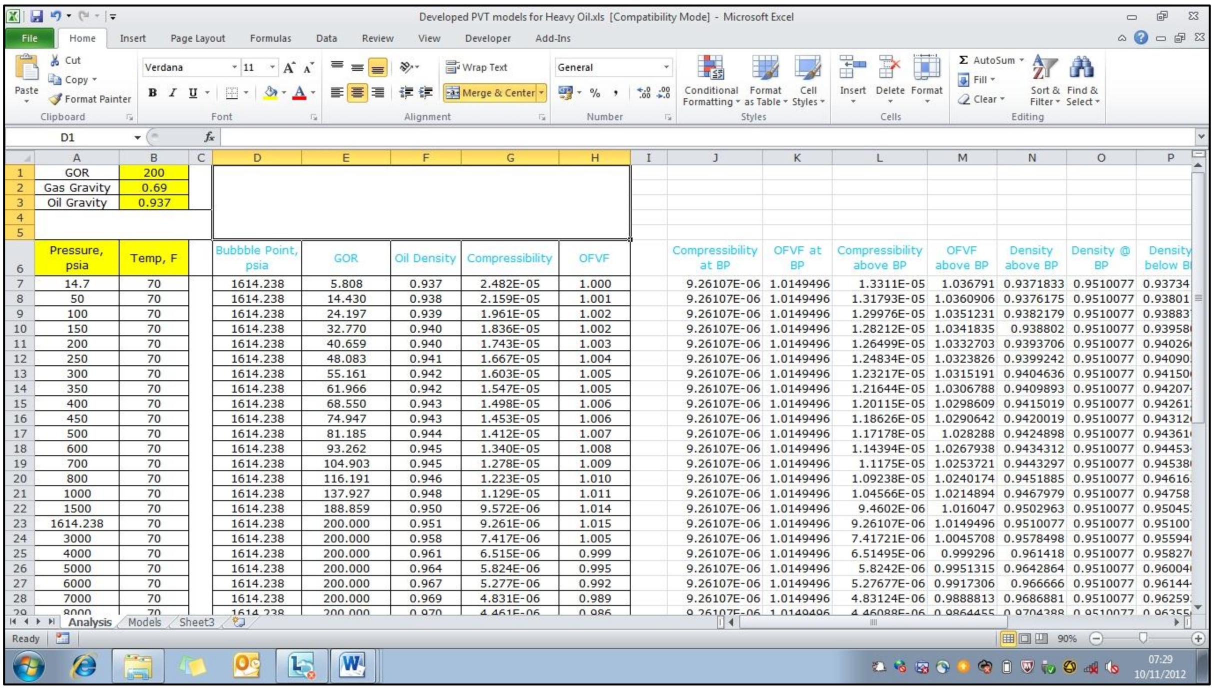


Figure 8.4: Real time rheology prediction

8.3.3 Real Time PVT Properties Simulator

If the user wants to use any other numeric simulator then the critical input to those simulators is PVT properties. User can use this SAGD simulator to generate PVT properties such as bubble point pressure, solution gas oil ratio, oil density, oil compressibility and oil formation volume factor for defined pressure and temperature range. As mentioned above it also gives the oil viscosity in real time. Figure 8.5 is the screenshot of PVT properties section from SAGD simulator. PVT values can only be simply copied from here to any other simulator to do further analysis.

Some of the models in PVT simulator are adopted and some of them are developed in this research which is already explained in chapter 7.



GOR	200
Gas Gravity	0.69
Oil Gravity	0.937

Pressure, psia	Temp, F	Bubbble Point, psia	GOR	Oil Density	Compressibility	OFVF	Compressibility at BP	OFVF at BP	Compressibility above BP	OFVF above BP	Density above BP	Density @ BP	Density below B
14.7	70	1614.238	5.808	0.937	2.482E-05	1.000	9.26107E-06	1.0149496	1.3311E-05	1.036791	0.9371833	0.9510077	0.93734
50	70	1614.238	14.430	0.938	2.159E-05	1.001	9.26107E-06	1.0149496	1.31793E-05	1.0360906	0.9376175	0.9510077	0.93801
100	70	1614.238	24.197	0.939	1.961E-05	1.002	9.26107E-06	1.0149496	1.29976E-05	1.0351231	0.9382179	0.9510077	0.93883
150	70	1614.238	32.770	0.940	1.836E-05	1.002	9.26107E-06	1.0149496	1.28212E-05	1.0341835	0.938802	0.9510077	0.93958
200	70	1614.238	40.659	0.940	1.743E-05	1.003	9.26107E-06	1.0149496	1.26499E-05	1.0332703	0.9393706	0.9510077	0.94026
250	70	1614.238	48.083	0.941	1.667E-05	1.004	9.26107E-06	1.0149496	1.24834E-05	1.0323826	0.9399242	0.9510077	0.94090
300	70	1614.238	55.161	0.942	1.603E-05	1.005	9.26107E-06	1.0149496	1.23217E-05	1.0315191	0.9404636	0.9510077	0.94150
350	70	1614.238	61.966	0.942	1.547E-05	1.005	9.26107E-06	1.0149496	1.21644E-05	1.0306788	0.9409893	0.9510077	0.94207
400	70	1614.238	68.550	0.943	1.498E-05	1.006	9.26107E-06	1.0149496	1.20115E-05	1.0298609	0.9415019	0.9510077	0.94261
450	70	1614.238	74.947	0.943	1.453E-05	1.006	9.26107E-06	1.0149496	1.18626E-05	1.0290642	0.9420019	0.9510077	0.94312
500	70	1614.238	81.185	0.944	1.412E-05	1.007	9.26107E-06	1.0149496	1.17178E-05	1.028288	0.9424898	0.9510077	0.94361
600	70	1614.238	93.262	0.945	1.340E-05	1.008	9.26107E-06	1.0149496	1.14394E-05	1.0267938	0.9434312	0.9510077	0.94453
700	70	1614.238	104.903	0.945	1.278E-05	1.009	9.26107E-06	1.0149496	1.1175E-05	1.0253721	0.9443297	0.9510077	0.94538
800	70	1614.238	116.191	0.946	1.223E-05	1.010	9.26107E-06	1.0149496	1.09238E-05	1.0240174	0.9451885	0.9510077	0.94616
1000	70	1614.238	137.927	0.948	1.129E-05	1.011	9.26107E-06	1.0149496	1.04566E-05	1.0214894	0.9467979	0.9510077	0.94758
1500	70	1614.238	188.859	0.950	9.572E-06	1.014	9.26107E-06	1.0149496	9.4602E-06	1.016047	0.9502963	0.9510077	0.95045
1614.238	70	1614.238	200.000	0.951	9.261E-06	1.015	9.26107E-06	1.0149496	9.26107E-06	1.0149496	0.9510077	0.9510077	0.95100
3000	70	1614.238	200.000	0.958	7.417E-06	1.005	9.26107E-06	1.0149496	7.41721E-06	1.0045708	0.9578498	0.9510077	0.95594
4000	70	1614.238	200.000	0.961	6.515E-06	0.999	9.26107E-06	1.0149496	6.51495E-06	0.999296	0.961418	0.9510077	0.95827
5000	70	1614.238	200.000	0.964	5.824E-06	0.995	9.26107E-06	1.0149496	5.8242E-06	0.9951315	0.9642864	0.9510077	0.96004
6000	70	1614.238	200.000	0.967	5.277E-06	0.992	9.26107E-06	1.0149496	5.27677E-06	0.9917306	0.966666	0.9510077	0.96144
7000	70	1614.238	200.000	0.969	4.831E-06	0.989	9.26107E-06	1.0149496	4.83124E-06	0.9888813	0.9686881	0.9510077	0.96259

Figure 8.5: Real time PVT Properties

8.3.4 Productivity Index Comparison For Horizontal Wells

As mentioned in chapter 6, there are more than 25 horizontal well flow models. It is very handy for user to have comparison for all of them before using it in further analysis. This SAGD simulator can do the calculation and comparison for all of them. All these models are grouped as per steady state, pseudo steady state, isotropic and anisotropic categories. Figure 8.6 shows the output of this section from SAGD simulator.

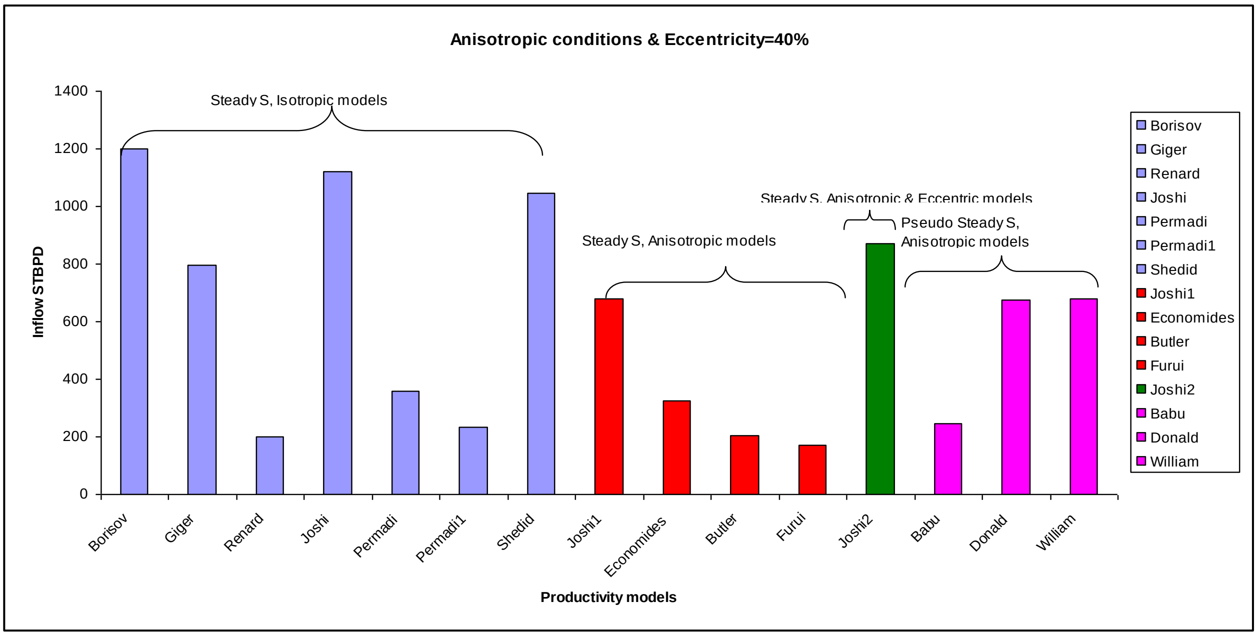


Figure 8.6: HW PI comparison

8.3.5 Effect Of Drainage Profile On Shear Viscosity

Shear viscosity of oil is dependent of shear stress and shear rate as mentioned in chapter 5. Shear rate which is pore velocity dependent varies with drainage area. Drainage area comes from the drainage profile assumed during the analysis. This simulator does the analysis for four different drainage profiles and allows user to do parametric study on drainage profile before using it in reservoir simulation. Figure 8.7 and 8.7 show the importance of different drainage profile on shear viscosity.

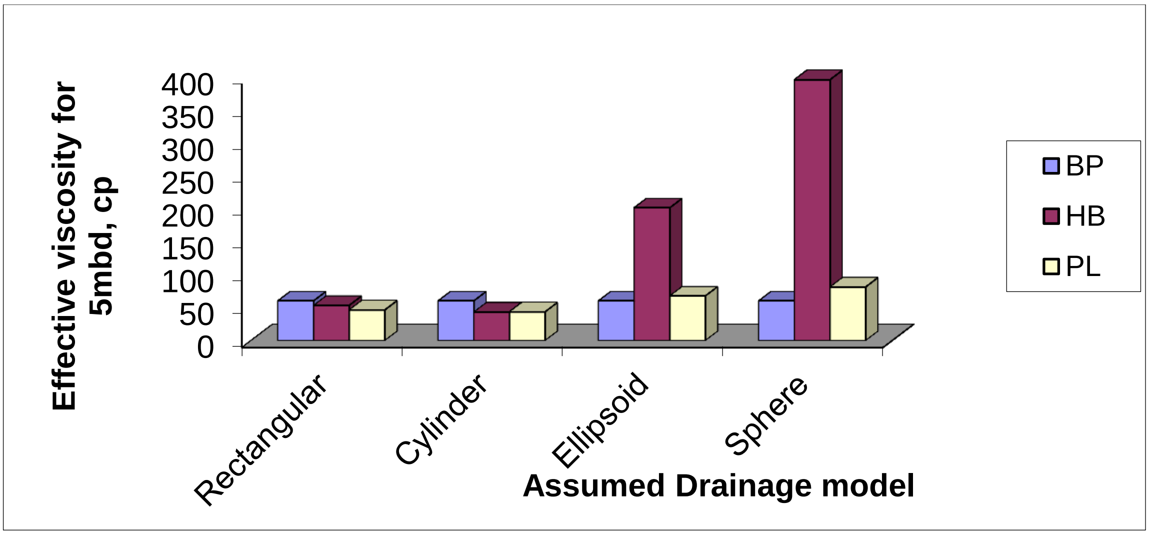


Figure 8.7: Effective viscosity for different drainage profile

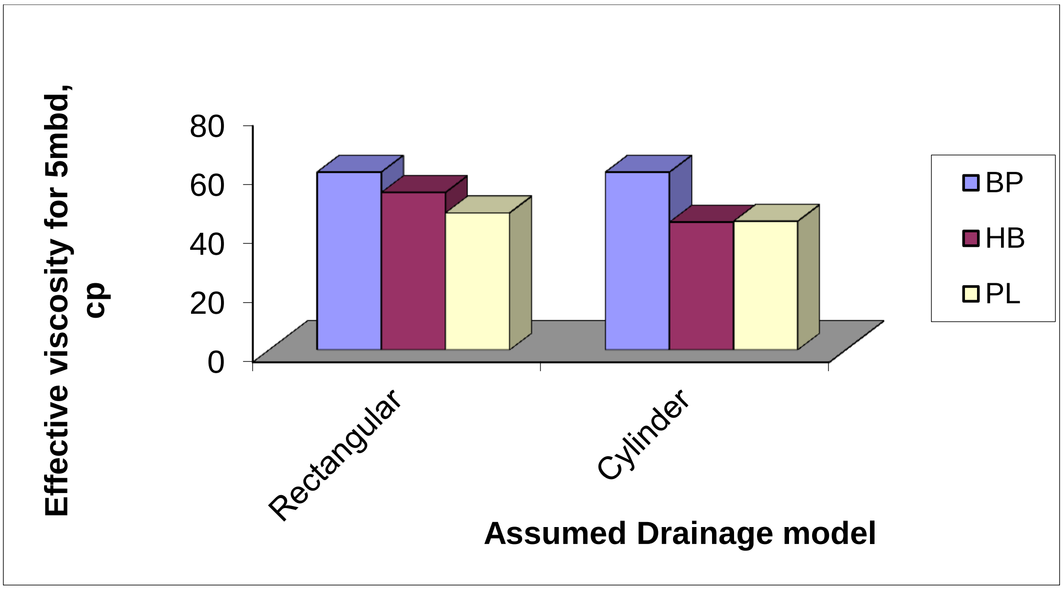


Figure 8.8: Effective viscosity for different drainage profile-2

8.3.6 Effect Of Rheology On Drawdown For Different Porosity

As mentioned above shear viscosity is shear rate and shear stress dependent. Applied drawdown on the well determines the shear stress and shear stress plays an important role in rheological characterisation. Hence it is useful for user to see the impact of different drawdown on assumed rheology. Figure 8.9 explains the criticality of rheology for different drawdown limits.

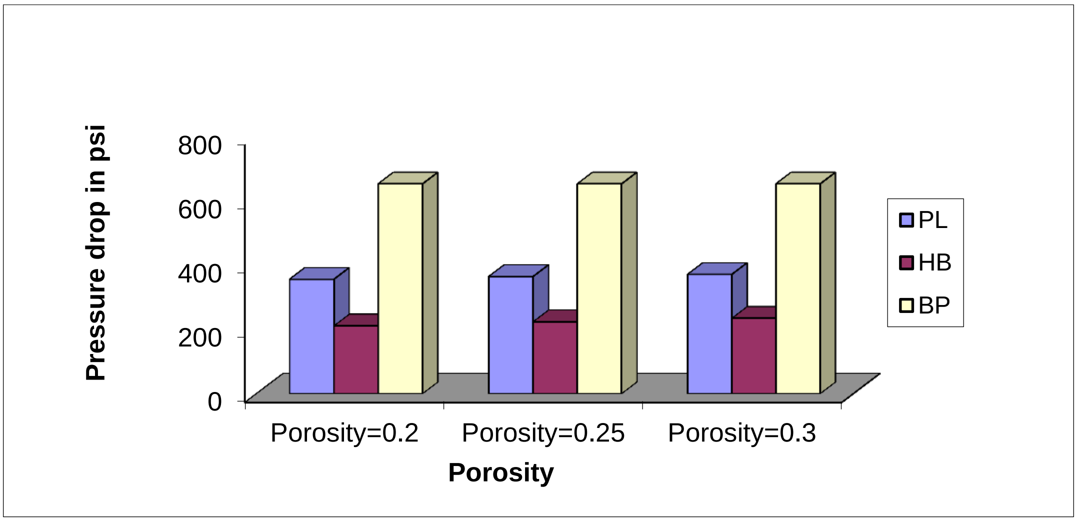


Figure 8.9: Effect of rheology on drawdown for different porosity

8.3.7 Criticality Of Rheology On Drawdown

SAGD simulator has demonstrated the criticality of rheology and production rate on drawdown. It can be used to limit the drawdown to unconfined compressive strength (UCS) by controlling production rate with understanding real fluid rheology. Figure 8.10 is a drawdown profile for different fluid type which is rate dependent. User can now use such plots to define the bottom hole pressure constraint to avoid the UCS limit.

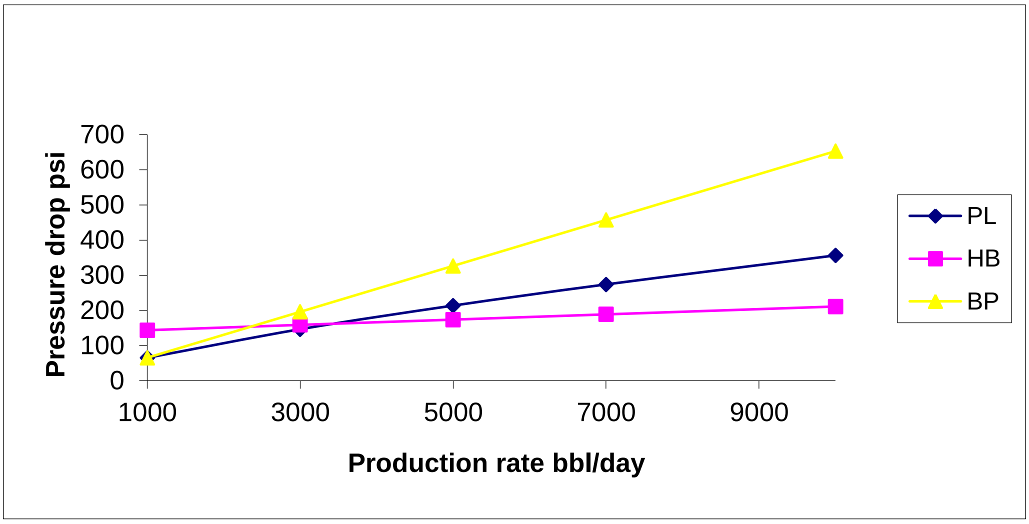


Figure 8.10: Criticality of rheology on drawdown

8.4 Summary

SAGD simulator has a quite wide range of applications as mentioned above. It also allows user to do a sensitivity analysis for different variables in real time. It is very user friendly and self-explanatory tool kit. It runs very quickly hence can be used onsite as well. SAGD simulator also justifies the contribution to knowledge as stated earlier. It also has some limitations which is given in next section.

8.5 Need for further work

This SAGD simulator cannot forecast the pressure and temperature during SAGD hence need to rely on other tool. This is only the limitation of current tool. This is still the area for development on this tool.

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APPENDIX A

1. Rheometer/ Viscometer readings

1.1. Sample A: Sudan PMAC (API 11.4)
Brookfield spindle 64

Temp, F							
	70 deg F		80 deg F		90 deg F		100 deg F
RPM	Viscosity, cp	RPM	Viscosity, cp	RPM	Viscosity, cp	RPM	Viscosity, cp
0.1	161965.33	0.1	62986.5	0.1	50989	0.1	26995
0.2	161965	0.5	62986.5	0.9	30047	0.9	21660
0.5	162565	0.9	63320	3	28894	3	22995
0.9	162965	3	61987	6	28394	6	23245
1.8	161132.5	1.8	61654	10	27984	10	22975
3	157266	4	59837	15	27514	15	22755
3.5	154953.5	10	57348	20	27084	20	22555
3.6	152134.5	10.5	55302	21	27123	25	22255
3.7	152152.5			22	26803	27	22095
3.8	152178						
3.9	152198						
3.8	151923						
3.5	153310						

Temp, F							
	112 degF		135 degF		145 degF		152 degF
RPM	Viscosity, cp	RPM	Viscosity, cp	RPM	Viscosity, cp	RPM	Viscosity, cp
0.1	11997	1	4199	5	2010	10	1680
0.9	13997	5	5149	10	2133	20	1770
3	13897	10	5009	20	2235	50	1746
6	13847	20	4979	50	2232	100	1700

10	13497	30	4759	70	2189.5	150	1584
15	13297	40	4536.5	100	2124	200	1567.5
20	12997	50	4411	140	2080	250	1531
25	12525	60	4295.66	170	2055		
30	12110.33	70	4176.3	200	2030		
35	11711.66	80	4069	230	2000		
40	11318	90	3914.6	250	1970		
50	10958	100	3821				
55	10721	110	3743				
56	10626	120	3664				
57	10467.66	150	3559				
58	10311.5	160	3532.66				
		170	3437				
		175	3409				
		178	3350				
		179	3328				

Brookfield spindle 62

Tempe	90 F	Temp	100 F	Temp	110 F	Temp	120 F	Temp	130 F
RPM	Viscosity, cp	RPM	Viscosity, cp	RPM	Viscosity, cp	RPM	Viscosity, cp	RPM	Viscosity, cp
0.1	16197	0.1	8096	0.1	4799	0.1	2999	0.1	3599
0.5	16496	0.5	7978	0.5	4859	0.5	2759	0.5	2280
0.9	16963	0.9	8232	0.9	4932	0.9	2666	0.9	2300
		1.8	8332	1.8	4982	1.8	2716	1.8	2183
		3	8498	3	5049	3	2749	3	2160
						6	2779	6	2140
						9	2813	9	2120
								12	2105

Fann 35

Temp	90	100	120	130
RPM	Fann 35 dial reading			
0.9	73	44	16	14
1.8	141	85	32	28
3	230	139	53	45
6		262	104	87

1.2. Sample B:

Brookfield spindle 64

Temp, F		Temp, F		Temp, F		Temp, F	
	70		80		95		115
RPM	Viscosity, cp	RPM	Viscosity, cp	RPM	Viscosity, cp	RPM	Viscosity, cp
0.1	140970	0.1	128972.5	0.1	14996.5	1	5999
0.2	142469.5	0.9	118974.5	0.9	21661.5	5	6854
0.9	132971.5	1.8	117475	1.8	21828.5	10	7048.5
1.8	130972	3	115675	3	21695	15	7098
3	128872.5	4	113976	6	22095	20	7138
3.5	127429.5	5	111816	9	21929	30	7148
4	126423			15	21915	50	7132
4.5	125373.5			20	21835	70	7121
				25	21667	80	7101
				26	21618	90	6319
				27	21462	95	6283
				28	21317		

Temp, F		Temp, F		Temp, F	
	125		140		150
RPM	Viscosity, cp	RPM	Viscosity, cp	RPM	Viscosity, cp
1	1200	1	600	5	1080
10	2879	5	1680	10	1260
20	2864	10	1890	50	1446
30	2859	50	1914	75	1436
40	2826.5	75	1888	100	1437
50	2831	100	1872	150	1430
75	2807	125	1833	200	1419
100	2765	150	1816	250	1401
125	2721	175	1811.5		
150	2679	200	1792.5		
175	2643	230	1775		
200	2606	250	1758.5		
225	2575				
230	2543				
235	2494				

1.3. Sample A old: (API 19.5)

Brookfield spindle 64

Temp	70 F	Temp	90 F	Temp	105 F
RPM	Viscosity,cp	RPM	Viscosity,cp	RPM	Viscosity,cp
0.9	3999	1	1200	10	900
1.8	4666	5	1320	25	888
3	4799	10	1380	50	900
6	4799	25	1440	75	904
10	4919	50	1428	100	918
30	4979	75	1368	125	907
50	5015	100	1332	150	908
60	5019	125	1296	175	908
75	5031	150	1264	200	903
100	5027	175	1237	230	905
110	5039	200	1215	250	902
115	5028	230	1200		
		250	1190		
Temperature	120 F	Temperature	135 F	Temperature	155 F
RPM	Viscosity, cp	RPM	Viscosity, cp	RPM	Viscosity, cp
10	300	20	240	25	144
25	432	30	260	50	192
50	456	50	315	75	192
75	472	75	328	100	198
100	492	100	336	125	202
125	504	125	341	150	204
150	504	150	344	175	209
175	521	175	346	200	210
200	525	200	351	230	216
230	527	230	355	250	226
250	540	250	353		

Brookfield spindle 62

Temperature	70 F	Temperature	100 F	Temperature	130 F	Temperature	160 F
RPM	Viscosity, cp	RPM	Viscosity, cp	RPM	Viscosity, cp	RPM	Viscosity, cp
0.1	4199	0.1	600	0.9	200	0.9	66.7
0.3	2999	0.9	500	1.8	200	1.8	66.7
0.9	3066	1.8	550	3	200	3	100
1.8	3166	3	520	6	205	6	115
3	3139	6	505	30	220	30	112
6	3174	30	526	60	224	60	115
9	3189	40	528	90	238	90	118
		50	530	100	231	100	119
				120	231	180	123
						200	126

Temp F	70	80	100	110	130	140	150
RPM	Fann 35 dial readings						
0.9	8	5	2	2	1	1	2
1.8	16	11	5	4	2	2	4
3	27	18	8	7	3	3	6
6	54	35	16	14	6	6	12
30	265	173	81	66	34	31	55
60			162	131	66	62	105
90			240	195	98	88	96
100			265	214	110	102	110
180					194	175	180
200					215	198	250
300						285	260

1.4. Sample B old: (API 20.65/ 19.5)
Brookfield spindle 64

Temperature	70 F	Temperature	98 F	Temperature	115 F
RPM	Viscosity, cp	RPM	Viscosity, cp	RPM	Viscosity, cp
0.1	2999	0.1	600	0.9	400
0.3	2899	0.9	633	1.8	417
0.9	3033	1.8	683	3	420
1.8	3066	3	695	6	415
3	3099	6	685	30	380
6	3134	30	666	60	360
9	3156	40	660	75	335
		45	640	85	324
				90	314

	80		90		103		110		130
RPM		RPM		RPM		RPM		RPM	
0.9	1566	0.9	1000	0.9	633	6	110	30	218
1.8	1583	1.8	1083	1.8	683	10	297	60	240
3	1570	3	1110	3	690	20	418	90	241
6	1605	6	1115	6	705	30	450	100	230
10	1620	10	1125	10	708	40	477	130	219
15	1642	20	1138	20	718	50	491		
				30	727	60	496		
				40	733				

Fann 35

Temp F	70	98	115	120
RPM	Fann 35 dial reading			
0.9	9	6	2	1
1.8	18	12	5	3
3	30	19		
6	60	37		
30		172	75	41
60			155	82
90			209	121
180				245

Temp, F	72	80	90	103	110	120	130
RPM	Fann 35 dial readings						
0.9	8	5	3	2	2	1	1
1.8	16	10	7	5	4	3	2
3	27	17	12	7	6	5	4
6	54	35	23	15	12	10	9
30	268	170	114	76	58	48	35
60			228	152	116	96	68
90				225	174	142	102
100				252	186	160	130
180							205
200							265

1.5. Sample C old : (API 22.3)

Brookfield spindle 62

Temp, F	100		120		142
RPM	Viscosity, cp	RPM	Viscosity, cp	RPM	Viscosity, cp
2	660	5	280	5	130
3	650	10	240	10	110
4	645	30	245	20	102
5	660	50	250	30	108
6	670	60	252	40	110
7	680	80	246	60	108
8	660	100	251	80	106
9	675	110	249	100	114
10	663	120	248	120	110
15	630			140	112
20	655			160	113

30	639			180	114
40	628			200	115
45	623			220	117
				230	117
				240	117
				250	117
Temp, F	165		240		252
RPM	Viscosity, cp	RPM	Viscosity, cp	RPM	Viscosity, cp
10	42	25	9	25	14
25	43	50	13	50	15
50	51	75	16	75	14
75	51	100	19.5	100	17
100	55	125	20.2	125	18
125	56	150	22	150	19.4
150	57	175	24	175	22.1
175	59	200	25.5	200	23.7
200	61	225	27.6	225	25.6
225	62	250	29	250	27.4
250	64				

