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Using Laboratory Results from New Methods of Measuring Proppant Conductivity to Model Hydraulic Fractures in Reservoir Simulation

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Abstract

Purpose: Hydraulic fracturing processes are conducted to create new fractures in a rock to increase the size, extent, and connectivity of existing fractures. The American Petroleum Institute (API) developed two testing procedures for measuring conductivity of proppants in a laboratory setting, namely; the Short-Term Proppant Conductivity Testing Procedure and Long-Term Proppant Conductivity Testing Method. However, these laboratory testing methods have produced inconsistent results, with a significant coefficient of variance of ±80% from one test to the other even with the use of the same proppants and procedures. Thus, this work seeks to use an improved laboratory variance from Montana Tech conductivity measurements to model hydraulic fractures in reservoir simulation to evaluate how it performs or compares with field performance.

Methodology: Montana Tech researchers have developed new proppant conductivity testing methods to lower this variance. These testing procedures showed more consistent results with an average variance of ±7.6% and ±14.3% in ceramic and sand proppants respectively. These tests were all done at laboratory conditions and therefore this work used field production data obtained from the Willison Bakken Formation and an arbitrary high permeability value as a benchmark against the fracture models built using laboratory results from the new methods of measuring proppant conductivity testing by Montana Technological University.

Findings: The conductivity values corresponding with 6,500 psi closure stress obtained for sand and ceramic were 2,133.5 md-ft and 4,870.3 md-ft respectively. The high permeability model recorded an incremental recovery increase of 42% over the unfractured model. Similarly, the laboratory sand and ceramic models had an incremental recovery increase of 12.9% and 33% respectively over the unfractured model. The dimensionless fracture conductivity for the laboratory sand, laboratory ceramic and high permeability models were 1,246, 2,844 and 233,577 respectively. Generally, laboratory conductivity overestimates field performance, however, this work did not show an improvement in modeling fractures using laboratory data as a result of the extremely low porosity and permeability values of the Bakken wells used for the study and the limitedness of the software package used. Simulation of low permeability reservoirs is still an area in development as traditional models often fail to produce results that match the physics. It is possible that as simulation methods for these types of reservoirs improve, the new laboratory data for fracture conductivity will prove beneficial in modeling.

Unique contribution to theory, practice and policy (recommendation): A sensitivity analysis should be performed in Petrel that starts with the laboratory fracture conductivity and ends with infinite fracture conductivity. This would help determine the effect of correctly measuring fracture conductivity. Again, a better technique in Petrel such as using a tartan grid is encouraged to better assess the performance of each of the fractures and lastly, more well data with associated measured porosity and permeability data is suggested for future works.

Keywords: *Ceramic and Sand Proppants, Hydraulic Fracturing, Hydrocarbons, Permeability, Conductivity, Unconventional Reservoir, Fractures, Variance, Willison Bakken Formation.*

1.0 Introduction

Hydraulic fracturing is a well-stimulation technique commonly used in low-permeability rocks such as tight sandstone, shale, and some coal beds to increase oil and/or gas flow to a well from petroleum-bearing rock formations [1]. Drilling of new oil and gas wells is capital intensive, as such, already discovered wells may be well exploited through well-stimulation to enhance production [2]. The use of proppants plays a key role during the fracturing process as they are carried into the formation via a well in a high-pressure fluid that cracks the rock, forming the fractures [3]. The withdrawal of the carrier fluid leaves the proppants behind to hold the fracture open. This process is intended to create new fractures in the rock as well as increase the size, extent, and connectivity of existing fractures. The conductivity of propped fractures is a major influence on the productivity of the well [4].

The American Petroleum Institute (API) has adopted and outlined two testing procedures for measuring conductivity of proppants in a laboratory setting. The first procedure is the Short-Term Proppant Conductivity Testing Procedure called the API RP61 [5], which has been updated with the Long-Term Proppant Conductivity Testing Method also referred as the API RP19D [6]. It included changes to help users obtain more consistent results yet the API RP 19D replacement testing method still produced inconsistent results; recording a coefficient variance of ±80% from different experimental tests with the same proppants and procedures [7]. The industry however considers a standard coefficient of ±20% variance in proppant conductivity to be desirable [8,9].

