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Modelling and Analysis of Mini-Fracture Tests in Hydraulic Fracturing

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Abstract

In hydraulic fracturing technology, Mini-Fracture Tests (MFTs) which are also known as Diagnostic Fracture Injection Tests (DFITs) have been utilized as an efficient technique to ascertain matrix permeability and closure pressure in petroleum reservoirs. An initial fracture, in Mini-Fracture Tests, is formed by injection of fluid until formation breaks down and the fracture propagates a small remoteness into the reservoir. After shut-in of the injection, the pressure decline is recorded. From the falloff data, the effective permeability of the formation can be estimated by Nolte's G-function, log-log plot, or square root of time analysis.

In this paper, case studies are considered by consistently applying analysis method from the G-function, its derivatives, and its relationship to other diagnostic techniques including square-root(time) and $\log(p_{wf}) - \log(t)$ plots and their appropriate diagnostic derivatives. By analyzing the obtaining results, the commonly applied G-function method yielded approximations of permeability over an order of magnitude higher than the simulated matrix permeability. Errors of permeability which are taken from the G-function and Square Root Time are higher than actual matrix permeability taken from After Closure Analysis.

Keywords: Mini-Fracture Tests (MFTs), Diagnostic Fracture Injection Tests (DFITs), Fracture, G-function, Log-log, MFrac.

I. INTRODUCTION

Over the last 20 years, petroleum productivity index represented from the unconventional reservoirs has been growing significantly owing to the approach of hydraulic fracturing (Barree et al. 2014) [1]. In hydraulic fracturing, a fluid, usually including some proppants and chemicals, is injected into the low-permeability formation at high pressure to create fracture networks. The injection pressure must exceed the minimum horizontal stress in the rock to initiate and form a fracture network. Indeed, the combined function of the effectiveness of the fracture network and the matrix permeability is presenting production from the reservoir. Consequently, it is vital to record the matrix permeability and minimum horizontal stress, for the evaluation of the production potential of an unconventional formation.

Although from pressure-transient tests, the matrix permeabilities can be attained, this method is not executable in unconventional reservoirs prior to fracturing reservoirs because there is not enough production unless the formation is fracture stimulated. Mini-frac tests have been used to estimate both the minimum horizontal stress and matrix permeability. A mini-frac is created, during the test, by injecting a high-pressure fluid. After stopping injection, pressure decay is supervised to estimate the closure pressure and the matrix permeability. To estimate those parameters from a Mini-Fracture Test, several methods have been proposed. These methods are the G Nolte time, Square Nolte time analysis, the log-log plot and After Closure Analysis (Barree et al. 2014, 2009) [1, 2].

In this study, by using MFrac Suite 12 - a professional software from Baker Hughes (a GE company), we calculate the Initial Shut-in Pressure (ISIP), Closure Pressure and Matrix permeability and make a comparison in three methods, especially for matrix permeability (Meyer & Associates, 2011) [3].

II. THEORETICAL BASIC OF MINI-FRAC TESTS

II.I. Acquisition Procedure for Mini-Frac Tests

Firstly, the fracturing fluid is pumped at low to moderate rate into the wellbore until the surface pressure is obtained. As seen in **Figure 1** (Barree et al. 2015) [1], pressure rises until the first breakdown is observed, where we call this a Break down test (Stage 1 in **Figure 1**). The break down test was performed at

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the same day with MFTs. Before the treatment there was 0 psi on the wellhead and the tubing was full with Sea water. Starting with step up rate test 1, 2, 3, 4, 5 bpm …up to 18.2 bpm by pumping treated water (Meyer & Associates, 2011) [3]. When a new fracture appears, pressure shows a fast decrease while it shows a plateau in case of dilation of existing fractures in the formation. When the breakdown is discovered, the injection rate is ramped up to the largest rate for the current horsepower. The maximum rate is then remained constant for 3 to 5 minutes (Stage 2 in **Figure 1**), which is regularly followed by a step-down rate (Stage 3 in **Figure 1**) to calculate pressure losses owing to perforations and tortuosity. After that, the rate is instantly decreased to zero, where the instantaneous shut-in pressure (ISIP) (Stage 4 in **Figure 1**) is calculated. Lastly, the decline pressure (fall-off period) (Stage 5 in **Figure 1**) is monitored to calculate the matrix permeability. The step-down is advised to make identification of ISIP easier.