2. Micro-PVT readings

2.1. Sample A (API 11.4)

Volume, mm^3	Pressure, MPa	Temp., °C	Time, sec	Vol. Traverse, mm	Pres. Traverse, mm
740.687	0.445	28.336	0.088	-14.731	-2.551
740.687	0.445	28.336	0.174	-14.731	-2.551
740.687	0.445	28.336	0.275	-14.731	-2.551
740.687	0.445	28.336	0.364	-14.731	-2.551
740.687	0.445	28.336	0.466	-14.731	-2.551
740.687	0.445	28.41	0.555	-14.731	-2.551
740.687	0.445	28.41	0.631	-14.731	-2.551
740.687	0.445	28.41	0.708	-14.731	-2.551
740.687	0.445	28.41	0.781	-14.731	-2.551
740.687	0.445	28.41	0.871	-14.731	-2.551
740.687	0.444	28.41	0.964	-14.731	-2.551
740.688	0.445	28.41	1.063	-14.731	-2.551
740.688	0.445	28.41	1.201	-14.731	-2.551
740.688	0.445	28.482	1.282	-14.731	-2.551
740.672	0.47	28.482	1.383	-14.729	-2.551
740.66	0.614	28.482	1.498	-14.728	-2.552

740.682	0.69	28.482	1.591	-14.73	-2.552
740.614	0.715	28.482	1.696	-14.723	-2.553
740.537	0.851	28.482	1.809	-14.715	-2.554
740.492	1.067	28.482	1.882	-14.71	-2.555
740.412	1.196	28.482	1.995	-14.702	-2.556
740.327	1.256	28.556	2.113	-14.694	-2.557
740.134	1.323	28.556	2.304	-14.675	-2.557
739.932	1.348	28.556	2.491	-14.655	-2.558
739.851	1.341	28.556	2.581	-14.647	-2.558
739.705	1.351	28.556	2.701	-14.633	-2.558
739.529	1.365	28.556	2.811	-14.616	-2.558
739.385	1.37	28.63	2.924	-14.602	-2.558
739.242	1.37	28.63	3.019	-14.588	-2.558
739.134	1.37	28.63	3.09	-14.578	-2.558
738.951	1.37	28.63	3.201	-14.56	-2.558
738.806	1.37	28.63	3.287	-14.546	-2.558
738.67	1.37	28.63	3.363	-14.533	-2.558
738.541	1.37	28.63	3.434	-14.52	-2.558
738.336	1.37	28.63	3.535	-14.5	-2.558
738.163	1.37	28.63	3.62	-14.484	-2.558
738.009	1.37	28.702	3.692	-14.469	-2.558
737.868	1.37	28.702	3.764	-14.455	-2.558
737.722	1.37	28.702	3.84	-14.441	-2.558
737.573	1.37	28.702	3.912	-14.426	-2.558
737.421	1.37	28.702	3.983	-14.412	-2.558
737.267	1.37	28.702	4.056	-14.397	-2.558
737.126	1.37	28.702	4.127	-14.383	-2.558
736.833	1.37	28.702	4.274	-14.355	-2.558
736.659	1.37	28.702	4.365	-14.338	-2.558
736.515	1.371	28.702	4.437	-14.324	-2.558
736.339	1.37	28.776	4.522	-14.307	-2.558
736.187	1.37	28.776	4.594	-14.292	-2.558
736.01	1.37	28.776	4.684	-14.275	-2.558
735.866	1.37	28.776	4.756	-14.261	-2.558
735.709	1.37	28.776	4.833	-14.246	-2.558
735.562	1.371	28.776	4.905	-14.232	-2.558
735.424	1.37	28.776	4.977	-14.218	-2.558
735.273	1.37	28.776	5.049	-14.204	-2.558
735.121	1.37	28.776	5.121	-14.189	-2.558
734.81	1.37	28.776	5.268	-14.159	-2.558
734.643	1.37	29.859	5.355	-14.143	-2.558
734.498	1.37	29.859	5.431	-14.129	-2.558
734.34	1.37	29.859	5.504	-14.113	-2.558
734.185	1.37	29.859	5.577	-14.098	-2.558
733.945	1.369	29.859	5.691	-14.075	-2.558
733.803	1.37	29.859	5.764	-14.061	-2.558
733.663	1.37	29.859	5.838	-14.048	-2.558
733.521	1.37	29.859	5.911	-14.034	-2.558
733.362	1.37	29.859	5.989	-14.019	-2.558
733.209	1.37	29.859	6.061	-14.004	-2.558

733.054	1.37	29.93	6.134	-13.989	-2.558
732.801	1.37	29.93	6.262	-13.964	-2.558
732.647	1.37	29.93	6.336	-13.949	-2.558
732.443	1.37	29.93	6.436	-13.93	-2.558
732.265	1.37	29.93	6.525	-13.912	-2.558
732.116	1.37	29.93	6.599	-13.898	-2.558
731.955	1.37	29.93	6.675	-13.882	-2.558
731.797	1.37	29.93	6.75	-13.867	-2.558
731.641	1.37	29.93	6.823	-13.852	-2.558
731.495	1.37	30	6.896	-13.838	-2.558
731.345	1.37	30	6.972	-13.823	-2.558
731.185	1.37	30	7.045	-13.808	-2.558
731.026	1.37	30	7.118	-13.792	-2.558
730.723	1.37	30	7.268	-13.763	-2.558
730.533	1.371	30	7.36	-13.745	-2.558
730.388	1.371	30	7.435	-13.731	-2.558
730.184	1.371	30	7.536	-13.711	-2.558
729.955	1.38	30	7.646	-13.689	-2.558
729.706	1.392	30.069	7.766	-13.665	-2.558
729.46	1.412	30.069	7.886	-13.641	-2.558
729.206	1.44	30.069	8.01	-13.616	-2.558
728.974	1.471	30.069	8.128	-13.593	-2.559
728.684	1.522	30.069	8.264	-13.565	-2.559
728.424	1.599	30.069	8.384	-13.54	-2.56
728.281	1.651	30.069	8.458	-13.526	-2.56
728.043	1.709	29.124	8.581	-13.502	-2.56
727.781	1.76	29.124	8.701	-13.477	-2.561
727.531	1.806	29.124	8.822	-13.453	-2.561
727.234	1.853	29.124	8.969	-13.424	-2.562
727.087	1.875	29.124	9.044	-13.409	-2.562
726.831	1.914	29.124	9.164	-13.384	-2.562
726.411	1.976	29.191	9.363	-13.344	-2.562
726.262	2	29.191	9.438	-13.329	-2.563
726.005	2.038	29.191	9.557	-13.304	-2.563
725.745	2.078	29.191	9.683	-13.279	-2.563
725.435	2.132	29.191	9.834	-13.249	-2.564
725.166	2.163	29.191	9.955	-13.222	-2.564
725.012	2.185	29.191	10.035	-13.207	-2.564
724.768	2.227	29.257	10.154	-13.184	-2.564
724.506	2.269	29.257	10.275	-13.158	-2.565
724.262	2.306	29.257	10.396	-13.134	-2.565
724.009	2.349	29.257	10.523	-13.11	-2.565
723.773	2.387	29.257	10.644	-13.087	-2.566
723.481	2.438	29.257	10.783	-13.058	-2.566
723.202	2.496	29.324	10.921	-13.031	-2.567
722.953	2.543	29.324	11.044	-13.007	-2.567
722.706	2.602	29.324	11.168	-12.983	-2.567
722.405	2.681	29.324	11.317	-12.954	-2.568
722.09	2.747	29.324	11.465	-12.923	-2.568
721.853	2.809	29.324	11.587	-12.9	-2.569

721.613	2.885	29.392	11.711	-12.876	-2.57
721.357	2.954	29.392	11.834	-12.851	-2.57
721.121	3.014	29.392	11.957	-12.828	-2.571
720.896	3.087	29.392	12.077	-12.806	-2.571
720.664	3.156	29.392	12.2	-12.783	-2.572
720.493	3.21	29.392	12.285	-12.767	-2.572
719.722	3.474	29.458	12.681	-12.691	-2.574
719.493	3.557	29.458	12.8	-12.669	-2.575
719.13	3.683	29.458	12.952	-12.633	-2.576
718.984	3.739	29.458	13.023	-12.619	-2.576
718.849	3.801	29.458	13.094	-12.606	-2.577
718.722	3.858	29.458	13.165	-12.593	-2.577
718.582	3.914	29.458	13.236	-12.579	-2.578
718.436	3.959	29.526	13.306	-12.565	-2.578
718.253	4.018	29.526	13.394	-12.547	-2.578
718.126	4.083	29.526	13.465	-12.535	-2.579
717.989	4.155	29.526	13.537	-12.521	-2.579
717.859	4.23	29.526	13.608	-12.508	-2.58
717.722	4.29	29.526	13.679	-12.495	-2.58
717.584	4.354	29.526	13.751	-12.481	-2.581
717.447	4.412	29.526	13.822	-12.468	-2.581
717.308	4.476	29.526	13.893	-12.454	-2.582
717.169	4.546	29.526	13.964	-12.441	-2.582
717.035	4.63	29.526	14.035	-12.427	-2.583
716.901	4.713	29.596	14.106	-12.414	-2.584
716.762	4.793	29.596	14.178	-12.4	-2.584
716.619	4.881	29.596	14.253	-12.386	-2.585
716.495	4.953	29.596	14.323	-12.374	-2.586
716.244	5.079	29.596	14.449	-12.349	-2.587
716.102	5.166	29.596	14.52	-12.335	-2.587
715.961	5.268	29.596	14.591	-12.321	-2.588
715.835	5.374	29.596	14.662	-12.309	-2.589
715.706	5.477	29.596	14.733	-12.296	-2.59
715.574	5.568	29.596	14.804	-12.283	-2.59
715.426	5.655	29.666	14.876	-12.268	-2.591
715.28	5.741	29.666	14.947	-12.254	-2.592
715.145	5.836	29.666	15.018	-12.241	-2.593
715.017	5.939	29.666	15.089	-12.228	-2.593
714.889	6.041	29.666	15.16	-12.215	-2.594
714.764	6.137	29.666	15.231	-12.203	-2.595
714.628	6.245	29.666	15.303	-12.189	-2.596
714.495	6.366	29.666	15.374	-12.176	-2.597
714.251	6.604	29.666	15.503	-12.152	-2.598
714.121	6.734	29.666	15.573	-12.139	-2.6
713.988	6.86	29.666	15.645	-12.125	-2.6
713.869	6.972	29.741	15.719	-12.114	-2.601
713.727	7.097	29.741	15.79	-12.099	-2.602
713.6	7.228	29.741	15.861	-12.087	-2.603
713.461	7.371	29.741	15.938	-12.073	-2.604
713.327	7.496	29.741	16.009	-12.059	-2.605

713.192	7.643	29.741	16.08	-12.046	-2.607
713.055	7.785	29.741	16.151	-12.032	-2.608
712.933	7.93	29.741	16.222	-12.02	-2.609
712.806	8.076	29.741	16.294	-12.007	-2.61
712.667	8.226	29.741	16.366	-11.993	-2.611
712.476	8.451	29.741	16.468	-11.974	-2.613
712.331	8.642	29.821	16.551	-11.959	-2.614
712.212	8.789	29.821	16.622	-11.947	-2.615
712.089	8.955	29.821	16.694	-11.935	-2.617
711.969	9.137	29.821	16.766	-11.923	-2.618
711.846	9.332	29.821	16.838	-11.91	-2.62
711.724	9.5	29.821	16.91	-11.898	-2.621
711.598	9.676	29.821	16.981	-11.885	-2.622
711.47	9.859	29.821	17.052	-11.872	-2.624
711.342	10.067	29.821	17.124	-11.859	-2.625
711.219	10.26	29.821	17.196	-11.847	-2.627
711.104	10.48	29.821	17.267	-11.835	-2.629
710.98	10.696	29.906	17.338	-11.822	-2.63
710.864	10.897	29.906	17.409	-11.81	-2.632
710.748	11.105	29.906	17.48	-11.798	-2.634
710.485	11.532	29.906	17.625	-11.772	-2.637
710.352	11.775	29.906	17.697	-11.758	-2.639
710.237	12.01	29.906	17.768	-11.746	-2.641
710.125	12.239	29.906	17.839	-11.735	-2.642
710.007	12.478	29.906	17.91	-11.722	-2.644
709.876	12.721	29.906	17.982	-11.709	-2.646
709.751	12.978	29.906	18.054	-11.696	-2.648
709.636	13.226	29.999	18.128	-11.684	-2.65
709.477	13.578	29.999	18.227	-11.668	-2.653
709.365	13.815	29.999	18.298	-11.656	-2.655
709.254	14.055	29.999	18.369	-11.644	-2.656
709.135	14.317	29.999	18.44	-11.632	-2.659
708.926	14.749	29.999	18.563	-11.611	-2.662
708.743	15.16	29.999	18.672	-11.592	-2.665
708.624	15.421	29.999	18.744	-11.579	-2.667
708.522	15.694	29.999	18.815	-11.568	-2.669
708.408	15.952	31.112	18.886	-11.557	-2.671
708.297	16.23	31.112	18.958	-11.545	-2.673
708.183	16.526	31.112	19.029	-11.533	-2.676
708.061	16.804	31.112	19.101	-11.52	-2.678
707.939	17.123	31.112	19.177	-11.508	-2.68
707.66	17.851	31.112	19.355	-11.478	-2.686
707.549	18.153	31.112	19.426	-11.467	-2.688
707.306	18.739	31.112	19.568	-11.441	-2.693
707.176	19.079	31.112	19.65	-11.428	-2.696
707.074	19.38	31.214	19.721	-11.417	-2.698
706.964	19.688	31.214	19.793	-11.405	-2.7
706.841	20.057	31.214	19.876	-11.392	-2.703
706.728	20.354	31.214	19.948	-11.38	-2.706
706.617	20.657	31.214	20.019	-11.369	-2.708

706.503	20.966	31.214	20.091	-11.356	-2.71
706.383	21.283	31.214	20.163	-11.344	-2.713
706.269	21.594	31.214	20.235	-11.332	-2.715
706.157	21.899	31.214	20.306	-11.32	-2.718
706.04	22.248	31.214	20.388	-11.308	-2.72
705.924	22.581	31.214	20.459	-11.295	-2.723
705.661	23.393	31.315	20.635	-11.267	-2.729
705.545	23.721	31.315	20.707	-11.255	-2.732
705.344	24.287	31.315	20.828	-11.234	-2.736
705.239	24.615	31.315	20.899	-11.223	-2.739
705.134	24.943	31.315	20.971	-11.212	-2.741
705.003	25.337	31.315	21.055	-11.198	-2.744
704.834	25.848	31.315	21.16	-11.18	-2.748
704.69	26.307	31.315	21.258	-11.164	-2.752
704.577	26.682	30.398	21.335	-11.152	-2.755
704.466	27.032	30.398	21.409	-11.14	-2.757
704.313	27.523	30.398	21.514	-11.124	-2.761
704.205	27.874	30.398	21.586	-11.112	-2.764
703.911	28.76	30.398	21.766	-11.081	-2.771
703.802	29.128	30.398	21.837	-11.069	-2.774
703.709	29.497	30.398	21.909	-11.059	-2.777
703.611	29.864	30.398	21.98	-11.049	-2.78
703.506	30.217	30.398	22.051	-11.037	-2.782
703.4	30.578	30.493	22.122	-11.026	-2.785
703.287	30.94	30.493	22.193	-11.014	-2.788
703.174	31.295	30.493	22.264	-11.002	-2.791
703.06	31.651	30.493	22.335	-10.99	-2.793
702.957	31.999	30.493	22.406	-10.979	-2.796
702.868	32.333	30.493	22.476	-10.969	-2.799
702.783	32.63	30.493	22.547	-10.96	-2.801
702.601	33.212	30.493	22.664	-10.94	-2.806
702.432	33.771	30.493	22.777	-10.922	-2.81
702.321	34.165	30.493	22.849	-10.91	-2.813
702.22	34.532	30.583	22.92	-10.899	-2.816
702.124	34.912	30.583	22.991	-10.889	-2.819
702.016	35.269	30.583	23.062	-10.877	-2.822
701.905	35.643	30.583	23.134	-10.865	-2.824
701.797	36.009	30.583	23.206	-10.854	-2.827
701.68	36.382	30.583	23.278	-10.841	-2.83
701.577	36.754	30.583	23.349	-10.83	-2.833
701.469	37.121	30.583	23.42	-10.819	-2.836
701.37	37.514	30.583	23.492	-10.808	-2.839
701.271	37.891	30.583	23.563	-10.797	-2.842
701.121	38.425	30.583	23.665	-10.781	-2.846
701.017	38.806	30.667	23.737	-10.77	-2.849
700.907	39.176	30.667	23.808	-10.758	-2.852
700.804	39.556	30.667	23.879	-10.747	-2.855
700.689	39.944	30.667	23.95	-10.734	-2.858
700.588	40.326	30.667	24.021	-10.723	-2.861
700.489	40.713	30.667	24.091	-10.712	-2.864

700.384	41.091	30.667	24.163	-10.701	-2.867
700.273	41.49	30.667	24.235	-10.689	-2.87
700.173	41.868	30.667	24.305	-10.678	-2.873
700.068	42.263	30.667	24.377	-10.667	-2.876
699.955	42.661	30.667	24.449	-10.655	-2.879
699.857	43.052	30.746	24.521	-10.644	-2.882
699.773	43.449	30.746	24.592	-10.635	-2.885
699.66	43.898	30.746	24.672	-10.622	-2.889
699.556	44.29	30.746	24.743	-10.611	-2.892
699.423	44.778	30.746	24.83	-10.596	-2.896
699.319	45.182	30.746	24.902	-10.585	-2.899
699.212	45.582	30.746	24.975	-10.573	-2.902
699.115	45.982	30.746	25.047	-10.563	-2.905
699.021	46.384	30.746	25.119	-10.552	-2.908
698.922	46.783	30.746	25.19	-10.542	-2.911
698.826	47.181	30.746	25.261	-10.531	-2.914
698.721	47.596	30.82	25.333	-10.52	-2.918
698.623	48.005	30.82	25.404	-10.509	-2.921
698.514	48.403	30.82	25.475	-10.497	-2.924
698.41	48.798	30.82	25.547	-10.486	-2.927
698.319	49.207	30.82	25.619	-10.476	-2.93
698.18	49.763	30.82	25.717	-10.46	-2.934
698.069	50.181	30.82	25.789	-10.448	-2.938
697.956	50.64	30.82	25.869	-10.436	-2.941
697.858	51.064	30.82	25.943	-10.425	-2.945
697.758	51.471	30.82	26.014	-10.414	-2.948
697.668	51.884	30.892	26.086	-10.404	-2.951
697.584	52.291	30.892	26.157	-10.395	-2.954
697.484	52.709	30.892	26.229	-10.384	-2.957
697.379	53.115	30.892	26.3	-10.372	-2.96
697.276	53.522	30.892	26.371	-10.361	-2.964
697.175	53.943	30.892	26.443	-10.35	-2.967
697.08	54.361	30.892	26.515	-10.34	-2.97
696.987	54.782	30.892	26.587	-10.329	-2.973
696.895	55.2	30.892	26.658	-10.319	-2.977
696.745	55.844	30.892	26.768	-10.302	-2.982
696.646	56.262	30.892	26.839	-10.292	-2.985
696.508	56.85	30.96	26.94	-10.276	-2.99
696.406	57.269	30.96	27.013	-10.265	-2.993
696.297	57.687	30.96	27.084	-10.253	-2.996
696.203	58.111	30.96	27.155	-10.243	-2.999
696.109	58.528	30.96	27.226	-10.232	-3.003
696.015	58.944	30.96	27.297	-10.222	-3.006
695.914	59.374	30.96	27.368	-10.211	-3.009
695.819	59.799	30.96	27.44	-10.2	-3.012
695.723	60.205	30.96	27.516	-10.19	-3.016
695.615	60.686	30.96	27.587	-10.178	-3.019
695.528	61.105	30.96	27.658	-10.168	-3.023
695.392	61.787	31.023	27.77	-10.153	-3.028
695.282	62.229	31.023	27.843	-10.141	-3.031

695.184	62.65	31.023	27.913	-10.13	-3.035
695.086	63.084	31.023	27.985	-10.119	-3.038
694.993	63.506	31.023	28.055	-10.109	-3.041
694.9	63.944	31.023	28.127	-10.098	-3.045
694.805	64.38	31.023	28.199	-10.088	-3.048
694.707	64.812	31.023	28.271	-10.077	-3.052
694.617	65.244	31.023	28.342	-10.067	-3.055
694.52	65.689	31.023	28.414	-10.056	-3.058
694.418	66.121	31.084	28.485	-10.045	-3.062
694.325	66.538	31.084	28.555	-10.035	-3.065
694.218	66.978	31.084	28.627	-10.023	-3.068
694.12	67.408	31.084	28.699	-10.012	-3.072
693.974	68.091	31.084	28.812	-9.996	-3.077
693.874	68.537	31.084	28.883	-9.985	-3.08
693.774	68.967	31.084	28.954	-9.974	-3.084
693.68	69.413	31.084	29.026	-9.963	-3.087
693.579	69.864	31.084	29.098	-9.952	-3.091
693.49	70.312	31.084	29.17	-9.942	-3.094
693.409	70.756	31.084	29.241	-9.933	-3.098
693.318	71.206	31.142	29.313	-9.922	-3.101
693.208	71.653	31.142	29.385	-9.91	-3.105
693.115	72.062	31.142	29.456	-9.9	-3.108
693.01	72.525	31.142	29.527	-9.889	-3.112
692.918	72.968	31.142	29.598	-9.878	-3.115
692.827	73.414	31.142	29.67	-9.868	-3.118
692.731	73.854	31.142	29.741	-9.857	-3.122
692.581	74.495	31.142	29.844	-9.841	-3.127
692.471	75.016	31.142	29.927	-9.828	-3.131
692.351	75.573	31.142	30.018	-9.815	-3.135
692.253	76.029	31.198	30.09	-9.804	-3.139
692.15	76.47	31.198	30.162	-9.793	-3.142
692.048	76.926	31.198	30.234	-9.781	-3.146
691.951	77.385	31.198	30.307	-9.771	-3.149
691.859	77.834	31.198	30.378	-9.76	-3.153
691.762	78.275	31.198	30.448	-9.75	-3.156
691.662	78.734	31.198	30.52	-9.738	-3.16
691.568	79.178	31.198	30.591	-9.728	-3.163
691.47	79.627	31.198	30.662	-9.717	-3.167
691.379	80.084	31.198	30.733	-9.707	-3.17
691.217	80.932	31.198	30.866	-9.688	-3.177
691.123	81.355	31.252	30.937	-9.678	-3.18
691.014	81.871	31.252	31.012	-9.666	-3.184
690.914	82.329	31.252	31.083	-9.655	-3.188
690.816	82.774	31.252	31.154	-9.644	-3.191
690.718	83.234	31.252	31.225	-9.633	-3.195
690.627	83.688	31.252	31.296	-9.623	-3.198
690.529	84.146	31.252	31.368	-9.612	-3.202
690.436	84.613	31.252	31.44	-9.601	-3.206
690.342	85.082	31.252	31.511	-9.591	-3.209
690.244	85.56	31.252	31.583	-9.58	-3.213

690.146	86.019	31.252	31.654	-9.569	-3.217
690.043	86.49	31.305	31.726	-9.557	-3.22
689.854	87.4	31.305	31.867	-9.536	-3.227
689.772	87.826	31.305	31.938	-9.527	-3.231
689.665	88.319	31.305	32.009	-9.515	-3.234
689.563	88.784	31.305	32.08	-9.504	-3.238
689.467	89.245	31.305	32.152	-9.493	-3.242
689.367	89.715	31.305	32.223	-9.482	-3.245
689.28	90.176	31.305	32.294	-9.472	-3.249
689.195	90.647	31.305	32.366	-9.462	-3.253
689.102	91.111	31.305	32.437	-9.452	-3.256
688.995	91.591	32.379	32.509	-9.44	-3.26
688.9	92.057	32.379	32.58	-9.429	-3.264
688.809	92.52	32.379	32.651	-9.419	-3.267
688.722	92.941	32.379	32.722	-9.409	-3.27
688.533	93.935	32.379	32.895	-9.388	-3.278
688.427	94.429	32.379	32.97	-9.376	-3.282
688.331	94.913	32.379	33.042	-9.365	-3.286
688.193	95.617	32.379	33.147	-9.349	-3.291
688.07	96.232	32.379	33.24	-9.336	-3.296
687.972	96.714	32.429	33.312	-9.325	-3.3
687.871	97.19	32.429	33.383	-9.313	-3.303
687.771	97.708	32.429	33.46	-9.302	-3.308
687.688	98.191	32.429	33.532	-9.292	-3.311
687.587	98.661	32.429	33.603	-9.281	-3.315
687.487	99.151	32.429	33.674	-9.27	-3.319
687.396	99.625	32.429	33.745	-9.26	-3.322
687.298	100.097	32.429	33.815	-9.249	-3.326
687.178	100.786	32.429	33.915	-9.235	-3.331
687.076	101.383	32.429	34.002	-9.223	-3.336
686.978	101.879	32.475	34.073	-9.212	-3.34
686.886	102.366	32.475	34.144	-9.202	-3.344
686.794	102.856	32.475	34.215	-9.191	-3.348
686.706	103.348	32.475	34.286	-9.181	-3.351
686.608	103.839	32.475	34.357	-9.17	-3.355
686.523	104.337	32.475	34.429	-9.16	-3.359
686.389	105.036	32.475	34.531	-9.145	-3.365
686.303	105.524	32.475	34.601	-9.135	-3.368
686.216	106.011	32.475	34.673	-9.125	-3.372
686.122	106.499	32.475	34.744	-9.115	-3.376
686.03	106.993	32.475	34.815	-9.104	-3.38
685.932	107.487	32.522	34.886	-9.093	-3.384
685.801	108.188	32.522	34.986	-9.078	-3.389
685.725	108.672	32.522	35.056	-9.069	-3.393
685.623	109.239	32.522	35.136	-9.058	-3.397
685.515	109.748	32.522	35.208	-9.046	-3.401
685.425	110.248	32.522	35.279	-9.035	-3.405
685.339	110.752	32.522	35.35	-9.025	-3.409
685.247	111.263	32.522	35.422	-9.015	-3.413
685.175	111.767	32.522	35.493	-9.006	-3.417

685.095	112.276	32.522	35.564	-8.997	-3.421
685	112.798	32.522	35.636	-8.986	-3.425
684.869	113.554	32.57	35.74	-8.971	-3.431
684.76	114.195	32.57	35.829	-8.959	-3.436
684.656	114.796	32.57	35.912	-8.947	-3.441
684.539	115.527	32.57	36.014	-8.933	-3.446
684.447	116.044	32.57	36.085	-8.922	-3.45
684.357	116.566	32.57	36.157	-8.912	-3.454
684.26	117.189	32.57	36.242	-8.901	-3.459
684.109	118.083	32.57	36.366	-8.883	-3.466
684.01	118.63	32.57	36.44	-8.872	-3.47
683.91	119.15	32.618	36.512	-8.861	-3.474
683.817	119.761	32.618	36.594	-8.85	-3.479
683.709	120.466	32.618	36.689	-8.837	-3.485
683.61	121	32.618	36.76	-8.826	-3.489
683.52	121.55	32.618	36.835	-8.815	-3.493
683.432	122.084	32.618	36.907	-8.805	-3.497
683.26	123.273	32.618	37.066	-8.785	-3.506
683.094	124.312	32.618	37.201	-8.765	-3.515
683.006	124.859	32.618	37.272	-8.755	-3.519
682.92	125.385	31.64	37.342	-8.745	-3.523
682.837	125.916	31.64	37.414	-8.735	-3.527
682.75	126.449	31.64	37.485	-8.725	-3.531
682.667	126.969	31.64	37.555	-8.716	-3.535
682.575	127.507	31.64	37.626	-8.705	-3.539
682.49	128.039	31.64	37.698	-8.695	-3.544
682.411	128.586	31.64	37.77	-8.686	-3.548
682.327	129.139	31.64	37.842	-8.676	-3.552
682.234	129.715	31.64	37.917	-8.665	-3.557
682.078	130.669	31.64	38.04	-8.647	-3.564
681.955	131.516	31.684	38.149	-8.632	-3.571
681.884	132.053	31.684	38.22	-8.624	-3.575
681.788	132.615	31.684	38.291	-8.613	-3.579
681.696	133.172	31.684	38.363	-8.602	-3.584
681.611	133.747	31.684	38.435	-8.592	-3.588
681.525	134.304	31.684	38.506	-8.582	-3.592
681.456	134.873	31.684	38.578	-8.574	-3.597
681.384	135.446	31.684	38.65	-8.565	-3.601
681.301	136.012	31.684	38.722	-8.555	-3.606
681.209	136.59	31.684	38.794	-8.544	-3.61
681.118	137.159	31.684	38.865	-8.534	-3.615
681.04	137.739	31.728	38.937	-8.524	-3.619
680.909	138.676	31.728	39.055	-8.509	-3.626
680.82	139.278	31.728	39.13	-8.498	-3.631
680.698	140.068	31.728	39.228	-8.484	-3.637
680.618	140.642	31.728	39.299	-8.474	-3.642
680.549	141.193	31.728	39.374	-8.466	-3.646
680.456	141.832	31.728	39.445	-8.455	-3.651
680.371	142.41	31.728	39.517	-8.445	-3.655
680.286	143.005	31.728	39.588	-8.435	-3.66