1.1 Proppant types and properties

A proppant is a solid material (typically natural sand, treated sand, or man-made ceramic materials) designed to maintain an induced hydraulic fracture following a fracturing treatment. Proppant materials used in the industry can be grouped into main categories such as; rounded silica sands, resin coated sands, and fused synthetic ceramic materials. Sand and ceramic proppants are the types used by earlier researchers at Montana Tech [10,11,12].

Naturally occurring sand proppants are relatively common and inexpensive when compared to the manufactured ceramic proppants. Frac sand (naturally occurring sand-type proppant) is generally irregular in shape depending on the source and as compared to others has low strength and packs together closely in fractures, resulting in a lower permeability when compared to other proppant types. Ceramic proppant is the most uniform-shaped and rounded proppant. It has a high strength which results in high permeability, allowing trapped oil or natural gas to flow easily through the fractures. Figure 1 compares the strength and conductivity of different proppants.

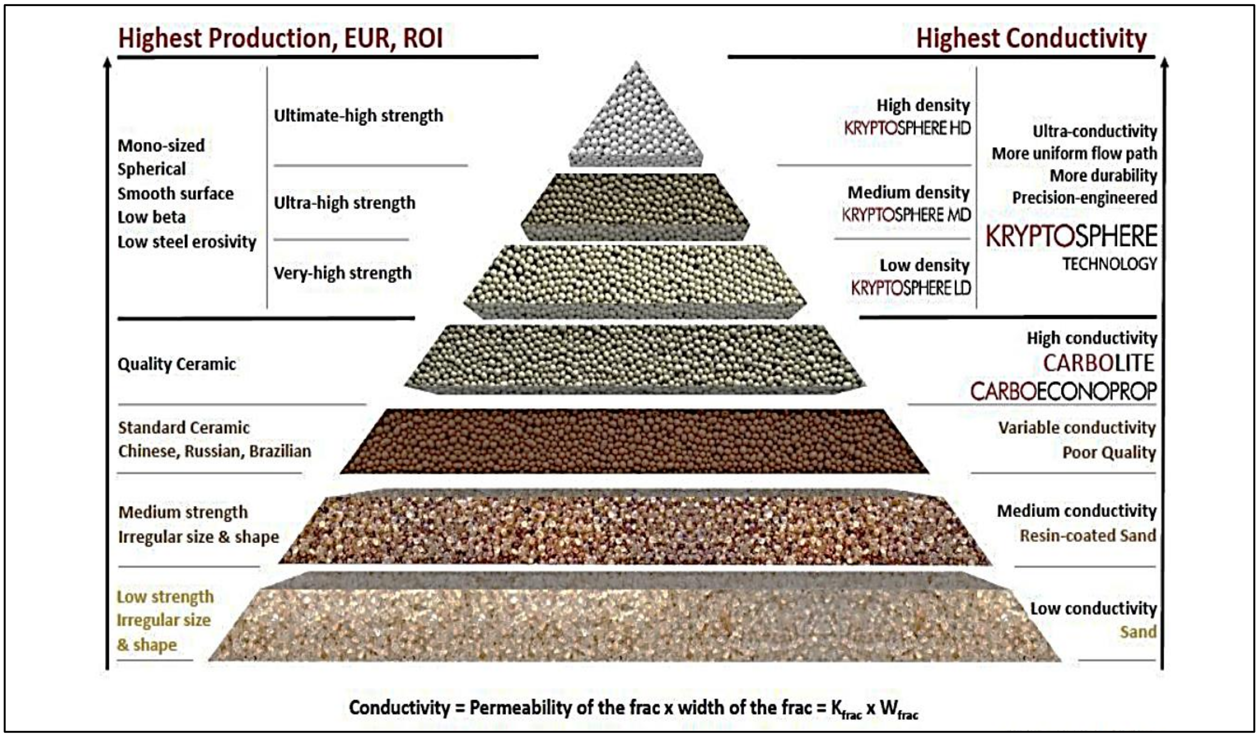

Figure 1: Strength and conductivity of different proppant types

1.2 Proppants used in the Bakken Formation of the Williston Basin

The improvement of hydraulic fracturing techniques focuses on determining the effective placement of proppants to provide and maintain fracture conductivity. The Bakken Formation of the Williston Basin is the primary source of production data for this research [13]. Several proppants have been used since production began in the Bakken Formation because the low permeability of the formation makes the Bakken commercially viable only with the application of hydraulic fracturing [3]. Sand, ceramic, and resin coated proppants have been used in this field to achieve appreciable impact.

