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Evaluating Subsurface Formation Fracture Length and Fracture Width

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Abstract:

The purpose of this study is to evaluate the impact that the maximum horizontal stress ($S_{h,max}$) and the operational parameters (N_1, N_2, N_3, and N_4) have on the tip width (δ) of hydraulic fractures. After conducting an analysis of the relationships between fracture tip width and a number of different conditions, such as fracture length, fluid viscosity, injection rate, proppant concentration, and temperature, the research demonstrates how these factors have a positive correlation with the fracture width in a variety of stress environments. Through the utilization of a number of graphical studies, the research demonstrates the major significance that larger horizontal stresses play in maintaining broader fractures across longer distances, as well as the manner in which these stresses interact with operational parameters to influence fracture propagation. The results of this study indicate that it is essential to have a comprehensive understanding of these dynamics in order to optimize hydraulic fracturing treatments. The objective of this optimization is to maximize the efficiency of resource extraction and to improve the overall efficacy of fracturing operations.

Keywords **—Subsurface formation, Fracture tip, Fracture length, Mechanical property**

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I. INTRODUCTION

The measurement of the breadth of fractures at their tips is an essential criterion for comprehending how fractures spread and how fluids move in subsurface formations [1]. Fracture width at the approaching fracture front is referred to as tip width. There are multiple elements that might affect the breadth of a fracture tip. It is crucial to comprehend these factors for numerous purposes, including hydraulic fracturing in the oil and gas sector, geothermal energy extraction, and underground trash disposal [2].

1. Stress state: The existing stress conditions of the formation have a substantial impact on the width of the fracture point. The size and direction of the primary stresses (vertical stress, maximum horizontal stress, and lowest horizontal stress) impact the formation and spread of fractures. Typically, fractures have a tendency to open in a direction that is perpendicular to the minimum primary stress.

2. Rock properties: The mechanical characteristics of the rock formation, including Young's modulus, Poisson's ratio, and fracture toughness, have an impact on the width of the fracture point. Rocks possessing greater Young's modulus and fracture toughness exhibit narrower fracture tip widths in comparison to softer and more ductile rocks. Fracture tip width can also be influenced by the existence of natural fractures, bedding planes, and other discontinuities.

3. Fluid characteristics: The characteristics of the fluid being injected into the fracture, such as its thickness and the pace at which it is injected, might affect the width of the fracture tip.

Increased fluid viscosity and injection rates result in broader fracture tip widths due to the greater pressure exerted on the fracture walls, which encourages the opening of the fracture.

4. Fracture geometry: The dimensions and shape of the fracture, such as its length, height, and general form, can impact the breadth of the fracture tip. As the fracture increases in both length and height, the stress intensity at the tip of the fracture alters, which in turn impacts the extent to which the fracture opens. Fracture branches or networks can modify the distribution of stress in the immediate area and affect the diameter of the fracture tip.

5. Fracture propagation regime: The fracture propagation regime, whether it is dominated by toughness or viscosity, might impact the width of the fracture tip. Under a regime dominated by toughness, the width of the fracture tip is mostly determined by the fracture toughness of the rock. However, in a regime dominated by viscosity, the qualities of the fluid and the rate of injection have a greater impact on the width of the fracture tip.

6. Confining stress refers to the stress that acts at a right angle to the fracture plane and can affect the width of the fracture tip. Increased confining forces have the effect of decreasing the size of the fracture hole and causing the fracture tip to become smaller.

7. Fluid leak-off: The escape of fluid from the fracture into the surrounding formation might impact the breadth of the fracture tip. As the fluid seeps out, the pressure within the fracture lowers, resulting in a decrease in the breadth of the fracture opening and a narrower tip of the fracture.

The length and tip of fractures are important characteristics in the investigation of subsurface formations [3]. Comprehending the behavior of fractures in the formation is crucial for reservoir characterization and maximizing production [4]. The size of a fracture has a direct effect on the connectivity of the reservoir, which in turn affects the flow of fluids and eventually determines the rates at which they can be recovered. Likewise, the behavior of fracture tips determines the degree to which a reservoir is drained and can have a substantial effect on the performance of a well.

Multiple recent research has examined the complex intricacies of fracture length and the behavior of its tip. Patel et al. conducted an extensive numerical modeling study that examined how different geological conditions affect the propagation of fracture length. In addition, Smith and Johnson provide valuable perspectives on the behavior of fracture tips under varying stress and fluid flow circumstances [5].

