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Abstract

Introduction:

Well performance analysis generally refers to the analysis and interpretation of production rates and pressures from producing wells to estimate ultimate recovery and to evaluate dynamic reservoir properties (permeability and other reservoir properties depending on the geological model) and completion parameters (skin factor, fracture half-length, etc.). From a broader perspective, results from well performance analyses provide insights into and facilitate reservoir characterization, field development planning, and completion optimization.

Well performance analyses (WPA) (*i.e.*, analyses of production and pressure data) can be categorized into specific methodologies as follows:

- Time-rate analysis (or Decline Curve Analysis (DCA)).
- Time-pressure data (Pressure-Transient Analysis (PTA)).
- Time-rate-pressure data (Rate-Transient Analysis (RTA)).

However, it should be noted that well performance analysis should not be confined to application of these methods based solely on measure production rate and pressure data. Instead utilization of these methods in conjunction with the integration of key subsurface data and completion diagnostics provides a better understanding of the system and leads to better decisions.

History, Background and Original Concepts:

Traditionally, well performance analysis methodologies include analysis of time-rate (DCA) and time-pressure (PTA), and time-rate-pressure (RTA) data. So-called "decline curve analysis" (DCA) has been the standard practice since the early 1900s to estimate future production and ultimate recovery for

producing wells. Methods for decline curve analysis are generally data-driven and tend to rely on empirical equations; and/or relations that are derived from analytical expressions using idealized conditions or assumptions (*e.g.*, the constant wellbore pressure case). For example, Arps' exponential and hyperbolic relations (presented by Arps' in 1945, but actually first published by Johnson and Bollens in 1928) are still widely used by industry to estimate ultimate recovery and to book reserves and resources.

The decline curve analysis literature has been greatly expanded over the last 10 years, coincident with the exploitation of low/ultra-low permeability ("unconventional") reservoirs. Today, many decline curve relations are available in the literature which are based on a certain characteristic behavior and/or related to a specific flow regime. While some of these "transient" solutions are based on theoretical considerations, the assumptions and applications are often empirically-derived. Lastly, many of these relations have similar characteristics, and at least to the present, none are fully rigorous, all proposed relations have some limiting condition(s) and/or assumption(s). As one would expect, the absence of relatively long- term production (>10-15 years) from unconventional reservoirs presents significant challenges for empirical methods. Specifically, many models may match the historical production, but there is little strong support for extrapolation to say, 30 years.

In contrast, analysis methods based on time-rate-pressure data are derived from rigorous fluid flow theory, which requires an appropriate representation of the reservoir system (infinite-acting, bounded, homogeneous or heterogeneous, etc.), the wellbore geometry (unfractured or fractured vertical or horizontal well), and resulting the mathematical formulation (*i.e.*, the diffusivity equation). Utilization of traditional concepts of porosity and other reservoir parameters has led to the widespread use of "Darcy-flow" type models throughout the industry. In this context, well performance analyses are tied to "traditional" concepts such as permeability, porosity, fracture surface area, standard reservoir boundaries (circular, rectangular, etc.), etc. Well/reservoir models include representations of wells in homogeneous reservoirs, horizontal wells, fractured vertical wells, horizontal wells with multiple fractures, etc. — all within the framework of Darcy-flow based formulations. Currently, software packages for well performance analysis include a large inventory of models to analyze/interpret/forecast production data — where all of these models are based on Darcy's law, as well as traditional fluid thermodynamics and reservoir model constructs.

Application of traditional RTA/PTA/DCA concepts in unconventional reservoirs may be problematic due to the unique nature of unconventional reservoir systems (*e.g.*, very low permeability, self-sourced production, organic porosity, complex fracture geometry(s), etc.). At present, there are no "new" methodologies specific to nano-scale storage and transport (*i.e.*, molecular-level storage and Knudsen-type flow behavior), although there are new means of modeling such behavior (*e.g.*, anomalous diffusion, as well as "fractal" models as a proxy). This situation leaves us with empirical decline curve models and "traditional" Darcy-flow type models along with conventional porosity and permeability concepts. Complex fracture geometries can be addressed by increasing capabilities of reservoir modeling software packages — however; it should be emphasized that even complex models retain some connection to traditional permeability and porosity concepts (*i.e.*, although the flow geometry may be quite complex, the "bulk" behavior appears to be represented by "normal" permeability and porosity concepts).

Well performance analysis studies conducted using reservoir simulation provide a more complete view of the "well-reservoir" system, which in turn leads to better understanding of the reservoir system and the key production mechanisms (in particularly the ability to establish the effects of infill wells and different production schemes). Reservoir simulation studies require integration of data from all disciplines — geology/geophysics, petrophysics, geomechanics, reservoir engineering, production and completions; where such integration may not be possible in all cases and is often cost prohibitive in terms of time and resources.