1.3 Conductivity measurement

Conductivity is the capability to flow reservoir fluids through a porous proppant medium. Conductivity is mathematically expressed as the propped width multiplied by the effective proppant permeability. The equation in SI units for the calculation of proppant pack permeability as presented in the API RP-19D [5] is shown in Equation 1.

$$K = \frac{\mu QL}{100A\Delta P} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{Equation 1}$$

K = the proppant pack permeability in Darcy,

μ = the viscosity of the test liquid at room temperature in cp,

Q = the flow rate in cm^3/s,

L = the length between pressure ports in cm,

A is the cross-sectional area in cm^2,

ΔP is the pressure drop ($P_{upstream}$ - $P_{downstream}$) in kPa.

The conductivity equation in SI units defined in API RP-19D [4] is shown in Equation 2 below.

$C = K * Wf$……………………………………………………………………….…...Equation 2

C = the conductivity
K = the proppant pack permeability in Darcy

Wf = the pack thickness in cm.

The propped width is the difference between permeability and conductivity. Proppant conductivity replicates the flow ability of a specific amount of proppant in an API flow-test apparatus. API standards for testing proppant conductivity make no reference to the distribution of proppant, correction for connection to the wellbore, and degree of effective reservoir exposure. [5,6] Fracture conductivity is the total of all components that affect the delivery of reservoir fluids to the wellbore, including (1) proppant conductivity, (3) propped fracture communication with the wellbore, and (3) post fracture conductivity decreases due to proppant changes under closure stress [10].

Fracture conductivity for a given well must be determined after a 'frac job' is completed. It is assumed that proppant conductivity is affected by proppant and gel damage. Based on this perspective, a lot of research about proppant conductivity applies to fracture conductivity and dimensionless fracture conductivity (FCD). The formula for FCD shows a high contrast between fracture conductivity and formation permeability. Dimensionless fracture conductivity is expressed in the Equation 3 below.

$$FCD = \frac{K_f w}{k * X_f}$$ ……………………..……………………………………………........Equation 3

K_f w = the fracture conductivity in md-ft,

k = the permeability in Darcy,

X_f = the fracture half-length in ft

While laboratory proppant conductivity testing methods allow operators to compare one proppant to another, this project uses field production data obtained from the Willison Bakken Formation and an arbitrary high permeability as a benchmark against the fracture models built using laboratory results from new methods of measuring proppant conductivity. Montana Tech researchers have developed new proppant conductivity testing methods to lower this variance which have shown more consistent results with an average variance of ±7.6% and ±14.3% in ceramic and sand proppants respectively [10]. While these testing methods allow operators to compare one proppant to another, the applicable rule of thumb is to relate lab results for measuring proppant performance to actual performance in the field. This research uses results of laboratory proppant conductivity measurements to model fractures in reservoir simulation.

2.0 Methodology

The research used the laboratory conductivity data to model fractures using real Bakken well data. The project focused on building reservoir simulation models for a fractured well using the middle Bakken data as contained in table 1. The Bakken well database was obtained from drilling info, and it focused on two wells fractured with the same types of proppants used in the Montana Tech laboratory in developing the new methods.