680.2	143.589	31.728	39.66	-8.424	-3.665
680.131	144.181	31.77	39.731	-8.416	-3.669
680.051	144.769	31.77	39.803	-8.406	-3.674
679.959	145.355	31.77	39.874	-8.396	-3.678
679.876	145.961	31.77	39.947	-8.386	-3.683
679.742	146.939	31.77	40.065	-8.37	-3.691
679.631	147.908	31.77	40.18	-8.356	-3.698
679.55	148.497	31.77	40.251	-8.346	-3.703
679.462	149.106	31.77	40.323	-8.336	-3.708
679.379	149.708	31.77	40.395	-8.326	-3.712
679.3	150.312	31.77	40.467	-8.316	-3.717
679.224	150.924	31.815	40.538	-8.307	-3.722
679.141	151.519	31.815	40.609	-8.297	-3.726
679.057	152.141	31.815	40.681	-8.287	-3.731
678.977	152.747	31.815	40.752	-8.277	-3.736
678.904	153.379	31.815	40.824	-8.268	-3.741
678.833	153.987	31.815	40.895	-8.259	-3.746
678.755	154.601	31.815	40.966	-8.25	-3.75
678.623	155.621	31.815	41.083	-8.234	-3.758
678.538	156.25	31.815	41.155	-8.224	-3.763
678.45	156.987	31.815	41.238	-8.213	-3.769
678.383	157.612	31.857	41.311	-8.204	-3.774
678.303	158.252	31.857	41.383	-8.195	-3.779
678.215	158.876	31.857	41.454	-8.184	-3.784
678.138	159.512	31.857	41.525	-8.175	-3.789
678.056	160.144	31.857	41.597	-8.165	-3.793
677.988	160.781	31.857	41.669	-8.156	-3.798
677.921	161.421	31.857	41.741	-8.148	-3.803
677.852	162.05	31.857	41.812	-8.139	-3.808
677.769	162.689	31.857	41.883	-8.129	-3.813
677.686	163.323	31.857	41.955	-8.119	-3.818
677.599	163.959	31.857	42.026	-8.108	-3.823
677.519	164.659	31.899	42.104	-8.098	-3.829
677.419	165.541	31.899	42.203	-8.086	-3.835
677.345	166.208	31.899	42.275	-8.077	-3.841
677.271	166.855	31.899	42.347	-8.068	-3.846
677.198	167.5	31.899	42.418	-8.058	-3.851
677.122	168.165	31.899	42.491	-8.049	-3.856
677.048	168.823	31.899	42.563	-8.04	-3.861
676.973	169.476	31.899	42.634	-8.03	-3.866
676.883	170.236	31.899	42.716	-8.019	-3.872
676.806	170.914	31.899	42.79	-8.01	-3.877
676.751	171.498	31.939	42.873	-8.002	-3.882
676.64	172.455	31.939	42.956	-7.989	-3.889
676.569	173.055	31.939	43.028	-7.98	-3.894
676.367	174.941	31.939	43.221	-7.954	-3.909
676.255	176.085	31.939	43.343	-7.94	-3.918
676.183	176.766	31.939	43.415	-7.931	-3.923
676.076	177.766	31.939	43.52	-7.917	-3.931
675.999	178.455	31.939	43.593	-7.908	-3.936

675.928	179.115	31.939	43.663	-7.899	-3.941
675.845	179.946	31.977	43.749	-7.888	-3.948
675.771	180.632	31.977	43.821	-7.879	-3.953
675.701	181.324	31.977	43.892	-7.87	-3.958
675.639	182.002	31.977	43.963	-7.862	-3.964
675.573	182.721	31.977	44.036	-7.853	-3.969
675.446	184.015	31.977	44.171	-7.837	-3.979
675.373	184.72	31.977	44.242	-7.827	-3.985
675.282	185.559	31.977	44.328	-7.816	-3.991
675.222	186.267	31.977	44.4	-7.808	-3.997
675.157	186.973	32.014	44.472	-7.799	-4.002
675.08	187.679	32.014	44.543	-7.79	-4.008
675.011	188.396	32.014	44.616	-7.781	-4.013
674.944	189.108	32.014	44.687	-7.772	-4.019
674.875	189.813	32.014	44.759	-7.763	-4.024
674.819	190.53	32.014	44.83	-7.755	-4.03
674.764	191.232	32.014	44.901	-7.748	-4.035
674.7	191.961	32.014	44.973	-7.739	-4.041
674.632	192.687	32.014	45.045	-7.73	-4.047
674.505	193.931	32.014	45.168	-7.714	-4.056
674.441	194.67	32.014	45.24	-7.706	-4.062
674.366	195.571	32.047	45.328	-7.696	-4.069
674.304	196.314	32.047	45.4	-7.687	-4.075
674.244	197.043	32.047	45.471	-7.679	-4.081
674.183	197.777	32.047	45.542	-7.671	-4.086
674.125	198.511	32.047	45.613	-7.663	-4.092
674.063	199.253	32.047	45.684	-7.655	-4.098
674.001	199.998	32.047	45.756	-7.646	-4.104
673.933	200.746	32.047	45.827	-7.637	-4.109
673.866	201.494	32.047	45.899	-7.628	-4.115
673.808	202.238	32.047	45.97	-7.62	-4.121
673.749	202.982	32.047	46.041	-7.612	-4.127
673.627	204.478	32.076	46.181	-7.596	-4.138
673.567	205.227	32.076	46.252	-7.588	-4.144
673.5	205.994	32.076	46.324	-7.579	-4.15
673.447	206.754	32.076	46.395	-7.571	-4.156
673.401	207.531	32.076	46.467	-7.564	-4.162
673.344	208.3	32.076	46.538	-7.556	-4.168
673.281	209.072	32.076	46.618	-7.548	-4.174
673.202	209.935	32.076	46.69	-7.537	-4.181
673.143	210.708	32.076	46.761	-7.529	-4.187
673.09	211.491	32.076	46.832	-7.522	-4.193
673.034	212.263	32.101	46.903	-7.514	-4.199
672.973	213.043	32.101	46.974	-7.506	-4.205
672.918	213.836	32.101	47.045	-7.498	-4.211
672.862	214.613	32.101	47.116	-7.49	-4.217
672.782	215.814	32.101	47.224	-7.478	-4.227
672.688	217.086	32.101	47.337	-7.465	-4.237
672.617	217.882	32.101	47.408	-7.456	-4.243
672.564	218.675	32.101	47.479	-7.448	-4.249

672.516	219.485	32.101	47.551	-7.441	-4.255
672.465	220.282	32.101	47.622	-7.434	-4.261
672.41	221.098	32.12	47.693	-7.426	-4.268
672.355	221.903	32.12	47.765	-7.418	-4.274
672.293	222.728	32.12	47.836	-7.409	-4.28
672.234	223.541	32.12	47.909	-7.401	-4.287
672.191	224.375	32.12	47.981	-7.394	-4.293
672.151	225.196	32.12	48.052	-7.388	-4.3
672.093	226.012	32.12	48.124	-7.379	-4.306
671.972	227.654	32.12	48.267	-7.363	-4.319
671.905	228.768	32.12	48.363	-7.353	-4.328
671.847	229.777	32.12	48.45	-7.344	-4.335
671.79	230.598	32.136	48.521	-7.336	-4.342
671.735	231.446	32.136	48.599	-7.328	-4.348
671.674	232.399	32.136	48.673	-7.319	-4.356
671.626	233.234	32.136	48.743	-7.311	-4.362
671.584	234.09	32.136	48.815	-7.305	-4.369
671.529	234.951	32.136	48.887	-7.297	-4.376
671.472	235.805	32.136	48.958	-7.288	-4.382
671.419	236.685	32.136	49.03	-7.28	-4.389
671.376	237.543	32.136	49.101	-7.274	-4.396
671.275	239.374	32.136	49.249	-7.258	-4.41
671.224	240.24	32.146	49.32	-7.25	-4.417
671.161	241.364	32.146	49.411	-7.241	-4.426
671.116	242.276	32.146	49.483	-7.233	-4.433
671.081	243.187	32.146	49.555	-7.227	-4.44
671.042	244.078	32.146	49.626	-7.221	-4.447
670.992	244.999	32.146	49.698	-7.213	-4.454
670.941	245.898	32.146	49.769	-7.205	-4.461
670.898	246.821	32.146	49.84	-7.198	-4.468
670.857	247.735	32.146	49.911	-7.191	-4.475
670.605	253.196	32.152	50.54	-7.149	-4.518
670.406	257.805	32.153	50.885	-7.116	-4.553
670.195	263.84	32.153	51.32	-7.076	-4.6
670.033	268.753	32.153	51.664	-7.045	-4.639
669.849	274.928	32.15	52.088	-7.008	-4.687
669.716	280.095	32.15	52.432	-6.979	-4.727
669.573	287.252	32.145	52.897	-6.942	-4.783
669.471	292.756	32.145	53.247	-6.915	-4.825
669.351	299.706	32.138	53.681	-6.881	-4.88
669.268	305.404	32.138	54.031	-6.855	-4.924
669.208	311.114	32.13	54.375	-6.832	-4.968
669.165	318.2	32.13	54.797	-6.805	-5.024
669.113	324.057	32.124	55.142	-6.782	-5.069
669.079	329.967	32.124	55.486	-6.76	-5.115
669.046	335.94	32.121	55.831	-6.737	-5.162
669.038	341.986	32.121	56.176	-6.718	-5.209
669.022	348.067	32.12	56.52	-6.697	-5.256
668.983	356.336	32.12	56.984	-6.667	-5.32
668.991	362.507	32.121	57.328	-6.648	-5.368

668.984	366.512	32.121	57.55	-6.635	-5.4
668.971	371.956	32.121	57.849	-6.617	-5.442
668.981	378.273	32.124	58.194	-6.598	-5.491
668.981	382.378	32.124	58.418	-6.585	-5.523
668.985	386.448	32.124	58.639	-6.572	-5.555
668.988	392.025	32.131	58.941	-6.555	-5.598
669.02	396.141	32.131	59.161	-6.545	-5.63
669.002	400.627	32.131	59.403	-6.529	-5.665
669.019	404.771	32.131	59.624	-6.518	-5.697
669.041	410.92	32.139	59.951	-6.5	-5.745
669.052	415.379	32.139	60.189	-6.487	-5.78
669.071	419.558	32.139	60.409	-6.476	-5.812
669.079	423.755	32.149	60.632	-6.464	-5.845
669.103	427.964	32.149	60.853	-6.453	-5.878
669.115	433.708	32.149	61.155	-6.436	-5.922
669.132	437.917	32.16	61.377	-6.424	-5.955
669.154	442.21	32.16	61.599	-6.413	-5.989
669.163	446.437	32.16	61.82	-6.4	-6.022
669.192	452.144	32.173	62.119	-6.385	-6.066
669.219	456.768	32.173	62.358	-6.373	-6.102
669.231	461.023	32.173	62.58	-6.361	-6.135
669.265	468.302	32.187	62.957	-6.341	-6.192
669.288	472.577	32.187	63.178	-6.33	-6.225
669.301	476.902	32.187	63.402	-6.317	-6.259
669.342	481.181	32.187	63.631	-6.308	-6.292
669.372	486.124	32.203	63.878	-6.295	-6.33
669.405	492.147	32.203	64.191	-6.279	-6.377
669.435	496.353	32.203	64.41	-6.269	-6.41
669.471	500.549	32.218	64.629	-6.259	-6.443
669.513	504.834	32.218	64.852	-6.25	-6.476
669.493	504.611	32.218	65.093	-6.248	-6.474
669.485	504.531	32.218	65.247	-6.248	-6.474
669.477	504.454	32.232	65.394	-6.247	-6.473
669.461	504.356	32.232	65.542	-6.246	-6.472
669.423	504.25	32.232	65.717	-6.243	-6.471
669.417	504.188	32.232	65.864	-6.242	-6.471
669.411	504.127	32.232	66.01	-6.242	-6.471
669.326	504.06	32.253	66.158	-6.234	-6.47
669.313	503.956	32.253	66.395	-6.233	-6.469
669.312	503.896	32.253	66.541	-6.233	-6.469
669.258	503.425	32.253	66.691	-6.229	-6.465
669.186	502.613	32.253	66.839	-6.225	-6.459
669.107	501.714	32.27	66.99	-6.22	-6.452
669.024	500.227	32.27	67.23	-6.217	-6.44
668.963	499.237	32.27	67.45	-6.214	-6.432
668.874	497.656	32.288	67.671	-6.21	-6.42
668.784	495.718	32.288	67.895	-6.208	-6.405
668.612	492.771	32.288	68.159	-6.2	-6.382
668.447	489.324	32.305	68.465	-6.195	-6.355
668.344	486.913	32.305	68.688	-6.193	-6.337

668.251	484.499	32.305	68.91	-6.191	-6.318
668.124	481.162	32.305	69.21	-6.19	-6.292
667.971	476.815	32.323	69.59	-6.188	-6.258
667.83	473.035	32.323	69.681	-6.187	-6.229
667.772	471.34	32.323	69.752	-6.186	-6.215
667.72	469.567	32.323	69.823	-6.187	-6.202
667.639	466.757	32.323	69.937	-6.188	-6.18
667.583	464.968	32.323	70.009	-6.188	-6.166
667.54	463.238	32.339	70.08	-6.19	-6.152
667.492	461.5	32.339	70.155	-6.19	-6.139
667.433	459.712	32.339	70.225	-6.19	-6.125
667.389	457.975	32.339	70.297	-6.191	-6.111
667.343	456.224	32.339	70.369	-6.192	-6.098
667.294	454.509	32.339	70.44	-6.193	-6.084
667.241	452.766	32.339	70.512	-6.193	-6.071
667.198	451.075	32.339	70.582	-6.195	-6.058
667.154	449.378	32.339	70.653	-6.196	-6.044
667.111	447.668	32.339	70.724	-6.197	-6.031
667.067	445.97	32.339	70.795	-6.198	-6.018
667.016	444.249	32.356	70.866	-6.199	-6.005
666.964	442.409	32.356	70.944	-6.199	-5.99
666.907	440.287	32.356	71.035	-6.201	-5.974
666.853	437.789	32.356	71.137	-6.203	-5.954
666.788	435.567	32.356	71.23	-6.204	-5.937
666.735	433.869	32.356	71.302	-6.204	-5.924
666.682	431.899	32.356	71.385	-6.205	-5.908
666.621	429.267	32.356	71.496	-6.208	-5.888
666.578	427.573	32.356	71.567	-6.209	-5.875
666.539	425.774	32.356	71.644	-6.211	-5.861
666.49	423.977	32.376	71.72	-6.212	-5.847
666.44	422.268	32.376	71.792	-6.212	-5.833
666.405	420.616	32.376	71.863	-6.214	-5.821
666.348	418.149	32.376	71.968	-6.216	-5.801
666.279	415.603	32.376	72.076	-6.218	-5.782
666.243	413.936	32.376	72.148	-6.219	-5.769
666.198	412.265	32.376	72.222	-6.22	-5.756
666.158	410.528	32.376	72.294	-6.222	-5.742
666.114	408.853	32.376	72.365	-6.223	-5.729
666.073	407.111	32.376	72.44	-6.224	-5.715
666.038	405.451	32.393	72.512	-6.226	-5.703
666.002	403.807	32.393	72.583	-6.228	-5.69
665.958	402.132	32.393	72.655	-6.229	-5.677
665.926	400.48	32.393	72.726	-6.231	-5.664
665.876	398.86	32.393	72.797	-6.231	-5.651
665.834	397.192	32.393	72.869	-6.232	-5.638
665.783	394.941	32.393	72.967	-6.235	-5.621
665.74	393.276	32.393	73.039	-6.236	-5.608
665.699	391.64	32.393	73.11	-6.237	-5.595
665.668	389.952	32.393	73.184	-6.239	-5.582
665.638	388.301	32.411	73.256	-6.241	-5.569

665.594	386.643	32.411	73.328	-6.242	-5.556
665.559	384.99	32.411	73.4	-6.244	-5.543
665.525	383.349	32.411	73.472	-6.246	-5.531
665.491	381.739	32.411	73.543	-6.248	-5.518
665.454	380.089	32.411	73.615	-6.25	-5.505
665.42	378.46	32.411	73.687	-6.251	-5.492
665.388	376.869	32.411	73.758	-6.253	-5.48
665.356	375.217	32.411	73.83	-6.255	-5.467
665.328	373.614	32.411	73.901	-6.258	-5.455
665.275	371.122	32.411	74.011	-6.26	-5.435
665.239	369.522	32.429	74.082	-6.262	-5.423
665.179	366.689	32.429	74.208	-6.265	-5.401
665.159	365.078	32.429	74.28	-6.268	-5.388
665.116	363.484	32.429	74.351	-6.269	-5.376
665.07	361.866	32.429	74.423	-6.27	-5.363
665.043	360.317	32.429	74.493	-6.272	-5.351
665.005	358.717	32.429	74.564	-6.273	-5.339
664.976	357.136	32.429	74.635	-6.276	-5.327
664.945	355.535	32.429	74.707	-6.278	-5.314
664.919	353.94	32.429	74.778	-6.28	-5.302
664.885	352.364	32.447	74.85	-6.282	-5.289
664.849	350.756	32.447	74.922	-6.283	-5.277
664.809	348.656	32.447	75.017	-6.286	-5.261
664.791	347.271	32.447	75.089	-6.289	-5.25
664.758	345.421	32.447	75.163	-6.291	-5.235
664.736	343.85	32.447	75.235	-6.294	-5.223
664.706	342.32	32.447	75.305	-6.296	-5.211
664.676	340.737	32.447	75.377	-6.298	-5.199
664.651	339.185	32.447	75.448	-6.301	-5.187
664.626	337.603	32.447	75.52	-6.303	-5.175
664.598	336.068	32.447	75.591	-6.305	-5.163
664.565	334.525	32.465	75.662	-6.307	-5.151
664.531	332.986	32.465	75.733	-6.309	-5.139
664.509	331.405	32.465	75.805	-6.311	-5.126
664.485	329.854	32.465	75.877	-6.314	-5.114
664.446	328.32	32.465	75.948	-6.315	-5.102
664.407	326.013	32.465	76.055	-6.319	-5.084
664.388	324.485	32.465	76.126	-6.322	-5.072
664.357	322.949	32.465	76.198	-6.323	-5.06
664.33	321.431	32.465	76.269	-6.326	-5.049
664.307	319.915	32.465	76.34	-6.328	-5.037
664.27	318.133	32.465	76.423	-6.33	-5.023
664.254	316.838	32.484	76.495	-6.333	-5.013
664.23	315.108	32.484	76.566	-6.336	-4.999
664.207	313.597	32.484	76.637	-6.338	-4.988
664.189	312.113	32.484	76.707	-6.341	-4.976
664.174	310.612	32.484	76.779	-6.345	-4.964
664.151	309.122	32.484	76.85	-6.347	-4.953
664.13	307.821	32.484	76.921	-6.349	-4.943
664.099	304.761	32.484	77.059	-6.356	-4.919

664.074	303.245	32.484	77.131	-6.358	-4.907
664.045	301.768	32.484	77.203	-6.36	-4.896
664.02	300.289	32.5	77.274	-6.362	-4.884
664.009	298.808	32.5	77.346	-6.366	-4.873
663.997	297.339	32.5	77.417	-6.369	-4.861
663.972	295.901	32.5	77.488	-6.371	-4.85
663.941	294.435	32.5	77.559	-6.373	-4.839
663.922	292.998	32.5	77.63	-6.376	-4.827
663.909	291.55	32.5	77.701	-6.379	-4.816
663.892	290.11	32.5	77.772	-6.382	-4.805
663.879	288.688	32.5	77.842	-6.385	-4.794
663.871	287.246	32.5	77.914	-6.389	-4.783
663.849	285.834	32.5	77.984	-6.391	-4.772
663.826	283.474	32.52	78.103	-6.396	-4.753
663.811	282.05	32.52	78.174	-6.399	-4.742
663.805	280.178	32.52	78.269	-6.405	-4.728
663.79	277.997	32.52	78.38	-6.41	-4.711
663.771	276.033	32.52	78.481	-6.415	-4.695
663.768	274.633	32.52	78.553	-6.419	-4.684
663.768	273.347	32.52	78.628	-6.423	-4.674
663.756	271.807	32.52	78.7	-6.426	-4.662
663.744	270.454	32.52	78.77	-6.43	-4.652
663.735	269.119	32.536	78.841	-6.433	-4.642
663.74	267.74	32.536	78.913	-6.438	-4.631
663.733	266.386	32.536	78.985	-6.441	-4.62
663.705	263.892	32.536	79.127	-6.446	-4.601
663.7	262.366	32.536	79.201	-6.451	-4.589
663.706	261.029	32.536	79.273	-6.456	-4.579
663.71	259.686	32.536	79.347	-6.46	-4.568
663.715	258.294	32.536	79.422	-6.465	-4.557
663.717	257.019	32.536	79.494	-6.469	-4.547
663.712	255.747	32.536	79.564	-6.473	-4.537
663.721	254.469	32.536	79.636	-6.478	-4.528
663.726	253.203	32.554	79.708	-6.482	-4.518
663.73	251.925	32.554	79.78	-6.487	-4.508
663.741	250.677	32.554	79.852	-6.492	-4.498
663.749	249.288	32.554	79.932	-6.497	-4.487
663.753	248.089	32.554	80.002	-6.501	-4.478
663.797	245.494	32.554	80.155	-6.513	-4.458
663.806	244.25	32.554	80.229	-6.518	-4.448
663.809	242.911	32.554	80.31	-6.523	-4.438
663.819	241.737	32.554	80.381	-6.527	-4.428
663.85	240.421	32.569	80.462	-6.535	-4.418
663.872	239.271	32.569	80.533	-6.54	-4.409
663.885	238.146	32.569	80.604	-6.545	-4.4
663.892	237.014	32.569	80.675	-6.549	-4.392
663.91	235.744	32.569	80.756	-6.555	-4.382
663.938	234.65	32.569	80.827	-6.561	-4.373
663.97	233.543	32.569	80.899	-6.568	-4.365
664.002	232.441	32.569	80.971	-6.574	-4.356

664.027	231.356	32.569	81.044	-6.58	-4.348
664.069	229.595	32.569	81.162	-6.59	-4.334
664.098	228.553	32.569	81.234	-6.596	-4.326
664.128	227.529	32.584	81.305	-6.602	-4.318
664.159	226.552	32.584	81.383	-6.608	-4.31
664.204	225.441	32.584	81.454	-6.616	-4.302
664.238	224.408	32.584	81.526	-6.623	-4.294
664.27	223.433	32.584	81.598	-6.629	-4.286
664.331	222.183	32.584	81.69	-6.639	-4.276
664.373	221.235	32.584	81.762	-6.646	-4.269
664.408	220.304	32.584	81.832	-6.652	-4.262
664.45	219.369	32.584	81.905	-6.659	-4.254
664.495	218.451	32.584	81.976	-6.666	-4.247
664.555	217.558	32.595	82.048	-6.675	-4.24
664.64	215.603	32.595	82.206	-6.689	-4.225
664.724	214.116	32.595	82.33	-6.702	-4.213
664.791	213.27	32.595	82.402	-6.711	-4.207
664.857	212.462	32.595	82.473	-6.72	-4.201
664.917	211.657	32.595	82.544	-6.729	-4.194
664.968	210.857	32.595	82.616	-6.736	-4.188
665.025	210.064	32.595	82.688	-6.744	-4.182
665.091	209.3	32.595	82.759	-6.753	-4.176
665.152	208.544	32.595	82.831	-6.761	-4.17
665.212	207.801	32.599	82.902	-6.769	-4.164
665.283	207.064	32.599	82.974	-6.779	-4.159
665.346	206.348	32.599	83.045	-6.787	-4.153
665.479	204.966	32.599	83.186	-6.804	-4.142
665.591	204.064	32.599	83.281	-6.818	-4.135
665.664	203.405	32.599	83.352	-6.827	-4.13
665.723	202.74	32.599	83.423	-6.835	-4.125
665.793	202.114	32.599	83.493	-6.844	-4.12
665.885	201.454	32.599	83.567	-6.855	-4.115
665.968	200.83	32.585	83.639	-6.865	-4.11
666.038	200.215	32.585	83.71	-6.873	-4.105
666.105	199.608	32.585	83.783	-6.882	-4.101
666.18	199.013	32.585	83.854	-6.891	-4.096
666.27	198.431	32.585	83.925	-6.902	-4.091
666.366	197.869	32.585	83.997	-6.913	-4.087
666.474	197.239	32.585	84.078	-6.925	-4.082
666.558	196.727	32.585	84.149	-6.935	-4.078
666.681	196.057	32.585	84.248	-6.949	-4.073
666.838	195.274	32.585	84.366	-6.967	-4.067
666.929	194.802	32.536	84.438	-6.977	-4.063
667.022	194.335	32.536	84.509	-6.987	-4.06
667.118	193.85	32.536	84.58	-6.998	-4.056
667.21	193.379	32.536	84.652	-7.009	-4.052
667.303	192.906	32.536	84.724	-7.019	-4.048
667.404	192.444	32.536	84.806	-7.03	-4.045
667.522	191.924	32.536	84.877	-7.043	-4.041
667.612	191.459	32.536	84.949	-7.054	-4.037

667.7	191.008	32.536	85.02	-7.064	-4.034
667.8	190.558	32.536	85.093	-7.075	-4.03
667.99	189.695	32.426	85.23	-7.096	-4.023
668.106	189.099	32.426	85.327	-7.109	-4.019
668.204	188.654	32.426	85.399	-7.12	-4.015
668.309	188.216	32.426	85.471	-7.131	-4.012
668.418	187.794	32.426	85.543	-7.143	-4.009
668.524	187.356	32.426	85.614	-7.155	-4.005
668.618	186.937	32.426	85.685	-7.165	-4.002
668.719	186.469	32.426	85.765	-7.177	-3.998
668.823	186.049	32.426	85.836	-7.188	-3.995
668.927	185.622	32.426	85.908	-7.2	-3.992
669.028	185.2	32.426	85.98	-7.211	-3.988
669.125	184.784	32.263	86.051	-7.221	-3.985
669.228	184.363	32.263	86.123	-7.233	-3.982
669.324	183.952	32.263	86.195	-7.243	-3.979
669.476	183.306	32.263	86.305	-7.26	-3.974
669.576	182.923	32.263	86.38	-7.271	-3.971
669.713	182.344	32.263	86.467	-7.286	-3.966
669.801	181.924	32.263	86.539	-7.296	-3.963
669.894	181.511	32.263	86.609	-7.306	-3.96
670.009	181.077	32.263	86.68	-7.319	-3.956
670.11	180.658	32.263	86.751	-7.33	-3.953
670.198	180.23	32.263	86.823	-7.34	-3.95
670.285	179.797	32.091	86.895	-7.349	-3.946
670.384	179.369	32.091	86.966	-7.36	-3.943
670.488	178.95	32.091	87.038	-7.372	-3.94
670.593	178.521	32.091	87.109	-7.383	-3.936
670.703	178.093	32.091	87.182	-7.395	-3.933
670.86	177.403	32.091	87.299	-7.413	-3.928
670.998	176.817	32.091	87.397	-7.428	-3.923
671.094	176.389	32.091	87.468	-7.439	-3.92
671.186	175.957	32.091	87.538	-7.449	-3.917
671.286	175.523	32.091	87.609	-7.46	-3.913
671.385	175.077	31.953	87.68	-7.471	-3.91
671.477	174.616	31.953	87.753	-7.481	-3.906
671.571	174.152	31.953	87.824	-7.492	-3.902
671.67	173.699	31.953	87.895	-7.503	-3.899
671.765	173.219	31.953	87.967	-7.514	-3.895
671.853	172.745	31.953	88.038	-7.524	-3.892
671.939	172.253	31.953	88.11	-7.534	-3.888
672.029	171.758	31.953	88.181	-7.544	-3.884
672.137	171.256	31.953	88.253	-7.556	-3.88
672.247	170.609	31.953	88.344	-7.569	-3.875
672.322	170.093	31.953	88.415	-7.577	-3.871
672.407	169.572	31.85	88.486	-7.587	-3.867
672.496	169.055	31.85	88.558	-7.598	-3.863
672.59	168.524	31.85	88.63	-7.608	-3.859
672.688	167.998	31.85	88.701	-7.62	-3.855
672.778	167.46	31.85	88.773	-7.63	-3.85

