A Comparative Study of Inflow Performance Models for Multilateral Wells under Single and 2-Phase Flow Production Conditions

by,

Nautiss Vijayakumar

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the requirements for the

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CERTIFICATE OF APPROVAL

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A project dissertation submitted to the
Petroleum Engineering Programme
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Approved by,

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CERTIFICATE OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgement and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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NAUTISS VIJAYAKUMAR

ABSTRACT

Over the last the last decade, multilateral well have emerged as a proven alternative to vertical as well as horizontal wells to optimize the recovery of hydrocarbon. These wells are designated to overcome the unfortunate events of discontinuous reserves. Although it was introduced in the year 1950, multilateral well become more popular over the last two decades with the advancement in directional drilling. These milestones achieved in directional drilling have steered the multilateral technology into a new phase of rapid exponential development.

Designing a multilateral well requires great innovation and experience in directional drilling. Unlike Multilateral Well, a conventional well such as vertical based design requires only a simple method of finding out the inflow performance rate and productivity index. Few new models have been introduced to overcome this shortcoming. These models vary in results in addition to the methods and assumptions taken into contemplation. A comparative study shall be conducted to these models and the results obtained will be reviewed.

This comparative analysis will be conducted for dual lateral well in one phase and also two phase flow condition. Both these phase inflow performance is generated in steady state condition. Sensitivity analyses are then performed to all this models to predict the inflow performance at different reservoir condition and well configuration such as the fluid properties and also reservoir geometry. This study is vital in judging the well reserves from the economic point of view. It will also aid in planning the entire process of producing the hydrocarbon from the well. The accurate prediction on the well reserves will help the petroleum engineers in optimizing the production rate of the reservoir.

ACKNOWLEDGMENT

First and foremost, my prayers and gratitude goes to God who has given me the strength to endure the challenging Final Year Project II and for offering me chances after chances to learn and providing me with great experience that will definitely benefit me in the future. Throughout this final year project I've managed to build on to my knowledge and understanding of Multilateral Well's behaviour. I understood that the well communicates to us engineers in a rather unique way. Here, I would like to express my gratitude to a number of individuals that have been my strength and inspiration to complete this Final Year Project.

My heartfelt gratitude goes to my parents, Mr and Mrs Vijayakumar for their encouragement throughout this period. Thank you for being understanding and for being my motivation towards further success in my life.

My enormous gratitude goes to Mr.Mohd Amin Shoushtari for guiding me throughout the Final Year Project I as well as II. Without your endless support and encouragement the completion of this project would not be possible.

My gratitude to my mentor Miss Mariam Annuar, for her tireless tips and step by step guidance given in tackling the challenges throughout this project. Mariam has been generous in sharing her knowledge and understanding on Multilateral Well IPR to me.

Credits to UTP for offering us the students a chance to fulfil our potential and express our creativity and innovation throughout this subject. In general, this project offers the students a chance to mature in the field of study as well as getting them prepared to the demands of the current Oil and Gas Industry that requires personnel to be inquisitive and equipped with research based knowledge.

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ABBREVIATIONS

TAML	Technical Advancement Multilaterals
PROSPER	Production System Performance
PETEX	Petroleum Experts
IPR	Inflow Performance Relationship
GOR	Gas Oil Ratio
AOF	Absolute Open Flow
PVT	Pressure Volume Temperature
FEM	Finite Element Model
PI	Productivity Index
B&O	Babu and Odeh model (1989)
H&W	Helmy and Wattenbarger model (1998)

NOMENCLATURES

Symbol	Description	Units
q	Flowrate	STB/day
k_H	Horizontal permeability	md
k_V	Vertical permeability	md
I_{ani}	Anistropy ratio	Dimensionless
k_y	Permeability of formation in y-direction	md
k_x	Permeability of formation in x-direction	md
k_z	Permeability of formation in z-direction	md
$\bar{P}$	Average reservoir pressure	Psia
P_e	Pressure at the external radius (r = re)	Psia
P_{wf}	Bottomhole flowing pressure	Psia
μ	Viscosity	psi^{-1}
B_o	Formation Volume Factor	res bbl/STB
T	Temperature of reservoir	°F
r_w	Wellbore radius	ft
r_{eH}	Equivalent cylinder drainage radius	ft
$\ln C_H$	Shape factor	Dimensionless
s	Skin due to formation damage	Dimensionless
S_R	Partial penetration skin	Dimensionless
P_{xyz}	Partial penetration skin component x-y-z plane	Dimensionless
P'_{xy}	Partial penetration skin component x-y plane	Dimensionless
P_y	Partial penetration skin component y-plane	Dimensionless
a	Width of reservoir	ft
b	Length of reservoir	ft

h	Height of the reservoir	ft
L	Length of lateral	ft
A	Drainage area	ft^2
x_0	Well location in x-direction	ft
y_0	Well location in y-direction	ft
z_0	Well location in z-direction	ft
x_{mid}	x-coordinate of the midpoint of the well	ft

CHAPTER ONE

1. INTRODUCTION

1.1 BACKGROUND STUDY

Multilateral well in simpler words can be defined as wells consisting of one main well bore with many branches that enable this unique well to produce from a vertically discontinuous reservoir. These branches are established through directional drilling towards the desired targets. First documented multilateral well was constructed in the year 1953 in Bashkiria, former Soviet Union. It’s an onshore well that connects 10 wells altogether. In Malaysia, the Bokor field was recorded as the first successful multilateral in the classification of trilateral well in Asia which is fully operated by PETRONAS. To further understand the behaviour and characteristics of multilateral well, one must understand the geometric terminologies that is used to describe the well.

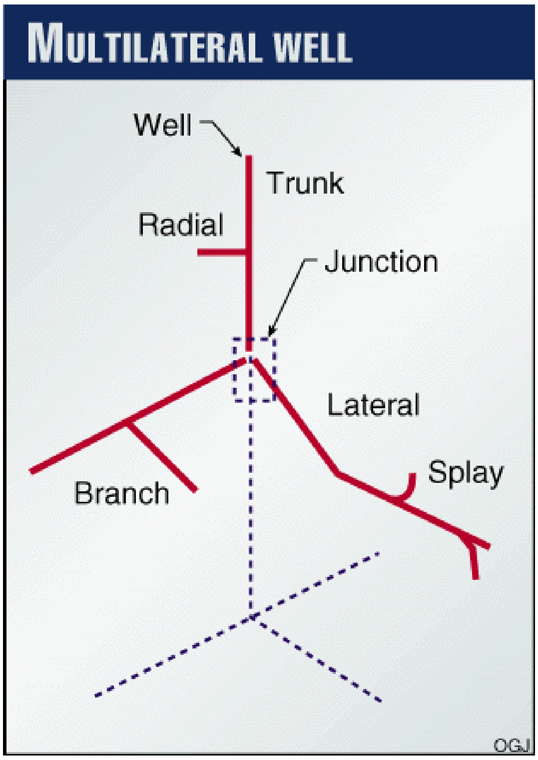

Figure 2.2.1-1 : Geometric Configuration of Multilateral Wells (Hill A.D., Ding Zhu & Economides M.J., 2008)

Figure 1.1-1 shows some of the geometric term that can describe the structure of a multilateral well. From this structure we can deduce that a significant application of directional drilling is involved in constructing multilateral wells. Familiarity to common types of multilateral well is also very vital to figure out more about multilateral wells.

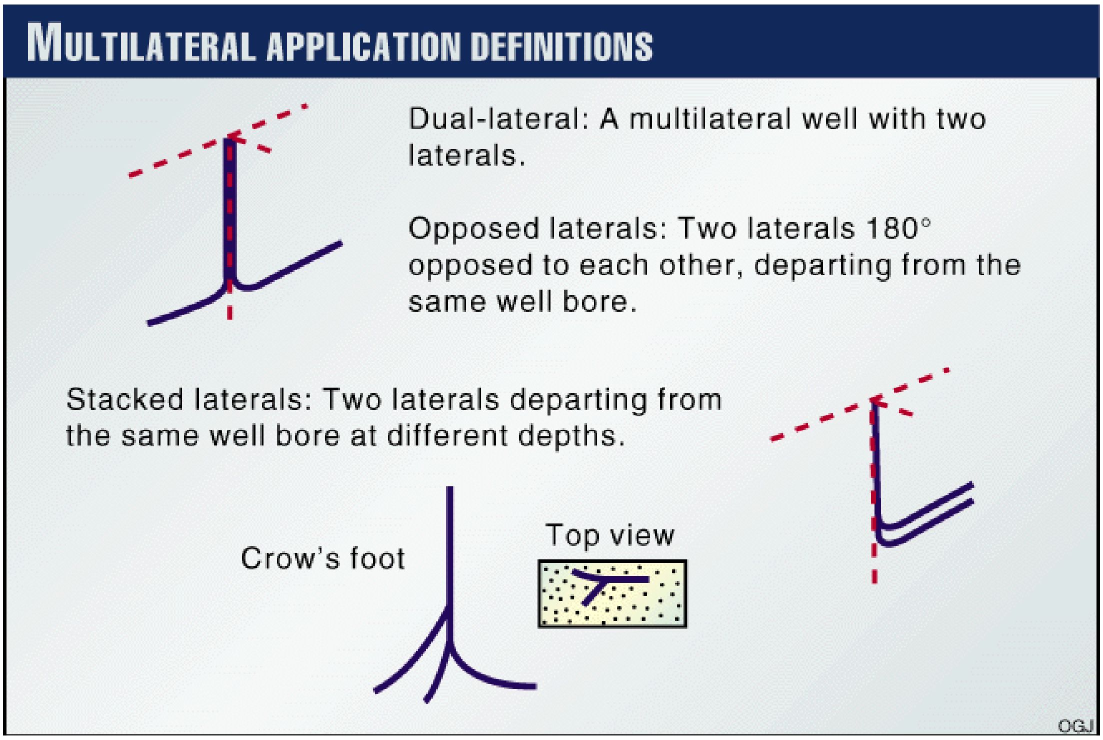

Figure 2.2.1-2 : Common Types of Multilateral Wells(Hill A.D., Ding Zhu & Economides M.J., 2008)

Figure 1.1-2 shows the common types of multilateral wells that are self explanatory. In the year of 1997 an important event took place in the history of multilateral wells when Technical Advancement of Multi-Laterals, an entity that works in aiding the development of multilateral wells came up with a general and widely accepted nomenclature that is still used until today. The classification is denoted as the TAML Classification of Multilateral Wells.

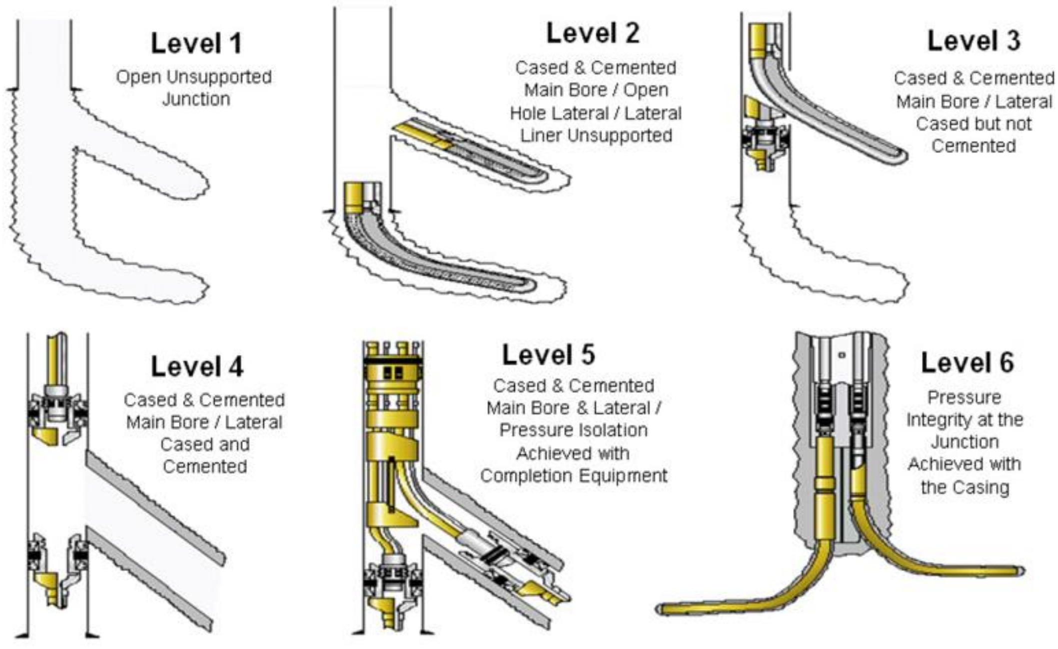

Figure 2.2.1-3 : TAML Classification of Multilateral Wells Completion (Hill A.D., Ding Zhu & Economides M.J., 2008)

Figure 1.1-3 shows the TAML classification. There are basically six type of completions model that differentiate the six levels of the classification. These are some basic ideas that will give great inside about multilateral well.

