SURVEILLANCE STUDY ON HYDRAULIC FRACTURE CHARACTERISTICS IN TIGHT FORMATION

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CERTIFICATION OF APPROVAL

Surveillance Study on Hydraulic Fracture Characteristics

in Tight Formation

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A project dissertation submitted to the Petroleum Engineering Programme
Universiti Teknologi PETRONAS in partial fulfilment of the requirements for the
Bachelor of Engineering (Hons) Degree in Petroleum Engineering

Approved by,

....
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MAY 2014

CERTIFICATION 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 acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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(NOR HANIZAH BINTI PIYASEK)

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ABSTRACT

Production on high reserves reservoirs will uplift the productivity index; hence increase the economic feasibility of a project. Nowadays, low permeability reservoir is possible to be produced. Production for tight reservoirs require appropriate stimulation jobs to increase the permeability. In this study, hydraulic fracturing is chosen as the stimulation method. With current depletion in conventional resources, many oil and gas players have found hydrocarbons in tight reservoirs as the alternatives. The emergence of hydraulic fracturing has made the United States become the world's largest natural gas producer in 2009.

About the study of hydraulic fracturing, it is important to understand how this stimulation method will affect the productivity index of the well. Researchers have to study the post-fracture behaviour, such as the fracture conductivity in the reservoirs and the fracture half-length and width. To calculate the post-fracture results, productivity improvement factor (PIF) is used as the indicator.

In hydraulic fracturing, a propping agent, usually sand particles, is used as the medium to contain the stresses acting on the fractures. Other than sand, water and chemical additives complete the composition of hydraulic fracturing fluid. In this study, the effect of fracture conductivity, half-length and width on production rate are investigated. Then, the post-fracture production rate will be compared with the initial production rate by calculating the PIF.

In conclusion, this study provides better understanding to the engineers on the minimum requirements of fracture conductivity and fracture half-length that the hydraulic fracturing process must achieve. Also, the study of hydraulic fracturing characteristics in tight formation will give benefits to the surveillance team, which they can predict the outcome and efficiency of the stimulation job.

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ABBREVIATIONS AND NOMENCLATURES

BP	British Petroleum
CBM	Coal Bed Methane
DFN	Discrete Fracture Network
E&P	Exploration & Production
FYP I	Final Year Project I
IFM	Implicit Fracture Model
md	milidarcy
UTP	Universiti Teknologi PETRONAS
PIF	Productivity Improvement Factor

CHAPTER 1
INTRODUCTION

1.1 Background study

In hydrocarbon production, certain numbers of wells are drilled for a specific oil or gas field. Each well has been set for a certain target reservoir to exploit any hydrocarbon that exists in it. To drill the well to the target reservoir, petroleum engineers have to decide the most suitable depth and the size. Petroleum engineers prefer the reservoirs that have higher hydrocarbon reserves as compared to the lower reserves' reservoirs. Production on higher reserves' reservoirs will uplift the productivity index; hence increase the economics' feasibility of a project.

However, petroleum engineers would not only take into account of the reservoirs' reserves. Instead, they will also look into the permeability of the target reservoirs or formations. Permeability is a measure of the ability of a fluid to pass through the formations. Furthermore, according to Pal, Joyce and Fleming (2006), permeability also can be defined as conductivity of a porous medium with respect to fluid flow. Also, he states that the unit of permeability used in the oil and gas industry is Darcy (K) and the equation for permeability is Darcy's equation. The equation is described below:

$$Q = \frac{K}{\eta}\frac{\Delta P}{\Delta L}A \quad \cdots\cdots\cdots\cdots\cdots \text{(1.1)}$$

Where,

Q	= Flow rate (ft^3/s)
K	= Permeability coefficient (md)
ΔP	= Pressure drop (psi)
ΔL	= Flow length (ft)
A	= Cross-sectional area to flow (ft^2)
η	= Fluid viscosity (cp)

In the case of high hydrocarbon reserves but low permeability formations, petroleum engineers would not abandon the formation without producing them nowadays. With the current high technology in petroleum industry, any possible opportunity to exploit the huge hydrocarbon reserves will not be missed just because of low permeability. In order to produce hydrocarbon from low-permeability or tight reservoirs, suitable stimulation jobs should be carried out in order to increase the permeability. One of the stimulation jobs that are commonly used nowadays is hydraulic fracturing. In this study, author will analyse the hydraulic fracturing in tight formations. A surveillance study will be carried out in order to investigate the effect of fracture geometry and conductivity on production rate of a tight formation reservoir.

1.2 Problem statement

With the current situation of depletion in conventional resources such as crude oil and primary-recovered natural gas, many of the industrial oil and gas players have looked at several ways to replace the conventional resources. United States of America is one of the countries that have found that unconventional resources such as shale gas and coal bed methane (CBM) can give alternative to the current conventional resources. With the current technology such as hydraulic fracturing, it gives the low-permeability or tight formations opportunity to be developed. In United States, hydraulic fracturing enables the shale gas formations to be developed economically to produce the natural gas. In 2009, United States becomes the world's largest country in natural gas production (Ratner & Tieman, 2014).

Besides increasing in natural gas production, the emergence of hydraulic fracturing has also contributed to the increase in oil production in United States over the past few years. Since 1991, oil production in the country has not increased. However, in 2009, the annual production was higher as compared to the previous year, and the good trending continues over the years until now. To strengthen the high impact of the hydraulic fracturing to the hydrocarbon production, United States' crude oil production increased by 2.7 million barrels per day between October 2007 and October 2013. During the period, about 92% of the crude oil contribution was from shale gas and tight oil formations in Texas and North Dakota (Ratner & Tieman, 2014). Thus, it is important to conduct a surveillance study on the characteristics of hydraulic fracturing in tight formations in order to maximize its application in the oil and gas industry.

1.3 Objectives

The objectives in a research study are actually the aim of the work or also known as the overall purpose of the study. Therefore, it should be clearly and concisely defined. For this research study, the objectives are listed below:

1. To build a spreadsheet model that relates the effect of fracture conductivity and geometry on production rate.
2. To determine the effect of fracture conductivity, fracture half-length, and fracture width on the flow rate of a producing well.
3. To compare the flow rate of tight formation before and after the hydraulic fracturing process.

1.4 Scope of study

In completing this project, there are few scopes of study that are emphasized along the project process flow. Firstly, this project focuses on fundamentals and basic techniques of hydraulic fracturing. After that, the scopes of study are further narrowed to the characteristics of reservoir and well that are used to investigate their effects towards production rate. As a result, the user can determine the flow rate of the well by using this predicted production rate. Also, this project provides a thorough spreadsheet model that enables the user to predict future production rate. Thus, this feature will give better outcome to the surveillance team, whether the hydraulic fracturing process is effective and efficient to that well or not.

CHAPTER 2
LITERATURE REVIEW

2.1 Hydraulic fracturing

Hydraulic fracturing is one of the methods to stimulate hydrocarbon production of a well (Hydraulic Fracturing, 2014). It involves a process of pumping a fluid into a wellbore at high rate, which is too great for the formation to accept in a radial flow pattern (Hydraulic Fracturing, 2014). Furthermore, hydraulic fracturing can also be defined as a stimulation process of injecting large volume of fluids into the target rock formation at high pressure. After the process finished, fractures are produced in the rock formation that help the flow of hydrocarbon, increasing the productivity of the well (PEH: Hydraulic Fracturing, 2013).

Hydraulic fracturing fluid creates and propagates fractures within the formation. It usually consists of propping agent, chemical additives and water. Sand, ceramic pellets or other small incompressible particles are commonly used as propping agents. The function of propping agent is to hold open the new fractures after hydraulic fracturing process, thus maintaining the gained permeability. The selection of propping agent or can be called as proppant depends on the depth of formation. For shallow formation, sand is used to open up and maintain the fractures while for deep formation, man-made ceramic beads are used (Hydraulic Fracturing, 2014).

Besides propping agent, water is commonly used as the base of hydraulic fracturing fluid. Water helps the fracturing fluid by transporting the propping agent to the newly-created fractures. Before consuming the water as the fluid's base, a compatibility analysis should be carried out to determine the minerals and bacteria present. Hence, the analysis will avoid the occurrence of any negative effect such as corrosion and formation damage. Other than transporting the propping agent, water will vary the selection of chemical additives to be used for the hydraulic fracturing fluid. Chemical additive in the fluid helps to create the fractures (The Process of Hydraulic Fracturing, 2013).

The composition of fracturing fluid can be described as in Figure 2.1. Based on Figure 2.1, about 99.5% of fracturing fluid's composition is comprised of water and sand (propping agent). Another 0.5% is for chemical additives such as scale and corrosion inhibitors, surfactant and biocide.

After mixing the right and compatible ingredients of hydraulic fracturing fluid, it is the time for the execution stage of hydraulic fracturing. Fracturing involves 4 basic steps which consist of pressurizing and pumping. The process can be illustrated by Figure 2.2. Prior to the execution of hydraulic fracturing, the well should have been perforated accordingly from wellbore to the formation to provide entrance for the fracturing fluid (Understanding Hydraulic Fracturing, 2013).

