T H E U N I V E R S I T Y O F T U L S A

THE GRADUATE SCHOOL

IMPACT OF PRESSURE TRAVERSE OF Y-TOOL DUAL ESP SYSTEM

by
Syed Umair Hasan

A thesis submitted in partial fulfillment of

the requirements for the degree of Masters of Science

in the Discipline of Petroleum Engineering

The Graduate School

The University of Tulsa

2023

T H E U N I V E R S I T Y O F T U L S A

THE GRADUATE SCHOOL

IMPACT OF PRESSURE TRAVERSE OF Y-TOOL DUAL ESP

by
Syed Umair Hasan

A THESIS

APPROVED FOR THE DISCIPLINE OF

PETROLEUM ENGINEERING

By the Thesis Committee

Hong-Quan Zhang, Chair
Paul Song
Haiwen Zhu

ABSTRACT

Syed Umair Hasan (Masters of Science in Petroleum Engineering)

Impact of Pressure Travers of Y-Tool Dual ESP System

Directed by Drs. Holden Zhang and Haiwen Zhu

118 pp, Chapter 6: Conclusions and Recommendations

(305 words)

The Y-tool ESP system, a dual ESP configuration, represents a more recent approach adopted in the industry as an alternative to the single ESP system. It finds application in wells with closely spaced layers, where two ESPs work in tandem to achieve the desired well production and enhance the well operational lifespan.

A parametric design study on dual Y-tool ESP is conducted in this study using the steady-state commercial simulator PIPESIM. To simulate the Y-tool ESP structure, a connector is created as a Y-tool junction, and two ESP wells are generated separately and connected to the connector. Then a flowline after the connector represents the wellbore. Parameters including reservoir pressure, production index, pump speed, water cut, GOR, viscosity, and pump design are investigated in this study. Results including production rate, Pump Intake Pressure (PIP), pressure distribution, boosting pressure, fluid properties, etc. are compared to evaluate the Y-tool ESP system design.

According to field data, two ESPs, namely REDA GN1300 and CENTRILIFT P11, are selected for the lower and upper layers. The Y-tool design is compared to the single ESP design as reservoir pressure declines, and its performance is parametrically studied. Then, the lower layer pump REDA GN1300 is replaced by REDA D2150N, and the corresponding sensitivity analysis is

conducted. Y-ESP pressure envelopes are evaluated using single ESP nodal analysis and Y-ESP PIPESIM system analysis. In summary, reservoir property still dominates the two zone's production behavior. A proper Y-tool pump design can help increase the system run lift and avoid one-layer early shutdown. Fluid properties also have some effect on the system. However, due to the PIPESIM ESP model's limitation, only a qualitative study is conducted, and the real fluid property effect, i.e. viscosity, gas void fracture, emulsion inversion point, etc., should be investigated in the future study.

ACKNOWLEDGEMENT

First, I want to thank my advisor, Dr. Holden Zhang, who gave me guidance, encouragement, and support throughout this study. I am also grateful for his scientific attitude and professionalism during the formation of this thesis.

I appreciate the sponsorship by the Kuwait Oil Company. The advice given by Ms. Maryam Al-Matrouk and Mr. Mohammad Farouk Hassan has been a great help in my case setup and simulation matrix design.

I am grateful for the support and help from the TUALP team. I wish to acknowledge the help from Dr. Haiwen Zhu, who introduced the project to me and guided me throughout the whole project including understanding the project objectives and getting the results from the simulations as well. I want to thank Ms. Donna Trankley for her administrative work throughout the project. I also want to thank my TUALP colleagues Dayo Tychus, Tanmay Rajiv Tatu, and Sai Praveen Adiraju for their assistance on this project.

I wish to acknowledge the comments and encouragement regarding my thesis from Dr. Holden Zhang, Dr. Haiwen Zhu, and Dr. Paul Song, who serve on my Master's committee.

Finally, my special thanks are extended for the support and love of my parents, Syed Zia-ul-Hasan and Samina Talat, during my Master's program and through my entire life.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

The Electrical Submersible Pump (ESP) was invented in the early 1900s as a tool for artificial lift systems. The main purpose of ESPs is to extend the life of the well and increase the liquid production of the well. However, there are certain issues with an ESP system which include sand erosion and corrosive problems, motor heat-up, and high gas intake problems (Takacs, 2017). A dual ESP system known as a Y-tool ESP system is a newer concept applied in the fields as a substitute for a single ESP system. In certain wells with layers fairly close to each other, this system is implied where two ESPs are used for providing the desired production of the well.

TUALP's sponsor company KOC provided a specific well that has two reservoir zones close to each other. Although only the lower layer is kept producing for 3 years, KOC plans to use Y-tool ESP to produce the upper layer, 200 ft above, in the future. Consequently, the primary objectives of the project are threefold: firstly, to assess the feasibility of employing the Y-tool ESP system; secondly, to establish well-defined pressure envelopes for the system; and lastly, to observe and understand the interaction between the two layers in the well. The simulation is mainly conducted using PIPESIM.

This study first proposed the Y-tool ESP simulation methodology in PIPESIM. Then the results are analyzed using PIPESIM nodal analysis and system analysis. The simulation can help to observe the normal issues that could cause failure in the well, for example, high ESP intake GVF, motor temperature issues, or low pump intake pressure. As a result, new pumps can be designed to improve the well performance. To summarize, the production behavior of the two zones is still primarily governed by reservoir properties. Implementing a well-designed Y-tool pump system can enhance the longevity of the system and prevent a premature shutdown of one layer. Additionally, fluid properties also influence the system's performance, but not as obvious as expected. Since both PIPESIM and OLGA used a simple homogenous ESP model in the simulation, future studies should be focused on fluid properties' effect on pump performance.

CHAPTER 1

LITERATURE REVIEW

Electrical Submersible Pump (ESP) is an effective artificial lift method for lifting high volumes of oil from the wellbores. The ranges of volumes vary from 150 BBL/D to 150,000 BBL/D. The long history of the ESP system is firm proof that this artificial lift system is one of the efficient methods for producing liquid in oil and gas wells. They are also used for water flooding applications. The pumps are used for water floods, injection, irrigation, and commercial water systems. The components of ESP include multistage centrifugal pumps, a three-phase induction motor, seals, power cables and electrical equipment, a junction box, and surface controls (Takacs, 2017 and Zhu et al., 2017).

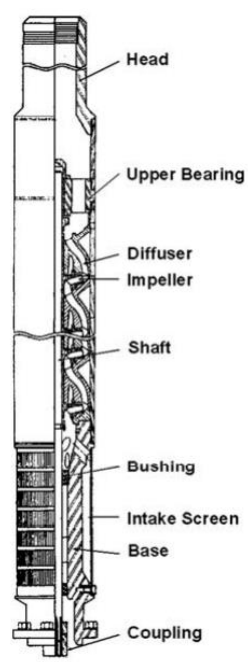

Figure 1.1 Components of ESP system

The submersible pumps used in ESPs are conventional multi-stage centrifugal pumps that operate vertically. Liquids that are produced which are exposed to centrifugal forces mainly caused by high rotational speeds of the impeller, lose kinetic energy in the impeller and are converted into potential energy. Figure 1.1 gives the main parts of the conventional ESP system (Zhu et al., 2022).

1.1 Y-tool Dual ESP System

Y-Tool ESP is a system, which can align multiple ESPs together. Figure 1.2 shows two ESPs, which are installed on different conduits, joined together to form a Y-shape form.

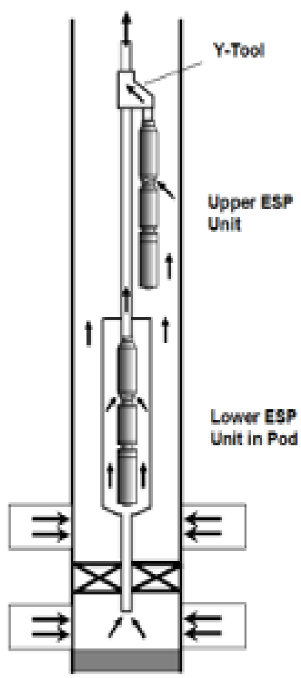

Figure 1.2 Typical Y-tool ESP system

Y-tool is a bypass system that is mostly run-on production tubing. A bypass system provides space for the equipment to run into the wellbore below the Y-tool without moving the ESP. The bypass Y-tool system has two conduits. One conduit is offset and is placed on top of the wellbore and shelters the ESP. The second one runs down the tubing and provides access to the wellbore below the system (Takacs, 2017). Dual Y-tool ESP can be installed in two ways, which are series and parallel. They are used in both single and multiple zones and depending on those zones different solutions are available.

1.1.1 Single Zone Installation

In single zones, problems occurring in the operation of the pump used much free gas production in the ESP system. To deal with this problem, motor shrouds are used acting as downhole separators and removing the free gas from the fluid before the gas even reaches the centrifugal pump. ESP can be connected in series and parallel and is used in production (Takacs, 2017).

In a parallel connection, two ESP work parallel to each other. The two ESP systems are connected in the tubing string with two Y-tools, which makes it possible to select between the two ESP systems at will.

Figure 1.*3* shows the parallel connection of Y-tool ESP in single zones (Takacs, 2017).

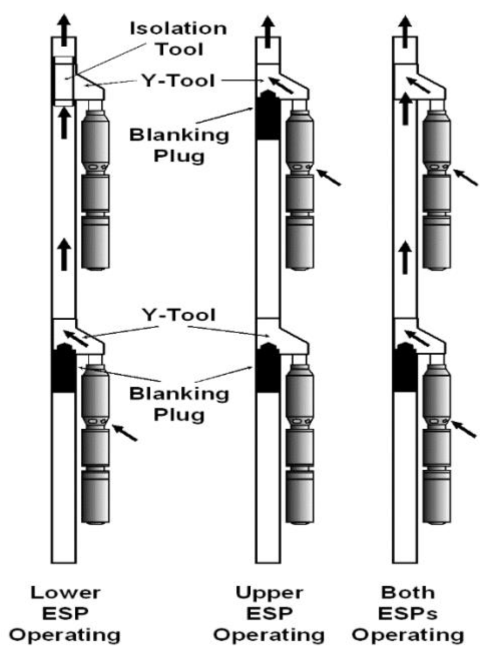

Figure 1.3 Parallel installation of Y-tool ESP

In

Figure 1.*3*, a blanking plug and an isolation valve are installed as well. The blanking plug is set in the lower unit, while the isolation tool is set in the upper one when operation is required. If there is a requirement to use the upper ESP system, a blanking plug is also installed on the upper part along with the isolation valve and is used to run any instrument down to the well bottom. These systems are used in reduce workover costs during operation. When there is a failure in any one of the ESP, there will not be a complete production loss as the other one is still capable of producing fluids. Parallel installation is also used in those wells where surface or downhole equipment such as casing can restrict flow rates (Takacs, 2017).

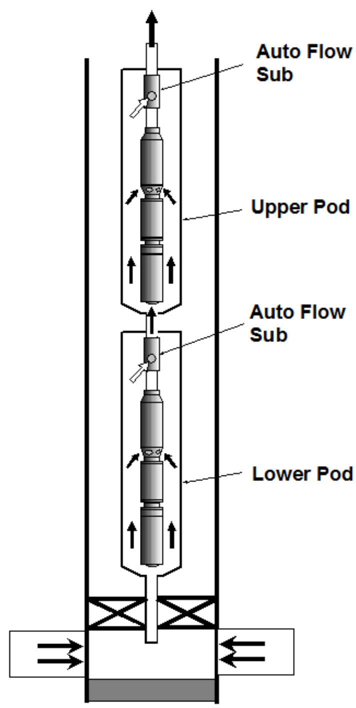

Figure 1.4 Series installation of Y-tool ESP system

Figure 1.*4* represents the Series connection for a single production zone. As seen, one ESP is a booster pump, which helps in increasing the depth for lifting production fluids and the total liquid flow rate for the same Total Dynamic Head (TDH). Series installation is usually used when

the motor cannot provide the required power. They are also used when the collapse of the casing string is expected due to the pressure drawdown required for the desired production rate.

In a series connection, both ESP units are enclosed within capsule-shaped pipes called "Pods," serving to seal the ESP units from the surrounding annulus and safeguard the casing strings even in challenging environments. Additionally, the system incorporates an "Auto Flow Sub (AFS)" that operates automatically in two ways: during ESP operation, the AFS valve facilitates fluid flow to either the upper valve into the ESP or the tubing string and when the ESP is turned off and fluid flow stops, the AFS valve closes the tubing and opens an alternate path from the annulus of the pods, allowing fluids to rise from the ESP to the tubing string for efficient fluid management (Takacs, 2017).

1.1.1 Multiple Zone Installation

The Y-tool ESP configuration is primarily designed for simultaneous production from two zones, utilizing a single tubing string for fluid mixing and production. Figure 1.5 depicts the installation of two ESP units, enabling production from multiple zones within the same well. The packer separates the formations, and an isolation valve sits just above it in the tubing string. A perforated pipe allows for fluid mixing from the formations, while the ESP unit is compressed within the pods. However, a drawback of this installation is the difficulty in optimizing all zones effectively. To address this, dual Y-tool installations shown in Figure 1.6 can be employed, offering solutions such as alternate production from individual zones, and facilitating commingled production from multiple zones, thereby enhancing operational flexibility and efficiency.

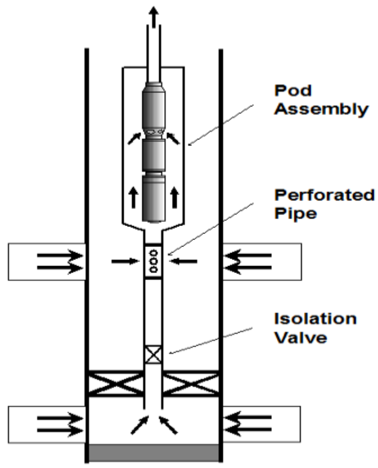

Figure 1.5 Multiple zone production of Y-tool ESP system

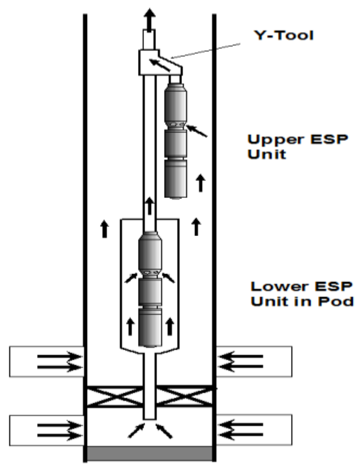

Figure 1.6 Multiple zone production using ESPs

This system uses two ESP units operating separately with different capabilities. The lower ESP unit is fixed at the bottom of the tubing string encased by a pod. The use of lower ESP is to pump all fluids coming from the formations from the lower region. The upper ESP unit is attached to the Y-tool as shown in Figure 1.*6*. The upper unit is used to transport all the fluid production to the tubing string. When there is a requirement to produce from the lower region, an isolation valve is injected in the Y-tool unit and stops the running of the upper ESP. Then, a blanking plug is run into the Y-tool and allow the production of the upper zone. Two ESPs are used in this installation type, which allows any equipment to be selected according to different zonal features. One more advantage of this installation type is that accurate well testing of multiple zones is available as the zones are isolated from each other (Takacs, 2017).

1.2 Applications of Y-tool ESP

Downhole conditions changing cyclic in both temperature and pressure integrity (Zheng et al. 2022 a,b, Zheng et al. 2023a,b.). The changing of temperature pressure will change the gas-liquid ratios. Newer ESP systems used in deep water, high-pressure, high-temperature (HPHT) environments are more sophisticated and must have longer service lives. In addition, many reservoirs have multi-layer formations, with each layer having its own depositional (Luo et al. 2023, Liu et al. 2023 a,b, Wang et al. 2023). The Dual ESP completion has been successfully achieved the target production in producing the two formations in an independent way from a single well bore.

Y-tool ESP is mainly used as a dual ESP system in multiple zone completion. The advantages are that well-logging and intervention procedures are conducted easily as the completion string does not need to be pulled out by the workover operators. The system is used to provide ease and convenience for the operators. For example, in case any workover operation, well stimulation or reservoir operations are to be conducted, the operators can easily perform them without even having to pull out the tubing or ESP in a Y-tool ESP system. The lifting capability of dual ESP gives an edge over a single ESP system.

The use of ESPs can be advantageous in reducing operating costs and enhancing production, making them suitable for the reperforation of wells. Employing a Y-tool assembly method can save rig time compared to conventional methods, particularly helpful in reducing lost production percentages during workovers that demand more time and cost. An example from a field east of Aberdeen, Scotland, illustrates that although the ESP system pumps nearly 75% of production, it faces a higher frequency of workover operations leading to significant formation damages.

In Dudley's (1987) study, a high-set packer is installed at the mudline, allowing gas production up the casing annulus. A Y-tool is used to offset the ESP from the producing string, and perforation guns are hung off by the end of the bypass tubing. A nipple below the Y-tool features a standing valve or plug. However, this completion system faces certain issues, including the impact of shock waves from perforating guns on the Y-tool ESP and insufficient rat holes for required gamma-ray logs for depth correlations. To overcome these problems, careful observation of perforation gun lengths and positioning the shock system in the production casing is essential. Additionally, using extra cables allows the completion to reach deeper depths safely to land the perforating guns. In certain cases where correlations are unnecessary, the landing of guns or completion becomes a simplified process.

Zaini et al., (2012) discuss the utilization of dual Y-tool ESP systems as a backup for gas lift methods in Enhanced Oil Recovery (EOR) operations. The case study conducted in the offshore Bokor field demonstrates the successful implementation of the dual ESP system, replacing conventional gas lift systems in three wells. The field faced challenges with unconsolidated sands, leading to well-completion with gravel packs. Water aquifers were considered, but water cut posed issues for surface facilities. The successful implementation of the dual ESP system prompted the installation of another Y-tool ESP system with a pod configuration to minimize ESP retrieval and replacement risks. The advantages of using the dual ESP system include eliminating the need to replace the packer in case of ESP failure. However, drawbacks were noted, such as limited reservoir access and the shorter lifespan of ESP compared to gas lift systems, resulting in higher workover costs. Efforts were made to optimize and operate the ESP within an optimal range to extend its lifespan, requiring continuous monitoring of pump performance and well parameters. The dual ESP system acts as a backup, with a secondary ESP that can be utilized if the primary one fails, potentially increasing the run life by one year compared to single ESP installations.

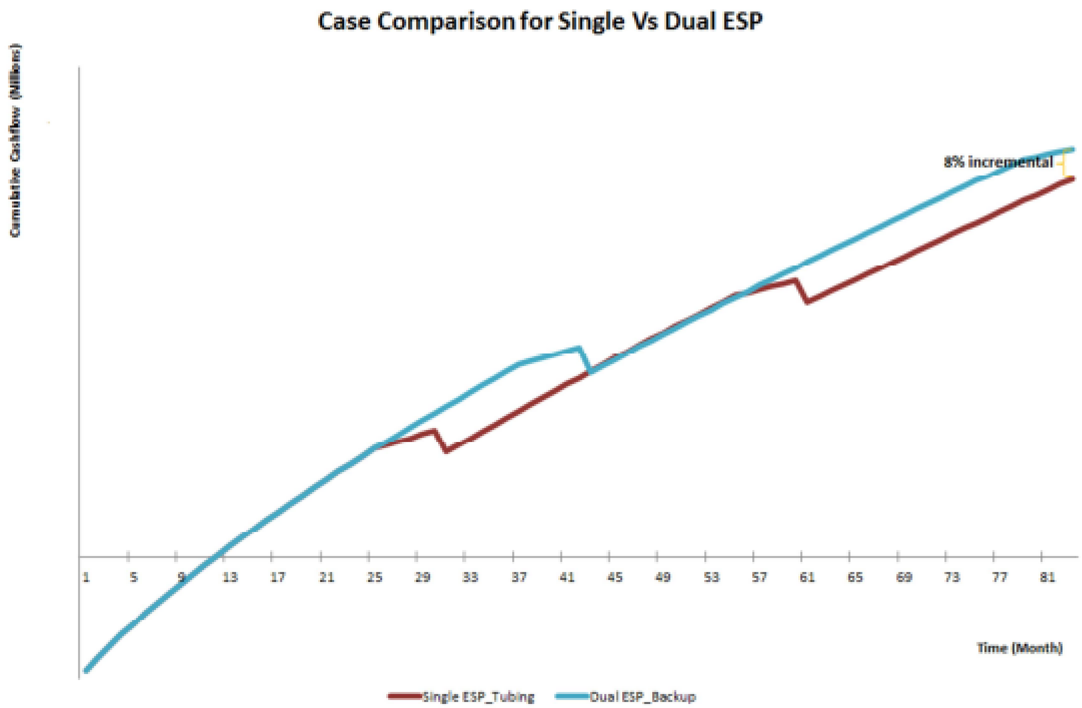

Figure 1.7 Comparison of single and dual ESP system

A cash flow comparison between ESP and dual ESP systems showed an 8% increment in cash flow for the dual ESP, indicating the effectiveness of using ESP as a backup for gas lift in these wells. This approach not only enhances cash flow but also extends the run life of the backup ESP system.

Hoy et al. (2016) introduced commingled production by a dual ESP system, which involves combining multiple reservoirs to accelerate production, is achieved using a dual ESP system in certain fields. An example from the Erdpress field in Austria illustrates the application of this technique to produce from close-together reservoirs. The challenge lies in planning well completion and production due to geological uncertainties. Candidate wells for the dual ESP system were selected to maximize production from the existing well stock. To ensure the success of the dual ESP system, critical pump design and stable flow are crucial, requiring a good understanding of fluid properties and reservoir parameters. The production history showed unusual behavior, necessitating careful analysis to achieve optimum ESP design for commingled production. Water cuts increased for the lower reservoir, while high productivity and GOR were observed in the upper one. When the well is shut-in, around 160 BBL/D of flow from the upper to the lower reservoir was calculated. However, the lower reservoir's target rate was 280 BBL/d based on the behavior of the reservoir. Therefore, a higher rate from the upper reservoir is necessary to achieve the required cash flow, which was difficult. Hence, it was decided that commingled production would only happen if the two reservoirs were separated.

Figure 1.*8* below shows the cash flow result at shut-in and dynamic conditions.