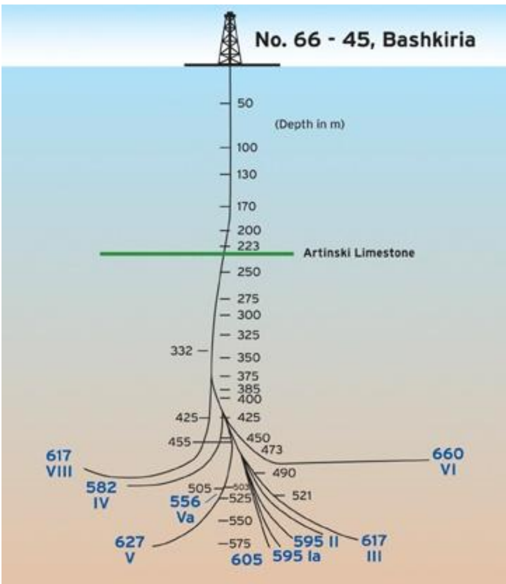

Figure 2.2.1-4 : First Documented Multilateral Well, Bashkiria Russia (Hill A.D., Ding Zhu & Economides M.J., 2008)

1.2 PROBLEM STATEMENT

As any well starts to produce, there will be declining pattern of the productivity index. This is a very common problem in any well that produces continuously. The pressure depletes and ceases the production altogether. To predict this declining pattern and the future productivity index, five models were developed. These models were used in order to predict the future performance of the well and assess the inflow performance of the well

All these five models have different ways of predicting the inflow performance rate. They have different parameters and assumptions. Ultimately, they produce varying results from each other. Our concern here is which model is suitable to our needs. This is important to identify the advantages and disadvantages of these models.

1.3 OBJECTIVE AND SCOPE OF STUDY

The main objective of this study is to evaluate the different models to calculate the inflow performance rate of multilateral well under single as well as 2-phase flow production condition. The other objectives are as per following:

a) To assess the inflow performance rate of multilateral wells

b) To justify the inflow performances' accuracy for all the 3 models developed

Generally, most multilateral well have two or three lateral design. In this study, the phase for the inflow hydrocarbon is specified to two one phase and two phase only under steady state condition. As for single phase of this comparative study, only gas phase is considered. As for the geometry of the well, the study is specified to dual lateral well. This is part of the scope focused in this research.

1.4 RELEVANCE OF PROJECT

The oil and gas industry have many challenges and hurdles over the past one decade. These challenges include overcoming the high cost of recovering them to geological challenges that shun us from reaching out to precious reserves. Multilateral well have been the greatest challenge yet to the booming industry. Engineers and researches in this field admits and understands the need to work and study multilateral as it has its major advantages that contributes to the productivity of in this industry. Some of the advantages are as per following

a) **Increase in reserve**

The discontinuous geometry of reserves with completion of multilateral well enables us to reach out to more than one target in a single well drilled. This in return gives us more reserve to be covered at a less production cost at upstream. The hydrocarbon is produced comingled, under the same wellbore.

b) **Reduced Wellbore Pressure Loss**

Due to the production from a single wellbore the pressure loss in various laterals have be reduced in another word being shared among these laterals. These in return will induce a slower pace of reservoir depletion and at the same time will save a substantial amount of production cost and indirectly optimizes the production.

c) **Slot Conservation**

Slots here are defined by grids or targets where the injection or production well will be constructed. The use of multilateral well will decrease the number of targets for injection as well as production well. The cost of constructing multilateral well is higher compared to developing a single horizontal well, but the processing cost at the wellhead of the multilateral well will be very much lower compared to many single production wells. In this case the benefit of multilateral well supersedes the cost of building one. With the current advancement in primary processing and segregation technology of hydrocarbon, producing the hydrocarbon at comingled condition will incur very minor problems which are ultimately insignificant.

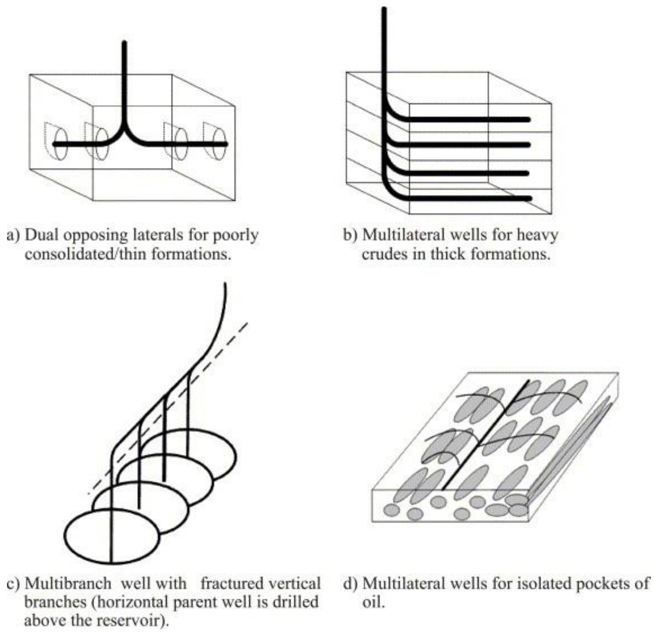

Figure 2.2.1-1: Types of Multilateral Well for Hydrocarbon Recovery (Hill A.D., Ding Zhu & Economides M.J., 2008)

1.5 FEASIBLITY OF PROJECT WITHIN SCOPE AND TIME FRAME

This project is believed to be feasible within the time frame provided with accordance to schedule and key milestone of Final Year Project II. The author has planned to complete the research and literature review by the middle of the FYP II time frame and at the same time familiarize himself with the production optimization software, PROSPER. After completely reviewing the literature, six weeks will be dedicated to input all the relevant data into the production optimization software. Macro is also created within this time frame to calculate and represent the analytical model of the inflow performance correlations of the multilateral well. The macros will be created by using simple Microsoft Excel software. Equipments and material required for this research has been prepared by the UTP management and the necessary optimization software is also provided by UTP, thus reducing any wastage of time in purchasing and installing the software.

CHAPTER TWO

2 LITERATURE REVIEW

2.1 REFERENCES

A number of references were used to generate the knowledge and understanding on this topic. The book entitled Multilateral Wells by A.D Hill, Ding Zhu and Michael J. Economides published by Society of Petroleum is used as the main reference for this research. The models used in this book are also used to conduct the comparative studies. A several research papers and dissertation were referred to as guidance in comparing all these models.

2.2 ANALYSIS OF LITERATURE

From thorough analysis of literature there are two ways of predicting the inflow performance of Multilateral Wells

- Numerical Approach
- Analytical Approach

2.2.1 Numerical Approach

In the Oil and Gas industry, PROSPER by Petroleum Experts is a widely used software to simulate a multilateral well. It is a useful tool that allows engineers to predict the IPR of Multilateral Well as well conduction sensitivity analysis on their models. The main functions of PROSPER as per the scope of this research

a) Determine inflow performance of a dual-lateral wells under two different conditions: Single Phase and 2-Phase Flow Condition of Steady-State Condition.

b) Modelling sensitivity analysis of the IPR against desired parameters that has been the input during the process of modelling the Multilateral Well.

2.2.2 Analytical Approach

Multilateral Well reference book published by the Society of Petroleum Engineer has listed the following models to calculate the inflow performance rate of multilateral well. The models are as per following.

a) Joshi's Model (1998)

b) Butler Model (1994)

c) Furui ***et al.,*** Model (2003)

d) Babu and Odeh Model (1989)

e) Helmy and Wattanbarger(1998)

These models were developed using different assumptions and parameters that are considered are also not similar. Through literature review on these models from the reference book as well as the research papers related to multilateral well, a comparative study is conducted.

Joshi's Model (1998)

This model assumes the ellipsoidal shape of a reservoir

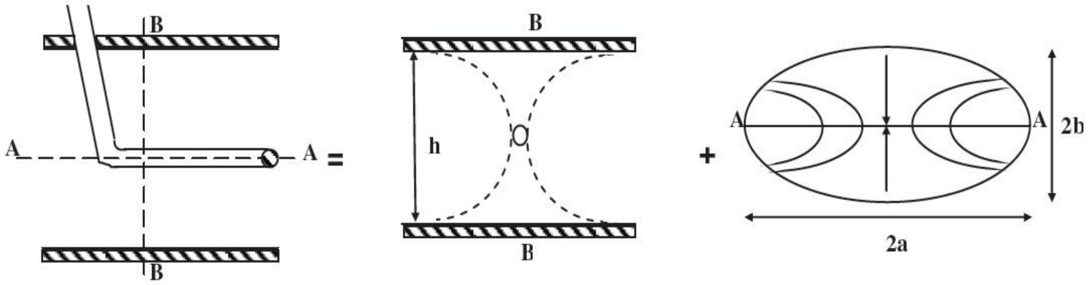

Figure 2.2.2-1 : Flow Geometries Assumed by Joshi's Model (Hill A.D., Ding Zhu & Economides M.J., 2008)

This model has been modified by Economides *et al.*, (1991) to take into consideration skin effect and also effects of anisotropic. Joshi's Model is presented as follow

$$q = \frac{k_H h\left(P_e - P_{wf}\right)}{141.2\mu B_o\left[ln\left(\frac{a+\sqrt{a^2-\left(\frac{L}{2}\right)^2}}{\frac{L}{2}}\right)+\frac{I_{ani}\,h}{L}\left(ln\left(\frac{I_{ani}\,h}{r_w\left(I_{ani}+1\right)}\right)+s\right)\right]} \quad - (2.1)$$

Whereas the anisotropic ratio I_{ani} is denoted as following:

$$I_{ani} = \sqrt{\frac{k_H}{k_V}} \quad - (2.2)$$

The drainage area is calculated with the formula:

$$\boldsymbol{a} = \frac{\boldsymbol{L}}{\boldsymbol{2}}\left\{\boldsymbol{0.5}+\left[\boldsymbol{0.25}+\left(\frac{\boldsymbol{r_{eH}}}{\frac{\boldsymbol{L}}{\boldsymbol{2}}}\right)^{\boldsymbol{4}}\right]^{\boldsymbol{0.5}}\right\}^{\boldsymbol{0.5}} \quad - (2.3)$$

Where,

q	=	Flowrate
k_H	=	Horizontal permeability
k_V	=	Vertical permeability
h	=	Height of the reservoir
P_e	=	Pressure at the external radius (r = re)
P_{wf}	=	Bottomhole flowing pressure
μ	=	Viscosity
B_o	=	Formation Volume Factor
a	=	Half length of the drainage ellipse
L	=	Length of lateral
I_{ani}	=	Anisotropy ratio
r_w	=	Wellbore radius
s	=	Skin due to formation damage
r_{eH}	=	Equivalent cylindrical drainage radius

However there are some conditions to Joshi's Model

$$L > h \; and \; \left(\frac{L}{2}\right) < 0.9 \, r_{eH} \qquad - (2.4)$$

Butler's Model (1994)

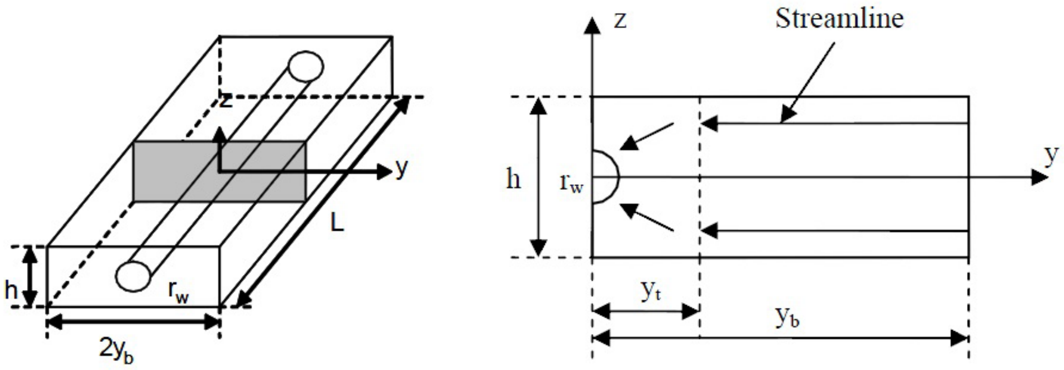

Figure 2.2.2-2 : Flow Geometry in a Box Shaped Reservoir (Hill A.D., Ding Zhu & Economides M.J., 2008)