After undergoing hydraulic fracturing, post-fracture well behaviour analysis is done to monitor and evaluate the gained production of the well. The analysis includes the productivity index of the well during both pre- and post-fracture and the ultimate hydrocarbon recovery. Other than the gained production rate from the fracturing, engineers would also interest about the analysis of the propped fracture geometry. They require data such as the propped fracture length, the fracture conductivity and the drainage area of the well (Holditch, 2013). After acquiring such data and results, then only would they know the effectiveness of the fracturing fluid used.

Figure 2.3 illustrates the fracture conductivity after fracturing. The fracture conductivity can be defined as the outcomes from the width of propped fracture and the propping agent's permeability. Unfortunately, the fracture conductivity will be reduced gradually as the results from increasing stress on the proppant (Holditch, 2013).

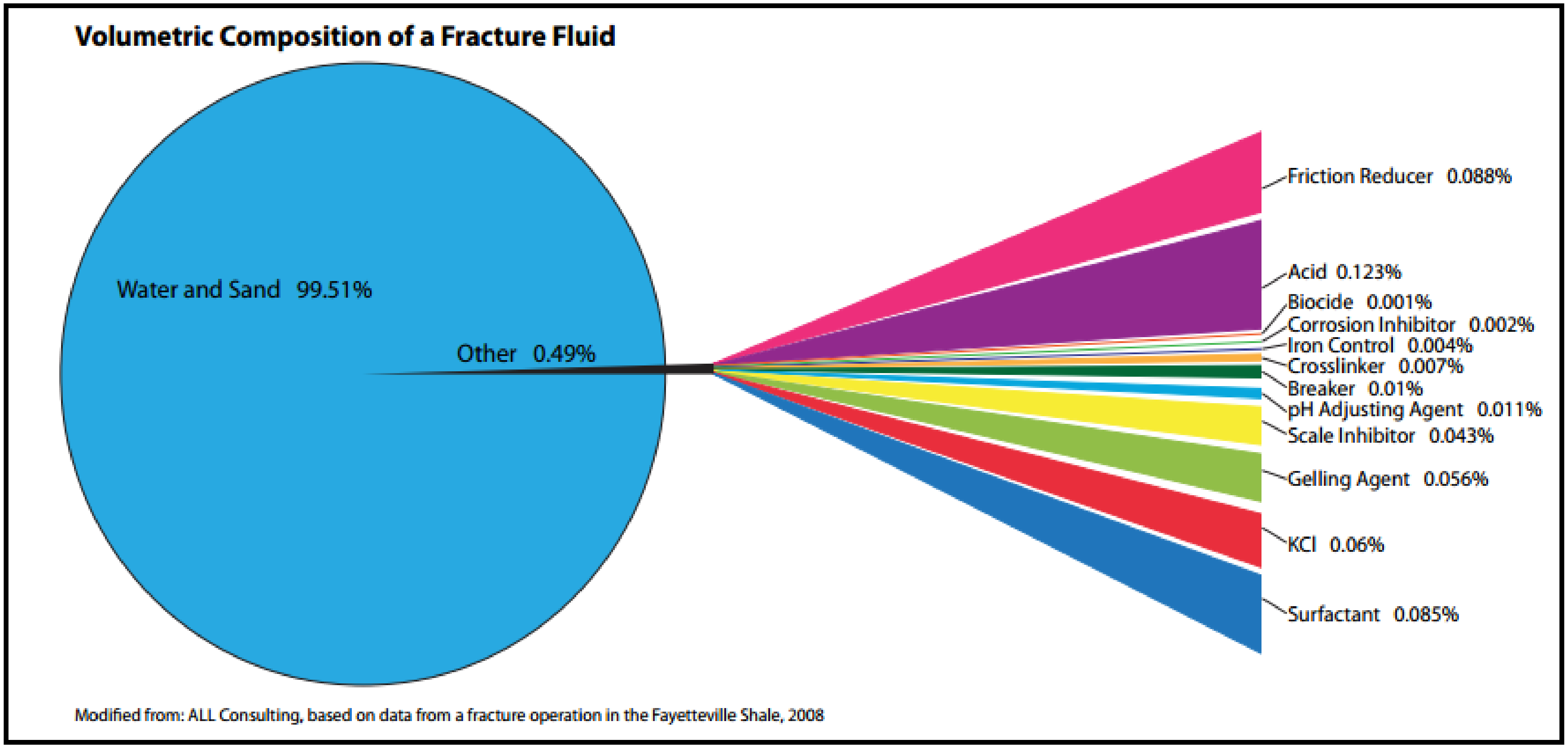


Figure 2.1: Volumetric composition of a hydraulic fracturing fluid (Understanding Hydraulic Fracturing, 2013)

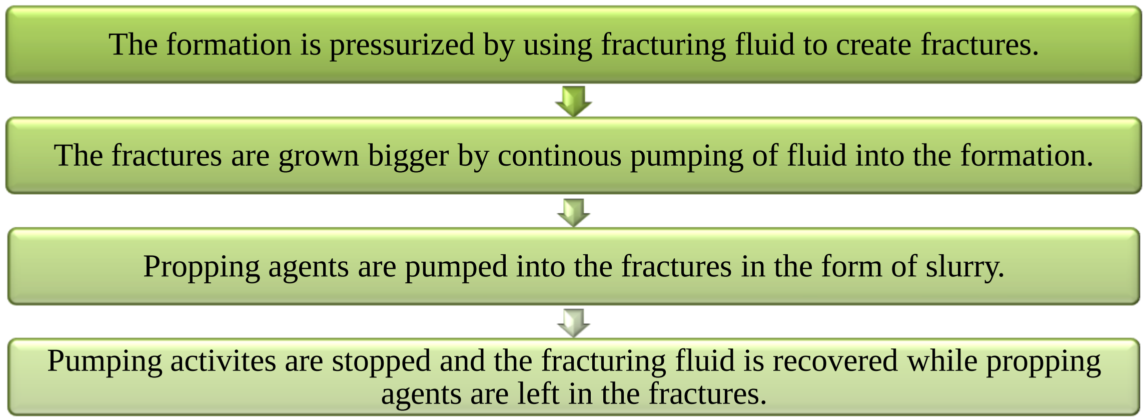


Figure 2.2: Four steps process of hydraulic fracturing

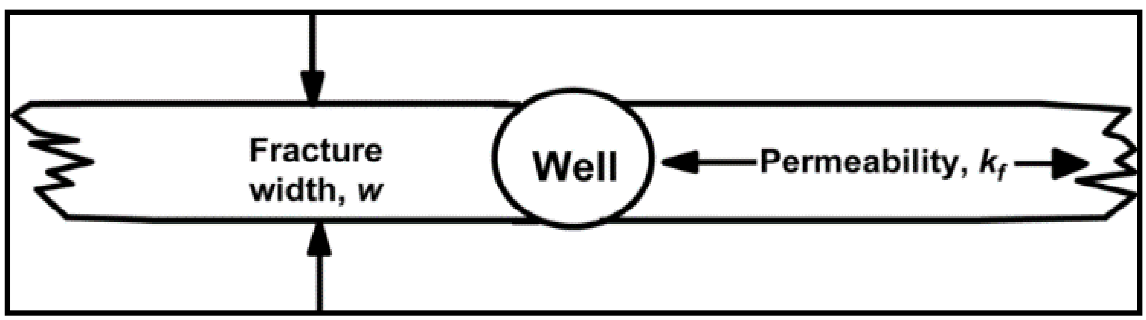
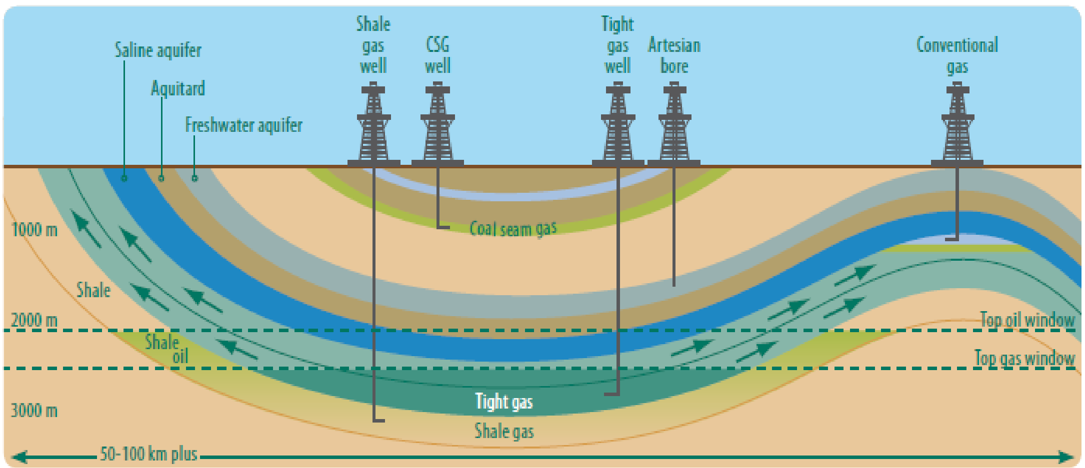


Figure 2.3: Definition of fracture conductivity (Holditch, 2013)

2.2 Tight formation

According to British Petroleum (BP) (Unconventional gas, 2014), conventional natural gas is produced from reservoirs that have good permeability such as sandstone or limestone. The production of the conventional natural gas is straightforward and easy as the gas flows naturally without the need of well stimulations. On the contrary, unconventional gas is located at the reservoir with low permeability. Also, the production of the unconventional gas is difficult as the formations need to be stimulated first. Nevertheless, the current technology, such as hydraulic fracturing, makes the unconventional gas possible to be produced economically (Unconventional gas, 2014).