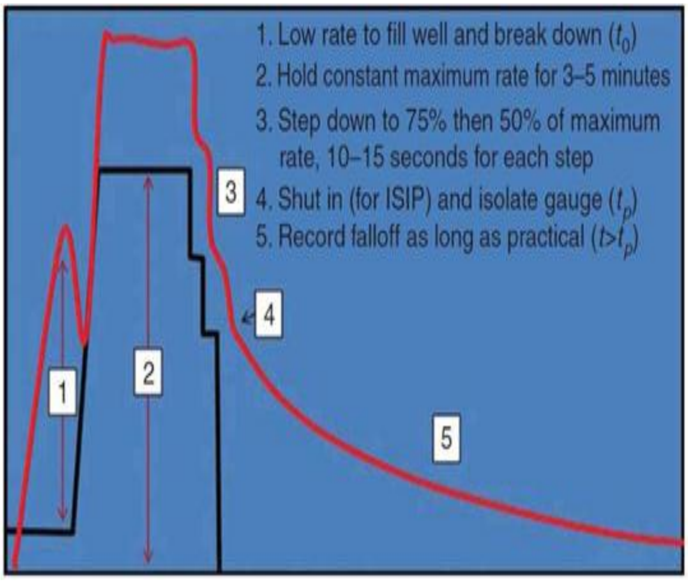

Figure 1. A common DFITs Procedure. Rate and surface pressure are marked by black and red, respectively (Barree et al., 2014) [1].

II.II. Background of Analysis Methods

In this paper, the three analysis methods for Mini-fracture Tests are mentioned, including Nolte G-function, Square-root of time analysis and After Closure Analysis.

The G-function, which was proposed by Nolte (1797, 1986, and 1988) [4-6], is a dimensionless function that is typically used in the Mini-Frac Tests data analysis. In G Nolte time analysis, pressure, derivative $\left(\frac{dP}{dG}\right)$and semi-log derivative $G \times \left(\frac{dP}{dG}\right)$ of pressure with respect to the G-function are sketched versus G-time **(Figure 2)**.

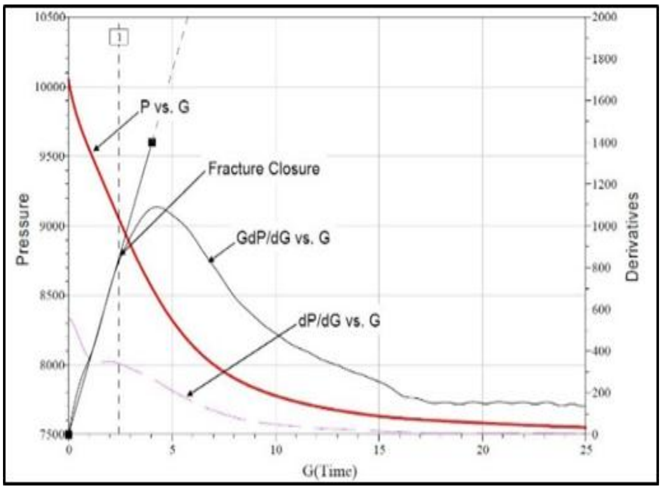

Figure 2. A common G-Function Plot (Barree et al. 2007) [2].

The matrix permeability may be directly estimated from G Nolte time analysis using the following equation (Barree et al. 2007) [2]:

$$k_m = 0.0086\mu \frac{\sqrt{0.01 * (p_{ISIP} - p_c)}}{\emptyset c_t \left(\frac{G_c E r_p}{0.038}\right)^{1.96}} \tag{1}$$

Square Nolte time is likewise utilized to analyze Mini-Fracture Test data. **Fig. 3** shows an instance of a √t plot where, pressure, its derivative $\left(\frac{dP}{d\sqrt{t}}\right)$ and semi-log derivative $\sqrt{t} \times \left(\frac{dP}{d\sqrt{t}}\right)$ with respect to square root of time are observed.