Butler model takes into consideration of the assumption, a horizontal well fully penetrated in a box shaped reservoir. This horizontal well is assumed to be located in the midway between the upper and lower boundary of the reservoir layer. The equation can be utilized for both isotropic and anisotropic reservoirs.

$$q = \frac{k_H L\left(P_e - P_{wf}\right)}{141.2\mu B_o \left[I_{ani}\, ln\left[\frac{I_{ani}\, h}{r_w\left(I_{ani} + 1\right)\sin\left(\frac{\pi y_b}{h}\right)}\right] + \frac{\pi y_b}{h} - 1.14 + s\right]} \qquad \text{- (2.5)}$$

Where,

q	=	Flowrate
k_H	=	Horizontal permeability
k_V	=	Vertical permeability
h	=	Height of reservoir
P_e	=	Pressure at the external radius (r = re)
P_{wf}	=	Bottomhole flowing pressure
μ	=	Viscosity
B_o	=	Formation Volume Factor
L	=	Length of lateral
I_{ani}	=	Anistropy ratio
r_w	=	Wellbore radius
s	=	Skin due to formation damage
y_b	=	Well location in y-direction

Furui *et al*,. Model (2003)

This model also assumes the box shaped reservoir geometry as Butler Model. The model can also be used to evaluate both isotropic and anisotropic reservoirs. The skin factor is added into this model to take into consideration of the formation damage. This model also assumes horizontal well penetrating throughout the box shaped reservoir layer which has a no flow boundary characteristics. The horizontal well is assumed to be located at the centre of the reservoir. Assumptions were also made to the flow pattern for this model. The flow pattern near the wellbore is assumed to be radial and this change to linear as it moves further away from the well. This model is also modified to predict the inflow performance of single phase gas well. (Kamkun and Zhu, 2006)

$$q = \frac{kL\left(P_e - P_{wf}\right)}{141.2\mu B_o\left[ln\left(\frac{I_{ani}\,h}{r_w\left(I_{ani}+1\right)}\right)+\frac{\pi y_b}{I_{ani}\,h}-1.224+s\right]} \qquad \text{- (2.6)}$$

Where permeability is defined as:

$$k = \sqrt{k_y k_z} \qquad \text{- (2.7)}$$

Where,

q	=	Flowrate
k_H	=	Horizontal permeability
k_V	=	Vertical permeability
h	=	Height of the reservoir
P_e	=	Pressure at the external radius (r = re)
P_{wf}	=	Bottomhole flowing pressure
μ	=	Viscosity
B_o	=	Formation Volume Factor
L	=	Length of lateral
I_{ani}	=	Anistropy ratio
r_w	=	Wellbore radius
s	=	Skin due to formation damage
y_b	=	Well location in y-direction
k_y	=	Permeability of formation at y-direction
k_z	=	Permeability of formation at z-direction

Babu and Odeh model (1989)

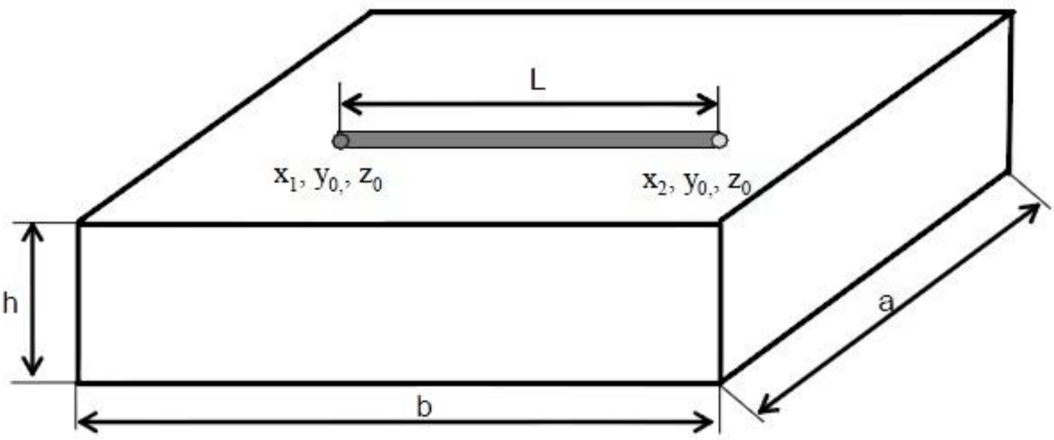

Figure 2.2.2-3 : Geometric Model Assumed by Babu and Odeh Model (Hill A.D., Ding Zhu & Economides M.J., 2008)

Figure shows the assumption made from the aspect of reservoir geometry in Babu and Odeh Model. This model considers shape factor to account for drainage area change and a partial penetration skin factor specifically for partially penetrated wellbores. The model can be utilized to evaluate both isotropic and anisotropic reservoirs. Unlike other models the well in this model can be in any position within the reservoir.

Babu and Odeh Model (1989) is presented as below

$$q = \frac{\sqrt{k_y k_z}\, b\left(\bar{P} - P_{wf}\right)}{141.2\mu B_o\left[ln\left(\frac{A^{0.5}}{r_w}\right) + \ln C_H - 0.75 + S_R + \left(\frac{b}{L}\right)s\right]} \qquad \text{- (2.8)}$$

Where $ln\ C_H$,

$$lnC_H = 6.28\frac{a}{I_{ani}\,h}\left[\frac{1}{3} - \frac{y_0}{a} + \left(\frac{y_0}{a}\right)^2\right] - \ln\left(sin\frac{\pi z_0}{a}\right) - 0.5ln\left[\frac{a}{I_{ani}\,h}\right] - 1.088 \qquad \text{- (2.9)}$$

Where,

q	=	Flowrate
k_H	=	Horizontal permeability
k_V	=	Vertical permeability
h	=	Height of the reservoir
$\bar{P}$	=	Average reservoir pressure
P_{wf}	=	Bottom hole flowing pressure
μ	=	Viscosity
B_o	=	Formation Volume Factor
L	=	Length of lateral
I_{ani}	=	Anisotropy ratio
r_w	=	Wellbore radius
s	=	Skin due to formation damage
y_b	=	Well location in y-direction
k_y	=	Permeability of formation at y-direction
k_z	=	Permeability of formation at z-direction
lnC_H	=	Shape factor
S_R	=	Partial penetration skin

Helmy and Wattenbarger Model (1998)

Helmy and Wattenbarger Model (1998) is an extended work of Babu and Odeh to account the case of uniform wellbore pressure. This is achieved by determining correlation constants for the Dietz shape factor and for partial penetration skin factor. They also modified the partial penetration skin model of Babu and Odeh's to take into consideration the uniform flux. The correlation was developed using correlation equations of Babu and Odeh as the base model. By adding some additional empirical constants and then finding the constants in these equations the model is modified to give the best match simulation results. These results were compared to multilateral wells worldwide.

Helmy and Wattenbarger Model (1998) is presented below:

$$J = \frac{k_{eq}\, b_{eq}}{141.2B\mu\left(\frac{1}{2}ln\left(\frac{4A_{eq}}{\gamma r_{weq}^2} - \frac{1}{2}lnC_A + S_R\right)\right)} \qquad \text{- (2.10)}$$

In the equations above, the subscript "eq" represents the altered variables used to portray an anisotropic reservoir.

2.3 COMPARING THE ANALYTICAL MODEL

Since the scope of this study is focusing on only Steady State condition for single phase and two phase inflow, a table is formed to compare and contrast between these analytical models to choose the models suitable to the scope of this project.

Table 2.2.2-1 : Comparing Analytical Model

	Boundary condition	**Model geometry**	**2-Phase Flow**	**1-Phase Flow Condition(GAS)**
Joshi's Model (1988)	Steady-state	Ellipsoidal-shaped reservoir	Applicable	Not Applicable
Butler Model (1994)	Steady-state	Box-shaped reservoir	Applicable	Not Applicable
Furui *et al.*, Model (2003)	Steady-state	Box-shaped reservoir	Applicable	Applicable
Babu and Odeh Model (1989)	Pseudo-steady state	Box-shaped reservoir	Applicable	Applicable
Helmy and Wattenbarger Model (1998)	Pseudo-steady state	Box-shaped reservoir	Applicable	Not Applicable

From the table above we can deduce that for 2-Phase flow condition under steady state reservoir condition, only Joshi's Model, Butler Model and Furui *et. al.* Model can be utilized. As for single phase (Gas) of the study only Furui *et. al.* Model can be utilized. This decision is made upon the scope of our study.

2.4 RESERVOIR INFLOW PERFORMANCE

It is important to understand the behaviour of IPR curves for phases such as one phase Gas flow, two phase flow and one phase oil flow. All these phases generates very different trend of IPR plot. IPR plot is generated through the relationship between (q) and the wellbore pressure (P_{wf}). These two parameters play an important role in controlling as well as predicting the IPR plot. In this part of the literature review the different behaviour and trend of IPR depending on the phase involved is discussed.

2.4.1 Liquid Inflow

For liquid inflow we consider the inflow of under saturated oil.

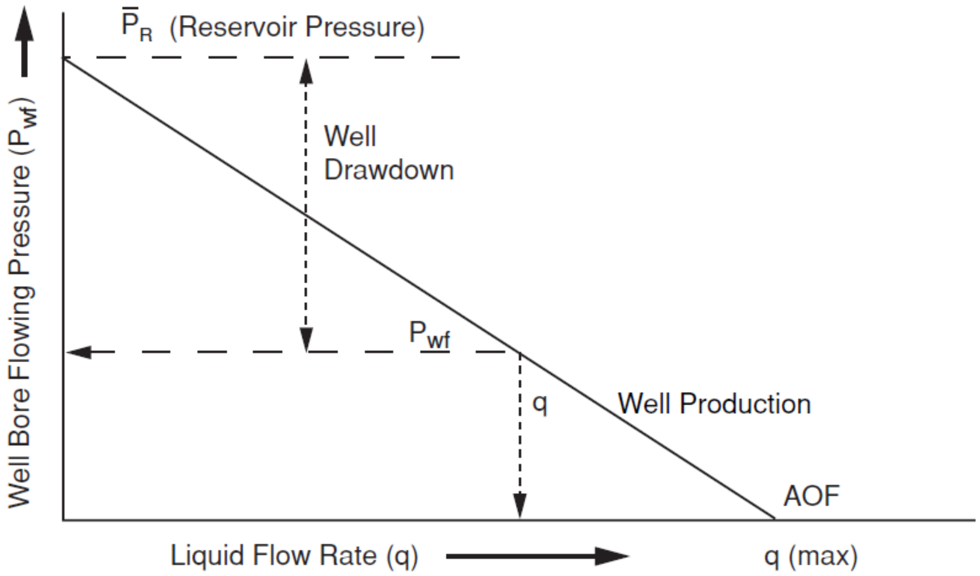

Figure 2.4.1-1 : Straight Line IPR Generated by One - Phase Liquid Flow (Incompressible Under Saturated Oil) (Hill A.D., Ding Zhu & Economides M.J., 2008)

The equation for straight line generated will be as follows

$$q = PI(\bar{P} - P_{wf}) \qquad - (2.11)$$

Where,

q	=	Flow Rate	STB/day
PI	=	Productivity Index	STB/day/psi
$\bar{P}$	=	Average reservoir pressure	Psig
P_{wf}	=	Bottom Hole flowing pressure	Psig

Another important parameter of IPR plot is AOF (Absolute Open Flow) or q_{max}. This parameter represents the flowing rate that occurs when flowing bottom hole pressure is zero. Though, this condition is impossible to take place. This parameter is useful in comparing all the IPR models for multilateral well since it is included in the calculation of Productivity Index.

