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On the pressure-saturation path in infinite-acting unconventional liquid-rich gas reservoirs

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ABSTRACT

Unconventional liquid rich natural gas reservoirs exhibit a number of unique technical challenges, including ultra-low rock permeability, which can lead to prolonged periods of infinite-acting flow. Despite this, traditional production data analysis techniques often assume boundary-dominated conditions, which may not be experienced by unconventional systems for very long stretches in their productive life. Analysis of two-phase flow and well production often relies on the use of two-phase pseudovariables calculations for which the fluid saturation-pressure relationship must be estimated *a priori*. The de-facto assumption is that such *a priori* reservoir saturation-pressure dependency can be acquired from available constant volume depletion (CVD) or constant composition expansion (CCE) laboratory test results. As a result, the influence of reservoir characteristics or drawdown conditions on saturation-pressure path has not been rigorously investigated in general; and even less for the particular case of infinite-acting reservoir systems under linear flow regime, which is the most commonly observed flow regime in multi-fractured horizontal wells. In the present work, a recently developed semi-analytical solution for the multiphase black-oil formulation, which considers both pressure and liquid saturation as independent variables, is employed to investigate the influence of reservoir and well conditions on saturation-pressure path in linear infinite-acting liquid rich gas systems. Here, the effects of constant bottomhole flowing pressure, initial reservoir pressure, and relative permeability characteristics on pressure-saturation path are explored in a reservoir system. Results are compared to constant composition expansion (CCE) and constant volume depletion (CVD) tests, which are routinely invoked to estimate saturation-pressure path, and it is demonstrated that these tests provide very poor estimations of saturation-pressure path for all cases considered. In addition, saturation-pressure paths exhibit significant sensitivity to the parameters investigated, as a result of the significant interplay between liquid dropout and phase mobility. Finally, following the results of the sensitivity study, we use the concept of the compositionally-extended black-oil formulation to further study the physical mechanisms that control saturation-pressure path behavior, which are elucidated through an investigation of the *in situ* and flowing compositions of surface gas and surface oil pseudocomponents. The results of this paper indicate that traditional methods for estimation of the saturation-pressure path in liquid-rich unconventional systems cannot account for the influence of system parameters on liquid-phase dropout and condensate accumulation. Furthermore, production data analysis techniques must account for these dependencies to develop reliable reservoir forecasts and reserve estimations.

1. Introduction

Unconventional hydrocarbon reservoirs continue to make up an increasing proportion of energy resources in North America (EIA, 2015). Despite this, exploitation of these resources presents a number of technical challenges compared to conventional reservoirs, mainly related to their rock and fluid properties (Clarkson, 2013; Javadpour, 2009; Whitson and Sunjerga, 2012). Among these, one of the principal difficulties arises from the fact that these reservoirs often exhibit long periods of infinite-acting early-transient flow, primarily due to their ultra-low permeabilities (Behmanesh et al., 2015; Wattenbarger et al., 1998; Zhang et al.

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2014, 2016). Because of this, traditional reservoir forecasting and production data analysis techniques, which were originally developed in the context of conventional reservoir behavior and boundary-dominated flow (BDF), must be reevaluated and reformulated to be applicable in unconventional systems.

One of the fundamental tenets of traditional two-phase reservoir analysis techniques is the use of two-phase pseudovariable integral transformations (Fevang and Whitson, 1996; Walsh and Lake, 2003) where the variable of integration is reservoir pressure. For this reason, the reservoir saturation-pressure relationship must be estimated *a priori* in order to relate relative permeability functions directly to reservoir pressure. In the case of conventional reservoir systems, reservoir saturation-pressure curves are traditionally approximated by constant composition expansion (CCE) and constant volume depletion (CVD) laboratory tests results. However, this approach is assumed to be exclusively related to the *in situ*, initial reservoir fluid and independent of initial reservoir pressure conditions and well drawdown levels, and thus inherently neglects the influence of phase mobility on reservoir saturation-pressure functions. This has led to a growing body of research that suggests that laboratory-estimated saturation-pressure relationships cannot successfully predict fluid behavior in the unconventional reservoir environment (Whitson and Sunjerga, 2012; Behmanesh et al., 2015), and therefore, will not appropriately represent liquid and gas phase mobility during analysis. Furthermore, saturation-pressure behavior in unconventional reservoirs will fundamentally influence reservoir production and wellstream GOR. Because of these factors, reliable estimates of reservoir saturation-pressure functions are crucial to production forecasts of unconventional systems. Moreover, analysis techniques for unconventional reservoirs must be developed that independently consider liquid and gas saturation and do not utilize mobility predictions from *a priori* estimates of reservoir saturation-pressure relationships. An alternative approach to employing laboratory measurements of saturation-pressure data considers the dependence of producing GOR on reservoir saturation-pressure (Fevang and Whitson, 1996). For unconventional systems, some recent studies used GOR as an input, which is later coupled with CVD/CCE data to estimate pressure and saturation relationship, following steady-state flow assumption/approximation (Behmanesh et al., 2015). Using this assumption, the ratio of gas to liquid relative permeability can be explicitly expressed exclusively as a function of reservoir pressure, and two-phase pseudopressure, which depends on relative permeability to liquid and gas, reduces to a function with exclusive dependence on pressure. This method is also employed in analysis of gas condensate reservoirs that reach BDF conditions early in their production life (Sureshjani and Gerami, 2011); however, this approach necessitates the availability of production and GOR data and thus is not fully predictive in nature.

