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Rate-transient analysis of liquid-rich tight/shale reservoirs using the dynamic drainage area concept: Examples from North American reservoirs

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ABSTRACT

The early-time performance of multi-fractured horizontal wells is mainly controlled by fracture geometry, total effective area of the fractures, and conductivity of the primary fracture system. Inverse modeling using rate-transient analysis (RTA) methods has historically been used to characterize MFHWs at different stages of well life, including the early-time performance. In particular, linear flow analysis is used to estimate the total effective fracture area from online production data, provided that reservoir and fluid properties are known. However, a primary complication in analytical linear flow analysis is the incorporation of nonlinearities such as multi-phase flow and pressure-dependent rock/fluid properties into the calculations.

A new linear flow analysis technique is presented in the current study, which can be applied to tight/shale systems with multi-phase flow and pressure-dependent rock/fluid properties. The method combines three important reservoir engineering concepts for linear flow analysis: dynamic drainage area (DDA), material balance, and decoupling of saturation and pressure (which is analogous to the decoupling of geomechanics and fluid flow). The DDA approach has been used previously by the authors for history-matching and forecasting using a semi-analytical model, but not for inverse modeling (RTA). The DDA concept, which uses a time-dependent well productivity index equation for the transient flow period, facilitates the incorporation of any sort of nonlinearity (including decoupled saturation functions) and operational constraints in modeling and RTA of linear flow in MFHWs.

The method is validated against numerical simulation and applied to various sets of field production data from tight/shale gas and oil wells with different levels of condensate- (oil-) gas ratio. For all the field cases, total effective fracture area obtained from the new analytical RTA method is in reasonable agreement with numerical modeling results.

Regarding accuracy and practicality, the new method represents an improvement in RTA of liquid-rich tight/shale reservoirs, particularly for cases with multi-phase flow and pressure-dependent rock/fluid properties. Further, the concepts used in the new model development are easy to understand and implement.

1. Introduction

Application of the game-changing multi-fractured horizontal well (MFHW) technology in tight/shale reservoirs results in a volume of the reservoir accessed through a complex fracture system created by high pressure injection of fracturing fluid. Characterization of such a complex system using physics-based flow models is a goal in reservoir engineering of tight/shale reservoirs. As summarized by Clarkson et al. (2016), there are multiple independent methods for characterization of MFHWs including fracture (geomechanical) modeling, fracture monitoring (microseismic), early-time fracturing fluid flowback analysis, and long-term (online) production data analysis (PDA) or RTA. Each method utilizes specific data collected during completion and production: integration of the results of the whole suite of analyses is a reasonable practice to better characterize the system and

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reduce the uncertainty. In a study by Clarkson et al. (2014), fracture half-lengths obtained from RTA were shown to be smaller than those derived from fracture modeling/monitoring or flowback analysis: the authors attributed this to various mechanisms reducing the effective contributing half-length of the fractures during long-term production.

Primary challenges for data analysts hoping to extract quantitative fracture and reservoir properties from RTA of tight/shale reservoirs include data quality and the lack of available rigorous, physics-based models. The former is essential in the current economic environment, and requires collaboration between different professionals in a company. As for the latter, all of the aforementioned characterization tools for MFHWs are indirect methods in which the collected data sets are analyzed using mathematical models with simplifying assumptions. Simplifying assumptions are inevitable primarily for two reasons: the lack of detailed data and information about the MFHW system (e.g. fracture geometry, fluid distributions, geological heterogeneity etc.); and limited capabilities of some of the existing mathematical tools, particularly analytical techniques. Standard RTA methods, in particular, are limited to the analysis of production from single-phase systems with slight pressure-dependency of rock and liquid phase properties. For linear flow analysis of oil systems, the slope of rate-normalized pressure, $(p_i - p_{wf})/q_o$, versus oil linear superposition time is used to calculate total $A_c\sqrt{k_i}$, which is equal to $4hx_{ft}\sqrt{k_i}$ for a MFHW (El-Banbi, 1998):

$$\frac{p_i - p_{wf}}{q_o} = m_{cq} t_{LST} \tag{1}$$

$$A_c\sqrt{k_i} = \frac{79.71 B_o}{m_{cq}} \sqrt{\frac{\mu_{oi}}{\varphi_i c_{ti}}} \tag{2}$$

Similarly, the slope of the linear flow plot for gas (plot of rate-normalized pseudopressure, $[m_g(p_i) - m_g(p_{wf})]/q_g$, versus gas linear superposition time) is used to calculate total $A_c\sqrt{k_i}$.

$$\frac{m_g(p_i) - m_g\left(p_{wf}\right)}{q_g} = m_{cq} t_{LST} \tag{3}$$

$$A_c\sqrt{k_i} = \frac{803.4T}{m_{cq}} \sqrt{\frac{1}{\varphi_i \mu_{gi} c_{ti}}} \tag{4}$$

