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Hydraulic Fracture Design Using the Perkins-Kern-Nordgren (PKN) Model for Produced Water Disposal: A Case Study in Niger-Delta

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Abstract**-** In the design of hydraulic fracture for oil and gas production enhancement or for waste disposal, it is pertinent to first predict the fracture growth and geometry as a function of certain critical parameters crucial for hydraulic fracturing design. The geometry of a fracture during hydraulic fracture operation is dependent on the rock properties and the stresses acting on them. The fracture simulation was done using the Perkins-Kern-Nordgren (PKN) 2D fracture model. The result from the simulation analysis shows that the integrity of the caprock rock in the formation to be fractured is critical. The fracture geometry (length, width and height) and the volume of liquid that can be pumped into the subsurface fractured formation were analyzed at different pumping rate. Different fracture heights were considered base on the formation thickness. Also the fracture orientation was determined using the information from well log. In order to achieve higher volume of produced water re-injection, a higher pumping rate was recommended based on the simulated result.

Keywords**-** *Hydraulic Fracture, Produced Water Disposal, PKN Model*

I. INTRODUCTION

With global energy demand continually growing, oil and gas plays an increasingly important role in supporting the development of society. The global petroleum daily consumption has increased from 80 million barrels in 2000 to 98 million barrels in 2017, indicating that every day a large amount of oil and gas is produced from conventional and unconventional fields (Yu et. al 2018). Produced water volumes from waste streams of oil and gas production are estimated globally at 77 billion barrels per year. During the production of oil and gas, the water produced contains chemicals, oil and radioactive materials in some cases which are detrimental to the environment. Produced water management involves high cost and stringent regulations which are aimed at toxicity minimization or reduction before it is discharged. For effective produced water management, the volume produced must be accurately estimated. There are still a lot of challenges faced in the proper management of produced water even in the United State. The need to properly manage this waste due to its effect on human lives and the environment has long been identified (Veil and Clark, 2010). At the first meeting in 1978, the Paris Commission (Oslo-Paris or OSPAR) set the temporary target for offshore oil installations discharges at 40 ppm, discouraging the discharge into water bodies (Veil and Clark, 2010). Subsurface disposal of produced water and drill cuttings through hydraulic fracturing provides zero discharge solution to the operating companies and eliminates any liability that may arise in the future when the loop is closed (Abou-Sayed and Guo 2001). Subsurface method of disposing waste materials has yielded great success both in the onshore and the offshore drilling operations. This method has gained widely acceptance in the sense that it complies with environmental legislation with respect to drilling waste disposal and the cost of operation is favorable economically(Abou-Sayed and Guo 2001). In order to efficiently dispose waste in the subsurface, proper job planning, proper design operations, strict systematic monitoring and quality assurance controls are critical (Abou-Sayed and Guo 2001). A lot of companies like BP-Amoco-ARCO, Chevron, Conoco, ExxonMobil, Phillips, Shell and Statoil have successfully carried out subsurface injection activities which is now a method adopted by most of these major operators as their waste disposal method (Abou-Sayed and Guo 2001).

A. *Hydraulic Fracture*

Hydraulic fracturing is a borehole stimulation technique in which the rock is fractured by a pressurized fluid. If the fluid is pumped into a well faster than it can escape into the formation, pressure will inevitably rise and eventually the formation will collapse with the well being split along its axis as a result of tensile hoop stresses due to high wellbore pressure (Montgomery et. al 2014). At any time on Earth, there are always three main principal stresses on the rocks. Except for regions with active tectonic, the vertical stress, the maximum and the minimum horizontal stress are the three principal stresses (Figure 1). In most geologic environments (except where there is a thrust or reverse fault environment), the minimum horizontal stress, σH_{max} is the minimum stress σH_{min} (Montgomery et. al, 2014).

