Production forecasting decline curve analysis

Decline curve analysis (DCA) is a graphical procedure used for analyzing declining production rates and forecasting future performance of oil and gas wells. Oil and gas production rates decline as a function of time; loss of reservoir pressure, or changing relative volumes of the produced fluids, are usually the cause. Fitting a line through the performance history and assuming this same trend will continue in future forms the basis of DCA concept. It is important to note here that in absence of stabilized production trends the technique cannot be expected to give reliable results.

Contents

Types of declines

The technique is not necessarily grounded in fundamental theory but is based on empirical observation of production decline.

Three types of declines are observed:

1. Exponential
2. Hyperbolic
3. Harmonic

There are theoretical equivalent to these decline processes. It can be demonstrated that under conditions such as constant well back pressure, equation of fluid flow through porous media under boundary dominated flow are equivalent to exponential decline. However for our purpose it is the empirical nature of this term which has a greater significance since it allows the technique to be applied to multiple fluid streams even ratios!

Back to top

Golden rule of decline curve analysis (DCA)

The basic assumption in this procedure is that whatever causes controlled the trend of a curve in the past will continue to govern its trend in the future in a uniform manner

Decline curve analysis (DCA) history

J.J. Arps (http://www.aimehq.org/programs/award/bio/j-j-arps) collected these ideas into a comprehensive set of equations defining the exponential, hyperbolic and harmonic declines. His work was further extended by other researchers to include special cases. Following section gives a historical perspective of work done on the subject;

- Arps 1945 and 1956.
- Brons 1963 and Fetkovitch 1983 applied constant pressure solution to diffusivity equation and demonstrated that exponential decline curve actually reflects single phase, incompressible fluid production from a closed reservoir. DCA is more than a empirical curve fit.
- Fetkovitch 1980 and 1983 developed set of type curves to enhance application of DCA.
- Doublet and Blasingame 1995 developed theoretical basis for combining transient and boundary dominated flow for the pressure transient solution to the diffusivity equation.

Back to top

Decline curve analysis (DCA) today

The major application of DCA in the industry today is still based on equations and curves described by Arps. Arps applied the equation of Hyperbola to define three general equations to model production declines.

In order to locate a hyperbola in space one must know the following three variables.

1. The starting point on Y axis, (qi), initial rate.
2. Initial decline rate (Di)
3. The degree of curvature of the line (b).

Arps did not provide physical reasons for the three types of decline. He only indicated that exponential decline (b=0) is most common and that the coefficient b generally ranges from 0 to 0.5.

$$q(t) = \frac{q_i}{(1 + bD_i t)^{1/b}}$$

Exponential Decline and Harmonic decline are special cases of the Hyperbolic case where the value of exponent b is 0 and 1 respectively

Arp's Equation for General Decline in a Well .... (1)

Clearly all wells do not exhibit exponential behavior during depletion. In many cases a more gradual hyperbolic decline is observed where rate time performance is better than estimated from exponential solutions implying that hyperbolic decline results from natural and artificial driving energies that slow down pressure depletion. Hyperbolic decline is observed when reservoir drive mechanism is solution gas cap drive, gas cap expansion or water drive. It is also possible where natural drive is supplemented by injection of water gas. The type of decline and its characteristic shape is a major feature of DCA. We shall be talking more about this as we go further. The various types of declines experienced by a well are documented in the **Fig 1** and**Fig 2**.

INSERT FIGURE 1 q vs. Time showing various types of declines on Cartesian plot. (b value for hyperbolic curve =0.5) (Pending permission approval)

INSERT FIGURE 2 Log q vs. Time showing various types of declines on Semilog plot. (b value for hyperbolic curve =0.5). Note change in shapes of curves. (Pending permission approval)

Observe the change in Shapes of curve from Cartesian to logarithmic; this is very helpful in identification of type of decline.

Two sets of curves are normally used while analyzing production decline.

1. Flow rate is plotted against Time:
    a. Very convenient since it provides future profiles directly.
1. Flow rate against cumulative production:
    a. Able to incorporate impact of intermittent operations that impact production.
    b. Provide recovery estimates at a specific economic limit.