Table 1: Middle Bakken formation parameters

Parameters	Value	Unit	Parameters	Value	Unit
Thickness	40	ft	Oil Compressibility	10*10^-6	1/psi
Porosity	0.01		Water Compressibility	3*10^-6	1/psi
API Gravity	41.5		Formation Compressibility	3*10^-6	1/psi
Gas specific gravity	0.9		Boi	1.377	rbl/stb
Permeability	0.005	md	Initial Oil Viscosity	0.593	Cp
GOC	1,200	scf/bbl	Total Compressibility	11.8*10^-6	1/psi
GOR	12,000	scf/bbl	Bubble Point Pressure	3,500	Psi
Temperature	100	degree celsius	Mini Pressure	2,500	Psi
Average Fracture Length	685	ft	Max Pressure	6,500	Psi
Well depth	20,000	ft	Lateral Length	10,000	ft

Source: 13,14

Subsequently, table 2 was tabulated with the parameters and average values from the middle Bakken formation in building the model.

Table 2: Parameters used in building the models

Parameters	Value	Field Unit
Top limit for subsea elevation	8,000	ft
Base limit for subsea elevation	8,040	ft
Length of model in X-direction (Xmax)	10,720	ft
Length of model in Y-direction (Ymax)	1,360	ft
Height of grid block	4	ft
Layers	10	
Surface elevation	2,000	ft

Source: 4,15

The laboratory conductivity results obtained from newest method developed, referred to as Sonic 3 method developed [10], was used in building the fracture model as described below.

I. Unfractured model (base model): This model used the values listed in table 1 and the parameters in Table 2 which contains a well completed without hydraulic fractures.
II. Laboratory Ceramic model: This model is the same as the base model with fractures built using the laboratory data from the ceramic proppant conductivity measurement.
III. Laboratory Sand model: This model is the same as the base model with fractures built using the laboratory data for sand proppant conductivity measurement.
IV. High Permeability model: This model shares the same parameters as the other three, but the fractures built was modeled at a high permeability of 10,000 md.

The development strategy selected for the models was an arbitrary 500 psi for the bottom whole pressure (well pressure production control). The wells were cased and completed with a simple completion, and used production dates of November 2, 2011 and October 1, 2013 for sand and ceramic models respectively as found in the field data.

2.1 Applying Sonic 3 Data to the Simulation Models

In building the fracture models, a closure stress value of 6,500 psi was used as it represents the average closure stress for the formation of interest. As such, an interpolation was done between the nearest SRV Method 3 laboratory closure stresses, 6,000 and 8,000 psi for sand and ceramic as can be seen in table 3 and table 4 respectively [10].

Table 3: Conductivity values for ceramic proppant using sonic method 3

Closure stress (psi)	Average Conductivity (md-ft)		Absolute Difference (md-ft)	Percent Difference (%)
	Long-term	Sonic Method 3		
1000	9888	8863	1026	10.4
2000	9032	8342	690	7.6
4000	7514	6993	521	6.9
6000	5186	5321	135	2.6
8000	2953	3518	565	19.1
10000	1736	2036	300	17.3
12000	1049	1177	129	12.3
14000	659	742	82	12.5
Average	-	-	-	11.1 ± 5.5

Table 4. Conductivity values for sand proppant using sonic method 3

Closure stress (psi)	Average Conductivity (md-ft)		Absolute Difference (md-ft)	Percent Difference (%)
	Long-term	Sonic Method 3		
1000	6468	5487	981	15.2
2000	5857	5236	621	10.6
4000	3532	4325	793	22.5
6000	1306	2510	1205	92.3
8000	549	1004	455	82.8
10000	276	464	188	68.1
Average	-	-	-	48.6 ± 36.6

The conductivity values corresponding with 6,500 psi closure stress obtained for sand and ceramic were 2,133.5 md-ft and 4,870.3 md-ft respectively. From the laboratory data, the average frac width and its corresponding pack permeabilities (from equation 2) were 0.017 ft (0.205 in) and 125 *103 md for sand, and 0.018 ft (0.212 in) and 276 *103 md for ceramic proppant. 40 fractures were built for both sand and ceramic models. The fractures were built with a length of 685 ft, fracture height of 40 ft and orientation of 90 degrees to suit the dimensions of the model. Each fracture was built with their corresponding permeability and width, 53.3 md and 0.017 ft for sand model and 121.8 md and 0.018 ft for ceramic model respectively. Figure 2 below shows a simulated fractured well showing all the 40 fractures.