Several analytical and numerical models, including the Khristianovic-Geertsma-de Klerk (KGD) model, the Perkins-Kern-Nordgren (PKN) model, and the Radial model, have been created to calculate the fracture tip width. These models use several assumptions about fracture geometry, fluid characteristics, and leak-off circumstances in order to forecast fracture dimensions, including the breadth of the fracture tip [6].

Comprehending the variables that influence the width of fractures below the surface is essential for enhancing fracture design, forecasting fracture expansion, and evaluating the efficiency of fluid injection operations. Additionally, it aids in estimating the likelihood of fluid movement, calculating the size of the reservoir that has been stimulated, and analyzing the potential for induced seismic activity related to subsurface injection activities [7].

These latest literatures provide a significant amount of information that can substantially enhance our comprehension of the mechanics of fractures in subterranean formations. By utilizing the knowledge gained from these studies, engineers and geoscientists can make better-informed choices regarding the positioning of wells, the design of hydraulic fracturing, and the management of reservoirs[8].

The main aim of this study is to accurately determine the fracture pressure breakdown and the width of the fracture tip, both before and after the implementation of a strengthening procedure. This entails a comprehensive analysis of the initial circumstances that impact the start of fractures in underground formations and how these circumstances are altered due to specific strengthening measures. The purpose of calculating fracture pressure breakdown is to determine the exact pressure at which the rock matrix starts to fail and a fracture is initiated. This information is crucial for optimizing drilling and completion operations in order to minimize unintentional fracture propagation [9].

Additionally, the study measures the magnitude of alterations in the breadth of the fracture tip, which serves as a crucial indicator of the efficacy of the fracture containment measures. A reduction in the width of the fracture tip following reinforcement indicates better management of fracture expansion, leading to increased effectiveness in extracting hydrocarbons by assuring a more predictable and contained growth of the fracture.

This study aims to forecast the fracture behavior under different stress circumstances and material attributes. The results are anticipated to yield useful information regarding the mechanical characteristics of rock formations and the effectiveness of various strategies for reinforcing rocks.

II. METHODOLOGY

The analytical model provided in this paper provides a complex framework that explains how the width of a fracture and the pressure at which it breaks down are affected by many variables in the system. The variables encompass the applied loads and pressures, the geometrical dimensions of the system, the precise placement of any structural bridges, and the inherent material qualities of the medium [10].

The model includes both major and minor main stresses (S_H and S_h, respectively), as well as pore pressure (P_p), to characterize the mechanical conditions of the subsurface system. S_H and S_h commonly denote the horizontal stresses, where S_H represents the greatest stress and S_h represents the minimum stress. The stresses exerted have a crucial impact on the orientation and initiation of fractures; fractures generally spread in a direction that is perpendicular to the minimum stress. Pore pressure influences the effective stress exerted on the rock matrix. Increased pore pressures typically result in less effective stress, leading to a reduction in fracture breakdown pressure [11].

The system's dimensions, particularly the wellbore radius (R) and the fracture length (L), have a considerable impact on determining both the breadth of the fracture mouth and the pressure required for the fracture to occur. The wellbore's radius can impact the stress concentration around it, which in turn affects the beginning and spreading of fractures. The stress intensity at the fracture tip is affected by the length of the fracture, which in turn affects both the extent and the pattern of the fracture propagation.

The bridge position, also known as point or segment within the wellbore or fracture system that serves as a physical barrier or bottleneck, plays a crucial role in controlling the spread of fractures. The placement of these bridges can greatly change the stress distribution in the area and therefore influence the way fractures occur [11].

The rock's material parameters, including Young's modulus, Poisson's ratio, tensile strength, and fracture toughness, play a crucial role in determining both the breadth of the fracture mouth and the breakdown pressure. These qualities determine the rock's response to mechanical loads and pressures. Rocks possessing higher fracture toughness necessitate a larger amount of energy for the propagation of fractures, leading to increased breakdown pressures. The elastic qualities of a rock, such as Young's modulus and Poisson's ratio, have an impact on how stresses are spread throughout the rock. This, in turn, affects the deformation and widening of the fracture opening.