Back to top

INSERT FIGURE 3 Rate verses Time and Rate verses Cum Oil (Pending permission approval)

Exponential Decline

Since b=0, Equation 1 can be re arranged as:

- $q = q_i e^{-dt}$ -- -(2)
- Variables
    - q = current production rate
    - q i = initial production rate (start of production)

  - d i = d = dt = nominal decline rate (a constant)
  - t = cumulative time since start of production
  - The most conservative and simplest equation of the decline curve family.
- Effective decline rate D remains constant over time.
- Log rate vs. time is a straight line on semi-log plot.
- Rate vs. cumulative is a straight line on a linear plot as shown below:

$$Np = \int_{t1}^{t2} q \, dt = \int_{t1}^{t2} q_i e^{-dt}$$

$$= \frac{q_1 - q_2}{d}$$

--------------(3)

Applies to a well producing at constant bottom hole pressure.

INSERT FIGURE 4 Rate vs. Time – Exponential Decline (Pending permission approval)

INSERT FIGURE 5 Rate vs. Cum Oil – Exponential Decline (Pending permission approval)

Reservoir types with exponential declines[1]:

- Oil reservoirs
  - Above the bubble point
  - Down dip wells with gravity drainage
  - Solution gas drive with unfavourable kg/ko
- Gas reservoirs
  - High reservoir pressure (liquid-like compressibilities)
  - Wells with liquid-loading problems
- Both oil and gas reservoirs
  - Produced with small drawdown relative to reservoir pressure
  - Tubing limited wells.

Back to top

Nominal and Effective decline

- There are two types of decline factors (often called the decline rate).
- The nominal decline factor d is defined as the negative slope of the curve representing the

natural logarithm of the production rate q vs. time t or :

d = $-\frac{d(\ln q)}{dt} = -\frac{1}{q}\frac{dq}{dt}$

- Nominal decline is a continuous function and it is the decline factor that is used in the various mathematical equations relating to decline curve analysis. For exponential decline it is a constant with time.
- The effective decline factor D is a stepwise function that is in better agreement with data recording practices. It is the drop in production rate from qi to q1 over a specific time period.
- It is defined as

D = $\frac{q_i - q_1}{q_i}$

- D is the effective decline rate = the decline rate over a time period.
    - This is the decline often quoted in e.g. commercial software decline graphs. Such software may, at users discretion, report nominal decline.
    - It is the proportion by which the production rate reduces over a given time period.
    - D is a constant only for constant percentage or exponential decline.
    - D decreases with time for hyperbolic and harmonic decline
    - (1> b > 0)
- It is easy to convert from a nominal decline factor to an effective decline factor and vice versa.

$D = 1 - e^{-d}$

- Thus an ‘effective’ decline of 10 % per year is equivalent to a nominal decline of 10.54% per year and vice versa

INSERT Figure 6 Effective and Nominal Decline, Shape and Relationship (Pending permission approval)

Back to top

Hyperbolic Decline

Flowrate

$$q = \frac{q_i}{\left(1+bd_i t\right)^{\frac{1}{b}}}$$ ---(4)

Cumulative production

$$N_p = \left[\frac{q_i^b}{(b-1)d_i}\right] * \left[q^{(1-b)} - q_i^{(1-b)}\right]$$ ----------------(5)

Variables

- q = current production rate
- q i = initial production rate (start of production)
- d i = initial nominal decline rate at t = 0
- t = cumulative time since start of production
- N p = cumulative production being analyzed
- b= hyperbolic decline constant (0 < b < 1)
- This is the most general formulation for decline curve analysis. Exponential (b=0) and harmonic (b=1) decline are special cases of this formula.

Back to top

Three constants

The mathematical equation defining hyperbolic decline has three constants

- The initial production rate
- The initial decline rate (defined at the same time as the initial production rate)
- The “hyperbolic exponent” b.
  - For most conventional analysis, 0 <b <1
  - However for some cases b > 1 has also been found.

Decline rate is not a constant

The decline rate is not a constant but changes with time, since the data plots as a curve on semi-log paper

Back to top

Hyperbolic exponent

The hyperbolic exponent (b) is the rate of change of the decline rate with respect to time. This means that "b" is the second derivative of production rate with respect to time.

$$d_t = \frac{d_i}{(1 + bd_i t)} \quad \text{----------------------------------(6)}$$

Hyperbolic decline constant

The hyperbolic decline constant at some future time, t, is defined by the following equation:

- High b exponents give small values of d, i.e. (= flat decline curves)—WATCH OUT!
- Unconstrained hyperbolic "curve fits" can severely overestimate future production
- Often useful (and safe) to use some value of minimum effective decline to avoid over-flattening the curve (say 5 % per annum)
- Hyperbolic curve fits with a decline constant (b) greater than 1 usually imply production is being influenced by transient behavior. For example b=2 corresponds to transient linear flow and is commonly found with unconventional reservoirs. However, be very careful with these cases – you should build limits into your forecast to capture the eventual transition from transient to boundary dominated flow.