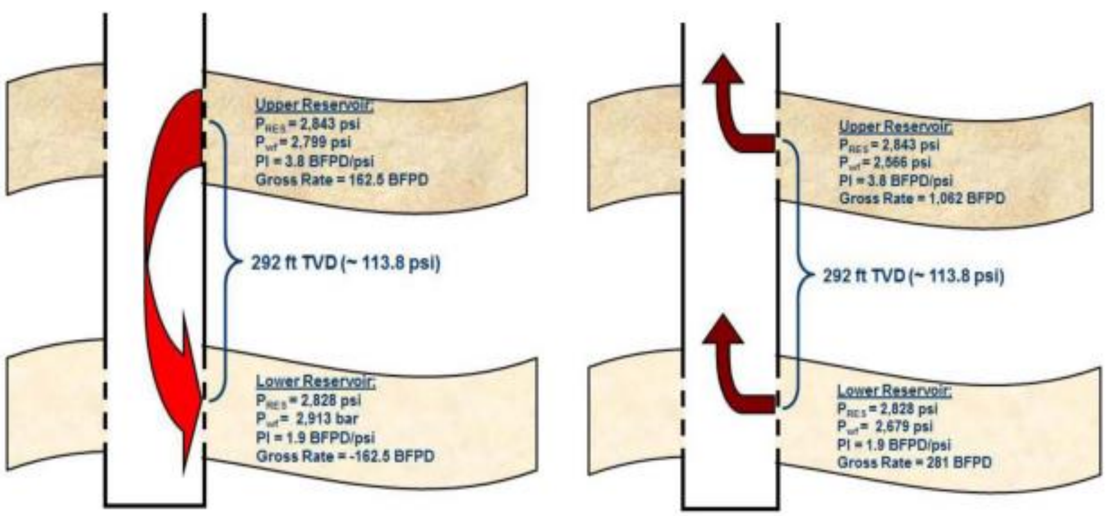

Figure 1.8 Production behavior at shut-in and dynamic conditions for Erdpress X

Despite initial challenges, the Y-tool ESP system successfully addressed issues and ensured proper flow distribution and stability with minimal intrusions. Overall, the implementation of the dual ESP system for commingled production proved to be beneficial for operators and vendors, offering an effective approach to enhance production rates and cash flow in the field.

Prabhu et al. (2022) conducted a study on using dual Y-tool ESP systems as a solution for wells experiencing variable flow conditions and frequent ESP failures in an offshore basin in India. The field had matured, and significant reservoir pressure decline had been observed over time. On the other hand, the Y-tool ESP system offered flexibility, enabling the selection of multiple pumps for the same well to handle changing flow conditions, high temperature, and gas-to-oil ratio (GOR). It also provided a wired tubing line below the ESP, allowing for easy production logging to check reservoir fluid properties. Additionally, the dual ESP system extended the operational life of the well, minimizing workover operations and reducing associated costs. By employing one ESP as a backup, the system ensured continuous production even in case of primary pump failure. To address the challenges, they tried the dual ESP system for the following well conditions:

Table 1.1 Well parameters for Y-tool ESP system

Parameters	Values
Well Temperature	240°F
Static Pressure	2791 psia
Productivity Index	1-3 BPD/psi
API	34-37
GOR	10-50 m^3/m^3
Water Cut	50-70%
Desired Flow Rate	1500-2500 BPD

In order to achieve the desired flow rate, one 3100-4000 horsepower pump is for the upper ESP, and one 1900-2500 horsepower pump is selected for the lower ESP. Motors are selected mostly based on the filed operating conditions so that the ESP has a longer range of operation. Sensitivity analysis is done for the required productivity index for the two ESP. Table 1.2 gives the summary of ESP design sensitivity analysis for different PI (Prabhu et al., 2022).

Table 1.2 ESP design parameter cases of productivity index

Upper ESP	PI (BPD/psi)	Flow (BBL/d)	Frequency (Hz)	PIP (psia)	Discharge Pressure (psia)	Motor Load (%)
Mid PI Design Case	2.21	2034	47	1118	2296	41
Low PI Design Case	1.33	1527	50	891	2290	40
High PI Design Case	3.1	2406	46.1	1221	2308	44
Lower ESP	PI (BPD/psi)	Flow (BBL/d)	Frequency (Hz)	PIP (psia)	Discharge Pressure (psia)	Motor Load (%)
Mid PI Design Case	2.21	1805	47.6	1240	2314	44
Low PI Design Case	1.33	1523	48.5	915	2312	44
High PI Design Case	3.1	2133	51	1369	2321	49

The study by Prabhu et al. (2022) focuses on the implementation of dual Y-tool ESP systems in oil wells to address ESP failures and optimize production. The primary ESP, located in the upper Y-tool, is backed up by a secondary ESP in the lower Y-tool. During workover operations, both ESPs can run at different intervals of time. Well testing is conducted to obtain production data, and simulations are performed to select the appropriate ESP based on the results and well conditions. Wireline operations are used to select the correct ESP, involving running both upper and lower Y-tools with banking plugs and analyzing their performance. Monitoring the ESP is also crucial, considering parameters like pump intake pressure, discharge pressure, and motor characteristics using a SCADA system to ensure the system's proper functioning.

The study compares a single ESP installation with a dual ESP setup. The single ESP failed due to electrical issues within a year, resulting in production loss and workover time. In contrast, the dual ESP installation, with the lower ESP acting as a backup, demonstrated a run life of over 500 days, three times longer than the single ESP.

Overall, the implementation of Y-tool ESP systems proved successful, offering benefits such as increased run life, reduced non-productive time, and improved production optimization. Although some challenges like decreased flow rate and changes in well parameters were observed, careful monitoring and standby options of the lower ESP effectively addressed these issues. The dual ESP setup was deemed economically viable, particularly in offshore environments with varying flow rate conditions (Prabhu et al., 2022).

According to Al-Kady et al. (2016) investigated an Egyptian water flood project. A sandstone reservoir field produced up to 70,000 STB/D for three years, but declining reservoir pressure caused a drop in production rates. To address this, water injection and natural flooding were considered, but high drilling costs were a challenge for water injection. An innovative solution involved using an Electrical Submersible Pump (ESP) with a bypass Y-tool system. The ESP pumped water from the upper zone to the lower injection zone, separated by a packer acting as a pressure barrier, ensuring the target injection rate was achieved. Many operational challenges are present in this well which are as follows:

- The injectivity of the hydraulically fractured lower zone was increased which did not produce accurate results and a new index could not be predicted.
- Challenges in operations which include the landing of tubing in the packer were to be done safely and the shear forces during the landing should be known.
- Unknown flow at the surface is an issue, as the full efficiency of the system is not checked.

The solutions are made:

- Sensitivity analysis is performed to design the required ESP design to achieve the target rate. A Variable Speed Drive (VSD) is also used to control the injection rate of the pump.
- Dealing with the operational challenges specifically for the landing of the tubing in the packer, a mule shoe was installed as a solution at the end of the bypass. A pump sub was present for dealing with the loss of any buckling forces during operation. Figure 1.9 below shows the flood system using Y-tool ESP (Al-Kady et al., 2016).

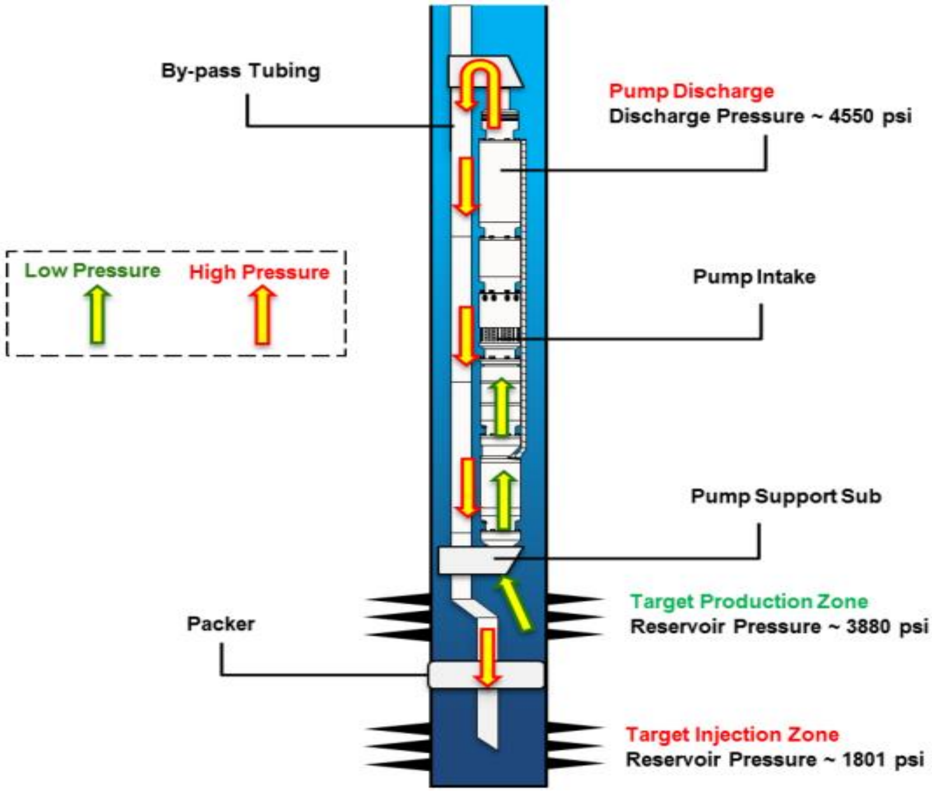

Figure 1.9 ESP flood application system

ESP was used as a solution for increasing the reservoir pressure and maintaining the target production rate and it happened as well for the injecting wells. The pressure readings in the downhole reading proved that the injection wells were present and both source wells showed instant effects. Monitoring the systems is gaining importance for operations that are happening daily and ESP gauges act as a monitoring tool for the reservoir (Al-Kady et al., 2016).

1.3 Failure Analysis of Y-tool ESP

The oil and gas industry recently has faced great challenges for operator companies all over the world. This mostly results in operations looking for opportunities to find more effective ways of increasing production by optimizing Electrical Submersible Pump operations. One main driver that is useful in extending the run life of ESP is to implement procedures. One key challenge is to identify problems that can directly affect ESP performance so that solutions can be used to avoid the failures of ESP. The failure is usually measured by a Failure Index (FI) which is the number of average intrusions in the field with ESP which are related to the wells which are active in the same period (Nunez et al., 2020).

Nunez et al. (2020) studied an oil production field in Columbia that has 450 active wells installed with ESP installed. They can handle between 50 BPD and 30,000 BPD but face problems with sand production and high water cut. These two problems provide many challenges for operators using ESP in the wells. One major challenge is to increase the run-life of an ESP cycle and check for the reliability of the pumps. Many approaches are taken to reduce the failure frequency of the ESP. One approach focused mainly on quick diagnosis of the operations of the ESP system for making important decisions concerning the ESP operations. This task is usually down to a combined work between the operator and the service companies that provide them with ESP systems. They summarize general challenges in Y-tool ESPs, i.e., fluid circulation, worn pump, and plugging.

Fluid circulation usually occurs because of holes being created at some point in time in the production pipes, wear in the pipes, and in the Y-tool which is due to the dismantling of the blanking plug (Zhu et al, 2021). Figure 1.10 shows the problems and leakage evidence which is done due to fluid recirculation given below.

Figure 1.10 Bottomhole extraction

Table 1.3 Behavior of parameters in failures

Parameter	Effect
PIP (Pump Intake Pressure)	Increases
PDP (Pump Discharge Pressure)	Decreases
Q (Surface Flow)	Decreases
WHP (Wellhead Pressure)	Decreases/Stable
M. Temp (Motor Temperature)	Increases
M. Amps (Motor Current)	Decreases/Stable

In this case, the parameters of the well behave in certain ways as above table. Pipe integrity tests can be carried out for this case by checking for pressure stability. The Y-tool can be run through a slick line in this case and by injecting the fluid, pressure is maintained up to the point. Operating equipment can be avoided with fluid velocity increased up to 12 ft/s. For this condition, well intervention is necessary to perform which includes checking pipe quality, and blanking plug's quality test to avoid corrosion and pipe reuse problems (Nunez et al., 2020).

Figure 1.11 Evidence of wear in equipment

Figure 1.11 shows wear on ESPs. A worn pump can be caused by deposits of wax and asphaltenes and sand production. Well, intervention is important in this case. It is required to design the fault's origin again if required like scaling, sand, and solids like Paraffin and Asphaltenes. The operation of an ESP component needs to be checked and it is required to evaluate the installation of any other ESP control system like sand. The pump operation parameters behave as below:

Table 1.4 Behavior of parameters in worn pumps

Parameter	Effect
PIP (Pump Intake Pressure)	Increases
PDP (Pump Discharge Pressure)	Decreases
Q (Surface Flow)	Decreases
WHP (Wellhead Pressure)	Decreases/Stable
M. Temp (Motor Temperature)	Increases
M. Amps (Motor Current)	Decreases/Stable

A pump plugging case occurs when high sand production results in the decantation of sand until it causes any sort of obstruction or causes any plugging in the ESP pump thus restricting the fluid movement. Many production pipe joints are found above the plugged ESP equipment due to severities, which may require workover jobs to improve the ESP system. Figure 1.12 shows an example of a pump plugging in the bottom hole assembly causing a failure of a Y-tool ESP.

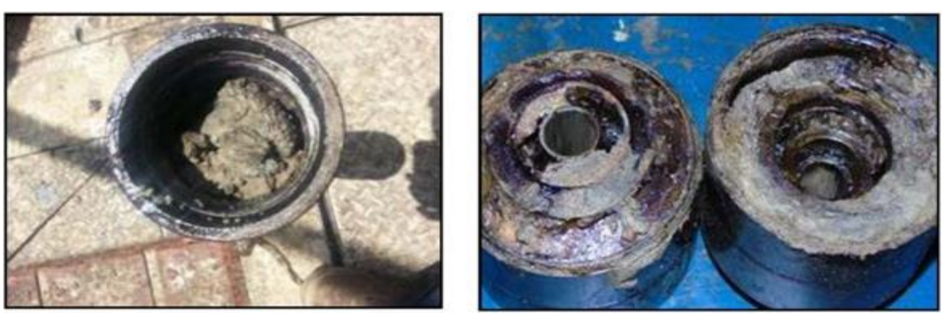

Figure 1.12 Evidence of pump plugging in assembly

The indication of plugging can be seen in Table 1.5. In wells with plugging, acceleration ramps are required. More pressure is suggested by the ESP operator along with us higher volumetric flow stages is also suggested (Nunez et al., 2020).

Table 1.5 Behavior of parameters in pump plugging

Parameter	Effect
PIP (Pump Intake Pressure)	Increases
PDP (Pump Discharge Pressure)	Decreases
Q (Surface Flow)	Decreases/Absence of flow/Flow fluctuation
WHP (Wellhead Pressure)	Decreases
M. Temp (Motor Temperature)	Increases
M. Amps (Motor Current)	Decreases

CHAPTER 2

Y-TOOL ESP CASE SETUP

In this study, the steady-state software "PIPESIM" is used to simulate the One ESP and Y-tool ESP systems. The purpose of this simulation is to conduct a sensitivity analysis to evaluate parameters like reservoir pressure, productivity index, motor frequency, PIP, and motor cooling. The results can guide future Y-tool ESP design for the field.

2.1 Introduction

The selection of artificial lift methods primarily relies on a comprehensive evaluation of reservoir conditions, fluid characteristics, and well-operating conditions. In Kuwait, over 90% of wells necessitate artificial lift techniques to achieve economical oil and gas production rates. Among these methods, ESPs have become prevalent due to their effectiveness. ESPs are employed to counteract bottom hole pressure, enabling the wells to attain the desired production rates economically.

The ESP system is only a partial solution for operators in Kuwait. Although the ESP operators can obtain accurate diagnoses and secure corrective actions, the identified problems require immediate action. For this reason, some wells especially in multiple zone regions are equipped with a Y-tool to deal with these problems. The Y-tool is used to treat or work below the ESP through a bypass system, which has the advantage of adding new perforations, identifying oil and water zones, and sample collection. However, several challenges arise when employing the ESP system, including free gas in oil-water wells due to low PIP and motor cooling due to low flow rate. The increasing depths of wells further compound the challenges faced by ESP systems. To address these concerns, a sensitivity analysis of Y-tool ESP systems is essential to determine the best ESP solution procedure.

2.2 PIPESIM Y-ESP Case Setup and Parametric Study

An onshore well data is provided with two layers close to each other. The two layers have the same reservoir pressure but relatively different productivity index. The main objective of the case study is to evaluate important affecting factors. The objectives of the simulation to achieve the following results:

- Simulation of producing from the single zone.
- Simulation of producing from multiple zone reservoir using dual Y-tool ESP.
- Observe the reservoir depletion effect and pressure change in the two reservoirs.
- Parametric study of different affecting factors.
- Observe and achieve results for the Y-tool ESP system and check for failure analysis.

In this study, the well and reservoir information is provided by KOC. The wellbore trajectory is provided in Figure 2.1. The lower ESP is installed at 8235 ft., while the upper ESP is located at 7500 ft. The connection point is at 6500 ft.

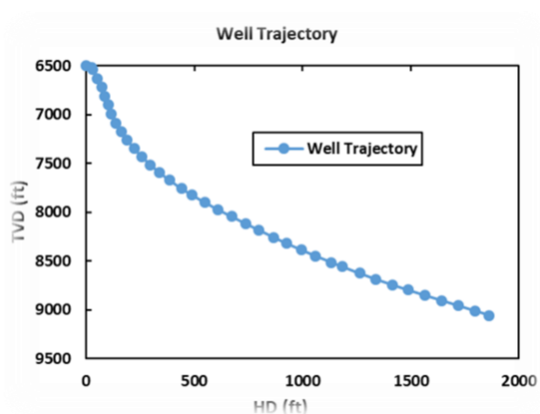

Figure 2.1 Wellbore trajectory of wells

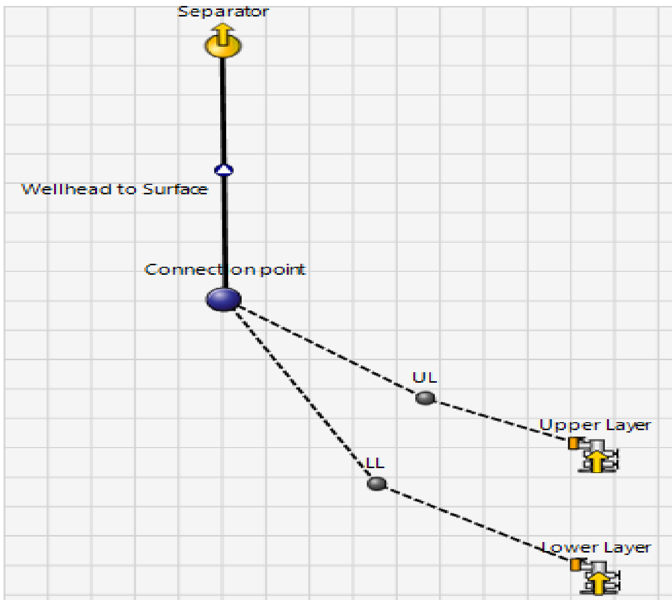

Figure 2.2 Y-tool setup of two ESP of two formations in one wellbore

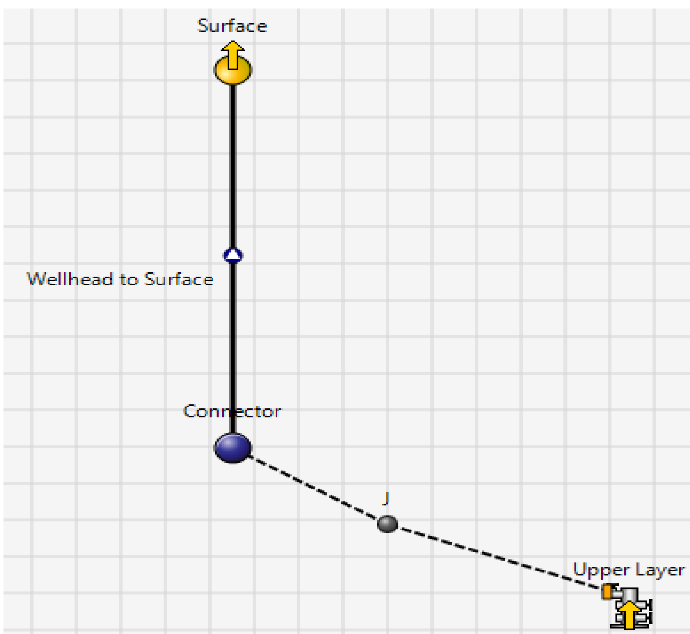

Figure 2.3 One ESP setup in the same well

Figure 2.2 gives the geometry of the two layers for a Y-tool ESP system from the reservoir to the surface. A connection point represents the combined point of the Y-tool equipment. The geometry setup for the one ESP system is made similarly and is given in Figure 2.3. Table 2.1 gives the gas composition of the well.

Table 2.1 Fluid composition for two layers

Composition	Mole %
N_2	11.86
CO_2	39.99
H_2S	8.1
C1	33.48
C2	2.4
C3	0.53
i-C4	0.06
n-C4	0.22
i-C5	1.18
n-C5	0.22
C6	0.50
C7	0.73
C8	0.56
C9	0.17
C10	0.02

Table 2.2 gives the data and reservoir inputs of the two layers for the PIPESIM case setup.

Table 2.2 Initial data for PIPESIM simulation

Parameters	Upper Layer	Lower Layer
Reservoir Pressure (psia)	2000	2200
Productivity Index (STB/D/psi)	3	6
Initial Liquid Flow Rate (STB)	1100	1300
Reservoir Temperature (°F)	180	180
GOR (SCF/STB)	150	150
Motor Frequency (Hz)	50	50
ESP Name	CENTRILIFT P11	REDA GN1300
ESP Depth (ft.)	7500	8235
ESP Stages	206	194
Y-tool Connection Depth (ft.)	6500	6500
Production Casing ID (in)	8.681	8.681
Tubing ID (in)	2.992	2.992
Water Cut (%)	61	61

The lower layer produces a higher productivity rate for three years with ESP REDA GN1300. The pump is designed and selected by KOC with a capacity from 1600-3200 STB/D. On the other hand, since the upper layer is not produced during these years, only recommendation is provided. Detailed design and comparison are conducted in this study.

