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Determination of Initial Gas in Place and Active Water Drive in Single-Phase Gas Reservoirs Using the Material Balance Method

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ABSTRACT: Oil and natural gas remain the world's primary energy resources and continue to play a fundamental role in the global economy. Consequently, the effective management and optimal exploitation of subsurface hydrocarbon reservoirs to maximize hydrocarbon recovery represent major challenges in petroleum engineering and related scientific disciplines. One of the fundamental objectives of reservoir engineering is the estimation of hydrocarbon reserves throughout both the early production stage and the depletion phase of a reservoir, as well as the identification of the natural reservoir drive mechanisms responsible for fluid flow from the reservoir formation to the production wells. These evaluations are essential for the proper characterization, management, and efficient development of oil and gas reservoirs. The present study demonstrates the application of the Material Balance Method to single-phase gas reservoirs for the determination of the Initial Gas in Place and the identification of the presence of an active water-drive mechanism. The proposed methodology integrates historical production data with the physical properties of reservoir gas over a specified production period. The obtained results illustrate the effectiveness of material balance analysis as a practical and reliable reservoir engineering tool for reservoir characterization, reserve estimation, and the evaluation of reservoir drive mechanisms, thereby providing valuable support for reservoir management and future field development planning.

KEYWORDS: cumulative production, reservoir, gas, volume factor, equation, water drive.

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Introduction

The existence and producibility of an oil or gas field are primarily governed by two fundamental conditions: the geological condition and the thermodynamic condition. While reservoir characterization commonly involves determining petrophysical properties such as permeability, porosity, fluid saturation, and other reservoir parameters, one of the most critical aspects of reservoir evaluation is the thermodynamic characterization of reservoir fluids through Pressure–Volume–Temperature (PVT) laboratory analysis. Reservoir fluid samples collected at the bottom of production wells are subjected to different pressure and temperature conditions in the PVT laboratory, allowing the investigation of fluid behavior through the phase transformations that occur under reservoir and laboratory conditions (Ahmed, Reservoir engineering handbook Second Edition, 2000) (Ahmed, Reservoir Engineering Handbook, 2019). The results of these thermodynamic investigations enable the construction of the pressure–temperature (P–T) phase diagram, which represents the fundamental basis for identifying the reservoir fluid type and understanding its phase behavior throughout reservoir depletion (Ahmed & McKinney, Advanced Reservoir Engineering, 2005). Accurate characterization of reservoir fluids is therefore essential for predicting reservoir performance, estimating hydrocarbon reserves, and selecting appropriate field development and production strategies.

Furthermore, continuous monitoring of production performance and reservoir pressure throughout the exploitation period, combined with periodic PVT analyses of reservoir fluid samples and the determination of their physicochemical properties as functions of pressure, provides the necessary information for the application of the Material Balance Method (Ahmed & McKinney, Advanced Reservoir Engineering, 2005) (Dake, Last Accessed Date November 06, 2024). Material balance analysis constitutes one of the fundamental techniques of reservoir engineering for estimating hydrocarbon reserves and identifying the dominant reservoir drive mechanism (Fuentes-Cruz & Vásquez-Cruz, 2022). Unlike purely volumetric approaches, the Material Balance Method evaluates the actual energy available within the reservoir to displace hydrocarbons from the porous formation toward the production wells, thereby providing a more realistic representation of reservoir performance and depletion behavior (Fuentes-Cruz & Vásquez-Cruz, 2022). The present study considers a single-phase gas reservoir under the assumption of volumetric reservoir behavior. Using historical production data, reservoir pressure measurements, cumulative gas production, and the gas formation volume factor over a specified production period, the Initial Gas in Place (IGIP) is determined through material balance analysis (Ahmed & McKinney, Advanced Reservoir Engineering, 2005) (James G. Speight PhD, 2016). Subsequently, the calculated IGIP values at different reservoir pressures are plotted to assess the presence of an active water-drive mechanism. The proposed methodology provides an effective reservoir engineering approach for simultaneous reserve estimation and identification of reservoir drive mechanisms, thereby supporting more reliable reservoir management and field development decisions.

Methodology

Based on the reservoir pressure measurements, cumulative gas production, and gas formation volume factor values presented in Table 1, the Initial Gas in Place (IGIP) was estimated for three representative reservoir pressure levels: 2925 psia, 2525 psia, and 2125 psia. The calculations were performed using the general Material Balance Equation (MBE), followed by its simplification for a single-phase gas reservoir (Ronald E. Terry, 2014). The simplification of the material balance equation was based on the assumptions that the reservoir initially contained no oil, that the effects of rock compressibility and water compressibility were negligible, and that the reservoir exhibited volumetric behavior (Ronald E. Terry, 2014). Under these assumptions, the general material balance equation reduces to a simple linear relationship involving cumulative gas production, the gas formation volume factor, and reservoir pressure. This linear formulation provides a practical and reliable approach for estimating the Initial Gas in Place (IGIP) from production and pressure data (Ronald E. Terry, 2014).