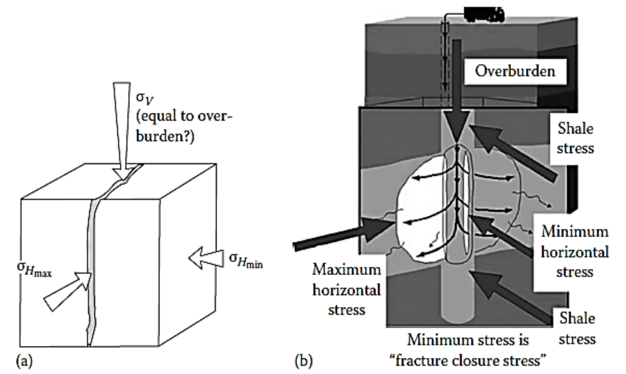

Figure 1. Fracture initiation and propagation. (a) Principal stresses. (b) Principal stresses in relation to fracture orientation (Montgomery et. al 2014)

Hydraulic fracturing is a process by which a fracking fluid is injected into the wellbore at a high pressure enough to create an opening in the rock formation. During hydraulic fracturing, two processes take place, the pad stage which involves the injection of fracturing into the formation to break the rock formation and the slurry stage in which proppant is added to the fracturing fluid and other additives. This proppants are pumped into the fracture to keep it open. Right from its inception, the use of hydraulic fracturing technology to improve well productivity well always remain a vital engineering tool (Montgomery et. al 2014). Hydraulic fracturing is achieved through

- Bypassing the near wellbore damage by placing a conductive channel through it
- Increased productivity by extending the channel to a significant depth into the reservoir
- Altering the reservoir fluid flow through the way the channel is placed

This implies that hydraulic fracturing is a tool for reservoir management, sand deconsolidation management and long-term exploitation strategies (Montgomery et. al 2014). Application of hydraulic fracturing in a well may be based on the following reasons according to Mehul Jain (2015):

1. To return a well to its initial natural state through bypass of the damaged wellbore.
2. Increase production of the well by extending the conductive path of the well deep into the formation.
3. Fluid flow alteration

Hydraulic fracturing may also be performed for the purpose of waste disposal through re-injection into a deep formation. In the case of fluid flow alteration, hydraulic fracture design may be affected by considering other wells that might be drilled within the field and how the wells will be placed, thereby making it a reservoir management tools

B. Hydraulic Fracture Models

The propagation of a fracture is a very complex process which involves several co-dependent sub-processes. For fracture geometry, various technical models have been developed that define the propagation of a fracture over time. These models combine elasticity, fluid flow, material balance and propagation criterion/in-situ stresses to describe fracture geometry in two-dimensional (2D) or three-dimensional (3D), fracture dimensions which are dependent on the number of dimensional variables. For two-dimensional (2D) fracture models, the size of the fracture is resolved by assuming a constant height (Prashanth et. al 2017). A hydraulically fractured formation using the PKN model will have a fracture shape as shown in figure 2. The shape of the fracture will follow an elliptic shape with maximum width in the centre.

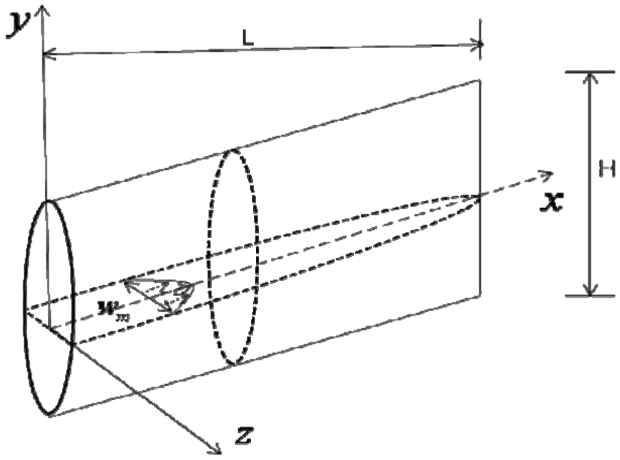

Figure 2. PKN fracture schematic diagram (Jing Xiang, 2011)

