Analyzing Well Production Data Using Combined Type Curve and Decline Curve Analysis Concepts

Abstract
This paper presents new production decline type curves for analyzing well production data from radial and vertically fractured oil and gas wells. These curves have been developed by combining Decline curve and Type curve analysis concepts to result in a practical tool which we feel can more easily estimate the gas (or oil) in place as well as to estimate reservoir permeability, skin effect, fracture length and conductivity, etc. Accuracy of this new method has been verified with numerical simulations and the methods have been used to perform analyses using production data from several different kinds of gas wells. Field and simulated examples are included to demonstrate the applicability and versatility of this technology.

Decline curve analysis methods, in a variety of forms, have been used in the petroleum industry for more than fifty years to analyze production data and forecast reserves. Type curve analysis methods have become popular, during the last thirty years, to analyze pressure transient test (e.g. buildup, draw-down) data.

Pressure transient data can be costly to obtain and may not be available for many wells, while well production data is routinely collected and is even available from industry data bases. In the absence of pressure transient data, a method that can use readily available well production data to perform pressure transient analysis would be very beneficial. The result is the development of these new production decline type curves.

These new production decline type curves represent an advancement over previous work because a clearer distinction can be made between transient and boundary dominated flow periods. The new curves also contain derivative functions, similar to those used in the pressure transient literature to aid in the matching process. These production decline curves are, to our knowledge, the first to be published in this format specifically for hydraulically fractured wells of both infinite and finite conductivity. Finally, these new curves have been extended to utilize cumulative production data in addition to commonly used rate decline data.

Introduction
Estimation of hydrocarbon-in-place and reserves for oil and gas reservoirs is needed from the time when such reservoirs are first discovered to future times when they are being developed by drilling step out wells or infill wells. These estimates are needed to determine the economic viability of the project development as well as to book reserves required by regulatory agencies.

During the last fifty years, various methods have been developed and published in the literature for estimating reserves from high permeability oil reservoirs to low permeability gas reservoirs. These methods range from the basic material balance methods to decline/type curve analysis techniques. They have varying limitations and are based on analytical solutions, graphical solutions (known as type curves and decline curves), and combinations of the two. Examples of these range from Arp’s¹ decline equations for liquids to Fetkovich’s² liquid decline curves, Carter’s³ gas type curves and Blasingame⁴ et. al.’s gas equivalent to liquid decline curves. Several other papers on the related subject, too many to quote here, have appeared in the SPE literature.

Purpose
The purpose of this paper is to document new production decline type curves for estimating reserves and determining other reservoir parameters for oil and gas wells using

References and illustrations at the end of paper
performance data. Depending on the amount of performance data available, these methods can provide lower bound and/or upper bound estimates of a well’s hydrocarbon-in-place. The accuracy of such estimates for reserves and other reservoir parameters will depend on the quality and kind of the performance data available.

Using the methods of Palacio and Blasingame\textsuperscript{4}, it will be demonstrated and confirmed, that solutions for constant rate or constant bottomhole pressure production for oil and gas can be converted in most cases to equivalent constant rate liquid solutions.

Initially, we will review background material. Next, we will briefly discuss the various methods which are commonly used for estimating gas reserves. Finally, we will present the new production decline type curves and demonstrate their utility and application by means of both synthetic and field examples.

Although the technology discussed in this paper is applicable to both oil and gas wells, we will limit our discussion mainly to gas wells.

Background Material

Transient & Pseudo Steady-State Flow Conditions.

When a well is first opened to flow, it is under a transient condition. It remains under this condition until the production from the well affects the total reservoir system. Then the well is said to be flowing under a pseudo steady-state (pss) condition or a boundary dominated flow condition. Transient rate and pressure data are used to determine reservoir permeability and near wellbore condition (damage or improvement), fracture length and/or fracture conductivity whereas the pss data are required to estimate the fluid-in-place and reserves.

Transient and pss flow conditions are schematically shown on a Cartesian paper in Figure 1 and on a log-log paper on Figure 2.

Review of Various Reserve Estimation Methods.

Volumetric method is used to make an initial estimate of gas-in-place using petrophysical data such as hydrocarbon porosity, pay thickness, initial reservoir pressure, reservoir temperature, PVT data, and reservoir size (or well spacing). Such estimates are useful and should always be made.