672.851	166.972	31.85	88.849	-7.639	-3.847
672.945	166.352	31.85	88.92	-7.65	-3.842
673.036	165.822	31.85	88.991	-7.66	-3.838
673.12	165.279	31.85	89.062	-7.67	-3.833
673.206	164.738	31.85	89.134	-7.68	-3.829
673.297	164.185	31.85	89.206	-7.691	-3.825
673.378	163.637	31.807	89.277	-7.7	-3.821
673.484	162.926	31.807	89.369	-7.713	-3.815
673.982	159.783	31.807	89.987	-7.771	-3.791
674.233	158.213	31.828	90.2	-7.8	-3.778
674.511	156.63	31.828	90.417	-7.832	-3.766
674.913	154.406	31.828	90.735	-7.878	-3.749
675.22	152.853	31.886	90.965	-7.913	-3.737
675.505	151.446	31.886	91.179	-7.945	-3.726
675.804	149.991	31.886	91.409	-7.978	-3.714
676.216	148.226	31.953	91.7	-8.024	-3.701
676.533	146.871	31.953	91.928	-8.059	-3.69
676.844	145.653	31.953	92.141	-8.093	-3.681
677.148	144.457	31.953	92.357	-8.126	-3.671
677.57	142.88	32.016	92.649	-8.172	-3.659
677.957	141.511	32.016	92.904	-8.214	-3.648
678.278	140.35	32.016	93.12	-8.248	-3.639
678.581	139.172	32.074	93.337	-8.281	-3.63
678.9	137.981	32.074	93.552	-8.316	-3.621
679.307	136.362	32.074	93.841	-8.361	-3.608
679.633	135.016	32.123	94.069	-8.396	-3.598
679.939	133.692	32.123	94.286	-8.43	-3.588
680.223	132.378	32.123	94.5	-8.462	-3.577
680.626	130.505	32.123	94.789	-8.507	-3.563
680.955	128.842	32.161	95.043	-8.544	-3.55
681.235	127.39	32.161	95.259	-8.576	-3.539
681.506	125.896	32.161	95.476	-8.607	-3.527
681.795	124.449	32.19	95.689	-8.639	-3.516
682.167	122.458	32.19	95.982	-8.681	-3.5
682.466	120.86	32.19	96.212	-8.715	-3.488
682.729	119.383	32.212	96.427	-8.746	-3.476
683.039	117.708	32.212	96.67	-8.781	-3.463
683.425	115.615	32.212	96.981	-8.825	-3.447
683.72	114.077	32.212	97.196	-8.858	-3.435
683.998	112.596	32.231	97.413	-8.89	-3.423
684.268	111.119	32.231	97.628	-8.921	-3.412
684.672	109.042	32.231	97.935	-8.966	-3.396
684.933	107.566	32.246	98.149	-8.996	-3.384
685.27	105.798	32.246	98.406	-9.034	-3.37
685.562	104.314	32.246	98.624	-9.067	-3.359
685.935	102.342	32.262	98.919	-9.11	-3.344
686.247	100.807	32.262	99.147	-9.145	-3.332
686.542	99.378	32.262	99.364	-9.178	-3.321
686.797	97.929	32.262	99.577	-9.207	-3.309
687.09	96.492	32.278	99.792	-9.24	-3.298

687.466	94.544	32.278	100.131	-9.282	-3.283
687.852	92.623	32.278	100.373	-9.326	-3.268
688.136	91.207	32.293	100.586	-9.358	-3.257
688.423	89.703	32.293	100.815	-9.39	-3.245
688.728	88.292	32.293	101.029	-9.424	-3.234
689.098	86.397	32.309	101.318	-9.466	-3.219
689.384	84.973	32.309	101.539	-9.498	-3.208
689.673	83.606	32.309	101.754	-9.53	-3.198
690.064	81.725	32.325	102.042	-9.574	-3.183
690.384	80.255	32.325	102.271	-9.61	-3.172
690.688	78.891	32.325	102.485	-9.644	-3.161
690.957	77.497	32.325	102.703	-9.674	-3.15
691.256	76.138	32.34	102.915	-9.707	-3.14
691.54	74.771	32.34	103.13	-9.739	-3.129
691.975	72.782	32.34	103.448	-9.787	-3.114
692.307	71.326	32.356	103.68	-9.824	-3.102
692.593	69.997	32.356	103.895	-9.856	-3.092
692.995	68.229	32.356	104.184	-9.9	-3.078
693.3	66.806	32.373	104.413	-9.934	-3.067
693.604	65.457	32.373	104.633	-9.968	-3.057
693.893	64.159	32.373	104.847	-10	-3.046
694.251	62.617	32.373	105.102	-10.04	-3.034
694.664	60.901	32.389	105.393	-10.085	-3.021
694.97	59.633	32.389	105.607	-10.119	-3.011
695.245	58.342	32.389	105.826	-10.149	-3.001
695.557	57.084	32.404	106.041	-10.184	-2.991
695.952	55.398	32.404	106.332	-10.227	-2.978
696.275	54.091	32.404	106.56	-10.262	-2.968
696.584	52.849	32.404	106.777	-10.296	-2.958
696.875	51.628	32.423	106.992	-10.328	-2.949
697.323	49.835	32.423	107.309	-10.377	-2.935
697.649	48.552	32.423	107.539	-10.413	-2.925
697.959	47.364	32.441	107.753	-10.447	-2.916
698.264	46.173	32.441	107.969	-10.48	-2.906
698.684	44.561	32.441	108.263	-10.526	-2.894
699.081	43.106	32.46	108.534	-10.569	-2.883
699.409	41.922	32.46	108.754	-10.604	-2.873
699.694	40.774	32.46	108.969	-10.635	-2.864
700.031	39.634	32.46	109.183	-10.671	-2.856
700.445	38.106	32.479	109.472	-10.716	-2.844
700.782	36.901	32.479	109.703	-10.753	-2.834
701.152	35.631	32.479	109.946	-10.792	-2.824
701.472	34.453	32.5	110.173	-10.827	-2.815
701.897	32.969	32.5	110.463	-10.873	-2.804
702.24	31.856	32.5	110.683	-10.91	-2.795
702.56	30.767	32.52	110.9	-10.944	-2.787
702.888	29.706	32.52	111.116	-10.979	-2.778
703.222	28.663	32.52	111.331	-11.015	-2.77
703.673	27.182	32.542	111.635	-11.063	-2.759
704.021	26.139	32.542	111.85	-11.1	-2.751

704.327	25.137	32.542	112.064	-11.133	-2.743
704.847	23.615	32.566	112.394	-11.188	-2.731
705.184	22.643	32.566	112.61	-11.224	-2.723
705.526	21.675	32.566	112.824	-11.26	-2.716
705.88	20.721	32.566	113.042	-11.297	-2.708
706.202	19.805	32.592	113.257	-11.331	-2.701
706.67	18.597	32.592	113.547	-11.38	-2.692
707.053	17.666	32.592	113.78	-11.42	-2.685
707.4	16.828	32.621	113.997	-11.456	-2.678
707.796	15.902	32.621	114.238	-11.498	-2.671
708.308	14.788	32.621	114.541	-11.551	-2.662
708.656	14.024	32.621	114.757	-11.587	-2.656
709.037	13.298	33.684	114.972	-11.626	-2.651
709.387	12.604	33.684	115.19	-11.662	-2.645
709.897	11.722	33.684	115.48	-11.714	-2.638
710.29	11.054	33.724	115.708	-11.754	-2.633
710.683	10.474	33.724	115.925	-11.794	-2.629
711.064	9.915	33.724	116.142	-11.833	-2.624
711.48	9.313	33.769	116.384	-11.875	-2.62
712.027	8.613	33.769	116.687	-11.93	-2.614
712.428	8.145	33.769	116.904	-11.97	-2.61
712.818	7.711	33.769	117.119	-12.009	-2.607
713.222	7.305	33.821	117.338	-12.05	-2.604
713.761	6.816	33.821	117.628	-12.104	-2.6
714.186	6.462	33.821	117.855	-12.146	-2.597
714.617	6.152	33.88	118.073	-12.188	-2.595
715.001	5.854	33.88	118.288	-12.227	-2.593
715.621	5.456	33.88	118.605	-12.288	-2.59
716.053	5.206	32.91	118.834	-12.331	-2.588
716.474	4.979	32.91	119.05	-12.372	-2.586
716.905	4.763	32.91	119.268	-12.414	-2.584
717.308	4.559	32.91	119.483	-12.454	-2.583
717.888	4.311	32.974	119.776	-12.511	-2.581
718.343	4.136	32.974	120.004	-12.556	-2.579
718.772	3.974	32.974	120.221	-12.598	-2.578
719.193	3.821	33.035	120.437	-12.639	-2.577
719.823	3.604	33.035	120.754	-12.701	-2.575
720.273	3.468	33.035	120.982	-12.745	-2.574
720.724	3.348	33.093	121.199	-12.789	-2.573
721.141	3.234	33.093	121.416	-12.829	-2.572
721.729	3.091	33.093	121.708	-12.887	-2.571
722.182	2.995	33.093	121.936	-12.931	-2.57
722.624	2.9	33.147	122.153	-12.974	-2.57
723.06	2.809	33.147	122.368	-13.017	-2.569
723.537	2.702	33.147	122.61	-13.063	-2.568
724.314	2.562	33.196	122.992	-13.139	-2.567
724.758	2.487	33.196	123.207	-13.182	-2.566
725.195	2.423	33.196	123.426	-13.224	-2.566
725.627	2.353	33.24	123.64	-13.267	-2.565
726.238	2.28	33.24	123.93	-13.326	-2.565

726.685	2.197	33.24	124.159	-13.369	-2.564
727.143	2.144	33.28	124.379	-13.414	-2.564
727.57	2.097	33.28	124.593	-13.455	-2.563
728.223	2.034	33.28	124.911	-13.519	-2.563
728.698	1.978	33.28	125.14	-13.565	-2.562
729.145	1.939	33.316	125.355	-13.608	-2.562
729.607	1.9	33.316	125.574	-13.653	-2.562
730.207	1.848	33.316	125.868	-13.712	-2.561
730.655	1.818	33.349	126.096	-13.755	-2.561
731.107	1.777	33.349	126.315	-13.799	-2.561
731.554	1.742	33.349	126.531	-13.842	-2.561
732.046	1.704	33.379	126.774	-13.89	-2.56
732.679	1.663	33.379	127.078	-13.952	-2.56
733.106	1.634	33.379	127.294	-13.993	-2.56
733.559	1.602	33.379	127.512	-14.037	-2.56
733.979	1.576	33.408	127.728	-14.078	-2.559
734.579	1.535	33.408	128.018	-14.136	-2.559
735.051	1.506	33.408	128.247	-14.182	-2.559
735.497	1.473	33.433	128.466	-14.225	-2.559
735.949	1.453	33.433	128.682	-14.269	-2.558
736.375	1.408	33.433	128.896	-14.31	-2.558
737.021	1.361	33.456	129.217	-14.373	-2.558
737.497	1.339	33.456	129.446	-14.419	-2.558
737.943	1.32	33.456	129.663	-14.462	-2.557
738.381	1.297	33.456	129.882	-14.505	-2.557
738.989	1.271	33.48	130.173	-14.564	-2.557
739.443	1.247	33.48	130.404	-14.608	-2.557
739.895	1.215	33.48	130.634	-14.652	-2.557
740.413	1.187	33.502	130.875	-14.702	-2.556
741.036	1.156	33.502	131.282	-14.762	-2.556
741.698	1.131	33.522	131.608	-14.827	-2.556
Volume, mm^3	Pressure, MPa	Temp., °C	Time, sec	Vol. Traverse, mm	Pres. Traverse, mm
740.771	1.858	64.19	0.089	-14.735	-2.562
740.771	1.858	64.19	0.187	-14.735	-2.562
740.77	1.858	64.19	0.279	-14.735	-2.562
740.77	1.858	64.19	0.361	-14.735	-2.562
740.77	1.858	64.19	0.439	-14.735	-2.562
740.771	1.857	64.19	0.535	-14.735	-2.562
740.771	1.858	64.19	0.615	-14.735	-2.562
740.771	1.858	64.19	0.696	-14.735	-2.562
740.771	1.858	64.187	0.783	-14.735	-2.562
740.771	1.858	64.187	0.862	-14.735	-2.562
740.771	1.858	64.187	0.937	-14.735	-2.562
740.771	1.857	64.187	1.057	-14.735	-2.562
740.77	1.858	64.187	1.178	-14.735	-2.562
740.771	1.858	64.187	1.253	-14.735	-2.562
740.771	1.858	64.187	1.328	-14.735	-2.562
740.77	1.858	64.187	1.411	-14.735	-2.562

740.77	1.858	64.187	1.507	-14.735	-2.562
740.763	1.891	64.186	1.614	-14.734	-2.562
740.782	2.035	64.186	1.73	-14.735	-2.563
740.758	2.197	64.186	1.804	-14.732	-2.564
740.702	2.446	64.186	1.923	-14.726	-2.566
740.636	2.754	64.186	2.038	-14.719	-2.569
740.468	2.915	64.186	2.253	-14.702	-2.57
740.361	2.955	64.184	2.371	-14.692	-2.57
740.277	2.976	64.184	2.487	-14.683	-2.57
740.113	3.006	64.184	2.62	-14.667	-2.57
740.009	3.014	64.184	2.735	-14.657	-2.571
739.786	3.027	64.184	2.88	-14.636	-2.571
739.671	3.027	64.184	2.988	-14.625	-2.571
739.535	3.033	64.184	3.082	-14.611	-2.571
739.336	3.034	64.182	3.212	-14.592	-2.571
739.186	3.034	64.182	3.309	-14.577	-2.571
739.065	3.034	64.182	3.382	-14.566	-2.571
738.933	3.034	64.182	3.457	-14.553	-2.571
738.792	3.034	64.182	3.531	-14.539	-2.571
738.645	3.035	64.182	3.606	-14.525	-2.571
738.466	3.034	64.182	3.698	-14.508	-2.571
738.302	3.034	64.182	3.776	-14.492	-2.571
738.158	3.034	64.182	3.849	-14.478	-2.571
738.014	3.034	64.182	3.921	-14.464	-2.571
737.858	3.034	64.18	3.997	-14.449	-2.571
737.705	3.034	64.18	4.07	-14.434	-2.571
737.439	3.034	64.18	4.201	-14.408	-2.571
737.288	3.034	64.18	4.274	-14.394	-2.571
737.118	3.034	64.18	4.362	-14.377	-2.571
736.951	3.034	64.18	4.44	-14.361	-2.571
736.802	3.034	64.18	4.515	-14.347	-2.571
736.56	3.034	64.18	4.632	-14.323	-2.571
736.411	3.034	64.18	4.708	-14.309	-2.571
736.246	3.034	64.177	4.786	-14.293	-2.571
736.085	3.035	64.177	4.86	-14.277	-2.571
735.93	3.035	64.177	4.936	-14.262	-2.571
735.779	3.034	64.177	5.01	-14.248	-2.571
735.505	3.035	64.177	5.141	-14.221	-2.571
735.322	3.034	64.177	5.232	-14.203	-2.571
735.157	3.034	64.177	5.309	-14.187	-2.571
735.006	3.034	64.177	5.384	-14.173	-2.571
734.794	3.034	64.177	5.486	-14.152	-2.571
734.642	3.035	64.172	5.561	-14.137	-2.571
734.453	3.034	64.172	5.652	-14.119	-2.571
734.303	3.034	64.172	5.727	-14.105	-2.571
734.138	3.035	64.172	5.807	-14.089	-2.571
733.991	3.035	64.172	5.882	-14.074	-2.571
733.838	3.034	64.172	5.958	-14.06	-2.571
733.689	3.035	64.172	6.033	-14.045	-2.571
733.529	3.034	64.172	6.11	-14.03	-2.571

733.259	3.035	64.172	6.241	-14.003	-2.571
733.07	3.035	64.172	6.332	-13.985	-2.571
732.901	3.035	64.169	6.408	-13.969	-2.571
732.752	3.035	64.169	6.484	-13.954	-2.571
732.593	3.037	64.169	6.561	-13.939	-2.571
732.345	3.045	64.169	6.681	-13.915	-2.571
732.096	3.072	64.169	6.803	-13.891	-2.571
731.849	3.143	64.169	6.926	-13.867	-2.572
731.616	3.224	64.169	7.046	-13.844	-2.572
731.375	3.352	64.165	7.166	-13.82	-2.573
731.059	3.446	64.165	7.331	-13.789	-2.574
730.824	3.501	64.165	7.454	-13.766	-2.574
730.588	3.547	64.165	7.573	-13.743	-2.575
730.409	3.584	64.165	7.661	-13.726	-2.575
730.142	3.636	64.165	7.795	-13.7	-2.575
729.898	3.69	64.165	7.914	-13.676	-2.576
729.648	3.749	64.163	8.039	-13.652	-2.576
729.41	3.808	64.163	8.159	-13.628	-2.577
729.102	3.882	64.163	8.311	-13.598	-2.577
728.832	3.955	64.163	8.445	-13.572	-2.578
728.588	4.023	64.163	8.568	-13.548	-2.578
728.353	4.091	64.163	8.688	-13.525	-2.579
728.063	4.173	64.161	8.837	-13.497	-2.58
727.793	4.246	64.161	8.975	-13.47	-2.58
727.557	4.315	64.161	9.095	-13.447	-2.581
727.134	4.452	64.161	9.309	-13.406	-2.582
726.841	4.559	64.161	9.459	-13.377	-2.583
726.591	4.653	64.161	9.583	-13.353	-2.583
726.35	4.742	64.161	9.704	-13.329	-2.584
726.015	4.871	64.161	9.869	-13.296	-2.585
725.776	4.97	64.161	9.991	-13.273	-2.586
725.534	5.079	64.161	10.116	-13.249	-2.587
725.201	5.235	64.161	10.286	-13.216	-2.588
724.964	5.354	64.163	10.409	-13.193	-2.589
724.678	5.487	64.163	10.563	-13.165	-2.59
724.409	5.623	64.163	10.698	-13.138	-2.591
724.167	5.747	64.163	10.82	-13.115	-2.592
723.932	5.884	64.163	10.945	-13.091	-2.593
723.677	6.027	64.163	11.068	-13.066	-2.594
723.441	6.161	64.169	11.189	-13.043	-2.595
723.031	6.426	64.169	11.404	-13.002	-2.597
722.89	6.52	64.169	11.481	-12.988	-2.598
722.639	6.697	64.169	11.605	-12.964	-2.599
722.404	6.856	64.169	11.727	-12.94	-2.6
722.169	7.034	64.169	11.85	-12.917	-2.602
721.981	7.198	64.181	11.952	-12.898	-2.603
721.751	7.391	64.181	12.075	-12.876	-2.605
721.521	7.583	64.181	12.197	-12.853	-2.606
721.213	7.847	64.181	12.354	-12.822	-2.608
720.98	8.078	64.181	12.479	-12.799	-2.61

720.739	8.307	64.181	12.6	-12.775	-2.612
720.509	8.534	64.181	12.723	-12.752	-2.614
720.286	8.777	64.196	12.846	-12.729	-2.615
720.045	9.032	64.196	12.972	-12.705	-2.617
719.822	9.306	64.196	13.095	-12.683	-2.62
719.406	9.802	64.196	13.324	-12.641	-2.623
719.164	10.119	64.196	13.457	-12.617	-2.626
718.941	10.431	64.219	13.581	-12.594	-2.628
718.683	10.823	64.219	13.731	-12.568	-2.631
718.543	11.027	64.219	13.807	-12.554	-2.633
718.316	11.367	64.219	13.93	-12.53	-2.636
718.101	11.701	64.219	14.057	-12.509	-2.638
717.873	12.051	64.219	14.181	-12.485	-2.641
717.49	12.732	64.249	14.409	-12.446	-2.646
717.276	13.135	64.249	14.536	-12.424	-2.649
717.067	13.51	64.249	14.659	-12.403	-2.652
716.914	13.795	64.249	14.748	-12.387	-2.654
716.787	14.032	64.249	14.824	-12.374	-2.656
716.578	14.449	64.249	14.947	-12.353	-2.66
716.358	14.873	64.249	15.077	-12.33	-2.663
716.152	15.299	64.287	15.201	-12.309	-2.666
715.952	15.721	64.287	15.324	-12.288	-2.669
715.686	16.266	64.287	15.479	-12.261	-2.674
715.569	16.542	64.287	15.555	-12.248	-2.676
715.357	17.021	64.287	15.683	-12.226	-2.68
715.147	17.491	64.287	15.807	-12.205	-2.683
714.953	17.96	62.814	15.935	-12.184	-2.687
714.689	18.604	62.814	16.1	-12.157	-2.692
714.489	19.079	62.814	16.223	-12.136	-2.696
714.147	19.943	62.814	16.44	-12.1	-2.702
713.94	20.448	62.814	16.566	-12.078	-2.706
713.742	20.963	62.814	16.695	-12.058	-2.71
713.552	21.458	62.856	16.819	-12.038	-2.714
713.347	21.972	62.856	16.946	-12.016	-2.718
713.142	22.49	62.856	17.071	-11.995	-2.722
712.959	23.008	62.856	17.195	-11.975	-2.726
712.754	23.55	62.856	17.32	-11.954	-2.73
712.505	24.298	62.856	17.492	-11.927	-2.736
712.306	24.84	62.9	17.619	-11.907	-2.74
712.078	25.501	62.9	17.772	-11.882	-2.746
711.859	26.133	62.9	17.912	-11.859	-2.75
711.669	26.685	62.9	18.037	-11.839	-2.755
711.471	27.253	62.9	18.163	-11.818	-2.759
711.275	27.825	62.9	18.293	-11.797	-2.764
710.93	28.877	62.94	18.524	-11.761	-2.772
710.732	29.48	62.94	18.652	-11.74	-2.777
710.549	30.071	62.94	18.78	-11.72	-2.781
710.385	30.549	62.94	18.882	-11.703	-2.785
710.189	31.152	62.94	19.012	-11.682	-2.79
709.997	31.763	62.974	19.143	-11.661	-2.794

709.808	32.364	62.974	19.268	-11.641	-2.799
709.481	33.407	62.974	19.486	-11.606	-2.807
709.359	33.792	62.974	19.567	-11.593	-2.81
709.151	34.403	62.974	19.694	-11.571	-2.815
708.963	35.02	62.974	19.821	-11.551	-2.82
708.827	35.454	62.974	19.912	-11.536	-2.823
708.615	36.132	63.006	20.053	-11.514	-2.828
708.415	36.746	63.006	20.18	-11.493	-2.833
708.231	37.386	63.006	20.311	-11.473	-2.838
708.029	38.004	63.006	20.437	-11.451	-2.843
707.776	38.835	63.006	20.607	-11.424	-2.849
707.577	39.475	63.033	20.739	-11.403	-2.854
707.39	40.104	63.033	20.865	-11.383	-2.859
707.162	40.883	63.033	21.02	-11.358	-2.865
706.964	41.524	63.033	21.148	-11.337	-2.87
706.847	41.908	63.033	21.225	-11.325	-2.873
706.661	42.56	63.033	21.353	-11.305	-2.878
706.357	43.584	63.054	21.577	-11.272	-2.886
706.148	44.301	63.054	21.719	-11.249	-2.892
705.96	44.981	63.054	21.85	-11.229	-2.897
705.759	45.654	63.054	21.981	-11.207	-2.902
705.524	46.457	63.054	22.137	-11.182	-2.909
705.412	46.848	63.054	22.214	-11.17	-2.912
705.207	47.529	63.071	22.345	-11.148	-2.917
705.01	48.225	63.071	22.477	-11.127	-2.922
704.79	49.03	63.071	22.632	-11.103	-2.929
704.664	49.43	63.071	22.711	-11.09	-2.932
704.468	50.123	63.071	22.841	-11.068	-2.937
704.279	50.803	63.071	22.97	-11.048	-2.942
704.096	51.478	63.071	23.099	-11.028	-2.948
703.962	51.956	63.084	23.191	-11.014	-2.951
703.733	52.746	63.084	23.346	-10.989	-2.958
703.547	53.48	63.084	23.476	-10.969	-2.963
703.208	54.648	63.084	23.695	-10.932	-2.972
703.104	55.078	63.084	23.775	-10.921	-2.976
702.9	55.784	63.084	23.905	-10.899	-2.981
702.712	56.489	63.095	24.036	-10.878	-2.987
702.489	57.332	63.095	24.192	-10.854	-2.993
702.373	57.746	63.095	24.27	-10.842	-2.997
702.18	58.468	63.095	24.402	-10.821	-3.002
701.995	59.169	63.095	24.532	-10.801	-3.008
701.687	60.39	63.107	24.753	-10.767	-3.017
701.573	60.833	63.107	24.834	-10.755	-3.021
701.4	61.548	63.107	24.962	-10.736	-3.026
701.303	61.94	63.107	25.032	-10.725	-3.029
701.066	62.804	63.107	25.192	-10.699	-3.036
700.872	63.625	63.107	25.335	-10.678	-3.042
700.676	64.36	63.107	25.465	-10.657	-3.048
700.498	65.088	63.113	25.594	-10.637	-3.054
700.185	66.368	63.113	25.821	-10.603	-3.064

700.003	67.101	63.113	25.951	-10.583	-3.069
699.825	67.822	63.113	26.081	-10.563	-3.075
699.652	68.573	63.113	26.212	-10.544	-3.081
699.476	69.33	63.119	26.343	-10.525	-3.087
699.298	70.128	63.119	26.472	-10.505	-3.093
699.117	70.831	63.119	26.603	-10.485	-3.098
698.796	72.102	63.119	26.825	-10.45	-3.108
698.6	72.934	63.119	26.97	-10.429	-3.115
698.411	73.695	63.119	27.102	-10.408	-3.121
698.233	74.464	63.124	27.234	-10.388	-3.127
698.1	74.995	63.124	27.327	-10.374	-3.131
697.896	75.83	63.124	27.471	-10.352	-3.137
697.72	76.596	63.124	27.604	-10.332	-3.143
697.412	77.936	63.124	27.83	-10.298	-3.154
697.207	78.792	63.126	27.975	-10.276	-3.16
697.026	79.6	63.126	28.112	-10.255	-3.167
696.841	80.378	63.126	28.242	-10.235	-3.173
696.652	81.171	63.126	28.375	-10.214	-3.179
696.532	81.718	63.126	28.467	-10.201	-3.183
696.415	82.203	63.126	28.548	-10.188	-3.187
696.218	83.004	63.126	28.682	-10.167	-3.193
695.915	84.358	63.127	28.908	-10.133	-3.204
695.798	84.841	63.127	28.988	-10.12	-3.207
695.63	85.673	63.127	29.123	-10.101	-3.214
695.45	86.472	63.127	29.254	-10.081	-3.22
695.237	87.447	63.127	29.414	-10.058	-3.228
695.034	88.332	63.13	29.56	-10.035	-3.235
694.861	89.134	63.13	29.692	-10.016	-3.241
694.532	90.532	63.13	29.92	-9.98	-3.252
694.359	91.36	63.13	30.054	-9.96	-3.258
694.179	92.172	63.13	30.185	-9.94	-3.264
693.997	92.987	63.13	30.317	-9.92	-3.271
693.812	93.814	63.13	30.451	-9.9	-3.277
693.63	94.644	63.13	30.585	-9.879	-3.284
693.459	95.46	63.13	30.716	-9.86	-3.29
693.235	96.535	63.13	30.89	-9.835	-3.298
693.14	96.973	63.13	30.96	-9.825	-3.302
692.949	97.833	63.13	31.096	-9.803	-3.308
692.715	98.914	63.13	31.269	-9.777	-3.317
692.523	99.759	63.13	31.404	-9.756	-3.323
692.428	100.196	63.13	31.476	-9.746	-3.327
692.338	100.663	63.13	31.547	-9.735	-3.331
692.157	101.505	63.13	31.68	-9.715	-3.337
691.976	102.351	63.13	31.813	-9.695	-3.344
691.742	103.441	63.13	31.985	-9.669	-3.352
691.568	104.214	63.13	32.121	-9.65	-3.358
691.433	104.974	63.13	32.252	-9.634	-3.364
691.244	105.816	63.13	32.386	-9.613	-3.371
691.125	106.409	63.13	32.479	-9.6	-3.375
691.01	106.947	63.13	32.562	-9.587	-3.379

690.819	107.813	63.13	32.698	-9.566	-3.386
690.519	109.282	63.127	32.924	-9.532	-3.398
690.398	109.833	63.127	33.01	-9.519	-3.402
690.272	110.435	63.127	33.103	-9.505	-3.407
690.169	110.965	63.127	33.185	-9.493	-3.411
689.988	111.87	63.127	33.322	-9.473	-3.418
689.805	112.739	63.127	33.455	-9.452	-3.425
689.622	113.629	63.123	33.59	-9.432	-3.431
689.445	114.518	63.123	33.724	-9.412	-3.438
689.149	116.007	63.123	33.949	-9.378	-3.45
689.051	116.516	63.123	34.031	-9.367	-3.454
688.86	117.456	63.123	34.17	-9.346	-3.461
688.73	118.086	63.123	34.264	-9.331	-3.466
688.629	118.623	63.122	34.346	-9.32	-3.47
688.532	119.092	63.122	34.416	-9.309	-3.474
688.347	119.988	63.122	34.551	-9.288	-3.481
688.181	120.879	63.122	34.684	-9.269	-3.488
688.007	121.766	63.122	34.817	-9.25	-3.495
687.836	122.657	63.122	34.95	-9.23	-3.502
687.627	123.727	63.122	35.11	-9.207	-3.51
687.517	124.288	63.119	35.193	-9.194	-3.514
687.344	125.183	63.119	35.327	-9.175	-3.521
687.224	125.823	63.119	35.421	-9.161	-3.526
687.116	126.383	63.119	35.503	-9.149	-3.531
687.034	126.866	63.119	35.574	-9.139	-3.534
686.854	127.786	63.119	35.71	-9.119	-3.542
686.677	128.695	63.119	35.844	-9.099	-3.549
686.472	129.787	63.118	36.003	-9.076	-3.557
686.283	130.788	63.118	36.149	-9.054	-3.565
686.199	131.279	63.118	36.219	-9.044	-3.569
686.032	132.194	63.118	36.354	-9.025	-3.576
685.871	133.12	63.118	36.488	-9.007	-3.583
685.698	134.051	63.118	36.622	-8.987	-3.59
685.516	135.003	63.116	36.758	-8.967	-3.598
685.343	135.935	63.116	36.893	-8.947	-3.605
685.145	137.056	63.116	37.052	-8.924	-3.614
685.046	137.666	63.116	37.14	-8.913	-3.618
684.87	138.607	63.116	37.275	-8.893	-3.626
684.697	139.554	63.116	37.41	-8.873	-3.633
684.577	140.222	63.116	37.505	-8.859	-3.638
684.38	141.25	63.113	37.654	-8.837	-3.646
684.209	142.206	63.113	37.791	-8.817	-3.654
684.037	143.174	63.113	37.929	-8.798	-3.661
683.838	144.313	63.113	38.089	-8.775	-3.67
683.663	145.283	63.113	38.226	-8.755	-3.678
683.494	146.244	63.111	38.362	-8.735	-3.685
683.33	147.217	63.111	38.497	-8.716	-3.693
683.154	148.176	63.111	38.632	-8.696	-3.7
682.99	149.146	63.111	38.768	-8.677	-3.708
682.899	149.645	63.111	38.838	-8.667	-3.712