2.3 Parametric Study Data Inputs

The parametric study can be used to study different pressure changes for the dual ESP system and compare it with a single ESP system. The parameters involved in the sensitivity analysis of a dual Y-tool ESP system are reservoir pressure, motor frequency, Gas Oil Ratio (GOR), water cut, viscosity, and pump design. A range of these parameters is provided in the table below to observe the results for different scenarios.

Table 2.3 Parametric table for upper and lower layers

Layers	Reservoir Pressure (psia)	Productivity Index (STB/D/psi)	Pump Frequency (Hz)	GOR (SCF/STB)	Water Cut (%)	Viscosity (cP)
Upper	2000-750	6	45-60	150-1500	20-80	8-1000
Lower	2200-850	3	45-60	150-1500	20-80	8-1000

Table 2.3**Error! Reference source not found.** lists the range of simulated parameters. The parametric study is conducted by changing one parameter while keeping others the same. Firstly, the reservoir pressure effect is investigated step by step until one layer stops producing. Then the same reservoir declining matrix is incorporated into other parameter sensitivity studies individually. A detailed simulation matrix for each parameter is introduced in this section. These parameters are important in getting the production results and comparing the run life of the Y-tool ESP system with a single ESP system. The results obtained will help in providing the best possible ESP design procedure which is provided in Chapter 3.

2.3.1 Reservoir Properties: depleting reservoir pressure effect

The reservoir pressure of both layers decreases from 2000 to less than 1000 psia to determine how the ESP will affect production in both cases. Table 2.4 gives the data inputs for the parametric study of reservoir pressure.

Table 2.4 Parametric data for reservoir pressure

Parameters		Case A	Case B	Case C	Case D	Case E	Case F
Reservoir Pressure (psia)	UL	2000	1800	1550	1350	900	750
	LL	2200	2000	1700	1500	1000	850
Productivity Index (STB/D/psi)	UL	3	3	3	3	3	3
	LL	6	6	6	6	6	6
ESP Name	UL	P11	P11	P11	P11	P11	P11
	LL	GN1300	GN1300	GN1300	GN1300	GN1300	GN1300
ESP Stages	UL	206	206	206	206	206	206
	LL	194	194	194	194	194	194
Pump Speed (Hz)	UL	50	50	50	50	50	50
	LL	50	50	50	50	50	50

2.3.2 Motor Speed Analysis

In this study, the motor speed is changed to observe the change in production rates and ESP run life. As shown in Table 2.5, fluid properties are kept constant and only reservoir pressure and motor frequencies (underlined) are changed accordingly. Twelve parametric cases in Table 2.6 are conducted to observe motor frequency effects on both layers. One layer's motor frequency is changed to observe the results on the other layer.

Table 2.5 Parametric data for motor frequency

Layers	Reservoir Pressure	Productivity Index	Pump Frequency	GOR (SCF/STB)	Water Cut (%)	Viscosity (cP)
Upper	<u>2000-750</u>	6	<u>40-60</u>	150	61	8
Lower	<u>2200-850</u>	3	<u>40-60</u>	150	61	8

Table 2.6 Simulation matrix table for motor frequencies

Parametric	UL MF (Hz)	LL MF (Hz)	UL PR (psia)	LL PR (psia)
1	45	45	2000	2200
2	50	50		
3	55	55	1800	2000
4	60	60		
5	50	45	1600	1700
6	50	55		
7	50	60	1350	1500
8	45	50		
9	55	50	900	1000
10	60	50		
11	55	60	750	850
12	60	55		

2.3.3 GOR Effect Analysis

High GOR impacts the ESP system. Therefore, a parametric study is conducted for high GOR as well. Table 2.7 and gives the varying GOR for both layers to see the effect on other layer's fluid flow behavior.

Table 2.7 Parametric table for GOR

Varying upper layer GOR			Varying lower layer GOR		
Parametric	Upper layer GOR	Lower layer GOR	Parametric	Upper layer GOR	Lower layer GOR
1	150	150	1	150	150
2	300	150	2	150	300
3	450	150	3	150	450
4	600	150	4	150	600
5	1500	150	5	150	1500

2.3.4 Viscosity Effect Analysis

A parametric study for high to low viscosity is done to observe the viscosity behavior in in-situ and standard conditions. Table 2.8 gives the varying viscosity for both layers to see the effect on other layer's production and other factors.

Table 2.8 Parametric table for viscosity

Varying upper layer GOR			Varying lower layer GOR		
Parametric	Upper layer viscosity	Lower layer viscosity	Parametric	Upper layer viscosity	Lower layer viscosity
1	8	8	1	8	8
2	12	8	2	8	12
3	100	8	3	8	100
4	500	8	4	8	500
5	1000	8	5	8	1000

2.3.5 Water Cut Effect Analysis

The inversion water cut is set at 60% default in PIPESIM. Table 2.9 and gives the varying water cut for both layers to see the effect on other layers.

Table 2.9 Parametric table for water cut

Varying upper layer GOR			Varying lower layer GOR		
Parametric	Upper layer WC, %	Lower layer WC, %	Parametric	Upper layer WC, %	Lower layer WC, %
1	20	61	1	61	20
2	50	61	2	61	50
3	61	61	3	61	61
4	80	61	4	61	80

2.3.6 Pump Design Analysis

The ESP case study shows that the lower layer is not producing at low reservoir pressure. To have a better ESP design analysis, a new case study is made by selecting a new pump, with higher flow capacity and more stages, for the lower layer. Therefore, the upper layer and lower layer can produce and shut down at the same time. Table 2.10 shows the changed parameters in this study, i.e., reservoir pressure and pump.

Table 2.10 Parametric table for new pump design

Layers	Reservoir Pressure (psia)	Productivity Index (STB/D/psi)	Pump Frequency (Hz)	GOR (SCF/STB)	Water Cut (%)	Viscosity (cP)	Pump
Upper	2000-750	6	50	150	61	8	Centrilift P11
Lower	2200-850	3	50	150	61	8	REDA D2150N

CHAPTER 3

RESULTS AND DISCUSSION

The Y-tool ESP system is simulated by PIPESIM to study the production of the two layers and the performance of the two ESP used in the simulation. The results obtained will be discussed in this chapter. Parametric studies are conducted to study the different reservoir conditions including pressure and productivity index, GOR, water cut, viscosity, and pump design. The results are introduced separately in this chapter. All simulation results are included in the appendix.

3.1 Reservoir Properties: Reservoir Pressure

The first parametric study analyzes the declining reservoir pressures for the two layers given in Table 2.4 to study the production graph and ESP effect to compare present and future data.

Nodal analysis is important to observe the pressure envelopes of the two layers. The Outflow Performance Relationship (OPR) of the two layers is going down with a decrease in the reservoir pressure. While using a Y-tool ESP case for multiple reservoir zones, it is important to evaluate the ESP's work life and failure analysis. Many factors could result in the early stop of the simulation, e.g. reverse flow in ESP or extreme temperature or pressure. The analyzed parameter includes intake pressure, Intake Gas Volume Fraction (GVF), oil viscosity, and motor velocity. The Nodal Analysis of the two layers is given in Figure 3.1 and Figure 3.2 below:

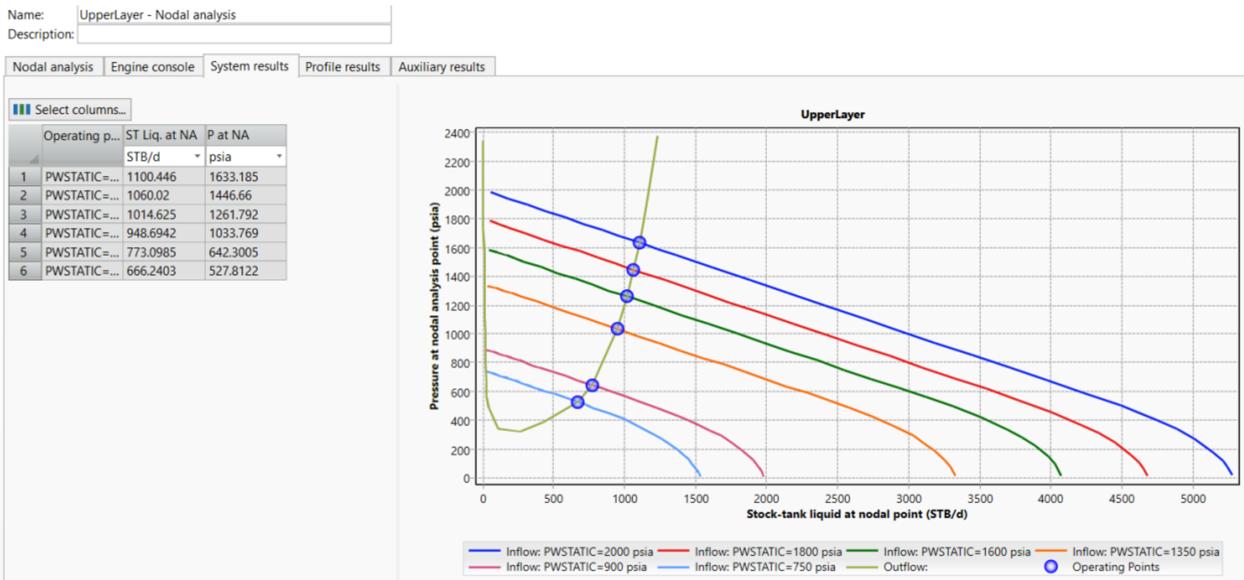

Figure 3.1 Nodal Analysis of the upper layer at 50 Hz

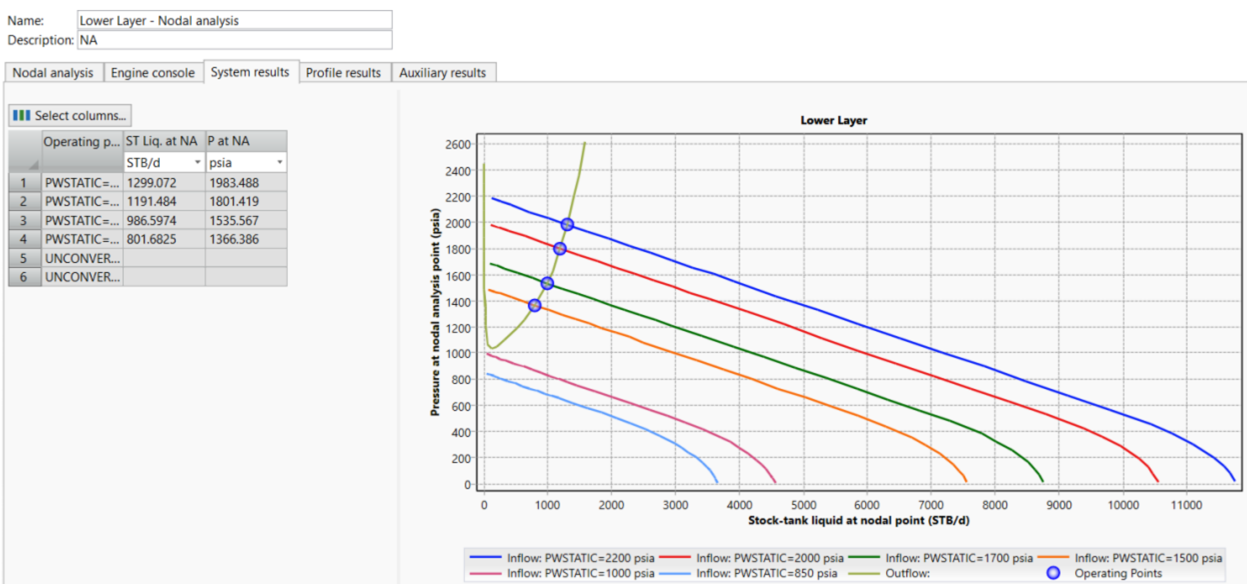

Figure 3.2 Nodal Analysis of the lower layer at 50 Hz

ESP design procedure is important while determining the ESP characteristics required for the well. A comparison between single and Y-tool ESP systems can give an idea for the operator to choose the better option between the two artificial lift methods. For this purpose, a single ESP system simulation was done for two layers separately using PIPESIM software, and results were compared with the Y-tool ESP simulation. Liquid production and pump intake pressure are two important results to see in an ESP producing well. Table 3.1 and Table 3.2 gives the comparison of both layers' production and PIP for one ESP and Y-tool ESP case.

Table 3.1 Flow rate comparison of both layers for one ESP and Y-tool ESP system

Pres (psia)	LL Q_L Y-tool (STB/D)	LL Q_L One ESP (STB/D)	Diff (%)	Pres (psia)	UL Q_L Y-tool (STB/D)	UL Q_L One ESP (STB/D)	Diff (%)
2200	1296	1315	-1.471	2000	1102	1104	-0.181
2000	1156	1209	-4.583	1800	1045	1062	-1.673
1700	946	1007	-6.425	1600	1001	1014	-1.27
1500	766	842	-9.915	1350	938	949	-1.16
1000	None	None	None	900	768	759	+1.212
850	None	None	None	750	623	650	-4.372

Table 3.2 PIP Comparison of both layers for one ESP and Y-tool ESP system

Pres (psia)	LL PIP Y-tool (psia)	LL PIP One ESP (psia)	Diff (%)	Pres (psia)	UL PIP Y-tool (psia)	UL PIP One ESP (psia)	Diff (%)
2200	1688	1678	+0.477	2000	1175	1165	+0.838
2000	1507	1498	+0.582	1800	990	980	+1.34
1700	1243	1233	+0.806	1600	803	770	+4.418
1500	1074	1064	+0.923	1350	578	570	+1.363
1000	None	None	None	900	217	231	-6.369
850	None	None	None	750	151	156	-3.235

The well with single ESP has more production rate than Y-tool ESP. But the advantage of Y-tool ESP is that it is used in multiple zone completion, while the decrease of each layer's production rate is neglectable in the ideal flow condition. As shown in the two tables, the lower layer production rate decreased more compared to only producing from that layer. It is presumably due to the higher production index of this layer. Therefore, any change in the flowline has more effect on the production compared to the lower production index layer (upper layer). On the other hand, the PIP in both cases increased slightly, indicating the pressure drawback at the bottom hole slightly increased. The result agrees with the decrease in production rate. More results can be found in the appendix.

The pressure profile is given in Figure 3.3, and the critical limit of PIP is 750 psia due to the gas composition. The PIP for both layers decreases with the reservoir pressure, and it is below the critical limit for the last cases for the upper layer. As a result, free gas may enter the pump below the pump. However, the pump performance is not severely affected in the simulation, which could be due to the low GOR of this field and the homogenous ESP model used in PIPESIM. More studies on the gas effect will be concluded in section 3.3. The lower layer is unable to produce although PIP is still above the critical point. The early shutdown of the lower layer is mainly due to the pump capacity.

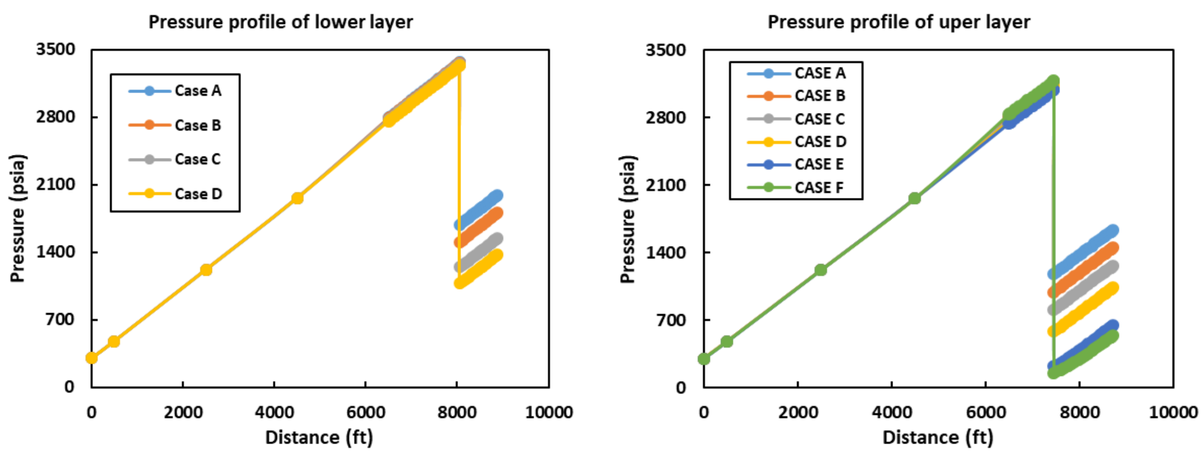

Figure 3.3 PT Profile of two layers for different reservoir pressure

Figure 3.4 gives the production decline graph for the two layers. The lower layer production decreases much more rapidly than the upper layer production and does not produce below the PIP critical limit. The upper layer produces at low reservoir pressure, but the PIP goes below the critical limit which could result in gas issues for the future life of the well. The two layers do not reach the PIP critical limit at the same time and the lower layer comes to a premature shutdown in production. Increasing the pump's working speed can temporarily solve the problem. But in the future, the lower layer will always stop producing earlier than the upper layer due to the pump capacity. Redesigning the pump, for example, increasing the pump stage number or working range is necessary to help keep the production of both layers. Overall, in the studied case, the lower layer stops producing first and its ESP needs to be replaced. The Y-tool design is less efficient.

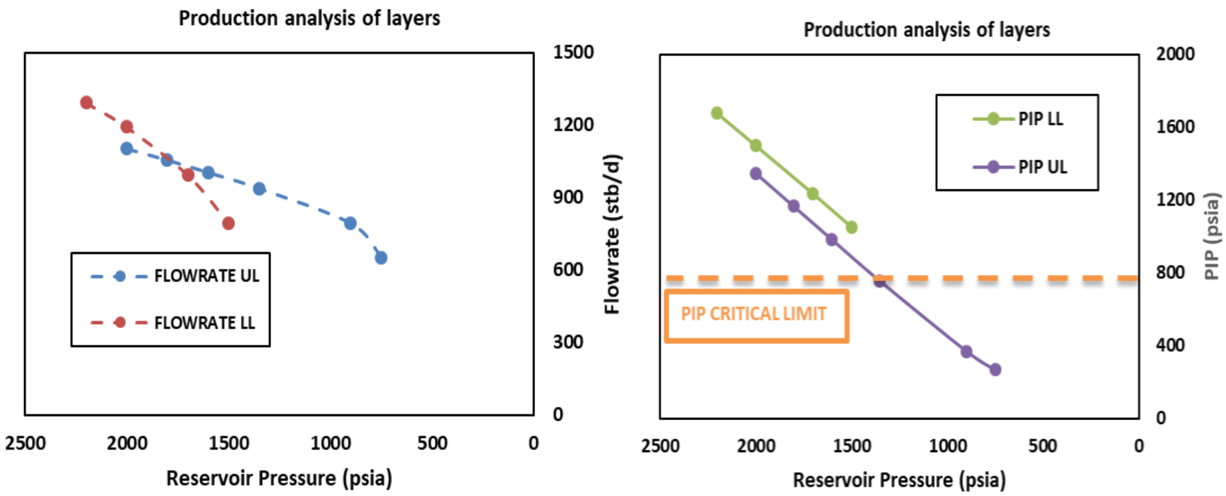

Figure 3.4 Production analysis of two layers

Figure 3.5 shows the PDP graph for the two layers, which is another proof of the pump capacity limitation in the lower layer. The upper layer's PDP is constant at all reservoir pressure, while the lower layer's PDP starts to decrease at a certain point. As a result, the lower layer's ESP cannot provide enough boosting pressure to match the Y-tool connection point's pressure. Therefore, the lower layer stops producing, or it may even have a reverse flow from the upper layer to the lower layer. Due to the limitation of PIPESIM's ESP model, the reverse flow cannot be calculated in this study.

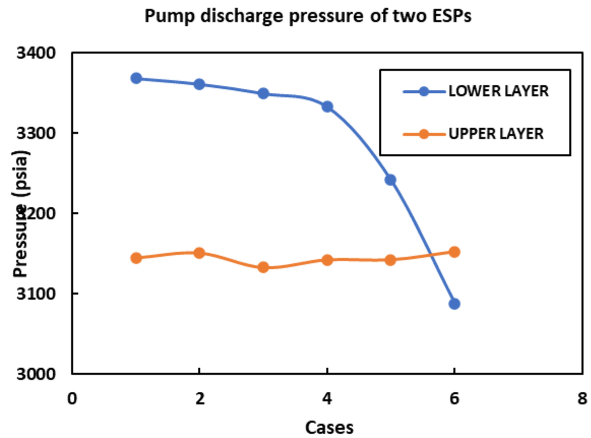

Figure 3.5 Pump discharge pressure of two layers

Motor temperature is also an important factor for ESP. It directly affects the fluid properties and the bottom hole pressure. The optimum fluid velocity for Y-tool ESP is set at 1 ft/s according to field experience. When the fluid velocity is below 1 ft/s, the pump motor may be heated up, causing tripping. Gas presents may also result in the temperature increase of the pump motor. However, due to the limitation of the PIPESIM simulator, this effect cannot be considered. And future studies should focus on how to include the gas and fluid property effect on motor cooling problems. Figure 3.6 gives the fluid velocity around two ESP motor, which is indicated as motor velocity. It is below the limit as the production decreases with the declining reservoir pressure for the upper layer.

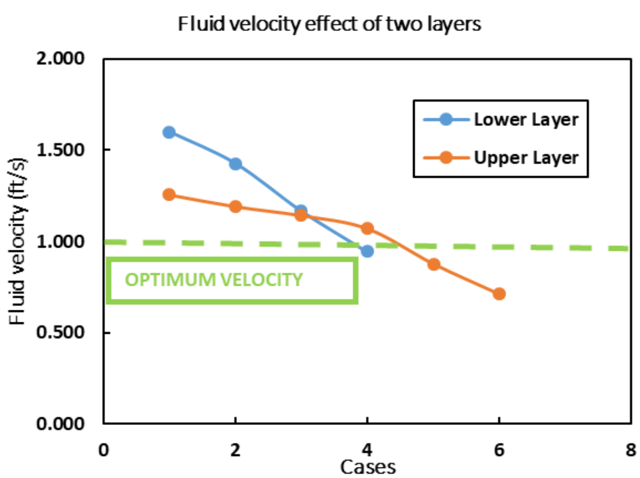

Figure 3.6 Fluid velocity effect of two layers

3.2 Motor Speed Analysis

The simulated test results are summarized in the appendix. The results obtained from the parametric study are liquid and gas production, PIP, bottom hole pressure, and motor velocity. The production is higher with higher motor speed. Figure 3.7 and Figure 3.8 gives the nodal analysis example of the two layers for different motor frequencies when the reservoir pressures of the upper layer and lower layer are 1000 psia and 900 psia, respectively.