Material balance method for gas wells makes use of the material balance equation, \( \frac{p}{z} = \left( \frac{p_i}{z_i} \right) \left( 1 - \frac{G_p}{G'_p} \right) \) and the material balance graph where \( \frac{p}{z} \) is plotted as a function of cumulative gas production. Although the material balance graph may have a limited application in certain cases (for example tight gas wells) it provides useful guidelines for reserves and can also give insight regarding the drive mechanism of a reservoir.

Reservoir limit test is based on the constant rate drawdown solution. A well is produced at a constant rate and wellbore pressure response is plotted as a function of time on Cartesian graph paper (see Figure 1). During the pss condition, the slope of this line is inversely proportional to the fluid in place. This kind of test is not limited to, but is usually run on new exploration type wells for estimating reserves.

Arp’s Decline Equation is based on empirical relationships of rate vs. time for oil wells and is shown below:

\[
q(t) = \frac{q_i}{\left(1 + bD_r \right)^{\lambda}}
\]

In this equation, \( b=0 \) and \( b=1 \) represent exponential and harmonic decline, respectively. During pss for liquid systems, the exponential decline is a characteristic of constant pressure production whereas the harmonic decline is due to constant rate production. Any other value of \( b \) represents a hyperbolic decline (see Figure 2). Although Arp’s equation is strictly applicable for pss conditions, it has been often misused for oil and gas wells whose flow regimes are in a transient state.

Fetkovich Liquid System Decline Curves were published in 1980 for analyzing oil wells producing at a constant pressure. He combined early time, analytical transient solutions with Arp’s equations for the later time, pseudo steady-state solutions. A reproduction of his type curves are shown in Figure 3.

Although the value of the \( b \) stem ranges from 0 to 1, curves for \( b>1 \) are often added to this Figure and are misused to match transient data. These liquid system curves are not recommended for gas wells when the amount of pressure drawdown is moderate to large. Alternately, these curves (\( b=0 \) and \( b=1 \)) may be used for gas wells if gas well data are converted to an equivalent liquid system data. This concept has been used in this study and will be discussed later.

Carter Gas System Type Curves were developed in 1985 to fill the gap which existed with the Fetkovich decline curves. They are shown in Figure 4. Carter used a variable \( \lambda \) reflecting the magnitude of pressure drawdown in gas wells. His \( \lambda = 1.0 \) curves corresponds to \( b = 0 \) on the Fetkovich liquid decline curves and represents a liquid system curve with an exponential decline. Curves with \( \lambda = 0.75 \) and 0.55 are used for gas wells with an increasing magnitude of pressure drawdown. Obviously, Carter type curves are better suited to estimate reserves for gas wells.

Palacio & Blasingame Type Curves, first presented in 1993, provide a major advancement in the area of analyzing oil and/or gas well performance data using type curves. Their type curves are shown in Figure 5. This paper is an excellent culmination of their work and the work of other investigators whose goals were to convert gas well production data into equivalent constant rate liquid data. They also established a clear relationship among the previously discussed decline
curves.

Palacio-Blasingame type curves provide a useful tool to estimate gas in place (GIP), reservoir permeability and skin. However, the transient stems are strictly valid only for radial flow and thus may not be suitable for analyzing gas wells with relatively long vertical hydraulic fractures of infinite or finite conductivity. It is also difficult to pick up a clear transition between the transient and the pss flow periods from these and the other previously discussed decline curves. Palacio-Blasingame utilize derivative methods to help with the type curve matching process but this results in multiple curves even for the radial flow system. Details about their type curves as well as a comprehensive list of pertinent references on this subject can be found in their paper (Reference 4).

Discussion

Our first objective with this study was to verify, using a single phase finite difference reservoir simulator, a major finding of Palacio and Blasingame, that constant rate and constant bottomhole pressure solutions for liquid and gas systems, can be converted to an equivalent constant rate liquid solution. Constant rate liquid solutions are well understood for both transient and pss conditions and are widely used for pressure transient analysis (PTA) purposes. With constant rate liquid solutions, one can take advantage of the many well known PTA techniques for plotting decline curve data on different types of graph papers and for utilizing appropriate plotting variables such as pressure, rate, cumulative production, and time functions, and also the appropriate derivative functions.

Plotting Dimensionless Variables.

