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Material-balance analysis of gas and gas-condensate reservoirs with diverse drive mechanisms

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ABSTRACT

Material-balance (MB) analysis for in-place volume estimation in gas reservoirs has been in practice for decades. Nonlinear responses from geopressure reservoirs with or without aquifer influx present special interpretation challenges. One of the main challenges of in-place volume estimates involves the estimation of average-reservoir pressure with production. To that end, modern pressure sensors installed at bottomhole and/or surface largely help establish a given well's dynamic performance by way of rate-transient analysis.

This paper explores the applicability and limitations of the standard analytical tools in volumetric, geopressure, and waterdrive systems for a diverse array of fluids, from dry gas to near-critical gas/condensate. The systematic approach presented in this paper attempts to increase accuracy in results by ensuring consistency in solutions from multiple methods used to first assess the average-reservoir pressure from production performance data, followed by in-place volume estimation. In this context, we examined analytical tools, such as the p_{av}/z vs. cumulative gas production (G_p) plot, and cumulative reservoir voidage vs. cumulative total expansion plot. Both pot aquifer and unsteady-state Carter-Tracy aquifer models were considered to account for water influx. Besides the use of Cole and drive indices plots, two diagnostic log-log plots are introduced involving total expansivity and change in average-reservoir pressure. In addition, we sought solution objectivity by introducing a diagnostic tool in the Walsh and Yildiz-McEwen MB plots. Both MB methods involve plotting of cumulative reservoir voidage (F) vs. cumulative total expansion (E_t), whereas the diagnostic tool consists of plotting F/E_t vs. E_t on the same graph.

Initially, synthetic data helped us understand the overall system behavior and instilled confidence in the solutions obtained for various combinations of drive mechanisms. Statistical design of experiments prompted us to explore independent variables, such as aquifer-to-hydrocarbon PV ratio, production rate, degree of overpressure, and the aquifer source. Those learnings were validated with published and new field data encompassing an array of reservoirs with various drive mechanisms and fluid type.

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1. Introduction

Analytical material-balance tools form the cornerstone of reservoir engineering studies in most gas reservoirs. Historically, estimations of in-place volume and ultimate recovery have been primary drivers for the use of static material-balance (SMB) tools, such as the p_{av}/z versus cumulative production plot. With the advent of real-time surface and/or downhole pressure data, dynamic material-balance (DMB) methods have gained increasing acceptance. One advantage of DMB is that the average-reservoir pressure is an output of such analysis. In other words, DMB methods finesse issues associated with traditional pressure-buildup tests in multiwell systems with unknown drainage boundaries, reservoir layering, insufficient shut-in times, and off-bottom gauges, among other challenges.

Material-balance methods have evolved since the 1940's. Seminal studies by Woods and Muskat (1945) and Brownscombe and Collins (1949) paved the way for many studies that followed. For

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instance, McEwen (1962) observed that even modest errors in reservoir pressure data can create large uncertainty in establishing the in-place volume estimation with least-squares line fitting. Water influx has posed a challenge since the early days of investigation simply because it increases the number of unknowns. The studies of Agarwal et al. (1965), Bruns et al. (1965), and Chierici et al. (1967) are noteworthy when addressing this subject. Let us explore their major findings.

Agarwal et al. (1965) noted that high rate production was a requirement to ensure high gas recovery. During depletion, residual-gas saturation plays an important role, particularly at low rates. Agarwal et al. also found the Carter-Tracy (1960) aquifer model to be quite effective in modeling water influx. Bruns et al. (1965) also performed forward modeling to capture various waterdrive signatures in p_{av}/z vs. G_p plot, using Schilthuis (1936), Hurst simplified (1943), and van Everdingen and Hurst (1949) aquifer models. Because the aquifer size vis-à-vis its influx plays a major role in the performance response, the use of the p_{av}/z method can potentially lead to over 100% error in original gas-in-place (OGIP) estimates, if proper care is not taken. Similar to Agarwal et al. findings, Bruns et al. also recommended accelerated production to get a better understanding of OGIP in early production life. While discussing five field examples, Chierici et al. (1967) noted that unique determination of OGIP may be elusive. They argued that the internal structure of a coupled system (gas and associated water) cannot be uniquely determined from its external behavior. They suggested that large fluctuations in production rates can induce large perturbations in the system, thereby minimizing the uncertainty range in OGIP estimation. The notion that large perturbations improve signal quality is analogous to ideas prompted by transient-pressure testing.