2.4.2 Gas Inflow

Since gas has a compressible nature the IPR plot deducted from a gas inflow does not have a straight line trend. This resulted in another equation that takes into account of this unique behaviour of gas.

$$q = C(\bar{P}_R^2 - P_{wf}^2) \quad - (2.12)$$

C is a constant

However the equation above is only valid for low flow rate and not for high flow rate. As for high flow rate, the effect of non-Darcy flow effect should be taken into consideration in order to generate an accurate IPR for gas flow. The equation for high flow rate of gas is as following

$$q = C(\bar{P}_R^2 - P_{wf}^2)^n \quad - (2.13)$$

Where the value of n, 0.5 < n < 1.0

The figure below shows the characteristics of IPR generated by One-Phase Gas Flow.

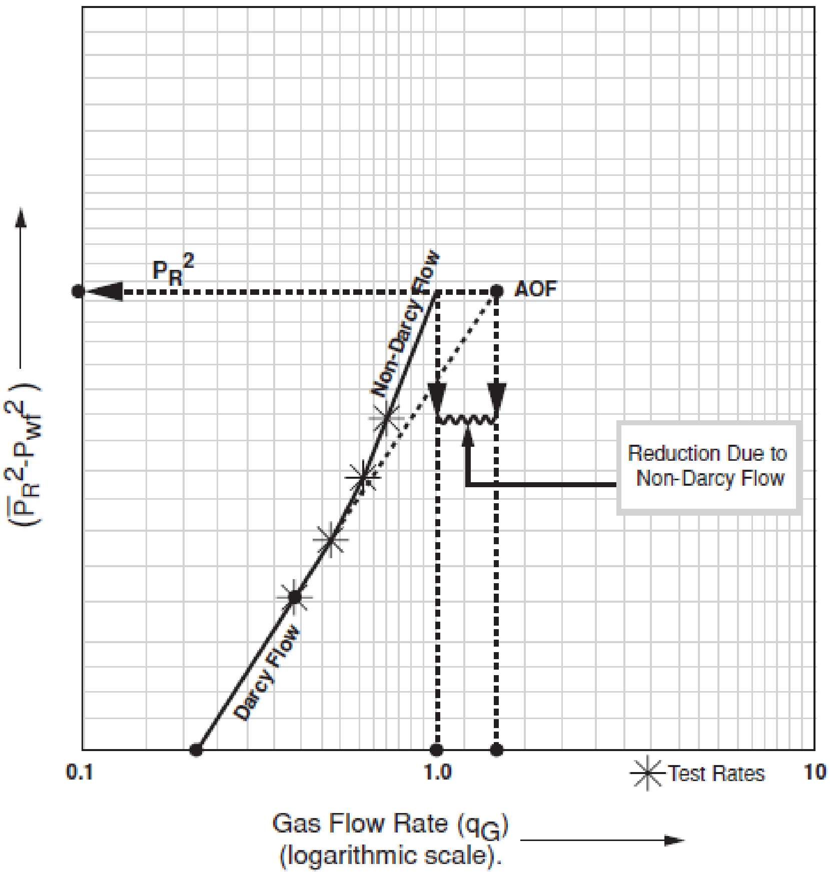

Figure 2.4.2-1 : Gas Well Deliverability Taking Into Account of Non-Darcy Flow Effect (Hill A.D., Ding Zhu & Economides M.J., 2008)

2.4.3 Two Phase Inflow Performance Relationship (IPR)

Straight line IPR is also not applicable for two phase flow. This is because the characteristics of two phase inflow that is compressible. The Vogel Equation is utilised in generating IPR for two phase inflow. Vogel Equation is as per following.

$$\frac{q}{q_{max}} = 1 - 0.2\left(\frac{P_{wf}}{\overline{P}}\right) - 0.8\left(\frac{P_{wf}}{\overline{P}}\right)^2 \qquad \text{- (2.14)}$$

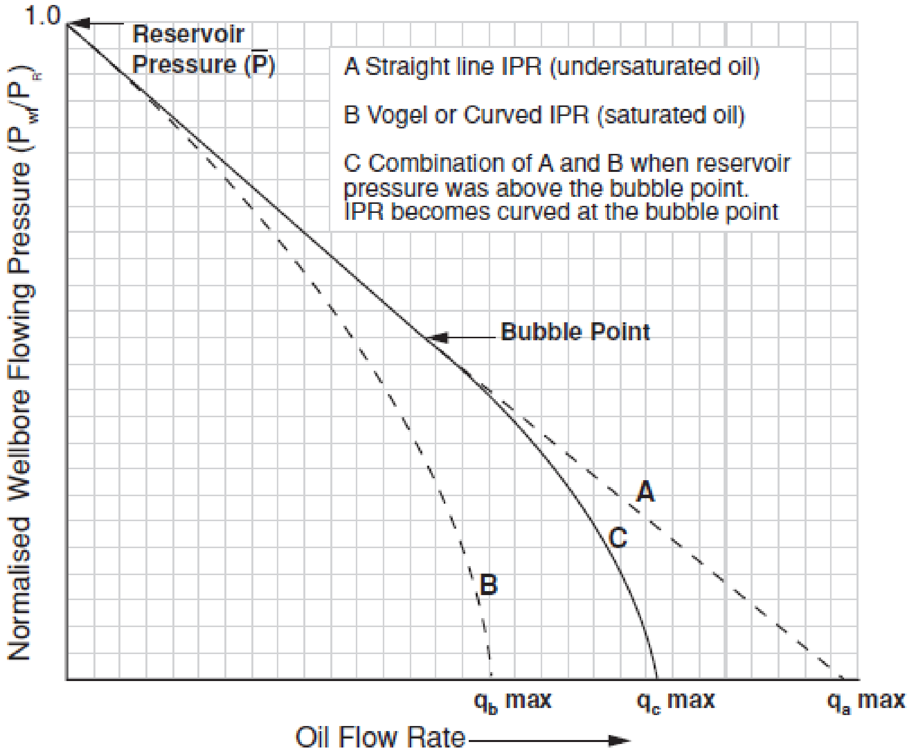

Figure 2.4.3-1 : Inflow Performance Relationship for Two Phase Inflow (Hill A.D., Ding Zhu & Economides M.J., 2008)

Figure 2.4.3 1 shows the IPR plot for two phase inflow. From the plot we can observe that Line A represent the pressure drawdown for under saturated flow. Curve C represent the case of when the wellbore pressure is below the bubble point and the reservoir pressure is above the bubble point. Lastly Curve B represents the two phase flow effect, a combination of straight line analytical model and Vogel's Correlation.

It is vital to investigate the analytical models and find out which one of this analytical model that gives the least difference compared to the numerical model developed using PROSPER. The analytical model that will generate the closest match to PROSPER simulation will be taken into consideration in conducting the sensitivity analysis at the later part of the research activity study to well configuration. PROPSER focuses on sensitivity study against reservoir condition where as the analytical model focuses on sensitivity study against the well configuration.

CHAPTER THREE

3 METHODOLOGY

3.1 RESEARCH METHODOLGY

This research is conducted using the following basic flow.

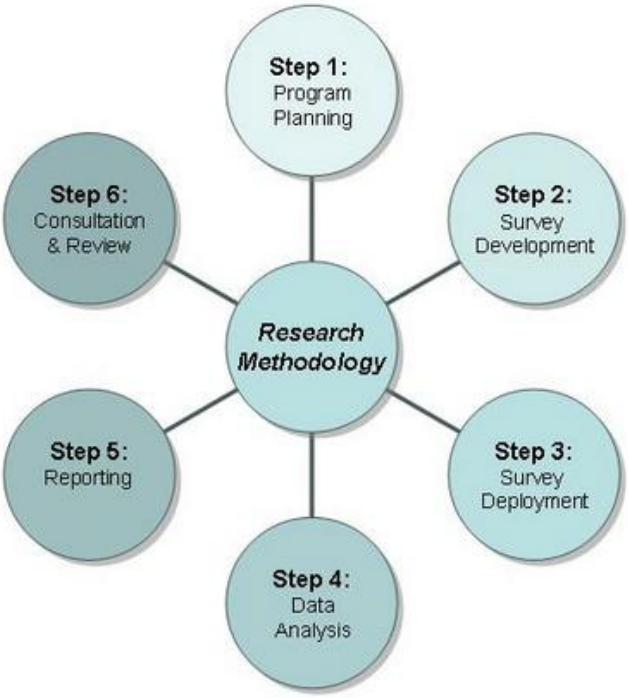

Figure 2.4.3-1 : Basic Flow of Research Methodology

Step One: Program Planning

Before beginning with this research, the very first step is to prepare a complete and a well thought out timeline and steps for the research. A Gantts chart is deployed to complete the entire research in a timely manner.

Step Two: Survey Development

The intended research needs adequate data to work on with. In this part of the methodology, the adequate information is collected. The information includes all reservoir data ranging from pressure to flow rate. The data can be collected from references or retrieved from a real field data of a multilateral well. A thorough survey is conducted to capture the most suitable set of data to work with.

Step Three: Survey Deployment

The received data will then later be included to our models to calculate inflow performance rate of the specific multilateral well. This will be conducted through Excel Spreadsheet. The data will also be deployed to our production optimization software, PROSPER. The results were collected from the outcome of calculation from the models as well as the result generated by PROSPER.

Step Four: Data Analysis

The result of the inflow performance rate calculated from different models is compared among them and also compared to the results provided by PROSPER. These results were analysed accordingly. The outcomes will be put on graph for graphical representation to ease the judgment when comparing these models. Sensitivity analysis is conducted to find out the change in IPR due to the changes of some significant parameters such as rock and fluid properties as well reservoir dimensions.

Step Five: Reporting

After analysing the results and running the required simulation, the outcome is documented and put into words to describe them and for future references. Reporting shall be done immediately after gaining the outcome and results to avoid redundancy.

Step Six: Consultation & Review

The complete report of the research will later be submitted to supervisors to seek for their consultancy and advice. These steps shall be carried out provided the results and data in the report is certified and endorsed by the supervisor at first place. The reviews and comments were taken into attention to improvise the research and to achieve the goals stated in the objective of the research.

3.2 DATA AVAILABILITY

3.2.1 Two Phase Flow

The table below shows an example of hypothetical Multilateral Well data adapted from a research paper by Boyun Guo, Jinkui Zhou, Kegang Ling and Ali Ghalambar from University of Louisiana at Lafayette, May 2008. The data in the research paper is also utilized for the same purpose that is to study multilateral well behaviour.

Table 3.2.1-1 : Data Table for 2-Phase Flow Condition

Symbol	Description	Units	Layer 1	Layer 2
k_h	Horizontal permeability	md	10	10
k_v	Vertical permeability	md	10	10
B_o	Oil formation volume factor	res bbl/STB	1.02	1.03
B_w	Water formation volume factor	res bbl/STB	1.03	1.03
μ	Viscosity of oil	cp	6	6
r_e	Drainage radius	ft	2200	2200
r_w	Wellbore radius	ft	0.208	0.208
s	Skin	Dimensionless	0	0
P_R	Reservoir pressure	psig	2635.3	2593.3
T_R	Reservoir temperature	^oF	195	195
h	Height	ft	100	60
a	Width of reservoir	ft	3000	3000
b	Length of reservoir	ft	4000	4000
L	Length of lateral	ft	2000	2000

Table 3.2.1-2 : PVT Data for 2-Phase Flow Model of Dual Lateral Well

Description	Units	Pay zone 1	Pay zone 2
Oil gravity	°API	31.14	31.14
Gas gravity	Sp. gravity	0.60	0.60
Water salinity	ppm	80000	80000
Water cut	fraction	0	0
Gas Oil Ratio (GOR)	scf/STB	500	500

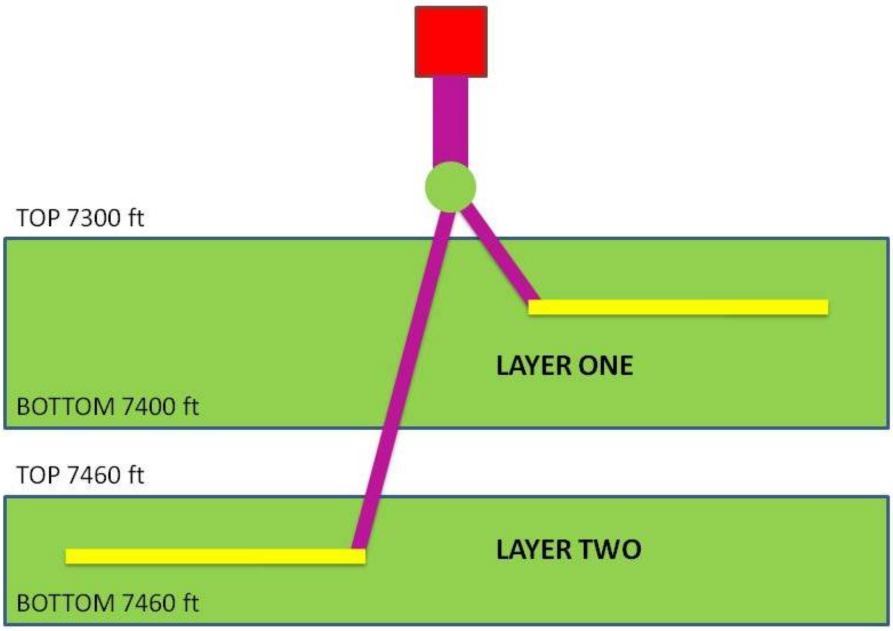

Figure 3.2.1-1 : Model Assumption for 2-Phase Inflow of Multilateral Well under Steady State Condition

Figure above shows the model assumption used in this scope of research. Certain assumption are made to the model above

- Each layer of reservoir is isolated from one another.
- Each lateral well produces from different reservoir and having the same tie in point.
- The lateral is horizontal and gravity effect is neglected
- The wellbore pressure drop due to inflow effect is rather small and negligible
- Turbulence effect is neglected and not taken into consideration in the model inflow performance
-

3.2.2 One Phase Flow (Gas)

For one phase flow of the Multilateral Well we are considering Gas phase inflow. The hypothetical reservoir data adapted from the same research paper. The table below is the summary of these data.