Constant rate liquid solutions are commonly used for pressure transient analysis. Dimensionless variables which are frequently used in type curves for pressure transient analysis are dimensionless pressure, $\frac{P}{P_0}$ and its derivatives with respect to dimensionless time, $\frac{\phi_p}{P_0}$ and with respect to log of dimensionless time, $\frac{\phi_p}{\ln t_0}$. To make a type curve graph appear like a decline curve, one can use the reciprocals of $\frac{P}{P_0}$ to produce graphs of $\frac{1}{\frac{P}{P_0}}$, $\frac{\phi_p}{P_0}$, and $\frac{1}{\ln t_0}$ plotted against dimensionless time. The reciprocal log time derivative, $\frac{1}{\frac{\phi_p}{\ln t_0}}$ does for the rate decline plot, what $\frac{\phi_p}{\ln t_0}$ does for the pressure build-up plot, namely, helping to identify flow regimes and to estimate permeability.

References to these 2 types of derivatives are used quite extensively in this paper, so for convenience in the text and in the figures, a short hand form representing the derivatives is used. $P_w D'$ is defined as the derivative of $P_w D$ with respect to the independent variable. For example, with $t_0$ as the independent variable, $P_w D' = \frac{\phi_p}{D}$. Similarly, $\frac{1}{\ln P_w D'}$ is defined as the reciprocal of the derivative of $P_w D$ with respect to the log of the independent variable. For example, $\frac{1}{\ln P_w D'} = \frac{1}{\frac{\phi_p}{\ln t_0}}$ for the independent variable, $t_0$.

Equivalence Between Constant Rate and Constant BHP Liquid Solutions.

To demonstrate this, two radial liquid system cases were considered. The two systems were identical, except in one case (LR) the well was produced at a constant rate and in the other case (LP) the well was produced at a constant bottomhole pressure.

Figure 6 shows graphs for both cases in terms of $\frac{1}{\phi_p}$, $P_w D'$ and $\frac{1}{\ln P_w D'}$. A comparison of these two cases show that during the transient period, the two sets of results are very similar. However, they are quite different during the pseudo steady-state (or boundary dominated flow period). This is to be expected since constant rate solutions during the pss period show a harmonic decline (straight line with negative unit slope on log-log paper), whereas constant bottomhole pressure solutions result in an exponential decline (concave line on log-log paper). If constant BHP results are replotted using a modified time, $t_e = (\text{Cumulative Production})/\text{(instantaneous rate)}$ and compared with the constant rate solutions, they become equivalent. This equivalence between the two solutions is shown in Figure 7. Notice during transient flow, $P_w D'$ has a negative unit slope while $\frac{1}{\ln P_w D'}$ is at a constant value of 2.0 (zero slope). During pss flow their roles reverse, that is $\frac{1}{\ln P_w D'}$ has a negative unit slope, while $P_w D'$ has a constant value which is inversely proportional to GIP. Therefore, it is possible to estimate GIP and to determine whether this value is a lower or upper bound estimate.

Equivalence Between Constant Rate and Constant BHP, Gas Solutions.

To illustrate this equivalence, two radial gas system cases, constant rate case (GR) and constant BHP case (GP) were considered. Except for the mode of production, the two systems were identical. These cases should provide a difficult litmus test for verifying the desired equivalence. Figure 8 shows graphs for both gas cases and is similar to Figure 6 in terms of plotting variables. During the transient period, both constant rate and constant BHP cases appear identical. However, the difference between the two cases during the pss period becomes significant. This is to be expected because additional complications are caused not only due to differences in modes of production but also due to varying gas properties. We go through the conversion to an equivalent constant rate liquid solution in a stepwise manner. First we use the dimensionless time based on the modified time, $t_e$ instead...
of real time as was done for the liquid cases. The second step is to redefine time in terms of pseudo time where gas properties product \((\mu c_p)\) is calculated as a function of average reservoir pressure \(\bar{p}\). Pseudo equivalent time, \(t_a\) was developed by Palacio and Blasingame\(^1\) by extending earlier work of Fraim and Wattenbargers and is shown below:

\[
t_a = \frac{1}{q(t)} \int_0^t q(t') dt' \frac{1}{\mu c_p} \frac{Z_i G_i}{2p_i} \Delta [\bar{p}(\bar{p})] \tag{2}
\]

Results, after this conversion is made, are found to be identical to those shown in Figure 7. That is, the two gas cases become identical during both the transient and pss periods. This verifies that it is possible to convert constant BHP liquid as well as constant rate and constant BHP gas cases into an equivalent constant rate liquid case. This is significant because it will permit us to focus our attention to mainly constant rate liquid systems. We have also found that for gas wells, when both the rate and pressure vary smoothly such that \(1/p_wD\) is monotonically decreasing, that the data can be converted into the constant rate liquid analogue.