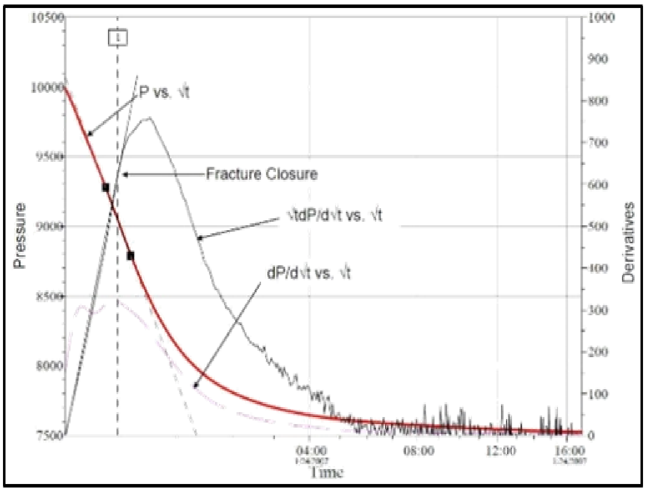

Figure 3. An example of Sqrt(t) Plot (Barree et al. 2007) [2].

The consistent issues of an After-Closure Analysis is to define the formation permeability and reservoir pressure from the pressure response of a fractured (or unfractured) well during the infinite-acting time period. In this method, Gu et al. (1993) [7] suggests permeability is estimated from the slope, m_H, of a straight trend on the graph of p versus $\frac{t_c}{t}$:

$$k_m = 0.0086 \frac{\mu \left(\frac{V_i}{t_c}\right)}{4\pi k m_H} \tag{2}$$

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The interpretation of matrix permeability from each above method has its own advantages and backwards depending on formation conditions. Therefore, we mostly focus on how to compute the matrix permeability by the package MFrac. Then a comparison of these methods above and a recommendation on the most appropriate results are presented.

III. CASE STUDY

The Case Study was taken at depth 1796-1810 m from data at Mexico of Baker Hughes, a GE Company. The Mini-Fracture Test Data is shown in the **Figure 4**:

Property	Value	Unit
Young's Modulus	2e+06	psi
Fracture Toughness	1400	psi-in^½
Poisson's Ratio	0.22	
Total Leakoff Height	33	ft
Total Fracture Height	33	ft
Ellipsoidal Aspect Ratio	4	
Flow Behavior Index - n'	1	
Consistency Index - K'	0.01	lbf-s^n'/ft²
Spurt Loss Coefficient	0	gal/ft²
Total Vertical Depth	5915.35	ft
Wellbore Fluid Specific Gravity	1	
Flowback Time (after ISIP)	0	min
Flowback Rate	0	bpm

Figure 4. The Input Data of Case Study.

IV. RESULTS AND DISCUSSION

For the Regression analysis two ranges must be selected. A range from the initiation to end of pumping (Pump Time) and a range from the end of pumping to the end of the pressure decline data (beyond closure) must be specified, as seen in **Figure 5**, which illustrated for the Horner Plot.

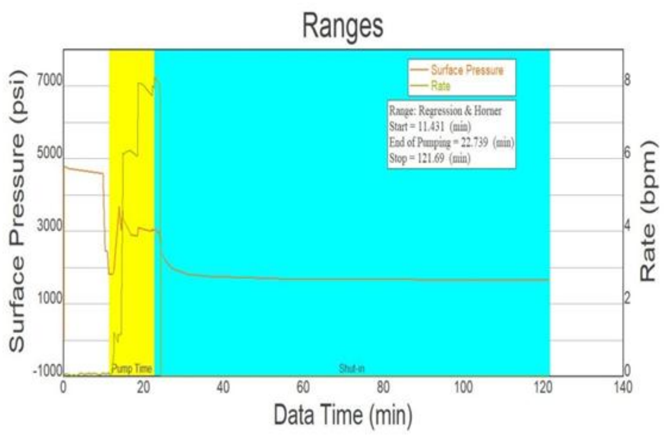

Figure 5. Acquisition Procedure of Mini-Frac Test from Case Study.