Table 3.2.2-1 : Hypothetical Data for One Phase (Gas) Flow for Multilateral Well

Symbol	Description	Units	Layer 1	Layer 2
k_h	Horizontal permeability	md	10	10
k_v	Vertical permeability	md	10	10
μ	Viscosity of Gas	cp	0.04	0.04
r_e	Drainage radius	ft	2200	2200
r_w	Wellbore radius	ft	0.208	0.208
s	Skin	Dimensionless	0	0
P_R	Reservoir pressure	psig	2635.3	2593.3
T_R	Reservoir temperature	^oF	186	188
h	Height	ft	100	60
a	Width of reservoir	ft	3000	3000
b	Length of reservoir	ft	4000	4000
L	Length of lateral	ft	2000	2000

Table 3.2.2-2 : PVT Data for One Phase Flow Model for Dual Lateral Well

Description	Units	Pay zone 1	Pay zone 2
Gas gravity	Sp. gravity	0.85	0.85
Gas Z-Factor	Dimensionless	0.87	0.87
Water salinity	ppm	80000	80000
Water cut	fraction	0	0

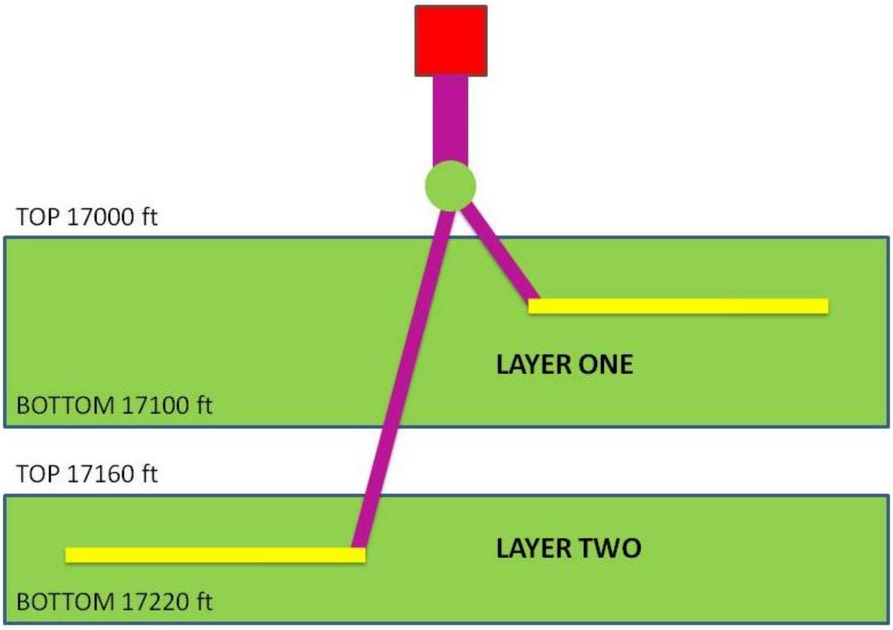

Figure 3.2.2-1 : Model Assumption for One Phase (Gas Flow) for Multilateral Well

Some assumptions are made to this model

- Each layer of reservoir is isolated from one another.
- Each lateral well produces from different reservoir and having the same tie in point.
- The lateral is horizontal and gravity effect is neglected
- The wellbore pressure drop due to inflow effect is rather small and negligible
- Turbulence effect is neglected and not taken into consideration in the model inflow performance

3.3 WORKFLOW SUMMARY

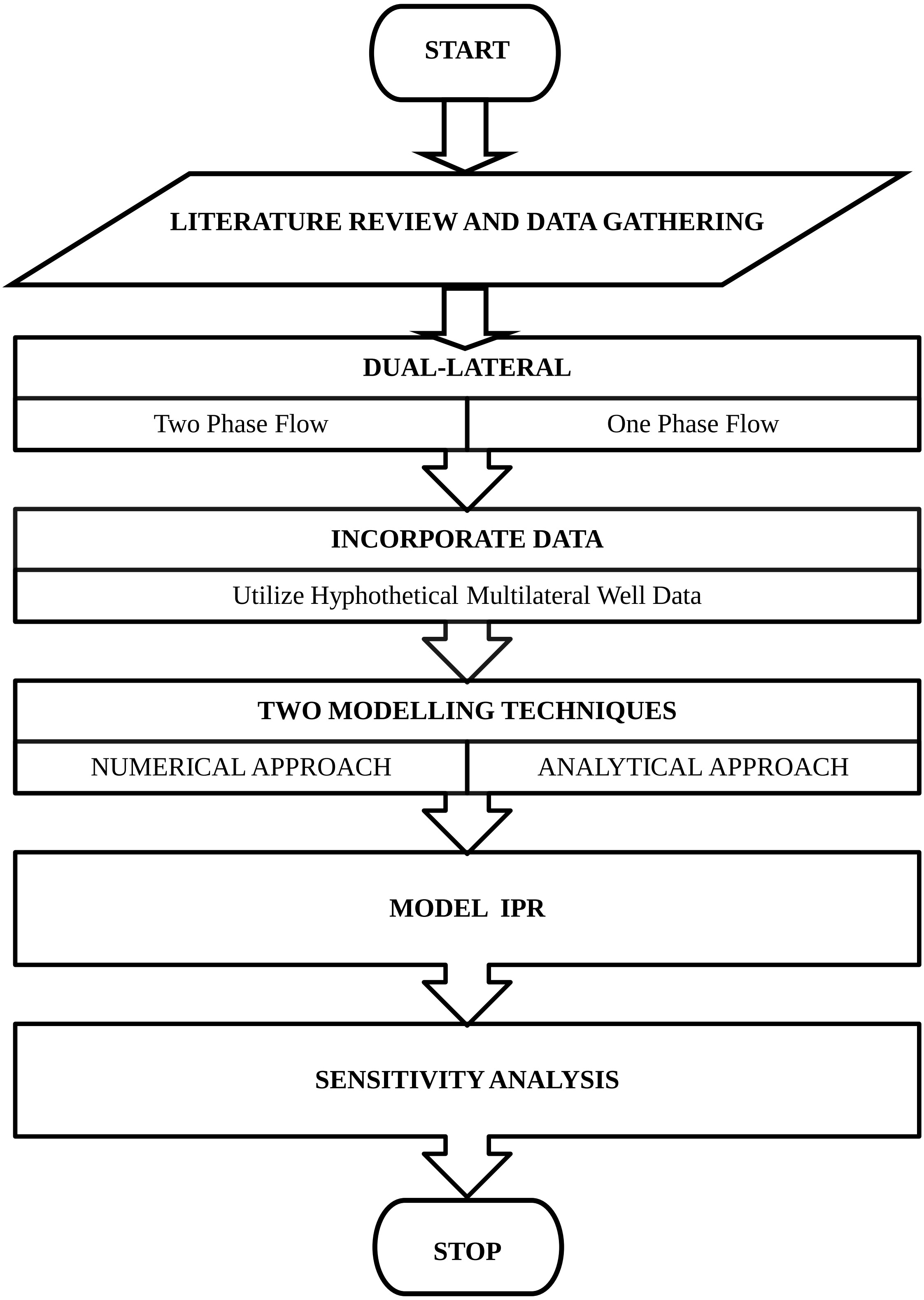

Figure 3.2.2-1 : Workflow Summary

3.4 GANTT CHART, KEY MILESTONE

Table 3.2.2-1 : Gantt Chart

No	Detail / Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14	15
1	Learning to use PROSPER software	■	■						Mid Semester Break								
2	Modeling IPR Curves in PROSPER Software			■	■	■	■	■									
3	Submission of Progress Report									○							
4	Validating the PROSPER IPR Using Excel Macros of all five IPR correlation									■	■	■					
4	Pre-EDX											○					
5	Submission of draft report											■	○				
6	Submission of dissertation(soft bound) and technical paper													■			
7	Oral presentation														○		
8	Submission of project dissertation (hard bound)															○	■

○ -Milestones

■ - Processes

3.5 TOOLS TO BE USED

Production Optimization Software-PROSPER

The PROSPER Software will be utilized throughout this research. PROSPER is a product of PETEX, Petroleum Experts. PROSPER is a well performance, design and optimisation program for modelling most types of well configurations found in the field. In this research this software will be used to configure multilateral well. This software is licensed to UTP and used in Block 15 of Academic Complex only.

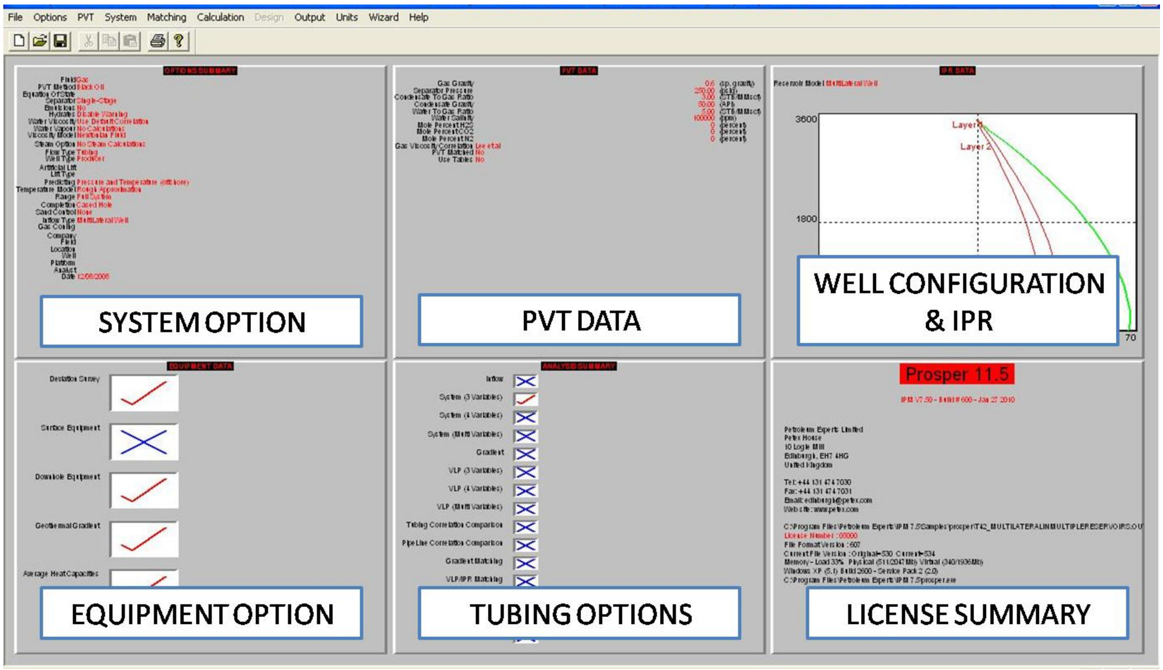

Figure 3.2.2-1 : PROSPER Graphical User Interface

The figure shows the layout for the user interface in Prosper. Each of the boxes in the user interface represents six major component of the program itself. In the first box, **System Option,** options were given to choose between a single well or multilateral well structure. Other options such as fluid type and also the company data can also be included in this configuration. Second box, the **PVT Data** collects fluid property data for the modelling. Third box, **Well Configuration & IPR** represents one of the most important parts of the modelling. Here, the well will be constructed according to the geometry and all the relevant data such as the true vertical depth (TVD) of the reservoir layers and their respective thickness. In the fourth box, **Equipment Option** some configuration on well facilities is finalised in this section of the GUI. Tubing options will be included in the fifth box, **Tubing Option.** The last box is only consisting of **License** details of the software.

