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Analysis of the Production Data from Marcellus Shale Wells

Amanda Parrish

Thesis to the
College of Engineering and Mineral Resources
at West Virginia University

In partial fulfillment of the requirements
For the degree of

MASTER OF SCIENCE
In
Petroleum and Natural Gas Engineering

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2017

Keywords: Analysis, Production Data, Marcellus Shale Wells, Decline Curves

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ABSTRACT

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Amanda Parrish

The increasingly prevalent practice of unconventional technologies has called for the need for the critical analysis of production decline rates to meet economic targets. The high early time production returns and transient flow make matching a production curve to known methods of decline curve analysis problematic.

This research focuses on finding a technique that best fits a known production curve and then applying that technique to another well to check its accuracy. The goal is to find the earliest time of production data necessary to predict an accurate production curve over the lifespan of the well. This is essential to the industry as early prediction is crucial to cost analysis.

The data used in this research is from research wells 4H and 6H. First, the data is simulated using generic simulation software. The data is then exported to excel and analyzed. The data that has been analyzed comes from production data of the lifespan of the well with actual completion practices and then looked at for each fracture.

This research has determined that the hyperbolic decline curve best predicts future returns for production in the Marcellus shale. Testing the methods on the MIP-4H and then applying to the MIP-6H, it is clear that the approach was successful in matching. The research also shows that in order to predict using the hyperbolic decline curve 6 to 8 months of data gives the best fit.

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1. INTRODUCTION

Unconventional technology is relatively new in respect to the lifespan of the oil and gas industry; therefore, there are many constraints that should be considered. It is often nearly impossible to determine dominant influencing parameters of the completion design of unconventional wells because of the mass of variables that could influence production. The lack of long duration production history due to the novelty of the practice makes for efforts in validation to become difficult. Similarly, there is limited availability to field data. Taking these constraints into account, it is necessary to find means of production prediction of unconventional wells at an early time.

For decades, the oil and gas industry has relied on the empirical method of the Arp's decline curve analysis to model production trends for conventional wells. In recent years, unconventional resource plays have become increasingly prevalent – and along with them, the necessity of technology similar to the traditional Arp's method in order to predict production. The application of the traditional decline curve to unconventional reservoirs often yields an unlikely result because of very long periods of transient flow and the assumption that the reservoir and operational conditions remain unchanged throughout the life of the well. This is because the extremely low permeability and heterogeneity of the shale make it challenging to predict the fluid flow behavior, and in hydraulically fractured shale wells the reservoir and operational conditions are continuously undergoing changes. Therefore, analytical, semi-analytical, and numerical models have been implemented to meet the demand for modeling unconventional reservoirs.

This study compares decline curve analysis techniques to forecast the future production of two wells given early production data. The techniques that are compared include Arps Hyperbolic Decline, Power Law Exponential Decline (PLE), Stretched Exponential Decline (SEPD), and Duong Method.

2. LITERATURE REVIEW

Arp's hyperbolic decline (DCA), power law exponential decline (PLE), stretched exponential decline (SEPD), and the Duong method are based on a concept of a "loss-ratio" and "loss-ratio derivative". The "loss-ratio," created for boundary-dominated flow under constant constraints represents the slope of the flow rate versus time on a semi-log graph. The "loss-ratio derivative" is the derivative of the "loss-ratio." Used together they obtain a D-Parameter and a b-Parameter that represent the constant change in declined flow rate of a well's production history. Each of the methods derived from the "loss-ratio" obtains its' own set of parameters that are used to specifically account for the various flow behaving production trends. It is intended that the parameters are established via methods of diagnostic plots and/or type curve fitting (Valkó).

The loss-ratio is defined as:

$$\frac{1}{D} = -\frac{q}{\frac{\Delta q}{\Delta t}} \dots\dots\dots 1$$

The loss-ratio derivative is defined as:

$$b = \frac{d}{dt} \left[-\frac{q}{\frac{\Delta q}{\Delta t}} \right] \dots\dots\dots 2$$

There are limits and constraints associated with the DCA methods derived from the "loss-ratio" and "loss-ratio derivative" equations. Where the limitations are unable to be met, in order to produce realistic production forecasting results, the method of curve-fitting is applied, creating a best-fit match of the production history. This alternative approach allows for more realistic production forecasting results. A best-fit curve match can be performed through the method of trial-and-error by adjusting the variables, or through non-linear regression. In an ideal non-linear regression, $R^2=1$, although it is very uncommon to reach this in shale gas field data (Arps).