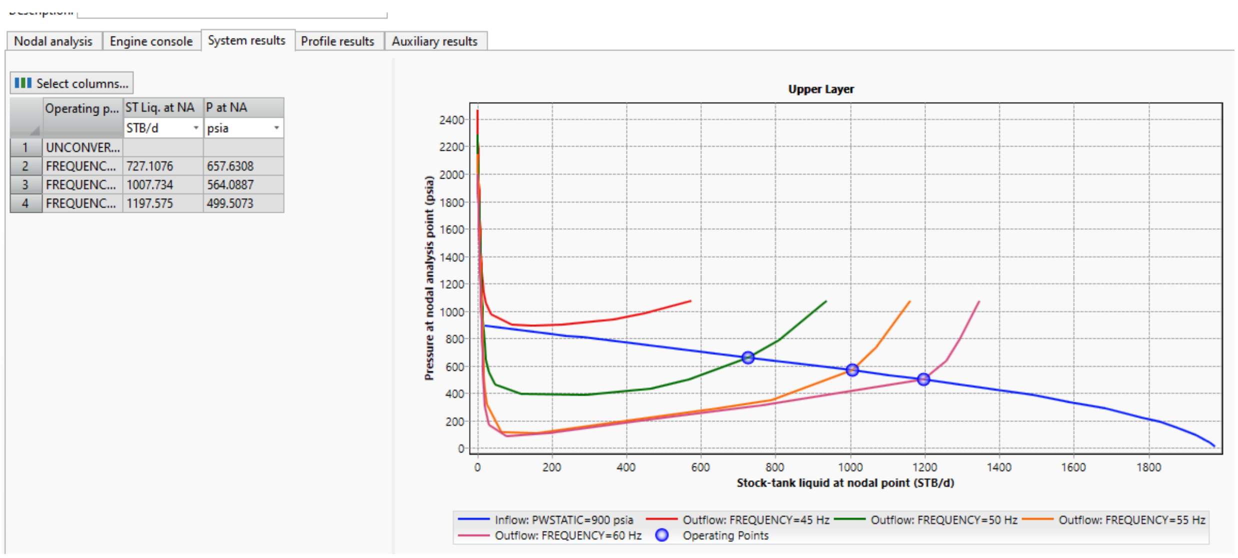

Figure 3.7 NA of the upper layer at different motor frequencies

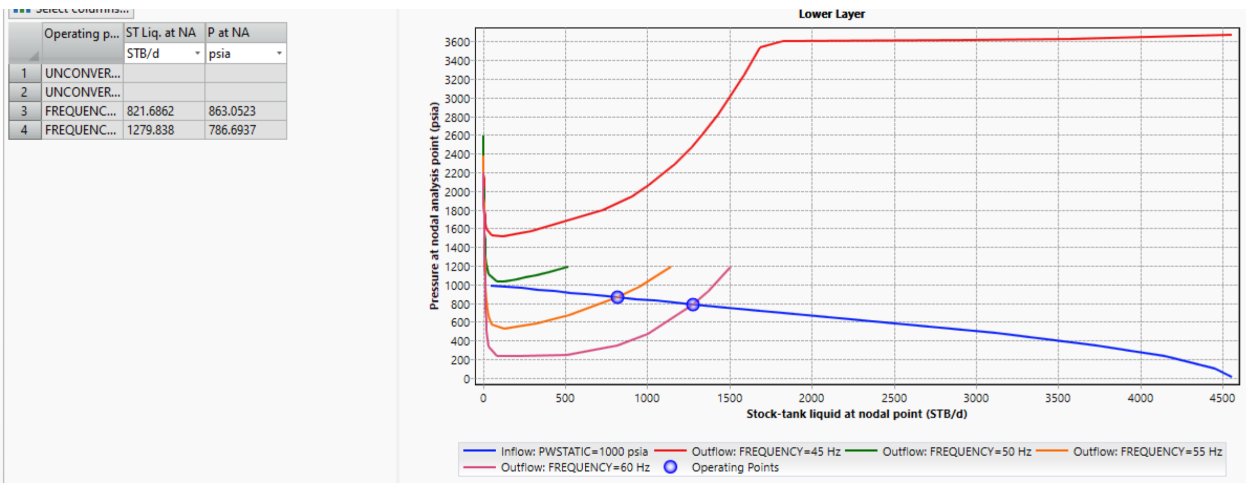

Figure 3.8 NA of the lower layer at different motor frequencies

Figure 3.9 and Figure 3.10 gives the production and PIP analysis of the upper and lower layer. At 45 Hz, the lower layer is unable to produce when the reservoir pressure is below 1700 psia. The upper layer can produce at low pressure, but it is still below the PIP critical limit which could create gas issues. The two layers are producing at higher frequencies of 55 and 60 Hz but the PIP is decreasing much rapidly and is below the critical limit.

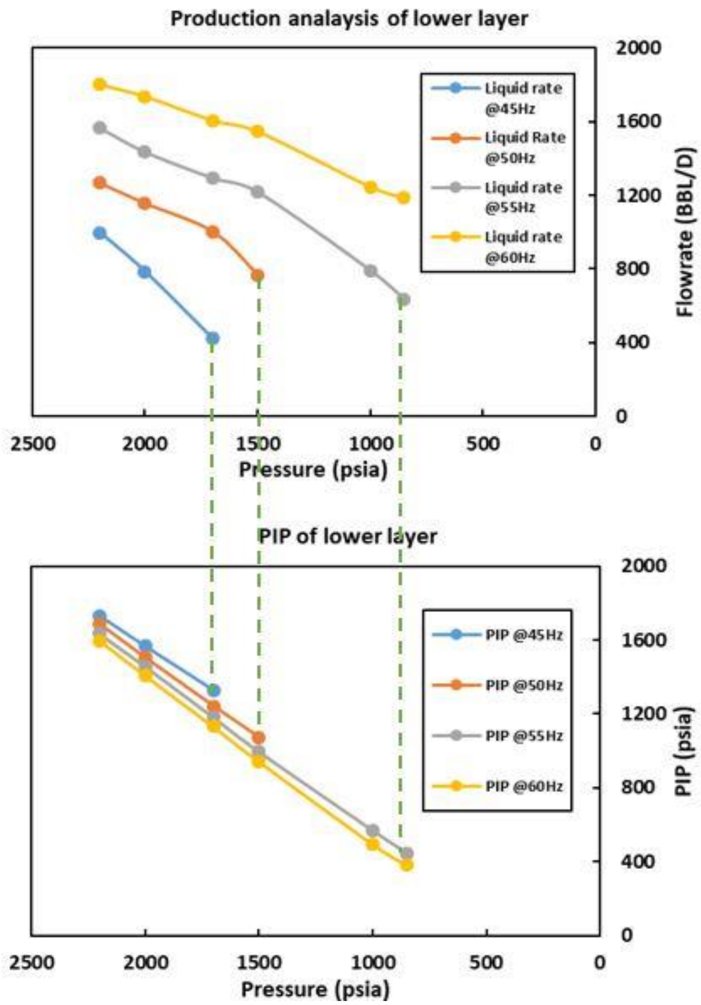

Figure 3.9 Production analysis of the lower layer for motor speed analysis

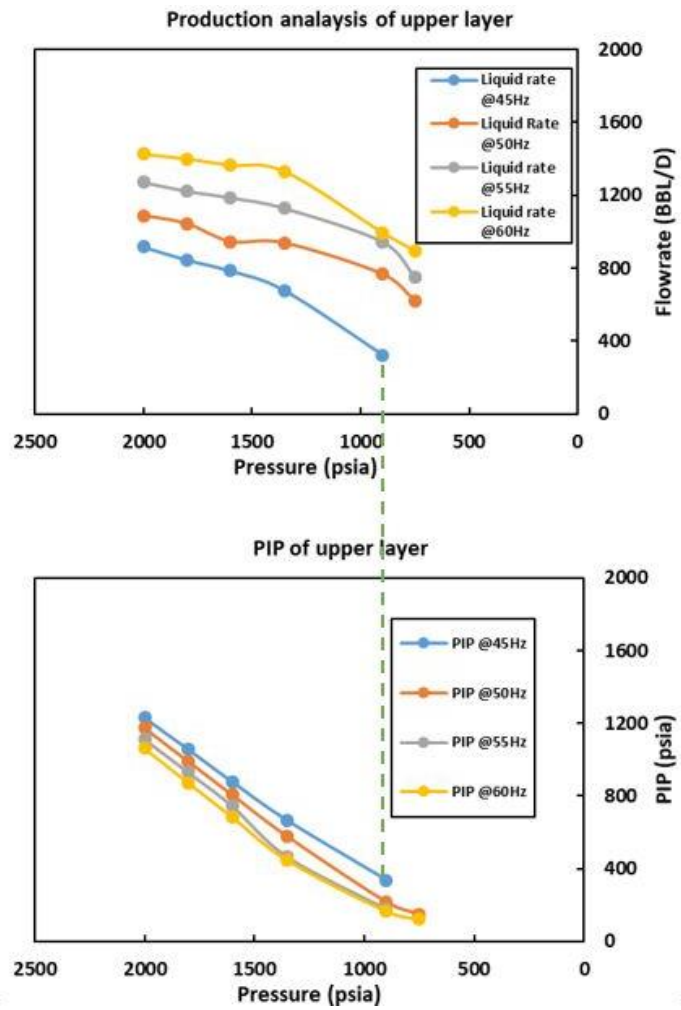

Figure 3.10 Production analysis of the upper layer for motor speed analysis

The fluid velocity along the motor for two layers is given in Figure 3.11 at different speeds. At lower frequencies, the fluid velocity is too low as the production rate is very low. In order to have an optimum fluid velocity, it is better to operate at higher frequencies. Obviously, when the lower layer stops producing while the upper layer can still produce, one solution is to increase the pump operating speed.

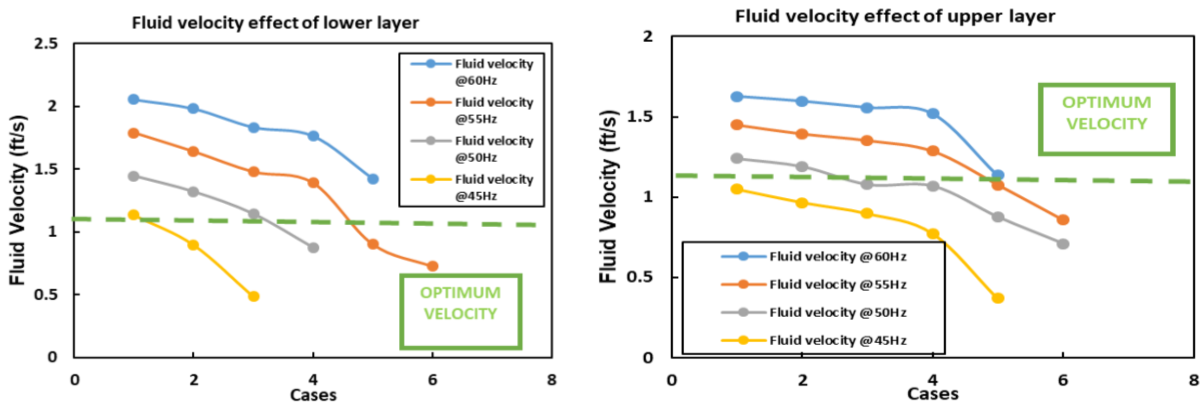

Figure 3.11 Fluid velocity analysis of both layers for motor speed

3.3 GOR Effect Analysis

Gas entrainment in the pump can cause a failure in the pump or loss of production. A parametric study was conducted, and liquid flow rate and pump intake pressure results were compared for lower to higher GOR. The effect of GOR on the lower layer by changing the upper layer is important to be determined if it is resulting in the lower layer's shutdown or production degradation. Simulation results for the 8 parametric study with different GOR values of the two layers are given in the appendix.

The effect of upper layer GOR on both layers' production is shown in Figure 3.12. Although only the upper layer's GOR is increased, both layers' production decreases. The lower layer's production even decreases more, presumably due to its higher production index.

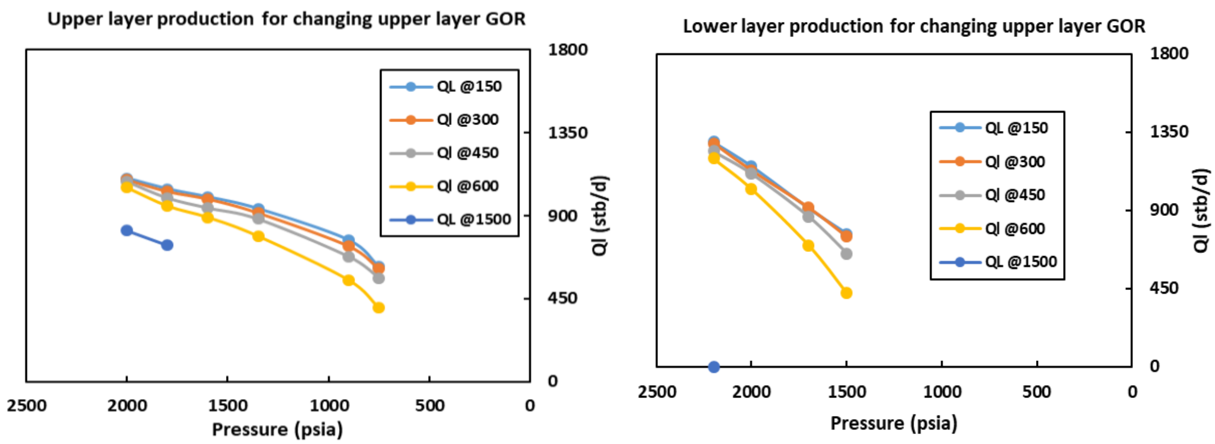

Figure 3.12 Liquid production for different upper layer GOR

The effect of lower layer GOR on both layer production is shown in Figure 3.13. The upper layer production also decreases with a change in lower layer GOR and simulation stops at a high GOR of 1500 SCF/STB. The gas intake in the pump might cause a loss of production in the system and a decrease in liquid holdup.

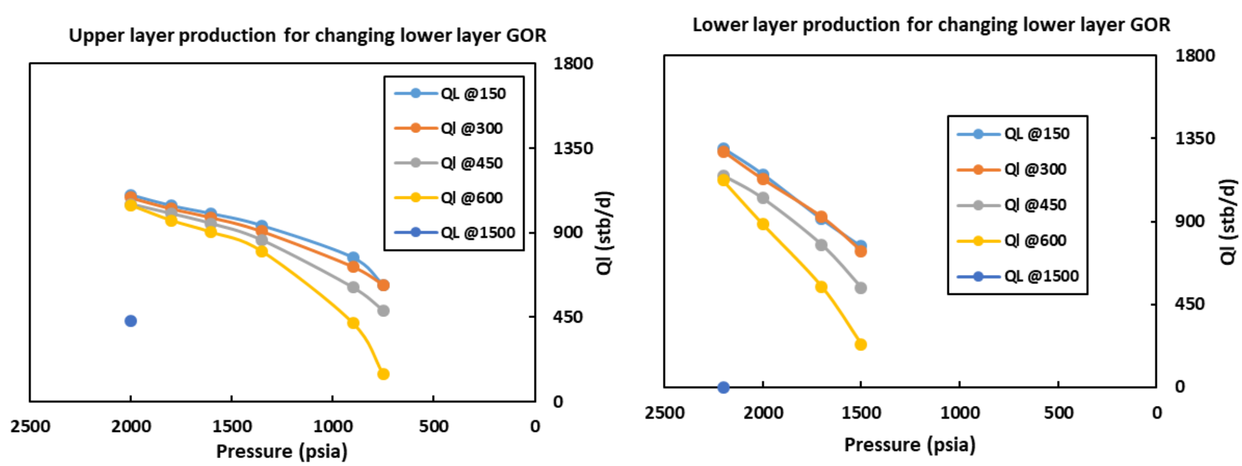

Figure 3.13 Liquid production for different lower layer GOR

Figure 3.14 shows the pressure profile of the upper layer when its reservoir pressure is 1700 psia. Since fluid mixture density decreases with GOR, and gravitational pressure loss dominates the fluid flow in the vertical wellbore, the pressure drop along the wellbore decreases with the increase of GOR, causing the decrease of the connection point pressure and PDP. On the other hand, although the mixture density decreases, the pressure drop in the horizontal wellbore is not significantly affected by the GOR and density. In addition, in most cases, the gas void fraction is low due to the high bottom hole in-situ conditions, and the gas is compressed in the liquid phase. Therefore, PIP is not affected in the simulated cases, and the pump boosting pressure decreases with the GOR.

According to the pump water catalog, the flow rate should increase with the decrease of the pump boosting pressure. However, it is the opposite in the simulation as shown in the figures below, which indicates there is free gas at pump intake and reduces pump boosting ability.

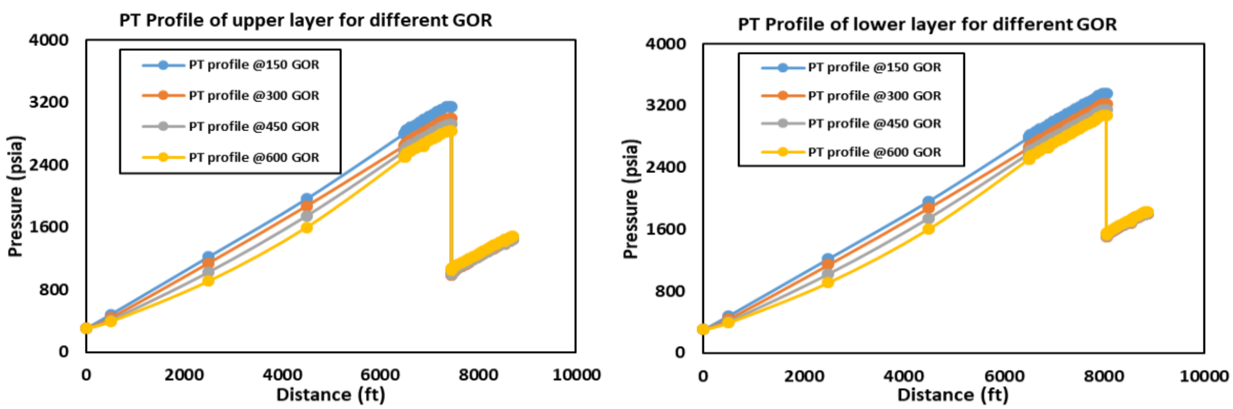

Figure 3.14 PT profile of two layers at different GOR values

As discussed, it is crucial to investigate the pump intake free gas void fraction. Therefore, Figure 3.15 use an example to show the liquid holdup of the two layers. The liquid holdup decreases as GOR decreases. The high pump intake GVF is presumably the reason for pump performance degradation discussed before. Although pump performance is already reduced in PIPESIM simulation due to the presence of the free gas at its intake, the real scenario may be worse due to gas lock and gas cavitation since the PIPESIM default ESP model is the simplified homogenous model. A more accurate ESP gas-liquid flow model should be incorporated into the future study.

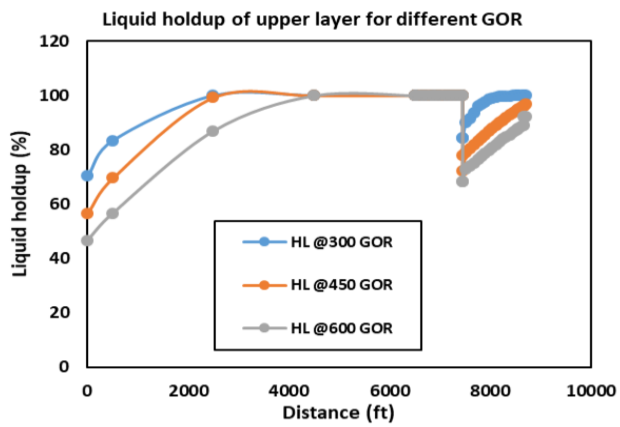

Figure 3.15 Liquid holdup of upper layers at different GOR values

Gas entrainment in the pump can cause a failure or loss of production. Figure 3.16 gives the percentage decrease in production for both layers when changing the upper layer GOR. Changing the upper layer's GOR only reduces its production by up to 30%, while will decrease the lower layer's production by up to 50%. This is a piece of evidence that one layer's fluid properties will have a significant effect on the other layer.

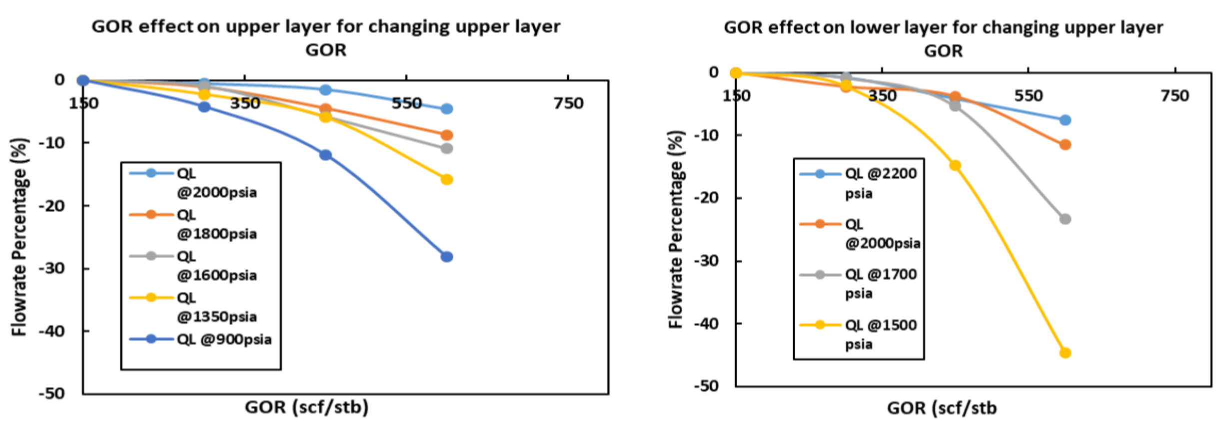

Figure 3.16 Percentage changes in both layers' productions at different GORs of the upper layer

On the other hand, changing the lower layer's GOR has a more obvious effect on its production, reducing up to 75%. It also has more effect on the upper layer as well. Similarly, the different effects from upper layer and the lower layer may be due to their production index.

