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The material balance equation for fractured vuggy gas reservoirs with bottom water-drive combining stress and gravity effects

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ABSTRACT

Compared with conventional porous-water-drive gas reservoirs, calculating the reserve of a fractured vuggy with water driving is a more difficult and challenging task because of its complex matrix types (matrix, fracture and cavity) and strong rock compressibility. Based on the principles of mass conservation, the material balance equation (MBE) for a fractured vuggy gas reservoir with bottom-water driving is established, and the effects of stress sensitivity and gravity segregation are both considered in the proposed model. The original gas in place (OGIP) and the distribution of the reserve in matrix, fracture and cavity can be determined with the proposed MBE. To test the validity of the model, a depletion test simulating the depleting process of fractured vuggy water-drive gas reservoirs and permeability stress sensitivity experiments with actual full-diameter cores under reservoir conditions are conducted. Then, validation and analysis of the model are compared with the experimental data. It is observed that the water production rate shows a stepped increasing trend instead of a gradually increasing trend during the depletion test. The reserve calculated with the proposed model has the lowest error (1.68%) compared with the experimental data, in which the reserve in the cavity is dominant. Thus, gravity and stress should not be neglected when calculating the reserve of a fractured vuggy gas reservoir with bottom water driving; otherwise, a lower accuracy would be introduced.

1. Introduction

Precisely forecasting the initial reserve is essential to the analysis of the production data of a reservoir. Currently, there are mainly four types of well-developed approaches to predict original gas in place (OGIP), including well testing, the empirical equation, typical curve fitting, and the material balance equation (Chen et al., 2009). Among them, well testing is mainly used for a single well reserve calculation. The initial gas reserve is obtained by analysing the variety of bottom/tube pressures for a shut-in/producing well. Several methods have been developed for this approach, including the elastic two-phase approach (Li, 2000), reservoir influence function (Huang et al., 2003), reservoir limit test (Zhong, 2000) and pressure build-up test (Mao et al., 2002). This approach has a lower accuracy when the production rate and reservoir pressure have not been tested accurately. The empirical equation method is utilized for reserve calculations in the early stage of a reserve due to a lack of production data. Therefore, it shows a lower accuracy for a complex oil-gas reservoir (Chen, 1998). The typical curve fitting method is one of the common approaches used for reserve calculations in fields, as it is easy to conduct (Hu and Yang, 1998). Several models have been developed for typical curve fitting, including Arps decline curves (Arps, 1945), Fetkovich (Fetkovich, 1980), and the Blasingame (Fraim, 1987; Blasingame et al., 1991), Agarwa Gardner (Agarwal et al., 1998) and normalization pressure integration (NPI) (Blasingame and Lee, 1988) type curve theories. For curve fitting, with the availability of more performance data, a higher calculation accuracy is achieved. This approach is generally used with the other approaches to confirm the final value of the reserve for a certain reservoir.

Compared with all of the other approaches, the material balance method (MBE) is preferred because fewer parameters are needed to characterize the fluid flowing processes and MBE is more practical than well testing. Moreover, MBE can be used at any stage of production with a high accuracy. However, because of the complexity of porous media and uniform distribution of fluid in a fractured vuggy gas reservoir, it is essential to investigate the adaptability of

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MBE. Per a review of the literature, a fractured vuggy gas reservoir is paid less attention, despite numerous works on fractured vuggy oil reservoirs (Li et al., 2007; Chen et al., 2007; Zhao et al., 2015). However, the MBE method is widely used to calculate the reserves of fractured gas reservoirs (Penuela et al., 2001; Sandoval Merchan et al., 2009). Fractured vuggy gas and oil reservoirs are similar, as they all show strong heterogeneity (Kang et al., 1992), and the porous media include a matrix, cavities and fractures. Some studies have suggested that fractures and cavities could be identical systems (Wang et al., 2015; Li and Zhang, 2009; Wang, 1998), as the behaviours of the fluid flowing in both media were the same. However, this is not the actual case in a reservoir. Furthermore, gravity and capillary pressure introduce gravity segregation in the fluid and capillary imbibition during reservoir formation (Kazemi et al., 1976; Hove et al., 1995). Some studies have shown that gravity segregation and capillary imbibition can enhance the recovery ratio in a gas reservoir (He, 2011; Golghanddashti, 2011; Han et al., 2016). Additionally, stress had a substantial effect on fracture formation; in fact, previous studies (Li et al., 2004; Gutierrez et al., 2015; He et al., 2014; Silva et al., 2015) concluded that the compressibility coefficients of rocks and fluids changed as the pore pressure decreased. Thus, it is not reasonable to consider the compressibility coefficients as constants in common MBEs.