682.732	150.632	63.111	38.974	-8.648	-3.719
682.445	152.264	63.107	39.201	-8.615	-3.732
682.337	152.874	63.107	39.286	-8.602	-3.737
682.172	153.865	63.107	39.421	-8.583	-3.745
682.008	154.852	63.107	39.557	-8.564	-3.752
681.886	155.551	63.107	39.653	-8.55	-3.758
681.699	156.649	63.107	39.803	-8.529	-3.766
681.527	157.65	63.102	39.941	-8.509	-3.774
681.239	159.389	63.102	40.176	-8.476	-3.788
681.145	159.999	63.102	40.259	-8.465	-3.792
680.971	161.033	63.102	40.398	-8.444	-3.8
680.805	162.039	63.102	40.534	-8.425	-3.808
680.686	162.748	63.102	40.631	-8.411	-3.814
680.58	163.349	63.102	40.716	-8.399	-3.818
680.399	164.391	63.098	40.853	-8.378	-3.826
680.238	165.433	63.098	40.993	-8.36	-3.835
679.958	167.158	63.098	41.223	-8.327	-3.848
679.769	168.287	63.098	41.373	-8.305	-3.857
679.596	169.338	63.098	41.514	-8.285	-3.865
679.434	170.361	63.095	41.65	-8.266	-3.873
679.217	171.707	63.095	41.827	-8.241	-3.883
679.052	172.748	63.095	41.964	-8.222	-3.892
678.769	174.506	63.095	42.196	-8.189	-3.905
678.571	175.763	63.09	42.36	-8.165	-3.915
678.474	176.393	63.09	42.442	-8.154	-3.92
678.391	176.958	63.09	42.515	-8.144	-3.924
678.172	178.327	63.09	42.693	-8.119	-3.935
678.002	179.392	63.09	42.831	-8.099	-3.943
677.836	180.46	63.09	42.968	-8.08	-3.952
677.661	181.569	63.09	43.111	-8.059	-3.96
677.58	182.106	63.086	43.181	-8.05	-3.964
677.309	183.918	63.086	43.412	-8.018	-3.978
677.212	184.539	63.086	43.495	-8.006	-3.983
677.124	185.144	63.086	43.567	-7.996	-3.988
677.047	185.681	63.086	43.637	-7.987	-3.992
676.972	186.246	63.086	43.708	-7.978	-3.997
676.771	187.549	63.086	43.873	-7.954	-4.007
676.608	188.645	63.082	44.01	-7.935	-4.015
676.522	189.306	63.082	44.093	-7.924	-4.02
676.244	191.161	63.082	44.325	-7.891	-4.035
676.079	192.309	63.082	44.468	-7.872	-4.044
675.916	193.414	63.082	44.606	-7.853	-4.052
675.761	194.532	63.077	44.745	-7.834	-4.061
675.675	195.094	63.077	44.815	-7.824	-4.065
675.52	196.229	63.077	44.954	-7.805	-4.074
675.368	197.359	63.077	45.093	-7.787	-4.083
675.214	198.477	63.077	45.231	-7.769	-4.092
675.135	199.047	63.077	45.301	-7.759	-4.096
674.948	200.386	63.077	45.463	-7.737	-4.107
674.789	201.651	63.072	45.617	-7.717	-4.116

674.619	202.822	63.072	45.759	-7.697	-4.126
674.535	203.414	63.072	45.83	-7.687	-4.13
674.341	204.92	63.072	46.01	-7.664	-4.142
674.256	205.494	63.072	46.08	-7.654	-4.146
674.095	206.664	63.072	46.219	-7.634	-4.155
673.906	208.191	63.067	46.4	-7.611	-4.167
673.834	208.788	63.067	46.471	-7.602	-4.172
673.751	209.408	63.067	46.545	-7.592	-4.177
673.593	210.596	63.067	46.685	-7.573	-4.186
673.494	211.417	63.067	46.781	-7.561	-4.192
673.407	212.155	63.067	46.867	-7.55	-4.198
673.326	212.747	63.067	46.938	-7.541	-4.203
673.161	213.982	63.067	47.081	-7.521	-4.212
673.096	214.579	63.063	47.151	-7.513	-4.217
672.947	215.784	63.063	47.291	-7.494	-4.226
672.755	217.194	63.063	47.454	-7.471	-4.237
672.587	218.561	63.063	47.611	-7.451	-4.248
672.508	219.162	63.063	47.681	-7.441	-4.253
672.438	219.79	63.063	47.753	-7.432	-4.258
672.252	221.388	63.063	47.933	-7.409	-4.27
672.173	222.006	63.058	48.003	-7.4	-4.275
672.101	222.635	63.058	48.074	-7.391	-4.28
672.031	223.256	63.058	48.145	-7.382	-4.285
671.878	224.537	63.058	48.289	-7.363	-4.295
671.621	226.728	63.058	48.535	-7.331	-4.312
671.544	227.369	63.058	48.606	-7.322	-4.317
671.47	228.044	63.058	48.681	-7.313	-4.322
671.327	229.318	63.055	48.823	-7.295	-4.332
671.249	229.93	63.055	48.894	-7.285	-4.337
671.133	230.825	63.055	48.991	-7.271	-4.344
671.049	231.636	63.055	49.08	-7.26	-4.35
670.976	232.288	63.055	49.152	-7.251	-4.355
670.894	232.951	63.055	49.225	-7.241	-4.36
670.82	233.582	63.055	49.295	-7.232	-4.365
670.692	234.869	63.055	49.435	-7.216	-4.375
670.521	236.38	63.048	49.6	-7.194	-4.387
670.439	237.149	63.048	49.684	-7.184	-4.393
670.358	237.857	63.048	49.759	-7.174	-4.398
670.278	238.504	63.048	49.83	-7.164	-4.403
670.179	239.538	63.048	49.941	-7.151	-4.411
670.105	240.205	63.048	50.013	-7.142	-4.417
669.948	241.524	63.048	50.154	-7.122	-4.427
669.87	242.233	63.048	50.229	-7.113	-4.432
669.811	242.89	63.048	50.3	-7.105	-4.437
669.636	244.5	63.045	50.471	-7.083	-4.45
669.544	245.225	63.045	50.549	-7.072	-4.456
669.476	245.889	63.045	50.619	-7.063	-4.461
669.401	246.592	63.045	50.694	-7.054	-4.466
669.325	247.262	63.045	50.765	-7.044	-4.471
669.253	247.936	63.045	50.837	-7.035	-4.477

669.188	248.618	63.045	50.908	-7.026	-4.482
669.105	249.535	63.045	51.005	-7.016	-4.489
669.03	250.209	63.045	51.078	-7.006	-4.494
668.956	250.878	63.039	51.149	-6.997	-4.5
668.882	251.552	63.039	51.22	-6.988	-4.505
668.796	252.353	63.039	51.305	-6.977	-4.511
668.718	253.01	63.039	51.376	-6.967	-4.516
668.557	254.566	63.039	51.54	-6.946	-4.528
668.482	255.241	63.039	51.611	-6.937	-4.534
668.412	255.929	63.039	51.683	-6.928	-4.539
668.334	256.599	63.039	51.754	-6.919	-4.544
668.262	257.323	63.039	51.829	-6.909	-4.55
668.193	258.007	63.039	51.902	-6.9	-4.555
668.122	258.688	63.034	51.973	-6.891	-4.56
668.039	259.362	63.034	52.044	-6.881	-4.566
667.957	260.051	63.034	52.116	-6.871	-4.571
667.892	260.733	63.034	52.188	-6.863	-4.576
667.824	261.431	63.034	52.261	-6.854	-4.582
667.746	262.12	63.034	52.333	-6.844	-4.587
667.672	262.806	63.034	52.404	-6.835	-4.592
667.608	263.478	63.034	52.475	-6.826	-4.598
667.457	265.052	63.034	52.64	-6.807	-4.61
667.374	265.873	63.034	52.725	-6.796	-4.616
667.307	266.552	63.028	52.796	-6.787	-4.622
667.222	267.288	63.028	52.872	-6.777	-4.627
667.139	267.982	63.028	52.944	-6.767	-4.633
667.08	268.693	63.028	53.018	-6.759	-4.638
666.974	269.768	63.028	53.129	-6.745	-4.647
666.898	270.463	63.028	53.201	-6.735	-4.652
666.821	271.177	63.028	53.273	-6.726	-4.658
666.748	271.867	63.028	53.344	-6.717	-4.663
666.685	272.579	63.028	53.416	-6.708	-4.668
666.62	273.284	63.028	53.489	-6.7	-4.674
666.447	274.939	63.023	53.656	-6.678	-4.687
666.376	275.73	63.023	53.741	-6.668	-4.693
666.3	276.533	63.023	53.817	-6.658	-4.699
666.225	277.235	63.023	53.888	-6.649	-4.705
666.156	277.968	63.023	53.96	-6.64	-4.71
666.106	278.681	63.023	54.033	-6.633	-4.716
666.029	279.68	63.023	54.132	-6.622	-4.724
665.94	280.553	63.023	54.219	-6.611	-4.731
665.877	281.277	63.023	54.291	-6.602	-4.736
665.815	282.016	63.016	54.363	-6.594	-4.742
665.743	282.764	63.016	54.438	-6.585	-4.748
665.666	283.514	63.016	54.511	-6.575	-4.754
665.612	284.241	63.016	54.582	-6.567	-4.759
665.459	285.924	63.016	54.747	-6.547	-4.772
665.382	286.794	63.016	54.832	-6.537	-4.779
665.315	287.576	63.016	54.908	-6.528	-4.785
665.253	288.311	63.016	54.979	-6.52	-4.791

665.19	289.082	63.016	55.054	-6.511	-4.797
665.132	289.818	63.016	55.125	-6.503	-4.803
665.029	290.846	63.01	55.225	-6.49	-4.811
664.972	291.578	63.01	55.296	-6.482	-4.816
664.902	292.491	63.01	55.384	-6.472	-4.823
664.832	293.245	63.01	55.456	-6.463	-4.829
664.765	293.982	63.01	55.528	-6.454	-4.835
664.635	295.697	63.01	55.693	-6.436	-4.848
664.575	296.448	63.01	55.765	-6.428	-4.854
664.509	297.254	63.01	55.842	-6.419	-4.861
664.453	298.004	63.01	55.914	-6.411	-4.866
664.388	298.769	63	55.987	-6.403	-4.872
664.314	299.526	63	56.059	-6.393	-4.878
664.259	300.312	63	56.134	-6.385	-4.884
664.202	301.077	63	56.205	-6.377	-4.89
664.138	301.826	63	56.276	-6.369	-4.896
664.075	302.605	63	56.35	-6.36	-4.902
664.004	303.37	63	56.421	-6.351	-4.908
663.949	304.135	63	56.494	-6.343	-4.914
663.889	304.924	63	56.567	-6.335	-4.92
663.753	306.678	63	56.731	-6.316	-4.934
663.672	307.617	62.991	56.817	-6.305	-4.941
663.604	308.423	62.991	56.893	-6.296	-4.947
663.537	309.217	62.991	56.965	-6.287	-4.954
663.477	310.006	62.991	57.038	-6.279	-4.96
663.425	310.805	62.991	57.11	-6.271	-4.966
663.382	311.592	62.991	57.186	-6.265	-4.972
663.293	312.729	62.991	57.287	-6.252	-4.981
663.216	313.672	62.991	57.373	-6.242	-4.988
663.154	314.46	62.991	57.446	-6.233	-4.994
663.095	315.273	62.991	57.519	-6.225	-5.001
663.029	316.051	62.98	57.591	-6.216	-5.007
662.904	317.945	62.98	57.76	-6.198	-5.022
662.84	318.754	62.98	57.833	-6.189	-5.028
662.784	319.584	62.98	57.907	-6.181	-5.034
662.718	320.406	62.98	57.979	-6.172	-5.041
662.666	321.204	62.98	58.051	-6.165	-5.047
662.617	322.032	62.98	58.123	-6.157	-5.053
662.56	322.869	62.98	58.197	-6.149	-5.06
662.495	323.708	62.98	58.269	-6.14	-5.066
662.432	324.603	62.966	58.347	-6.131	-5.073
662.384	325.441	62.966	58.419	-6.124	-5.08
662.333	326.267	62.966	58.491	-6.116	-5.086
662.275	327.136	62.966	58.564	-6.108	-5.093
662.216	327.995	62.966	58.638	-6.1	-5.1
662.168	328.848	62.966	58.71	-6.092	-5.106
662.059	330.822	62.966	58.875	-6.076	-5.122
661.996	331.851	62.966	58.961	-6.066	-5.13
661.948	332.742	62.966	59.037	-6.059	-5.137
661.896	333.634	62.966	59.11	-6.051	-5.144

661.838	334.521	62.949	59.182	-6.042	-5.151
661.797	335.409	62.949	59.256	-6.036	-5.157
661.745	336.298	62.949	59.328	-6.028	-5.164
661.67	337.558	62.949	59.431	-6.017	-5.174
661.606	338.634	62.949	59.517	-6.007	-5.183
661.556	339.561	62.949	59.592	-5.999	-5.19
661.508	340.481	62.949	59.665	-5.992	-5.197
661.413	342.569	62.949	59.831	-5.976	-5.213
661.359	343.561	62.949	59.908	-5.967	-5.221
661.312	344.487	62.928	59.981	-5.96	-5.228
661.271	345.435	62.928	60.055	-5.953	-5.235
661.214	346.381	62.928	60.128	-5.944	-5.243
661.17	347.326	62.928	60.2	-5.937	-5.25
661.131	348.282	62.928	60.274	-5.93	-5.258
661.097	349.227	62.928	60.347	-5.924	-5.265
661.052	350.201	62.928	60.421	-5.917	-5.273
661.005	351.186	62.928	60.495	-5.909	-5.28
660.964	352.162	62.928	60.569	-5.902	-5.288
660.917	353.122	62.928	60.642	-5.894	-5.295
660.865	354.115	62.928	60.716	-5.886	-5.303
660.783	356.343	62.9	60.881	-5.871	-5.32
660.722	357.547	62.9	60.97	-5.861	-5.33
660.683	358.527	62.9	61.043	-5.855	-5.337
660.647	359.581	62.9	61.12	-5.848	-5.346
660.614	360.581	62.9	61.192	-5.841	-5.353
660.578	361.647	62.9	61.269	-5.834	-5.362
660.543	362.645	62.9	61.342	-5.828	-5.369
660.487	364.053	62.9	61.444	-5.818	-5.38
660.44	365.299	62.9	61.532	-5.81	-5.39
660.405	366.328	62.869	61.606	-5.803	-5.398
660.365	367.374	62.869	61.68	-5.796	-5.406
660.331	368.402	62.869	61.754	-5.789	-5.414
660.252	370.994	62.869	61.936	-5.773	-5.434
660.214	372.071	62.869	62.01	-5.766	-5.443
660.177	373.176	62.869	62.087	-5.759	-5.451
660.155	374.229	62.869	62.16	-5.754	-5.46
660.107	375.291	62.869	62.234	-5.746	-5.468
660.061	376.387	62.869	62.309	-5.738	-5.476
660.042	377.458	62.834	62.382	-5.732	-5.485
660.012	378.528	62.834	62.455	-5.726	-5.493
659.961	380.241	62.834	62.571	-5.716	-5.506
659.927	381.329	62.834	62.645	-5.709	-5.515
659.906	382.446	62.834	62.72	-5.703	-5.524
659.878	383.537	62.834	62.793	-5.697	-5.532
659.818	386.1	62.834	62.963	-5.683	-5.552
659.788	387.21	62.834	63.037	-5.677	-5.561
659.761	388.326	62.834	63.11	-5.671	-5.569
659.734	389.468	62.795	63.186	-5.665	-5.578
659.703	390.584	62.795	63.259	-5.658	-5.587
659.679	391.707	62.795	63.333	-5.652	-5.596

659.663	392.856	62.795	63.407	-5.647	-5.605
659.647	393.985	62.795	63.481	-5.642	-5.613
659.619	395.118	62.795	63.554	-5.636	-5.622
659.591	396.307	62.795	63.631	-5.629	-5.631
659.574	397.453	62.795	63.704	-5.624	-5.64
659.549	398.592	62.795	63.778	-5.618	-5.649
659.524	399.734	62.795	63.851	-5.612	-5.658
659.5	402.392	64.27	64.019	-5.601	-5.679
659.468	403.772	64.27	64.107	-5.594	-5.689
659.442	405.021	64.27	64.185	-5.587	-5.699
659.439	406.192	64.27	64.259	-5.583	-5.708
659.43	407.435	64.27	64.336	-5.578	-5.718
659.407	409.257	64.27	64.45	-5.57	-5.732
659.39	410.477	64.27	64.526	-5.565	-5.742
659.366	411.663	64.27	64.599	-5.559	-5.751
659.348	412.917	64.27	64.676	-5.553	-5.761
659.327	414.182	64.226	64.754	-5.547	-5.771
659.314	415.392	64.226	64.828	-5.542	-5.78
659.278	418.14	64.226	64.996	-5.53	-5.801
659.264	419.604	64.226	65.085	-5.524	-5.813
659.251	420.892	64.226	65.163	-5.518	-5.823
659.247	422.111	64.226	65.237	-5.514	-5.832
659.238	423.35	64.226	65.311	-5.509	-5.842
659.219	424.607	64.226	65.386	-5.503	-5.852
659.215	425.841	64.226	65.461	-5.499	-5.861
659.208	427.557	64.182	65.563	-5.493	-5.875
659.193	429.029	64.182	65.651	-5.487	-5.886
659.18	430.278	64.182	65.725	-5.482	-5.896
659.177	431.574	64.182	65.802	-5.477	-5.906
659.177	432.822	64.182	65.876	-5.473	-5.916
659.171	434.08	64.182	65.95	-5.469	-5.925
659.125	437.229	64.182	66.134	-5.454	-5.95
659.122	438.505	64.182	66.209	-5.45	-5.96
659.115	439.858	64.182	66.288	-5.445	-5.97
659.093	441.137	64.137	66.362	-5.439	-5.98
659.088	442.445	64.137	66.438	-5.434	-5.99
659.082	444.42	64.137	66.553	-5.427	-6.006
659.078	445.743	64.137	66.629	-5.423	-6.016
659.068	447.042	64.137	66.704	-5.418	-6.026
659.063	448.352	64.137	66.78	-5.413	-6.036
659.057	449.741	64.137	66.859	-5.408	-6.047
659.045	451.038	64.137	66.934	-5.403	-6.057
659.056	454.001	64.137	67.103	-5.395	-6.08
659.039	456.015	64.095	67.217	-5.387	-6.096
659.019	457.813	64.095	67.319	-5.379	-6.11
659.023	459.438	64.095	67.412	-5.374	-6.123
659.029	461.132	64.095	67.508	-5.37	-6.136
659.009	462.936	64.095	67.609	-5.362	-6.15
658.983	464.25	64.095	67.684	-5.355	-6.16
658.983	465.619	64.095	67.76	-5.351	-6.171

658.99	466.944	64.095	67.834	-5.347	-6.181
658.975	469.166	64.054	67.959	-5.339	-6.198
658.962	472.167	64.054	68.127	-5.328	-6.222
658.962	473.842	64.054	68.219	-5.323	-6.235
658.959	476.039	64.054	68.341	-5.315	-6.252
658.961	477.808	64.054	68.439	-5.31	-6.266
658.952	479.176	64.054	68.515	-5.305	-6.276
658.969	480.824	64.054	68.606	-5.301	-6.289
658.967	482.631	64.054	68.705	-5.295	-6.303
658.956	484.392	64.015	68.803	-5.289	-6.317
658.959	486.178	64.015	68.901	-5.283	-6.331
658.963	487.903	64.015	68.996	-5.278	-6.344
658.962	489.693	64.015	69.094	-5.273	-6.358
658.937	492.29	64.015	69.235	-5.262	-6.378
658.949	493.669	64.015	69.31	-5.259	-6.389
658.959	495.757	64.015	69.424	-5.253	-6.405
658.939	498.312	63.979	69.563	-5.243	-6.425
658.951	500.128	63.979	69.661	-5.238	-6.439
658.946	501.003	63.979	69.756	-5.235	-6.446
658.937	500.897	63.979	69.828	-5.235	-6.445
658.932	500.774	63.979	69.923	-5.235	-6.444
658.909	500.639	63.979	70.021	-5.233	-6.443
658.893	500.515	63.979	70.181	-5.232	-6.442
658.888	500.463	63.979	70.259	-5.231	-6.442
658.794	500.386	63.94	70.36	-5.222	-6.441
658.787	500.304	63.94	70.474	-5.222	-6.441
658.784	500.222	63.94	70.565	-5.222	-6.44
658.75	499.932	63.94	70.663	-5.22	-6.438
658.638	499.089	63.94	70.762	-5.211	-6.431
658.548	498.104	63.94	70.861	-5.206	-6.424
658.481	497.036	63.94	70.961	-5.203	-6.415
658.375	494.667	62.401	71.154	-5.2	-6.397
658.309	492.984	62.401	71.272	-5.199	-6.384
658.201	490.773	62.401	71.401	-5.195	-6.367
658.097	488.762	62.401	71.514	-5.192	-6.351
658.021	486.951	62.401	71.615	-5.19	-6.337
657.955	485.021	62.401	71.719	-5.19	-6.322
657.892	483.111	62.401	71.82	-5.189	-6.307
657.826	481.17	62.401	71.918	-5.189	-6.292
657.752	479.164	62.366	72.017	-5.188	-6.276
657.681	477.029	62.366	72.118	-5.188	-6.26
657.59	473.941	62.366	72.265	-5.189	-6.236
657.518	471.247	62.366	72.382	-5.191	-6.215
657.453	469.495	62.366	72.46	-5.19	-6.201
657.383	466.854	62.366	72.574	-5.192	-6.18
657.312	464.392	62.366	72.677	-5.192	-6.161
657.243	461.984	62.329	72.777	-5.193	-6.143
657.175	459.567	62.329	72.878	-5.194	-6.124
657.104	457.154	62.329	72.979	-5.195	-6.105
657.007	452.557	62.329	73.173	-5.2	-6.069

656.925	449.819	62.329	73.289	-5.201	-6.048
656.877	447.417	62.329	73.391	-5.204	-6.029
656.847	445.561	62.329	73.47	-5.207	-6.015
656.772	442.816	62.295	73.588	-5.208	-5.993
656.708	440.503	62.295	73.688	-5.209	-5.975
656.659	438.179	62.295	73.789	-5.212	-5.957
656.611	435.849	62.295	73.891	-5.215	-5.939
656.555	433.544	62.295	73.991	-5.216	-5.921
656.498	431.255	62.295	74.092	-5.218	-5.903
656.422	427.995	62.295	74.236	-5.221	-5.878
656.352	424.751	62.26	74.38	-5.225	-5.853
656.283	422.135	62.26	74.496	-5.226	-5.832
656.228	419.82	62.26	74.6	-5.228	-5.814
656.198	417.545	62.26	74.702	-5.232	-5.797
656.159	415.304	62.26	74.804	-5.236	-5.779
656.111	413.068	62.26	74.906	-5.238	-5.762
656.085	410.838	62.26	75.008	-5.243	-5.744
656.044	408.677	62.26	75.107	-5.246	-5.728
655.993	406.463	62.227	75.21	-5.248	-5.71
655.941	403.368	62.227	75.352	-5.252	-5.686
655.901	400.822	62.227	75.471	-5.257	-5.667
655.859	398.654	62.227	75.574	-5.259	-5.65
655.833	396.696	62.227	75.666	-5.263	-5.634
655.796	394.565	62.227	75.767	-5.266	-5.618
655.753	392.364	62.227	75.872	-5.269	-5.601
655.724	390.239	62.194	75.974	-5.273	-5.584
655.688	388.097	62.194	76.076	-5.276	-5.568
655.651	384.123	62.194	76.27	-5.285	-5.537
655.638	382.71	62.194	76.34	-5.288	-5.526
655.614	381.074	62.194	76.42	-5.291	-5.513
655.599	378.602	62.194	76.542	-5.298	-5.494
655.584	376.592	62.194	76.643	-5.302	-5.478
655.552	374.565	62.161	76.745	-5.306	-5.462
655.529	372.545	62.161	76.847	-5.31	-5.446
655.527	370.559	62.161	76.94	-5.316	-5.431
655.52	368.842	62.161	77.038	-5.321	-5.418
655.503	366.924	62.161	77.138	-5.325	-5.403
655.496	363.94	62.161	77.296	-5.334	-5.379
655.483	361.942	62.161	77.402	-5.339	-5.364
655.486	359.765	62.161	77.512	-5.346	-5.347
655.476	358.094	62.125	77.611	-5.35	-5.334
655.475	356.179	62.125	77.709	-5.356	-5.319
655.484	354.796	62.125	77.786	-5.362	-5.308
655.497	353.427	62.125	77.864	-5.367	-5.298
655.496	352.072	62.125	77.94	-5.371	-5.287
655.499	350.752	62.125	78.017	-5.376	-5.277
655.523	349.408	62.125	78.095	-5.382	-5.266
655.536	348.104	62.125	78.172	-5.388	-5.256
655.552	345.267	62.086	78.342	-5.398	-5.234
655.581	343.751	62.086	78.435	-5.406	-5.222

655.607	342.499	62.086	78.513	-5.412	-5.213
655.63	340.82	62.086	78.619	-5.42	-5.2
655.647	339.588	62.086	78.697	-5.426	-5.19
655.696	338.177	62.086	78.789	-5.435	-5.179
655.727	336.948	62.086	78.871	-5.442	-5.169
655.75	335.808	62.086	78.947	-5.448	-5.161
655.782	334.651	62.086	79.026	-5.454	-5.152
655.816	333.547	62.086	79.102	-5.461	-5.143
655.846	332.443	62.037	79.18	-5.468	-5.134
655.883	331.353	62.037	79.258	-5.475	-5.126
655.956	329.557	62.037	79.39	-5.487	-5.112
656.005	328.234	62.037	79.49	-5.496	-5.102
656.054	327.204	62.037	79.569	-5.504	-5.094
656.117	326.19	62.037	79.647	-5.514	-5.086
656.192	324.715	62.037	79.766	-5.526	-5.074
656.238	323.701	62.037	79.849	-5.533	-5.066
656.286	322.798	62.037	79.925	-5.541	-5.059
656.349	321.883	61.971	80.003	-5.55	-5.052
656.417	320.995	61.971	80.081	-5.559	-5.045
656.482	320.123	61.971	80.159	-5.568	-5.038
656.633	318.264	61.971	80.33	-5.589	-5.024
656.722	317.267	61.971	80.425	-5.6	-5.016
656.79	316.463	61.971	80.504	-5.61	-5.01
656.888	315.401	61.971	80.609	-5.622	-5.002
656.973	314.492	61.971	80.702	-5.634	-4.995
657.046	313.746	61.871	80.781	-5.643	-4.989
657.123	313.005	61.871	80.86	-5.653	-4.983
657.209	312.247	61.871	80.942	-5.664	-4.977
657.292	311.562	61.871	81.02	-5.674	-4.972
657.376	310.868	61.871	81.097	-5.684	-4.966
657.47	310.195	61.871	81.177	-5.695	-4.961
657.563	309.52	61.871	81.256	-5.707	-4.956
657.699	308.426	61.871	81.388	-5.723	-4.947
657.802	307.664	61.871	81.483	-5.736	-4.942
657.938	306.824	61.727	81.588	-5.751	-4.935
658.046	306.11	61.727	81.681	-5.764	-4.929
658.149	305.46	61.727	81.766	-5.776	-4.924
658.246	304.865	61.727	81.845	-5.788	-4.92
658.357	304.279	61.727	81.924	-5.8	-4.915
658.453	303.704	61.727	82.002	-5.811	-4.911
658.551	303.136	61.727	82.08	-5.823	-4.906
658.644	302.561	61.727	82.16	-5.833	-4.902
658.737	301.988	61.727	82.238	-5.844	-4.897
658.958	300.75	61.545	82.412	-5.87	-4.888
659.069	300.092	61.545	82.505	-5.882	-4.883
659.164	299.501	61.545	82.587	-5.894	-4.878
659.269	298.936	61.545	82.67	-5.905	-4.874
659.388	298.342	61.545	82.75	-5.919	-4.869
659.491	297.756	61.545	82.831	-5.931	-4.864
659.585	297.198	61.545	82.909	-5.942	-4.86