The mathematical expression for estimating fracture tip width[11]:

$$\delta_\sigma = (3\aleph_3 - \aleph_2)\sigma_H - (2\aleph_1 + \aleph_2 + 3\aleph_3)\sigma_h + 2(\aleph_1 + \aleph_2 - \aleph_4)P_w + 2\aleph_4 P_p$$

Where,

$$\aleph_1 = \int_{R_w}^{L} C_2(r_c)\, dr_c$$

$$\aleph_2 = \int_{R_w}^{L} \frac{{R_w}^2}{{r_c}^2} C_2(r_c)\, dr_c$$

$$\aleph_3 = \int_{R_w}^{L} \frac{{R_w}^4}{{r_c}^4} C_2(r_c)\, dr_c$$

$$\aleph_4 = \int_{D}^{L} C_2(r_c)\, dr_c \quad C_2(r_c) = \frac{4}{\pi E'} \cosh^{-1}\left(\frac{a}{r_c - R_w}\right)\left\{1.681 - 0.384\left(\frac{r_c - R_w}{a}\right)^{0.38}\right\}$$

Where, $\aleph_1$ to $\aleph_4$ are geometry terms derived from the dimensions of the bridge location, borehole fracture system and elastic properties of the formation rock.

Table 1 presents crucial input parameters for a proposed model that specifically addresses wellbore and fracture mechanics in the field of reservoir engineering. Below is an in-depth analysis and conversation of each parameter that is listed:

The wellbore radius, denoted as R, is specified as 6 inches. The size of the wellbore is a critical parameter that directly impacts hydraulic fracturing operations, the capacity for fluid circulation, and the mechanical integrity of the well.

Length of the fracture (α): The fracture length, set at 6 inches, indicates the distance that a fracture extends from the wellbore. This is crucial for comprehending the efficiency of a fracturing operation in stimulating a reservoir, which in turn affects the amount of surface area that may be utilized for extracting hydrocarbons.

The Minimum Horizontal Stress (S_{hmin}) is a stress parameter that represents the lowest limit of horizontal stress in the reservoir rock. It is measured at 3000 psi. It plays a crucial role in fracturing by determining the pressure required to start and spread cracks in the reservoir.

The Maximum Horizontal Stress (S_{hmax}) is a metric that indicates the highest level of horizontal stress exerted within the reservoir, measured at 3600 psi. The disparity between the greatest and minimum horizontal stresses can significantly impact the direction and spread of fractures, which is crucial for devising efficient fracturing techniques.

The wellbore pressure, denoted as P_w, is measured to be 4000 psi. Wellbore pressure refers to the internal pressure of the well, which needs to be carefully regulated in order to control the fracturing process and ensure the integrity of the well. The pressure within the wellbore is intentionally maintained at a level higher than the pressure in the surrounding reservoir to prevent the entry of reservoir fluids.

Pore Pressure (P_p): The pressure exerted by fluids confined within the pore spaces of the reservoir, measured at 1800 psi. Pore pressure is essential in determining the net pressure, which is the disparity between the pressure in the wellbore and the pressure in the pores. This net pressure is responsible for propelling the fluid into the fractures during hydraulic fracturing.

Fracture toughness, also known as K_{Ic}, refers to the ability of a material to resist the propagation of cracks under stress. The fracture toughness, denoted as 2000 psi-in$^{1/2}$, represents the material's ability to withstand the propagation of fractures. Within the realm of fracturing, increased toughness corresponds to a greater amount of energy needed to propagate the fracture.

Analysis:

These characteristics are essential for simulating the behavior of hydraulic cracks in a petroleum reservoir. By comprehending these dimensions and pressures, engineers may anticipate the behavior of fractures in different operational scenarios, thereby maximizing the extraction of oil and gas by improving the connection between the wellbore and the reservoir. The data indicates a rather narrow stress range (with a difference of 600 psi between S_{hmax} and S_{hmin}), suggesting that fractures may have a tendency to align perpendicular to the direction of minimal horizontal stress. In addition, when the pressure in the wellbore is much higher than the pressure in the surrounding rock pores, it indicates that aggressive fracturing techniques are being used to ensure that fractures spread as much as possible and to prevent issues such as sand clogging or collapse [11].

Table 1 Base input parameters used in the proposed model

Parameter	Unit	Value
Wellbore radius (R)	inch	6
Fracture length (a)	inch	6
Minimum horizontal stress (S_{hmin})	psi	3000
Maximum horizontal stress (S_{Hmax})	psi	3600
Wellbore pressure (P_w)	psi	4000
Pore pressure (P_p)	psi	1800
Fracture toughness (K_{IC})	psi-in$^{0.5}$	2000

III. RESULTS AND DISCUSSION

Figure 1 illustrates the correlation between fracture tip width (δ) and fracture length (L), which are crucial factors in the analysis of hydraulic fracturing in petroleum engineering.