According to Kubala (2008), the challenging part when dealing with tight reservoirs is the low permeability, which is less than 0.1 millidarcy (md). However, it will be economical to produce from such reservoir if undergoing stimulation works. Low in permeability will affect the feasibility study of the reservoirs, whether it is economical to produce or not. When discussing about tight reservoirs, oil and gas industry players will focus more on tight gas reservoirs, for example, shale gas and coal bed methane (CBM). Occasionally, unconventional gas formation happens to be situated nearby the conventional natural gas formation. It can be described in Figure 2.4. Thus, there are possibilities of shale gas' existence in nearby gas field area which currently producing.



Source: US Energy Information Administration 2010.

Figure 2.4: Geological settings for unconventional gas (Unconventional gas, 2014)

2.3 Fracture Modelling in PETREL

Fracture modelling contains various steps and involves certain disciplines which are related to reservoir geomechanics and engineering. The purpose of fracture modelling is to illustrate the geological concepts and for data gathering. Data gathering includes interpretation of beds, faults and fractures from the image log data. Next, the data will be transferred into a description of fracture intensity, which can be generated into a 3D geological framework model. Multiple set of fractures can be identified from the analysis of fracture data. These might happen because of different tectonic events, such as over-thrusts, extension faults, and conjugate fractures related to bending or flexure of geological layers (Fracture Modelling, 2014). Simulation software that is commonly used in fracture modelling is PETREL by Schlumberger.

Previously, user had difficulties on the traditional discrete fracture modelling (DFM). The number of fractures that were going to be modelled at one time can be too large as the user was trying to state clearly about the fractures' geometry and attributes. As the results, the user could not explicit the real condition of the fractures due to system memory limitations (Fracture Modelling, 2014). However, recently PETREL came out with a proposal of original numerical representation of the fracture networks. Consequently, accurate calculations of fluid flow are presented in the reservoir model. Nowadays, users can create a composite model, which comprises of discrete fracture network (DFN) and implicit fracture model (IFM). The larger and more important fractures are modelled explicitly by using DFM, while the other fractures, commonly the smaller fractures, are represented statistically as grid properties.

Preliminary studies of the new type of model representation have resulted in faster fracture generation and scaled up the process by a factor of 15 (Fracture Modelling, 2014). Thus, the new model representation would enable the field-scale optimization and uncertainty workflows. Figure 2.5 illustrates the new model representation, which combine DFN and IFM altogether into one model.

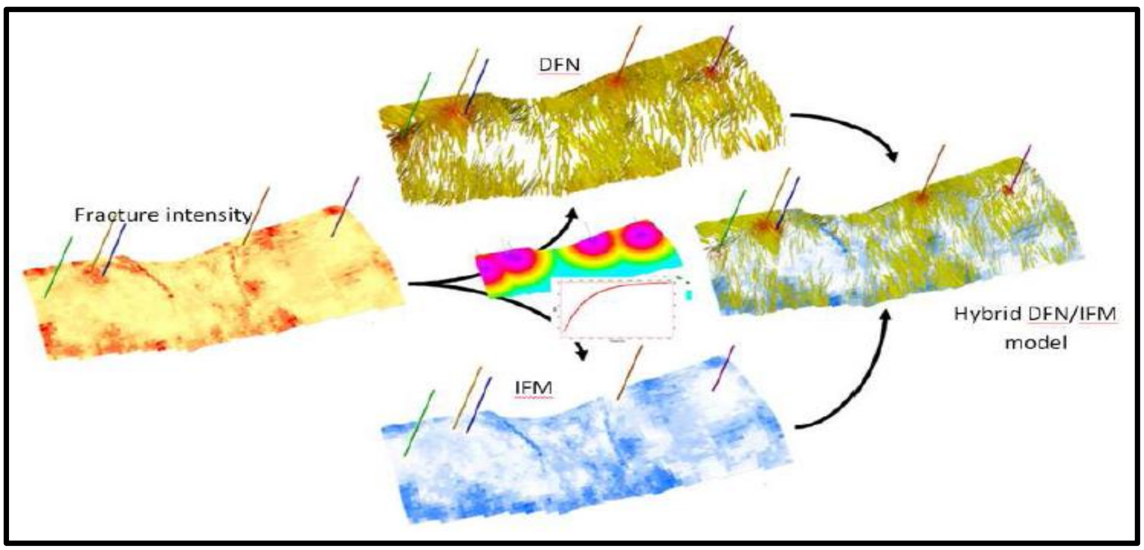


Figure 2.5: Hybrid model comprises of DFN and IFM (Fracture Modelling, 2014)

CHAPTER 3
METHODOLOGY

3.1 Process flow of the study

Essentially, process flow of the study is the procedures by which the author goes about her responsibility of describing, explaining, and completing every single thing regarding the project. In simple word, it is actually how the author's project is to be carried out. The process flow for this surveillance study is illustrated as per Figure 3.1.

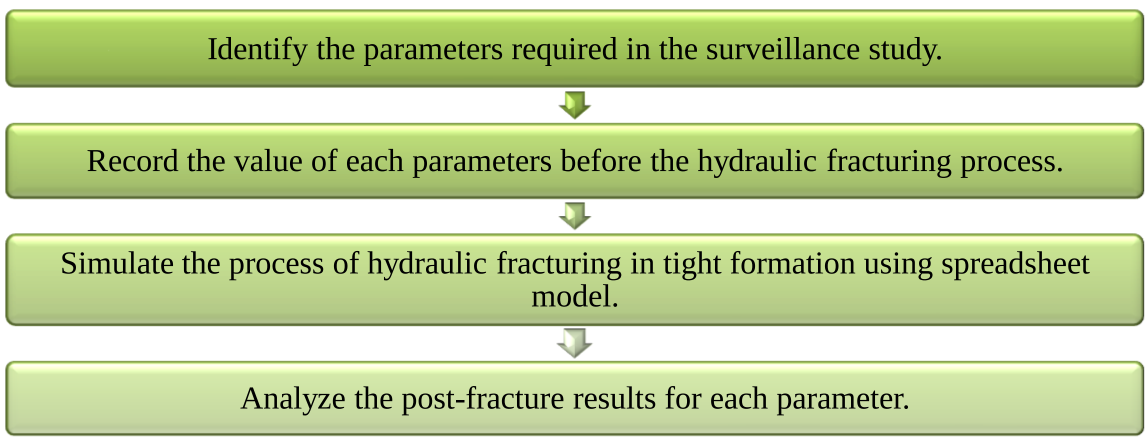


Figure 3.1: Process flow for the study

3.3 Gantt chart

A Gantt chart is a visual representation of a project schedule. It shows the start and finish dates of the different required elements of a project. For this surveillance study, the Gantt chart for FYP I is illustrated in Table 3.1, while the Gantt chart for FYP II is illustrated in Table 3.2.

Table 3.1: Gantt chart for FYP I

DESCRIPTION OF PLANNING	PERIOD OF PLANNING (WEEK)													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
FYP BRIEFING														
TOPIC SELECTION														
TOPIC AWARDED														
DATA COLLECTION														
STUDY THE TOPIC														
EXTENDED PROPOSAL SUBMISSION														
PROPOSAL DEFENCE														
FURTHER RESEARCH ON THE PROJECT														
INTERIM DRAFT REPORT SUBMISSION														
INTERIM REPORT SUBMISSION														

Table 3.2: Gantt chart for FYP II

DESCRIPTION OF PLANNING	PERIOD OF PLANNING (WEEK)														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
PROJECT WORK CONTINUES															
PROGRESS REPORT SUBMISSION															
PROJECT WORK CONTINUES															
PRE-SEDEX															
DRAFT FINAL REPORT SUBMISSION															
DISSERTATION SUBMISSION (SOFT BOUND)															
TECHNICAL PAPER SUBMISSION															
VIVA															
DISSERTATION SUBMISSION (HARD BOUND)															

Milestone

Process

3.4 Materials/equipment/software used

Throughout this research study, Microsoft Office Excel has been used. A theoretical calculation is prepared using Microsoft Office Excel to determine production flow rate by varying the values of fracture conductivity, fracture half-length and fracture width. Furthermore, this software is used to identify the relationship between fracture conductivity, fracture half-length, fracture width and production flow rate.

3.5 Effect of fracture conductivity on production rate

The followings are the steps to analyse the effect of fracture conductivity on production rate. In the analysis, fracture half-length, X_f is kept constant. Fracture conductivity are varied from 0.1 to 1300 md.ft.