C. Hydraulic Fracture Template

Some of the fracture treatments in the oil and gas industries today are designed using two-dimensional (2D) fracture propagation models. These models are the Perkins-Kern-Nordgren (PKN) and the Geertsma-deKlerk-Daneshy (GDK) models and they provide reasonable estimates of created fracture length and fracture width. There are also 3D models like fully 3D models and pseudo-three-dimensional (P-3D) models for analyzing fracture geometry and propagation. The two-dimensional fracture propagation models are used most often because of their assumptions and the complex issues involved in the 3D models. In this study, the PKN hydraulic fracture model was used to design a fracture template for determination of fracture geometry and propagation for produced water disposal in a well in the Niger-Delta region. This was done by acquiring the well offset well. The objective of this study was achieved by determining the fracture behavior of the identified formation and the integrity of the overlying caprock. The PKN model is mostly preferred when the following criteria are observed in the formation to be fractured:

1. If the zone to be fractured is a single layer
2. If there is upper and lower barrier to the aquifer making the use of a 2D model appropriate
3. If the sensitivity of the design factors such as leakoff coefficient, young modulus, injection rate and volume can thoroughly be investigated

II. METHODOLOGY

Hydraulic fracturing in rocks takes place when the fluid pressure within the rock exceeds the smallest principal stress plus the tensile strength of the rock. This results in tensile failure or splitting of the rock. The methodology employed in this study was computation of pore pressure and rock mechanical properties (UCS, Poisson's ration, Young Modulus, Cohesion, and Frictional Angle etc) and Fracture gradient which are important parameters in the design of the fracture geometry and propagation. The classical Perkins-Kern-Nordgren Model (PKN) was used the design of the fracture geometry. Fracture geometry includes width, length and height of the fracture. This information is necessary in the stimulation design in order to ascertain the volume of fluid to pump. The Perkins-Kern-Nordgren Model (PKN) is appropriate for use in fracture design and simulation when the ration of fracture length to height is greater than one. Engler (2011) stated three fundamental equations that are applied in the modeling of hydraulic fractures. These equations are the continuity equation, the fracture fluid flow equation and the linear elastic fracture mechanics. In this study, these three equations were coupled to simulate the fracture propagation using the Perkins-Kern-Nordgren Model (PKN). In the case of the PKN model, the fracture height is assumed to be constant.

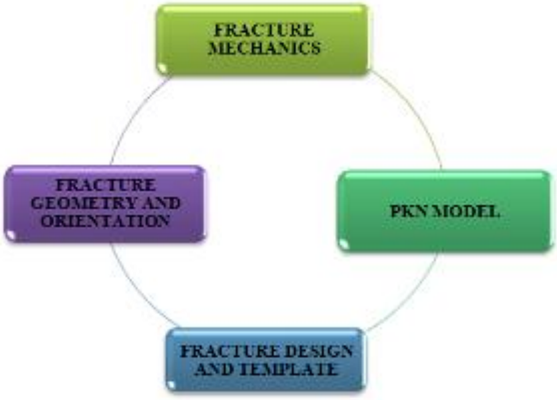

Figure 3. Hydraulic Fracture Model work flow

III. PERKINS-KERN-NORDGREN (PKN) MODEL

The following assumptions were made to simplify the complex problem (Engler, 2011):

- The fracture height (hf) is fixed and independent of fracture length (Multiple run options).
- The fracture fluid pressure is constant in the vertical cross sections perpendicular to the direction of propagation (in view of the overburden).
- Reservoir rock stiffness, its resistance to deformation prevails in the vertical plane; i.e., 2D plane-strain deformation in the vertical plane
- Each plane obtains an elliptic shape with maximum width in the center,

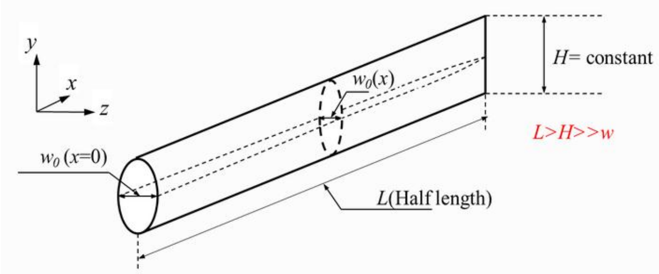

Figure 4. Schematic view of the PKN model (frackoptima.com)

IV. RESULTS AND DISCUSSION

The fracture geometry consists of the fracture width, length and the height of the fracture. This is critical in fracture design in order to know the volume of the fluid that can be pumped in. The PKN model has been used as a reasonable approximation of induced fractures in a great number of engineering design schemes.