The calculated IGIP values corresponding to the three reservoir pressure levels were subsequently compared through graphical analysis. The consistency of these values was used to verify the applicability of the volumetric reservoir assumption. In contrast, any systematic variation of the calculated IGIP with declining pressure was interpreted as an indication of the presence of an active water-drive mechanism.

Table 1

Data During the Exploitation History

Pressure (psia)	Gas Cumulative Production (MMSCF)	Gas Volume Factor (ft^3/SCF)
3200	0	0.0052622
2925	79	0.0057004
2525	221	0.0065311
2125	452	0.0077360

Furthermore, based on the selected reservoir pressure, gas formation volume factor, and reservoir temperature values, and by applying the formula $\beta_g = 0.02829 * \frac{Z*T}{P}$, the gas compressibility factor (Z-factor) was determined. Subsequently, the corresponding P/Z ratios were calculated, as summarized in Table 2.

Table 2

Calculation of z-factor and P/Z.

P	T	Z	P/Z
3200	680	0.8753	3656
2925	680	0.8667	3375
2525	680	0.8572	2946
2125	680	0.8545	2487

Using the data presented in Table 2, a P/Z versus cumulative gas production plot was constructed. This graphical analysis was employed not only to estimate the Initial Gas in Place (IGIP) but also to evaluate the existence of an active water-drive mechanism. Under volumetric reservoir conditions, the P/Z plot is expected to exhibit a linear trend, whereas systematic deviations from linearity provide evidence of water influx into the reservoir. The complete methodology including the formulation of the Material Balance Equation (MBE), its simplification for the single-phase gas reservoir considered in this study, the estimation of OGIP at three different reservoir pressure levels, and the construction and interpretation of the P/Z versus cumulative gas production plot is presented in the following section (Ronald E. Terry, 2014) (McKinney, 2005).

Results and Discussion

Based on the general Material Balance Equation, presented in Equation (1), and its subsequent simplification for the specific reservoir conditions considered in this study, as expressed in Equation (2), the Initial Gas in Place (IGIP) was calculated for the three selected reservoir pressure levels.

$$\mathrm{N} * (\mathrm{B_t} - \mathrm{B_{ti}}) + \frac{\mathrm{N} * \mathrm{m} * \mathrm{B_{ti}}}{\mathrm{B_{gi}}} * (\mathrm{B_g} - \mathrm{B_{gi}}) + (1 + \mathrm{m}) * \mathrm{N} * \mathrm{B_{ti}} * \left[\frac{\mathrm{C_W} * \mathrm{S_{wi}} + \mathrm{C_f}}{1 - \mathrm{S_{wi}}}\right] * \Delta\overline{\mathrm{P}} + \mathrm{W_e} =$$

$$= \mathrm{N_p} * \left[\mathrm{B_t} + (\mathrm{R_p} - \mathrm{R_{soi}}) * \mathrm{B_g}\right] + \mathrm{B_w} * \mathrm{W_p} \qquad (1)$$

$$G * (\mathrm{B_g} - \mathrm{B_{gi}}) + G * \mathrm{B_{gi}} * \left[\frac{\mathrm{C_W} * \mathrm{S_{wi}} + \mathrm{C_f}}{1 - \mathrm{S_{wi}}}\right] * \Delta\overline{\mathrm{P}} + \mathrm{W_e} = \mathrm{G_p} * \mathrm{B_g} + \mathrm{B_w} * \mathrm{W_p}$$

$$G * (\mathrm{B_g} - \mathrm{B_{gi}}) + \mathrm{W_e} = \mathrm{G_p} * \mathrm{B_g} + \mathrm{B_w} * \mathrm{W_p}$$

$$G * (\mathrm{B_g} - \mathrm{B_{gi}}) = \mathrm{G_p} * \mathrm{B_g} \rightarrow G = \frac{\mathrm{G_p} * \mathrm{B_g}}{\mathrm{B_g} - \mathrm{B_{gi}}} \qquad (2)$$