Communication Tool

Communication tool that will be used will be a basic PC that will be fit to run and simulate PROSPER. These PCs can be found in Block 15 of Academic Complex.

Software Lab

The Software Lab in Block 15 will be used to run the PROSPER software. This lab will be used subjected to availability and shall be booked earlier to conduct any work. The usage of this facility shall be strictly bounded by the rules and regulation of Universiti Teknologi Petronas.

CHAPTER FOUR

4 RESULTS AND DISCUSSIONS

4.1 RESERVOIR INFLOW RELATIONSHIP FOR 2-PHASE FLOW

4.1.1 2-Phase Flow under Steady State Condition

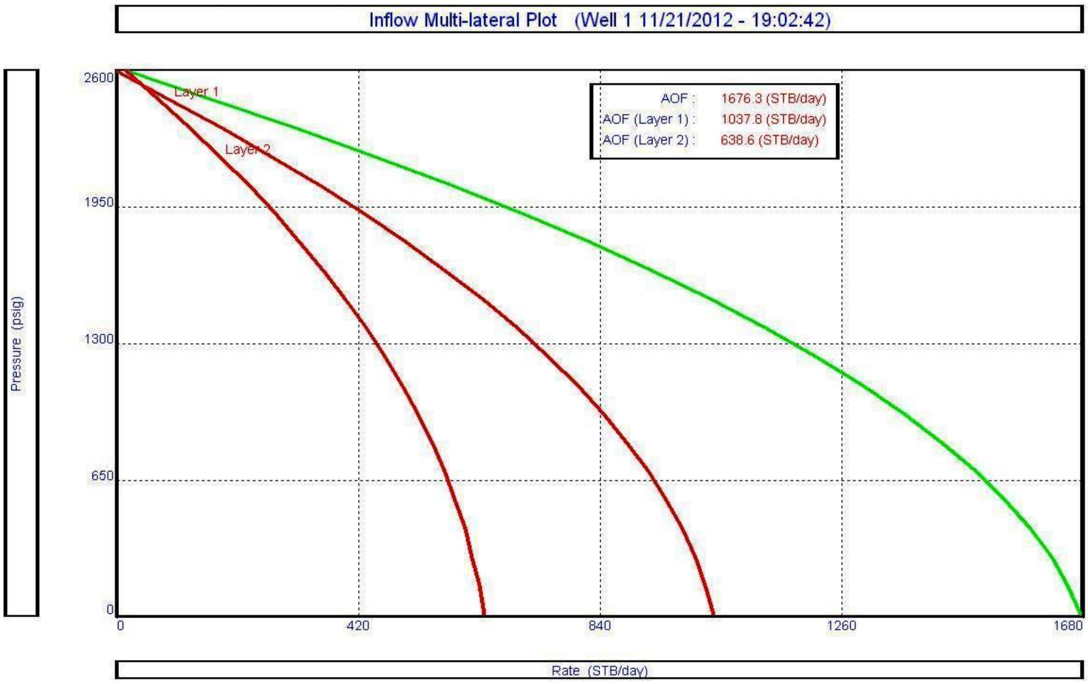

Figure 4.1.1-1 : IPR from PROSPER Under Steady State Two Phase Flow Condition for Dual Lateral Multilateral Well

Figure 4.1.1-1 indicates the outcome of the Inflow Performance Plot of numerical approach under infinite conductivity. The trend of the plot shows a typical pressure drawdown of a well under steady state condition of two phase flow.

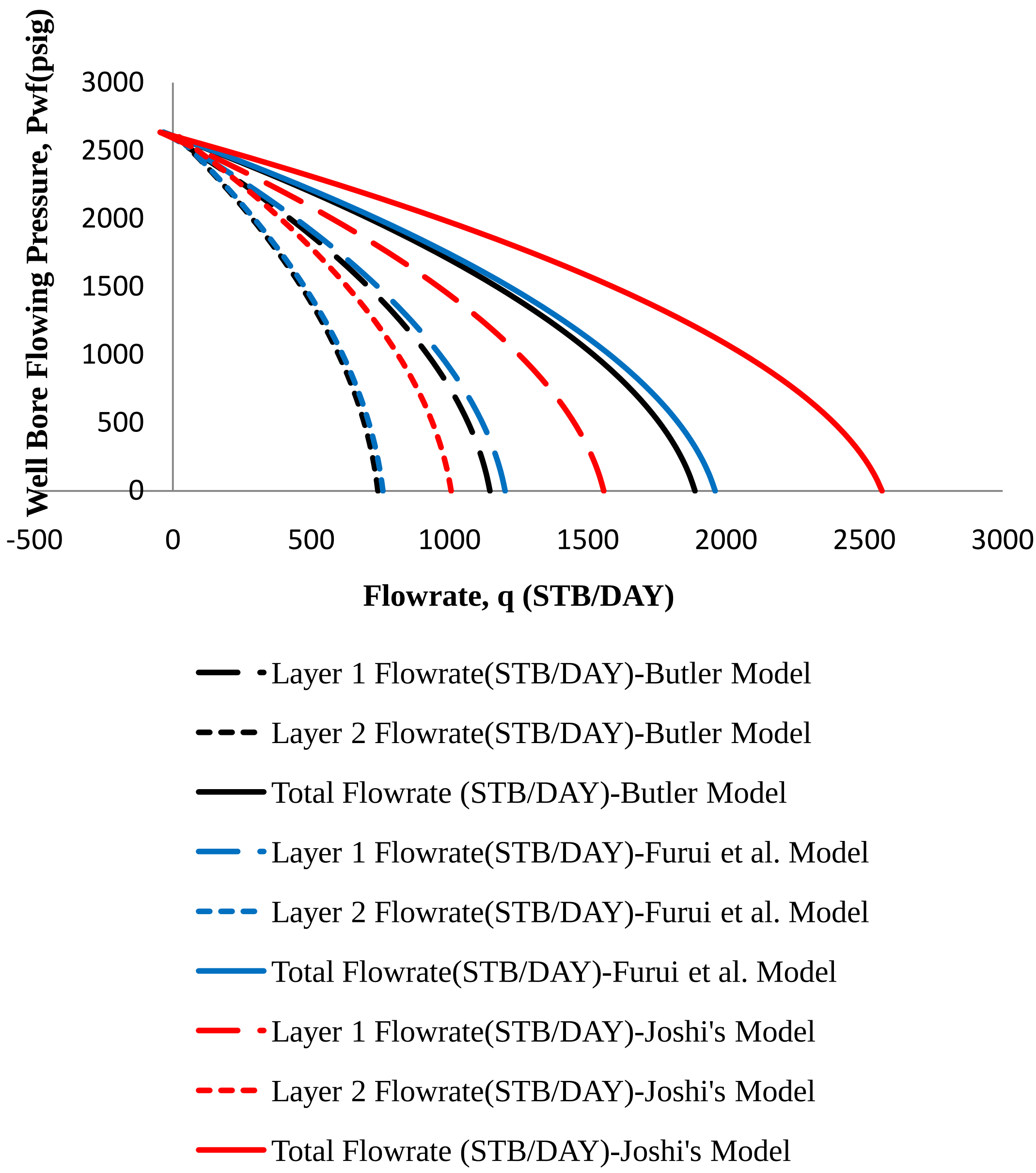

Figure 4.1.1-2 : IPR Plot from Analytical Approach under Steady State Two Phase Flow Condition for Dual Lateral Multilateral Well.

The reservoir data used for the two phase flow condition for this well consist of oil flow as well as water inflow. Hence the expected IPR will be reducing exponentially. These models were derived from the Vogel Equation after finding the Absolute Open Flow (AOF) of each layer. The models show a clear combination between a straight line IPR as well as the curve plot due to Vogel correlation. In all the models Layer 1 records higher inflow since the thickness of the Layer 1 that is higher than Layer 2.

Comparing the IPR of Joshi's Model (1998), Butler (1994) Model and Furui (2003) *et. al.* Model, there is a huge difference between the estimation of inflow rate of Joshi's Model compared to Butler's and Furui *et. al.* Model. Joshi's model represents the highest flow rate with comparison to Butler and Furui *et. al.* Models. This situation is contributed by the assumption made in Joshi's Model. Joshi's Model assumed that the reservoir is ellipsoidal shaped and the flow geometry is an ellipsoidal drainage area. Joshi's model also simplifies the 3 dimensional problem equations into 2 dimensions in order to obtain the productivity index. This in return results in either over estimating or under estimating of inflow performance and productivity index by Joshi's Model. Joshi model also presented an assumption that shall be valid before deploying the model.

$$L>h \text{ and } (L/2) < 0.9r_{eH}$$

As for Butler Model and Furui *et. al.* Model, there is only a little dissimilarity between the IPR generated by both this analytical model. Both this models uses the same reservoir configuration assumptions. Both these models consider a box shaped fully penetrating horizontal lateral in them. These two models are identical except for the constant that differs from each other, where in Butler Model the constant is 1.14 and for Furui *et. al.* Model it is 1.224. Butler Model assumes the position of the horizontal lateral well structure to be located at halfway from the top boundary as well as lower boundary of the reservoir layer. As for Furui *et. al.* Model, the assumption is that the flow is linear away from the well and as the flow draws close to the well the flow changes its pattern to radial type of flow.

4.1.2 Matching Process of 2-Phase Flow

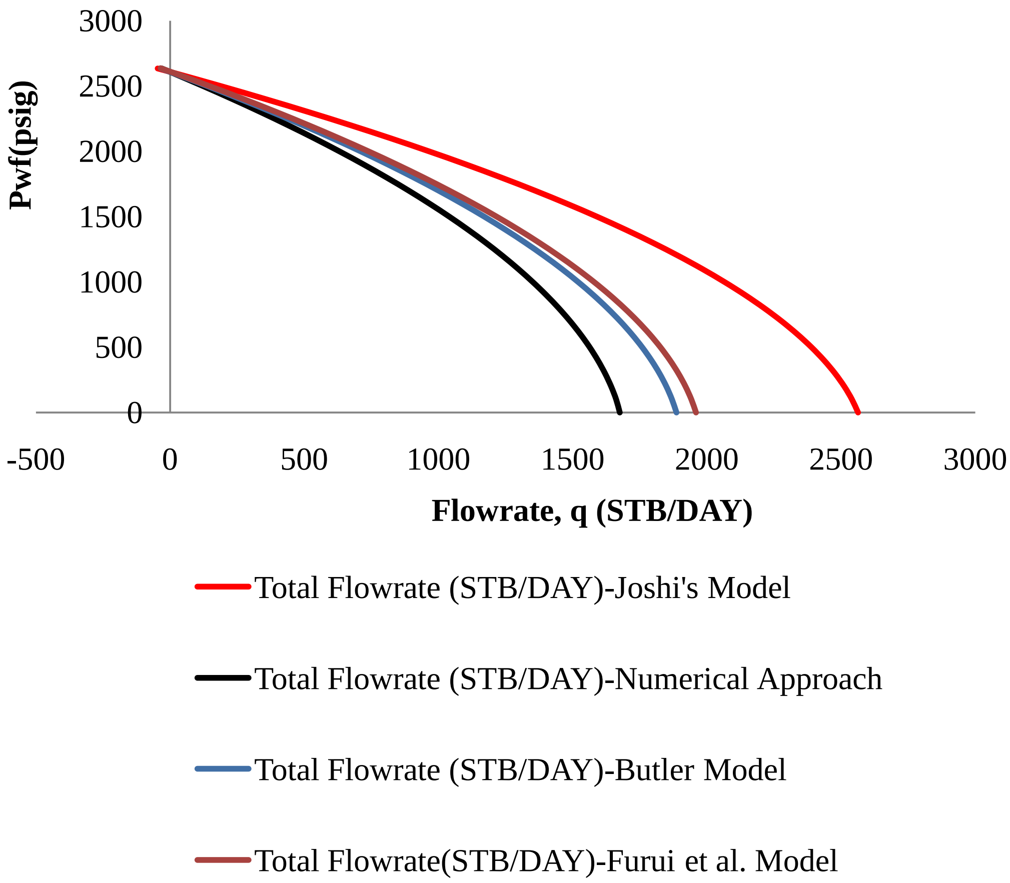

Figure 4.1.2-1 : Matching IPR for 2-Phase Flow

The comparison among the IPR Model is illustrated in the figure above. This process aims to select an analytical model that gives us a small number of differences when compared with numerical approach. The most accurate parameter to be used in this process is AOF (absolute open flow). This parameter aids us in comparing the inflow performance calculated from all the analytical method.

