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Production data analysis of tight gas condensate reservoirs

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A B S T R A C T

The current focus on liquids-rich shale (LRS) plays in North America underscores the need to develop reservoir engineering methods to analyze such reservoirs. Commercialization of LRS plays is now possible due to new technology, such as multi-fractured horizontal wells (MFHW). Efficient production from such reservoirs necessitates understanding of flow mechanisms, reservoir properties and the controlling rock and fluid parameters. Production-decline analysis is an important technique for analysis of production data and obtaining estimates of recoverable reserves. Nevertheless, these techniques, developed for conventional reservoirs, are not appropriate for ultra-low permeability reservoirs. There are substantial differences in reservoir performance characteristics between conventional and ultra-low permeability reservoirs. LRS reservoirs produce much leaner wellstreams compared to conventional reservoirs due to very low permeabilities that result in very large drawdowns. Methods for analysis of two-phase flow in conventional reservoirs, with underlying simplifying assumptions, are no longer applicable.

This paper discusses production data analysis of constant flowing bottomhole pressure (FBHP) wells producing from LRS (gas condensate) reservoirs. A theoretical basis is developed for a gas condensate reservoir during the transient matrix linear flow (drawdown) period. The governing flow equation is linearized using appropriately defined two-phase pseudopressure and pseudotime functions so that the solutions for liquids can be applied. The derived backward model is employed to compute the linear flow parameter, $x_f\sqrt{k}$.

Simulation results show that the liquid yield will be approximately constant for LRS wells during the transient linear flow, from the early days of initial testing, if FBHP is almost constant. An analytical formulation is used to prove this finding for 1D transient linear flow of LRS wells.

The proposed production data analysis (PDA) method is illustrated using simulated production data for different fluid models and relative permeability curves. Fine-grid compositional and black oil numerical models are used for this purpose.

1. Introduction

Unconventional resources have become a reasonably reliable source of energy in North America. Horizontal drilling followed by multi-stage hydraulic fracturing (multi-fractured horizontal wells or MFHW) has become a widely employed practice for development of unconventional light oil (ULO) and unconventional gas (UG) reservoirs. There is an increased importance placed on reservoir engineering methods to analyze such reservoirs; specifically, production analysis techniques for ULO/UG must be adapted to account for the unique aspects of MFHW production. Although there have been a number of recent studies of this topic, particularly for shale gas, typically the developed PDA techniques rely on simplifying assumptions about the reservoir rock and fluid properties. In particular these studies generally assume single-phase flow, which is not valid for saturated black oil and gas condensate reservoirs.

Hydraulically-fractured vertical and horizontal wells completed in tight formations typically exhibit long periods of transient linear flow. Large drawdowns are imposed on these very low permeability formations to yield economic production. For dry gas and gas condensate reservoirs, this can give rise to large variations in gas physical properties and large gas-to-oil mobility ratio gradients near the fracture face, respectively. Some techniques for analyzing

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transient linear flow in single-phase gas reservoirs have recently been proposed (e.g. Nobakht and Clarkson, 2012). However, relatively little attention has been applied to the development of analytical methods to address the two-phase flow complexities associated with transient linear flow analysis of gas condensate reservoirs. This paper addresses production data analysis of liquids-rich shale (LRS) reservoirs with a focus on gas condensate fluid systems. The results can be used in support of short- and long-term production forecasts for liquid-rich shale.

2. Background and statement of problem

Well test analysis relies heavily upon solutions to flow equations assuming single-phase flow of a liquid with small and constant compressibility and viscosity. These solutions are often adapted for rate-transient analysis (RTA) problems. If the wellbore pressure falls below the bubble or dew point pressure, two-phase flow conditions exist and the solutions for liquids are no longer valid. However, liquid solutions for pressure- and rate-transient analysis can still be used if (for example) pseudovariables are used to correct for pressure-dependent fluid properties and for multi-phase flow (Fraim and Wattenbarger, 1987).