V. PKN MODEL SIMULATION

In the simulation of the hydraulic fracture model, the 2D PKN model was adopted in the generation of the fracture geometry (fracture width, Fracture length, and fracture height) and the volume of liquid that can be pumped in the fractured formation. Based on the thickness of the bed in consideration, a fracture height of 100ft, 80ft, and 60ft was considered. In two dimensional fracture models (The PKN and GDK fracture models), the fracture height is assumed to be constant during the propagation processes while width and length are the dimensions that are changing. The fluid leakoff coefficient is an important parameter that controls the size and geometry of induced fracture formation. Fracturing fluid loss coefficient for Water and Oil base systems ranges from 0.001 to 0.003 ft/min1/2 as reported by Lewis and Michael (2001). For this study, a fluid loss coefficient of 0.001823 ft/min1/2 was used in line with industry standard for this kind of operation. The results from the analysis at different fracture heights of 100ft, 80ft and 60ft are plotted as shown figures 5 to 12.

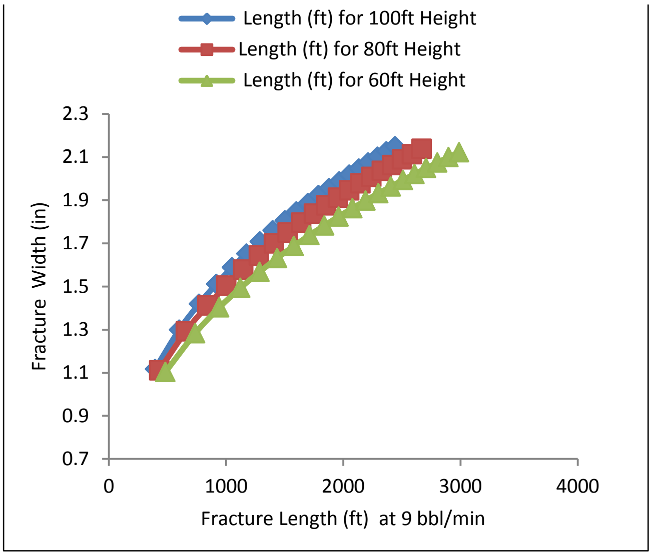

Figure 5. Fracture width and length at 9 bbl/min

Figure 5 shows the simulation result of the fracture width and fracture length at 9 barrels per minutes. The plot shows that at 60ft fracture height, higher fracture length is achieved compare to the 80ft and 100ft fracture height.

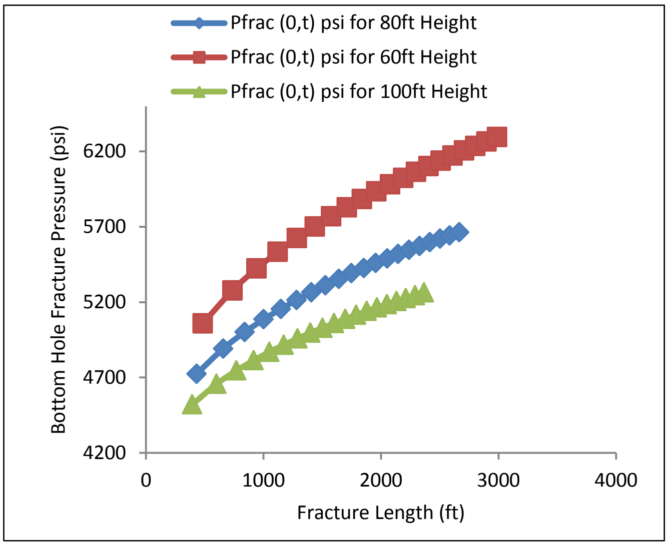

Figure 6. Fracture pressure and length at 9 bbl/min

Figure 6 is the plot of fracture pressure and fracture length at 9 barrels per minute. The plot shows that higher fracture length is achieved when lower fracture pressure is imposed on the formation. From the plot, 60ft fracture height requires more pressure to break the formation compared to that for the 80ft and 100ft height.