The sum of the squares of error in determining the straight line is defined as:

$$S_{SE} = \sum_{i=1}^n (y_i - y_i^{DC})^2 \dots\dots\dots 3$$

The sum of the squares of total average deviations is defined as:

$$S_{ST} = \sum_{i=1}^n (y_i - \bar{y})^2 \dots\dots\dots 4$$

The metric for non-linear regression is defined as:

$$R^2 = (1 - \frac{S_{SE}}{S_{ST}}) \dots\dots\dots 5$$

2.1. Arp's Hyperbolic Decline Curve Analysis

The method of hyperbolic decline, developed by Arp's, uses the estimation of the D-parameter, the curvature b-parameter and the initial flow rate “q_i” to formulate a history matching curve fit that is extrapolated to predict future production rates. With conventional reservoirs, it is required that 0<b<1 to be of hyperbolic decline, as well as remain a constant value for the lifespan of the reservoir.

The general derivative of the hyperbolic decline is defined as:

$$D \left(\frac{q}{q_i} \right)^b = - \frac{1}{q} \frac{\Delta q}{\Delta t} \dots\dots\dots 6$$

The flow rate for the hyperbolic decline is defined as:

$$q = q_i (1 + D_i b t)^{-\frac{1}{b}} \dots\dots\dots 7$$

The cumulative production for the hyperbolic decline is defined as:

$$G_p = \frac{q_i^b}{(1-b)D_i} [q_i^{1-b} - q^{1-b}] \dots\dots\dots 8$$

The Arp's hyperbolic decline curve requires that 0<b<1, there must be stabilized, non-transient flow, as well as a long period of production history data. In the case of shale gas reservoirs with extremely low permeability, transient flow will almost always occur at some point throughout the well's lifespan. Because of this, the b-parameter will almost always be greater than one and does not remain constant when curve fitting the production history. The diagnostic derivative plot also becomes invalid when using actual shale gas data, due to the commonly seen sporadic production data. In addition, obtaining the b-parameter through the hyperbolic type curves becomes an obsolete method when the value is larger than one (Arps). After applying the most fitting b-parameter through best-fit curve matching, the forecasts can still be problematic since the b-parameter will continue to decrease with time. Shale wells have an

exponential decline behavior in the long term; the use of the best fit b-parameter can lead to excessively large reserve estimates.

2.2. Power Law Exponential Decline Curve Analysis

The empirical method of power law exponential decline, developed by D. Ilk. uses the estimation of the decline rate parameters to exhibit a power-law behavior. Derived from the Arp's original exponential decline equation, it contains an infinite decline rate parameter, " D_{∞} ." This allows the model to follow a power law function at early production times of transient flow while providing a better fit for the late-time, boundary-dominated flow patterns commonly seen in low permeability shale reservoirs.

The flow rate for the Arp's original exponential decline is defined as:

$$q = q_i e^{(-Dt)} \dots\dots\dots 9$$

The flow rate for the power law exponential decline is defined as:

$$q = q_i e^{(-D_{\infty}t - \frac{D_1}{n}t^n)} \dots\dots\dots 10$$

The power law exponential decline is more applicable in representing the boundary-dominated and transient flow patterns seen in shale gas reservoirs with a sufficient length of history data. Although the D_{∞} -parameter allows for a smoother transition of these patterns, it can trigger unrealistic results when there is not a long enough period of boundary dominated flow. When performing a non-linear regression analysis, the Excel program, Solver, is unable to accurately manipulate the parameter for its intended use. Thus, the D_{∞} -parameter is omitted from the non-linear regression analysis and becomes an assumed value to obtain realistic results. This regression analysis is the preferred method opposed to conducting diagnostic plots or using the type curve fitting method. When these methods are applied to intermittent shale gas production history data, the parameters that are established yield unfitting curve matches (Ilk).

2.3. Stretched Exponential Decline Curve Analysis

The empirical method of stretched exponential decline, developed by Valkó, is very similar to the power law exponential decline method, except for the inclusion of the “ D_∞ ” parameter. In this case, “ D_∞ ” is always equal to zero, not allowing the method to account for late-time flow patterns. On the other hand, this method can be used for smoother curve fitting of cumulative production than that of the power law exponential decline method.