However, there is a computational problem. The calculation of pseudo time in Equation 2 assumes that we know GIP (a parameter value we normally don’t know) and would like to determine. The implication of this assumption suggests an iterative procedure for GIP. This can be easily accomplished using a spreadsheet program.

**Production Decline Type Curves.**

These new decline type curves will be presented under three categories: 1) Rate - Time, 2) Rate - Cumulative Production, and 3) Cumulative Production - Time. Under each category, we will present decline type curves for radial systems and for vertically fractured wells with infinite and finite fracture conductivity, as appropriate.

**Rate-Time Production Decline Type Curves.**

1. **Radial System.**

For the radial system log-log type curves, we generated three cases corresponding to \(r_e/r_w = 10,000, 1,000, \) and 100, and utilized the previously discussed approach for plotting the results. Dimensionless time variable for the x-axis was calculated in two different ways: (1) based on the drainage area, \(A\), and (2) the apparent wellbore radius squared, \(r_w^2\). Results are shown in Figures 9 and 10, respectively.

In Figure 9, where data has been plotted as a function of dimensionless time based on \(r_w^2\), a single curve is obtained during the transient flow period for \(1/p_wD\) for all \(r_e/r_w\) values and also for each of the two types of derivatives. However, these curves start peeling off for each \(r_e/r_w\) value during the pss period. The use this kind of type curve graph is recommended for estimating reservoir parameters such as permeability and skin effect.

2. **Infinite Conductivity Fracture.**

Figures 11 and 12 show similar graphs but for vertically fractured wells with infinite conductivity fractures. Here, data are plotted in a manner similar to Figures 9 and 10. The main differences here in plotting the results are that, \(x_f/x_f\) has been used as a parameter compared to \(r_e/r_w\) and \(r_w^2\) which was used for the radial system cases and dimensionless time is based on the fracture half length, \(x_f\) instead of \(r_w\). In this case \(x_f/x_f\) values of 1, 2, 5, and 25 have been used. Comparison of Figures 11 and 9 shows that for the fractured well multiple derivative curves are obtained as opposed to obtaining a single curve for each kind of derivative for the radial case.

3. **Finite Conductivity Fracture.**

Figures 13 and 14 show graphs of \(1/p_wD\) and \(1/dlnPwD'\) for vertically fractured wells with finite conductivity fractures. These graphs are similar to those shown for infinite conductivity vertically fractured wells with one exception. Here we have also included the effect of varying dimensionless fracture conductivity, \(F_{CD} = \left(\frac{k_{rw}}{k_{x_f}}\right)\). Three values of \(F_{CD}\) have been used which range from 500 to .05. The value of 500 corresponds to a fracture of infinite conductivity whereas the value of 0.05 represents very low fracture conductivity. In this case \(x_f/x_f\) values of 1, 2, 5, and 25 have been used for each value of fracture conductivity.

**II. Rate-Cumulative Production Decline Type Curves.**

Another kind of graph which is commonly made by operations and field engineers is to plot rate, \(q(t)\), or normalized rate, \(q(t)/\Delta m(p)\) as a function of cumulative
production. A recent paper on this topic is due to Callard et al. To investigate the character of these graphs, the dimensionless groups \( \frac{Q}{D_o} \) and the derivative of \( p_{wD} \) with respect to dimensionless cumulative production, \( Q_{DA} \) (where \( Q_{DA} = \frac{t_{DF}}{p_{wD}} \)), were plotted as functions of \( Q_{DA} \) on log-log coordinates. Results in the form of type curves for radial flow systems for \( r_f/r_w = 10,000, 1,000, \) and 100 are shown in Figures 15, and 16.

Figure 15 shows that during the transient flow period, separate \( \frac{Q}{D_o} \) curves are obtained for each \( r_f/r_w \) value. However, during pss flow they asymptotically merge into a single value of \( Q_{DA} = 1/(2\pi) = 0.159 \). We call it an anchor point value and find it useful in estimating GIP.