Back to top

Definition of b

The term 'b' has no units and is normally known as hyperbolic constant. Generally 'b' can range in value from 0 to 1 in the context of DCA for oil and gas wells. It is evident from **Eq 1** that a large value of b (close to 1) has a dominant effect on shape of the curve q vs. t as t becomes large. This causes and maintains the shape of the curve during this time to be essentially flat. For a given set of values for q and b the short term shape for the curve is not largely effected by the value of b but the long terms shape is. This implies that in short term all decline curves; exponential, hyperbolic and harmonic give similar results. However due the very same reasons make it extremely difficult to determine the value of b. The problem is aggravated if the data is noisy (which is often the case) making it possible to fit a wide range of b values to the same dataset. However since the value of b has large impact in the late time, it will lead to different estimates of EUR. Reliability in estimation of b increases with maturity of production data. The value of b captures a large number of physical events and processes. A large body of publications are dedicated to this topic.

Minimum decline

- Need to use some value of minimum decline slope to avoid over-flattening of curve
  - Convert to exponential decline when dt< dmin
  - Dmin obtained from most mature wells in the field, analogous fields of "experience"
- Forecast of ultimate recovery should give a reasonable recovery factor based on estimated volumes of hydrocarbons in place.

INSERT Figure 7 Application of minimum decline concept (Pending permission approval)

Back to top

Harmonic decline

- Flowrate

$$q = \frac{q_i}{(1 + d_i t)}$$

- Cumulative production

$$N_p = \left[\frac{q_i}{d_i}\right] * \ln\left[\frac{q_i}{q}\right]$$

- Variables
  - q = current production rate
  - q i = initial production rate (start of production)
  - d i = initial nominal decline rate at t = 0
  - t = cumulative time since start of production
  - N p = cumulative production being analyzed

    - A simple formula – often the most optimistic case
- Plot of log rate vs. cumulative production is a straight line on semi-log plot

Back to top

Determining the type of decline

Based on what has been covered so far, the engineer performing a DCA analysis needs to be aware of the following:

1. The most representative period in history that will also represent future.
2. The decline trend during that period.
3. The start point(rate) of forecast .
4. The constraints under which the forecast needs to be made.

However one more factor, also extremely important at this stage is to determine type of decline. Since the signature of shape may not be apparent on a log q vs. time (most used plot), literature provides many ways was to look at the same data, combine this information with other knowledge about the fields before we make our conclusions. .

As shown in Figures 8 to 11 Shapes of curves for the same data plotted in different ways helps determine the type of declines. (Pending permission approval)

INSERT Figure 8: Rate vs. Cum Oil - Cartesian Axes – Exponential decline is a straight line (Pending permission approval)

INSERT Figure 9: Log Rate vs. Cum Oil - Semilog – Harmonic decline is a straight line (Pending permission approval)

INSERT Figure 10: Rate vs. Time - Cartesian Axes (Pending permission approval)

INSERT Figure 11: Log Rate vs. Time - Semilog – Exponential decline is a straight line (Pending permission approval)

Back to top

Decline curves for reserve estimates

A major use of decline curve analysis is made in estimation of reserves. Even for the assets where history matched simulation models are available, a cross check with DCA is normally made to give increased confidence in numbers.

The fact that DCA does not have a theoretical basis is an asset here since financial institutions are more acceptable to DCA estimates than other more technical methodologies. A major difference when applying DCA for estimation of reserves arises understandably due the very nature of definitions of reserves and financial implications associated with the process. The ultimate recovery numbers become more important than the profiles. Application of constraints in the production system, operating costs, capital costs and well behavior itself all need to be put into right perspective to come up with reliable estimations.

An in-depth description of application of DCA to reserves estimation is outside the purview of this guideline, however some typical situation and their treatment are discussed in section II of this chapter.

While everything else remains same, estimation of reserves does come up with several typical situations to which there are no ready answers. Some of these situations are listed out below for reference. The solutions to these problems could vary from engineer to engineer or organization to organization. Some of the best practices have however been compiled and can be found in production forecasting principles and definition (http://petrowiki.org/Production_forecasting_principles_and_definition).