Different methods have been introduced over the past few years for incorporation of nonlinearities associated with pressure-dependent fluid and rock properties and two-phase (gas and oil/condensate) flow in RTA of tight/shale systems. Ibrahim and Wattenbarger (2006) used an empirical correction factor (based on numerical simulation results) for linear flow analysis of single-phase gas systems. Qanbari and Clarkson (2013a, 2013b) developed an analytical correction factor for linear flow analysis of gas and oil systems with stress-dependent permeability and two-phase flow of gas and oil using an iterative integral method. Nobakht and Clarkson (2012), Tabatabaie (2014), and Behmanesh et al. (2015b) employed pseudotime functions evaluated at average pressure in the investigated area during transient flow to linearize the nonlinear flow equation. Qanbari and Clarkson (2014) correlated pressure-dependent diffusivity with a pressure function for which the corresponding flow equation has an exact analytical solution. Mohan et al. (2013) and Eker et al. (2014) incorporated multiphase flow into RTA of tight systems using total equivalent rate instead of the primary fluid rate.

In this paper, the concept of dynamic drainage area (DDA), combined with material balance and decoupling of saturation and pressure, is used to construct a modified linear flow plot (plot of rate normalized pseudopressure vs. square-root of time), referred to herein as the DDA-corrected linear flow plot. In the previous work by the authors (Clarkson and Qanbari, 2016a, b), the DDA concept was used for forecasting, while in the current work, it is used for inverse modeling. This is an alternative method for incorporation of nonlinearities into the RTA of tight/shale reservoirs. In the following sections, the method is introduced, validated against synthetic cases (generated by numerical models), and applied to field cases.

2. Theory and method development

2.1. Dynamic drainage area

Recently, Clarkson and Qanbari (2016a) used the dynamic drainage area (DDA) concept as an approximate semi-analytical method for history matching and forecasting MFHWs in tight/shale reservoirs; the method was later extended to history matching and forecasting horizontal wells completed in low-permeability, undersaturated coalbed methane reservoirs Clarkson and Qanbari (2016b). In this method, the distance of investigation is calculated at each time step during the transient flow period and a time-dependent linear productivity index equation with pseudo-pressure is used for rate calculation. As noted by Clarkson and Qanbari (2016a), various forms of the time-dependent productivity index equation have been used by Muskat (1937), Lee et al. (1998), and Shahamat et al. (2014). Fig. 1 illustrates the distance of investigation concept and the parameters that are calculated at two time steps (including distance of investigation, average pressure and saturation, gas and oil rates).

In the current work, the DDA method is applied in backward mode as an RTA tool in which gas and oil rates are known. In backward mode, the DDA equations for linear flow of oil and gas are as follows (derivations are provided in the Appendix for completeness):

$$\frac{m_o(\overline{p}_{inv}) - m_o\left(p_{wf}\right)}{q_o} \sqrt{\frac{\mu_{oD}(\overline{p}_{inv})\varphi_D(\overline{p}_{inv})c_{tD}(\overline{p}_{inv})}{k_D(\overline{p}_{inv})}} = \frac{57.16 B_{oi}}{A_c\sqrt{k_i}} \sqrt{\frac{\mu_{oi}}{\varphi_i c_{ti}}}\sqrt{t} \tag{5}$$

and

$$\frac{m_g(\overline{p}_{inv}) - m_g\left(p_{wf}\right)}{q_g} \sqrt{\frac{\mu_{gD}(\overline{p}_{inv})\varphi_D(\overline{p}_{inv})c_{tD}(\overline{p}_{inv})}{k_D(\overline{p}_{inv})}} = \frac{576.56T}{A_c\sqrt{k_i}} \frac{\sqrt{t}}{\sqrt{\varphi_i \mu_{gi} c_{ti}}} \tag{6}$$

Eqs. (5) and (6) use pseudo-pressure drawdown with respect to average pressure in the investigated area during transient linear flow, which is obtained from material balance equations as discussed in the following subsection. Oil and gas pseudo-pressures in Eqs. (5) and (6) are defined as:

$$m_o(p) = \int\limits_{p_0}^{p} \left\{ \frac{k_D(\widehat{p}) k_{ro}(S_o)\widehat{p}}{\mu_{oD}(\widehat{p}) B_{oD}(\widehat{p})} \right\} d\widehat{p} \tag{7}$$

$$m_g(p) = \int\limits_{p_0}^{p} \left\{ \frac{2k_D(\widehat{p}) k_{rg}(S_o)\widehat{p}}{k_i \mu_g(\widehat{p}) Z_g(\widehat{p})} \frac{B_g(\widehat{p})}{B_{gd}(\widehat{p})} \right\} d\widehat{p} \tag{8}$$