Figure 16 is a Cartesian (linear) graph of the same \( \frac{D}{D_o} \) data as is used in Figure 15. Notice that during the pss flow period, the different \( \frac{D}{D_o} \) curves become linear and converge at \( Q_{DA} = 1/(2\pi) \). The significance of this attribute is that for an optimistic estimate of GIP the trajectory of the field data will intersect the anchor point and it will over shoot the anchor point for a pessimistic estimate of GIP. We find this graph very useful in converging to a correct value of GIP.

Figure 17 shows \( \frac{1}{p_{wD}} \) and the derivative of \( p_{wD} \) with respect to dimensionless cumulative production based on \( r_f^2 \), \( Q_{DA} \) (where \( Q_{DA} = \frac{t_{DF}}{p_{wD}} \)) plotted against \( Q_{DA} \). A notable feature of this graph is that \( \frac{1}{p_{wD}} \) along with this derivative, form an envelope. A vertical tangent to this envelope corresponds to the GIP. The derivative plot shows a negative unit slope line during the transient period but it assumes a rapidly increasing positive slope during the pss period. These characteristics can be utilized to identify the transient and pss flow periods and the transition between them. Moving to the left of this graph where the \( r_f/r_w \) value decreases, \( \frac{1}{p_{wD}} \) and its derivative become closer to one another. Although not shown, they intersect one another for smaller values of \( r_f/r_w \). We utilize similar graphs for infinite and finite conductivity vertically fractured wells but they are not included in this paper.

The above discussed characteristics of cumulative type curves have been found to be advantageous for diagnostic purposes as well as type curve matching purposes.

III. Cumulative-Time Production Decline Type Curves.

We generated cumulative production vs. time decline type curves using the same data as we used and discussed for radial systems and vertically fractured wells. We find such curves useful because field cumulative production data is often smoother than the corresponding rate data. Moreover, such curves have their own characteristics which can be used to our benefit in estimating reservoir parameters and reserves. Figures 18 and 19 show such curves respectively for radial wells and finite conductivity fractured wells.

In Figure 18, dimensionless cumulative production, \( Q_{DA} \) has been plotted on a log-log graph paper as a function of dimensionless time based on wellbore radius. During the transient flow a single curve is obtained for all \( r_f/r_w \) values. It has a unit slope line except at dimensionless times less than about 100. During pss flow, the curves peel off and become flat when going from smaller to larger values of \( r_f/r_w \).

In Figure 19, dimensionless cumulative production, \( Q_{DA} \) for a fractured well has been plotted on a log-log graph paper as a function of dimensionless time based on fracture half-length, \( x_f \). In this case a separate curve is obtained for each value of dimensionless fracture conductivity. During transient flow, for each fracture conductivity value, a single curve is obtained for all \( x_f/x_r \) values. Their slope ranges from a unit slope for low conductivity fractures to half-slope for infinite conductivity fractures. During pss flow, these curves peel off and become flat for each value of \( x_f/x_r \).

Comments About These & Other Published Type Curves.

The type curves presented in Figures 9-19, in total represent a new contribution to technology and contribute to recent work within the industry in advanced type curve methods. Our contributions in this area are mainly in the integration of recent developments from several published sources into more complete sets of type curves for both radial and fracture flow, in both transient as well as boundary dominated flow conditions. These new contributions include derivative type curves for both radial and fracture flow in terms of dimensionless rate and rate derivatives vs. dimensionless time which are based on normalized rate and equivalent fluid properties. We have also made contributions through the creation of new dimensionless rate and rate-derivative type curves in terms of dimensionless cumulative production, \( Q_{DA} \) (which is also based on normalized rate and equivalent fluid properties). For lack of a better name, this new suite of type curves are referred to as Agarwal-Gardner (A-G) type curves, not because we discovered the previously discussed mathematical relationships, but because we have compiled the requisite information from various recently published sources and have constructed original type curves based on those relationships.

These A-G type curves consider both the transient and the pss flow conditions, as well as the transition between the two, in a rigorous manner. They can be easily generated using a simulator for any desired flow system such as radial and that resulting from vertically fractured wells. Analyses of tight gas wells require that a much longer transient period be included with such type curves. This can be easily accomplished with these type curves. Alternately, published infinite and finite conductivity fracture type curves (such as published by Agarwal, Carter, and Pollock and Cinco et al.) can be used for the analysis of transient data. Infinite conductivity fracture type curves published by Gingarten et al. can be used for transient as well as pss periods. Similar comments apply to other published type curves.
Application of A-G Type Curves

These type curves such as shown in Figures 9-19 can be easily programmed into a spreadsheet program. Modern spreadsheet programs provide a convenient medium to history match field data to determine parameter values with these new type curves.