- What should be the start point of the forecast if rate changes significantly in last or last few months.
- How to get a P10, P50, P90 estimate using decline curves.

Back to top

Using decline curves

Decline analysis and forecasts generated based on such analysis (whether production profiles or reserves) should be fundamentally grounded in good understanding of the factors that control this behavior.

'No One size fits all ' this principal applies truly and universally when it comes to application of DCA. Specifically always arbitrarily using an exponential decline approach for water drive, solution gas drive and gravity drainage systems is neither technically not empirically justified.

DCA in waterflood and ratio plots

Field cases as well as analytical / simulation generally support hyperbolic/harmonic decline for late stage waterflood behavior meaning that value of b lies $0<b<1$. This is not to say that exponential decline or super harmonic decline will/may not occur in waterflood reservoirs. However whenever such phenomenon is observed, usually non reservoir factors are at play.

In order to estimate future waterflood performance we need to examine what is controlling the oil decline rate. After substantial water breakthrough, the rate is usually controlled by

- Relative permeability
- Changing volumetric sweep
- Water handling constraints
- Fluid rates handling constraints
- Permeability injectivity in near wellbore regions
- Well positions.

Back to top

DCA as applied to Waterflood cases needs to consider the following criteria (Reservoir Management for Waterfloods, R O Baker, JCPT, Jan 1998):

- Watercut is greater than 50%
- Voidage replacement ration is close to or equal to 1
- Well count is relatively stable
- Injection rates and fluid production rates remain fairly stable
- Reservoir pressure remains relatively constant
- The volume of water injected should be greater than 25% of the hydrocarbon pore volume.

RF vs. HCPVI, Log (WOR) vs. Np, Log (Qo+Qw) vs. Np and Masoner plots should be also used in waterflood cases in addition to conventional methods mentioned earlier to ensure estimation of incremental recoveries due to Waterflood and/or impact on recovery due to constraints in the system. As a special case, Roland

Horne..et al (SPE 83470) have proposed techniques to apply DCA on naturally fractured reservoirs that have been developed using waterflooding.

Ratio plots

Reservoirs producing with high watercut, high GOR need to be analyzed using ratio plots in conjunction with conventional plots to ensure there is no overestimation of volumes based on rate plots only. (Log WOR vs. Np, Log GOR vs. Np, Watercut vs. Np). Care needs to be taken to understand the minimum criteria for application of these plots. For example Log WOR vs. Cum Oil should only be used if WOR is equal to or higher than 1 (water cut is equal to higher than 50%).

INSERT Figure 12: Ratio plot WOR vs. Cum Oil – Characteristic Shapes (Pending permission approval)

Back to top

Advanced Work

The DCA technique is most reliable for wells producing at high drawdown against relatively constant flowing pressures, such that the production rate decline mirrors the decline in reservoir pressure. Because of this tie to reservoir pressure, most practitioners restricted its use to the boundary-dominated flow period. However, development of tight and unconventional reservoirs has extended its usage in the transient flow period, necessitating the development of alternative techniques that generally attempt to match the transient and boundary-dominated flow periods using separate parameters. The decline curve treatment offered by Arps was largely applicable to boundary dominated flow (depletion period), whereas Fetkovich focused on the early period of production i.e. transient flow and came up with set of type curves that could be combined with Arps empirical decline curve equation.

Accordingly, the Fetkovich type curves are made up of two regions which have been blended to be continuous and thereby encompass the whole production life from early time (transient flow) to late time (boundary dominated flow)

The right hand side of Fetkovich type curves is identical to Arps type curve as shown below:

INSERT Figure 13: Arp's Dimensionless curve for empirical Rate-time decline Equations (Pending permission approval)

The left hand side of Fetkovich type curves are derived from the analytical solution to the flow of a well in the center of a finite circular reservoir producing at a constant wellbore flowing pressure. Fetkovich was able to demonstrate that for all sizes of reservoirs, when transient flow ended, the boundary dominated flow could be represented by an exponential decline as shown below:

Back to top

INSERT Figure 14: Fetkovich Rate Decline Curves (Pending permission approval)

Combining the Fetkovich transient type curves with Arps decline curves and blending them where the two sets of curves meet, results in Fetkovich Decline Type Curves as shown below:

Important: Fetkovich noted that sometimes the value of b as determined using Arps decline curves was greater than 1(expected to be between 0 and 1). He explained that this could happen if the data being analyzed was still in transient condition and has not reached boundary dominated flow.