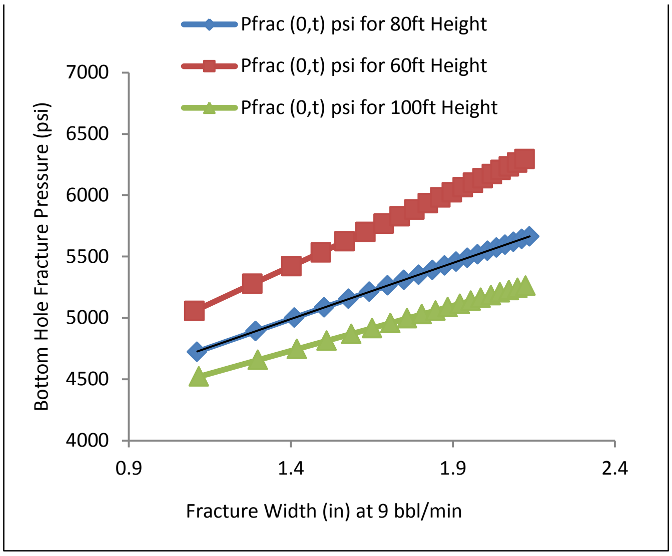

Figure 7. Fracture pressure and width at 9 bbl/min

For figure 7, the plot of the different fracture width was plotted against fracture pressure to show the variations in fracture width. The result shows no significant difference in the simulated fracture width for the fracture width of 60ft, 80ft and 100ft fracture height. This implies that any of the fracture height of 100ft, 80ft and 60ft could be appropriate depending on the pump capacity and thickness of the zone to be fractured.

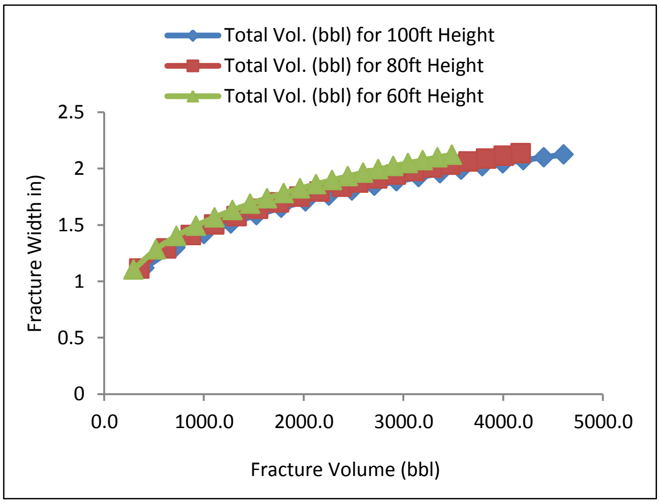

Figure 8. Fracture width and volume at 9 bbl/min

Figure 8, shows the plot of fractured width and volume. Greater volume of liquid would be pumped into the subsurface if the fracture height of 100ft is considered compared to the 80ft and 60ft fracture height.

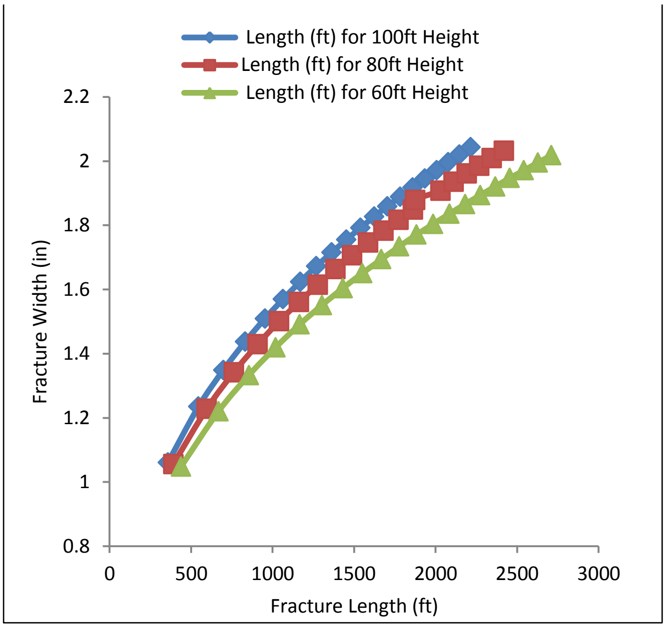

Figure 9. Fracture width and length at 8 bbl/min

Also, figure 9 shows the result of the fracture width and fracture length at 8 barrels per minutes. The plot shows that at 60ft fracture height, higher fracture length is achieved compare to fracture height at 80ft and 100ft fracture height.