Step 1: Define the reservoir and well characteristics

The reservoir and well characteristics that need to be defined are:

P_e = Initial reservoir pressure (psi)

P_{wf} = Flowing bottom hole pressure (psi)

$K_f.W$ = Fracture permeability × fracture width (md.ft)

K = Permeability (md)

r_e = Drainage radius (ft)

r_w = Wellbore radius (ft)

B_o = Formation volume factor

μ = Viscosity (cp)

h = Total vertical depth (ft)

X_f = Fracture half-length (ft)

Step 2: Find the corresponding value of equivalent skin factor, α in the graph

Value of α need to be correspond to the value of dimensionless fracture conductivity, F_{CD} by looking at Figure 3.2. Equation for α is per below:

$$\alpha = S_f + \ln \frac{X_f}{r_w} \quad \cdots \cdots \cdots \cdots \cdots (3.1)$$

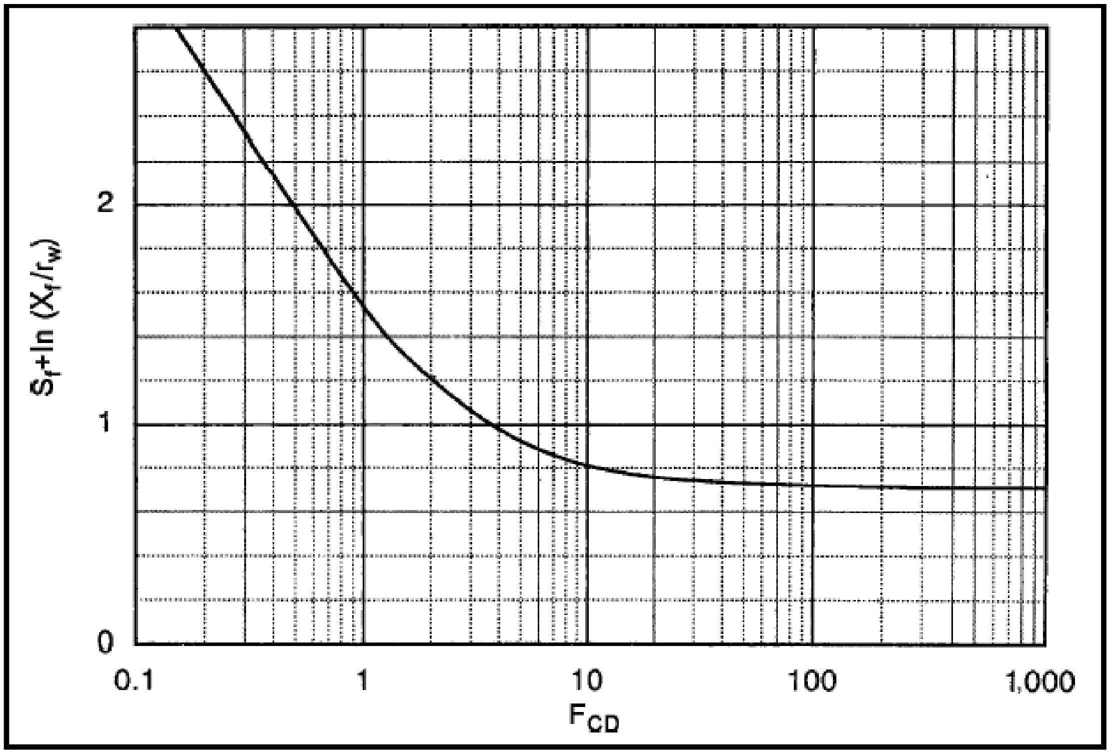


Figure 3.2: Relationship between fracture conductivity and equivalent skin factor [11]

Step 3: Calculate skin factor, S_f by using the following formula:

$$s_f = \alpha - \ln\left(\frac{x_f}{r_w}\right) \quad \cdots\cdots\cdots\cdots\cdots (3.2)$$

Step 4: Calculate flow rate of the well, Q by using the following formula:

$$Q = \frac{(k)(h)\left(P_e - P_{wf}\right)}{(141.2)(B_o)(\mu)\left[\ln\left(\frac{r_e}{r_w}\right) + S_f\right]} \quad \cdots\cdots\cdots\cdots\cdots (3.3)$$

3.6 Effect of fracture half-length on production rate

The steps to analyse the effect of fracture half-length on production rate are quite similar with the methods to investigate the effect of fracture conductivity on production rate. In the analysis, dimensionless fracture conductivity, F_{CD} is kept constant. Fracture half-length is varied from 50 to 2000 *ft*.

Step 1: Define the reservoir and well characteristics

The reservoir and well characteristics that need to be defined are:

P_e	= Initial reservoir pressure (psi)
P_{wf}	= Flowing bottom hole pressure (psi)
$K_f.W$	= Fracture permeability × fracture width (md.ft)
K	= Permeability (md)
r_e	= Drainage radius (ft)
r_w	= Wellbore radius (ft)
B_o	= Formation volume factor
μ	= Viscosity (cp)
h	= Total vertical depth (ft)
F_{CD}	= Fracture conductivity

Step 2: Find the corresponding value of equivalent skin factor from Figure 3.2

The value of equivalent skin factor needs to be corresponding to the value of dimensionless fracture conductivity, F_{CD}. In this case, there is only one value of as F_{CD} is constant.

Step 3: Calculate skin factor, S_f by using equation 3.2.

Step 4: Calculate flow rate of the well, Q by using equation 3.3.

3.7 Effect of fracture width on production rate

Methods to investigate the relationship between fracture width, w and production rate, Q are quite similar to the steps of analysing the effect of fracture conductivity and half-length on production rate. In this analysis, F_{CD} and X_f are kept constant and user will define the value for skin factor, S_f. The values of fracture width are assumed to be varied from 0.001 ft to 0.020 ft.

Step 1: Define the reservoir and well characteristics

P_e = Initial reservoir pressure (psi)

P_{wf} = Flowing bottom hole pressure (psi)

K_f = Fracture permeability (md)

r_e = Drainage radius (ft)

r_w = Wellbore radius (ft)

B_o = Formation volume factor

μ = Viscosity (cp)

h = Total vertical depth (ft)

F_{CD} = Fracture conductivity (md.ft)

X_f = Fracture half-length (ft)

S_f = Skin factor

Step 2: Calculate flow rate of the well, Q by using equation 3.3.

3.8 Estimation of future production rate

This is the additional feature in the spreadsheet model that allows user to estimate productivity of the fractured well. The user can identify the Productivity Improvement Factor (PIF) of the stimulated well based on the input value of the pre-fractured production flow rate.

Step 1: Input the pre-fractured production flow rate.
User need to define and input the pre-fractured flow rate which is then needed to compare with the post-fractured flow rate later.

Step 2: Calculate the PIF

$$PIF = \frac{Q_f}{Q_o} \quad \cdots \cdots \cdots \cdots \cdots (3.4)$$

3.9 Fracture Modelling in PETREL

During the period of FYP I, the author had a chance to study on the procedures to model fractures by using PETREL. However, there will be no PETREL simulation in this project due to certain limitations. These methods are intended for future work and continuation on this project. Prior to fracture modelling, standard procedures were involved such as modelling the reservoir itself in terms of its geometrical and petro-physical. User needed to specify certain characteristics of the reservoir, such as the reservoir's volume and size, porosity, initial permeability and others. Later, the user can generate the desired fracturing model based on the specified reservoir's characteristics. There are six major steps in the process of generating a fracture model.

3.9.1 Import, quality check (QC) and display

First, any required fracture interpretation data was imported to the PETREL software. Interpretation data can be imported as ASCII format, which contained several attributes. The attributes described about the fractures, such as fractures type and quality, dip angle and azimuth, and also well's measured and vertical depth. Figure 3.2 illustrates the fractures' attributes from the ASCII file.

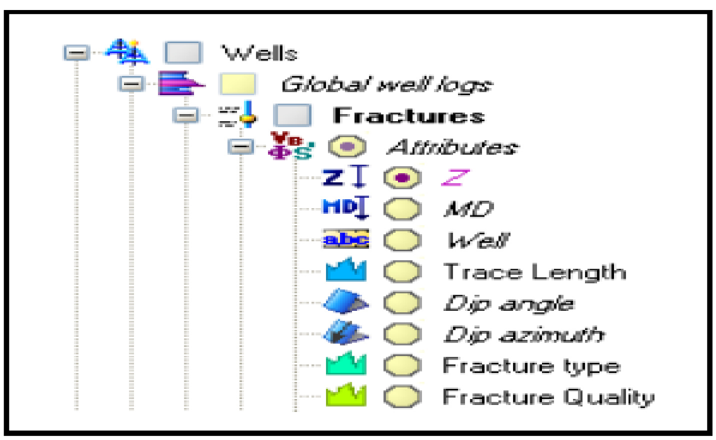


Figure 3.3: Screenshot of fractures' attributes in PETREL

The procedures of importing the data can be described as followed:

i. An ASCII file was prepared with attributes such as well's name, dip angle, dip azimuth and other attributes.
ii. Prior to ASCII file importing, the well's data was already imported to the software.
iii. The ASCII file was selected and the point well data format was used.
iv. Columns in the import dialog were added based on the data columns in the ASCII file.
v. "User" was selected as the attribute for the different types of fractures.
vi. "OK" button was clicked and the data was stored under the Global well logs folder as screenshot in Figure X.