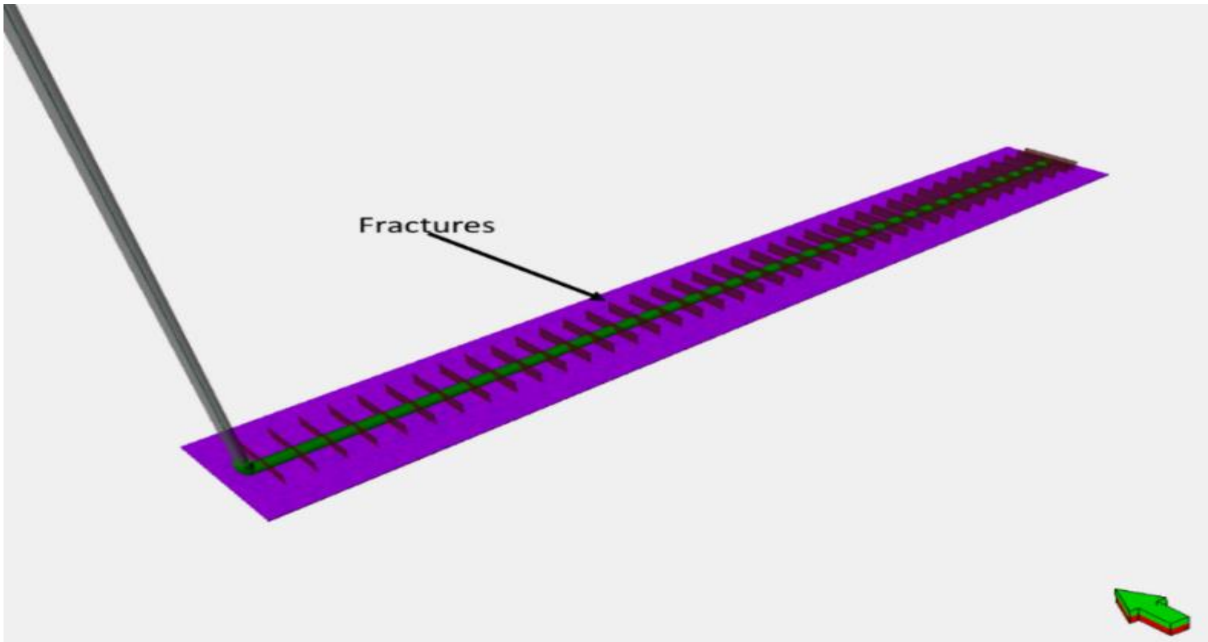

Figure 2: Simulated fractured well showing 40 fractures

3.0 Results and Discussion

3.1 Laboratory Ceramic Model Result

Figure 3 shows the cumulative oil production of three simulation models (unfractured, laboratory ceramic and high permeability fracture) and includes the measured cumulative production from the Bakken well fractured with ceramic proppant.