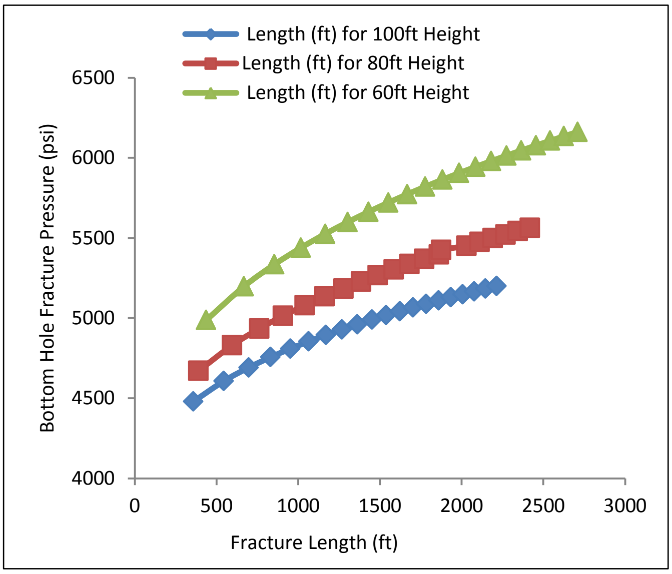

Figure 10. Fracture pressure and Length at 8 bbl/min

Figure 10 shows the plot of fracture pressure and fracture length at 8 barrels per minute. The plot indicates that higher fracture length is achieved with higher pressure imposed at 60ft fracture height compared to fracture height of 80ft and 100ft.

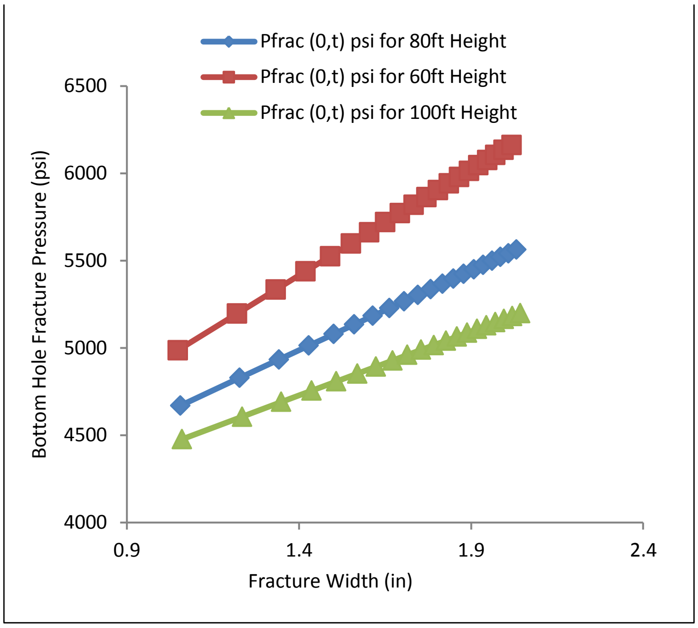

Figure 11. Fracture pressure and width at 8 bbl/min

Figure 11 shows the plot of fracture width against the imposed fracture pressure. The result also shows no significant difference in fracture width for 100ft, 80ft and 60ft height. This implies that any of the fracture height of 100ft, 80ft and 60ft could be appropriate depending on the pump capacity and thickness of the zone to be fractured.