A set of basic data is required to do the type curve matching for gas wells regardless of which kind of type curve is being used. They are listed below:

1. Reservoir Data: Initial reservoir pressure (p_i), reservoir temperature (T), formation thickness (h), reservoir permeability (k), hydrocarbon porosity (\phi_h).

2. Gas Properties Data: Tables of viscosity (\mu), z-factor, and gas compressibility (c_g) vs. pressure including values of \mu_i, z_i, and c_gi. Tables of real gas pseudopressure [m(p)] vs. pressure.

3. Performance Data: Well rate (q), bottomhole pressure (p_{BHP}), and cumulative gas production (Q) as a function of producing time (t).

Normally the parameters to be determined that are of primary interest are GIP, formation flow capacity (kh), and wellbore skin or for fractured wells, fracture length and conductivity.

Estimating GIP

With these new decline/type curves, we recommend that GIP be determined first. This is because the independent variable, Q_{DA}, used to estimate GIP, is independent of permeability, whereas estimates of permeability, etc., are dependent upon GIP.

A good initial estimate of GIP is not necessary, convergence to the proper GIP is usually very rapid. The cumulative gas production can provide a lower bound estimate for GIP, whereas a volumetric estimate obtained from petrophysical data could provide an upper bound estimate. A value somewhere between the two would suffice for an initial estimate.

Figure 20 shows the rate-cumulative production decline type curves and illustrates the concept of graphically estimating GIP based on responses to changes in GIP values relative to the type curves. In this Figure, we use values of plus and minus 20 percent of the true value of GIP to showcase this effect. Notice that with the correct GIP, the data follows the trajectory of one of the 1/2\pi rays. It doesn't matter which of these rays are used, all focus to the same point on the Q_{DA} axis of 1/(2\pi).

Estimating formation flow capacity, kh

Figure 21 shows rate-time production decline type curves and illustrates the concept of graphically estimating kh based on responses to changes in kh values relative to the type curves.

In this Figure, we use kh values of 2.0 and 0.5 md, which are twice and 1/2 the true value of 0.10 md, in order to showcase the sensitivity to permeability.

Field Application of A-G Type Curves

Figures 22 and 23 show history matched parameter estimates for GIP, permeability, etc. for an infill gas well in the low permeability Red Oak sand of southeastern Oklahoma. The well was drilled in December, 1991 and has slightly over six years of production history with a cumulative production of 1.9 Bscf. This production data is typical of that obtained from industry or field data bases and the noise or inaccuracies in measured or reported data is reflected in the dimensionless data.

Figure 22 shows that the plot of 1/p_{wD} vs Q_{DA} is converging nicely to the GIP anchor point and that the estimate of GIP can be used with some confidence. The character of the derivative data on the plot of 1/p_{wD} vs t_{DA} (Figure 23) clearly shows that the well has transitioned to boundary dominated flow. This plot also illustrates a match for estimating permeability, fracture half-length, and dimensionless fracture conductivity. Only minor modifications to the parameter values obtained from this type curve match were needed in order to match the well's history using a finite difference simulator.

Figure 24 is a plot of the same production data on a Palacio-Blasingame type curve. The estimates of GIP between the two type curves are in excellent agreement, differing by less than three percent. There is, however, some ambiguity about which transient stem to match the data with in order to calculate permeability and wellbore skin. This illustrates a benefit of using these new type curves for low permeability fractured wells which typically have long linear or bilinear transient flow periods.

Summary and Conclusions

1. A new set of rate-time, rate-cumulative, and cumulative-time production decline type curves and their associated derivatives have been developed using pressure transient analysis concepts and are presented in this paper.

2. They have been developed for radial systems as well as vertically fractured wells with infinite and finite conductivity fracture. These production decline curves are, to our knowledge, the first to be published in this format especially for fractured wells.

3. These new production decline type curves represent an advancement over previous work in that a clearer distinction can be made between transient and boundary dominated flow periods.