Coupled with the analysis of saturation-pressure behavior in multi-phase systems, significant effort has also been dedicated to development of analytical and semi-analytical models for the purpose of rapid characterizations and analysis of reservoir and production data. One such technique utilizes the similarity method to transform the governing partial differential equations for fluid flow into a system of ordinary differential equations. This method has been routinely employed to develop semi-analytical solutions for pressure in single- and multi-phase systems (Ayala and Kouassi, 2007; Boe et al., 1989; Doughty and Pruess, 1990; O'Sullivan, 1981). Most notably, Boe et al. employed this method to derive explicit expressions for dS_o/dp in solution-gas and gas-condensate reservoirs (Boe et al., 1989). However, a simulated saturation profile is still needed in order to solve the diffusivity for pressure due to the lack of a reliable saturation-pressure relationship in their analytical model. Furthermore, because this traditional approach considers saturation-pressure path as a known function, changes in saturation-pressure path with reservoir and well properties have not been investigated in linear infinite-acting flow regime.

Recently, Zhang et al. (2016) developed a rapid and robust similarity-based semi-analytical method that solves for pressure and saturation simultaneously. Since saturation is solved independently as a function of similarity variable, this method does not require *a priori* knowledge of the saturation-pressure path, and therefore, can be implemented to determine reservoir saturation-pressure behavior without the need for computationally intensive reservoir simulation. Following Zhang et al., this work focuses on the early-transient flow behavior of gas condensate reservoirs under linear infinite-acting constant BHP flow regime. As shown by Zhang and Ayala (2016), the saturation vs. pressure has a unique relationship under such flow regime and production conditions, regardless of the location within the reservoir or production time. The 1-D linear flow regime is the most commonly observed flow regime for fluid flowing from matrix towards infinite-conductivity fractures in unconventional reservoirs. The aim of the present work is to employ the semi-analytical approach of Zhang et al. to explore the influence of reservoir and drawdown characteristics on saturation-pressure path behavior in infinite-acting liquid-rich gas reservoirs.

To that end, saturation-pressure paths are solved in a variety of drawdown, undersaturation, and mobility conditions. Though the validity of the semi-analytical similarity-based method for multiphase conditions was previously verified in Zhang et al. (2016), its ability to capture these effects are now highlighted in this study and validated via simulation results. CCE and CVD test results are also included in comparisons in order to understand the ability of these tests to capture saturation-pressure path behavior for the systems and conditions under investigation. Later, the interplay between thermodynamic and fluid mobility behavior is explored in an effort to develop improved understanding of the controlling mechanisms of saturation-pressure path shape in these systems.

2. Methods

2.1. Reservoir and fluid conditions

Constant reservoir parameters that were used in this study are presented in Appendix A (Table A1). All simulations were conducted using a single set of PVT properties that were generated by simulating a standard constant-volume-depletion (CVD) procedure applying flash calculation using the Peng-Robinson equation of state (Peng and Robinson, 1976) to a ten-component gas condensate fluid (compositional data is presented in Appendix A, Table A2) with dewpoint equal to 2787.7 psia. The typical procedure for obtaining black-oil properties from CVD data can be found in Wlash and Lake (2003). The resulting black-oil properties are provided in Appendix A (Figure A-1). Relative permeability curves were determined by using a modified Corey correlation coupled with the van Genuchten function (Corey, 1954; van Genuchten, 1980):

$$k_{ro} = \sqrt{S_o^*}\left\{1 - \left[1 - \left(S_o^*\right)^{\frac{1}{\lambda}}\right]^{\lambda}\right\}^2 \quad (1)$$

$$k_{rg} = (1 - S_o)^2\left(1 - S_o^2\right) \quad (2)$$

Where $S_o^* = (S_o - S_{oc})/(1 - S_{oc})$, S_{oc} is the critical saturation, and λ is the van Genuchten tuning parameter. For the simulation base-case, S_{oc} is set to be 0.25, and saturation-path sensitivity to S_{oc} is evaluated in Section 3.4.