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Development of material balance equations for coalbed methane reservoirs considering dewatering process, gas solubility, pore compressibility and matrix shrinkage

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ABSTRACT

As one of the important unconventional resources, coalbed methane (CBM) can mitigate energy shortage issue, and its efficient exploitation has received widespread attention globally. The development of CBM is of great significance to coal mine safety and energy supply. CBM reserve evaluation provides a basis for selecting development zones and determining development strategies. However, most existing CBM reserve evaluation methods do not consider the effects of dissolved gas, free gas and the difference between initial reservoir pressure and critical desorption pressure. Thus, the predicted results usually deviate from the actual reserve.

In this paper, firstly, the material balance equation (MBE) for early dewatering stage considering the effect of stress sensitivity on porosity is established, and the initial free gas and dissolved gas reserves of undersaturated CBM reservoirs can be obtained. Secondly, the MBE for gas desorption stage is derived, in which the effects of stress sensitivity, matrix shrinkage and dissolved gas are considered. So the original gas in place (OGIP) of CBM reservoirs can be solved. Next, the correctness and rationality of MBEs for early dewatering stage and gas desorption stage are verified against King's MBE method and CBM dynamic analysis software. Finally, this method is applied to actual production wells.

The results show that in early dewatering stage, $\frac{1-S_{wi}\alpha}{c_p+\alpha S_{wi}c_w}\frac{\bar{p}}{Z} - (p_i - \bar{p})\frac{\bar{p}}{Z}$ and $(W_p B_w - W_e)\alpha\frac{\bar{p}}{Z} + G_p\frac{p_{sc}T}{Z_{sc}T_{sc}}$ have a linear shape, and the control area of CBM reservoir can be calculated based on the slope of the straight line. In addition, the ratio of the intercept to the slope of the straight line can be used to calculate the initial free gas and dissolved gas reserves of undersaturated CBM reservoirs. During gas desorption stage, p/Z^* and G_p have a linear relationship. OGIP of CBM reservoirs can be obtained by the ratio of y-intercept to the slope of the straight line. Using gas and water production data provided by CBM dynamic analysis software, the reserves of undersaturated CBM reservoirs evaluated by the proposed method are in good agreement with those from CBM dynamic analysis software, which proves that the proposed material balance equations and corresponding methods are reasonable and reliable.

The material balance equations and methods presented in this paper take into account the effects of various factors such as the difference between initial reservoir pressure and critical desorption pressure, pore compressibility, water compressibility, coal matrix shrinkage, dissolved gas, and free gas. The proposed reserve calculation methods for undersaturated CBM reservoirs can provide an important basis for selecting dominant production area, determining well spacing and guiding development policy.

1. Introduction

With the rapid depletion of conventional petroleum resources (Sun et al., 2017a, 2017b, 2017c), CBM reservoirs are gaining more and more attention to oil industry. CBM reservoirs have complex reservoir characteristics and production mechanisms compared with conventional gas reservoirs. CBM is mainly adsorbed in coal matrix pores, while the cleats are filled with water. In order to produce gas from CBM reservoirs, the processes of dewatering, depressurization, desorption, diffusion and seepage are needed. These complex characteristics of

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CBM make it more difficult to evaluate dynamic reserves and limit the use of common methods to predict gas recovery and well performance, such as the typical curves analyses method (Arps, 1945; Clarkson, 2013). Meanwhile, lots of researches on pressure drop methods for CBM reservoirs have been done in recent decades, but some important factors were ignored, such as the difference between initial reservoir pressure and critical desorption pressure and matrix shrinkage. Stress sensitivity and matrix shrinkage are two important factors that change permeability/porosity during production of CBM. In the production process, stress sensitivity occurring at both dewatering and gas desorption stages decreases permeability/porosity. At the early stage of production, stress sensitivity dominates the shrinkage effect and a reduction in permeability will occur; while at the late stage, shrinkage effect dominates stress sensitivity and the permeability will increase. Hence, the change of permeability/porosity depends on the relative effect of stress sensitivity and matrix shrinkage. (Clarkson et al., 2011; Salmachi and Karacan., 2017; Yarmohammadtooski et al., 2017; Sun et al., 2017d, 2017e; Sun et al., 2018a; Sun et al., 2018b; Shi et al., 2018). Clarkson and Salmachi (2017) considered porosity/permeability change above and below critical desorption pressure in the development of flowing material balance equations (FMBE), but free gas and gas solubility in water should be further considered in the OGIP evaluation of CBM reservoirs. MBE is a simple yet powerful method for original gas in place (OGIP) determination and CBM performance forecasting.

A straight line material balance form, p/Z vs. cumulative gas production G_P for conventional volumetric dry gas reservoirs has been developed by many researchers. Cumulative gas production, corresponding average reservoir pressure, and properties of produced gas are required in this plot to determine the y-intercept and slope of the straight line, which can then be utilized to calculate OGIP. The simplicity of p/Z plots has led to many efforts to extend this approach to CBM reservoirs. Lots of researchers modified MBE to incorporate the mechanism of CBM reservoirs (King, 1990, 1993; Jensen and Smith, 1997; Gerami et al., 2008; Penuela et al., 1998; Seidle, 1999; Clarkson and McGovern's MBE, 2001; Ahmed et al. 2006; Clarkson et al., 2007a, b; Morad and Clarkson, 2008; Gonzalez, 2008; Moghadam et al., 2009, 2011; Firanda, 2011; Thararoop et al., 2015; Ibrahim and Nasr-El-Din, 2015; Kalam et al. 2015).