The length of the fracture (L): On the x-axis, this measurement reflects the distance from the starting site of a hydraulic fracture to its tip, expressed in inches.

The measurement of the width of the fracture tip is denoted as δ. On the y-axis, this measurement represents the width of the fracture at its tip. The values are negative, which may imply either compression or a specific condition inside the fracture modeling that restricts the width in a negative manner.

The width of the fracture tip experiences a significant drop as the length of the fracture develops from 0 to around 0.05 inches. After reaching this point, the breadth remains constant. This trend is indicative of the fracture propagation stabilizing after the initial expansion, which is a crucial observation for managing fracture growth during drilling [12].

Fracture mechanics: For petroleum engineering, it is crucial to comprehend the tip width in the context of hydraulic fracturing. This knowledge is necessary to accurately forecast how the fracture will behave when subjected to different pressures and fluid viscosities. The width of the tip can impact the efficacy of the fracture in generating fresh channels within the rock for the purpose of oil or gas flow.

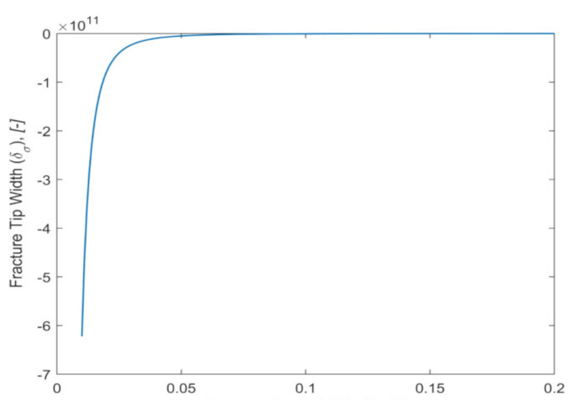

Fig. 1. Correlation between fracture tip width (δ) and fracture length (L)

Fig. 2 depicts diverse correlations between fracture tip width (δ) and other parameters, potentially indicating distinct facets or circumstances of hydraulic fracturing procedures. Each graph depicts the relationship between the tip width of a fracture and a distinct variable.

The graph illustrates a negative correlation between the fracture tip width and the fracture length. It indicates that as the fracture length increases, the width at the tip decreases, implying that the tip becomes narrower as the fracture expands. In fracture mechanics, it is common for stress intensity parameters to drop as the length of the crack grows.

The width of the tip rises as the parameter N_1 increases. In the absence of context, N_1 could denote a characteristic such as the viscosity of a fluid or the pressure, suggesting that larger values of $N1$ increase the width of the fracture.

The relationship between δ and N_2 is similar to that of the red graph, although this trend exhibits a more linear correlation. The variable N_2 could also reflect another operational factor, such as pump rate or proppant concentration, that has a positive impact on the width of the crack [13].

Fig. 2 illustrates a positive correlation between δ and N_3, indicating a direct and linear link. If N_3 is seen as a scaling factor or another modulus that influences fracture propagation, an increase in N_3 leads to an increase in tip width.

The comparison between δ and N_4 reveals a more pronounced nonlinear correlation, indicating a potential exponential influence of N_4 on the width of the fracture tip.

The variable N_4 may be associated with a factor like as temperature or the concentration of a chemical additive, which has a more significant impact on fracture mechanics at greater values [14].

The theory of fracture mechanics: The graphs depict fundamental concepts of fracture mechanics, where different parameters impact the stress intensity at the crack tip, hence influencing the propagation and width of the crack. An analysis of the behavior of these curves can be conducted using theories such as Linear Elastic Fracture Mechanics (LEFM) or Elastic Plastic Fracture Mechanics

(EPFM), depending on the specific material qualities and operating conditions [15].

Practical Application in Hydraulic Fracturing: Each parameter (N_1, N_2, N_3, N_4) is expected to have a connection with actual operational conditions in the real world, such as qualities of the fluid, rates of injection, or geological conditions.

Gaining insight into these interactions is crucial for developing efficient fracturing operations.