4. They provide a practical tool to field engineers for estimating gas (or oil)-in-place as well as to estimate reservoir permeability, skin effect, fracture length, and fracture conductivity. Also because this technology can be easily programmed into an electronic spreadsheet, it is more readily used.

5. These type curves enable us to utilize routinely collected production data and those available from industry
data bases in the absence of costly pressure transient data.
6. These concepts can be extended to other well and/or reservoir models such as horizontal wells or naturally fractured reservoirs, to name a few.

Nomenclature

A = Drainage Area, sq ft
b = Arp's decline curve exponent
c = Gas compressibility, 1/psi
(c) = Gas compressibility at initial reservoir pressure, 1/psi
c = Total system compressibility, 1/psi
D = Arp's dimensionless decline rate
e = 2.7183, Napierian constant
FCD = dimensionless fracture conductivity
G = Initial gas in place, MMSCF or BSCF
GP = Cumulative gas produced, MMSCF or BSCF
k = Effective permeability to gas, md
k = Fracture permeability, md
m(p) = Real gas pseudo pressure, psia²/cp
Δ(m(p)) = m(p)−m (p), psia²/cp
Δ(m(p)) = m(p)−m (p), psia²/cp
PBHP = Bottomhole producing pressure, psia
p = Average reservoir pressure, psia
p = Initial reservoir pressure
PwD = Dimensionless wellbore pressure
q = Initial flow rate, MSCF/D
q(t) = Flow rate, MSCF/D
QDA = Dimensionless cumulative production based on
Area (A)
QD = Dimensionless cumulative production based on
r², or x²
r = Reservoir radius, ft
s = skin factor
t = time, days
T = reservoir temperature, degrees Rankine
t = Pseudo equivalent time
t = Equivalent time (cumulative(t)/q(t)), days
tDA = Dimensionless time based on area, A
tD = Dimensionless time, based on r²
Ω = Dimensionless time, based on x²
w = Fracture width, ft
x = Distance from well to reservoir boundary
(Cartesian coordinate system)
x = Fracture half length, ft
z = Initial gas compressibility factor
z = Gas compressibility factor at average pressure

Greek letters:
φ = Hydrocarbon porosity, fraction
λ = Carter's draw-down variable

μ = Viscosity, cp
π = 3.1416

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References


Appendix A

\[ t_e = \frac{Q(t)}{q(t)} \quad (A-1) \]

\[ t_d = \frac{1}{q(t)} \int_{\varnothing}^{t_e} \frac{q(t)\varphi'}{\mu(\varphi)} \, d\varphi = \frac{1}{q(t)} \int_{\varnothing}^{t_e} \frac{ZG}{2p_i} \cdot \Delta(m(\varphi)) \quad (A-2) \]

where, \[ \Delta(m(\varphi)) = m(p_i) - m(p) \]

and, \[ m(p) = 2 \int_{\varnothing}^{p} \frac{p' dp'}{\mu(p') \varepsilon(p')} \]

\[ t_d = \alpha \cdot t \quad (A-3) \]
\[ t_{ad} = \alpha \cdot t_c \]  
\[ t_{ab} = \alpha \cdot t_a \]  
(A-4)  
(A-5)  

where, \( \alpha = \frac{(2.637 \times 10^{-4})(24)k}{\phi(\mu_c_i) \cdot r_{w}^2} \)

\[ \frac{1}{\frac{1}{P_{w0}}} = \frac{14227\beta_0(t)}{k h \Delta m(p)} \]  
(A-6)  

\[ P_{w(1)} = (P_{f}) + s \]  
(A-7)  

\[ Q_{ad} = \frac{L_{ad}}{P_{w(1)}} = \frac{9.0T}{\phi h \Delta m(p) r_{w}^2} \int q(t') dt' \mu(p) \varepsilon_2(p) \]  
(A-8)  

\[ and, \ Q_{ad} = \frac{4.50Tz_i G_i}{\phi h w_{wa} p_i} \frac{\Delta m(\bar{p})}{\Delta m(p)} \]  
(A-9)  

where: \( \Delta m(p) = [m(p) - m(p_{BHP})] \)

Dimensionless times in Eqs. (A-3) through (A-9) are based on \( r_{w}^2 \). These are multiplied by \( \frac{r_{w}^2}{A} \) to convert them so that they are based on the area, \( A \). For example, \( t_{ad} = \frac{t_{ad}}{A} \),

\[ Q_{ad} = \frac{Q_{ad}}{A} = \frac{Q_{ad}}{P_{w(1)}} \]