The flow rate for the stretched exponential decline is defined as:

$$q = q_i e^{(-\frac{D_1}{n} t^n)} \dots\dots\dots 11$$

The stretched exponential decline, although very similar to power law exponential decline, does not share all of the same constraints. Because the D_∞ parameter is equal to zero, it has difficulty forecasting the EUR with boundary-dominated flow data. In these boundary-dominated flow situations, the production forecasts tend to become overly conservative. In order to produce more realistic production forecasts, SEPD needs an ample amount of production history for analysis. Just like with power law exponential decline, when applying the diagnostic derivative plot methods, or using the suggested type curves in order to establish the decline parameters, unfitting curve representations occur. The primary reason for this is due to the inconsistencies in production data history for shale gas wells (Valkó).

2.4. Duong’s Method of Decline Curve Analysis

The empirical Duong method was developed to adjust to linear and bilinear flow. When production rate versus time is plotted on a log-log scale, it is assumed that they will have a power law relationship with one another and will form a linear trend. It obtains the parameters “a” and “m,” in Duong’s modified time/material-balance-time equation. They are a function of one another forming the later used parameter “ $t_{(a,m)}$.” To obtain the a-parameter and m-parameter, the flow rate divided by the cumulative production data (q/G_p) are plotted versus time

on a log-log scale. Within the power law trend of this line, the a -parameter is the intercept and m -parameter is the absolute value of the slope. The $t_{(a,m)}$ -parameter can then be calculated for all the data through an equation representing exponential flow behavior. The rate is then graphed versus $t_{(a,m)}$ on a cartesian plot. The straight line is formed yielding an equation where the slope is the flow rate at $t=1$ (q_1). This q_1 -parameter is multiplied by the $t_{(a,m)}$ values giving the flow rates for decline curve analysis. An additional q_∞ -parameter is added to this rate-time equation to better fit the field data and account for the abandonment rate. Although this method is slightly more complicated, it generally performs better with realistic field data. The Duong method equations are more easily illustrated in the equations following.

The flow rate for Duong's modified time/material-balance-time relation is defined as:

$$\frac{q}{G_p} = at^{-m} \dots\dots\dots 12$$

The flow rate for Duong's rate-time relation is defined as:

$$q = q_1 t(a, m) + q_\infty \dots\dots\dots 13$$

The $t(a,m)$ function used for Duong's rate-time relation is defined as:

$$t(a, m) = t^{-m} e^{\left(\frac{a}{1-m}(t^{1-m}-1)\right)} \dots\dots\dots 14$$

Unlike the other methods, Duong's method is not as limited by the inconsistencies in shale gas history data. Due to its ability to model linear and bi-linear flow and correct for the physics of flow for fractured formations, the Duong method is typically the best representative of realistic history data. On the other hand, the method is limited to single flow regimes, and is not suggested for boundary-dominated flow. The complexity of the method makes for clear observations, but limits it to more sophisticated computational tools. Shown below in Figure 1 are some typical a - and m - parameter values including probability distributions of reserves in terms of P90 (lower side) and P10 (higher side) for shale (Duong).

TABLE 2—PARAMETERS FOR TYPE-CURVE GENERATION FOR BARNETT SHALE						
$q_{lim}, 10^6$ $m^3/month$	Vertical well			Horizontal well		
	0.51			1.10		
	P90	P50	P10	P90	P50	P10
a	1.88	1.42	1.00	1.88	1.42	1.00
m	1.21	1.14	1.07	1.21	1.14	1.07
$q_i, 10^3$ m^3/d	12.19	19.09	32.58	26.40	41.37	70.59

Figure 1. Table of Parameters for Type-Curve Generation for Barnett Shale (Duong)

For the purpose of this research, similar a - and m -parameters for horizontal wells in the P10 column are used.

2.6. Study Site

The unconventional Marcellus Shale will be the primary focus for the purpose of this research. This is due to the available resources given courtesy of the Marcellus Shale Energy and Environment (MSEEL) project in Monongalia County West Virginia. The MSEEL project was developed in order to develop and validate new knowledge and technology to improve recovery efficiency and minimize environmental implications of unconventional source development as a collaboration between NETL, Northeast Natural Energy, Ohio State University, and West Virginia University.