659.672	296.618	61.545	82.987	-5.952	-4.856
659.773	296.017	61.545	83.071	-5.964	-4.851
659.878	295.42	61.348	83.149	-5.976	-4.846
659.971	294.83	61.348	83.229	-5.987	-4.842
660.182	293.474	61.348	83.407	-6.011	-4.831
660.304	292.75	61.348	83.499	-6.026	-4.825
660.396	292.132	61.348	83.58	-6.036	-4.821
660.496	291.448	61.348	83.664	-6.048	-4.815
660.623	290.484	61.348	83.783	-6.064	-4.808
660.722	289.811	61.348	83.865	-6.075	-4.803
660.808	289.123	61.179	83.947	-6.086	-4.797
660.887	288.457	61.179	84.027	-6.096	-4.792
660.964	287.784	61.179	84.106	-6.105	-4.787
661.06	287.108	61.179	84.186	-6.117	-4.782
661.159	286.422	61.179	84.265	-6.128	-4.776
661.304	285.269	61.179	84.397	-6.146	-4.767
661.396	284.45	61.179	84.491	-6.158	-4.761
661.472	283.711	61.179	84.574	-6.167	-4.755
661.588	282.765	61.179	84.679	-6.182	-4.748
661.683	281.913	61.072	84.774	-6.193	-4.741
661.763	281.182	61.072	84.853	-6.204	-4.735
661.841	280.463	61.072	84.932	-6.213	-4.73
661.939	279.678	61.072	85.017	-6.225	-4.724
662.022	278.947	61.072	85.095	-6.236	-4.718
662.105	278.208	61.072	85.176	-6.246	-4.712
662.181	277.467	61.072	85.254	-6.256	-4.707
662.251	276.732	61.072	85.334	-6.265	-4.701
662.427	275.116	61.072	85.506	-6.287	-4.688
662.517	274.216	61.023	85.602	-6.299	-4.681
662.59	273.451	61.023	85.684	-6.308	-4.675
662.675	272.712	61.023	85.765	-6.319	-4.67
662.767	271.949	61.023	85.846	-6.33	-4.664
662.853	271.213	61.023	85.926	-6.341	-4.658
662.933	270.461	61.023	86.007	-6.351	-4.652
663.013	269.693	61.023	86.091	-6.361	-4.646
663.089	268.969	61.023	86.171	-6.371	-4.64
663.176	268.225	61.023	86.251	-6.382	-4.635
663.259	267.511	61.023	86.331	-6.392	-4.629
663.35	266.794	61.009	86.411	-6.403	-4.623
663.496	265.668	61.009	86.544	-6.421	-4.615
663.618	264.896	61.009	86.639	-6.435	-4.609
663.709	264.215	61.009	86.722	-6.446	-4.603
663.796	263.525	61.009	86.803	-6.456	-4.598
663.922	262.47	61.009	86.924	-6.472	-4.59
664.005	261.722	61.009	87.005	-6.482	-4.584
664.089	260.95	61.009	87.088	-6.493	-4.578
664.17	260.188	61.013	87.17	-6.503	-4.572
664.24	259.432	61.013	87.249	-6.512	-4.566
664.322	258.677	61.013	87.33	-6.523	-4.56
664.407	257.926	61.013	87.409	-6.533	-4.554

664.536	256.667	61.013	87.543	-6.55	-4.545
664.636	255.778	61.013	87.638	-6.562	-4.538
664.72	254.993	61.013	87.722	-6.573	-4.532
664.833	253.994	61.013	87.83	-6.587	-4.524
664.927	253.109	61.013	87.925	-6.599	-4.517
665.006	252.364	61.024	88.006	-6.609	-4.511
665.08	251.627	61.024	88.086	-6.618	-4.505
665.177	250.888	61.024	88.168	-6.63	-4.5
665.274	250.121	61.024	88.252	-6.642	-4.494
665.365	249.397	61.024	88.334	-6.653	-4.488
665.439	248.675	61.024	88.415	-6.663	-4.482
665.522	247.951	61.024	88.496	-6.673	-4.477
665.684	246.646	61.024	88.645	-6.693	-4.467
665.774	245.927	61.024	88.729	-6.704	-4.461
665.907	244.875	61.041	88.851	-6.72	-4.453
666	244.181	61.041	88.932	-6.731	-4.447
666.092	243.471	61.041	89.017	-6.742	-4.442
666.183	242.768	61.041	89.099	-6.753	-4.436
666.269	242.092	61.041	89.18	-6.764	-4.431
666.355	241.408	61.041	89.262	-6.774	-4.426
666.458	240.746	61.041	89.343	-6.787	-4.421
666.553	240.078	61.041	89.425	-6.798	-4.416
666.723	238.925	61.058	89.569	-6.818	-4.407
666.815	238.22	61.058	89.657	-6.829	-4.401
666.919	237.567	61.058	89.739	-6.841	-4.396
667.051	236.723	61.058	89.846	-6.857	-4.389
667.148	236.086	61.058	89.929	-6.868	-4.384
667.252	235.349	61.058	90.024	-6.88	-4.379
667.359	234.7	61.058	90.109	-6.893	-4.374
667.457	234.062	61.058	90.193	-6.904	-4.369
667.555	233.451	61.058	90.275	-6.916	-4.364
667.654	232.84	61.073	90.356	-6.927	-4.359
667.757	232.238	61.073	90.438	-6.939	-4.355
667.946	231.179	61.073	90.585	-6.961	-4.346
668.054	230.578	61.073	90.669	-6.973	-4.342
668.148	229.996	61.073	90.751	-6.984	-4.337
668.286	229.236	61.073	90.861	-7	-4.331
668.399	228.672	61.073	90.942	-7.013	-4.327
668.534	228.026	61.073	91.037	-7.028	-4.322
668.637	227.471	61.073	91.119	-7.04	-4.317
668.746	226.895	61.088	91.206	-7.052	-4.313
668.86	226.353	61.088	91.289	-7.065	-4.309
668.967	225.807	61.088	91.371	-7.077	-4.304
669.079	225.266	61.088	91.454	-7.089	-4.3
669.178	224.734	61.088	91.537	-7.101	-4.296
669.37	223.886	61.088	91.672	-7.122	-4.29
669.504	223.284	61.088	91.768	-7.137	-4.285
669.624	222.74	61.088	91.855	-7.15	-4.281
669.733	222.227	61.088	91.937	-7.162	-4.277
669.843	221.729	61.101	92.019	-7.175	-4.273

669.936	221.306	61.101	92.089	-7.185	-4.269
670.075	220.706	61.101	92.189	-7.2	-4.265
670.198	220.173	61.101	92.272	-7.214	-4.261
670.308	219.631	61.101	92.359	-7.226	-4.256
670.42	219.127	61.101	92.441	-7.239	-4.252
670.539	218.627	61.101	92.524	-7.252	-4.249
670.771	217.518	61.101	92.699	-7.278	-4.24
670.895	216.902	61.113	92.795	-7.292	-4.235
671.009	216.342	61.113	92.881	-7.305	-4.231
671.118	215.793	61.113	92.964	-7.317	-4.227
671.273	214.972	61.113	93.088	-7.335	-4.22
671.381	214.415	61.113	93.171	-7.347	-4.216
671.488	213.849	61.113	93.254	-7.359	-4.211
671.601	213.253	61.113	93.341	-7.372	-4.207
671.715	212.682	61.113	93.426	-7.385	-4.202
671.813	212.108	61.113	93.508	-7.396	-4.198
671.993	211.142	61.118	93.643	-7.416	-4.19
672.112	210.446	61.118	93.739	-7.43	-4.185
672.216	209.821	61.118	93.826	-7.442	-4.18
672.312	209.21	61.118	93.909	-7.454	-4.175
672.421	208.599	61.118	93.992	-7.466	-4.171
672.526	207.971	61.118	94.075	-7.478	-4.166
672.626	207.36	61.118	94.157	-7.49	-4.161
672.718	206.709	61.118	94.244	-7.501	-4.156
672.814	206.105	61.118	94.326	-7.512	-4.151
672.916	205.482	61.112	94.409	-7.524	-4.146
673.015	204.843	61.112	94.493	-7.535	-4.141
673.116	204.201	61.112	94.577	-7.547	-4.136
673.319	202.84	61.112	94.755	-7.571	-4.126
673.441	202.064	61.112	94.856	-7.585	-4.12
673.552	201.411	61.112	94.941	-7.598	-4.115
673.679	200.564	61.112	95.052	-7.613	-4.108
673.797	199.8	61.099	95.15	-7.627	-4.102
673.905	199.164	61.099	95.233	-7.64	-4.097
674.005	198.484	61.099	95.321	-7.651	-4.092
674.101	197.821	61.099	95.405	-7.663	-4.087
674.197	197.17	61.099	95.489	-7.674	-4.082
674.307	196.524	61.099	95.573	-7.687	-4.077
674.409	195.883	61.099	95.656	-7.699	-4.072
674.561	194.851	61.099	95.792	-7.717	-4.064
674.672	194.104	61.099	95.888	-7.73	-4.058
674.776	193.427	61.082	95.976	-7.742	-4.052
674.875	192.776	61.082	96.06	-7.754	-4.047
674.972	192.127	61.082	96.144	-7.765	-4.042
675.047	191.591	61.082	96.214	-7.774	-4.038
675.165	190.824	61.082	96.311	-7.788	-4.032
675.261	190.168	61.082	96.396	-7.799	-4.027
675.38	189.501	61.082	96.483	-7.813	-4.022
675.482	188.836	61.082	96.57	-7.825	-4.017
675.578	188.199	61.082	96.653	-7.836	-4.012

675.684	187.561	61.082	96.736	-7.849	-4.007
675.852	186.503	61.062	96.872	-7.868	-3.999
675.96	185.74	61.062	96.971	-7.881	-3.993
676.061	185.069	61.062	97.058	-7.893	-3.987
676.177	184.419	61.062	97.143	-7.906	-3.982
676.32	183.577	61.062	97.253	-7.923	-3.976
676.424	182.818	61.062	97.353	-7.935	-3.97
676.52	182.168	61.062	97.436	-7.947	-3.965
676.63	181.487	61.062	97.526	-7.959	-3.96
676.739	180.804	61.044	97.614	-7.972	-3.954
676.835	180.166	61.044	97.697	-7.983	-3.949
676.989	179.132	61.044	97.833	-8.002	-3.941
677.091	178.482	61.044	97.919	-8.013	-3.936
677.213	177.736	61.044	98.016	-8.028	-3.93
677.32	177.06	61.044	98.104	-8.04	-3.925
677.414	176.428	61.044	98.188	-8.051	-3.92
677.503	175.89	61.044	98.258	-8.062	-3.916
677.636	175.138	61.025	98.357	-8.077	-3.91
677.737	174.478	61.025	98.443	-8.089	-3.905
677.838	173.822	61.025	98.531	-8.101	-3.9
677.941	173.179	61.025	98.616	-8.113	-3.895
678.056	172.531	61.025	98.702	-8.126	-3.89
678.266	171.182	61.025	98.879	-8.15	-3.879
678.366	170.534	61.025	98.964	-8.162	-3.874
678.476	169.894	61.025	99.049	-8.175	-3.869
678.59	169.14	61.008	99.148	-8.188	-3.863
678.689	168.499	61.008	99.234	-8.2	-3.858
678.789	167.831	61.008	99.322	-8.212	-3.853
678.895	167.169	61.008	99.408	-8.224	-3.848
678.995	166.534	61.008	99.493	-8.236	-3.843
679.102	165.919	61.008	99.576	-8.248	-3.838
679.209	165.278	61.008	99.662	-8.26	-3.833
679.454	163.846	61.008	99.853	-8.288	-3.822
679.571	163.182	61.008	99.941	-8.302	-3.817
679.672	162.547	60.991	100.027	-8.314	-3.812
679.816	161.596	60.991	100.154	-8.331	-3.805
679.929	160.978	60.991	100.238	-8.344	-3.8
680.042	160.336	60.991	100.324	-8.357	-3.795
680.156	159.68	60.991	100.414	-8.37	-3.79
680.26	159.048	60.991	100.499	-8.382	-3.785
680.374	158.42	60.991	100.585	-8.395	-3.78
680.477	157.787	60.991	100.671	-8.407	-3.775
680.58	157.149	60.975	100.758	-8.419	-3.77
680.741	156.132	60.975	100.895	-8.438	-3.762
680.868	155.372	60.975	100.997	-8.452	-3.756
680.975	154.746	60.975	101.083	-8.465	-3.751
681.12	153.912	60.975	101.195	-8.481	-3.745
681.219	153.293	60.975	101.28	-8.493	-3.74
681.347	152.558	60.975	101.38	-8.507	-3.734
681.466	151.933	60.975	101.465	-8.521	-3.73

681.572	151.301	60.957	101.551	-8.533	-3.725
681.68	150.654	60.957	101.641	-8.546	-3.72
681.784	150.023	60.957	101.727	-8.558	-3.715
681.898	149.408	60.957	101.812	-8.571	-3.71
682.067	148.412	60.957	101.948	-8.59	-3.702
682.193	147.64	60.957	102.053	-8.605	-3.696
682.418	146.345	60.957	102.235	-8.631	-3.686
682.525	145.709	60.957	102.321	-8.643	-3.681
682.624	145.08	62.412	102.408	-8.655	-3.676
682.731	144.463	62.412	102.493	-8.667	-3.671
682.822	143.959	62.412	102.564	-8.677	-3.667
682.944	143.246	62.412	102.663	-8.691	-3.662
683.052	142.635	62.412	102.748	-8.704	-3.657
683.155	141.979	62.412	102.839	-8.716	-3.652
683.419	140.59	62.412	103.032	-8.746	-3.641
683.519	139.95	62.412	103.121	-8.758	-3.636
683.621	139.346	62.395	103.206	-8.769	-3.632
683.728	138.727	62.395	103.292	-8.782	-3.627
683.848	138.109	62.395	103.379	-8.795	-3.622
683.949	137.483	62.395	103.468	-8.807	-3.617
684.056	136.868	62.395	103.555	-8.819	-3.612
684.167	136.262	62.395	103.641	-8.832	-3.608
684.286	135.624	62.395	103.731	-8.846	-3.603
684.393	135.017	62.395	103.816	-8.858	-3.598
684.605	133.762	62.38	103.997	-8.882	-3.588
684.736	133.051	62.38	104.097	-8.897	-3.583
684.842	132.423	62.38	104.188	-8.909	-3.578
684.948	131.813	62.38	104.274	-8.922	-3.573
685.038	131.308	62.38	104.345	-8.932	-3.569
685.146	130.702	62.38	104.431	-8.944	-3.564
685.28	130	62.38	104.532	-8.959	-3.559
685.399	129.395	62.38	104.619	-8.973	-3.554
685.514	128.76	62.38	104.711	-8.986	-3.549
685.616	128.156	62.364	104.796	-8.998	-3.544
685.726	127.551	62.364	104.883	-9.01	-3.54
685.895	126.601	62.364	105.019	-9.03	-3.532
686.023	125.882	62.364	105.123	-9.044	-3.527
686.146	125.278	62.364	105.211	-9.058	-3.522
686.3	124.505	62.364	105.325	-9.075	-3.516
686.424	123.819	62.364	105.425	-9.09	-3.511
686.522	123.232	62.364	105.512	-9.101	-3.506
686.632	122.621	62.349	105.6	-9.114	-3.501
686.755	122.001	62.349	105.69	-9.127	-3.497
686.86	121.4	62.349	105.778	-9.139	-3.492
686.974	120.801	62.349	105.865	-9.152	-3.487
687.081	120.217	62.349	105.952	-9.165	-3.483
687.272	119.29	62.349	106.089	-9.186	-3.475
687.403	118.61	62.349	106.19	-9.201	-3.47
687.521	117.977	62.349	106.281	-9.214	-3.465
687.626	117.393	62.335	106.367	-9.226	-3.461

687.728	116.915	62.335	106.44	-9.238	-3.457
687.863	116.245	62.335	106.54	-9.253	-3.452
687.97	115.652	62.335	106.628	-9.265	-3.447
688.084	115.02	62.335	106.721	-9.278	-3.442
688.215	114.423	62.335	106.81	-9.293	-3.438
688.33	113.846	62.335	106.896	-9.306	-3.433
688.556	112.658	62.335	107.076	-9.331	-3.424
688.695	111.967	62.319	107.18	-9.347	-3.418
688.82	111.369	62.319	107.27	-9.361	-3.414
688.927	110.783	62.319	107.359	-9.373	-3.409
689.018	110.314	62.319	107.43	-9.383	-3.406
689.146	109.626	62.319	107.532	-9.398	-3.4
689.268	109.027	62.319	107.62	-9.412	-3.396
689.398	108.431	62.319	107.709	-9.426	-3.391
689.511	107.829	62.319	107.799	-9.439	-3.386
689.627	107.249	62.319	107.887	-9.452	-3.382
689.743	106.673	62.305	107.974	-9.465	-3.377
689.949	105.683	62.305	108.125	-9.488	-3.37
690.057	105.075	62.305	108.217	-9.5	-3.365
690.165	104.493	62.305	108.305	-9.513	-3.36
690.34	103.747	62.305	108.42	-9.532	-3.355
690.48	103.08	62.305	108.523	-9.548	-3.349
690.596	102.479	62.305	108.615	-9.561	-3.345
690.705	101.92	62.305	108.702	-9.573	-3.34
690.831	101.347	62.29	108.791	-9.587	-3.336
690.937	100.781	62.29	108.878	-9.599	-3.331
691.05	100.211	62.29	108.967	-9.612	-3.327
691.232	99.333	62.29	109.104	-9.632	-3.32
691.381	98.665	62.29	109.206	-9.649	-3.315
691.502	98.081	62.29	109.296	-9.662	-3.31
691.622	97.5	62.29	109.387	-9.676	-3.306
691.713	97.042	62.29	109.458	-9.686	-3.302
691.86	96.373	62.274	109.561	-9.702	-3.297
691.986	95.811	62.274	109.648	-9.716	-3.293
692.111	95.199	62.274	109.744	-9.73	-3.288
692.217	94.636	62.274	109.832	-9.742	-3.284
692.34	94.074	62.274	109.921	-9.756	-3.279
692.602	92.925	62.274	110.101	-9.785	-3.27
692.73	92.283	62.274	110.206	-9.8	-3.265
692.856	91.687	62.274	110.297	-9.814	-3.261
692.956	91.227	62.261	110.369	-9.825	-3.257
693.087	90.577	62.261	110.472	-9.839	-3.252
693.203	90.022	62.261	110.561	-9.852	-3.248
693.33	89.441	62.261	110.653	-9.867	-3.243
693.465	88.887	62.261	110.742	-9.881	-3.239
693.593	88.328	62.261	110.831	-9.896	-3.235
693.714	87.771	62.261	110.92	-9.909	-3.23
693.966	86.63	62.261	111.102	-9.937	-3.221
694.098	86.075	62.246	111.192	-9.951	-3.217
694.244	85.45	62.246	111.293	-9.968	-3.212

694.36	84.887	62.246	111.386	-9.981	-3.208
694.482	84.34	62.246	111.475	-9.994	-3.203
694.666	83.531	62.246	111.605	-10.014	-3.197
694.792	82.979	62.246	111.694	-10.028	-3.193
694.906	82.409	62.246	111.786	-10.041	-3.188
695.035	81.853	62.246	111.876	-10.055	-3.184
695.155	81.299	62.231	111.966	-10.069	-3.18
695.387	80.19	62.231	112.148	-10.095	-3.171
695.545	79.537	62.231	112.254	-10.112	-3.166
695.679	79.005	62.231	112.342	-10.127	-3.162
695.803	78.468	62.231	112.431	-10.14	-3.158
695.978	77.666	62.231	112.562	-10.16	-3.152
696.109	77.103	62.231	112.655	-10.174	-3.147
696.243	76.549	62.218	112.747	-10.189	-3.143
696.375	75.978	62.218	112.843	-10.204	-3.138
696.488	75.431	62.218	112.932	-10.216	-3.134
696.6	74.885	62.218	113.022	-10.229	-3.13
696.855	73.794	62.218	113.203	-10.257	-3.121
696.997	73.169	62.218	113.308	-10.273	-3.117
697.118	72.628	62.218	113.399	-10.286	-3.112
697.244	72.099	62.218	113.489	-10.3	-3.108
697.409	71.326	62.203	113.619	-10.318	-3.102
697.525	70.8	62.203	113.71	-10.331	-3.098
697.657	70.275	62.203	113.799	-10.346	-3.094
697.804	69.726	62.203	113.893	-10.362	-3.09
697.927	69.206	62.203	113.982	-10.375	-3.086
698.173	68.136	62.203	114.165	-10.402	-3.077
698.32	67.526	62.203	114.269	-10.419	-3.073
698.454	66.969	62.19	114.363	-10.433	-3.068
698.577	66.437	62.19	114.453	-10.447	-3.064
698.674	66.008	62.19	114.527	-10.458	-3.061
698.81	65.405	62.19	114.63	-10.473	-3.056
698.935	64.881	62.19	114.722	-10.486	-3.052
699.069	64.356	62.19	114.815	-10.501	-3.048
699.184	63.832	62.19	114.906	-10.514	-3.044
699.319	63.32	62.19	114.996	-10.528	-3.04
699.443	62.799	62.19	115.087	-10.542	-3.036
699.686	61.761	62.176	115.269	-10.569	-3.028
699.848	61.173	62.176	115.373	-10.586	-3.023
699.989	60.643	62.176	115.466	-10.602	-3.019
700.117	60.126	62.176	115.558	-10.616	-3.015
700.278	59.47	62.176	115.676	-10.633	-3.01
700.43	58.849	62.176	115.785	-10.65	-3.005
700.568	58.331	62.176	115.876	-10.665	-3.001
700.707	57.805	62.161	115.97	-10.68	-2.997
700.827	57.293	62.161	116.06	-10.693	-2.993
701.09	56.186	62.161	116.258	-10.722	-2.984
701.233	55.674	62.161	116.351	-10.738	-2.98
701.402	55.031	62.161	116.469	-10.756	-2.975
701.559	54.463	62.161	116.573	-10.773	-2.971

701.689	53.952	62.161	116.665	-10.787	-2.967
701.822	53.44	62.147	116.76	-10.802	-2.963
701.944	52.949	62.147	116.849	-10.815	-2.959
702.088	52.453	62.147	116.941	-10.831	-2.955
702.234	51.966	62.147	117.031	-10.846	-2.952
702.363	51.485	62.147	117.121	-10.86	-2.948
702.62	50.503	62.147	117.303	-10.888	-2.94
702.785	49.937	62.147	117.409	-10.906	-2.936
702.925	49.442	62.147	117.502	-10.921	-2.932
703.026	49.064	62.133	117.575	-10.932	-2.929
703.17	48.486	62.133	117.681	-10.948	-2.924
703.302	48.006	62.133	117.771	-10.962	-2.921
703.442	47.501	62.133	117.867	-10.977	-2.917
703.577	47.029	62.133	117.958	-10.992	-2.913
703.699	46.553	62.133	118.047	-11.005	-2.909
703.968	45.573	62.133	118.232	-11.034	-2.902
704.119	45.027	62.119	118.337	-11.051	-2.898
704.256	44.54	62.119	118.432	-11.065	-2.894
704.406	44.07	62.119	118.523	-11.081	-2.89
704.522	43.688	62.119	118.597	-11.094	-2.887
704.675	43.145	62.119	118.702	-11.11	-2.883
704.81	42.655	62.119	118.797	-11.125	-2.879
704.944	42.188	62.119	118.888	-11.139	-2.875
705.088	41.696	62.119	118.983	-11.155	-2.872
705.227	41.235	62.119	119.075	-11.17	-2.868
705.356	40.762	62.107	119.167	-11.184	-2.864
705.555	40.07	62.107	119.304	-11.205	-2.859
705.71	39.53	62.107	119.411	-11.222	-2.855
705.854	39.052	62.107	119.505	-11.237	-2.851
705.982	38.585	62.107	119.597	-11.251	-2.847
706.119	38.122	62.107	119.688	-11.266	-2.844
706.294	37.529	62.107	119.807	-11.285	-2.839
706.455	37.014	62.107	119.913	-11.302	-2.835
706.598	36.57	62.094	120.006	-11.317	-2.832
706.758	36.12	62.094	120.101	-11.334	-2.828
706.9	35.674	62.094	120.192	-11.349	-2.825
707.169	34.778	62.094	120.378	-11.378	-2.818
707.342	34.275	62.094	120.483	-11.396	-2.814
707.499	33.817	62.094	120.578	-11.413	-2.81
707.64	33.378	62.094	120.669	-11.428	-2.807
707.776	32.947	62.084	120.762	-11.442	-2.804
707.917	32.518	62.084	120.853	-11.458	-2.8
708.123	31.9	62.084	120.986	-11.479	-2.795
708.264	31.474	62.084	121.077	-11.494	-2.792
708.407	31.03	62.084	121.173	-11.51	-2.789
708.632	30.372	62.084	121.311	-11.533	-2.783
708.802	29.879	62.084	121.418	-11.551	-2.78
708.946	29.435	62.084	121.514	-11.567	-2.776
709.102	29.02	62.073	121.606	-11.583	-2.773
709.26	28.598	62.073	121.699	-11.6	-2.77

709.38	28.261	62.073	121.772	-11.612	-2.767
709.55	27.769	62.073	121.881	-11.63	-2.763
709.691	27.346	62.073	121.974	-11.645	-2.76
709.857	26.907	62.073	122.071	-11.663	-2.757
710.004	26.5	62.073	122.162	-11.678	-2.753
710.141	26.089	62.073	122.254	-11.693	-2.75
710.383	25.421	62.062	122.407	-11.718	-2.745
710.53	24.993	62.062	122.503	-11.734	-2.742
710.738	24.408	62.062	122.636	-11.756	-2.737
710.882	24.008	62.062	122.729	-11.771	-2.734
711.033	23.608	62.062	122.821	-11.787	-2.731
711.184	23.195	62.062	122.918	-11.803	-2.728
711.323	22.801	62.062	123.01	-11.818	-2.725
711.472	22.397	62.062	123.103	-11.833	-2.721
711.629	22.01	62.052	123.196	-11.85	-2.718
711.78	21.613	62.052	123.293	-11.866	-2.715
712.065	20.831	62.052	123.477	-11.896	-2.709
712.243	20.398	62.052	123.584	-11.914	-2.706
712.4	20.018	62.052	123.681	-11.931	-2.703
712.551	19.66	62.052	123.774	-11.946	-2.7
712.66	19.373	62.052	123.848	-11.958	-2.698
712.836	18.956	60.587	123.955	-11.976	-2.695
712.985	18.602	60.587	124.047	-11.992	-2.692
713.134	18.252	60.587	124.14	-12.007	-2.689
713.279	17.882	60.587	124.237	-12.022	-2.686
713.43	17.535	60.587	124.33	-12.038	-2.684
713.655	17.02	60.587	124.47	-12.062	-2.68
713.838	16.62	60.587	124.579	-12.08	-2.676
713.993	16.287	60.587	124.673	-12.096	-2.674
714.149	15.95	60.583	124.767	-12.113	-2.671
714.28	15.682	60.583	124.844	-12.126	-2.669
714.454	15.304	60.583	124.951	-12.144	-2.666
714.595	14.986	60.583	125.044	-12.159	-2.664
714.759	14.654	60.583	125.14	-12.176	-2.661
714.926	14.344	60.583	125.235	-12.193	-2.659
715.083	14.025	60.583	125.328	-12.209	-2.656
715.231	13.726	60.583	125.421	-12.224	-2.654
715.471	13.287	60.581	125.561	-12.249	-2.651
715.664	12.976	60.581	125.671	-12.269	-2.648
715.824	12.705	60.581	125.766	-12.285	-2.646
715.983	12.445	60.581	125.86	-12.301	-2.644
716.191	12.095	60.581	125.981	-12.322	-2.641
716.394	11.801	60.581	126.089	-12.343	-2.639
716.552	11.519	60.581	126.187	-12.359	-2.637
716.725	11.267	60.581	126.282	-12.377	-2.635
716.898	11.025	60.586	126.375	-12.394	-2.633
717.049	10.787	60.586	126.469	-12.41	-2.631
717.293	10.451	60.586	126.609	-12.434	-2.628
717.505	10.183	60.586	126.718	-12.456	-2.626
717.724	9.902	60.586	126.84	-12.478	-2.624