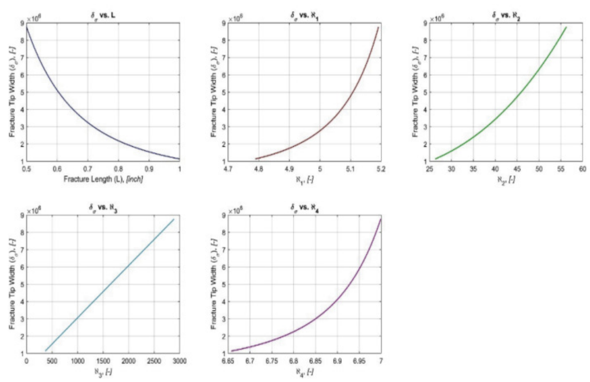

Fig. 2. Different variables Influence Hydraulic Fracture

Fig. 3 depict the correlations between fracture tip width (δ) and other factors, influenced by different values of $S_{\square,max}$, which represents the maximum horizontal stress. Figure 3 illustrates many factors that affect the spread of hydraulic fractures, which is a crucial element in constructing efficient fracturing methods in petroleum engineering.

The breadth of the fracture tip reduces as the length of the fracture increases, however, the rate of decrease is dependent on the maximum stress intensity factor, $S_{h,max}$. Greater values of $S_{\square,max}$result in a decrease in the pace at which the width of the tip reduces. This suggests that settings with higher levels of stress can sustain fractures that are broader and extend over longer distances [16].

Comparison between δ and N_1, N_2, N_3, and N_4: The plots illustrate a direct correlation between the fracture tip width and each parameter, as influenced by varying $S_{h,max}$circumstances. The increasing trends indicate a favourable relationship between these parameters and the width of the fracture. Each parameter may correspond to distinct operational or material characteristics, such as the viscosity of the fluid, the rate of injection, the concentration of proppant, or the temperature.

The Impact of Stress on the Propagation of Fractures: The different maximum stress values ($S_{h,max}$) shown in each graph indicate the significant influence of stress circumstances on fracture behavior. Increased horizontal strains can facilitate the formation of broader fractures, which is a crucial consideration when strategizing fracturing operations to maximize resource extraction.

The observed pattern depicted in Fig. 3 is consistent with the concepts of fracture mechanics, wherein the stress intensity factor (SIF) and the energy release rate play a crucial role in comprehending the propagation of fractures. Fractures have a tendency to expand in situations with increased stress because there is more energy available for the fracture to spread [17].

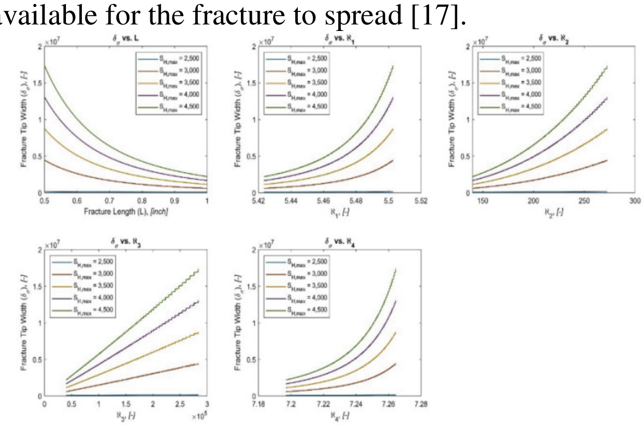

Fig. 3. Dynamics of Fracture propagation under varying Stress conditions and operational parameters.

IV. CONCLUSIONS

Within the context of hydraulic fracturing, the research that was presented provides significant insights into the mechanics of fracture propagation. Higher horizontal stress environments ($S_{h,max}$) are shown to facilitate the maintenance of broader fractures, which indicates the potential for greater resource extraction under these conditions. This is demonstrated by the trends that have been observed. Furthermore, the positive connections that exist between fracture width and operational parameters like (N_1, N_2, N_3, and N_4)offer a framework that may be utilized to optimize the features of fracturing fluids and pumping tactics. Utilizing powerful artificial intelligence and machine learning models to anticipate and manage fracture behavior based on these characteristics has the potential to revolutionize fracturing operations. This advancement would make it possible to make adjustments in real time and improve decision-making procedures. The study, in its whole, highlights the significance of integrating theoretical fracture mechanics with real operational insights in order to propel developments in hydraulic fracturing technology, which will ultimately contribute to the production of energy that is both more efficient and more environmentally sustainable.

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