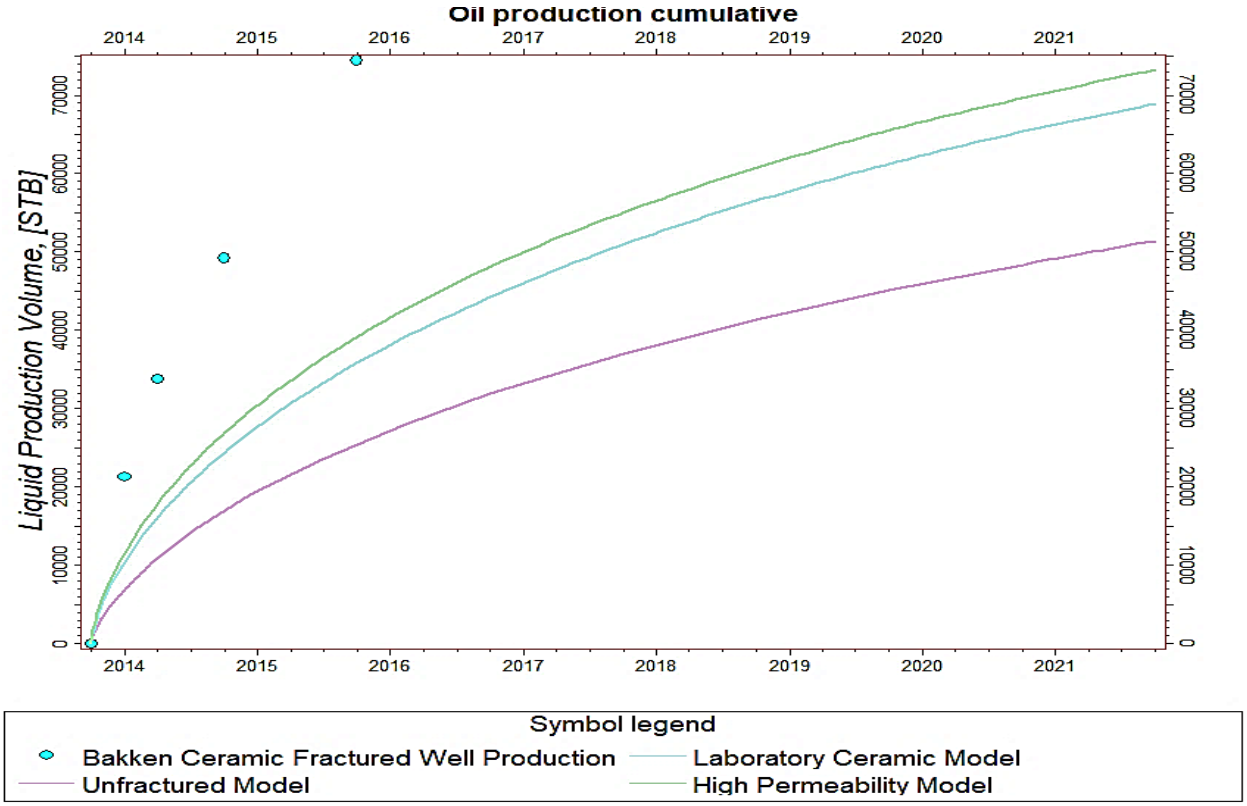

Figure 3: Comparison of production data with lab ceramic model, unfractured model and high permeability model

The three simulation models all fell short of matching the actual production. As expected, the unfractured model recorded a much lower production, and the introduction of fractures brings the simulation results closer. However, the high permeability model outperformed the model using the laboratory data. The huge difference in cumulative production between the unfractured and the rest of the models emphasizes on the importance of hydraulic fracturing in the industry.

3.2 Results of Laboratory Sand Model

The results of the comparison of the cumulative production from the sand fractured well to the unfractured, Laboratory sand and High Permeability models as presented in Figure 4 shows a similar trend, but there also is an unusual high production for this well that may make it a poor choice to model. This is an unusual well deep for a sand fractured well, and with a short lateral length. The depth and lateral length of this sand well was about 14,000 ft deep and 4,000 ft respectively.