Overall, the Regression analysis for both G Nolte time and Square Nolte time has been defined in **Figure 6** and **Figure 7** respectively, which yield the Initial Shut-in Pressure (ISIP), Closure Pressure and Closure Time.

As shown in these figures, the ISIP from G Nolte time and Square Nolte time analysis is approximately 3130 psi and 3484 psi, respectively. In both these methods, ISIP is determined by the interception between the line with slope 1 and the vertical axis on these figures.

Moreover, the closure pressure and closure time are obtained from the closure point, which is the interception of the lines with slope 1 and slope 2. The closure pressure and closure time will be 1786.3 psi and 16.116 min from G Nolte time analysis **(Figure 6)** while they are 1791.4 psi and 16.710 min from Square Nolte time analysis **(Figure 7)**. As the results, the error value of closure pressure between two methods may be acceptable, just around 3%. However, the closure time Δt_c from Square Nolte time analysis method from these above figures is always higher than that of G Nolte time.

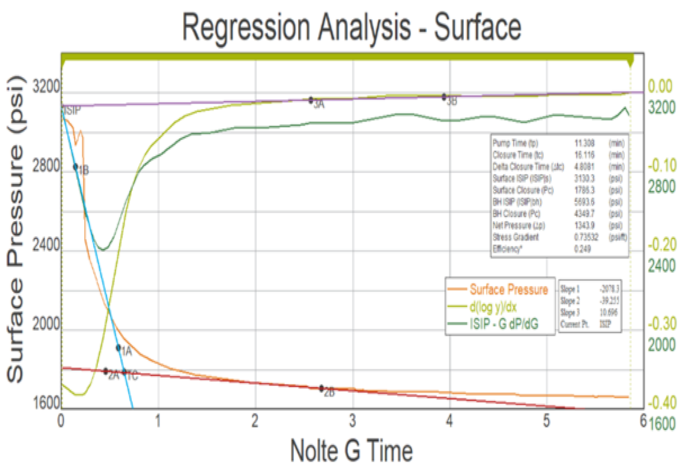

Figure 6. Regression – Nolte G Time Analysis.

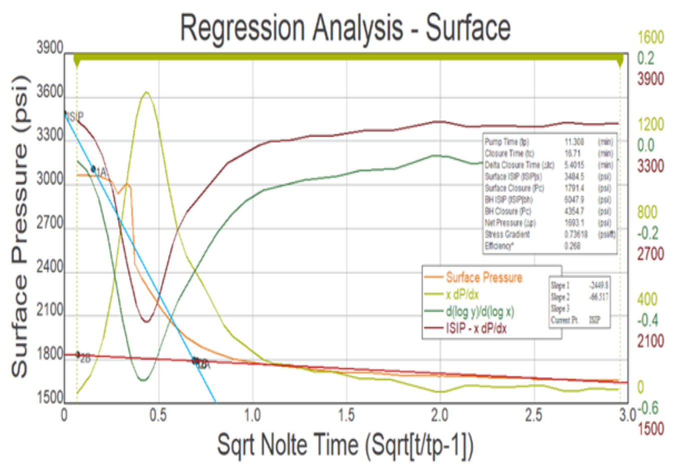

Figure 7. Regression – Square Nolte Time Analysis.

Figure 8 shows a Nolte After Closure plot in linear coordinates while **Figure 9** shows the corresponding Delta Surface

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Pressure plot in log coordinates with the $x \times \left(\frac{dP}{dx}\right)$ derivative. Overall, both figures show that there was a threefold increase in the value of pressure from the surface (1640 psi) to the bottom hole (4203 psi). However, the results taken from Log-log plot illustrating smaller errors in terms of matrix permeability measurement.