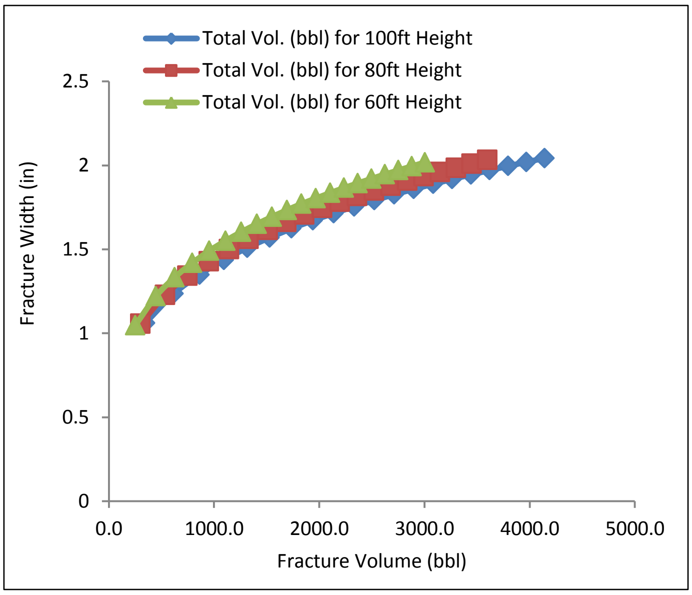

Figure 12. Fracture width and volume at 8 bbl/min

Figure 12, shows the relationship of the fractured width and volume. Greater volume of liquid would be pumped into the subsurface if fracture height of 100ft is considered compared to the 80ft and 60ft fracture height.

VI. HYDRAULIC FRACTURE ORIENTATION

The orientation and propagation of hydraulic fractures are controlled by the in situ stresses. They are also dependent on well depth and geologic conditions. Hydraulic fractures are tensile fractures which open in the direction of the least resistance stress (Nolen-Hoeksema, 2013). If the maximum principal compressive stress is the overburden stress which is the situation in this case, then the fractures are vertical, propagating parallel to the maximum horizontal stress when the fracturing pressure exceeds the minimum horizontal stress (Nolen-Hoeksema, 2013).

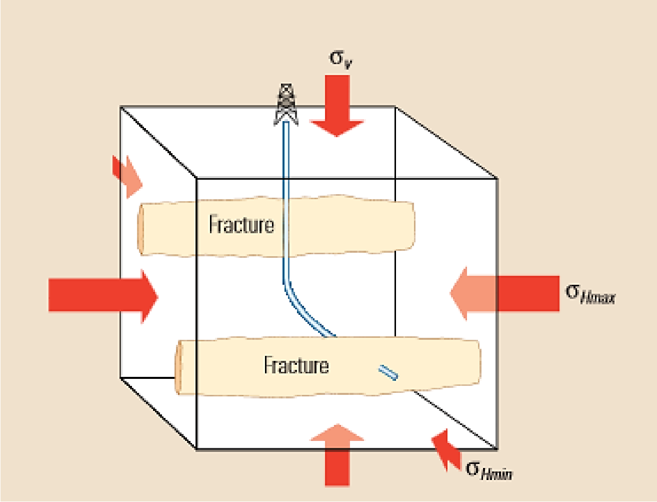

Figure 13. In-situ stresses and fracture orientation (Nolen-Hoeksema, 2013)

Because hydraulic stimulation fractures open normal to the least principal stress, most fractures are vertical and propagate in the direction of the maximum horizontal in-situ stress (Nolen-Hoeksema, 2013). This area is a normal faulting environment typical of the Niger Delta. For the Niger Delta region (which is Normally Faulted), the maximum principal compressive stress is the overburden stress, and this implies that the fractures are vertical, propagating parallel to the maximum horizontal stress when the fracturing pressure exceeds the minimum horizontal stress. Figure 18 (b) depicts the case scenario of the fracture orientation in Niger-Delta where the overburden stress is the maximum principal compressive stress.

VII. CONCLUSIONS

The fracture geometry and orientation was determined using the designed fracture template. Based on the analysis and result from the simulation using the PKN fracture model, the following conclusion was reached:

1. The model was used to generate the fracture geometry for produced water disposal in the subsurface formation
2. The fracture width, length and volume was determined with respect to time at pump rate of 9 and 8 barrels per minute
3. The fractures are vertical in the direction of the maximum horizontal stress
4. Fractures are vertically oriented and perpendicular to the maximum stress.

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