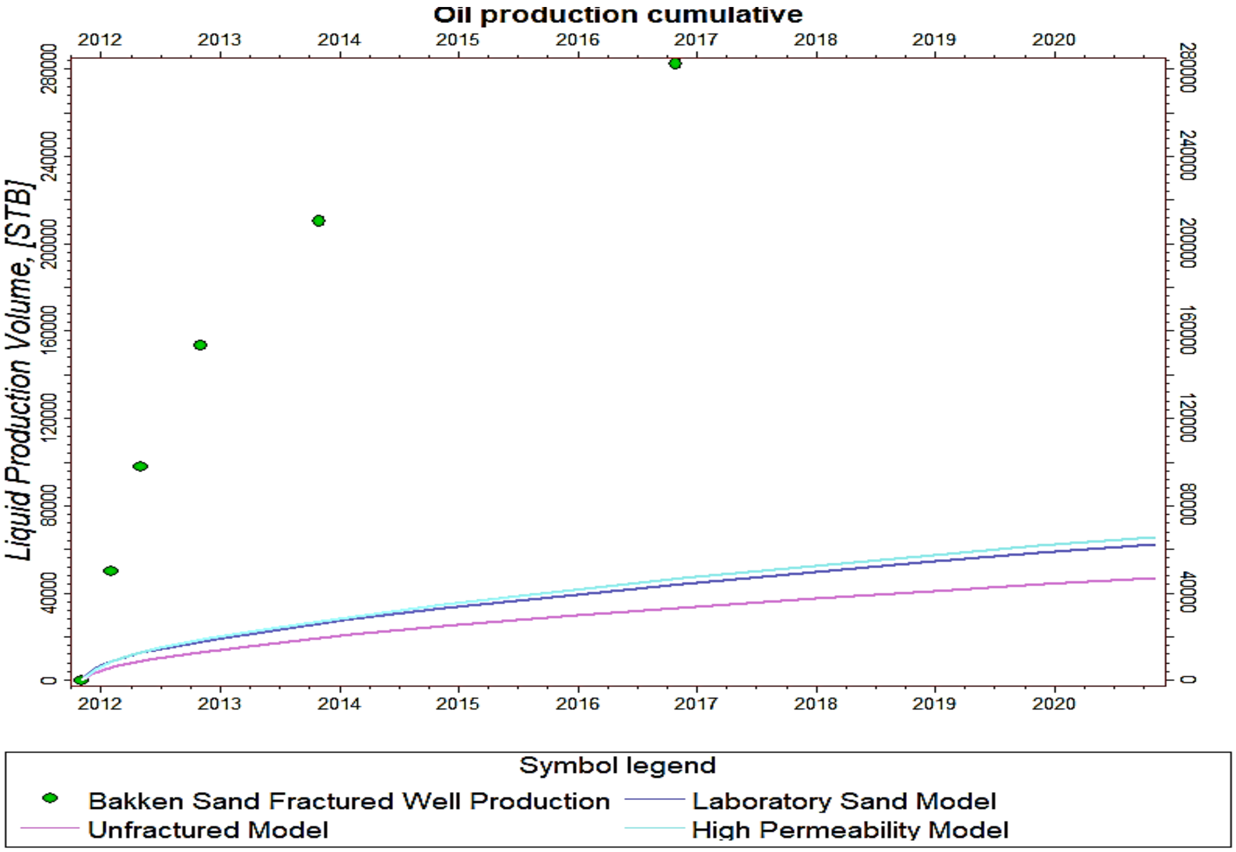

Figure 4: Comparison of production data with lab sand model, unfractured model and high permeability model

For these reservoir and wellbore characteristics, the high permeability model recorded an incremental recovery increase of 42% over the unfractured model. Similarly, the laboratory sand and ceramic models had an incremental recovery increase of 12.9% and 33% respectively over the unfractured model. Subsequently, the dimensionless fracture conductivity for the models was estimated. The laboratory sand model had the lowest dimensionless fracture conductivity, followed by the laboratory ceramic model. The model with the highest dimensionless fracture conductivity was the high permeability model. From the approximation, the dimensionless fracture conductivity for the laboratory sand, laboratory ceramic and high permeability models were 1,246, 2,844 and 233,577 accordingly.

4.0 Conclusions and Recommendations

4.1 Conclusions

This work did not show an improvement in modeling fractures by using the laboratory data as the models built using the laboratory data underestimated production more than the high permeability models. Reasons for the lack of improvement when using the laboratory data to model include a possible lack of sensitivity in Petrel software package to changes in fracture permeability. It is a somewhat common practice to set fracture permeability to infinite [16] in order to gain a good history match. Simulation of low permeability reservoirs is still an area in development as traditional models often fail to produce results that match the physics. So, simulation parameters are often adjusted outside the physical ranges of the data in order to obtain a good history match. It is possible that as simulation methods for these types of reservoirs improve, the new laboratory data for fracture conductivity will prove beneficial in modeling.

4.2 Recommendations

I. A sensitivity analysis should be performed in Petrel that starts with the laboratory fracture conductivity and ends with infinite fracture conductivity. This would help determine the effect of correctly measuring fracture conductivity.
II. A better technique in Petrel such as using a tartan grid is encouraged to better assess the performance of each of the fractures.
III. More well data with associated measured porosity and permeability data is suggested for future works.

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