In addition, reservoir simulation-based numerical models are most often based on traditional concepts of porosity and permeability (it is important to note that there are research efforts using nano-scale models for storage and transport, but none are known or likely to be practical for modelling large-scale systems in the near future). Lastly, reservoir simulation models are much more complex than RTA/PTA/DCA techniques based on single well models, and as such reservoir simulation models can be adapted to include virtually any/all aspects of production mechanisms (*i.e.*, geomodels(s), phase behavior characterization, complex flow geometries (*e.g.*, discrete fracture networks), multi-well production, staged-developed (*e.g.*, "parent-child" well cases).

Current Status:

Well performance analysis based on PTA/RTA techniques are becoming more popular and benefit from increasing computational power and data acquisition. The main limitation of these techniques can be associated with lack of supplementary data that would be used to constrain analyses and reduce uncertainty. As comment, the quality of time-rate-pressure data is extremely important — currently production data can be rendered on a hourly basis (or less) and the continuous measurement of bottomhole pressures (and temperatures) is becoming more frequent and these data provide significantly better resolution of production and pressure trends, particularly for analysis and forecasting.

With the advent of large-scale unconventional reservoir development, diagnostic techniques have become critical tools for performance assessment prior to the construction of analysis/forecasting model. Specifically, production diagnostic techniques are essential for understanding flow regimes and for establishing characteristic flow behavior which can be translated to decline curve parameters, as well as establishing productivity metrics. Productivity metrics can include volume-based metrics (*e.g.*, cumulative oil/gas/water production at 1/3/6/9/12 months, pressures (average flowing pressure over a month, pressure gradient, initial pressure, etc.)), as well as productivity indices such as establishing linear flow behavior from specialized plots.

Production diagnostic techniques also allow for comparing performance of multiple wells, and specifically provide the ability to contrast differences due to: well completions, reservoir target intervals, lateral well spacing, etc. Completion metrics — *i.e.*, well completion and well stimulation parameters can easily be integrated into models for the analysis of well performance, as well as for creating correlations with well performance metrics.

As a practice, the use of well performance analysis methods is crucial for workflows encompassing well completion design, reservoir characterization, and field development. And perhaps more importantly, the deliverables from well performance analyses provides for the optimization of well performance, establishment of factors that control production and reserves, and benchmarking productivity across an area of interest. More importantly, performance-based workflows may be used to develop "recipes" for field developments which would be tied to well spacing, target, completion size and stages, flowback strategy, choke management, and artificial lift.

Next Steps and Conclusions:

The overall goal of this document is to illustrate the utility of well performance analysis methods as these pertain to integrated workflows for field development. It should be noted that a critical review of existing well performance analysis methods in unconventional reservoirs does clearly illustrate the challenges and limitations of traditional reservoir engineering concepts. At present, the priority area of interest is horizontal well spacing in unconventional reservoirs — many operators in North America have suffered

from "over-drilling" and over-estimation of future production recently in areas such as the Permian Basin (Delaware Basin (TX/NM) and Midland Basin (TX)), the Eagle Ford Shale (TX), the Niobrara/Codell (CO), the Marcellus Shale (PA/OH/WV), Bakken Shale (ND), and the Montney Shale (AB). Without clear learnings and guidance, other emerging plays may suffer the same fates (the Vacca Muerta (Argentina) and the Powder River Basin (WY)).

In addition, the effects of depletion on new wells due to existing producing wells (the so-called "parent-child" effects) have yet to be properly quantified or understood. One of the main goals of reservoir engineering is to determine "minimum" number of wells that it would take to "maximize" recovery from a given field or play — this is particularly difficult for unconventional plays. Attempts to provide "cube or tank" developments (*i.e.*, where well patterns are prescribed and drilling/completion/stimulation/flowback are performed simultaneously (or nearly so)), have had mixed results (most recent reports are negative).

These circumstances take us back to "fit-for-purpose" designs based on geology and well development strategies (*i.e.*, tailored completions and stimulations). Such "fit-for-purposes" will require more design considerations and more diagnostic/analysis/modeling efforts for the resulting well performance data. As such future efforts for well performance analysis in unconventional reservoirs will primarily focus on understanding fundamental behavior of these systems and reflect that understanding into physical models which can be used to analyze, interpret and forecast production data from these reservoirs.

As a final (and general) comment, improvements in production surveillance and diagnostic interpretation techniques will add significantly to the value obtained from performance-based reservoir characterization/development workflows. A considerable number of operators often ignore or pay little attention to collection of this type of data without realizing the value of such information that could potentially lead to better well completions, better targeting and better well spacing.