Before displaying the data in the software, quality check (QC) on the data should be done in order to have accurate results. The user has to check each data attribute to maintain the accuracy of the post-fracture outcomes. After that, Stereonet was used to illustrate and visualize the fracture data. Stereonet simplified the tediousness in determining the orientations of planes and lines by showing a set of great circles and small circles that were perpendicular to one another. Those circles will form number of grids that could be used in locating the desired planes and lines.

3.9.2 Data analysis

The second step in setting up the fracture model was data analysis. Previously, quality check was done on the data to check the data accuracy. The quality check would help to smoothen the data analysis as the fracture data was already in complete condition and accurate. The purpose of data analysis was to describe the occurred fractures. For example, the user can analyse the post-fracture outcomes in the modelling. The user could know the trend of the fractures as well as the geometry of the fractures. In data analysis, the user would define mechanical zones in the fractures modelling. Mechanical zones can be described as the zones which were fractured. There were various scales of fractures existed in the mechanical zones. The data information of mechanical zones was very important as it would lead to any possibility of water breakthrough and well interference.

3.9.3 Modelling fracture network properties

The third step in standard fracture modelling was modelling fracture network properties. The fracture network parameters such as intensity, orientation, and geometry can be assigned numerically or as properties. If the parameters were assigned by using properties, the parameters can vary either laterally or vertically across the area where fractures were created. These properties can be created by using any of the standard property modelling methods available in PETREL. An intensity log must be upscaled and populated in 3D grid if the user wanted PETREL to use the properties of fracture intensity. By using this way, a property can be used as input for the fracture distribution in the create fracture network process.

3.9.4 Create fracture network

The fourth step of fracture modelling was creating a fracture network. A number of planes that contained fractures were called a fracture network. Those fractures were similar type to each other, generated at the same time, and grouped into a fracture set. Every fracture network should contain at least one fracture set and would probably have more than one fracture sets, depending on the user's defined fracture modelling.

There were two methods in order to create a fracture network. There are deterministic and stochastic. Figure 3.3 shows the screenshot of a command in PETREL, where user needs to select the method when creating a fracture network. For deterministic, the method was meant for the simplest fracture sets and they were defined as a group of previously defined fractures. Fracture sets can be created from "point well data". Fracture sets were imported with the fracture observations and generated by selecting the required fracture points by using filter selection tool. Meanwhile, the fracture types that were used as inputs were fault patches, DFN fractures that were defined previously, fractures that were imported by using FAB format, surfaces, polygons and points.

On the contrary to the deterministic method, a stochastic fractures model can be described statistically by using either one of these input: numerical input, surfaces or properties. Properties in the 3D grid can be easily modelled by using standard algorithms or it can be taken directly from 3D or 2D seismic data and maps. However, due to the stochastic method, a seed point from a random number generator was required. Figure 3.4 shows the command box when creating a fracture network by stochastic model. Unlike deterministic method, the user needed to key-in a seed point besides the random seed column. If the "Random Seed" was fixed by the user, PETREL would generate the same results. Otherwise, PETREL would produce a newly-equalled output that honours all input parameter settings.

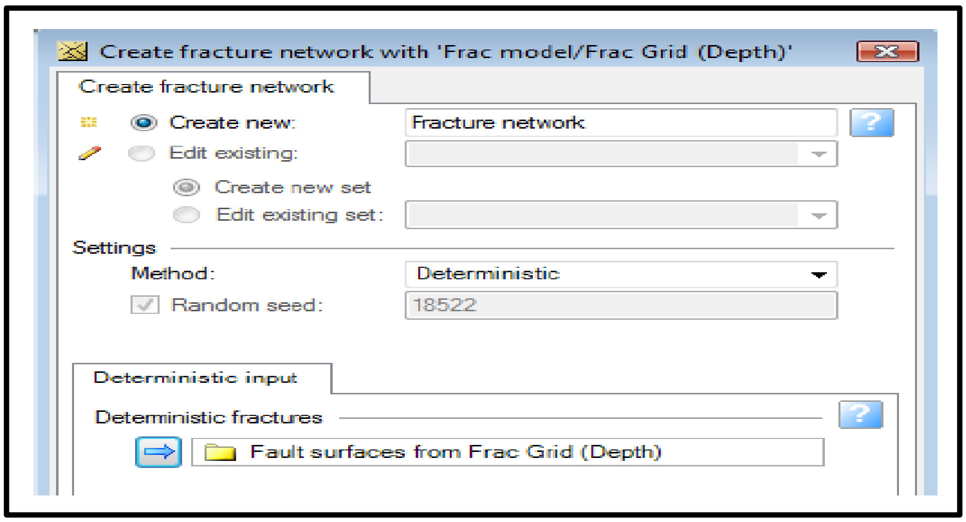


Figure 3.4: Screenshot of creating a fracture network command box (deterministic)

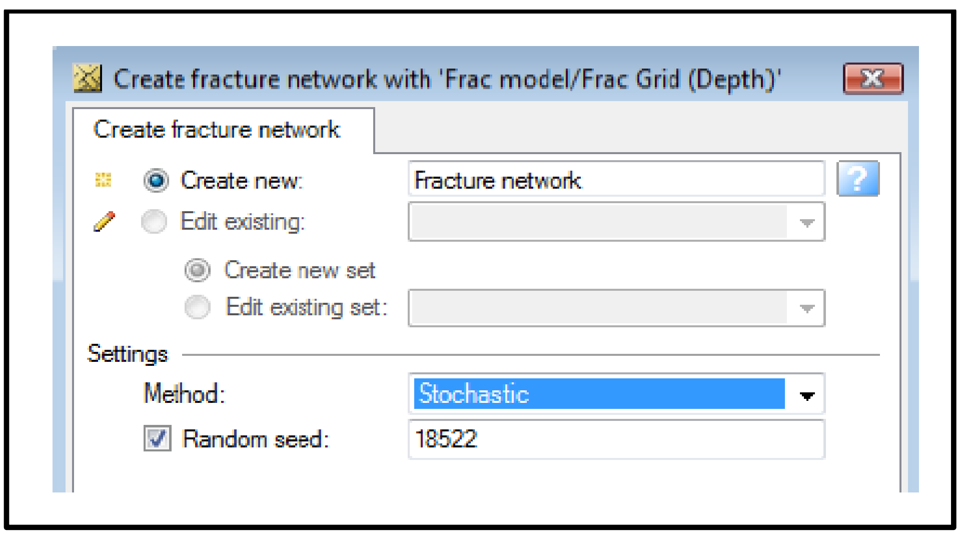


Figure 3.5: Screenshot of creating a fracture network command box (stochastic)

In order to build a fracture network by stochastic method, user needed to define some inputs such as fractures' distribution, geometry and orientation. Distribution of fractures would decide which part of the grid should be modelled. User would define the desired fracture intensity, which it can be described as the amount of fractures per unit volume. The expressions that can be found in PETREL were fracture's area over volume (Frac area / volume), fracture's length over volume (Frac length / volume) and number of fractures over volume. In the meantime, fractures' geometry would describe the shape and length of the fractures. User would specify the number of sides on the plane, which the default number of sides is 4 and it is a square plane. For the fracture length, it would determine the various lengths of the fractures in the model. Other than fractures' distribution and geometry, means of dip and azimuth were used as the input to the orientation of fractures.

3.9.5 Upscale fracture network to properties

The procedures for scaling up the fracture properties were described as followed:

i. Scale up "fracture network properties" process was opened under the fracture modelling and the correct 3D grid was made sure in active mode.
ii. "Create new/Prefix" was selected and the prefix was named. The prefix will be used to name the porosity, permeability and sigma factor output properties.
iii. A fracture network made in the "Create fracture network" process was dropped in.
iv. Either three of the options was selected: "Whole fracture network", "Only discrete fracture network" or "Only implicit fracture network".
v. Then, the "Oda method" or the "Flow based" upscaling method was selected.
vi. Alternatively, user could filter the part of the grid by using the filter icon.
vii. "Apply" button was pressed.
viii. The results of fracture porosity, permeability and sigma factor were stored in the "Properties" folder of the 3D grid.

3.9.6 Simulation

Before running a simulation, a simulation case was defined by the user. Then, matrix properties (standard properties) and fracture properties (from scaling up process) were used in dual porosity simulation. Figure 3.5 shows the command box for the user to define the simulation case.