INSERT Figure 15: Fetkovich Decline type curves (Pending permission approval)

Methods specifically developed for unconventional resources are covered in detail in Types of decline analysis in production forecasting (http://petrowiki.org/Types_of_decline_analysis_in_production_forecasting).

Back to top

References

1. Fetkovich, M. J., Fetkovich, E. J., & Fetkovich, M. D. 1996. Useful Concepts for Decline Curve Forecasting, Reserve Estimation, and Analysis.

Society of Petroleum Engineers. http://dx.doi.org/10.2118/28628-PA

Noteworthy papers in OnePetro

Noteworthy books

Society of Petroleum Engineers (U.S.). 2011. Production forecasting. Richardson, Tex: Society of Petroleum Engineers. WorldCat (http://www.worldcat.org/oclc/776204491) or SPE Bookstore (http://store.spe.org/Production-Forecasting-P623.aspx)

External links

Back to top

See also

Production forecasting glossary (http://petrowiki.org/Production_forecasting_glossary)

Aggregation of forecasts (http://petrowiki.org/Aggregation_of_forecasts)

Challenging the current barriers to forecast improvement (http://petrowiki.org/Challenging_the_current_barriers_to_forecast_improvement)

Commercial and economic assumptions in production forecasting (http://petrowiki.org/Commercial_and_economic_assumptions_in_production_forecasting)

Controllable verses non controllable forecast factors (http://petrowiki.org/Controllable_verses_non_controllable_forecast_factors)

Discounting and risking in production forecasting (http://petrowiki.org/Discounting_and_risking_in_production_forecasting)

Documentation and reporting in production forecasting (http://petrowiki.org/Documentation_and_reporting_in_production_forecasting)

Empirical methods in production forecasting (http://petrowiki.org/Empirical_methods_in_production_forecasting)

Establishing input for production forecasting (http://petrowiki.org/Establishing_input_for_production_forecasting)

Integrated asset modelling in production forecasting (http://petrowiki.org/Integrated_asset_modelling_in_production_forecasting)

Long term verses short term production forecast (http://petrowiki.org/Long_term_verses_short_term_production_forecast)

Look backs and forecast verification (http://petrowiki.org/Look_backs_and_forecast_verification)

Material balance models in production forecasting (http://petrowiki.org/Material_balance_models_in_production_forecasting)

Probabilistic verses deterministic in production forecasting (http://petrowiki.org/Probabilistic_verses_deterministic_in_production_forecasting)

Production forecasting activity scheduling (http://petrowiki.org/Production_forecasting_activity_scheduling)

Production forecasting analog methods (http://petrowiki.org/Production_forecasting_analog_methods)

Production forecasting building blocks (http://petrowiki.org/Production_forecasting_building_blocks)

Production forecasting decline curve analysis (http://petrowiki.org/Production_forecasting_decline_curve_analysis)

Production forecasting expectations (http://petrowiki.org/Production_forecasting_expectations)

Production forecasting flowchart (http://petrowiki.org/Production_forecasting_flowchart)

Production forecasting frequently asked questions and examples (http://petrowiki.org/Production_forecasting_frequently_asked_questions_and_examples)

Production forecasting in the financial markets (http://petrowiki.org/Production_forecasting_in_the_financial_markets)

Production forecasting principles and definition (http://petrowiki.org/Production_forecasting_principles_and_definition)

Production forecasting purpose (http://petrowiki.org/Production_forecasting_purpose)

Production forecasting system constraints (http://petrowiki.org/Production_forecasting_system_constraints)

Quality assurance in forecast (http://petrowiki.org/Quality_assurance_in_forecast)

Reservoir simulation models in production forecasting (http://petrowiki.org/Reservoir_simulation_models_in_production_forecasting)

Types of decline analysis in production forecasting (http://petrowiki.org/Types_of_decline_analysis_in_production_forecasting)

Uncertainty analysis in creating production forecast (http://petrowiki.org/Uncertainty_analysis_in_creating_production_forecast)

Uncertainty range in production forecasting (http://petrowiki.org/Uncertainty_range_in_production_forecasting)

Using multiple methodologies in production forecasting (http://petrowiki.org/Using_multiple_methodologies_in_production_forecasting)

Back to top

Category