Figure 2 Devonian Stratigraphy of the Appalachian Basin

The Northeast Natural Energy's Morgantown Industrial Park (MIP) well pad near Morgantown, West Virginia. The pad includes two wells that will be analyzed for this research: MIP-4H and MIP-6H.

Figure 3 Location of the MIP wells

Figure 4 Azimuths of the MIP wells

2.7. Previous Modeling Studies

These wells provided data that was used in the generation of simulation models with CMG in an earlier study by a former colleague. The models were built based on the given data and history matching using the CMOST module of CMG. Single well models were constructed for both MIP-4H and 6H and a production simulation was run. This simulation was compared to given production data in order to determine whether the wells had significant impact on one another. It was determined that the production was almost identical to the production given with the two well model and had too great of distance between one another to affect production. The fracture half-length for both wells were approximately 225' and fractures were spaced approximately 80' apart.

Unlike unconventional reservoirs, conventional reservoirs allow for fluid migration through relatively high porosity and permeability throughout the formation. Most conventional plays are made of limestone or sandstone and can often be produced from without the need of complex

stimulation treatments. However, in order to contact the maximum amount of hydrocarbon trapped within the unconventional play it is necessary to hydraulically stimulate the reservoir. The evolution of technologies for horizontal drilling and fracturing make it possible to contact these plays.

The evolving technology has introduced us to the concept of stimulated reservoir volume (SRV) – the contacted volume of reservoir. The stimulated reservoir volume is the area stimulated times the net pay times the spacing of natural fractures. This volume is a key parameter influencing the well's production. As the SRV increases, so does the production. Creating an optimum SRV is done through stimulation. This is when water, sand, and chemicals are pumped into the fractures.

3. OBJECTIVE AND METHODOLOGY

3.1. Objective

The purpose for this research is to evaluate the applicability of the different DCA methods for predicting production performance of the horizontal wells in unconventional formations. Furthermore, the minimum required production history to achieve reasonable production perdition will be investigated.

3.2. Methodology

The study is divided into two main parts. Part one involves modeling with a reservoir simulator and to develop numerous scenarios. The main objective of this part of the study was to determine the impact of stimulation on the production performance.

The second part of the study will focus primarily on decline curve matching. Each DCA method will be evaluated using the production data from two horizontal wells (MIP-4H and MIP-6H) to determine which method provides the best fit. Once the best method is determined, early production data from each well will be used to predict the later production.

In order to obtain reliable results, the production history must first be smoothed out. To gain insight to the minimum required production history will be achieved by iterative procedures.

3.3. Data Collection

To begin the study, a data set of production data and variables were made available through the MSEEL project in regards to production and pressure data. MSEEL also provided access to well logs, fracture completion reports, well trajectories, completion modifications, and other miscellaneous data.

3.4. Reservoir Modeling Studies

The previously built CMG model was used to simulate fracture scenarios. Simulated data allows for a curve generation with less noise than actual production data. Therefore, this data was useful in fitting decline curves. However, it is should be kept in mind that the simulated

data, while similar, is not the same as using actual production data. The model was used to create scenarios for the following analysis.

Models for different fracture scenarios were made using CMG in order to compare the number of stages over time and their impact on predicting. Because the data for the 4H was more reliable than the data for the 6H due to operational conditions (liquid loading, etc.), it was determined that the data for the 4H was best to use for all initial tests and scenarios and then applied to the 6H for validation.

First, the simulated data was exported to excel. Then, the production data was analyzed individually for 1 frac, 3 fracs, 5 fracs, 7 fracs, 9 fracs, and 11 fracs. In order to develop dimensionless decline curves, the cumulative gas production was divided by the stimulated reservoir volume and the flow rate by the initial flow rate.

The same method used on the MIP-4H was then applied to the MIP-6H for validation.

3.5. Decline Analysis

Upon completion of this scenario, the next focus for this research was to perform an analysis of the actual production data. First, the full data set of daily production over time was graphed along with each DCA method for each well to decide which method best fit the data and would likely give accurate prediction.