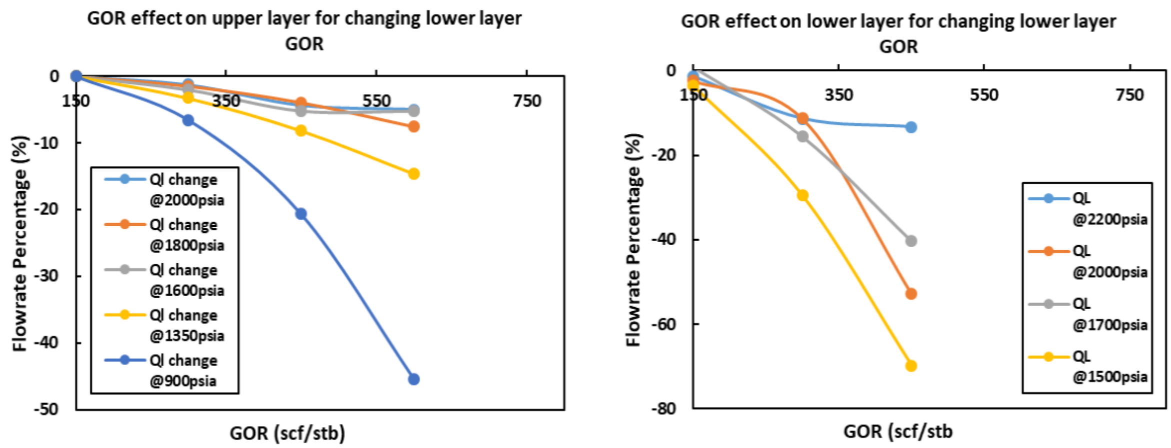

Figure 3.17 Percentage changes in both layers' productions at different GORs of the lower layer

3.4 Viscosity Effect Analysis

Viscosity is another factor that can affect two layers. Simulation is conducted by only changing one layer's viscosity and evaluating its effect on both layers' production. Figure 3.18 shows the production degradation of both layers when only the upper layer's producing oil's viscosity is changed. As can be seen, the viscosity effect is not as strong as gas, and the lower layer's production rate still decreases more than the upper layer.

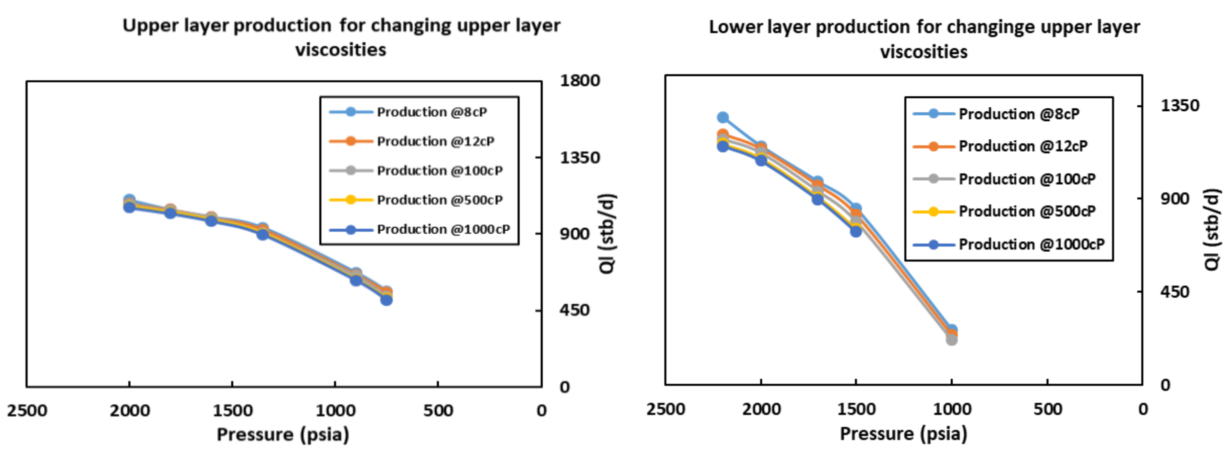

Figure 3.18 Two layers of production at different oil viscosity of the upper layer

Figure 3.19 shows the producing oil's effect on the lower layer. Similarly, the viscosity does not show a strong effect as expected. But the lower layer's production decreases more compared to the previous case, which is reasonable since the viscosity increase of the lower layer's producing oil directly reduces its pump's boosting ability.

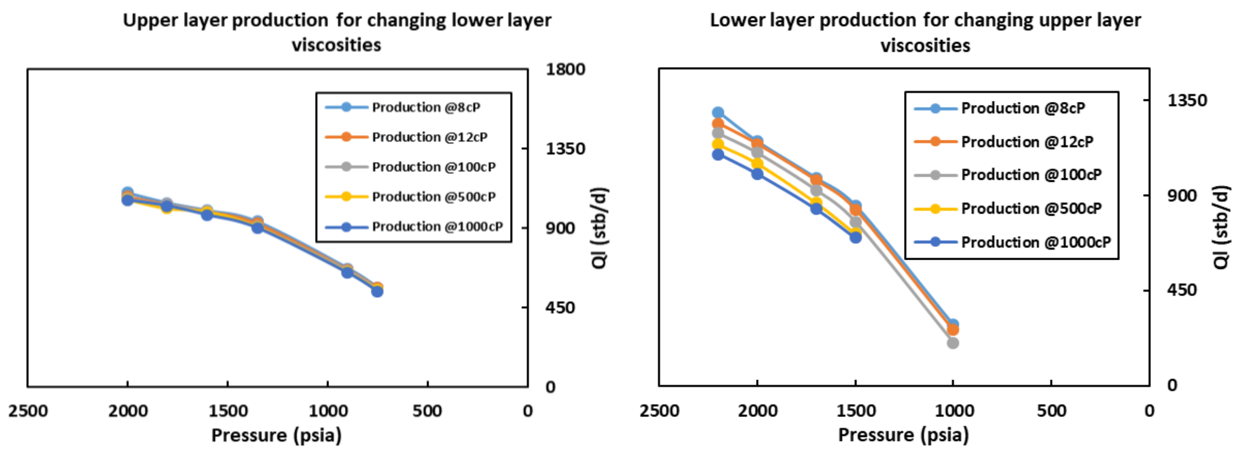

Figure 3.19 Two layers of production at different viscosity of the lower layer

As discussed, the viscosity is expected to have more effect on the pump and pipe flow. The limited effect shown in this result raises a question in the PIPESIM simulation. Therefore, the viscosity of the liquid phase along the wellbore is plotted in Figure 3.20. As can be seen, the in-situ viscosity at the bottom hole and pump intake is much lower than its rated viscosity. For example, 1000 cP oil in-situ viscosity at pump intake is only around 175 cP and gradually increased to 500 cP at the wellhead. It is mainly due to the high temperature in the wellbore. As fluid flows from the bottom to the surface, its temperature gradually decreases as shown in Figure 3.21, increasing the oil viscosity. Although viscosity has an effect on the pipe flow, the pressure drop in the vertical wellbore is mainly controlled by gravity. In this study, only the viscosity is changed, and the density is kept the same. Future studies should incorporate more accurate oil properties to accurately reflect the oil properties effect. In addition, as discussed previously, PIPESIM only incorporated the simplified hydraulic institute pump correlation to consider the oil viscosity effect, which significantly predicts the oil viscosity effect on pump boosting pressure. Future studies should be focused on a better ESP model for high-viscosity oil flow.

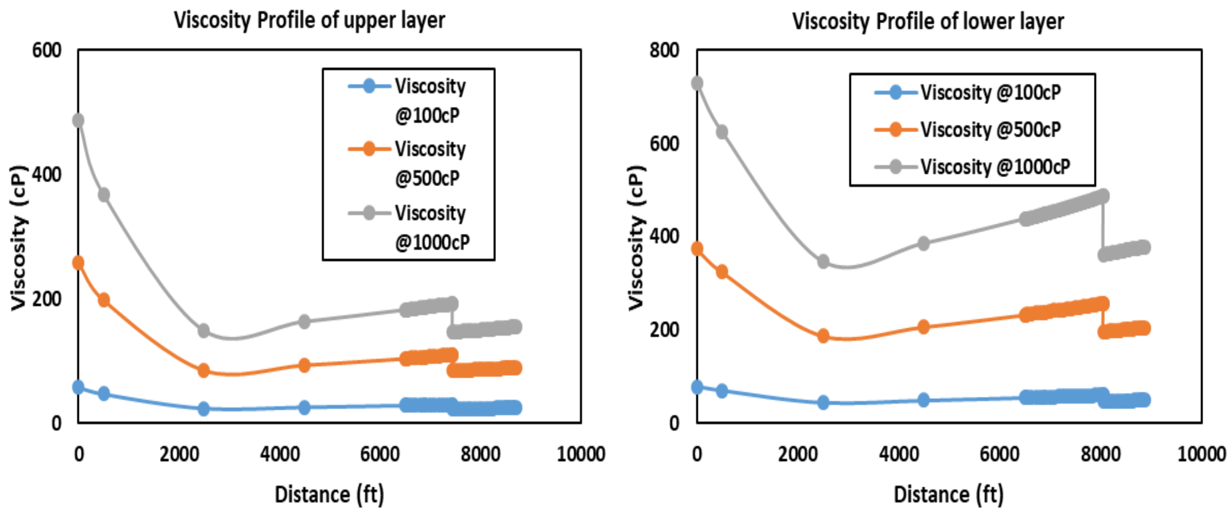

Figure 3.20 Viscosity profile at different viscosities of the two layers

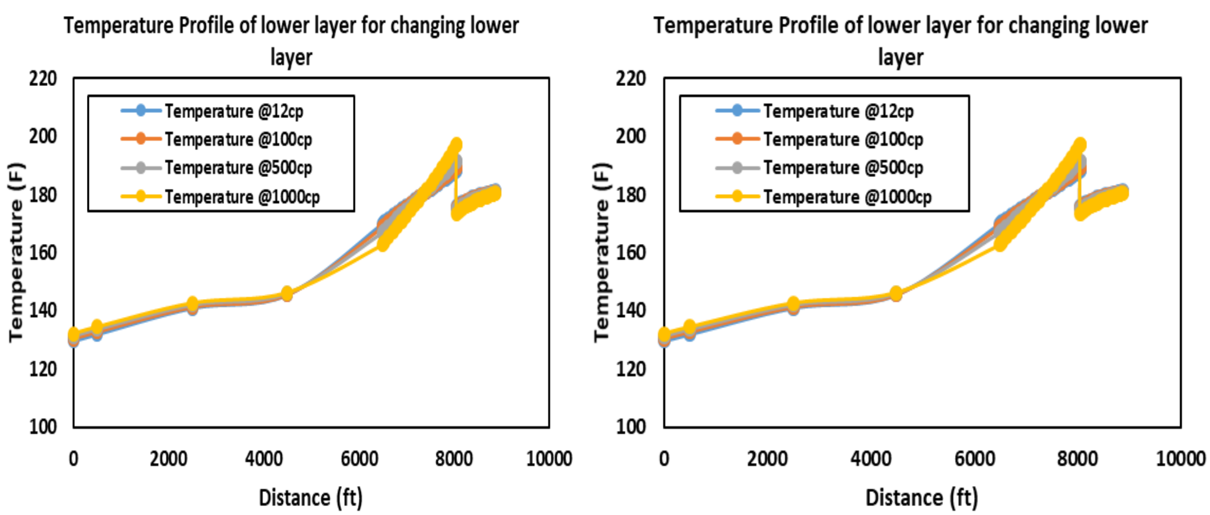

Figure 3.21 Temperature profiles of two layers at different viscosities of the lower layer

Figure 3.22 shows the percentage decrease in production for both layers for changing the upper layer oil viscosity. The percentage decrease is up to 10% and 15% for upper layer and lower layer separately. Figure 3.23 gives the percentage decrease in production when changing the lower layer's oil viscosity. As seen, the decrease rate is up to 5% and 20%. Similarly, changing one layer's oil viscosity affects both layers' production. The lower layer's reduction is always more, which is assumed due to its higher production index or less pump capacity design.

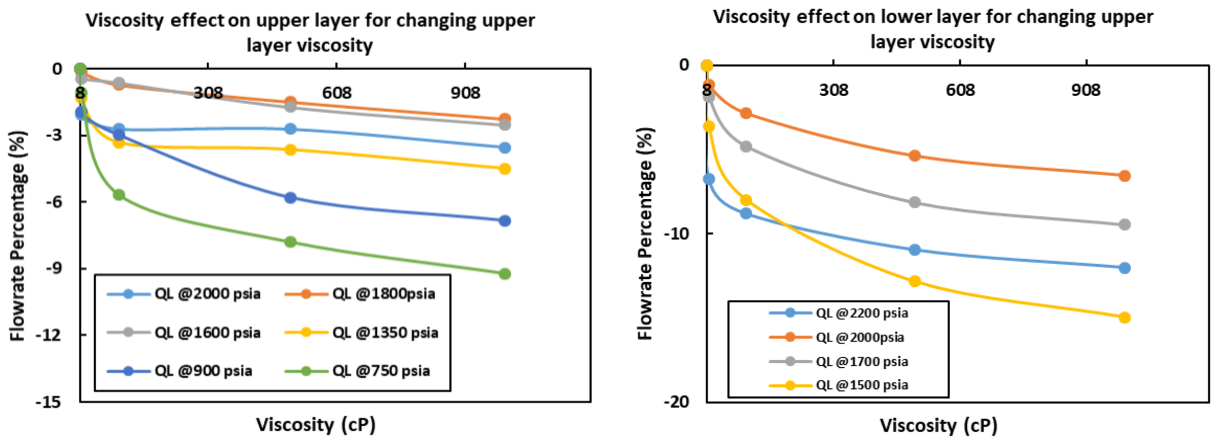

Figure 3.22 Percentage changes in both layers' productions for different upper layer viscosities

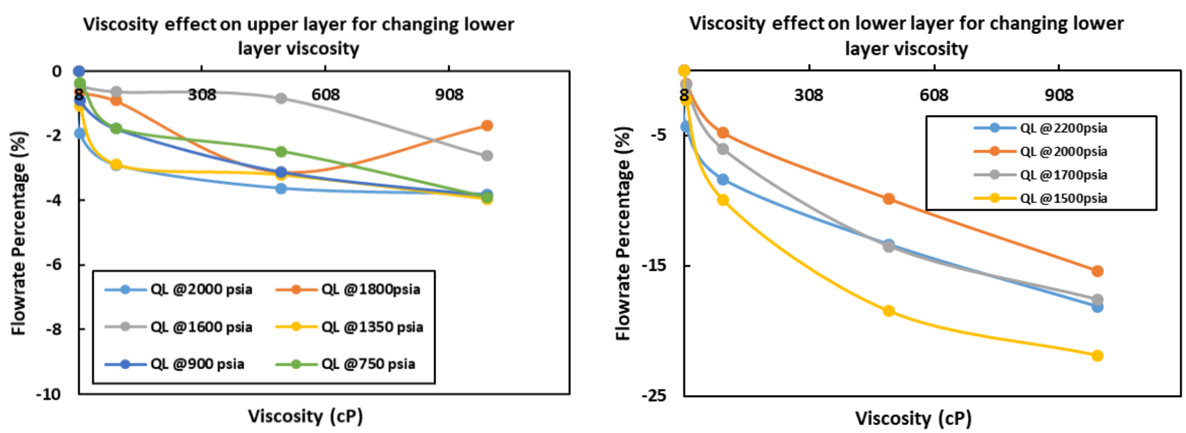

Figure 3.23 Percentage changes in upper layer productions for different lower layer viscosities

3.5 Water Cut Effect Analysis

Figure 3.24 shows the upper layer water cut effect on both layers. As discussed in section 3.4, high fluid viscosity decreases pump performance. Therefore, decreasing the water cut will increase the fluid mixture viscosity. As a result, the pump boosting ability and production rate decrease. Similarly, changing one layer's water cut affects both layers.

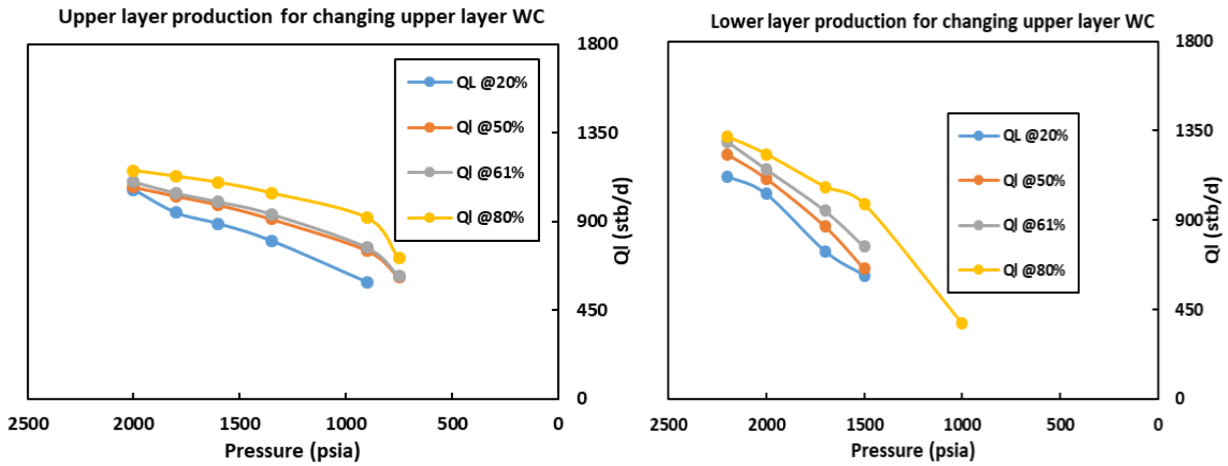

Figure 3.24 Liquid productions of both layers at different water cuts of the upper layer

Figure 3.25 shows the effect of the lower layer water cut. The results are similar, the lower layer is always affected more, which again indicates the effect of the reservoir production index. Future studies should be conducted for more production index and fluid properties.

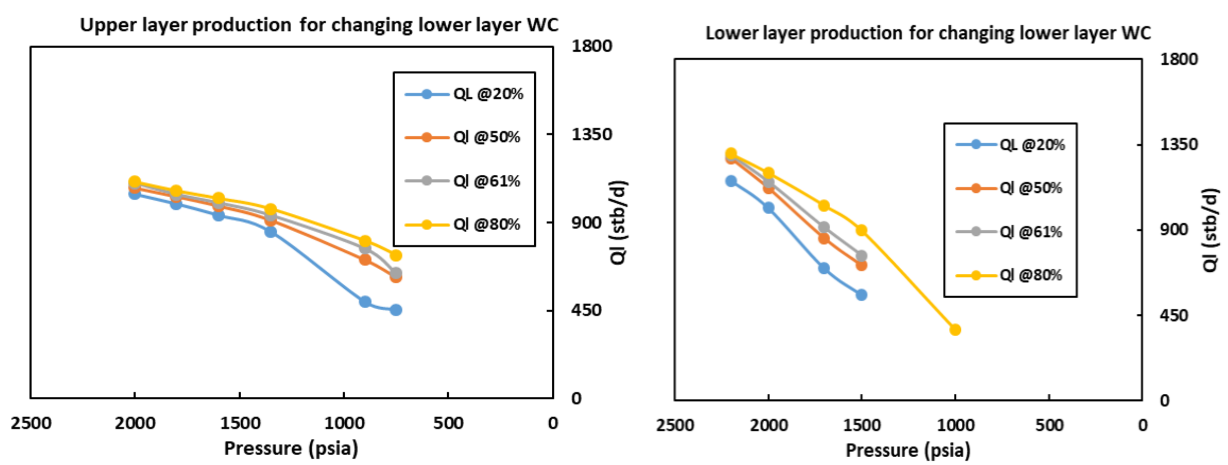

Figure 3.25 Liquid productions of both layers at different water cuts of the lower layer

Since the oil-water emulsion's viscosity does not linearly relate to the water cut, the pressure profile is plotted to investigate the viscosity effect in both pipe flow and pump boosting pressure. However, both Figure 3.26 shows a smooth change of pressure profile with the change of oil viscosity. Therefore, it is presumed that PIPESIM oil-water emulsion property model is not accurate enough. In addition, the default 60% water cut for the oil-water continues phase inversion point is incorporated in all cases. The emulsion property model and inversion point for different oils should be future investigated in the future study.

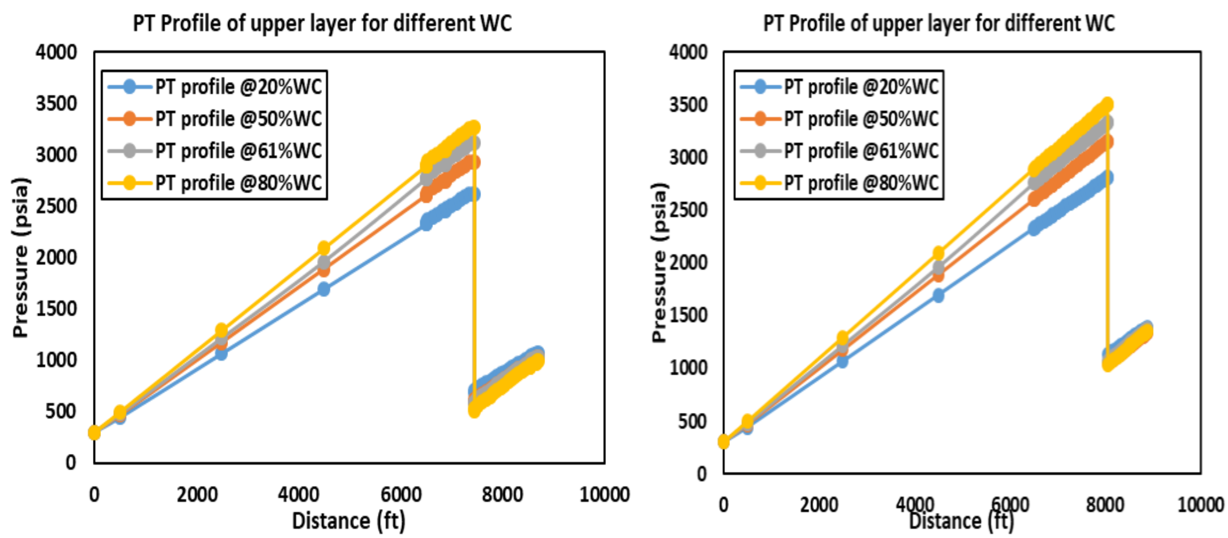

Figure 3.26 PT profile of two layers at different water cuts of the lower layer

Figure 3.27 and Figure 3.28 gives the percentage decrease in production for both layers with the change of only one layer's water cut to future investigates the water cut and emulsion effect. Again, the results do not show a significant difference at the oil-water inversion point (60% water cut). The decrease ratio is up to 40% in this parametric study. Therefore, it is concluded the effect of fluid property is followed by gas, water cut, and viscosity.