For P=2925 psia

$$G = \frac{79 * 10^6 * 0.0057004}{0.0057004 - 0.0052622} = 1028\ MMSCF$$

For P=2525 psia

$$G = \frac{221 * 10^6 * 0.0065311}{0.0065311 - 0.0052622} = 1138\,MMSCF$$

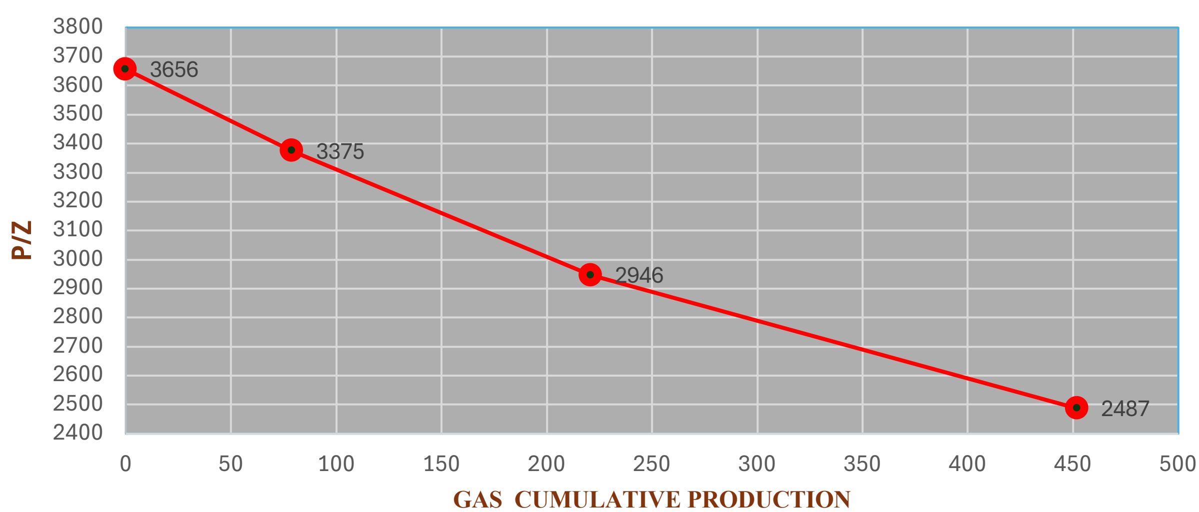
For P=2125 psia

$$G = \frac{452 * 10^6 * 0.0077360}{0.0077360 - 0.0052622} = 1414\,MMSCF$$

The calculated IGIP values indicate the presence of an active water-drive mechanism. This conclusion is supported by the observation that the estimated original gas reserves obtained at successive stages of reservoir pressure depletion, under the assumption of no water influx, exhibit progressively increasing values. Since the Initial Gas in Place is a fixed reservoir property and should remain constant throughout reservoir depletion, this apparent increase demonstrates that water influx contributes additional reservoir energy, thereby violating the assumptions of a purely volumetric gas reservoir. Consequently, the observed trend provides clear evidence of an active water-drive mechanism. Conversely, if the calculated IGIP values had remained essentially constant over the entire pressure depletion range, the reservoir would have been classified as a volumetric gas reservoir, indicating negligible or no water influx and depletion driven exclusively by gas expansion. Furthermore, based on the calculated values presented in Table 2, the P/Z versus cumulative gas production plot shown in Figure 1 was constructed. At the initial stage of reservoir depletion, the plot exhibits an approximately linear trend, characteristic of a volumetric gas reservoir and initially suggesting depletion driven solely by gas expansion.

Figure 1

Variation of P/Z with Gas Cumulative Production



However, as reservoir pressure declines and the P/Z ratio decreases to approximately 2946, then to 2487, the plotted data progressively deviate from linearity. If reservoir depletion continues, this deviation becomes increasingly pronounced. Such behavior is widely recognized as a characteristic response of reservoirs influenced by an active water-drive mechanism, where water influx provides additional reservoir energy and alters the pressure-depletion relationship predicted for a purely volumetric gas reservoir. Therefore, the observed departure of the P/Z plot from a straight-line trend confirms the existence of active water influx and demonstrates that reservoir performance is governed not only by gas expansion but also by the contribution of the surrounding aquifer.

Conclusion

The application of the Material Balance Equation (MBE), based on historical production and reservoir pressure data acquired throughout the exploitation period of an oil and gas reservoir, together with the reservoir fluid properties determined from Pressure–Volume–Temperature (PVT) analyses of bottom-hole fluid samples, provides a reliable and practical approach for reservoir evaluation.

The methodology enables not only the estimation of hydrocarbon reserves, including the Original Gas in Place (OGIP), but also the identification of the prevailing reservoir drive mechanism and the assessment of the reservoir depletion stage. Consequently, material balance analysis represents an essential reservoir engineering tool for reservoir characterization and performance evaluation. Furthermore, the results of this analysis provide a sound technical basis for reservoir management, production optimization, and strategic decision-making for the planning, development, and long-term exploitation of oil and gas fields.

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