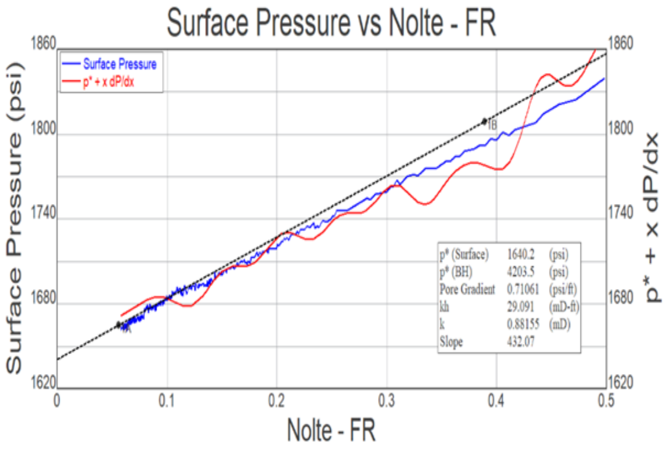

Figure 8. After Closure Analysis - Surface Pressure vs. Nolte - FR Linear Plot.

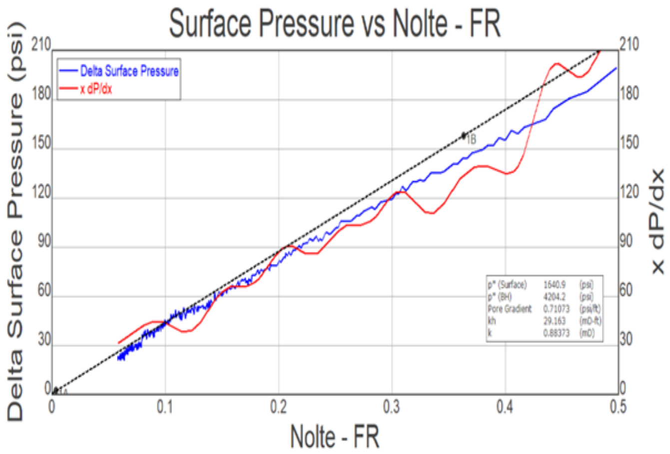

Figure 9. After Closure Analysis - Delta Surface Pressure vs. Nolte - FR Log-Log Plot with $x \times \left(\frac{dP}{dx}\right)$ derivative.

Moreover, matrix permeability calculated by three mentioned methods from MFrac are also shown in **Table 1**. It is noted that both Nolte G Time and Square Nolte Time are built in three separating models as PKN, GKD and Ellipsoidal. Meanwhile, After Closure Analysis examinations do not require these mentioned models.

As shown in **Table 1**, the matrix permeability calculated by After Closure Analysis method is the most accurate value. Moreover, the Nolte G time and Square Nolte time permeability calculated is much higher than the actual matrix permeability (from Actual Analysis Method). However, the permeability taken from GKD model from both mentioned methods can be considered because they are quite closed the actual value.

Table 1. Matrix Permeability calculated by different methods and models

	PKN	GKD	Ellipsoidal
Nolte G Time - ISIP (Log-Log) (TC = 26.6641 min, 1883.28 psi)	2.3809	0.70664	1.3688
Square Nolte Time - ISIP-P (Log-Log) (TC = 28.1407 min, 1791.43 psi)	1.9959	0.48154	1.1345
After Closure Analysis - Surface Nolte - FR, Pressure	0.88155		
After Closure Analysis - Surface Nolte - FR, Delta Pressure (Log-Log)	0.88105		

V. CONCLUSION

The determination for Initial Shut-In Pressure (ISIP), closure pressure and closure time from MFrac Suite 12 is rather reliable and useful in Mini-Fracture Tests for petroleum reservoirs.

By analyzing the obtained results, it is concluded that After Closure Analysis yields the most accuracy value of matrix permeability. The estimations on the matrix permeability from G Nolte time and Square Nolte Time examinations (except GKD model) are usually higher than the actual matrix permeability taken from After Closure Analysis.

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