717.883	9.68	60.586	126.935	-12.494	-2.622
718.085	9.42	60.586	127.045	-12.514	-2.62
718.257	9.223	62.055	127.137	-12.531	-2.619
718.433	9.006	62.055	127.235	-12.549	-2.617
718.596	8.811	62.055	127.33	-12.566	-2.616
718.961	8.407	62.055	127.532	-12.602	-2.613
719.147	8.228	62.055	127.627	-12.621	-2.611
719.315	8.06	62.055	127.721	-12.638	-2.61
719.494	7.899	62.055	127.816	-12.655	-2.609
719.667	7.742	62.055	127.905	-12.673	-2.607
719.839	7.583	62.072	128	-12.69	-2.606
720.014	7.433	62.072	128.095	-12.707	-2.605
720.199	7.283	62.072	128.194	-12.726	-2.604
720.383	7.137	62.072	128.287	-12.744	-2.603
720.567	6.99	62.072	128.383	-12.762	-2.602
720.922	6.732	62.072	128.57	-12.797	-2.599
721.136	6.59	62.072	128.681	-12.818	-2.598
721.319	6.461	62.096	128.776	-12.837	-2.597
721.573	6.287	62.096	128.91	-12.862	-2.596
721.746	6.169	62.096	129.004	-12.879	-2.595
721.926	6.054	62.096	129.1	-12.897	-2.594
722.131	5.943	62.096	129.199	-12.917	-2.593
722.307	5.836	62.096	129.294	-12.934	-2.593
722.497	5.732	62.096	129.387	-12.953	-2.592
722.691	5.63	62.096	129.483	-12.972	-2.591
722.945	5.488	62.124	129.622	-12.997	-2.59
723.12	5.396	62.124	129.715	-13.014	-2.589
723.316	5.305	62.124	129.809	-13.034	-2.588
723.541	5.197	62.124	129.918	-13.056	-2.588
723.729	5.107	62.124	130.016	-13.074	-2.587
723.914	5.027	62.124	130.111	-13.092	-2.586
724.105	4.95	62.124	130.206	-13.111	-2.586
724.295	4.872	62.124	130.301	-13.13	-2.585
724.482	4.796	62.155	130.397	-13.148	-2.584
724.662	4.723	62.155	130.492	-13.166	-2.584
725.036	4.585	62.155	130.68	-13.202	-2.583
725.319	4.488	62.155	130.82	-13.23	-2.582
725.536	4.417	62.155	130.929	-13.251	-2.581
725.733	4.358	62.155	131.026	-13.271	-2.581
725.921	4.299	62.183	131.124	-13.289	-2.581
726.124	4.244	62.183	131.225	-13.309	-2.58
726.322	4.191	62.183	131.322	-13.328	-2.58
726.531	4.136	62.183	131.419	-13.349	-2.579
726.729	4.091	62.183	131.514	-13.368	-2.579
727.036	4.014	62.183	131.672	-13.398	-2.578
727.231	3.966	62.183	131.768	-13.417	-2.578
727.418	3.915	62.183	131.863	-13.435	-2.578
727.567	3.877	62.211	131.937	-13.45	-2.577
727.784	3.826	62.211	132.046	-13.471	-2.577
727.979	3.781	62.211	132.142	-13.49	-2.577

728.174	3.739	62.211	132.241	-13.509	-2.576
728.371	3.697	62.211	132.337	-13.528	-2.576
728.56	3.658	62.211	132.433	-13.546	-2.576
728.77	3.618	62.211	132.531	-13.567	-2.575
729.141	3.541	62.232	132.722	-13.603	-2.575
729.369	3.5	62.232	132.837	-13.625	-2.574
729.581	3.462	62.232	132.934	-13.646	-2.574
729.74	3.432	62.232	133.011	-13.661	-2.574
729.966	3.398	62.232	133.121	-13.683	-2.574
730.16	3.367	62.232	133.221	-13.702	-2.573
730.368	3.335	62.232	133.321	-13.723	-2.573
730.569	3.301	62.232	133.421	-13.742	-2.573
730.757	3.271	62.249	133.517	-13.76	-2.573
730.947	3.239	62.249	133.613	-13.779	-2.572
731.317	3.178	62.249	133.803	-13.815	-2.572
731.551	3.134	62.249	133.915	-13.838	-2.571
731.748	3.092	62.249	134.014	-13.857	-2.571
731.945	3.043	62.249	134.109	-13.876	-2.571
732.207	2.999	62.249	134.246	-13.902	-2.57
732.395	2.974	62.262	134.342	-13.92	-2.57
732.594	2.952	62.262	134.439	-13.939	-2.57
732.817	2.924	62.262	134.544	-13.961	-2.57
733.102	2.895	62.262	134.686	-13.989	-2.57
733.324	2.875	62.262	134.798	-14.01	-2.569
733.518	2.856	62.262	134.894	-14.029	-2.569
733.696	2.833	62.262	134.983	-14.046	-2.569
733.883	2.811	62.262	135.079	-14.065	-2.569
734.086	2.788	62.271	135.179	-14.084	-2.569
734.285	2.767	62.271	135.274	-14.104	-2.569
734.469	2.753	62.271	135.37	-14.122	-2.569
734.658	2.735	62.271	135.465	-14.14	-2.568
734.86	2.719	62.271	135.56	-14.16	-2.568
735.064	2.705	62.271	135.655	-14.179	-2.568
735.341	2.686	62.271	135.796	-14.206	-2.568
735.556	2.67	62.275	135.908	-14.227	-2.568
735.759	2.654	62.275	136.003	-14.247	-2.568
735.967	2.64	62.275	136.099	-14.267	-2.568
736.124	2.63	62.275	136.173	-14.282	-2.568
736.332	2.616	62.275	136.281	-14.302	-2.567
736.532	2.606	62.275	136.377	-14.322	-2.567
736.728	2.595	62.275	136.475	-14.341	-2.567
736.93	2.58	62.275	136.572	-14.36	-2.567
737.308	2.552	62.275	136.761	-14.397	-2.567
737.55	2.537	62.275	136.879	-14.421	-2.567
737.735	2.526	62.275	136.972	-14.439	-2.567
738.017	2.502	62.275	137.109	-14.466	-2.567
738.221	2.489	62.275	137.204	-14.486	-2.566
738.418	2.479	62.275	137.299	-14.505	-2.566
738.609	2.471	62.275	137.399	-14.523	-2.566
738.801	2.456	62.275	137.495	-14.542	-2.566

739.008	2.443	62.273	137.59	-14.562	-2.566
739.397	2.423	62.273	137.779	-14.6	-2.566
739.623	2.408	62.273	137.893	-14.622	-2.566
739.819	2.399	62.273	137.987	-14.641	-2.566
740.07	2.38	62.273	138.111	-14.665	-2.566
740.287	2.365	62.273	138.221	-14.686	-2.566
740.492	2.353	62.269	138.318	-14.706	-2.565
740.689	2.341	62.269	138.414	-14.725	-2.565

3. Density cell data

3.1. Sample A (API 11.4)

Upstream Pressure (bar)	Downstream Pressure (bar)	Displacement (mm)	Change in displacement (mm)	Temperature (^{0}f)
20	0	7.35	0	79.7
40	10	7.29	0.06	80
50	20	7.22	0.13	80.1
60	30	7.14	0.21	80.3
70	40	7.06	0.29	80.4
80	50	6.99	0.36	80.5
90	60	6.92	0.43	80.7
105	70	6.85	0.5	80.9
120	80	6.78	0.57	81.3
135	90	6.69	0.66	81.4
150	100	6.62	0.73	81.5
175	120	6.51	0.84	81.7
210	140	6.37	0.98	81.8
230	160	6.27	1.08	81.9
260	180	6.13	1.22	82
285	200	6.02	1.33	82.3
310	220	5.9	1.45	82.3
340	240	5.76	1.59	82.4
365	260	5.64	1.71	82.5
390	280	5.54	1.81	82.6
415	300	5.43	1.92	82.7
Upstream Pressure (bar)	Downstream Pressure (bar)	Displacement (mm)	Change in displacement (mm)	Temperature (^{0}f)
25	0	8.2	0	99.4
40	10	8.11	0.09	99.5
55	20	8.01	0.19	99.7
65	30	7.9	0.3	99.8

70	40	7.83	0.37	99.9
85	50	7.73	0.47	100
100	60	7.66	0.54	100.1
110	70	7.6	0.6	100.3
125	80	7.51	0.69	100.4
140	90	7.43	0.77	100.5
150	100	7.37	0.83	100.6
175	120	7.24	0.96	100.6
200	140	7.11	1.09	100.7
230	160	6.98	1.22	100.9
260	180	6.81	1.39	101.3
290	200	6.68	1.52	101.4
310	220	6.56	1.64	101.6
340	240	6.43	1.77	101.7
365	260	6.31	1.89	101.9
390	280	6.19	2.01	102
410	300	6.09	2.11	102.3
Upstream Pressure (bar)	Downstream Pressure (bar)	Displacement (mm)	Change in displacement (mm)	Temperature (^{0}f)
50	0	12.96	0	200
55	10	12.92	0.04	200.4
65	20	12.84	0.12	200.5
75	30	12.75	0.21	200.7
85	40	12.68	0.28	200.8
95	50	12.59	0.37	200.9
110	60	12.51	0.45	201
125	70	12.41	0.55	201.3
140	80	12.33	0.63	201.6
150	90	12.26	0.7	201.7
160	100	12.16	0.8	201.9
190	120	11.99	0.97	202.3
215	140	11.82	1.14	202.5
245	160	11.61	1.35	202.9
270	180	11.46	1.5	203
300	200	11.28	1.68	203.2
320	220	11.13	1.83	203.4
340	240	10.94	2.02	203.5
380	260	10.78	2.18	203.6
400	280	10.62	2.34	203.7
420	300	10.39	2.57	203.7

PUBLICATIONS

Rheological Characterisation of Heavy Oil and Impact on its Production Enhancement

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Keywords: Heavy Oil, non-Newtonian fluid, Rheological characterisation, Shear and Bulk Viscosity, Productivity model for horizontal well, Critical drawdown

Abstract

Criticality of rheology for heavy oil recovery is the main purpose of this paper supported by different results. The Bingham Plastic, Power Law and Herschel Bulkley rheological models have been adopted for the purpose of this paper. Rheological characterisation was carried out for different temperature. Rheological behaviour of non-Newtonian heavy oil for different shear rates is analysed in this paper. Effective shear and bulk viscosities for different flow rates are compared for all rheological models. Using the horizontal well productivity model, the drawdown values for all rheological models are determined. Similarly for the sand management purpose the critical rates of Newtonian and these three non-Newtonian fluids are plotted to determine the critical drawdown values for each type of fluid. Impact of drainage profile on the effective viscosities is also compared for different drainage profiles. Shear rate models are proposed in this paper for Bingham Plastic, Power Law and Herschel Bulkley rheological models. The new Micro-PVT equipment is also introduced for determining the PVT properties and rheological behaviour of heavy oil.

Nomenclature:

$A - Drainage\ Area$	$[m^2]$
$a - Reservoir\ length\ X - direction$	$[feet]$
$B - Formation\ Volume\ Factor$	$[\frac{RB}{STB}]$
$b - Reservoir\ width\ Y - direction$	$[feet]$
$C_H - Geometric\ Factor$	$[Dimensionless]$
$D_{pore} - Pore\ Diameter$	$[inches]$
$D_{50} - Grain\ Size$	$[inches]$
$h - Reservoir\ thickness$	$[feet]$
$L - Well\ Length$	$[feet]$
$n - Flow\ Index$	$[Dimensionless]$
$P - Pressure$	$[psi]$
$p_r - Reservoir\ Pressure$	$[psi]$
$p_{wf} - Bottomhole\ Pressure$	$[psi]$
$q - Production\ rate$	$[STBPD]$
$r_w - Wellbore\ radius$	$[feet]$
$S_R - pseudo\ skin\ factor$	$[Dimensionless]$
$T - Temperature$	$[^0F]$
$\mu - Viscosity$	$[cp]$
$V - Volume$	$[cm^3]$

$V_{pore} - Pore \quad Velocity$ $[ft.\sec^{-1}]$

$\phi - Porosity$ $[Dimensionless]$

Introduction

In the recovery process of fossil fuels either oil or gas the ultimate recovery depends upon the mobility of fluid, productivity index of reservoir and recovery techniques. In the process of production optimisation the mentioned issues are very critical. The mobility of oil is the ratio of effective permeability to effective viscosity of oil at reservoir conditions. For instance the effective viscosity depends on the type of fluid if the fluid is Newtonian then the effective viscosity is constant at any shear rate but if the fluid is non-Newtonian then the effective viscosity will change with the shear rate and the shear rate in reservoir depends on the applied drawdown and the flow through pores. Hence the mobility also depends on the type of fluid. In this paper Newtonian and three popular Power-Law, Herschel Bulkley and Bingham Plastic non-Newtonian fluids are considered. Previous studies [1,2] on heavy oil have established that they are predominantly non-Newtonian at reservoir conditions but the actual behaviour has not been well defined. So now to get the critical drawdown of heavy oil reservoirs and to estimate the critical flow rate from reservoir it is important to understand the rheological behaviour of the heavy oil which may change with reservoir pressure and temperature. The high API conventional oil has been classified as a Newtonian fluid as the effective viscosity of conventional oil is independent of shear rate. While deciding critical drawdown or flow rate for conventional Newtonian oil the effective viscosity has only single value at particular pressure and temperature but this is not same for non-Newtonian fluids. For non-Newtonian fluids the effective viscosity will change with shear rate and shear rate depends on applied drawdown or flow through pores hence the mobility of non-Newtonian fluids varies with the operating parameters like the choke opening at wellhead. To recover maximum from reservoir with non-Newtonian fluids heavy oil reservoirs one has to understand the rheological behaviour of the fluid at that operating condition. Also the rheological behaviour of heavy oil may change with pressure and temperature. It is therefore possible that at higher temperature it may behave like a Newtonian fluid which can give some extra margin to production rate. These are some of the key areas in the heavy oil recovery which are discussed in detail in the later section of this paper.

The non-Newtonian fluid can be characterised into different categories like Power-Law, Herschel Bulkley and Bingham Plastic. All these fluids have different flow index, consistency index and inertia force. These parameters play an important role in the behaviour of the fluid. Hence to have a total tracking of the behaviour of heavy oil from reservoir to separator one must have to monitor all these rheological parameters at different pressures and temperatures. In this paper most of the critical issues related to reservoir recovery especially for heavy oil reservoirs and rheological behaviour of oil are considered.

Rheological characterisation of Heavy Oil

Preliminary studies [1,2] on different heavy oils have established that they are predominantly non-Newtonian at standard and higher temperatures and pressures.[Figure 1]

There are a number of models available which characterise the flow behaviour of the pure heavy oil and heavy oil-steam mixture from specific gravity and temperature of oil [2]. The Bingham Plastic, Power law and Herschel Bulkley rheological models have been adopted for the purpose of this paper.

The following models are used to define the flow mechanics of these non-Newtonian fluids through a porous reservoir [3].

Power Law $\tau = K\gamma^n$ [1]

Herschel Bulkley $\tau = \tau_0 + K\gamma^n$ [2]

Bingham Plastic $\tau = \tau_y + \mu_p\gamma$ [3]

For the purpose of this paper, the Herschel Bulkley model is treated as a modified Power Law fluid defined as :

$$\tau' = K'\gamma^{n'}$$ [4]

Where

$$\tau' = \tau - \tau_o'$$ [5]

Rheological characterisation of different heavy oil samples using the 12-Speed Fann 35 viscometer have confirmed the non-Newtonian behaviour of all the heavy oils both at standard and higher temperatures as shown in [Figure 1]. Preliminary studies to date have confirmed that the heavy oils are largely Bingham Plastic in terms of flow behaviour at standard and higher temperature. The rheological behaviour of the heavy oil at reservoir pressure and temperature is of extreme importance and form a major part of future work presented in the later part of this paper.

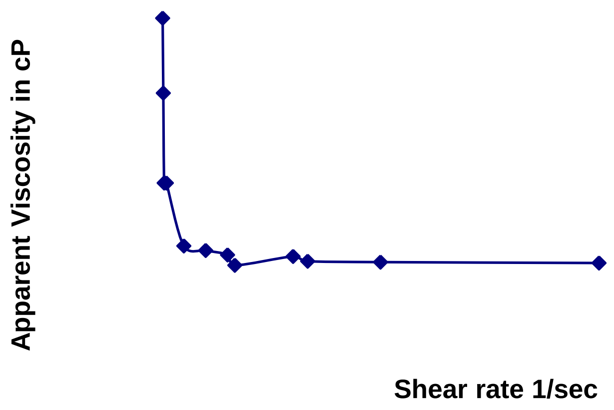

Figure 1: Apparent viscosity verses shear rate

Shear rate models for non-Newtonian fluids

It is already discussed in the introduction that the rheology of fluid plays an important role in determining the critical drawdown to maximise oil production. Different drawdown or different flow rates in reservoir exert different shear rates on fluid. Newtonian fluid's behaviour will not change with shear rates but the non-Newtonian fluids get affected by different shear rates. The following shear rate models by Oyeneyin [1] are used to calculate the shear rate for different flow rates.

For Power-law and Herschel Bulkley, the shear rate (γ) can be expressed as:

$$\gamma = \frac{A \times V_{pore}}{D_{pore}}[B + \frac{1}{n}]$$ [4]

The shear rate (γ) for Bingham plastic fluid can be obtained as:

$$\gamma = \frac{A \times V_{pore}}{D_{pore}} + B \times \frac{\tau_y}{\mu_p} \qquad [5]$$

Where A and B are constants.

For given flow rate and using Blake-Kozeny-Carman equation, pore velocity for Newtonian and non-Newtonian fluids can be calculated and using equations 4 and 5, the shear rates are computed for non-Newtonian heavy oil. The respective effective viscosities at respective shear rate for Power Law(PL), Herschel Buckley(HB) and Bingham Plastic(BP) fluids is given by equation 6,7 and 8 respectively.

For PL Fluid $\mu_{effective} = K\gamma^{n-1}$ [6]

For HB Fluid $\mu_{effective} = K^{'}\gamma^{n^{'}-1}$ [7]

For BP Fluid $\mu_{effective} = \frac{\tau_y}{\gamma} + \mu_p$ [8]

n = Flow Index for the Power Law Fluid

K = Consistency Index for the Power Law Fluid

n′ = Flow Index for the HB Fluid

K′ = Consistency index for the HB Fluid

τ_y = Bingham Yield Point for the BP Fluid

μ_p = Plastic Viscosity of the BP Fluid

The pore size was computed using the Blake-Kozeny-Carman equation [1]. For known range of production rates the shear rates for each model are compared and from the values of shear rate the effective viscosity values for each model are calculated which are plotted in Figure 2.

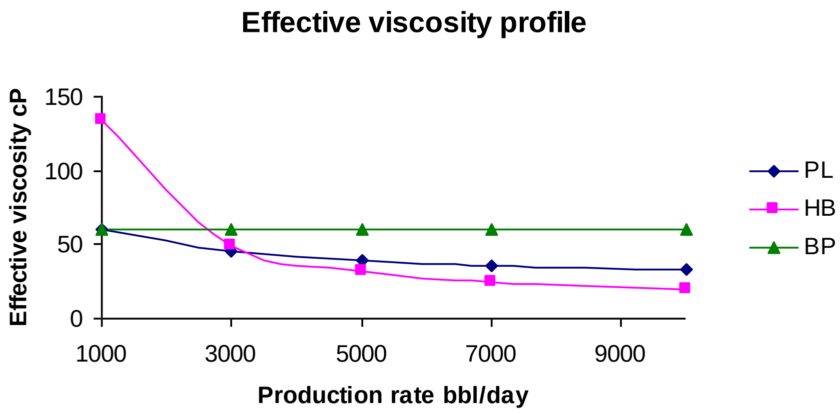

Figure 2: Effective viscosity for different production rate

Role of rheology in determining the critical drawdown

In horizontal wells the critical drawdown has more importance because of pressure losses in the horizontal section of well which results in unwanted inflow profiles. Using the respective effective viscosity for non-Newtonian fluids and adopting Babu and Odeh's [4] productivity model for horizontal well, the drawdown for given flow rates are compared to see the role of rheology. Babu and Odeh derived an expression for productivity from horizontal well. In their method, all boundaries were no-flow boundaries. They considered a uniform flux solution given by equation 9.

$$q = \frac{7.08 \times 10^{-3} \times b\sqrt{(k_x k_y)} \times (p_r - p_{wf})}{B\mu[Ln\frac{A^{0.5}}{r_w} + LnC_H - 0.75 + S_R]} \qquad [9]$$

The viscosity parameter in this equation is the effective shear viscosity of the reservoir fluid at the prevailing average reservoir pressures and temperatures. It is therefore a function of the flow behaviour of the reservoir fluid. For heavy oil, it has been established that the behaviour of the oil is non-Newtonian.

Another critical parameter is the effective permeability to the reservoir fluid. For Babu and Odeh's model this is presented in terms of directional effective permeabilities k_x and k_y. Irrespective of how this is presented, there is the need to appreciate the absolute permeability and corresponding relative permeability of the reservoir to the heavy oil and heavy oil-steam interaction. The transient nature of the relative permeability in thermal recovery like SAGD environment demands the development of appropriate model to forecast this all important parameter.

Additionally, the geometric factor is important to reservoir fluid inflow and injector well placement. The definition of this parameter together with the skin factor as presented by Babu and Odeh [4] will also be reviewed in the course of this project.

The corresponding productivity index from the above model can be presented as:

$$J = \frac{7.08 \times 10^{-3} \times b\sqrt{(k_x k_y)}}{B\mu[Ln\frac{A^{0.5}}{r_w} + LnC_H - 0.75 + S_R]} \quad [10]$$

Using Babu and Odeh's model [4] for the productivity of horizontal well, the drawdowns for different production rates as part the parametric studies to identify the dominating parameters. The adopted well length was 1000 ft and the wellbore diameter was 8 inches.

Figure 3 shows the impact of production rate from the same reservoir and therefore correspondingly changing shear viscosity on the drawdown. Hence wrong understanding of rheology will give the incorrect values for critical rate and critical wellbore pressure.

Hence to optimise the life of reservoir, to maximise the production rate the detailed and exact knowledge about rheology of fluid is very crucial.

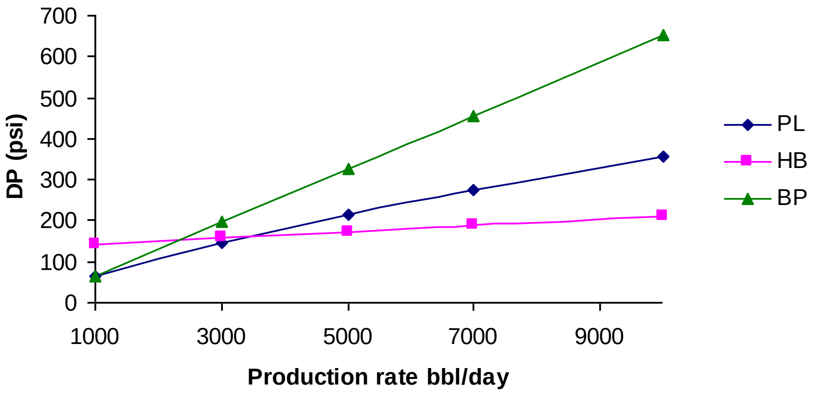

Figure 3: Drawdown profile

Effect of Rheology on shear and bulk viscosities

Figure 4 shows the result of the effect of production rate as a function shear rate on the shear and bulk viscosities of heavy oil samples tested.

It was observed that for Bingham plastic fluid the effective shear viscosity was same as the plastic viscosity indicating that the viscoelasticity and corresponding compressibility of the heavy oil data presented would be low [5]. The viscosity i.e. the shear viscosity appears to dominate. The heavy oil tested showed relatively low yield strength with the plastic viscosity dominating the shear viscosity of the heavy oil. Further tests are planned for ultra low API gravity heavy oils and a universal model would then be developed to forecast the viscosities at different production rates, reservoir conditions and effects of prevailing pressures and temperatures.

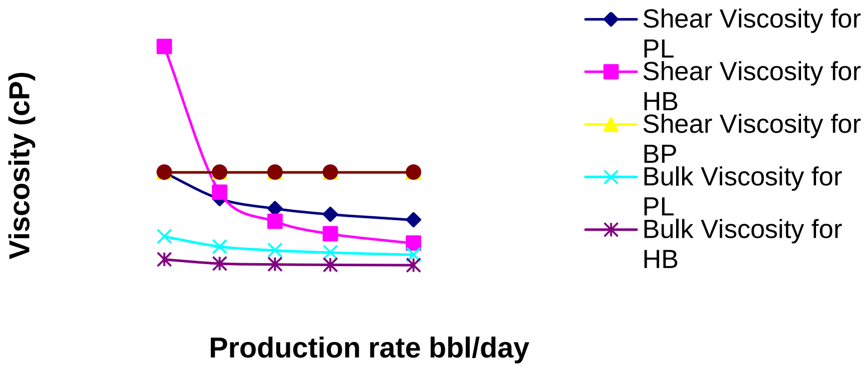

Figure 4: Bulk and shear viscosity profile

Impact of shear viscosity on Inflow Performance of Well (IPR)

It was discussed above that the shear viscosity was not constant for PL and HB fluids for different production rates but it was constant for BP fluid. At the high shear rate for the condition considered, the effective viscosity was at the minimum plateau point of effective viscosity equal to 60cp. The effective viscosities for PL and HB fluids were varied from 60.44 to 32.91 cp and from 133.61 to 19.34 cp respectively. The result further highlights the importance of fluid rheological characterisation in order to apply the prevailing and correct effective viscosity at the prevailing pressure and temperature (Figure 5). Similarly Inflow Performance curves (IPR) are plotted for the given BP fluid at different temperature (Figure

6). The shifting of IPR curve because of temperature rise can be illustrated in following graph.

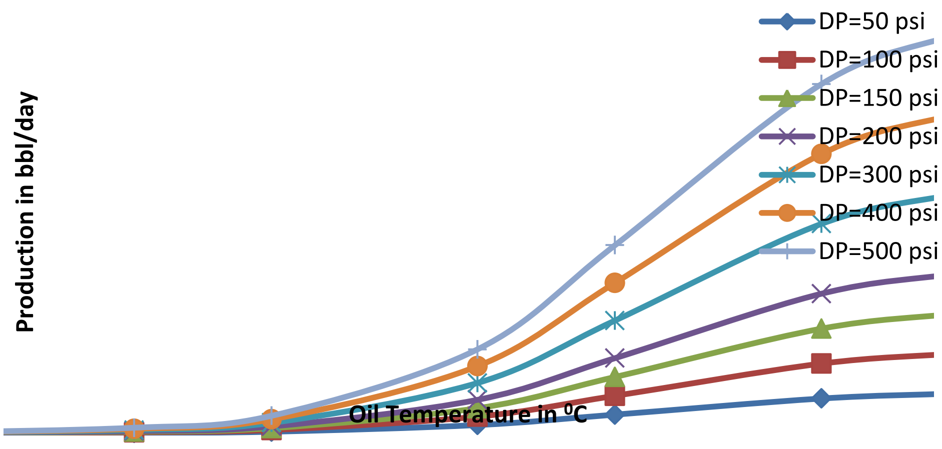

Figure 5: Production profile at different temperature

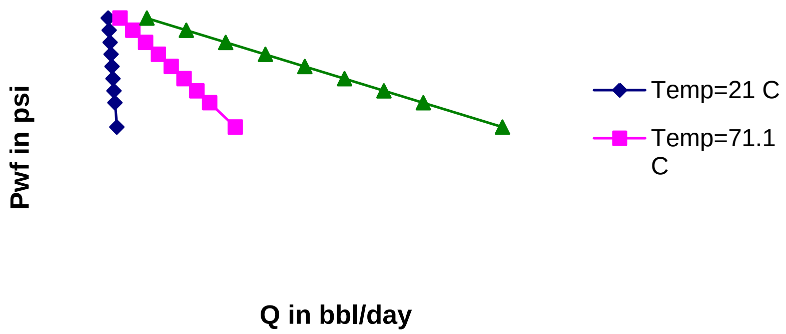

Figure 6: Inflow performance curves for BP

Impact of rheology on sand production forecast

The Unconfined Compressive Strength [UCS] values are very low for unconsolidated reservoirs and most of the heavy oil rocks are unconsolidated reservoirs. Sand failure and eventual production will start when the drawdown value crosses the UCS or critical drawdown . For a low UCS reservoir the critical drawdown values for different fluids were calculated and plotted [Figure 7] against the different flow rates. The results show that the critical drawdown threshold is different for the different fluids at different production rates. The results highlight the fact that the HB fluid can be subjected to a wider operating window at higher production rates without rock failure and sand production.

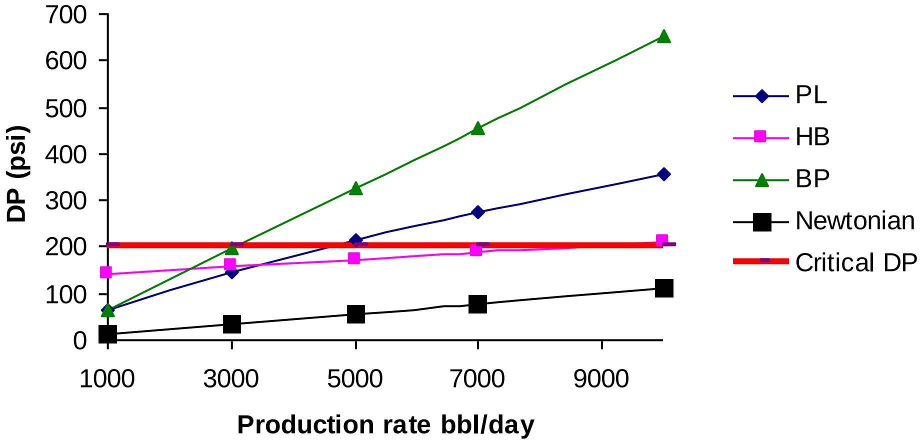

Figure 7: Comparison of critical drawdown for Newtonian and non-Newtonian fluid

Summary of Future Work

The preliminary results presented in this paper have highlighted the depth of research that needs to be carried out in order to provide a comprehensive understanding of the combination effects of heavy oil rheological behaviour on different key reservoir, fluid and operating parameters. The key drivers for the rheological behaviour of heavy oil are fluid composition, reservoir rock pore size, distribution fluid production rate and conditions of pressure and temperature. For given reservoir flow properties it is essential to track the fluid flow behaviour through every section of the composite production system from the reservoir through to the topside facility. Tracking the fluid flow behaviour requires the establishment of precise rheological model for heavy oil at different conditions of pressure and temperature.