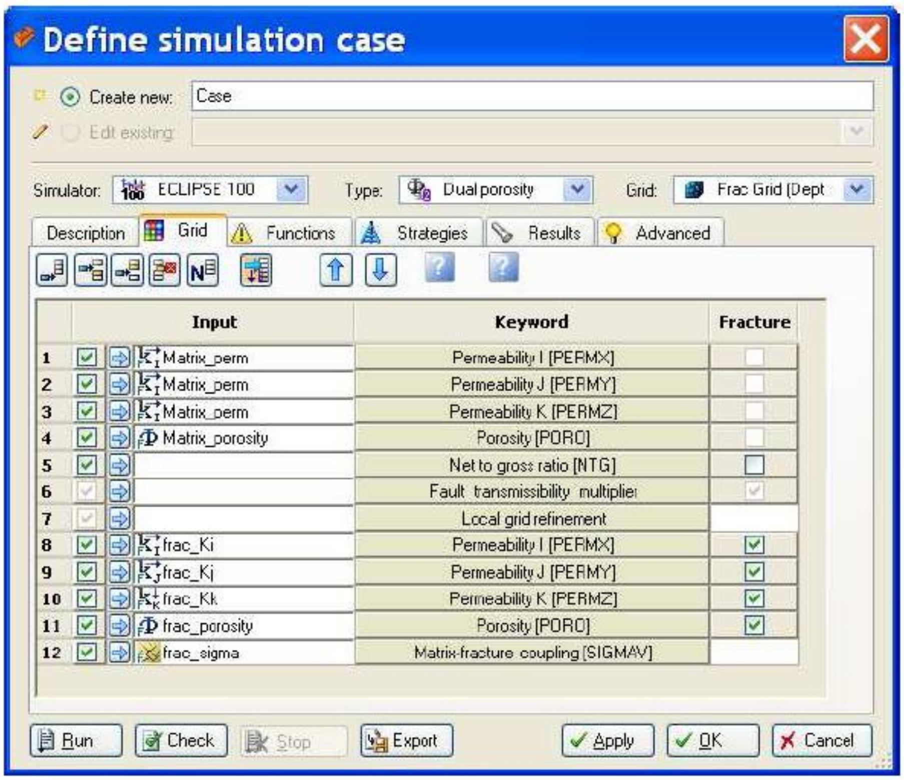


Figure 3.6: Screenshot of define simulation case command box

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Effect of fracture conductivity on production rate

Several analysis using Microsoft Office Excel have been carried out in order to investigate the direct relationship of fracture conductivity towards production rate of a fractured well when the fracture half-length, X_f is constant. Following are the steps taken to calculate the production rate of the fractured well.

Step 1: Define the reservoir and well characteristics

Initial reservoir pressure, P_e = 5000 *psi*

Flowing bottom hole pressure, P_{wf} = 1500 *psi*

Fracture permeability × fracture width, $k_f.w$ = 2000 *md.ft*

Permeability, k = 0.5 *md*

Drainage radius, r_e = 1490 *ft*

Wellbore radius, r_w = 0.328 *ft*

Formation volume factor, B_o = 1 *rb/stb*

Viscosity, μ = 1 *cp*

Total vertical depth, h = 1000 *ft*

Fracture half-length, X_f = 1000 ft

Step 2: Find the corresponding value of equivalent skin factor, α in the graph attached in Figure 3.2.

At F_{CD} = 0.1,

$s_f + \ln\frac{x_f}{r_w} = 3$

Step 3: Calculate skin factor, S_f

$$s_f = \alpha - \ln\left(\frac{x_f}{r_w}\right) \quad \cdots \cdots \cdots \cdots \cdots (3.2)$$

$$s_f = 3.0 - \ln\left(\frac{1000}{0.328}\right)$$

$$s_f = -5$$

Step 4: Calculate flow rate of the well, Q

$$Q = \frac{(k)(h)(P_e - P_{wf})}{(141.2)(B_o)(\mu)\left[\ln\left(\frac{r_e}{r_w}\right) + S_f\right]} \quad \cdots \cdots \cdots \cdots \cdots (3.3)$$

$$Q = \frac{(0.5)(1000)(5000 - 1500)}{(141.2)(1)(1)\left[\ln\left(\frac{1490}{0.328}\right) + (-5)\right]}$$

$$Q = 3{,}647\ bbl/d$$

Table 4.1 shows the different values of flow rate, Q in which effective fracture conductivity, F_{CD} are varied in the range from 0.1 to 1300. Figure 4.1 represents the relationship between flow rate and fracture conductivity. In this case, fracture half-length, X_f, is maintained at constant value of 1000 ft while fracture conductivity varies from 0.1 to 1000. From the log graph, the flow rate increases exponentially when the fracture conductivity increases. The increase in flow rate is significant when the fracture conductivity increases from 0.2 to 10. From 10 to 90, the increase of flow rate is very marginal. Beyond 90, we can see that the flow rates are constant until fracture conductivity of 1000. The constant values of flow rates are due to the constant value of skin factor.

Table 4.1: Effective fracture conductivity and production flow rate

Flow rate, Q *(bbl/d)*	Skin, S_f	$(S_f + \ln\frac{X_f}{r_w})$	Effective fracture conductivity, F_{CD}
3,647	-5	3.000	0.1
3,936	-5	2.750	0.2
4,509	-6	2.350	0.3
4,960	-6	2.100	0.4
5,391	-6	1.900	0.5
5,637	-6	1.800	0.6
5,905	-6	1.700	0.7
6,201	-6	1.600	0.8
6,360	-6	1.550	0.9
6,527	-7	1.500	1.0
7,752	-7	1.200	2.0
8,674	-7	1.030	3.0
8,989	-7	0.980	4.0
9,327	-7	0.930	5.0
9,543	-7	0.900	6.0
9,692	-7	0.880	7.0
9,925	-7	0.850	8.0
10,169	-7	0.820	9.0
10,339	-7	0.800	10.0
10,789	-7	0.750	20.0
10,980	-7	0.730	30.0
11,178	-7	0.710	40.0
11,188	-7	0.709	50.0
11,208	-7	0.707	60.0
11,229	-7	0.705	70.0
11,249	-7	0.703	80.0
11,269	-7	0.701	90.0
11,280	-7	0.700	100.0
11,280	-7	0.700	200.0
11,280	-7	0.700	300.0
11,280	-7	0.700	400.0
11,280	-7	0.700	500.0
11,280	-7	0.700	600.0
11,280	-7	0.700	700.0
11,280	-7	0.700	800.0
11,280	-7	0.700	900.0
11,280	-7	0.700	1000.0

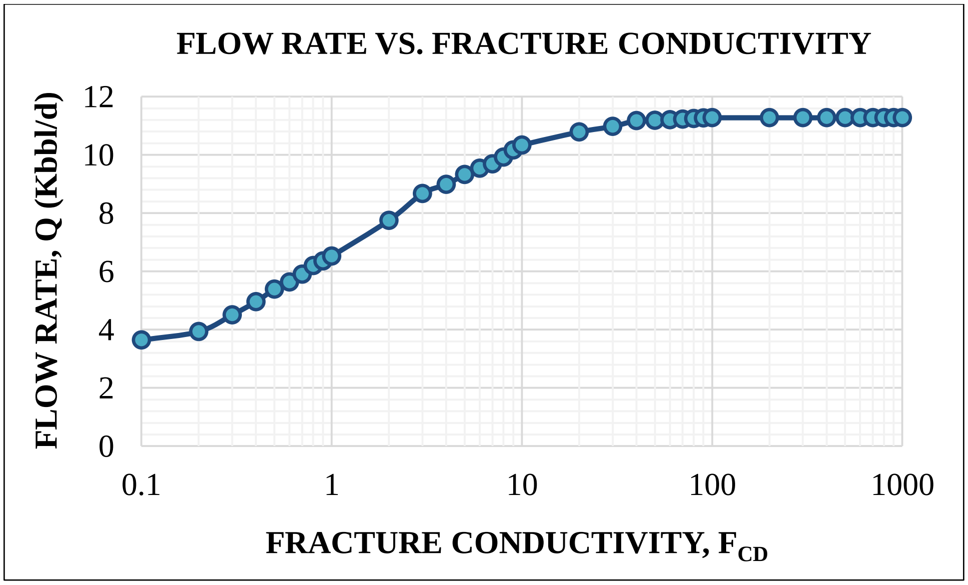


Figure 4.1: Flow rate vs. fracture conductivity

4.2 Effect of fracture half-length on production rate

Similar methods for the effect of fracture conductivity on production flow rate have been used to determine the relationship between fracture half length, X_f and production flow rate, Q. However, effective fracture conductivity, F_{CD} is kept constant during this time. The steps to calculate the flow rate based on a few assumptions are explained as follows.

Step 1: Define the reservoir and well characteristics

Initial reservoir pressure, $P_e = 5000\ psi$

Flowing bottom hole pressure, $P_{wf} = 1500\ psi$

Fracture permeability × fracture width, $k_f.w = 2000\ md.ft$

Permeability, $k = 0.5\ md$

Drainage radius, $r_e = 1490\ ft$

Wellbore radius, $r_w = 0.328\ ft$

Formation volume factor, $B_o = 1\ rb/stb$

Viscosity, $\mu = 1\ cp$

Total vertical depth, $h = 1000\ ft$

Fracture conductivity, $F_{CD} = 1$

Step 2: Find the corresponding value of equivalent skin factor, α from Figure 3.2

At $F_{CD} = 1$,

$s_f + \ln \frac{x_f}{r_w} = 1.5$

Step 3: Calculate skin factor, S_f

Take the value of fracture half-length, X_f to be 50 ft. The values of X_f varies from 50 to 2000 ft.

$$s_f = \alpha - \ln\left(\frac{x_f}{r_w}\right) \quad \cdots\cdots\cdots\cdots\cdots (3.2)$$

$$s_f = 1.5 - \ln\left(\frac{50}{0.328}\right)$$

$$s_f = -3.53$$

Step 4: Calculate flow rate of the well, Q

$$Q = \frac{(k)(h)(P_e - P_{wf})}{(141.2)(B_o)(\mu)\left[\ln\left(\frac{r_e}{r_w}\right) + S_f\right]} \quad \cdots\cdots\cdots\cdots\cdots (3.3)$$

$$Q = \frac{(2000)(1000)(5000 - 1500)}{(1)(50)(141.2)(1)(1)\left[\ln\left(\frac{1490}{0.328}\right) + (-3.53)\right]}$$

$$Q = 202{,}574\ bbl/d$$

Table 4.2 shows the different values of flow rate, Q in which fracture half-length, X_f are varied from 50 to 2000. Figure 4.2 illustrates the relationship between flow rate and fracture half-length. In this graph, fracture conductivity is fixed to 1 and fracture half-length varies from 50 to 2000. Based on the graph, the longer the fracture half-length, the higher the flow rate of the well. The flow rates are increasing almost in a linear trend when the fracture half-lengths are between 100 and 1850. Below fracture half-length of 100, the increment of flow rate is quite significant.