King (1990, 1993) firstly established a material balance equation according to the adsorption/desorption characteristics of CBM reservoirs. By introducing a pseudo deviation factor Z^*, a linear material balance equation of the pseudo average reservoir pressure P/Z^* vs. cumulative gas production G_P was obtained. According to the linear equation, King proposed an iterative method to determine the volume of coal seam, and then calculated the OGIP. However, some important mechanisms of CBM reservoirs, such as matrix shrinkage, gas solubility, and the difference between initial reservoir pressure and critical desorption pressure, were not considered in King's MBE.

Jensen and Smith (1997) proposed a simpler MBE for CBM than King's MBE (1990, 1993) by assuming there is no water storage in the fracture system of volumetric CBM reservoirs. CBM were considered as saturated and sorption followed the Langmuir isotherm. This equation was analogous to the traditional p/Z vs G_p plot. OGIP can be identified from the x-intercept of the straight line in the plot of $p/(p + p_L)$ versus G_p. Obviously, this method did not consider the effects of pore compressibility and coal matrix shrinkage.

Penuela et al. (1998) developed a generalized MBE for CBM reservoirs and the corresponding straight-line method, in which the diffusion process of desorbed gas into cleat system was considered. Their method could be used to estimate OGIP for CBM reservoirs in equilibrium, saturated and undersaturated conditions. However, from practical applications, it can be seen that this method deviates the straight line at the early dewatering stage of CBM reservoirs, and the y-intercept of the straight line is not zero for equilibrium CBM reservoirs, indicating this method also has some limitations. In addition, their method did not account for the effect of dissolved gas.

Seidle (1999) pointed out that the denominator of the Z^* expression in King's method was insensitive to water saturation change, which might result in large error in evaluation of the volume of coal seam, OGIP, and initial reservoir pressure. Seidle (1999) also mentioned that the iterative method of King was complex, so they simplified King's method by ignoring formation compressibility, water compressibility, and water influx. Using the modified method, the OGIP can be directly determined by the x-intercept of the $P/Z^* \sim G_P$ straight line for a volumetric gas reservoirs, and the drainage area can be determined either from the slope of the straight line or from the calculated OGIP and initial pressure. However, Seidle neglected many characteristics of CBM, such as dewatering process for undersaturated CBM reservoirs, gas solubility, water compressibility, formation compressibility, and coal matrix shrinkage effect.

Ahmed et al. (2006) proposed a generalized MBE considering initial free gas, water expansion, Langmuir isotherm, and formation compaction, and developed a straight line x-y method to estimate OGIP. Then, he extended the MBE to predict average reservoir pressure and forecast future reservoir performance. His method eliminated iterative solution process for drainage area in King's method. However, the modified MBE did not account for coal matrix shrinkage, the solution gas in water, and the difference between initial reservoir pressure and critical desorption pressure.

On the basis of the assumptions of King's MBE, Firanda (2011) further modified King's p/Z^* straight line by accounting for some other driving mechanisms such as mobile water expansion, connate water compressibility, moisture compressibility. Firanda (2011) also modified the Ahmed's straight line x-y method for CBM proposed by considering these driving mechanisms. However, during calculation of moisture expansion, the adsorbed gas volume in reservoir condition was calculated by the method for free gas, which is not reasonable because the adsorbed gas in the reservoir condition is not gas phase but liquid-like phase. In addition, the y-intercept of the modified straight line in the x-y plot was not a constant but a function of pressure, indicating that the straight line relationship was not strictly right. Furthermore, dissolved gas and coal matrix shrinkage have not been considered.

Moghadam et al. (2009, 2011) presented a new gas material balance equation for both conventional and unconventional gas reservoirs. In MBE for CBM reservoirs and shale gas reservoirs, formation compressibility, residual fluids expansion, gas desorption and aquifer support were considered. For CBM reservoirs with free gas at the initial state, they proposed that the plot of $(p/Z)(S_{gi}\text{-}c_{wip}\text{-}c_{ep}\text{-}c_d)$ vs. G_p is a straight line with initial free gas reserve as x-intercept. In order to extrapolate original gas in place in the same scale of p/Z, they developed Z^{**} to replace King's Z^* and obtained a same format equation as the conventional gas MBE. However, for some CBM reservoirs without free gas at initial state, $(p/Z)(S_{gi}\text{-}c_{wip}\text{-}c_{ep}\text{-}c_d)$ vs. G_p straight line method will be inapplicable. Moreover, dissolved gas and coal matrix shrinkage effect were not considered.

Thararoop et al. (2015) developed a new MBE for CBM reservoirs considering water presence in the coal matrix and coal shrinkage and swelling. Comparative studies of the proposed and existing MBEs (King' and Ahmed et al.' MBEs) were conducted for four cases using the production data generated from a two-phase, dual-porosity, dual-permeability coalbed methane simulator developed at Penn State (Thararoop et al., 2012). The results showed that the proposed MBE was more accurate in predicting reservoir size and OGIP, because the presence of water and coal shrinkage and swelling were considered. If ignoring these factors, the reservoir size and OGIP would be underestimated. Based on the proposed MBE for CBM reservoirs, the procedures and methods for production performance and average reservoir pressure predictions considering the presence of water in coal matrix and coal shrinkage and swelling effect were presented. However, in the MBE and OGIP evaluation method for CBM reservoirs proposed by Thararoop et al. (2015), the y-intercept is actually a function of pressure, because