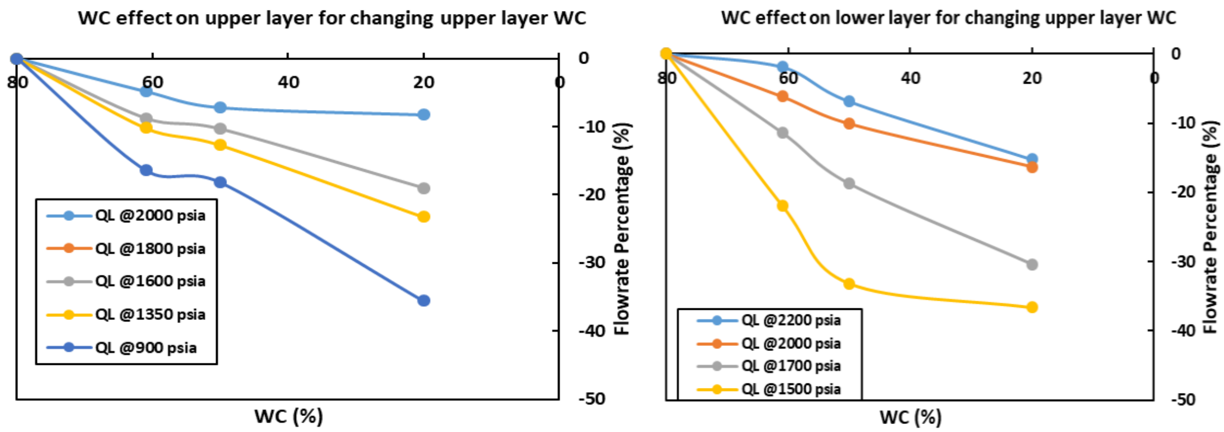

Figure 3.27 Percentage changes in both layers' productions for different upper layer water cut

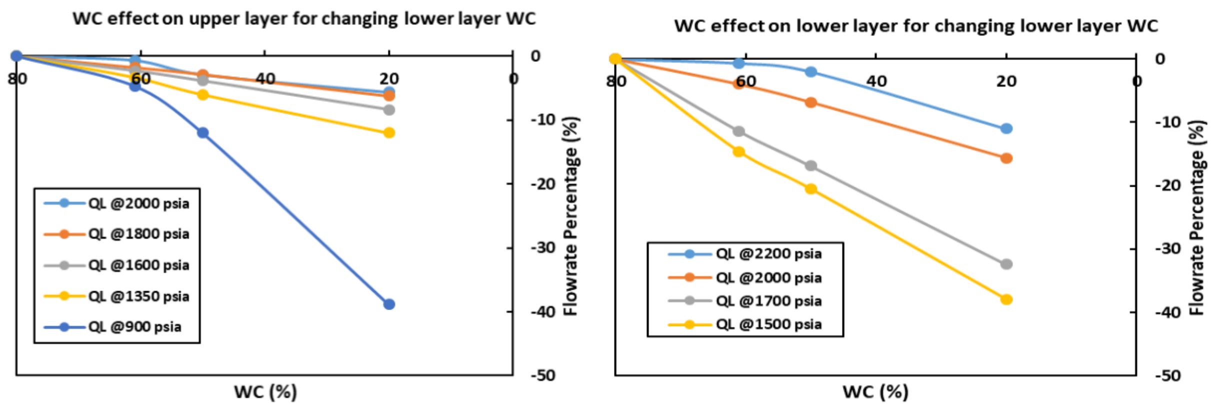

Figure 3.28 Percentage changes in both layers' productions for different lower layer water cut

3.6 Pump Design Analysis

Since the lower layer's ESP stops producing first, a new pump is designed in this section to ensure that both pumps produce and stop at the same time. A new pump is selected for the lower layer according to the working range (flow rate from 1200-1800 STB/D), and stage numbers are increased from 321 to 400 to ensure two layers' ESPs have similar run life. The Nodal Analysis is given in Figure 3.29 and Figure 3.30 below. The OPR of the two layers is going down with a decrease in the reservoir pressure.

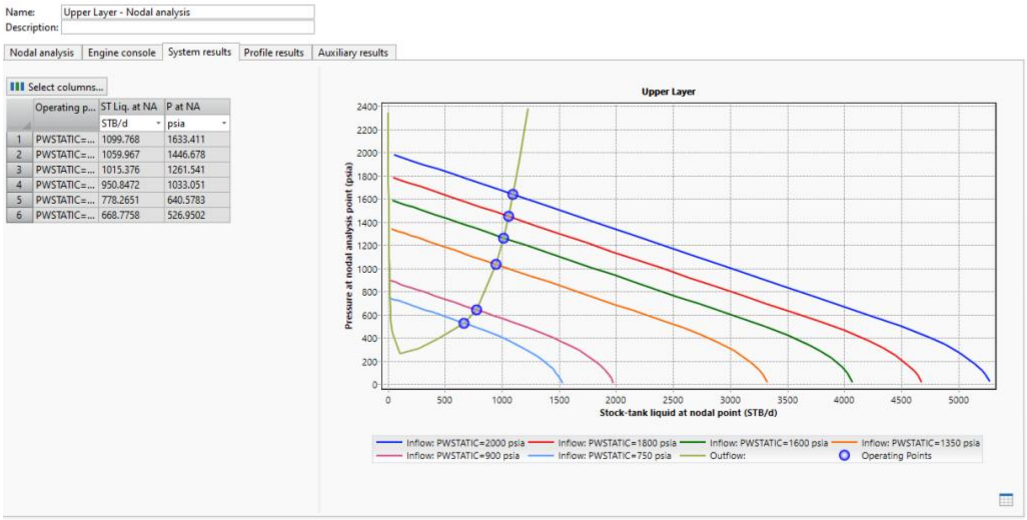

Figure 3.29 Nodal Analysis of upper layer at 50Hz

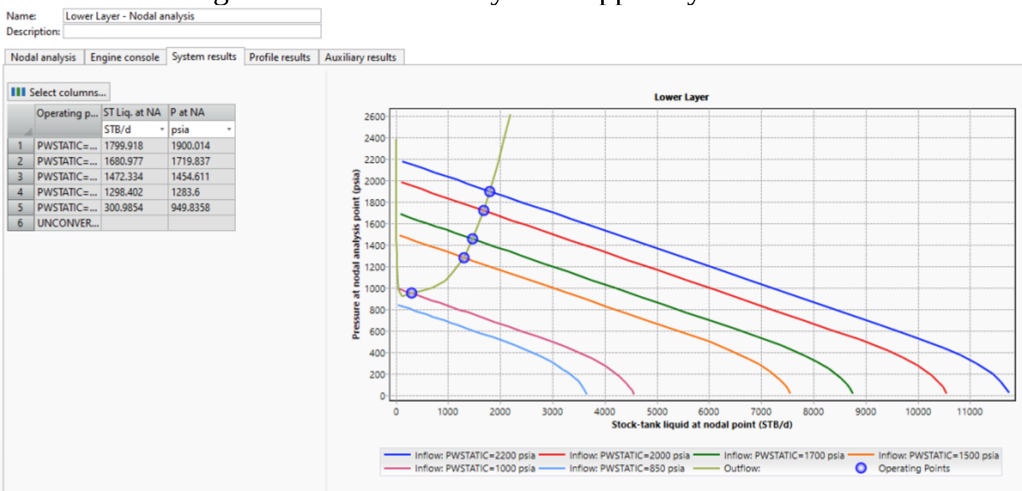

Figure 3.30 Nodal Analysis of the lower layer at 321 stages

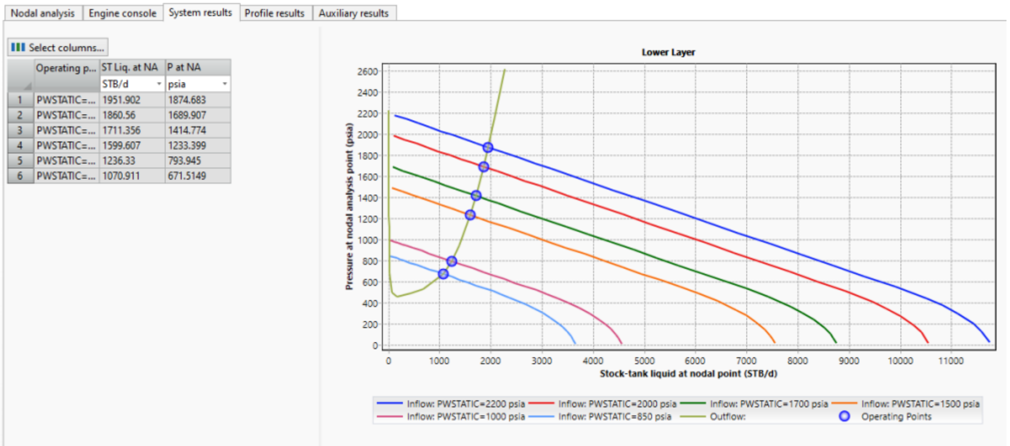

Figure 3.31 Nodal Analysis of the lower layer at 400 stages

The nodal analysis of the two layers shows that both layers will shut down at a reservoir pressure of 400 psia. Again, single ESP and Y-tool ESP comparison is included in the appendix. Producing by Y-tool ESP will only slightly reduce the production from each layer.

The pressure profile of the cases for the two layers is given in Figure 3.32 below. Again, the pressure profile above the connection point is almost the same, which indicates that the fluid flow in the wellbore is mainly controlled by the gravitational loss, and the flow rate has a limited effect. On the other hand, when reservoir pressure reduces, the two ESPs can provide more boosting pressure. Assuming the reservoir decline rate is comparable, both pumps will have similar run life.

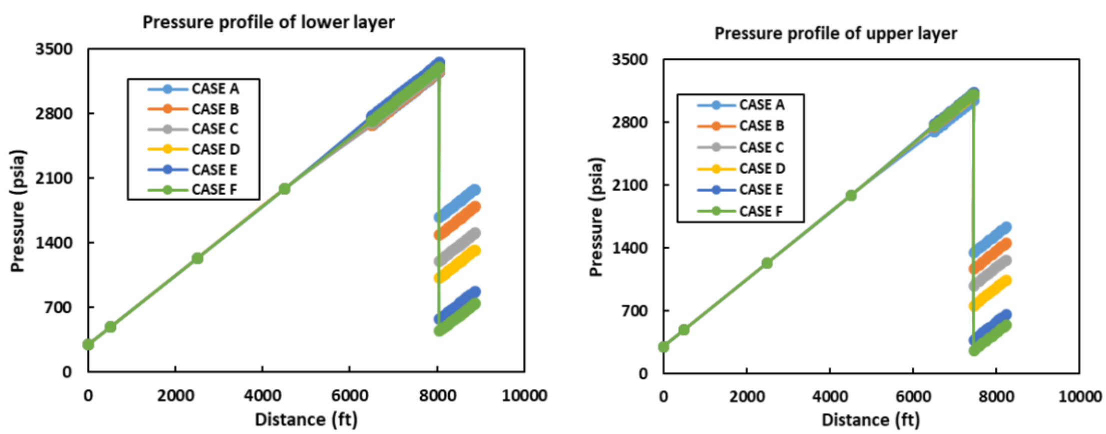

Figure 3.32 PT profiles of two layers for new pump design

Figure 3.33 gives the production and PIP decline graph for two layers, which again proves that the two pumps have a similar run lift. However, both pumps' PIP run below the suggested critical PIP. Future studies need to focus on the gas effect on Y-tool ESP.

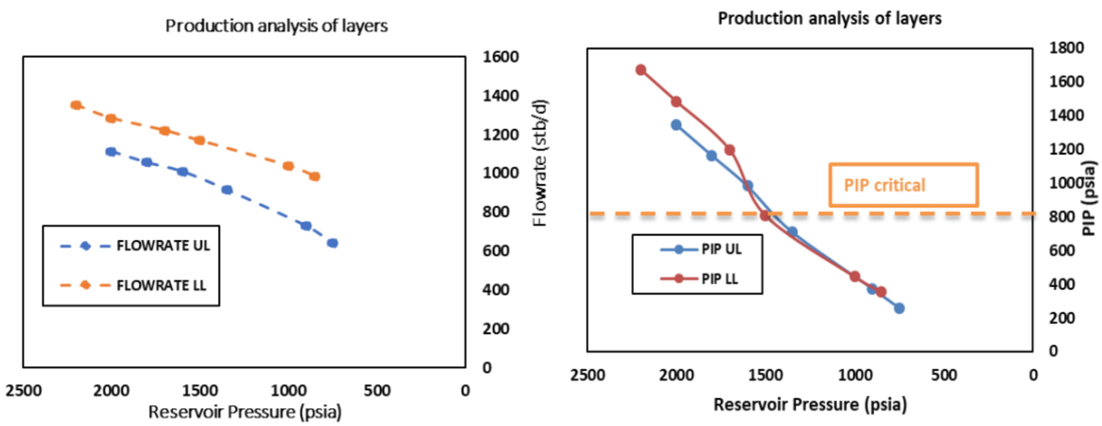

Figure 3.33 Production analysis of two layers for pump design analysis

Similarly, the fluid velocity around the ESP motor is calculated and Figure 3.34 gives the results of both layers. The fluid velocity around the upper layer's ESP motor is slightly lower than the optimum suggestion, indicating motor shroud design is needed to restrict the flow and increase the liquid flow velocity near the ESP motor.

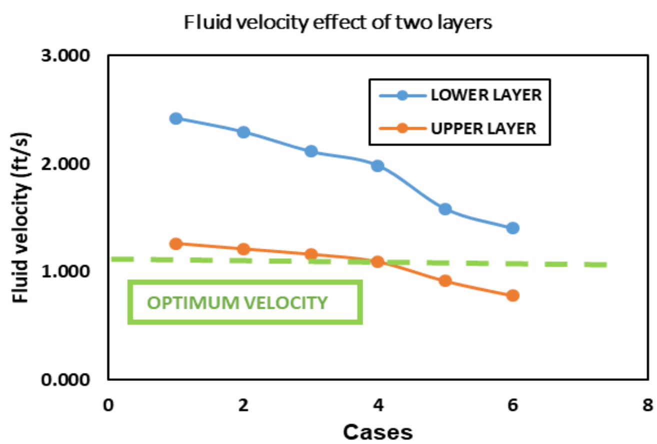

Figure 3.34 ESP fluid velocity effect of layers

A pump speed parametric study is also conducted. As can be seen, it is also possible to control pump speed to avoid low PIP. However, it should be noted that PIP can only be increased by reducing ESP speed, resulting in a decrease in the production rate. The gas issue can be avoided, but motor cooling issues need to be considered, and a special motor shroud is necessary.

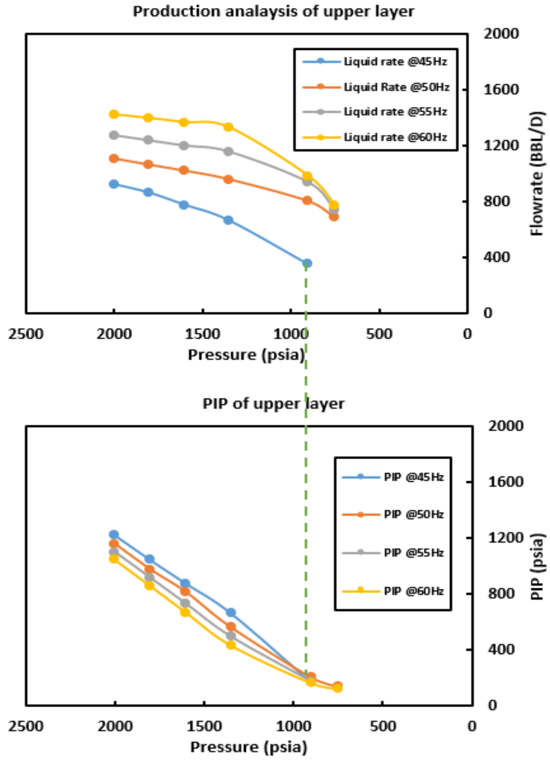

Figure 3.35 Production analysis of the upper layer for simulation matrix

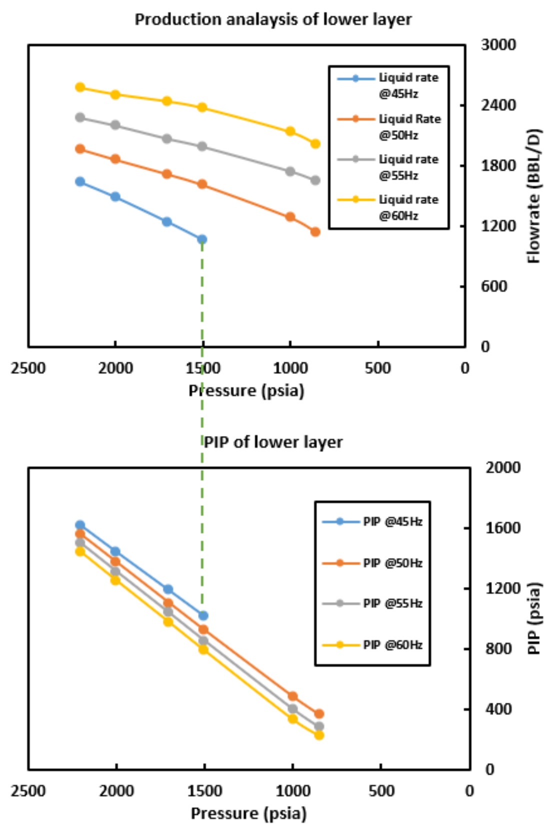

Figure 3.36 Production analysis of the lower layer for simulation matrix

CHAPTER 4

CONCLUSIONS AND RECOMMENDATION

The Y-tool ESP design and simulation are conducted with PIPESIM. The performance of two ESPs is affected by pump design, reservoir properties, and fluid properties. A proper pump selection and design can help improve the Y-tool system's run-life and reduce the workover frequency.

4.1 Conclusions

1. According to the field recommendation, the lower layer stops producing earlier than the upper layer due to the ESP design flow capacity and booting pressure. Although pump speed can be controlled to achieve production by both layers, the lower layer's ESP needs to be replaced.

2. Assuming the same reservoir decline rate, it is possible to design two ESPs that have a similar run life. However, the critical PIP and motor cooling problems need to be evaluated carefully. It is possible that they cannot be satisfied together and one ESP needs to use a special shroud to increase the fluid flow velocity near its motor.

3. Operating ESPs at different speeds for different layers may help prevent potential failures.

4. Among all fluid properties studied, gas has the most effect, then water cut, and finally viscosity. The oil viscosity effect is not as strong as expected mainly due to the high reservoir temperature. The in-situ oil viscosity is significantly reduced.

5. There is always an interaction between two layers, i.e., changing one layer's fluid property will affect the other layer as well. According to the simulation in this study, the reservoir production index has a strong effect on dual ESP production. The zone that has a higher production index is more affected by the produced fluid, no matter which zone it is produced.

6. Results for certain cases are not reliable due to the limitation of PIPESIM models, including high pump intake GVF, high viscosity, and water cut close to the oil-water inversion point. More accurate models that can reflect the real pump performance behavior should be incorporated in the future.

4.2 Recommendations

1. In case a shale layer presents between two formations, different decline rates should be considered in the dual ESP design.

2. More parameters of the simulated cases should be evaluated to prove the validity of this study and understand the production and pump performance.

3. A better fluid flow model, emulsion rheology model, and ESP performance model for complex fluid flow should be considered. Either user-defined models should be used in PIPESIM, or an in-house computer program should be developed for those complex flow conditions.

4. More parametric studies should be conducted. ESP operation method should be balanced according to motor cooling and gas issues.

5. A transient simulator like OLGA should be incorporated for unconverted cases (failure cases) in this study. The reverse flow effect in ESPs should be investigated.

NOMENCLATURE

ESP	Electrical submersible pump
GVF	Gas volume fraction
BBL/D	Barrels per day
TDH	Total dynamic head
LER	Local equipment room
VSD	Variable speed drive
GOR	Gas oil ratio
WC	Water cut
PI	Productivity index
HP	Horsepower
PIP	Pump intake pressure
PDP	Pump discharge pressure
NPT	Non-productive time
STB	Stock tank barrel
WHP	Wellhead pressure
MT	Motor temperature
Hz	Hertz
GLR	Gas liquid ratio
PSI	Pounds per square inch
UL	Upper lower
LL	Lower layer
BHP	Bottomhole pressure
NA	Nodal analysis
SCF	Standard cubic feet
OLGA Simulator	Oil and gas simulator
ID	Inner diameter
PT	Pressure Temperature

BIBLIOGRAPHY

Al-Kady, M., Selim, A., Omar, A., Ginawi, I., Bahgat, A., Abdelmotaal, H. and Botros, K., 2016, September. Improved field recovery and drilling costs in Agiba using ESP reversed Y-tool dump-flood solution. In *SPE Annual Technical Conference and Exhibition*. One Petro.

Dudley, R.W., 1987, September. Reperforation of North Sea electric submersible pump wells using an ESP/Y-tool/TCP system. In *SPE Offshore Europe Conference and Exhibition* (pp. SPE-16534). SPE.

Hoy, M., Florian, T. and Geier, H., 2016, November. Candidate selection and operation of commingled production with a dual ESP system in a green field development. In *Abu Dhabi International Petroleum Exhibition and Conference* (p. D031S073R005). SPE.