Analytical modeling of pressure/rate transients for multiphase flow in porous media is challenging because the nonlinearities associated with the fluid must be contended with. Since the 1950's, many investigators have proposed different approaches to tackle this problem. Perrine (1956) and Martin (1959) suggested the application of total mobility and the single-phase-flow concepts for analyzing well responses when the pressure at the wellbore falls below the bubble-point or the dew-point pressure. The premise of their theory is that at some distance from the wellbore, the saturation gradient is small enough that can be ignored. Under such circumstances, mobility and compressibility term in the single-phase flow expression may be replaced by total mobility (sum of the mobility of each of the flowing phases) and total compressibility (sum of the compressibility of each phase with each compressibility term weighted by the saturation of that phase). Later on, different investigators adapted various methods for two-phase flow in radial models. Raghavan (1976) examined solution-gas-drive systems and proposed that a two-phase pseudopressure be used to determine formation permeability from well test data. Aanonsen (1985) extended Raghavan's work and introduced the concept of the reservoir integral. Jones and Raghavan (1988) and Camacho and Raghavan (1989) analyzed drawdown and buildup responses in gas-condensate and solution-gas-drive systems respectively by using Aanonsen's concept. Jones and Raghavan (1988), Camacho and Raghavan (1989) and Hamdi et al., 2013 used the ideas of Aanonsen (1985) to analyze drawdown and buildup responses in gas-condensate and solution-gas-drive systems. Some investigators utilized the powerful "similarity method" mathematical technique for analysis of these nonlinear problems. O'Sullivan and Pruess (1980) and O'Sullivan (1981) proposed similarity solutions to highly nonlinear multiphase flow problems in geothermal well test analysis. The similarity method has also been applied in the study of multiphase flow in solution gas-drive and gas condensate reservoirs (Bøe et al., 1989; Vo et al., 1990).

In recent years, attention has shifted to low-permeability (unconventional) wells where transient linear flow is a dominant flow-regime and pressure gradients are large. Several studies (Ibrahim and Wattenbarger, 2006, Poe, 2002, Miller et al., 2010 and Nobakht and Clarkson, 2012) focused mainly on the flow of single phase gas to obtain the linear flow parameter, $x_f\sqrt{k}$. Ibrahim and Wattenbarger noted that the transient linear flow solution, derived for liquids, required the use of pseudopressure and empirical drawdown factor to account for changing gas properties with pressure. Nobakht and Clarkson (2012) later used a corrected pseudotime (as well as pseudopressure) to account for these effects. More recently, Qanbari and Clarkson (2013) and Chen and Raghavan (2013) independently presented a similarity-based methodology for infinite-acting gas linear flow analysis for constant flowing bottomhole pressure.

The analysis of two-phase flow, during the transient linear flow period, provides unique challenges that are now receiving attention. The nonlinearities associated with two-phase flow (pressure-dependent properties and high saturation gradients near the wellbore) cannot be accounted for only by incorporating saturation changes in the two-phase pseudopressure − more rigorous treatment is required to account for pressure-dependent properties of the fluids. Furthermore, the techniques that have been developed for calculation of two-phase pseudopressure in radial models cannot be confidently used for linear models. This is because, for radial flow, a steady-state region of significant size develops, whereas in linear flow, the steady state region progresses only a small distance away from the wellbore.

In this work, we have developed a novel rate transient analysis (RTA) technique for analyzing tight gas condensate reservoirs during the transient linear flow period. The new method includes evaluation of two-phase (gas + condensate) pseudopressure, which incorporates a new method for calculation of the saturation−pressure relationship analytically, and two-phase pseudotime, which are used to linearize the diffusivity equation. The reservoir fluid is assumed to be a rich gas condensate fluid. The initial reservoir pressure is set close to the saturation pressure, and the well is producing against a constant FBHP. The suggested techniques presented in this work are valid for any multiphase flow scheme provided that fluid flow can be described by the diffusivity equation based on formation volume factor formulations. This manuscript is focused on the theoretical development of our multiphase analytical methods. We demonstrate the practical applicability of the presented method with field cases. The significance of this work is that we have proven that the liquid-analog solution can be applied (through use of carefully defined pseudovariables) for low-permeability gas condensate reservoirs (under certain conditions), which are currently being exploited extensively by industry. Several commonly observed behaviors of tight gas condensate wells are also explained analytically.

The manuscript is organized as follows. First, we will discuss two methods for linearizing the diffusivity equation as well as backward solutions in the "Model Development" section. Next we will discuss the setup of numerical simulation models in the "Simulation Model Setup" section, followed by validation of our new approaches using numerical simulation in the "Model Verification Using Simulation" section. Application of our new methods for establishing the linear flow parameter ($x_f\sqrt{k}$) is demonstrated in the "Application of New Methods for Determination of $x_f\sqrt{k}$" section. Finally, we will provide some brief conclusions obtained from this work.

3. Model development

The emphasis of this study is on the transient (matrix) linear flow regime associated with hydraulically-fractured tight gas and shale gas condensate reservoirs. As observed from simulations, when the pressure falls below the dew point pressure, the oil saturation buildup near the fracture plane can cause a considerable reduction in gas phase mobility (up to 70% according to our simulation results). The corresponding diffusivity equation is highly nonlinear because the fluid properties are a strong function of pressure and mobility is changing with saturation. Linearization of