The daily production data however exhibited significant fluctuation which made it difficult to select the best DCA method. Consequently, the monthly production for each which had smooth trends were utilized for further analysis. Once the monthly production data was plotted it was much easier to match the curves as there was less noise present in comparison to the daily production data. For prediction purposes, the production history was broken down further into monthly increments in order to determine the least amount of monthly data necessary to provide an accurate prediction. It should be noted that the first “month” of production data was only 11

days for the MIP-4H and was included for the 6, 8, 10, 12, and 14 month production matching. Therefore each model is shown with 11 days added (i.e. 6 months 11 days, 8 months 11 days, etc.).

The first step in modeling the early months of production data with Duong's method took into account the table shown earlier in the Literature Review section for Duong's constants. The P_{10} constants were first utilized in effort to find a close match.

The first analysis was performed for MIP-4H on the 6 month analysis and was based on the equations given with trend lines built-in to MS excel. The trend line that best fit the production data did not best fit the Duong's prediction according to the R^2 value shown. Therefore, there were two types of trend lines utilized for this match based on best fit. The actual production data was best matched with the logarithmic trend line. The Duong's prediction was best fit to the power trend line. Using these trend lines, the parameters were then modified on a guess and check method.

It was found that lowering the initial flow rate to 3550 and using value 1.008 for a , and 1.030 for m , with a q - of 3 gave the best match. This is significantly different for the prediction used for the entire production data length and the charts with the modified values are shown in the results. The same method was repeated for 8, 10, 12 and 14 months of actual production data with Duong's prediction. To validate, the same methods were applied to the MIP-6H data and then plotted.

Arp's Hyperbolic DCA was then modeled using similar methods discussed with Duong's method. The parameters manipulated here for 6month, 8 month, 10 month, 12 month, and 14 month curves were q_i , D_i , and b . These values were 3750, 0.0056, and 2.00 respectively. It is shown that the DCA curve trends below the production data, but have less of a difference than with Duong's.

4. RESULTS AND DISCUSSIONS

To view the results for the fracture simulation analysis for the MIP-4H, the daily rate was plotted against the dimensionless time for the first 6 months. A trend line was added and forecasted by 25 steps in order to see if the forecast matched simulated data. Then, the simulated data was plotted for 6 months to end of data and it was found that there was a good match using the power trend line.

This process was used for 9 months to end of data and 12 months to end of data. The best fit for the one fracture scenario validated with the R^2 value the trend line produced was found with the 12 month to end of data plot. However, as you add fractures, the opposite is just as true. The best R^2 value trend is displayed toward the 6 month to end of data plots as fractures are added.

Because the scenario with 11 fractures is simulated off the same number of fractures used in actual completions for this well, it should be considered to be the most accurate and useful in terms of predictive modeling. Therefore, it can be concluded that a good match can be made at 6 months for 11 fracs, (R^2 being 96%) while 12 months of data yields lower accuracy (R^2 being 94%). That being said, it can be concluded that with the actual number of fractures seen made on the 4H the best fit is found with 6 months of data.

As for the MIP-6H, the results were similar. The one fracture scenario with 6 months data displayed a higher R^2 value than the 12 months to end of data. This trend remained for the full data set through 9 fractures, with the exception of 3 fracs. The difference between the 6 months and 12 month to end of data R^2 values here are negligible.

This analysis led to the conclusion that 6 months of data was likely the shortest amount of production data necessary to make future predictions. This theory will be validated with decline curve analysis.

After matching the MIP-4H wells' production history for each method, the unique equation parameters established are then used to determine how much data is necessary to make good predictions.

By looking at the coefficient given on the trend line, it was determined that the most conservative and most likely to predict future production is found to be the Hyperbolic DCA method. The second best fit was made with Duong's method.

Generation of Duong's curve with the guess-and-check method found that while the curve shows a good match for the 6 month prediction, the future predictions trend away from one another. This difference is greater as the monthly data added increases.

It can be seen that the end of 6 month production yields a better match with these parameters than the end of the 14 month data does. The P_{10} constants were first utilized in effort to find a close match. However, it was found that for the short increments of production taken into account the suggested parameters did not match. Instead, it was found that lowering the initial flow rate and using a guess and check method with a , m , and q_{∞} parameters found a best match. Therefore, the prediction with this method over estimates the final production and is too optimistic to use.