Overpressure reservoirs with increasing drilling depth added another level of complexity because the p_{av}/z plot generates a quadratic signature (Gonzalez et al., 2008). Roach (1981) reformulated the material-balance equation to incorporate rock and water compressibility because the rock compressibility becomes comparable to that of gas in overpressure systems. Ambastha (1993) pointed out issues with the Roach formulation because of the method's reliance on high quality data. Furthermore, he illuminated the uniqueness issue by studying challenges in decoupling effective compressibility and initial in-place gas volume in overpressure reservoirs. Subsequently, water influx was incorporated implicitly into the analysis with studies by Poston et al. (1994) and Fetkovich et al. (1998), among others. In particular, Fetkovich et al. incorporated an effective pressure-dependent compressibility term in their reformulation of the material-balance equation. This compressibility term accounts for pore volume, water saturation, gas solubility, and aquifer associated with the gas. Although this approach is comprehensive, Walsh (1998) showed that a simpler straight-line method can provide an equally robust solution with the F vs E_t plot, where F represents total fluid withdrawal and E_t is the total net expansivity. This approach mimics the straight-line method of Havlena and Odeh (1963), but necessitates a trial-and-error solution. The pot aquifer model is implicit in this formulation.

More recently, Yildiz (2008) showed a hybrid approach for handling MB in waterdrive gas reservoirs to minimize the range of uncertainty in OGIP estimation. Yildiz argued that multiple combinations of OGIP and aquifer parameters can match the same field data, thereby suggesting a range of possible solutions. He offered modifications to Roach (1981), Havlena-Odeh (1963), and McEwen (1962) plots. The reformulation of the McEwen plot involved the use of the van Everdingen and Hurst (1949) unsteady-state aquifer model. The key to minimizing the OGIP uncertainty range in the McEwen plot is that a time-invariant horizontal response exists for the estimated OGIP trend with increasing producing time. Other notable papers in this area include those of Gonzalez et al. (2008) and Mogadham et al. (2011), among others.

The preceding discussion suggests diverse analytical static- and dynamic-material-balance methods for estimating in-place hydrocarbon pore volume associated with a well. However, the appropriate use of commonly used methods, such as static material-balance method of p_{av}/z vs. G_p plot, decline-curve analysis, and various dynamic material-balance analyses, remain unclear in a given situation. Such clarity is particularly lacking when various combinations of reservoir fluid and drive mechanisms are involved. Given this reality, our overall objective is to provide clarity in use of methods that yield credible solutions under combinations of reservoir-drive mechanisms. To achieve this goal, we focus on four major objectives:

- First, to demonstrate the use of rate-transient analysis to compensate for the sparse buildup tests and their associated issues in most assets.
- Second, to share ways to ascertain drive mechanisms with diagnostic plots, such as the reservoir-drive indices, modified-Cole, and gas phase net expansivity plots to gain insights into reservoir drive mechanisms.
- Third, to describe the reformulated versions of Roach (1981), Walsh (1998), and McEwen (1962) methods. Reformulation involved obtaining a horizontal signature for the F/E_t or G_i vs. E_t plot for the Walsh and McEwen methods, while fitting a MB straight line on the F vs. E_t plot. In addition, we used a simplified form of Carter-Tracy (1960) aquifer model to avoid iterative calculations. The Roach method also entailed generating a diagnostic horizontal trace, analogous to the other two methods.
- Fourth, to describe the findings from the investigation of the whole gamut of reservoir complexity, from normal-pressure, dry-gas reservoir to over-pressure, near-critical fluid system with water influx. Both field and synthetic examples constituted the diverse array of examples pursued here.

2. Material-balance models

This section presents the basic formulations of the MB equations pertaining to both the pot aquifer (Walsh, 1998; Yildiz, 2008), and the unsteady-state water influx involving a simplified version of the Carter-Tracy model. The latter is rooted in the McEwen (1962) formulation, which was modified by Yildiz (2008).

2.1. Pot aquifer solutions for partial waterdrive systems

The Walsh (1998) MB formulation in terms of total fluid production F may be written as

$$F = G_i\,E_t + W_e \tag{1}$$

where W_e represents the encroached aquifer, and total expansivity E_t and the ratio of aquifer and reservoir pore volume M are given by the following expressions:

$$E_t = E_g + E_w\frac{B_{gi}(S_{wi}+M)}{B_{wi}(1-S_{wi})} + E_f\frac{B_{gi}(1+M)}{(1-S_{wi})} \tag{2}$$

$$M = V_{pA}/V_{pR} \tag{3}$$

Eq. (1) suggests that a plot of F vs. E_t will generate a straight line whose slope yields the desired initial gas-in-place, G_i. In essence, the aquifer influx is controlled by its relative size M (aquifer to

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