Based on the pressure data used in calculating reserves, the MBE method can be classified into two types: the conventional material balance (CMB) and flowing material balance (FMB). The conventional material balance method uses the average formation pressures, which are obtained from build-up tests. However, in some cases, it is impossible to conduct a longer shut-in period build-up test in a lower permeability reservoir or in a critical demand-supply situation (Satter et al., 2008). Therefore, flowing material balance (Mattar and McNeil, 1998) was proposed by using the flowing pressure data in the pseudo-steady state period. However, the original FMB is limited to a constant flow rate; hence, the dynamic Material Balance (DMB) (Mattar and Anderson, 2005), which is validated for variable flow rates, was established. FBM and DMB have been widely used in many gas reservoirs (Choudhury and Gomes, 2000; Mohammed and Enty, 2013).

To improve the accuracy of a reserve calculation with MBE for a fractured vuggy gas reservoir, this paper establishes a new method that combines the effects of gravity and stress simultaneously for triple-porosity formation. In addition, a depletion test and a stress sensitivity experiment with actual full-diameter cores under reservoir conditions are conducted. The reserve forecasted by the proposed and common MBEs are compared with the tested results, and the adaptability of the new MBE is confirmed. The proposed model has the advantage of that not only can OGIP be determined but the distribution of the reserve in the pore space can also be obtained. In addition, the proposed method can also be integrated with the flowing material balance or dynamic material balance if the pseudo-steady state pressure is adopted instead of the average formation pressure.

2. Presentation of the proposed material balance equation

2.1. Assumptions

(1) In a triple-porosity formation, porous medium is composed of fractures, cavities and a matrix. A matrix with lower porosity and permeability is homogenous. The pressure of the matrix is different than that of the fracture or the vuggy.
(2) The distribution of fluid in the matrix/fracture/vuggy is homogeneous. All of the fluids are produced through the fractures, and the fluids in the matrix and vuggy systems can flow into the fractures.
(3) The compression and expansion of the water phase, hydrocarbon phase and rocks are considered, and the coefficient of the compressibility of the fluid and rock vary as the reservoir pressure declines.
(4) A pressure difference exists among the matrix, fracture and vuggy. The capillary pressure in the matrix is considered, whereas the capillary pressure in the fracture and vuggy can be ignored.
(5) At the initial time, the connate water only exists in the matrix.
(6) Bottom-water exists in fractured vuggy gas reservoirs. At the initial time, the pressure of the bottom-water is in equilibrium with the reservoir pressure. The density difference between the water and gas is affected by gravity.

2.2. Derivation of the proposed equation

Traditionally, the following formula is the material balance equation (MBE) used to calculate the volume of the gas phase (V_g) at a certain P (see the derivation in Appendix A); V_g is equal to the value of the initial gas volume underground (V_{gi}) minus the volume changes induced by water invasion (W), water expansion ($\triangle V_w$), pore volume ($\triangle V_p$) and matrix rock ($\triangle V_s$) deformation:

$$V_g = V_{gi} - W - \Delta V_w - \Delta V_p - \Delta V_s \tag{1}$$

2.2.1. vol change induced by gravity segregation and capillary imbibition

When there is a difference in density between the gas and water phases, gravity segregation causes the gas phase to move upward and the water phase to flow downward (Zhou, 2003). According to Poiseuille's law, the bulk volume change ($\triangle V_F$) of the gas phase due to the buoyancy driving force is

$$\begin{aligned}\Delta V_F &= \Delta V_{Fgm} + \Delta V_{Fgf} + \Delta V_{Fgv}\\ &= A_g\left(1-\phi_f-\phi_v\right)\phi_m\frac{r_m^2\Delta\rho_{wg}g}{8\mu_g}t + A_g\phi_f\frac{r_f^2\Delta\rho_{wg}g}{8\mu_g}t + A_g\phi_v\frac{r_v^2\Delta\rho_{wg}g}{8\mu_g}t\end{aligned} \tag{2}$$

where ΔV_{Fgm}, ΔV_{Fgf} and ΔV_{Fgv} are the volume changes of the gas outflow from the matrix, fracture and cavity due to the buoyancy force, respectively.

Conversely, the volume change of the water phase due to of gravity is

$$\begin{aligned}\Delta V_G &= \Delta V_{Gwm} + \Delta V_{Gwf} + \Delta V_{Gwv}\\ &= A_g\left(1-\phi_f-\phi_v\right)\phi_m\frac{r_m^2\rho_w g}{8\mu_w}t + A_g\phi_f\frac{r_f^2\rho_w g}{8\mu_w}t + A_g\phi_v\frac{r_v^2\rho_w g}{8\mu_w}t\end{aligned} \tag{3}$$

where ΔV_{Gwm}, ΔV_{Gwf}, and ΔV_{Gwv} are the volume changes of the water phase induced by gravity in the matrix, fracture and cavity, respectively.

According to Hagen-Poiseuille's law, Washburn (1921) introduced an equation to calculate the imbibition volume in a single capillary. According to the results of Guo et al. (1998), the capillary imbibition effect only existed in the matrix system, and this effect could be ignored for fractures and cavities. If the porous medium is assumed to be composed of a number of capillary tubes, the overall imbibition volume is