The opposite behavior was observed for well 6H as compare to well 4H. The 14 month production was closer at the end of the curve than the 6 month production. Therefore, a trend line was added similarly to the method used to show the curves for the frac models. When it was observed that the end results were closest with this scenario, it was determined that the 40 month actual monthly production should be added to the plot along with a forecasted trendline for the Duong plot with the modified parameters. It is shown that the curve, while still too optimistic, is not far off from a good match.

The guess-and-check method used for the MIP-4H well using hyperbolic DCA displayed a better match than with Duong. The parameters manipulated here for 6month, 8 month, 10 month, 12 month, and 14 month curves were q_i , D_i , and b . These values were 3750, 0.0056, and 2.00 respectively. The match found with this curve generation and actual production curve yield a good match.

To validate, the methods were applied to the MIP-6H. The results conclude that this method is successful in matching with 6 months of production data.

Figure 5. MIP-4H Analysis Fracture Method

Figure 6. MIP-4H Analysis Fracture Method Continued

Figure 7. MIP-6H Analysis Fracture Method

Figure 8. MIP-6H Fracture Method Analysis Continued

Figure 9. MIP-4H Full Daily Production

Figure 10. MIP-6H Full Daily Production

Figure 11. MIP-4H Full Monthly Production

Figure 12. MIP-6H Full Monthly Production

Figure 13. MIP-4H Total Monthly Production with Duong's Prediction

Figure 14. MIP-4H 6 Month Production with Duong's prediction

Figure 15. MIP-4H 8 Month Production with Duong's prediction

Figure 16. MIP-4H 10 Month Production with Duong's Prediction

Figure 17. MIP-4H 12 Month Production with Duong's Prediction

Figure 18. MIP-4H 14 Month Production with Duong's Prediction

Figure 19. MIP-6H 6 Month Production with Duong's Prediction

Figure 20. MIP-6H 8 Month Production with Duong's Prediction

Figure 21. MIP-6H 10 Month Production with Duong's Prediction

Figure 22. MIP-6H 12 Month Production with Duong's Prediction

Figure 23. MIP-6H 14 Month Production with Duong's Prediction

Figure 24. MIP-6H 14 Month Forecasted and Total Production with Duong's Prediction

Figure 25. MIP-4H 6 Month Production with DCA Prediction

Figure 26. MIP-4H 8 Month Production with DCA Prediction

Figure 27. MIP-4H 10 Month Production with DCA Prediction

Figure 28. MIP-4H 12 Month Production with DCA Prediction

Figure 29. MIP-4H 14 Month Production with DCA Prediction

Figure 30. MIP-6H 6 Month Production with DCA Prediction

Figure 31. MIP-6H 8 Month Production with DCA Prediction

Figure 32. MIP-6H 10 Month Production with DCA Prediction

Figure 33. MIP-6H 12 Month Production with DCA Prediction

Figure 34. MIP-6H 14 Month Production with DCA Prediction

5. CONCLUSIONS

The following conclusions were reached in this study:

1. The hyperbolic decline curve provides the best predictions for the Marcellus shale production.
2. The results obtained from the MIP-4H were successfully applied to the MIP-6H.
3. The analysis also indicated that at least 6 to 8 months of production history must be available to make reliable predictions using the hyperbolic decline curve.

NOMENCLATURE

a	<i>Duong constant (dimensionless)</i>
b	<i>hyperbolic exponent (dimensionless)</i>
D_i	<i>initial decline rate (at $t = 0$), (Days^{-1})</i>
D_∞	<i>decline rate constant ($t = \infty$), (Days^{-1})</i>
n	<i>time constant for PLE and SEPD (dimensionless)</i>
G_p	<i>cumulative gas production (MMCF)</i>
q	<i>production flow rate (MMCFD)</i>
q_1	<i>production flow rate (at $t = 1$) (MMCFD)</i>
q_i	<i>initial production flow rate (MMCFD)</i>
q_∞	<i>infinite production flow rate or abandonment rate (MMCFD)</i>
R^2	<i>coefficient of determination (fraction)</i>
SS_{err}	<i>error of sum of squares</i>
SS_{res}	<i>residual of sum of squares</i>
t	<i>time</i>
$t(a, m)$	<i>Duong time function</i>
$\bar{y}$	<i>mean of data</i>
y_i	<i>data at row i</i>
Δq	<i>change in production flow rate (MMCFD)</i>
Δt	<i>change in time</i>

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