The summary of the comparison between all AOF deduced from Analytical Model and Numerical Model is summarised in the table below. As for Numerical Model, PROSPER the point calculation option is utilized to generate Flow Rate (STB/DAY) at each Bottom Hole Flowing Pressure (Psig)

Table 4.1.2-1 : Matching Table for 2-Phase Flow

	AOF Value			
	Layer 1 (STB/DAY)	**Layer 2 (STB/DAY)**	**Total (STB/DAY)**	**% Difference from Numerical Approach**
Joshi's Model	1557.64	1005.81	2563.45	52.92
Furui et. al. Model	1201.20	758.84	1960.04	17.10
Butler's Model	1146.12	741.32	1887.45	12.77
Numerical Approach	1037.76	638.56	1676.30	N/A

From the table above, it shows that Butler and Furui *et. al.* Model gives us the low percentage of difference compared to Joshi's Model. The factors that affect these differences are discussed in the section 4.4.1. Since Butler model yield the least percentage of difference this model will be utilized in Sensitivity Analysis.

4.2 RESERVOIR INFLOW RELATIONSHIP FOR ONE PHASE (GAS) INFLOW

4.2.1 Single Phase (Gas) Flow under Steady State Condition

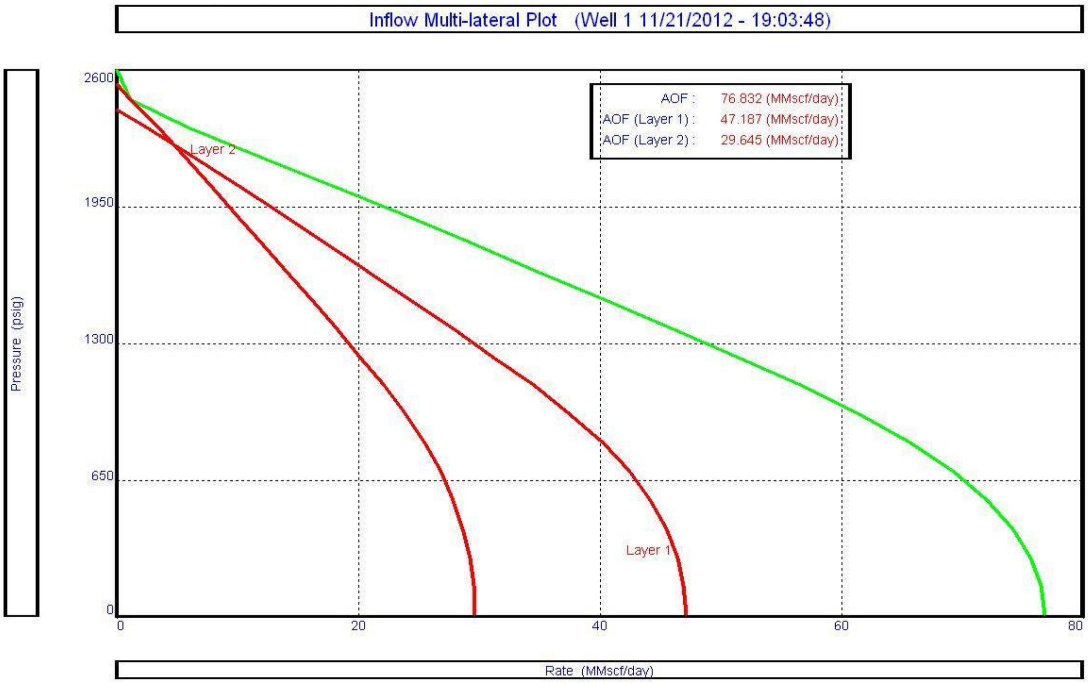

Figure 4.2.1-1: IPR Generated for One Phase (Gas) Inflow from PROPSER

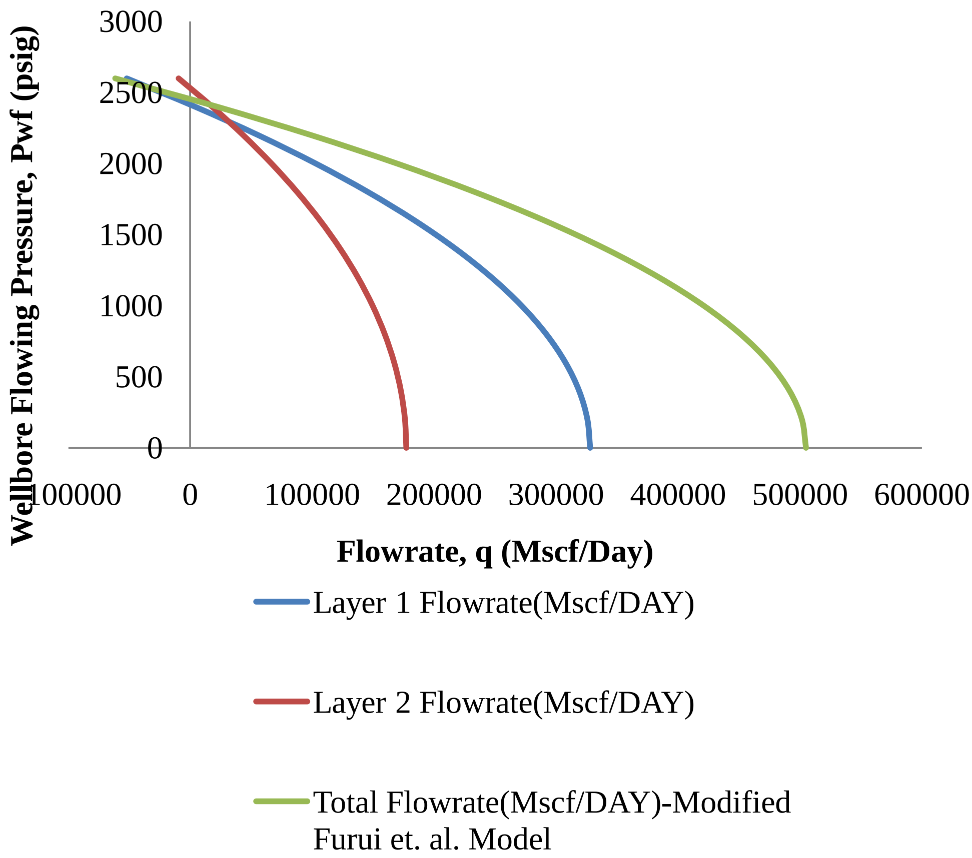

Figure 4.2.1-2 : Analytical Plot for One Phase (Gas) Inflow of Multilateral Well

The Analytical Plot above is generated through Modified Furui *et. al.* Model. This modified model is expressed as below

$$q_g = \frac{kL\left(P_e^2 - P_{wf}^2\right)}{1424\bar{Z}\mu T\left[ln\left(\frac{I_{ani}\,h}{r_w\,(I_{ani}+1)}\right) + \frac{\pi y_b}{I_{ani}\,h} - 1.224 + s\right]} \qquad \text{- (4.1)}$$

Where k is still defined as in the original Furui *et. al.*Model

$$k = \sqrt{k_y k_z} \qquad \text{- (4.2)}$$

Where,

q	=	Flow Rate
k_y	=	Horizontal permeability
k_z	=	Vertical permeability
h	=	Height of the reservoir
P_e	=	Pressure at the external radius (r = re)
P_{wf}	=	Bottom hole flowing pressure
μ	=	Viscosity
$\bar{Z}$	=	Formation Volume Factor
L	=	Length of lateral
I_{ani}	=	Anisotropy ratio
r_w	=	Wellbore radius
s	=	Skin due to formation damage
y_b	=	Well location in y-direction

4.2.2 Matching Process of 1-Phase (Gas) Flow

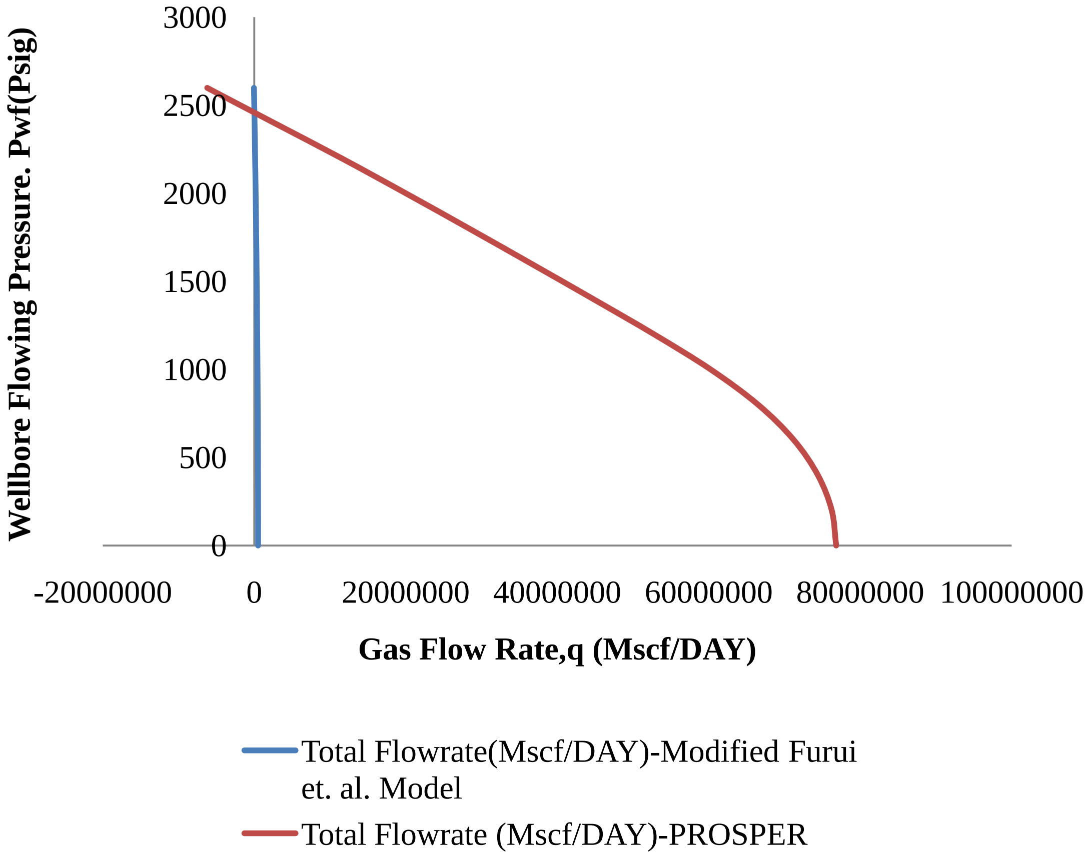

Figure 4.2.2-1 : Matching IPR for 1-Phase Flow (Gas)

The comparison among the IPR Model is illustrated in Figure 4.2.2-1 above. As observed the difference in calculated AOF for gas in Analytical Model and also the Numerical Model differs significantly.

Table below shows the difference in AOF generated by both this method.

Table 4.2.2-1 : Matching Table of Single Phase (Gas) Flow

	AOF Value		
	Layer 1 (Mscf/DAY)	**Layer 2 (MScf/DAY)**	**Total (Mscf/DAY)**
Modified Furui *et. al*. Model	327889	177093	504983
Numerical Approach	47187000	29645000	76832000

This section discusses the great deviation of results between analytical result and numerical outcome. Equation 4.1 assumes that compressibility factor, Z and gas viscosity,u_g to be constant over the pressure drawdown that ranges from bottom hole flowing pressure up to the reservoir pressure. This is not applicable to all cases as reservoir pressure change influences the compressibility factor as well as gas viscosity specifically on gas wells. To account for this situation, Equation 4.1 is modified by Al-Hussain and Ramey (1966).

$$m(p) = 2\int_{p_0}^{p} \frac{p}{u_g Z} dp \qquad - (4.3)$$

Where, p_o represent any form of base pressure where in many case separator pressure is utilised here. The IPR correlation of Modified Furui *et. al.* is now modified further by Al-Hussain and Ramey (1996).