Table 4.2: Fracture half-length and production flow rate

Flow rate, *Q (bbl/d)*	Skin, S_f	Fracture half-length, X_f *(ft)*	$(S_f + \ln\frac{X_f}{r_w})$	Effective fracture conductivity, F_{CD}
2,532	-3.53	50	1.50	1
2,950	-4.22	100	1.50	1
3,265	-4.63	150	1.50	1
3,533	-4.91	200	1.50	1
3,773	-5.14	250	1.50	1
3,994	-5.32	300	1.50	1
4,203	-5.47	350	1.50	1
4,403	-5.61	400	1.50	1
4,595	-5.72	450	1.50	1
4,782	-5.83	500	1.50	1
4,964	-5.92	550	1.50	1
5,143	-6.01	600	1.50	1
5,320	-6.09	650	1.50	1
5,495	-6.17	700	1.50	1
5,668	-6.23	750	1.50	1
5,841	-6.30	800	1.50	1
6,013	-6.36	850	1.50	1
6,184	-6.42	900	1.50	1
6,356	-6.47	950	1.50	1
6,527	-6.52	1000	1.50	1
6,699	-6.57	1050	1.50	1
6,872	-6.62	1100	1.50	1
7,046	-6.66	1150	1.50	1
7,221	-6.70	1200	1.50	1
7,396	-6.75	1250	1.50	1
7,574	-6.78	1300	1.50	1
7,753	-6.82	1350	1.50	1
7,933	-6.86	1400	1.50	1
8,115	-6.89	1450	1.50	1
8,300	-6.93	1500	1.50	1
8,486	-6.96	1550	1.50	1
8,674	-6.99	1600	1.50	1
8,865	-7.02	1650	1.50	1
9,059	-7.05	1700	1.50	1
9,255	-7.08	1750	1.50	1
9,454	-7.11	1800	1.50	1

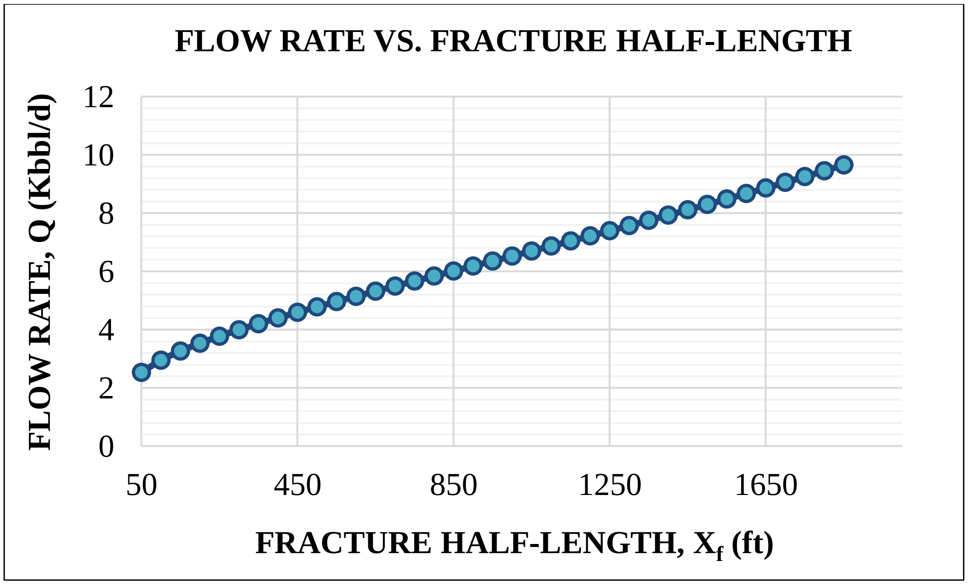


Figure 4.2: Flow rate vs. fracture half-length

4.3 Effect of fracture width on production rate

Methods to investigate the relationship between fracture width, w and production flow rate, Q are very much alike with the steps to analyse the effect of fracture half-length on production rate. However, in this analysis, F_{CD} and X_f are kept constant and we define ourselves the value for skin factor, S_f. The values of fracture width are varied from 0.001 ft to 0.020 ft. The steps to calculate the flow rate based on a few assumptions.

Step 1: Define the reservoir and well characteristics

Initial reservoir pressure, P_e = 5000 psi

Flowing bottom hole pressure, P_{wf} = 1500 psi

Fracture permeability, k_f = 200000 md

Drainage radius, r_e = 1490 ft

Wellbore radius, r_w = 0.328 ft

Formation volume factor, B_o = 1 rb/stb

Viscosity, μ = 1 cp

Total vertical depth, h = 1000 ft

Fracture conductivity, F_{CD} = 2 ft

Skin factor, S_f = 0

Step 2: Calculate flow rate of the well, Q

Take 0.001 ft as the value of w,

$$Q = \frac{(k_f)(w)(h)(P_e - P_{wf})}{(F_{CD})(X_f)(141.2)(B_o)(\mu)\left[\ln\left(\frac{r_e}{r_w}\right) + S_f\right]} \quad \cdots\cdots\cdots\cdots\cdots (3.3)$$

$$Q = \frac{(200000)(0.001)(5000 - 1500)}{(2)(1000)(141.2)(1)(1)\left[\ln\left(\frac{1490}{0.328}\right) + 0\right]}$$

$$Q = 294\ bbl/d$$

Table 4.3 shows the different values of flow rate, Q in which fracture width, w are varied from 0.001 to 0.020. Figure 4.3 describes the correspondence of flow rate with fracture width. It indicates that the flow rate is directly proportional with fracture width. Based on the graph, the flow rate increases linearly when the fracture width increases. These results correspond to the theory where hydraulic fracturing stimulates and produces better reservoir performance. Theoretically, the higher the fracture width, the higher the fracture conductivity. Thus, higher fracture conductivity would definitely produce higher flow rate, which indicates better reservoir performance.

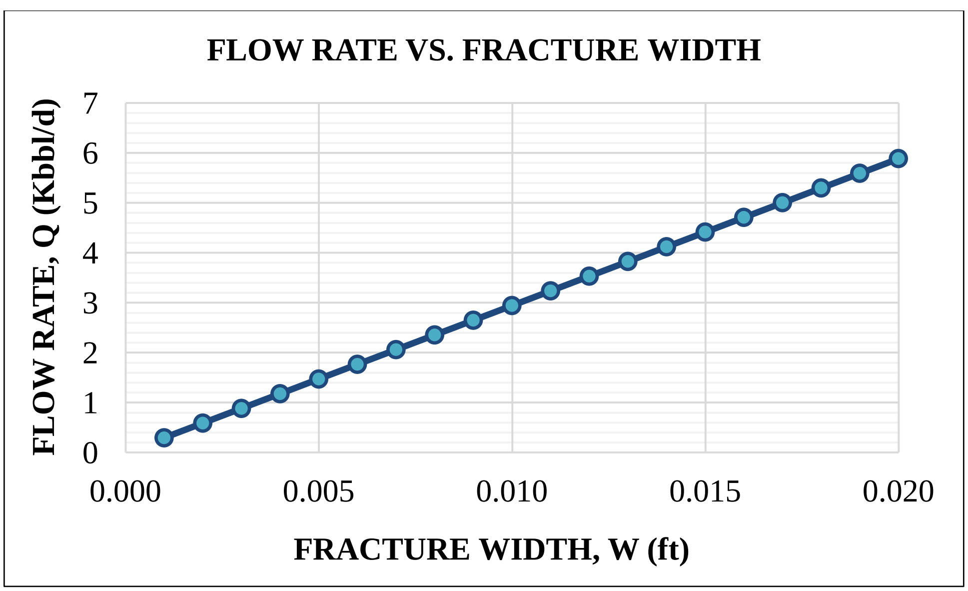


Figure 4.3: Flow rate vs. fracture width

Table 4.3: Fracture width and production flow rate

Fracture width, *w (ft)*	Flow rate, *Q (bbl/d)*
0.001	294
0.002	589
0.003	883
0.004	1177
0.005	1472
0.006	1766
0.007	2060
0.008	2355
0.009	2649
0.010	2943
0.011	3238
0.012	3532
0.013	3826
0.014	4121
0.015	4415
0.016	4710
0.017	5004
0.018	5298
0.019	5593
0.020	5887

4.4 Estimation of Productivity Improvement Factor (PIF)

The user can identify the Productivity Improvement Factor (PIF) of the stimulated well based on the input value of the pre-fractured production flow rate. This is the additional feature in the spreadsheet model that allows user to estimate productivity of the fractured well.