Liu, Y., Upchurch, E.R., Ozbayoglu, E.M., Baldino, S., Zheng, D. and Wang, J., 2023a, March. Gas Migration Model for Non-Newtonian Fluids under Shut-in Well Conditions. In *SPE/IADC Drilling Conference and Exhibition* (p. D011S006R005). SPE.

Liu, Y., Upchurch, E.R., Ozbayoglu, E.M., Baldino, S., Wang, J. and Zheng, D., 2023b, March. Design and Calculation of Process Parameters in Bullheading and Pressurized Mud Cap Drilling. In *SPE/IADC Drilling Conference and Exhibition* (p. D011S006R002). SPE.

Luo, C., Cao, Y., Liu, Y., Zhong, S., Zhao, S., Liu, Z., Liu, Y. and Zheng, D., 2023. Experimental and modeling investigation on gas-liquid two-phase flow in horizontal gas wells. *Journal of Energy Resources Technology*, *145*(1), p.013102.

Manoj, D. V., Kumar, P. A., Matla, S., & Rao, K. S. (2021). Design and Simulation Studies on An ESP System. *International Journal of Engineering Research & Technology*, *10*(08).

Nunez, W., Del Pino, J., Gomez, S., Rosales, D., Puentes, J. and Rivera, H., 2020, July. Electric submersible pump troubleshooting guide, an effective way to improve system performance and reduce avoidable system failures. In *SPE Latin American and Caribbean Petroleum Engineering Conference*. One Petro.

Prabhu, K., Tirawadekar, D., Gorde, N. and Vasilev, S., 2022, October. Application of Dual ESP Completion with Remote Monitoring in Offshore Wells Having Variable Flow Conditions. In *SPE Middle East Artificial Lift Conference and Exhibition*. One Petro.

Selman, K., Raglin, M., & Energy, W. NEW GAS BYPASS SYSTEM FOR UNCONVENTIONAL WELLS ON ESP.

Shafiq, M., & Arraour, A. A. (2015, September). Case Studies of Formation Isolation Valves for ESP and Intelligent Completions in Multi-Lateral Wells and Horizontal Wells. In *SPE North Africa Technical Conference and Exhibition*. OnePetro.

Takacs, G., 2017. *Electrical submersible pumps manual: design, operations, and maintenance*. Gulf professional publishing.Dudley, R. W. (1987, September). Reperforation of North Sea electric submersible pump wells using an ESP/Y-tool/TCP system. In *SPE Offshore Europe*. One Petro.

Wang, J., Ozbayoglu, E., Baldino, S., Liu, Y. and Zheng, D., 2023, April. Time Series Data Analysis with Recurrent Neural Network for Early Kick Detection. In *Offshore Technology Conference* (p. D021S020R002). OTC.

Wilson, A. (2014). Applying Root-Cause Failure Analysis Enhances Artificial-Lift Performance. *Journal of Petroleum Technology*, *66*(07), 110-112.

Zaini, M.Z., Rivero, M.E., Sepulveda, W., Salim, M.M. and Bela, S.M., 2012, October. Introduction of a Dual ESP with bypass tubing and backup gas lift system in an offshore brownfield. In *SPE Asia Pacific Oil and Gas Conference and Exhibition*. One Petro.

Zheng, D., Ozbayoglu, E., Miska, S.Z., Liu, Y. and Li, Y., 2022a, April. Cement sheath fatigue failure prediction by ANN-based model. In *Offshore Technology Conference* (p. D011S013R009). OTC.

Zheng, D., Ozbayoglu, E.M., Miska, S.Z. and Liu, Y., 2022b, October. Cement sheath fatigue failure prediction by support vector machine based model. In SPE Eastern Regional Meeting. OnePetro.

Zheng, D., Ozbayoglu, E., Baldino, S., Miska, S., Hoamidov, E., and Liu, Y., 2023a. "Cement Sheath Fatigue Failure Prediction Using Machine Learning Method", ARMA-2023-0241, June 2023

Zhu, H., Zhu, J., Zhang, J. and Zhang, H.Q., 2017, November. Efficiency and critical velocity analysis of gravitational separator through CFD simulation. In *ASME International Mechanical Engineering Congress and Exposition* (Vol. 58424, p. V007T09A067). American Society of Mechanical Engineers.

Zhu, H., Zhu, J., Lin, Z., Zhao, Q., Rutter, R. and Zhang, H.Q., 2021. Performance degradation and wearing of Electrical Submersible Pump (ESP) with gas-liquid-solid flow: Experiments and mechanistic modeling. *Journal of Petroleum Science and Engineering*, *200*, p.108399.

Zhu, H., Zhu, J. and Zhang, H.Q., 2022. Mechanistic modeling of gas effect on Multi-stage Electrical submersible pump (ESP) performance with experimental validation. *Chemical Engineering Science*, *252*, p.117288.

APPENDIX A

SIMULATION MATRIX AND PARAMETRIC MATRIX RESULTS

This section presents all simulation results shown in Chapter 3. gives the simulation results of the parametric study conducted for reservoir depletion effect. The analyzed parameters are the flowrates, bottomhole pressure, PIP and pump discharge pressure.

Table A.1 Simulation results of parametric study for declining reservoir pressure

Parameters	Reservoir	Case A	Case B	Case C	Case D	Case E	Case F
Reservoir Pressure (psia)	UL	2000	1850	1600	1350	900	750
	LL	2200	2000	1700	1500	1000	850
PI (STB/D/psi)	UL	3	3	3	3	3	3
	LL	6	6	6	6	6	6
ESP Stages	UL	230	230	230	230	230	230
	LL	195	195	195	195	195	195
Oil Flowrate (STB/D)	UL	434.	407	390	366	299	243
	LL	502	450	369	299	None	None
Water Flowrate (STB/D)	UL	669	637	611	572	469	380
	LL	792	705	577	467	None	None
Liquid Flowrate (STB/D)	UL	1102	1045	1001	938	768	623
	LL	1296	1156	946	766	None	None
Gas Flowrate (STB/D)	UL	0.064	0.061	0.058	0.055	0.045	0.036
	LL	0.074	0.068	0.055	0.045	None	None
PIP (psia)	UL	1175	990	805	578	217	151
	LL	1684	1507	1243	1074	None	None
PDP (psia)	UL	3145	3150	3133	3114	3088	3183
	LL	3368	3361	334	3333	None	None
Bottomhole Pressure (psia)	UL	1637	1451	1266	1037	644	542
	LL	1989	1807.	1542	1372	None	None

It can be seen that the bottomhole pressure in the upper layer is too low which could be because of low productivity index. The lower layer production stops at reservoir pressure of 1000 psia and lower. The reason could be lower pump capacity design which is not capable of having enough phase envelope to produce at low reservoir pressures. The advantage of using a Y-tool ESP system is mainly to increase the run life of the well and to produce in multiple zone reservoirs. Appendix Table A.2 and Table A.3 gives the simulation results for both layers for one ESP case for the parametric study.

Table A.2 Simulation results of lower layer for one ESP and Y-tool ESP system

Parameters	Layers	Case A	Case B	Case C	Case D	Case E	Case F
Oil Flowrate (STB/D)	One ESP	512	472	392	321	None	None
	Y-tool ESP	493	451	369	299	None	None
Water Flowrate (STB/D)	One ESP	802	738	614	503	None	None
	Y-tool ESP	772	705	577	467	None	None
Liquid Flowrate (STB/D)	One ESP	1315	1209	1007	824	None	None
	Y-tool ESP	1295	1156	946	766	None	None
Gas Flowrate (STB/D)	One ESP	0.077	0.071	0.059	0.048	None	None
	Y-tool ESP	0.074	0.068	0.055	0.045	None	None
PIP (psia)	One ESP	1679	1498	1233	1064	None	None
	Y-tool ESP	3368	3361	3349	3333	None	None
Bottomhole Pressure (psia)	One ESP	1980	1798	1532	1363	None	None
	Y-tool ESP	1989	1807	1542	1372	None	None

Table A.3 Simulation results of upper layer for one ESP and Y-tool ESP system

Parameters	Layers	Case A	Case B	Case C	Case D	Case E	Case F
Oil Flowrate (STB/D)	One ESP	430	414	395	370	296	253
	Y-tool ESP	424	407	390	366	300	243
Water Flowrate (STB/D)	One ESP	673	647	618	579	463	396
	Y-tool ESP	663	637	61	572	469	380
Liquid Flowrate (STB/D)	One ESP	1103	1062	1013	948	759	650
	Y-tool ESP	1101	1044	1001	938	768	622
Gas Flowrate (STB/D)	One ESP	0.064	0.062	0.059	0.055	0.044	0.038
	Y-tool ESP	0.064	0.061	0.058	0.055	0.045	0.036
PIP (psia)	One ESP	1165	980	796	570	231	156
	Y-tool ESP	1174	990	806	578	217	151
Bottomhole Pressure (psia)	One ESP	1632	1446	1262	1034	645	527
	Y-tool ESP	1637	1451	1266	1037	644	542

Table A.4 gives the matrix results for changing motor frequencies from 45 to 60 Hz. The matrix results is based on Table 2.*6* and twelve parametric results were created which are shown in the table below:

Table A.4 Simulation parametric matrix for pump speed analysis

Case Inputs			Reservoir Inputs		Production Results				ESP Inputs	
Parametric	Cases	Layers	P_{RES} (psia)	Pump Speed (Hz)	Q_O (STB/D)	Q_L (STB/D)	Q_G (MMSCF/D)	Pwf (psia)	PIP (psia)	Motor Velocity (ft/s)
1	1	Upper	2000	50	424	1088	0.064	1637	1175	1.241
		Lower	2200	50	494	1266	0.074	1989	1688	1.444
	2	Upper	1800	50	407	1045	0.061	1452	990	1.917
		Lower	2000	50	451	1156	0068	1807	1507	1.319
	3	Upper	1600	50	369	946	0.055	1542	806	1.079
		Lower	1700	50	390	1001	0.059	1266	1243	1.142
	4	Upper	1300	50	366	938	0.055	1037	578	1.079
		Lower	1500	50	299	766	0.045	1372	1074	0.874
	5	Upper	900	50	300	768	0.045	644	217	0.877
		Lower	1000	50	None	None	None	None	None	None
	6	Upper	750	50	243	623	0.036	542	151	0.711
		Lower	850	50	None	None	None	None	None	None
2	7	Upper	2000	45	358	918	0.054	1694	1232	1.048
		Lower	2200	45	388	995	0.058	2034	1734	1.135
	8	Upper	1800	45	330	846	0.049	1518	1056	0.966
		Lower	2000	45	307	786	0.046	1869	1569	0.897
	9	Upper	1600	45	307	786	0.046	1338	877	0.897
		Lower	1700	45	166	425	0.025	1629	1330	0.485
	10	Upper	1300	45	264	678	0.039	1493	665	0.773
		Lower	1500	45	None	None	None	None	None	None
	11	Upper	900	45	127	325	0.019	792	336	0.370
		Lower	1000	45	None	None	None	None	None	None
	12	Upper	750	45	None	None	None	None	None	None
		Lower	850	45	None	None	None	None	None	None
3	13	Upper	2000	55	495	1270	0.074	1577	1114	1.449
		Lower	2200	55	611	1567	0.092	1939	1637	1.787
	14	Upper	1800	55	477	1222	0.071	1393	931	1.394
		Lower	2000	55	560	1436	0.084	1761	1460	1.639
	15	Upper	1600	55	462	1185	0.069	1205	744	1.352
		Lower	1700	55	505	1295	0.076	1484	1184	1.477
	16	Upper	1300	55	440	1127	0.066	924	465	1.286
		Lower	1500	55	475	1219	0.071	1297	998	1.390
	17	Upper	900	55	368	943	0.055	586	177	1.075
		Lower	1000	55	309	792	0.046	868	571	0.903
	18	Upper	750	55	293	751	0.044	498	128	0.857
		Lower	850	55	248	637	0.037	744	448	0.726
	19	Upper	2000	60	556	1426	0.083	1525	1062	1.627
		Lower	2200	60	702	1800	0.105	1900	1597	2.054
	20	Upper	1800	60	546	1400	0.082	1333	871	1.597
		Lower	2000	60	677	1736	0.101	1711	1409	1.981

4	21	Upper	1600	60	532	1365	0.079	1145	684	1.558
		Lower	1700	60	626	1606	0.094	1432	1132	1.833
	22	Upper	1300	60	519	1332	0.078	906	446	1.519
		Lower	1500	60	603	1545	0.090	1243	943	1.763
	23	Upper	900	60	388	996	0.058	568	166	1.136
		Lower	1000	60	486	1246	0.073	792	495	1.421
	24	Upper	750	60	375	895	0.051	523	122	1.022
		Lower	850	60	462	1185	0.067	646	379	1.352
5	25	Upper	2000	50	429	1100	0.064	1633	1171	1.255
		Lower	2200	45	388	995	0.058	2034	1734	1.135
	26	Upper	1800	50	409	1049	0.061	1450	989	1.196
		Lower	2000	45	302	776	0.045	1871	1571	0.885
	27	Upper	1600	50	393	1008	0.059	1264	803	1.149
		Lower	1700	45	159	408	0.024	1632	1333	0.468
	28	Upper	1300	50	374	960	0.056	1030	570	1.096
		Lower	1500	45	None	None	None	None	None	None
	29	Upper	900	50	300	768	0.045	644	217	0.877
		Lower	1000	45	None	None	None	None	None	None
	30	Upper	750	50	243	623	0.036	542	151	0.710
		Lower	850	45	None	None	None	None	None	None
6	31	Upper	2000	50	423	1085	0.063	1638	1176	1.238
		Lower	2200	55	596	1527	0.089	1945	1644	1.743
	32	Upper	1800	50	406	1042	0.061	1453	991	1.188
		Lower	2000	55	562	1441	0.084	1760	1459	1.644
	33	Upper	1600	50	389	997	0.058	1268	807	1.137
		Lower	1700	55	507	1300	0.076	1483	1184	1.483
	34	Upper	1300	50	364	932	0.054	1039	580	1.063
		Lower	1500	55	464	1191	0.069	1302	1003	1.358
	35	Upper	900	50	293	751	0.044	650	221	0.857
		Lower	1000	55	313	803	0.047	866	569	0.916
	36	Upper	750	50	237	608	0.035	547	154	0.694
		Lower	850	55	252	646	0.038	742	446	0.737
7	37	Upper	2000	50	430	1104	0.064	1632	1170	1.259
		Lower	2200	60	703	1802	0.105	1900	1597	2.056
	38	Upper	1800	50	414	1061	0.062	1446	985	1.210
		Lower	2000	60	678	1738	0.102	1710	1409	1.983
	39	Upper	1600	50	388	993	0.058	1269	808	1.133
		Lower	1700	60	619	1587	0.093	1435	1135	1.811
	40	Upper	1300	50	362	927	0.054	1041	581	1.058
		Lower	1500	60	587	1504	0.088	1249	950	1.716
	41	Upper	900	50	289	741	0.043	653	224	0.846
		Lower	1000	60	489	1254	0.073	791	494	1.430
	42	Upper	750	50	232	594	0.035	552	156	0.678
		Lower	850	60	450	1155	0.067	657	363	1.318
8	43	Upper	2000	45	351	901	0.053	1700	1237	1.028
		Lower	2200	50	495	1271	0.074	1988	1687	1.449
	44	Upper	1800	45	328	840	0.049	1520	1058	0.959
		Lower	2000	50	453	1162	0.068	1806	1506	1.326
	45	Upper	1600	45	303	777	0.045	1341	880	0.887
		Lower	1700	50	372	955	0.056	1541	1242	1.09
	46	Upper	1300	45	257	660	0.039	1130	670	0.753
		Lower	1500	50	304	781	0.046	1370	1071	0.890
	47	Upper	900	45	119	306	0.018	798	342	0.369

		Lower	1000	50	None	None	None	None	None	None
	48	Upper	750	45	None	None	None	None	None	None
		Lower	850	50	None	None	None	None	None	None
9	49	Upper	2000	55	490	1256	0.073	1581	1141	1.433
		Lower	2200	50	492	1262	0.074	1990	1689	1.439
	50	Upper	1800	55	477	1225	0.072	1392	930	1.397
		Lower	2000	50	449	1150	0.067	1808	1508	1.312
	51	Upper	1600	55	463	1189	0.069	1204	743	1.356
		Lower	1700	50	366	938	0.055	1544	1244	1.071
	52	Upper	1300	55	441	1132	0.066	923	463	1.291
		Lower	1500	50	318	815	0.048	1364	1066	0.929
	53	Upper	900	55	369	614	0.055	584	177	0.701
		Lower	1000	50	None	None	None	None	None	None
	54	Upper	750	55	293	751	0.044	498	128	0.857
		Lower	850	50	None	None	None	None	None	None
10	55	Upper	2000	60	557	1427	0.083	1524	1061	1.629
		Lower	2200	50	510	1310	0.077	1982	1681	1.494
	56	Upper	1800	60	541	1389	0.081	1337	875	1.584
		Lower	2000	50	444	1145	0.067	1809	1509	1.307
	57	Upper	1600	60	532	1365	0.079	1145	684	1.558
		Lower	1700	50	384	987	0.058	1536	1236	1.259
	58	Upper	1300	60	514	1319	0.077	910	451	1.505
		Lower	1500	50	291	747	0.044	1375	1077	0.852
	59	Upper	900	60	388	996	0.058	568	166	1.136
		Lower	1000	50	None	None	None	None	None	None
	60	Upper	750	60	325	785	0.048	521	135	0.896
		Lower	850	50	None	None	None	None	None	None
11	61	Upper	2000	45	349	896	0.052	1701	1239	1.022
		Lower	2200	55	597	1531	0.089	1945	1643	1.747
	62	Upper	1800	45	326	836	0.049	1521	1060	0.953
		Lower	2000	55	563	1446	0.084	1759	1459	1.649
	63	Upper	1600	45	300	771	0.045	1343	883	0.88
		Lower	1700	55	509	1306	0.076	1482	1182	1.49
	64	Upper	1300	45	253	650	0.038	1133	674	0.741
		Lower	1500	55	468	1199	0.070	1300	1001	1.368
	65	Upper	900	45	102	261	0.015	813	356	0.298
		Lower	1000	55	322	826	0.048	862	565	0.942
	66	Upper	750	45	None	None	None	None	None	None
		Lower	850	55	266	684	0.040	736	440	0.781
12	67	Upper	2000	55	494	1266	0.074	1578	1115	1.444
		Lower	2200	45	388	995	0.058	2034	1734	1.135
	68	Upper	1800	55	479	1228	0.072	1391	929	1.401
		Lower	2000	45	298	765	0.045	1872	1573	0.873
	69	Upper	1600	55	465	1193	0.069	1202	741	1.361
		Lower	1700	45	154	394	0.023	1634	1336	0.449
	70	Upper	1300	55	449	1152	0.067	916	457	1.314
		Lower	1500	45	None	None	None	None	None	None
	71	Upper	900	55	369	947	0.055	584	177	1.081
		Lower	1000	45	None	None	None	None	None	None
	72	Upper	750	55	293	751	0.044	498	128	0.857
		Lower	850	45	None	None	None	None	None	None

Table A.5 shows that high GOR increase in upper layer results in failure in lower layer simulation. The main reason would be the gas entrainment in the pump causing it to fail.

Table A.5 Simulation results of parametric study for GOR effect

Parameters	Cases	Layers	GOR (SCF/STB)	Case A	Case B	Case C	Case D	Case E	Case F
Q_L (STB/D)	Base	Upper	150	1101	1045	1001	938	768	623
		Lower	150	1295	1156	946	766	None	None
	1	Upper	300	1095	1033	992	917	736	613
		Lower	150	1285	1130	916	750	None	None
	2	Upper	450	1085	997	943	882	677	561
		Lower	150	1241	1113	864	652	None	None
	3	Upper	600	105	953	892	790	552	401
		Lower	150	1198	1023	699	425	None	None
	4	Upper	1500	819	740	None	None	None	None
		Lower	150	None	None	None	None	None	None
	5	Upper	150	1087	1029	981	907	717	621
		Lower	300	1278	1128	923	740	None	None
	6	Upper	150	1053	1003	949	861	609	487
		Lower	450	1149	1025	772	540	None	None
	7	Upper	150	1046	965	902	800	419	149
		Lower	600	1123	886	545	232	None	None
	8	Upper	150	429	None	None	None	None	None
		Lower	1500	None	None	None	None	None	None
PIP (psia)	Base	Upper	150	117	990	805	578	217	151
		Lower	150	1683	1507	1243	1074	None	None
	1	Upper	300	1180	993	807	588	270	207
		Lower	150	1685	1505	1243	1075	None	None
	2	Upper	450	1191	1004	827	627	335	262
		Lower	150	1692	1537	1257	1093	None	None
	3	Upper	600	1211	1053	893	689	405	328
		Lower	150	1732	1529	1285	1131	None	None
	4	Upper	1500	1364	1213	None	None	None	None
		Lower	150	None	None	None	None	None	None
	5	Upper	150	1175	996	813	588	229	151
		Lower	300	1691	1516	1252	1083	None	None
	6	Upper	150	1187	1004	823	604	256	172
		Lower	450	1717	1538	1282	1122	None	None
	7	Upper	150	1205	1017	839	624	307	246
		Lower	600	1719	1566	1325	1179	None	None
	8	Upper	150	1394	None	None	None	None	None
		Lower	1500	None	None	None	None	None	None
Qg (mmscf/d)	Base	Upper	150	0.064	0.061	0.058	0.055	0.045	0.036
		Lower	150	0.074	0.068	0.055	0.045	None	None
	1	Upper	300	0.128	0.124	0.119	0.112	0.086	0.072
		Lower	150	0.075	0.068	0.055	0.044	None	None
	2	Upper	450	0.190	0.185	0.178	0.164	0.119	0.098
		Lower	150	0.073	0.063	0.051	0.038	None	None
	3	Upper	600	0.246	0.223	0.209	0.185	0.129	0.093

		Lower	150	0.071	0.060	0.041	0.025	None	None
	4	Upper	1500	0.479	0.433	None	None	None	None
		Lower	150	None	None	None	None	None	None
	5	Upper	150	0.064	0.06	0.057	0.053	0.042	0.036
		Lower	300	0.149	0.195	0.108	0.086	None	None
	6	Upper	150	0.062	0.059	0.055	0.050	0.036	0.028
		Lower	450	0.202	0.179	0.133	0.095	None	None
	7	Upper	150	0.061	0.056	0.053	0.047	0.024	0.009
		Lower	600	0.265	0.207	0.127	0.054	None	None
	8	Upper	150	0.023	None	None	None	None	None
		Lower	1500	None	None	None	None	None	None

Table A.6 and Table A.7 gives the flowrate and PIP comparison for one ESP and Y-tool ESP system for GOR of 300 SCF/STB.