Including equation 4.3 into Modified Furui *et. al.* will generate the following equation.

$$q_g = \frac{kL\left(m(\bar{p}) - m(p_{wf})\right)}{1424\,T\left[ln\left(\frac{I_{ani}\,h}{r_w(I_{ani} + 1)}\right) + \frac{\pi y_b}{I_{ani}\,h} - 1.224 + s\right]} \quad \text{- (4.4)}$$

Gas well has the characteristics of flow velocity that is higher than usual oil wells. This occurs near the wellbore region. Due to this high velocity flow of gas in this region, additional pressure drop will incur during depletion. This phenomenon is known as the non-Darcy flow effect. To account non-Darcy Flow Effect, the additional pressure drop is included into Equation 4.4. A modified version of this equation is expressed as following.

$$q_g = \frac{kL\left(m(\bar{p}) - m(p_{wf})\right)}{1424\,T\left[ln\left(\frac{I_{ani}\,h}{r_w(I_{ani} + 1)}\right) + \frac{\pi y_b}{I_{ani}\,h} - 1.224 + s + Dq_g\right]} \quad \text{- (4.5)}$$

The added function in this equation is D, represent non-Darcy coefficient that takes into account of non-Darcy Flow Effect. This parameter can be obtained from correlations (Economides *et. al.* 1994) or from laboratory experiment data. It is important to first produce the gas at first place to predict the IPR of the gas flow in Multilateral Wells.

4.3 SENSITIVITY ANALYSIS

For sensitivity analysis of this research Butler Model is utilised since this analytical generated the least difference in AOF when compared with numerical model. Three parameters of this research are selected. The Butler Model's outcome of 2-Phase Flow is altered by changing the value of the following parameters.

- Length of lateral, ft
- Horizontal Permeability, mD
- Viscosity, cp

4.3.1 Length of Lateral

For this parameter, three value of lateral length is incorporated into the Butler Model.

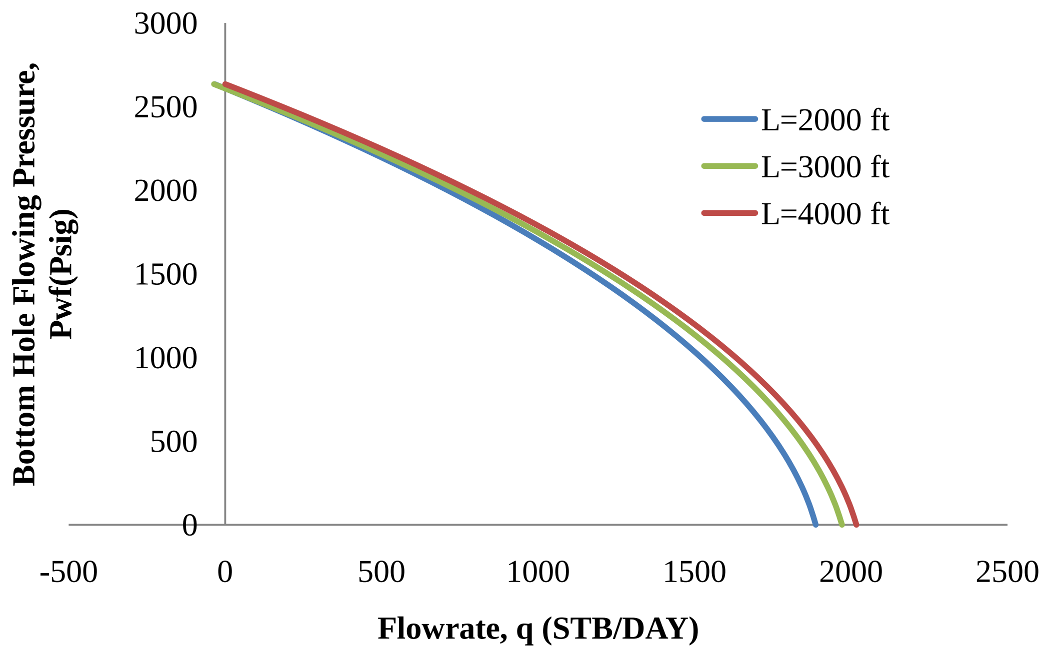

Figure 4.3.1-1 : Sensitivity Analysis Plot of IPR for Lateral Length

The plot shows different total flow rate in STB/DAY for different lateral length. To analyse this further, the % of difference between the initial AOF to that of the altered ones with different lateral length. The results are tabulated in the table below.

Table 4.3.1-1: Sensitivity Analysis Summary for Lateral Length

Lateral Length(ft)	**Total AOF (STB/DAY)**	**% Difference from Initial Condition(L=2000ft)**
2000	1887.45	N/A
3000	1971.68	4.46
4000	2016.86	8.85

4.3.2 Horizontal Permeability

For horizontal permeability, three value of horizontal permeability including the initial condition is incorporated into Butler Model to assess their sensitivity to AOF in this research

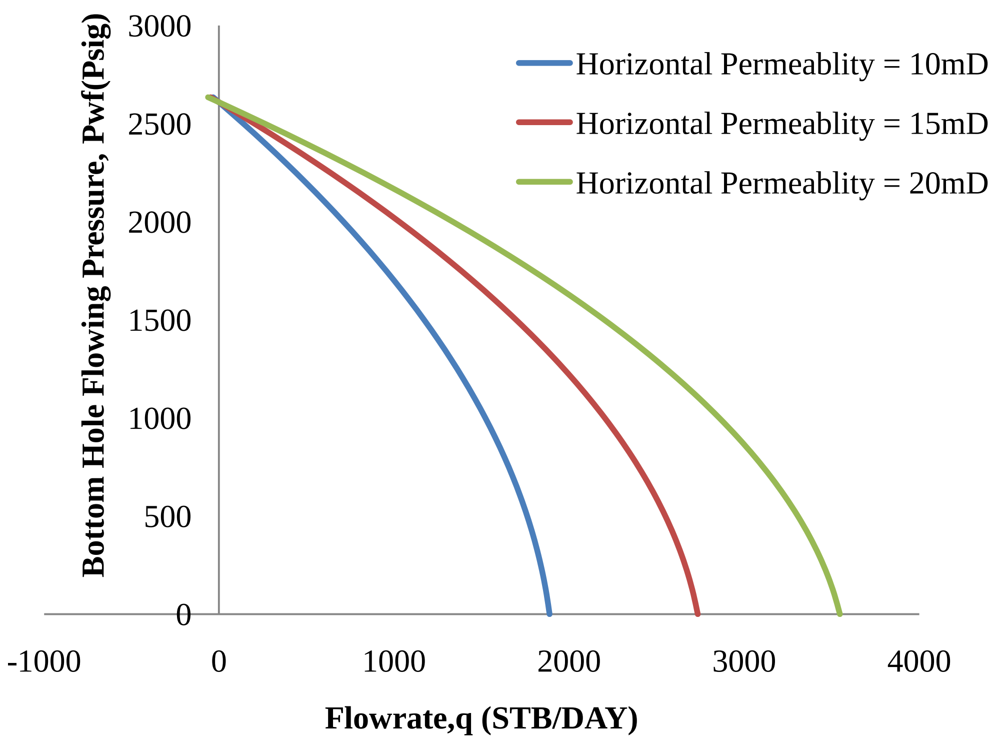

Figure 4.3.2-1: Sensitivity Analysis Plot of IPR for Horizontal Permeability

The plot shows different total flow rate in STB/DAY for different horizontal permeability. To analyse this further, the % of difference between the initial AOF to that of the altered ones with different horizontal permeability. The results are tabulated in the table below.

Table 4.3.2-1: Sensitivity Analysis Summary for Horizontal Permeability

Horizontal Permeability(mD)	**Total AOF (STB/DAY)**	**% Difference from Initial Condition(Horizontal Permeability=10mD)**
10	1887.45	N/A
15	2735.91	44.95
20	3547.19	87.91

4.3.3 Viscosity

For this parameter, three distinct values are chosen including the initial condition. Unlike other parameters, the increase in this parameter will reduce the AOF of the Multilateral Well.

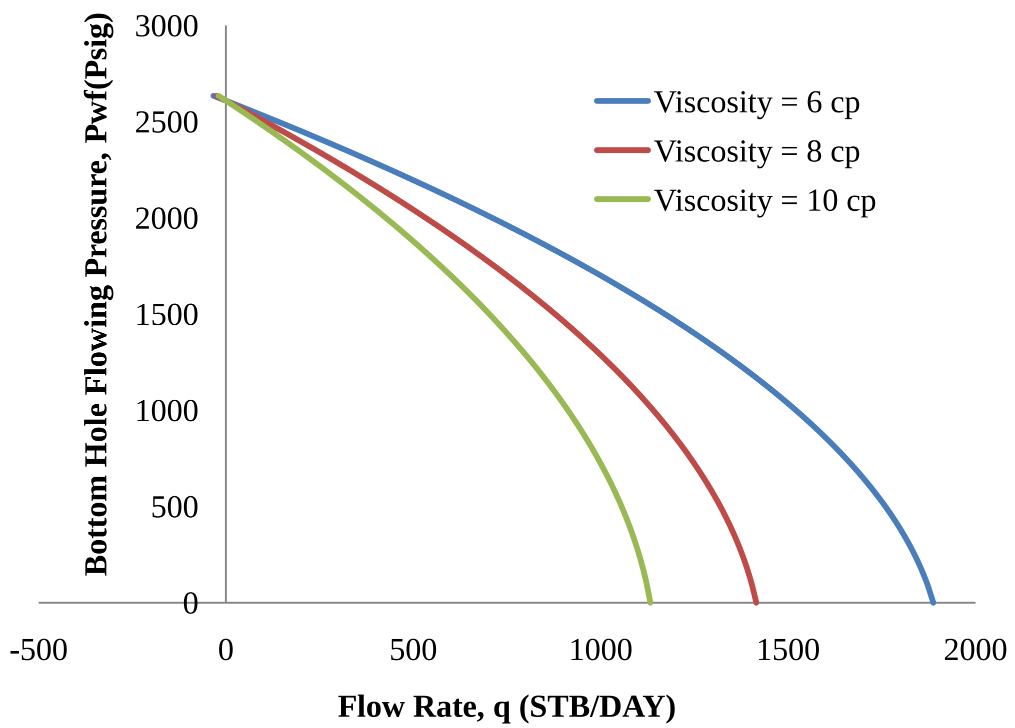

Figure 4.3.3-1: Sensitivity Analysis Plot of IPR for Viscosity

The table below summarizes the effect of viscosity change to the AOF of our multilateral well in 2-Phase flow condition.

Table 4.3.3-1: Sensitivity Analysis Summary for Viscosity

Viscosity(cp)	**Total AOF (STB/DAY)**	**% Difference from Initial Condition(Viscosity=10cp)**
6	1887.45	N/A
8	1415.58	-25.00
10	1132.47	-40.00

From sensitivity analysis we can observe that change in permeability effects the value of AOF significantly and the value of lateral length have very little effect on AOF of the multilateral well in steady state with 2-phase flow condition. Sensitivity analyses are necessary to find out what are the parameters to be altered in order to maximise the recovery of hydrocarbon from Multilateral Well.

CHAPTER FIVE

5 CONCLUSIONS AND RECOMMENDATIONS

As a result of an analysis from this comparative study, the following conclusion can be drawn.

- Butler Model and Furui *et. al.* Model can be used to generate IPR of Multilateral Wells as this models record the least difference compared to Joshi's Model
- For Joshi's Model, the result shall be confirmed by utilising the Numerical method to ensure the generated IPR is accurate enough.
- For steady state Multilateral Well with gas inflow it is important to produce the gas first in order to determine the non-Darcy coefficient using laboratory procedure.

Multilateral well is a complex analogy of the oil and gas field. Since the technology is relatively young, it promises more and more groundbreaking discoveries as engineers and experts in reservoir engineering are continuously striving to optimize its production and performance. Through this research, we can acquire a basic idea on which model best suites in evaluating the inflow performance of the any well with multilateral geometry. Through this, the performance and also the production from the multilateral well can be predicted accurately.

Further recommendations to explore further in issues related this research.

- Take into account the effect of turbulence in order to precisely estimate the AOF and generate an accurate IPR Model.
- Study and research on "thief zone" phenomenon in the Multilateral Well configuration.

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