**SI Metric Conversion Factors**

- \( \text{acre} \times 4.046 = \text{m}^2 \)
- \( \text{bbl} \times 1.589 = \text{m}^3 \)
- \( \text{cp} \times 1.0 = \text{E-03} = \text{Pa} \cdot \text{s} \)
- \( \text{ft} \times 3.048 = \text{E-01} = \text{m} \)
- \( \text{md-ft} \times 3.008 = 142 \text{E+02} = \mu \text{m}^{-1} \)
- \( \text{psi} \times 3.048 = \text{E+00} = \text{kPa} \)
- \( \text{psi}^{-1} \times 1.450 = 377 \text{E-04} = \text{Pa}^{-1} \)
- \( \text{cu ft} \times 2.831 = 685 \text{E-02} = \text{m}^3 \)
- \( \text{md} \times 9.869 = 233 \text{E-04} = \mu \text{m}^{-1} \)

\( ^* R \times 5/9 = ^* K \)

*Conversion factor is exact.*
Fig. 5: Palacio-Blasingame Type Curves (Ref. 4)
- Transient Stems 4, 12, 28, 800, 1000

Fig. 6: Comparison of Constant Rate and Constant BHP
Liquid Production Data - Radial Case

Fig. 7: Converting Constant Rate and Constant BHP Data to
An Equivalent Constant Rate Liquid Data - Radial Case

Fig. 8: Comparison of Constant Rate and Constant BHP
Gas Production Data - Radial Case
Fig. 9: Rate - Time Production Decline Type Curves for Radial Systems Using rD Based on Area (re/rwa = 100, 1000, 10000)

Fig. 10: Rate - Time Production Decline Type Curves for Radial Systems Using rD Based on rwa (re/rwa = 100, 1000, 10000)

Fig. 11: Rate - Time Production Decline Type Curves for Infinite Conductivity Fracture Using rD Based on Area (xe/xf = 1, 2, 5, 25)

Fig. 12: Rate - Time Production Decline Type Curves for Infinite Conductivity Fracture Using rD Based on xf (xe/xf = 1, 2, 5, 25)
Fig. 13: Rate - Time Production Decline Type Curves for Finite Conductivity Fracture Using tD Based on Area (xe/xf = 1, 2, 5, 25 & FCD = .05, 0.5, 500)

Fig. 14: Rate - Time Production Decline Type Curves for Finite Conductivity Fracture Using tD Based on xf (xe/xf = 1, 2, 5, 25 & FCD = .05, 0.5, 500)

Fig. 15: Rate - Cumulative Production Decline Type Curves on Log-Log Graph for Radial Systems Using QD Based on Area (re/rwa = 100, 1000, 10000)

Fig. 16: Rate - Cumulative Production Decline Type Curves on Cartesian Graph for Radial Systems Using QD Based on Area (re/rwa = 100, 1000, 10000)
Fig. 17: Rate - Cumulative Production Decline Type Curves for Radial Systems Using QD Based on rwa (r_e/rwa = 100, 1000, 10000)

Fig. 18: Cumulative - Time Production Decline Type Curves for Radial Systems Using tD Based on rwa (r_e/rwa = 100, 1000, 10000)

Fig. 19: Cumulative - Time Production Decline Type Curves for Fractured Wells Using tD Based on x_f (r_e/x_f = 1, 2, 5, 25 & FCD = .05, 0.5, 500)

Fig. 20: Showing the Effect of Changing GIP Estimates on Rate - Cumulative Production Decline Type Curves on Cartesian Graph for Radial Systems
Fig. 21: Showing the Effect of Changing $kh$ Estimates on Rate - Time Log-Log Production Decline Type Curves for Radial Systems Using $tD$ Based on Area

Fig. 22: Application of Field Data to Estimate GIP Using Rate - Cumulative Production Decline Type Curves on Cartesian Graph for Finite Conductivity Fracture Using $QD$ Based on $xf$

Fig. 23: Application of Field Data to Estimate $kh$ Using Rate - Time Production Decline Type Curves for Finite Conductivity Fracture Using $tD$ Based on Area

Fig. 24: Application of Field Data to Estimate GIP & $kh$ Using Palacio-Blasingame Type Curves (Reference 4)