Step 1: Input the pre-fractured production flow rate.
The pre-fractured flow rate is needed to compare with the post-fractured flow rate later. In this case, the pre-fractured flow rate is 3000 bbl/d. The set of data to be taken as the post-fractured flow rates are from Table 4.1.

Step 2: Calculate the PIF

$$PIF = \frac{Q_f}{Q_o} \cdots \cdots \cdots \cdots \cdots (3.4)$$

$$PIF = \frac{3647}{3000}$$

$$PIF = 1.22$$

Table 4.4 shows the different in Productivity Improvement Factor (PIF) when fracture conductivity is varied from 0.1 to 1000. Based on Figure 4.4, it shows that PIF increases when the fracture conductivity increases until to certain extent. The increase in PIF is significant when the fracture conductivity increases from 0.2 to 10. From 10 to 90, the increase of PIF is less significant. When fracture conductivity is higher than 90, the graph illustrates that the PIF is constant until fracture conductivity of 1000. Thus, these results reflect to the relationship between production flow rate and fracture conductivity.

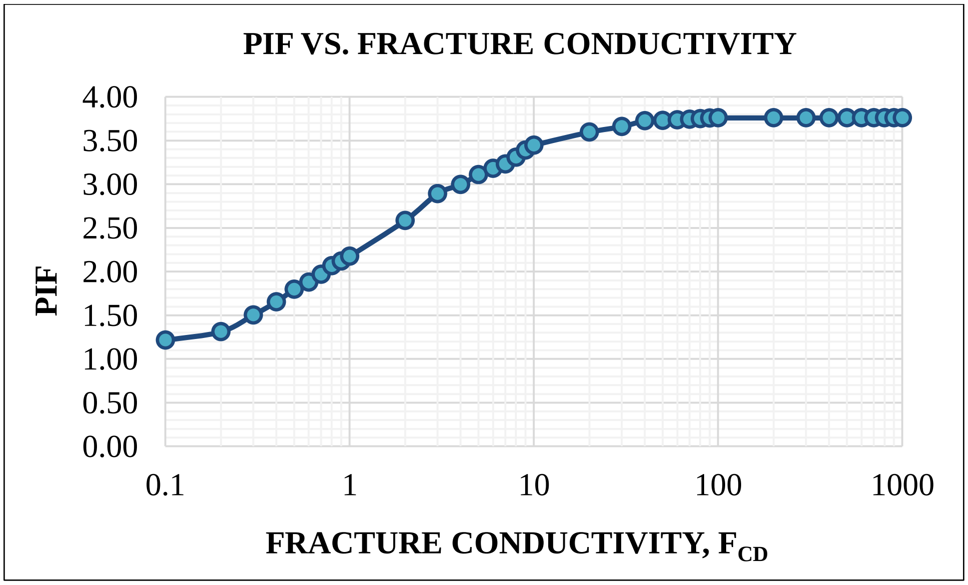


Figure 4.4 PIF vs. fracture conductivity

Table 4.4: Productivity improvement factor (PIF)

Effective fracture conductivity, F_{CD} (ft)	Flow rate, Q (bbl/d)	Productivity Improvement Factor
0.1	3,647	1.22
0.2	3,936	1.31
0.3	4,509	1.50
0.4	4,960	1.65
0.5	5,391	1.80
0.6	5,637	1.88
0.7	5,905	1.97
0.8	6,201	2.07
0.9	6,360	2.12
1.0	6,527	2.18
2.0	7,752	2.58
3.0	8,674	2.89
4.0	8,989	3.00
5.0	9,327	3.11
6.0	9,543	3.18
7.0	9,692	3.23
8.0	9,925	3.31
9.0	10,169	3.39
10.0	10,339	3.45
20.0	10,789	3.60
30.0	10,980	3.66
40.0	11,178	3.73
50.0	11,188	3.73
60.0	11,208	3.74
70.0	11,229	3.74
80.0	11,249	3.75
90.0	11,269	3.76
100.0	11,280	3.76
200.0	11,280	3.76
300.0	11,280	3.76
400.0	11,280	3.76
500.0	11,280	3.76
600.0	11,280	3.76
700.0	11,280	3.76
800.0	11,280	3.76
900.0	11,280	3.76
1000.0	11,280	3.76
1100.0	11,280	3.76

CHAPTER 5

CONCLUSION & RECOMMENDATION

5.1 Conclusion

As a conclusion, the study met its objectives, which are to build a spreadsheet model that relates to the effects of fracture conductivity and fracture geometry on production rate, to determine and discuss on the effect of those parameters on the production rate and to compare the productivity index of the well before and after the hydraulic fracturing job.

Based on the calculations and the analysis done in spreadsheet model, it is proven that the fracture geometry such as fracture conductivity, fracture half-length and fracture width have important roles in determining the production rate of the well. According to the sensitivity analysis on the effects of fracture geometry on production rate, the wider the fracture width, the higher the production rate of the well. Meanwhile, increase in fracture conductivity and fracture half-length will also increase the production rate. Hence, this study provides better understanding to the engineers on the minimum fracture conductivity and fracture half-length that the process must achieve.

Furthermore, this study or the built spreadsheet model would also provide a feature where the user can determine the productivity index of the fractured well. The user needs to input the initial or pre-fractured production rate. Then, the spreadsheet model would estimate the Productivity Improvement Factor (PIF) of the fractured well. This feature would help the surveillance team on the effectiveness of the applied hydraulic fracturing. From the PIF, the team can analyse on the efficiency of the proppant itself, whether there will be any necessity to increase the amount of proppant or to upgrade the proppant characteristics. Certainly, the surveillance study on hydraulic fracture characteristics in tight formation would encourage the people in industry to learn more about this treatment and work towards achieving the best proppant geometry that would be able to generate an optimum production flow rate and higher productivity index.

5.2 Recommendation

The relevancy of this study will be improved later when PETREL is used to model the hydraulic fracturing simulation. By using this software, the fracture geometry parameters which are the fracture half-length, fracture width and fracture height will be manipulated until the optimum production rate with the highest productivity index are achieved. Other than analysing the production rate of the well, the scope of study can further be diverged to the analysis on closure pressure of the fractured zone. When the optimum hydraulic fracturing characteristics are determined to generate the optimum production rate, the data will be used to design suitable proppant which can withstand the in-situ stress from the formation and to keep the fracture open. As a result, the newly created fracture will be able to maintain its permeability for longer period of time. Also, the selection of the best proppant can be selected more precisely when considering more than one factors.

Besides investigating on just the technical sides, the study can be improved when the commercial factors are considered. The commercial factors include the cost of the whole hydraulic fracturing system and the economics analysis of the hydraulic fracturing. By analysing on the economics of the hydraulic fracturing, one can determine how much does the hydraulic fracturing generate towards the existing project or well. This economics analysis is called as an incremental economics, where the new project, which in this case is hydraulic fracturing, is evaluated concurrently with the existing project. It will give a better economic analysis when the project is not being evaluated on the stand-alone basis. Stand-alone economics analysis will give an optimistic outcome, thus broaden the uncertainty of the project.

In continuation to the economics analysis, a feature which enables the user to choose the required type of proppant will be added to the spreadsheet model as to enhance the surveillance study of the hydraulic fracturing. Different in proppant properties will affect the hydraulic fracturing process, thus will vary the outcomes of hydraulic fracturing. The best properties of proppant will definitely enhance the permeability of the reservoir. Higher permeability reservoir will generate higher productivity index, and higher reserves can be recovered. However, the user must consider the cost of the best proppant, which in reality is more expensive than the normal proppant. Hence, the user will find the spreadsheet model attractive as it intersects two main factors; technical and commercial.

In addition, the development of this study should follow the primary objective of hydraulic fracturing which is to create and maintain a stable fracture with excellent conductivity to maximize well productivity and the ultimate recovery. In order to appreciate the effects of the hydraulic fracturing, the relationship between the reservoir and the fracture variables of permeability, fracture half-length, and fracture conductivity must be clearly understand. Therefore, in the next stage of this surveillance study, sensitivity analysis should always be done to all variables while determining the fracture closure rate in tight formation with time and also the production rate of the well. The interdependence of all the variables can actually be described by the dimensionless fracture conductivity, F_{CD}.

Here, k is the formation permeability, k_f is the permeability of the fracture, w is the fracture width and X_f is the fracture half-length. The equation above relates the ability of the fracture to flow fluids to the fracture. Fracture half-length and fracture conductivity can be considered as the critical fracture parameters since the well performance can be changed by manipulating the fracture length value to get the fracture conductivity until an optimum F_{CD} is achieved.

Furthermore, it is recommended for UTP to have such facilities that can cater for hydraulic fracturing studies since the technology is frequently used nowadays. For example, UTP should have appropriate software, like Petrel E&P Software and ECLIPSE, to conduct further studies on the hydraulic fracturing in tight formation. Currently, UTP only has few computers with these software installed, which bring limitations when a large number of students want to use them.

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