Critical to developing the precise and accurate models for simulating rheological behaviour is the prediction of the key PVT properties at different conditions of pressure and temperature. Development of the appropriate fit-for-purpose models to forecast the PVT properties requires detailed characterisation of different heavy oils. A key instrument for this characterisation is the MicroPVT System.

The MicroPVT Analyser

The MicroPVT [Figure 8] was developed to provide precise and rapid analysis of the physical and thermodynamic properties of fluids. Weighing less than 10 Kg and working with a sample of less than 10 mls. The MicroPVT can be used in the laboratory or at the well site. The pressure range of MicroPVT is 1.45 to 50000 psi and temperature range is -22 to 300 ^{0}F.

Figure 8: Micro PVT Analyser
(Source: http://www.pmacsystems.com/products/pdf/Micro%20PVT%20System.pdf)

Using the MicroPVT analyser, the PVT database can be generated in real-time to determine the pressure function, relative volume, specific volume, density, compression ratio, bulk modulus, strain relaxation, thermal coefficient and viscosity of heavy oil at high pressure and temperature.

The MicroPVT is the only system available, which can cope with such small volumes of sample and will enhance its usefulness at the well site when only small volumes of sample are available. The MicroPVT can provide a pressure volume curve within 10 minutes for “quick look” PVT data or can be programmed to build up or reduce pressure over any time frame.

The MicroPVT system also has a special core holder attachment, allowing for permeability and porosity measurements of core samples

Conclusions

The main conclusions that can be drawn from this work are:

1. Rheology of heavy oil is a very critical factor to determine the efficiency of heavy oil production and also to determine the efficiency of any improved oil recovery technique such as the Steam Assisted Gravity Drainage Technique.
2. Rheology of heavy oil is pressure, temperature and shear rate dependent hence rheology is not constant. It will change with time and temperature and the new rheology may change the ultimate production and operating parameters of a well.
3. Accurate knowledge of fluid rheology is very important for heavy oil reservoir management.

Acknowledgement:

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Optimisation of Steam Assisted Gravity Drainage [SAGD] for Improved Recovery from Unconsolidated Heavy Oil Reservoirs

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Keywords: Heavy Oil, non-Newtonian fluid, Steam Assisted Gravity Drainage, Rheological characterisation, Productivity model for horizontal well

Abstract

Most of the heavy oil resources in the world are in sandstone reservoir rocks, the majority of which are unconsolidated sands which presents unique challenges for effective sand management. Because they are viscous and have less mobility, then appropriate recovery mechanisms that lower the viscosity to the point where it can readily flow into the wellbore and to the surface are required. There are many cold and thermal recovery methods assisted by gravity drainage being employed by the oil industry. These are customised for specific reservoir characteristics with associated sand production and management problems**.** Steam Assisted Gravity Drainage (SAGD) based on horizontal wells and gravity drainage, is becoming very popular in the heavy oil industry as a thermal viscosity reduction technique. SAGD has the potential to generate a heavy oil recovery factor of up to 65% but there are challenges to ''realising the limit''. The process requires elaborate planning and is influenced by a combination of factors. This paper presents unique models being developed to address the issue of multiphase steam-condensed water-heavy oil modelling. It addresses the effects of transient issues such as the changing pore size distribution due to compaction on the bulk and shear viscosities of the non-Newtonian heavy oil and the impact on the reservoir productivity, thermal capacity of the heavy oil, toe-to-heel steam injection rate and quality for horizontal well applications. Specific case studies are presented to illustrate how the models can be used for detailed risk assessment for SAGD design and real-time process optimisation necessary to maximise production at minimum drawdown.

Nomenclature

A – Drainage Area	$[m^2]$
a – Reservoir length X – direction	[feet]
B – Formation Volume Factor	$[\frac{RB}{STB}]$
b – Reservoir width Y – direction	[feet]
C_H – Geometric Factor	[Dimensionless]
D_{pore} – Pore Diameter	[inches]
D_{50} – Grain Size	[inches]
h – Reservoir thickness	[feet]
L – Well Length	[feet]
n – Flow Index	[Dimensionless]
P – Pressure	[psi]
p_r – Reservoir Pressure	[psi]
p_{wf} – Bottomhole Pressure	[psi]
q – Production rate	[STBPD]
r_w – Wellbore radius	[feet]
S_R – pseudo skin factor	[Dimensionless]
T – Temperature	$[^0F]$
T_s – Steam Temperature	$[^0F]$
T_R – Reservoir Temperature	$[^0F]$
μ – Viscosity	[cp]

$v - Kinematic \quad viscosity$ $[\frac{cP}{Kg/m^3}]$

$V - Volume$ $[cm^3]$

$V_{pore} - Pore \quad Velocity$ $[ft.\sec^{-1}]$

$\phi - Porosity$ $[Dimensionless]$

$\Delta S_0 - (Initial - Residual) oil \quad saturation$ $[Dimensionless]$

$\alpha - Thermal \quad Diffusivity$ $[\frac{Ft^2}{Day}]$

Introduction

Heavy oils are hydrocarbon liquids of 0.93 specific gravity (SG) or more [water SG = 1] and viscosity of more than 200cp at reservoir rock conditions [1]. Because they are viscous and have less mobility, then appropriate recovery mechanisms that lower the viscosity to the point where it can readily flow into the wellbore and to the surface are required. There are many cold and thermal recovery methods assisted by gravity drainage being employed by the oil industry. These are customised for specific reservoir characteristics with associated sand production and management problems**.** Steam Assisted Gravity Drainage (SAGD) based on horizontal wells and gravity drainage [2], is becoming very popular in the heavy oil industry as the thermal viscosity reduction technique. This is because of its high recovery factor especially for deep reservoirs both onshore and in deepwater environments. SAGD uses two multilateral horizontal wells drilled into the reservoir which are parallel and vertically aligned on top of each other (Figure 1). The upper well acts as the "Injection Well" for the steam. As new reservoir surfaces are heated and the oil viscosity decreases, the oil flows downward along the boundaries of the steam chamber and facilitates the gravity drainage of the lighter oil into the lower lateral well which is the "Production Well". SAGD has the potential to generate a heavy oil recovery factor of up to 65% but there are challenges to ''realising the limit''. The process requires elaborate planning and is influenced by a combination of factors that include the Steam Oil Ratio (SOR), well length, heterogeneities above and in between the well pair, steam pressure and temperature, steam injection rate, steam quality, flow properties of the heavy oil such as bulk/shear viscosities, oil density, thermal coefficient and response to prevailing reservoir pressure and temperature and completion strategy, to name a few [3]**.** Although there are classic inflow performance models for horizontal wells, no accurate models/algorithms exist for predicting the SAGD process especially with respect to toe-to-heel steam injectivity and inflow performance for clastic unconsolidated heavy oil reservoirs. Some attempts have been made to adapt conventional models, with mixed results. However, none of the models has addressed the issue of multiphase steam-condensed water-heavy oil modelling nor the effects of transient issues such as the changing pore size distribution due to compaction on the bulk and shear viscosities of the non-Newtonian heavy oil and the impact on the reservoir productivity, thermal capacity of the heavy oil, toe-to-heel steam injection rate and quality for horizontal well applications. More importantly, in all of these studies, the reservoir was considered as an independent entity. Hardly any of the published work to date has attempted to integrate the reservoir model with the wellbore model in real time in order to have a coupled system where changes in the reservoir would be reflected in the viscosity and corresponding pressure profile/optimisation from toe to heel of the horizontal well, especially for SAGD operations.

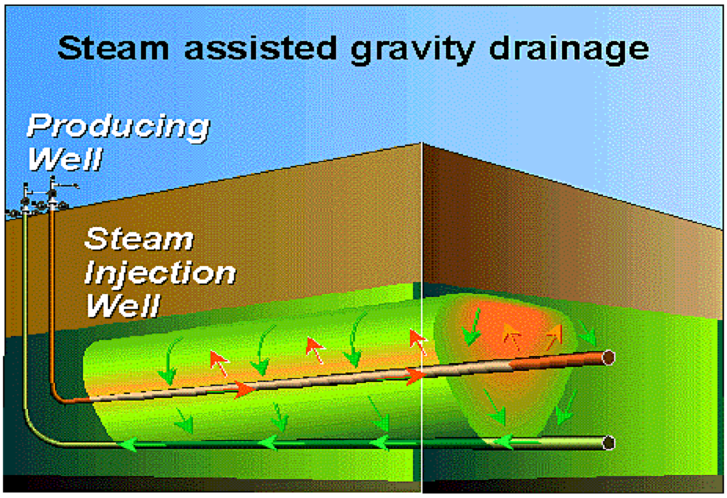

Figure 1: Steam Assisted Gravity Drainage (Source: ASPO Annual Meeting 2003)

A new project has therefore been initiated by the Well Engineering Research Group at The Robert Gordon University to address the critical issues of heavy oil recovery. The project, funded by the Northern Research Partnership and PMAC Systems Ltd of the UK, is designed to:

- Carry out detailed inflow performance and steam injectivity performance evaluation for horizontal wells for different reservoir flow and textural scenarios,
- Assess the probability of using any of the classic horizontal well models that are fit-for-purpose

- Test different heavy oils using a newly patented MicroPVT testing facility. This will generate PVT properties of the heavy oils at different pressures up to 50000psi and temperatures up to 300^{o}F which represent the boundary conditions of HP-HT reservoirs.
- Develop and validate a new simulator which can be used for SAGD process simulation/diagnosis, optimisation and proactive "looking ahead" capability.

Critical Factors Affecting SAGD for Heavy Oil Recovery

The mobility of heavy oil [k_h/μ] and eventual fluid recovery are affected by a combination of factors which include:

- The Shear Viscosity and the bulk viscosities which together define the viscoelastic characteristic of the heavy oil in relation to the steam-oil interaction, the reservoir fluid inflow, the outflow from the well and delivery to the surface
- Other critical PVT properties such as oil density, thermal coefficient that will be strongly affected by the changing reservoir fluid composition and prevailing pressure and temperature
- The reservoir-wellbore interaction including well length. There would appear to be an optimum well length required for uniformly distributed steam injection through the injection well and rectangular inflow of the reservoir fluid into the producer wellbore
- Steam-Oil Ratio[SOR] which will be influenced by the steam quality, oil thermal coefficient among other factors
- Reservoir absolute and relative permeabilities and impact of steam injection over time and impact on eventual effective permeability to ''heated'' the heavy oil
- Steam pressure and temperature, injection rate, steam quality,

Preliminary background work carried out as part of the project objectives, the subject of a parallel paper[4], has confirmed that heavy oil is highly non-Newtonian , with the shear viscosity strongly affected by the fluid flow behaviour, the shear rate as a function of flow rate and reservoir pore size distribution. This in effect will impact on the reservoir inflow and recovery.

Update on Key SAGD Models – Key Requirements

Optimum HW Productivity/Injectivity Model

Several productivity models for horizontal well are available in literature [2, 4, 5, 7, 8, 9, 10, 11]. The geometry and the skin factors mainly differentiate these models from each others. Some of them have assumed the rectangular and some of them have assumed the circular drainage area. All productivity models can be grouped in four main categories.

a. Models for isotropic steady state reservoir
b. Models for anisotropic steady state reservoir
c. Models for isotropic, steady state and eccentric reservoir
d. Models for anisotropic pseudo steady state reservoir

As stated in the introduction there is no accurate productivity model for steam assisted gravity drainage technique. A typical example of productivity and injectivity models for horizontal well is the Babu and Odeh model presented below.

Productivity model for horizontal well

Babu and Odeh [11] derived an expression for productivity from horizontal well. In their method, all boundaries are no-flow boundaries. They consider a uniform flux solution given by the equation.

$$q = \frac{7.08\times 10^{-3}\times b\sqrt{(k_x k_y)}\times(p_r - p_{wf})}{B\mu[Ln\frac{A^{0.5}}{r_w} + LnC_H - 0.75 + S_R]} \qquad [1]$$

The viscosity parameter in this equation is the effective shear viscosity of the reservoir fluid at the prevailing average reservoir pressures and temperatures. It is therefore a function of the flow behaviour of the reservoir fluid. For heavy oil, it has been established that the behaviour of the oil is non-Newtonian, the details of which are presented in the follow-up section below.

Another critical parameter is the effective permeability to the reservoir fluid. For Babu and Odeh's model this is presented in terms of directional effective permeabilities k_x and k_y. Irrespective of how this is presented, there is the need to appreciate the absolute permeability and corresponding relative permeability of the reservoir to the heavy oil and heavy oil-steam interaction. The transient nature of the relative permeability in SAGD environment demands the development of appropriate model to forecast this all important parameter. This is one of the key objectives of this newly initiated programme of research at RGU.

Additionally, the geometric factor is important to reservoir fluid inflow and injector well placement. The definition of this parameter together with the skin factor as presented by Babu and Odeh [11] will also be reviewed in the course of this project.

The corresponding productivity index from the above model can be presented as:

$$J = \frac{7.08 \times 10^{-3} \times b\sqrt{(k_x k_y)}}{B\mu[Ln\frac{A^{0.5}}{r_w} + LnC_H - 0.75 + S_R]} \quad [2]$$

Injectivity model for horizontal well

For the purpose of this paper, the injectivity based on Babu and Odeh's model can also be presented as:

$$q_{injection} = \frac{7.08 \times 10^{-3} \times b\sqrt{(k_x k_y)} \times (p_i - p_r)}{B\mu[Ln\frac{A^{0.5}}{r_w} + LnC_H - 0.75 + S_R]} \quad [3]$$

p_i - Injection pressure at the sand face, psi

p_r - Prevailing reservoir pressure, psi

In summary, the key parameters in this model are:

1. The Shear viscosity

2. Effective permeability which is a function of the rock flow properties [directional absolute permeabilities (k_x, k_y) , relative permeability(k_r) and porosity(ϕ)]

The directional permeabilities and porosity impact on the pore size distribution of the reservoir and vice- versa and therefore the pore fluid velocity. Changes in pore fluid velocity impact on the fluid shear rate and therefore the corresponding shear viscosity. In this regard, it is essential to understand the rheological behaviour of the heavy oil prior to and during steam injection.

Preliminary Results & Discussion

There are number of horizontal well flow models in the market. The selection of the appropriate model that is fit for purpose for the planning and SAGD process optimisation are critical to the success of the operation and eventual well performance.

In this section, the results of the comparative analysis carried out on HW models are presented. Likewise the effect of temperature on effective shear and bulk viscosity is considered. Effect of composition is the objective in next stage of this project. In non-Newtonian fluid the Power-Law (PL), Herschel Bulkley (HB) and Bingham Plastic (BP) types are considered. The effective viscosity and the shear rate for all of these rheological models are compared against same flow through reservoir and the corresponding impact on Inflow Performance of well (IPR) and Steam-Oil-Ratio (SOR) are discussed.

Productivity models for horizontal well

First step towards the development of productivity model for SAGD is to select or shortlist any one these models which then can be modified as per boundary conditions. The productivity by all models in STB/day is plotted for same reservoir and operating conditions in figure 2.

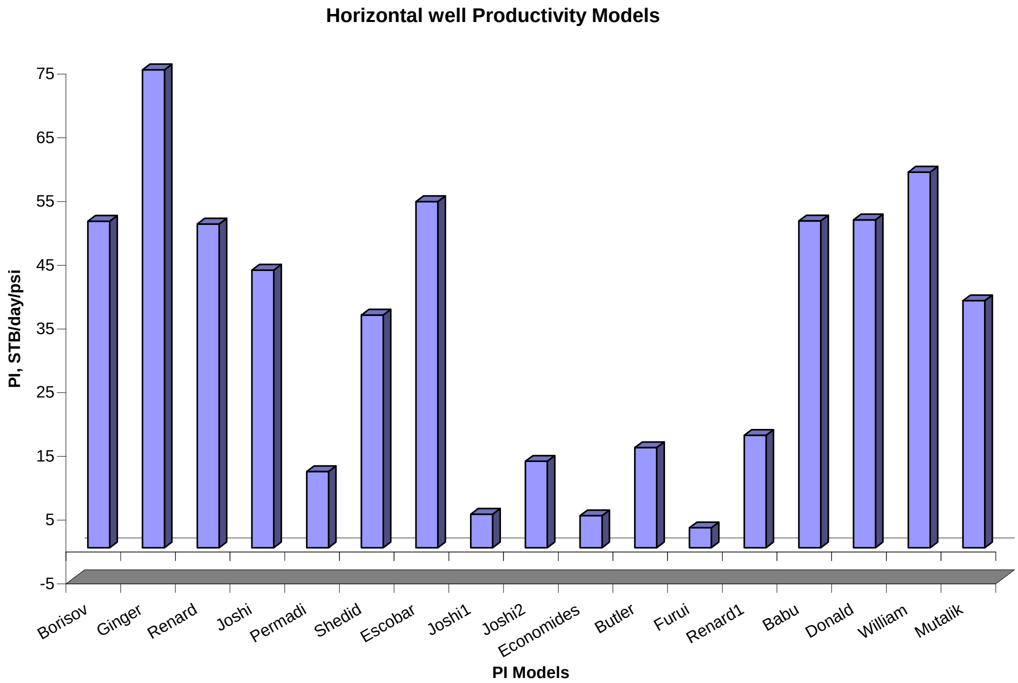

Figure 2: Comparison of horizontal well productivity models for an anisotropic reservoir

Screening of horizontal well Productivity models

From Figure 3, it is very clear that each horizontal well productivity model is generating different productivity values for the same input. Here the screening exercise has been carried out using different popular industry reservoir simulators namely Eclipse100, Prosper and Reveal to benchmark the recommendation. Different types of isotropic and anisotropic reservoirs were considered. In anisotropic reservoir the ratio of horizontal to vertical permeability was taken as 10. For the purpose of wellbore simulation , consideration was given to the following three conditions:

1. Fully penetrated well in bounded reservoir
2. Partially penetrated well in bounded reservoir
3. Partially penetrated well in infinite reservoir

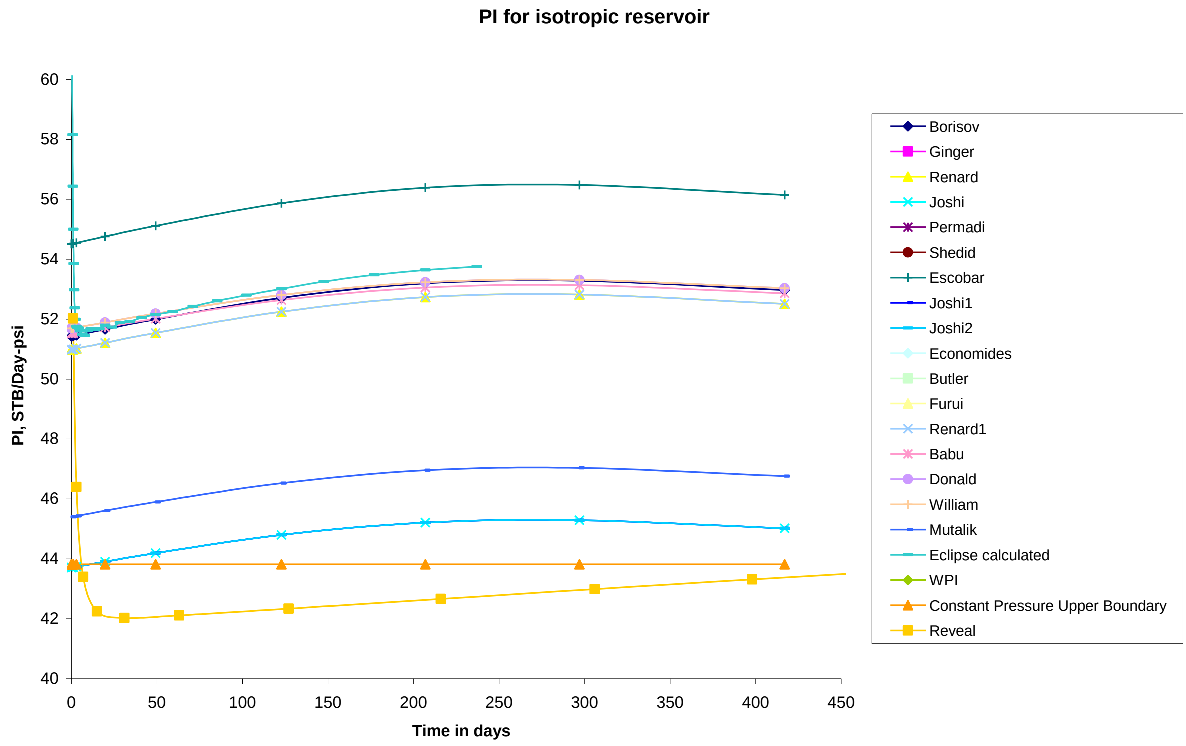

Figure 3: Comparison of horizontal well productivity for isotropic reservoir using different

Reservoir simulators

Shortlisted Productivity models

	Isotropic	Anisotropic
Full Penetration	**Joshi2**	**<u>Renard's anisotropic model</u>**
Partial Penetration	**Mutalik**	
Infinite reservoir	**Escobar**	

Analytical Derivation for SAGD

Butler et al. [6] established the analytical expression to describe the mechanism of SAGD. The laboratory observations were used as a basis for developing the SAGD analytical expressions. The analytical expression for the production rate per unit well length is written as:

$$q = \sqrt[2]{\frac{2 \times \phi \times \Delta S_0 \times K \times g \times \alpha \times (h-Z)}{mv_s}} \frac{RBPD}{length} \quad [4]$$

Where

$$\frac{1}{mv_s} = \int_{T_r}^{T_s} \left[\frac{1}{v} - \frac{1}{v_r} \right] \frac{dT}{(T-T_r)} \quad [5]$$

For uniform flow distribution the total flow equation is given below.

$$q_T = \sqrt[2]{\frac{2 \times \phi \times \Delta S_0 \times K \times g \times \alpha \times h}{\left[\frac{1}{v} - \frac{1}{v_r} \right] \times \log(T_s - T_r)}} \times \frac{L}{B_0} \frac{STB}{day} \quad [6]$$

Case Study

The density of heavy oil used for this analysis was 930 Kg/m^3. Viscosity of heavy oil was calculated at different temperature using Egbogah-Jack's correlation and modified Bennison correlation.

Table 1: Dead oil viscosity calculations at different temperatures

		Dead Oil Viscosity, cp	
Temperature		Viscosity by Egbogah-Jack's	Modified Bennison

^{0}F	API	Heavy oils	Extra Heavy	>20,250	<20,250
70	20.6	325.9196346	1546.376865	276.1886669	202.2280827
80	20.6	193.7019053	864.7611752	176.5528652	140.3460901
100	20.6	89.63829667	362.136436	83.58516421	76.22474848
110	20.6	66.70052774	258.5966501	60.73265432	58.73045014
120	20.6	51.73311073	193.3831829	45.3725042	46.29030053
130	20.6	41.4574636	150.0238057	34.69803571	37.18739492
150	20.6	28.66922751	98.20220868	21.48063816	25.14118144
160	20.6	24.53093686	82.09067025	17.30305918	21.07225877
180	20.6	18.74083476	60.25762551	11.66032698	15.26791321

Using the Butler's analytical model for SAGD, the production rate was calculated at 120 ^{0}F as a desired temperature and 130 ^{0}F as a steam temperature. Egbogah-Jack's correlation was used for the dead oil viscosity.

Above correlations assumes the heavy oil as a Newtonian fluid but preliminary studies on different heavy oils have established that they are predominantly non-Newtonian at standard and higher temperatures and pressures.[Figure 1]

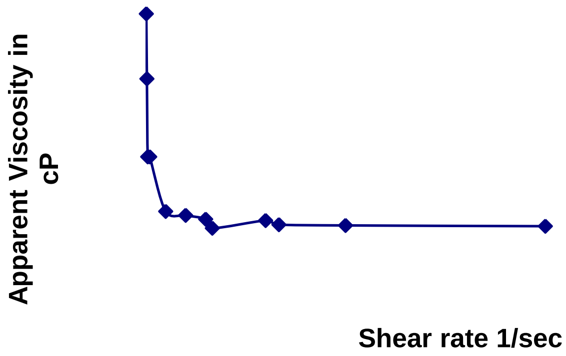

Figure 4: Apparent viscosity verses shear rate

The detailed rheological characterisation of heavy oil is being discussed in a parallel paper[4].

After back calculating the effective viscosities for Bingham Plastic, Power Law and Herschel Bulkley using shear rate models for the flow rate which we got from Butler's model and then compared the effective viscosities of Newtonian and Non-Newtonian fluids.

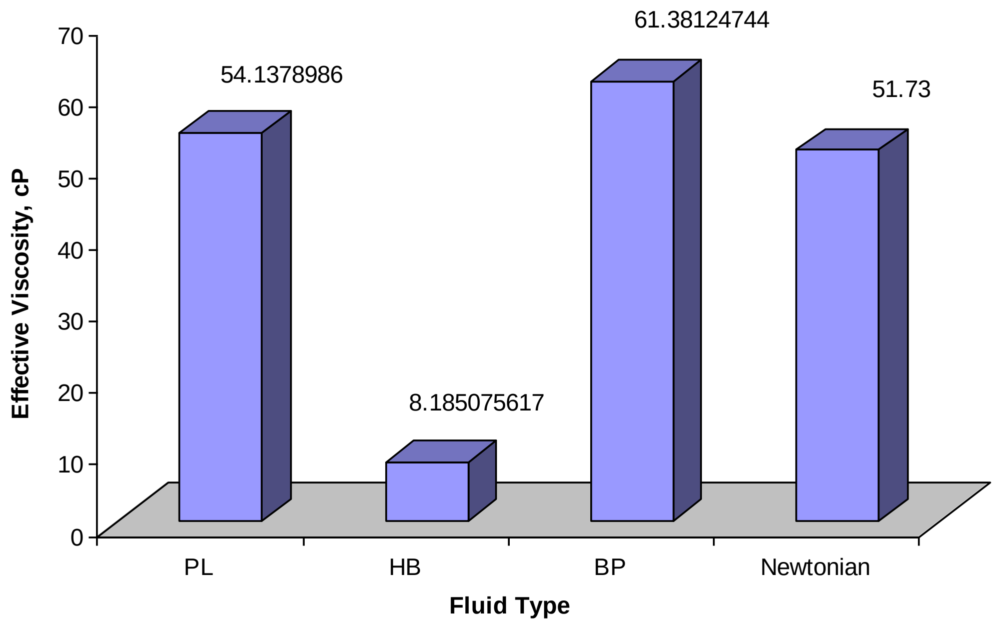

Figure 5: Effective viscosity comparison for different fluids

Summary of Future Work

The preliminary results presented in this paper have highlighted the depth of research that needs to be carried out in order to provide a comprehensive understanding of the combination effects of different key reservoir, fluid and operating combinations affecting the SAGD process and its optimisation The aim of this project is to improve the efficiency of Steam Assisted Gravity Drainage technique. Highlights on future work are listed below.

1. Multiphase steam-condensed water-heavy oil flow modelling
2. Model to track the changes in pore size distribution due to compaction on the bulk and shear viscosities of the non-Newtonian heavy oil and the impact on the reservoir productivity, thermal capacity of the heavy oil, toe-to-heel steam injection rate
3. Time and steam composition dependent models for the absolute and relative permeabilities
4. Reservoir cold and thermal simulation for different present productivity and injectivity models
5. Models for the PVT properties of heavy oil like density, viscosity, thermal capacity of oil which will be robust and these models will be the function of composition, temperature and pressure. The complexity of the relationship between the PVT properties and the prevailing pressures and temperatures demands extensive experimental analysis of different heavy oils in order to build appropriate database for the semi-empirical model that would be required. A key part of the planned future work is the use of a newly developed MicroPVT tool kit.
6. Model for Steam Assisted Gravity Drainage technique

Conclusion

1. The different productivity models for horizontal well give different values for same input but for heavy oil, Renard and Dupuy's model for anisotropic reservoir gives the close results to different industrial reservoir simulators. This model will be taking further for the Inflow Performance analysis of heavy oil reservoirs.
2. Butler's rate equation for steam assisted gravity drainage is not addressing the number of issues like the anisotropic conditions, well locations, well parameters, rheology of heavy oil with steam, relative permeability of oil and grain compaction due to high temperature and high drawdown.
3. From the rheological characterisation it is clear that rheology plays an important role in determining the production forecast of heavy oil reservoirs with steam injection. To predict accurate forecast, it is necessary to track rheology of oil with time and steam composition.

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