Table A.6 Flowrate comparison of upper layer for one ESP and Y-tool ESP system for GOR

Reservoir Pressure (psia)	Flowrate Y-tool (STB/D)	Flowrate One ESP (STB/D)	Difference (%)
2000	1095.134	1107.901	-1.152
1800	1060.991	1072.916	-1.111
1600	1021.189	1034.967	-1.331
1350	961.772	970.954	-0.946
900	735.842	733.627	+0.302
750	613.096	611.618	+0.242

Table A.7 PIP comparison of upper layer for one ESP and Y-tool ESP system for GOR

Reservoir Pressure (psia)	PIP Y-tool (STB/D)	PIP One ESP (STB/D)	Difference (%)
2000	1180.096	1175.919	+0.355
1800	992.539	988.652	+0.393
1600	807.111	802.713	+0.548
1350	587.595	585.033	+0.438
900	269.756	270.697	-0.348
750	206.845	207.550	-0.339

Table A.8 gives the parametric result table for parametric study of viscosity effect. The production reduces at higher viscosities.

Table A.8 Simulation results of parametric study for viscosity effect

Parameters	Cases	Layers	Viscosity (cP)	Case A	Case B	Case C	Case D	Case E	Case F
Q_L (STB/D)	Base	Upper	8	1101	1045	1001	938	768	623
		Lower	8	1295	1156	946	766	None	None
	1	Upper	12	1084	1045	1004	935	769	637
		Lower	8	1269	1158	949	765	None	None
	2	Upper	100	1103	1065	1001	938	761	667
		Lower	8	1305	1207	976	795	None	None
	3	Upper	400	1105	1061	1018	956	757	664
		Lower	8	1314	1211	1013	842	None	None
	4	Upper	8	1087	1047	1004	937	794	668
		Lower	12	1265	1157	955	780	None	None
	5	Upper	8	1104	1065	1025	961	794	668
		Lower	100	1314	1216	1031	868	None	None
	6	Upper	8	1113	1087	1012	970	846	692
		Lower	400	1326	1242	1063	923	None	None
PIP (psia)	Base	Upper	8	1117	990	805	578	217	151
		Lower	8	1683	1507	1243	1074	None	None
	1	Upper	12	111	933	748	522	178	120
		Lower	8	1688	1507	1243	1074	None	None
	2	Upper	100	1170	984	806	578	219	143
		Lower	8	1681	1499	1243	1074	None	None
	3	Upper	400	1169	1007	800	572	220	144
		Lower	8	1680	1498	1232	1061	None	None
	4	Upper	8	1168	983	798	572	208	141
		Lower	12	1681	1501	1237	1069	None	None
	5	Upper	8	1162	976	791	564	208	141
		Lower	100	1672	1490	1224	1053	None	None
	6	Upper	8	1158	971	786	557	207	140
		Lower	400	1668	1486	1221	1049	None	None
Qg (mmscf/d)	Base	Upper	8	0.064	0.061	0.058	0.055	0.045	0.036
		Lower	8	0.074	0.068	0.055	0.045	None	None
	1	Upper	12	0.063	0.061	0.059	0.055	0.045	0.037
		Lower	8	0.074	0.068	0.055	0.045	None	None
	2	Upper	100	0.064	0.062	0.058	0.055	0.044	0.039
		Lower	8	0.076	0.071	0.055	0.045	None	None
	3	Upper	400	0.065	0.062	0.059	0.056	0.044	0.039
		Lower	8	0.077	0.071	0.059	0.049	None	None
	4	Upper	8	0.063	0.061	0.059	0.055	0046	0.039
		Lower	12	0.074	0.068	0.056	0.046	None	None
	5	Upper	8	0.064	0.062	0.059	0.056	0.046	0.039
		Lower	100	0.077	0.071	0.052	0.041	None	None
	6	Upper	8	0.065	0.061	0.059	0.055	0.046	0.040
		Lower	400	0.079	0.072	0.053	0.040	None	None

Table A.9 and Table A.10 gives the flowrate and PIP comparison for one ESP and Y-tool ESP system for viscosity of 12 cP.

Table A.9 Flowrate comparison of upper layer for one ESP and Y-tool ESP system for viscosity

Reservoir Pressure (psia)	Flowrate Y-tool (STB/D)	Flowrate One ESP (STB/D)	Difference (%)
2000	1082.342	1107.971	-2.313
1800	1048.137	1070.894	-2.125
1600	1011.132	1028.023	-1.643
1350	946.34	961.398	-1.566
900	710.415	748.682	-5.111
750	638.258	633.951	+0.679

Table A.10 PIP comparison of upper layer for one ESP and Y-tool ESP system for viscosity

Reservoir Pressure (psia)	PIP Y-tool (STB/D)	PIP One ESP (STB/D)	Difference (%)
2000	1132.395	1113.757	+1.673
1800	944.639	928.850	+1.699
1600	759.938	749.466	+1.397
1350	546.306	538.259	+1.495
900	222.855	211.246	+5.495
750	143.136	144.162	-0.712

Table A.11 gives the parametric result table for parametric study of water cut effect. The production reduces at lower water cuts.

Table A.11 Simulation results of parametric study of water cuts

Parameters	Cases	Layers	Water Cut (%)	Case A	Case B	Case C	Case D	Case E	Case F
Q_L (STB/D)	Base	Upper	61	1101	1045	1001	938	768	623
		Lower	61	1295	1156	946	766	None	None
	1	Upper	20	1062	944	889	802	502	None
		Lower	61	1119	1031	743	525	None	None
	2	Upper	50	1074	1029	984	912	752	616
		Lower	61	1230	1108	868	656	None	None
	3	Upper	80	1158	1129	1098	1045	919	714
		Lower	61	1321	1232	1068	981	379	None
	4	Upper	61	1047	997	938	854	493	377
		Lower	20	1161	1016	697	425	None	None
	5	Upper	61	1077	1033	985	912	709	620
		Lower	50	1278	1122	957	813	None	None
	6	Upper	61	1099	1063	1024	970	806	596
		Lower	80	1305	1204	1031	897	382	None
PIP (psia)	Base	Upper	61	1117	990	805	578	217	151
		Lower	61	1683	1507	1243	1074	None	None
	1	Upper	20	1256	1097	917	697	354	None
		Lower	61	1730	1528	1277	1114	None	None
	2	Upper	50	1199	1016	832	607	242	172
		Lower	61	1694	1515	1256	1092	None	None
	3	Upper	80	1115	926	737	455	138	88
		Lower	61	1679	1494	1223	1038	640	None
	4	Upper	61	1181	999	821	601	288	202
		Lower	20	1747	1573	1330	1177	None	None
	5	Upper	61	1171	987	804	581	229	150
		Lower	50	1684	1502	1232	1058	None	None
	6	Upper	61	1173	985	799	568	168	107
		Lower	80	1659	1476	1206	1028	616	None
Qg (mmscf/d)	Base	Upper	61	0.064	0.061	0.058	0.055	0.045	0.036
		Lower	61	0.074	0.068	0.055	0.045	None	None
	1	Upper	20	0.127	0.113	0.107	0.096	0.06	None
		Lower	61	0.069	0.06	0.043	0.031	None	None
	2	Upper	50	0.081	0.077	0.074	0.068	0.056	0.047
		Lower	61	0.072	0.065	0.051	0.038	None	None
	3	Upper	80	0.035	0.034	0.033	0.031	0.027	0.021
		Lower	61	0.077	0.072	0.062	0.057	0.022	None
	4	Upper	61	0.061	0.058	0.055	0.049	0.029	0.022
		Lower	20	0.139	0.122	0.084	0.051	None	None
	5	Upper	61	0.062	03.061	0.058	0.053	0.041	0.036
		Lower	50	0.096	0.092	0.079	0.068	None	None
	6	Upper	61	0.064	0.062	0.059	0.057	0.047	0.035
		Lower	80	0.039	0.036	0.031	0.027	0.011	None

Table A.12 and Table A.13 gives the flowrate and PIP comparison for one ESP and Y-tool ESP system for water cut of 50%.

Table A.12 Flowrate comparison of upper layer for one ESP and Y-tool ESP system for WC

Reservoir Pressure (psia)	Flowrate Y-tool (STB/D)	Flowrate One ESP (STB/D)	Difference (%)
2000	1074.599	1106.26	-2.862
1800	1028.833	1066.202	-3.505
1600	984.031	1020.867	-3.608
1350	911.806	952.619	-4.284
900	752.132	762.384	-1.345
750	626.413	649.180	-3.507

Table A.13 PIP Comparison of upper layer for one ESP and Y-tool ESP System for WC

Reservoir Pressure (psia)	PIP Y-tool (STB/D)	PIP One ESP (STB/D)	Difference (%)
2000	1199.518	1183.443	+1.325
1800	1015.8	997.737	+1.81
1600	831.792	813.824	+2.208
1350	607.241	587.95	+3.281
900	241.883	253.381	-4.538
750	171.851	179.868	-4.457

The data provided in Table 2.10 was used to provide results for the well with a Y-tool ESP system. Table A.14 gives the simulation results for new pump design analysis.

Table A.14 Simulation results of parametric study for new pump design

Parameters	Layers	Case A	Case B	Case C	Case D	Case E	Case F
Reservoir Pressure (psia)	UL	2000	1850	1600	1350	900	850
	LL	2200	2000	1700	1500	1000	750
Oil Flowrate (STB/D)	UL	432	415	398	375	314	268
	LL	765	725	668	627	500	443
Water Flowrate (STB/D)	UL	676	649	623	586	490	419
	LL	1197	1135	1045	980	782	693
Liquid Flowrate (STB/D)	UL	1109	1065	1021	961	804	686
	LL	1962	1860	1713	1607	1283	1137
Gas Flowrate (STB/D)	UL	0.065	0.062	0.060	0.056	0.047	0.040
	LL	0.115	0.109	0.100	0.094	0.075	0.066
PIP (psia)	UL	1160	976	815	564	205	137
	LL	1555	1374	1101	921	482	361
PDP (psia)	UL	3046	3071	3065	3056	3014	3008
	LL	3294	3316	3307	3295	3247	3239S
Bottomhole Pressure (psia)	UL	1630	1445	1259	1232	632	521
	LL	1873	1690	1414	1030	786	661

Lower ESP was changed to see the effect on lower layer and have a better run life and increasing production rates. Table A.15 and Table A.16 gives the flowrate and PIP comparison for one ESP and Y-tool ESP system for lower layer for new pump

Table A.15 Flowrate comparison of lower layer for One ESP and Y-tool ESP system

Reservoir Pressure (psia)	Flowrate Y-tool (STB/D)	Flowrate One ESP (STB/D)	Difference (%)
2200	1962.47	1985.496	-1.159
2000	1860.21	1875.105	-0.794
1700	1713.17	1747.155	-1.945
1500	1606.79	1637.916	-1.900
1000	1282.642	1289.055	-0.497
850	1136.959	1135.764	+0.105

Table A.16 PIP Comparison of lower layer for one ESP and Y-tool ESP system

Reservoir Pressure (psia)	PIP Y-tool (STB/D)	PIP One ESP (STB/D)	Difference (%)
2200	1554.66	1594.187	-2.479
2000	1373.61	1415,506	-2.959
1700	1101.48	1152.587	-4.434
1500	921.434	983.663	-6.326
1000	481.619	487.720	-1.251
850	361.349	366.566	-1.423

Another matrix simulation is made for the new pump design, which would show that the lower ESP is capable of producing at lower reservoir pressure. Table A.17 gives the simulation matrix result for the new pump design.

Table A.17 Simulation matrix results for new pump

Case Inputs			Reservoir Inputs		Production Results				ESP Inputs	
Parametric	Cases	Layers	P_{RES} (psia)	Pump Speed (Hz)	Q_O (STB/D)	Q_L (STB/D)	Q_G (MMSCF/D)	Pwf (psia)	PIP (psia)	Motor Velocity (ft./s)
1	1	Upper	2000	50	432	1109	0.065	1630	1160	1.265
		Lower	2200	50	765	1962	0.115	1873	1555	2.239
	2	Upper	1800	50	415	1065	0.062	1445	976	1.214
		Lower	2000	50	725	1860	0.109	1690	1374	2.122
	3	Upper	1600	50	398	1022	0.060	1259	815	1.165
		Lower	1700	50	668	1713	0.100	1414	1101	1.955
	4	Upper	1300	50	375	961	0.056	1232	564	1.096
		Lower	1500	50	627	1607	0.094	1030	921	1.833
	5	Upper	900	50	314	804	0.047	632	205	0.917
		Lower	1000	50	500	1283	0.075	786	482	1.463
	6	Upper	750	50	268	687	0.04	521	137	0.783
		Lower	850	50	443	1137	0.066	661	361	1.297
2	7	Upper	2000	45	360	924	0.054	1692	1224	1.054
		Lower	2200	45	638	1636	0.096	1927	1614	1.866
	8	Upper	1800	45	337	864	0.050	1512	1045	0.985
		Lower	2000	45	580	1487	0.087	1752	1442	1.697
	9	Upper	1600	45	303	777	0.045	1341	876	0.887
		Lower	1700	45	483	1238	0.072	1494	1187	1.413
	10	Upper	1300	45	260	667	0.039	1128	665	0.761
		Lower	1500	45	414	1062	0.062	1323	1017	1.211
	11	Upper	900	45	138	354	0.021	782	170	0.404
		Lower	1000	45	None	None	None	None	None	None
	12	Upper	850	45	None	None	None	None	None	None
		Lower	750	45	None	None	None	None	None	None
3	13	Upper	2000	55	498	1276	0.075	1575	1101	1.456
		Lower	2200	55	886	2272	0.133	1821	1496	2.592
	14	Upper	1800	55	483	1239	0.072	1387	915	1.413
		Lower	2000	55	856	2195	0.128	1634	1311	2.504
	15	Upper	1600	55	469	1202	0.070	1199	729	1.371
		Lower	1700	55	805	2064	0.121	1356	1037	2.354
	16	Upper	1300	55	452	1159	0.068	964	495	1.322
		Lower	1500	55	774	1984	0.116	1169	852	2.264
	17	Upper	900	55	366	938	0.055	587	174	1.069
		Lower	1000	55	679	1741	0.102	710	400	1.986
	18	Upper	750	55	290	742	0.043	502	173	0.846
		Lower	1000	55	643	1648	0.096	575	279	1.879
4	19	Upper	2000	60	556	1425	0.083	1525	1049	1.626
		Lower	2200	60	1001	2568	0.150	1772	1440	2.929
	20	Upper	1800	60	545	1398	0.082	1334	859	1.595
		Lower	2000	60	977	2504	0.146	1583	1253	2.856
	21	Upper	1600	60	534	1369	0.080	1144	669	1.562
		Lower	1700	60	945	2432	0.103	1325	975	2.775
	22	Upper	1300	60	520	1333	0.078	906	434	1.521
		Lower	1500	60	907	2368	0.136	1113	788	2.701
	23	Upper	900	60	384	983	0.057	572	164	1.122
		Lower	1000	60	831	2132	0.125	645	332	2.432
	24	Upper	750	60	302	775	0.045	490	121	0.884
		Lower	850	60	784	2010	0.118	514	222	2.294

5	25	Upper	2000	50	431	1106	0.065	1631	1161	1.261
		Lower	2200	45	638	1637	0.096	1927	1614	1.867
	26	Upper	1800	50	420	1078	0.063	1441	971	1.230
		Lower	2000	45	582	1492	0.087	1751	1441	1.702
	27	Upper	1600	50	404	1035	0.060	1255	787	1.180
		Lower	1700	45	522	1338	0.078	1477	1170	1.526
	28	Upper	1300	50	372	953	0.056	1032	567	1.087
		Lower	1500	45	427	1094	0.064	1318	1014	1.248
	29	Upper	900	50	312	800	0.047	633	207	0.912
		Lower	1000	45	None	None	None	None	None	None
	30	Upper	750	50	266	683	0.039	522	138	0.779
		Lower	850	45	None	None	None	None	None	None
6	31	Upper	2000	50	429	1100	0.064	1633	1163	1.255
		Lower	2200	55	885	2269	0.133	1822	1497	2.589
	32	Upper	1800	50	417	1070	0.063	1443	974	1.221
		Lower	2000	55	856	2195	0.128	1634	1311	2.504
	33	Upper	1600	50	399	1022	0.059	1259	792	1.166
		Lower	1700	55	808	2073	0.121	1355	1035	2.364
	34	Upper	1300	50	374	959	0.056	1030	565	1.094
		Lower	1500	55	774	1986	0.116	1169	852	2.265
	35	Upper	900	50	309	793	0.046	636	208	0.905
		Lower	1000	55	680	1742	0.102	710	400	1.988
	36	Upper	900	50	265	680	0.039	523	138	0.776
		Lower	1000	55	643	1648	0.096	575	279	1.879
7	37	Upper	2000	50	429	1100	0.064	1633	1163	1.255
		Lower	2200	60	1003	2571	0.150	1772	1439	2.933
	38	Upper	1800	50	414	1062	0.062	1446	977	1.211
		Lower	2000	60	994	2549	0.149	1575	1244	2.909
	39	Upper	1600	50	397	1018	0.059	1261	793	1.161
		Lower	1700	60	876	2375	0.103	1301	975	2.710
	40	Upper	1300	50	374	959	0.056	1030	565	1.094
		Lower	1500	60	908	2328	0.136	1112	788	2.656
	41	Upper	900	50	310	795	0.046	635	208	0.906
		Lower	1000	60	829	2127	0.124	646	333	2.426
	42	Upper	900	50	265	679	0.039	523	173	0.775
		Lower	1000	60	787	2018	0.118	513	221	2.302
8	43	Upper	2000	45	348	893	0.052	1702	1235	1.019
		Lower	2200	50	744	1907	0.112	1907	1564	2.176
	44	Upper	1800	45	339	870	0.051	1510	1043	0.992
		Lower	2000	50	732	1877	0.109	1687	1371	2.142
	45	Upper	1600	45	299	767	0.045	1344	880	0.875
		Lower	1700	50	648	1661	0.097	1423	1111	1.895
	46	Upper	1300	45	255	655	0.038	1132	669	0.747
		Lower	1500	50	606	1553	0.091	1241	931	1.772
	47	Upper	900	45	109	280	0.016	799	351	0.319
		Lower	1000	50	469	1203	0.07	807	496	1.373
	48	Upper	900	45	None	None	None	None	None	None
		Lower	1000	50	436	1118	0.065	664	364	1.276
9	49	Upper	2000	55	498	1276	0.075	1575	1101	1.456
		Lower	2200	50	764	1958	0.114	1874	1555	2.234
	50	Upper	1800	55	483	1239	0.072	1387	915	1.413
		Lower	2000	50	726	1861	0.109	1690	1373	2.124
	51	Upper	1550	55	468	1200	0.070	1200	729	1.369

		Lower	1700	50	663	1699	0.099	1417	1104	1.938
	52	Upper	1300	55	452	1160	0.068	963	922	1.323
		Lower	1500	50	626	1605	0.094	1232	495	1.831
	53	Upper	900	55	366	938	0.055	587	174	1.069
		Lower	1000	50	491	1259	0.074	790	486	1.437
	54	Upper	900	55	289	742	0.043	502	173	0.846
		Lower	1000	50	439	1125	0.066	663	363	1.283
10	55	Upper	2000	60	555	1422	0.083	1526	1050	1.622
		Lower	2200	50	755	1936	0.113	1877	1559	2.208
	56	Upper	1800	60	546	1400	0.082	1333	858	1.597
		Lower	2000	50	725	1860	0.109	1690	1374	2.122
	57	Upper	1550	60	533	1367	0.079	1144	671	1.559
		Lower	1700	50	660	1692	0.099	1418	1105	1.930
	58	Upper	1300	60	521	1335	0.078	905	434	1.523
		Lower	1500	50	626	1604	0.094	1233	922	1.830
	59	Upper	900	60	384	983	0.057	572	164	1.122
		Lower	1000	50	497	1274	0.074	788	483	1.453
	60	Upper	900	60	302	775	0.045	490	121	0.883
		Lower	1000	50	429	1099	0.064	667	368	1.254
11	61	Upper	2000	45	357	914	0.053	1695	1227	1.043
		Lower	2200	55	881	2260	0.132	2260	1499	2.578
	62	Upper	1800	45	338	867	0.051	1511	1044	0.987
		Lower	2000	55	855	2193	0.128	1634	1312	2.502
	63	Upper	1600	45	299	767	0.045	1344	671	0.875
		Lower	1700	55	657	1834	0.098	1419	1107	2.092
	64	Upper	1300	45	255	655	0.038	1132	440	0.747
		Lower	1500	55	598	1533	0.090	1244	935	1.749
	65	Upper	900	45	133	341	0.019	786	332	0.389
		Lower	1000	55	677	1736	0.101	711	401	1.981
	66	Upper	900	45	None	None	None	None	None	None
		Lower	1000	55	643	1649	0.096	575	279	1.882
12	67	Upper	2000	55	495	1268	0.074	1577	1104	1.447
		Lower	2200	45	629	1612	0.094	1931	1619	1.839
	68	Upper	1800	55	486	1247	0.073	1384	912	1.422
		Lower	2000	45	582	1492	0.087	1751	1441	1.702
	69	Upper	1550	55	470	1206	0.071	1198	727	1.376
		Lower	1700	45	506	1298	0.076	1484	1177	1.481
	70	Upper	1300	55	453	1162	0.068	963	494	1.326
		Lower	1500	45	433	1110	0.065	1315	1011	1.266
	71	Upper	900	55	366	938	0.055	587	174	1.070
		Lower	1000	45	None	None	None	None	None	None
	72	Upper	850	55	289	742	0.043	502	127	0.846
		Lower	750	45	None	None	None	None	None	None