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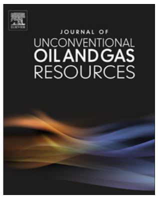

Development of a material balance equation for coalbed methane reservoirs accounting for the presence of water in the coal matrix and coal shrinkage and swelling

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ABSTRACT

The effects of water presence in the coal matrix and coal shrinkage and swelling phenomena are often ignored in the production performance predictions of coalbed methane reservoirs. This paper presents the development of a new material balance formulation for coalbed methane reservoirs that accounts for water presence in the coal matrix and coal shrinkage and swelling phenomena. The development entails the governing gas and water flow equations in dual-porosity, dual-permeability coalbed methane reservoirs. Various comparative studies are conducted to investigate the capabilities of the proposed and existing material balance equations using the production data generated from a robust two-phase, dual-porosity, dual-permeability coalbed methane simulator developed at Penn State. The results show that exclusion of the two aforementioned phenomena in coalbed methane material balance formalisms reduces the estimated reservoir production capacity resulting in under-predictions of reservoir size. In addition, iterative methods for predicting production performance and average reservoir pressure using the proposed material balance formulation are developed and successfully tested against the simulation model.

Introduction

The material balance equation (MBE) has been widely used by reservoir engineers for reserve estimation and production performance predictions. The general material balance equation, which is known as the conventional material balance equation (CMBE), was initially developed by Schilthuis (1936) for conventional reservoirs. The development of the CMBE is based on a volumetric balance. As reservoir pressure is reduced, the changes in the oil and free gas volumes in the reservoirs become equal to the changes in the water and rock volumes. Havlena and Odeh (1963) developed a method of applying the material balance equation as a straight line. This method has been found to be effective for black-oil and dry gas reservoirs. Walsh et al. (1994a,b) incorporated a straight-line method and proposed the generalized material balance equation (GMBE), which also takes into account volatized-oil. The GMBE can be applied to all reservoir types, especially volatile oil, gas-condensate and wet gas reservoirs.

King (1993) developed a material balance equation for coal-seam and Devonian shale gas reservoirs to estimate original gas in place and predict reservoir performance by incorporating adsorbed gas into the material balance equation of dry gas reservoirs. Gas stored by adsorption is expressed using the Langmuir's equation. Eqs. (1)–(4) show the material balance equation developed by King (1993) for coalbed methane (CBM) reservoirs:

$$G_p = \frac{V_{b2}\phi_i Z_{sc} T_{sc}}{p_{sc} T}\left\{\left[\frac{(1-S_{wi})p_i}{Z_i} + \frac{RTC_{MEi}}{\phi_i}\right] - \left[\frac{(1-c_\phi(p_i-p))(1-\overline{S_w})p}{Z} + \frac{RTC_{ME}}{\phi_i}\right]\right\} \tag{1}$$

$$\overline{S_w} = \frac{S_{wi}(1+c_w(p_i-p)) + \frac{5.615(W_e-B_wW_p)}{\phi_i V_{b2}}}{(1-c_\phi(p_i-p))} \tag{2}$$

$$C_{MEi} = \frac{p_{sc}}{Z_{sc}RT_{sc}}\left(\frac{V_L p_i}{p_i+p_L}\right) \tag{3}$$

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Nomenclature

Symbol	Description
A	reservoir drainage area (acre)
B_g	gas formation volume factor (RB/SCF)
B_w	water formation volume factor (RB/STB)
$B_{g,i}$	initial gas formation volume factor (RB/SCF)
$B_{w,i}$	initial water formation volume factor (RB/STB)
c_p	rock compressibility (psi^{-1})
$\tilde{f}$	sorption capacity factor
G_p	cumulative gas production (SCF)
h	thickness (ft)
k_{rg}	relative permeability to gas
k_{rw}	relative permeability to water
p	pressure (psia)
p_i	initial pressure (psia)
p_L	Langmuir pressure constant (psi)
p_{sc}	pressure at standard conditions (psi)
R_{sw}	solution gas–water ratio (SCF/STB)
$R_{sw,i}$	initial solution gas–water ratio (SCF/STB)
$S_{w,F}$	water saturation in the fracture domain
$S_{w,M}$	water saturation in the matrix domain
$S_{w,F,i}$	initial water saturation in the fracture domain
$S_{w,M,i}$	initial water saturation in the matrix domain
T	temperature (R)
T_{sc}	temperature at standard conditions (R)
V_b	bulk volume (ft^3)
V_L	Langmuir volume constant (SCF/ton)
W_p	cumulative water production (STB)
z	compressibility factor
β	matrix shrinkage–swelling coefficient (ft^3/SCF)
ϕ_F	fracture porosity
$\phi_{F,i}$	initial fracture porosity
ϕ_M	matrix porosity
$\phi_{M,i}$	initial matrix porosity
μ_g	gas viscosity (cp)
μ_w	water viscosity (cp)
ρ_b	coal density (ton/ft^3)

$$C_{ME} = \frac{p_{sc}}{Z_{sc}RT_{sc}}\left(\frac{V_L p}{p + p_L}\right) \tag{4}$$

In Eqs. (1–4), V_{b2} is the bulk volume of the fracture system. c_ϕ and c_w are compressibility of the formation and compressibility of water and G_p and W_p are cumulative gas production and cumulative water production, respectively. In addition, $\overline{S_w}$ represents the average water saturation remaining in the cleats.

Ahmed et al. (2006) proposed a generalized material balance equation that can be used to estimate drainage area and predict reservoir pressure and production performance for CBM reservoirs. The generalized material balance equation accounts for free gas, adsorbed gas, water expansion and formation compaction. Similar to King's material balance equation, Langmuir's equation is used to characterize the gas sorption. The generalized material balance equation developed by Ahmed et al. (2006) is shown below:

$$\begin{aligned} G_p + \frac{B_w W_p}{B_g(1 - c_\phi(p_i - p))} &= Ah\left\{1359.7\rho_B\left(G_c - \frac{V_m p}{p + p_L}\right)\right. \\ &\left.+7758\phi\frac{[(p_i - p)(c_\phi + c_{wi}S_{wi}) - (1 - S_{wi})]}{B_g(1 - c_\phi(p_i - p))}\right\} + \frac{7758Ah\phi(1 - S_{wi})}{B_{gi}} \end{aligned} \tag{5}$$

where G_c is initial adsorbed gas content in scf/ton.

Although widely used, the two material balance equations mentioned above ignore the presence of water in the coal matrix and coal shrinkage and swelling effects. Water in the coal matrix can be classified in two types including bulk water and bound water. Bulk water is referred as free mobile water in the coal matrix while bound water is referred to as immobile water molecules in a vapor phase tightly adsorbed on the hydrophilic parts of the coal matrix. Both types of water yield different effects on gas sorption capacity. Bulk water blocks the flow path of gas while bound water reduces the gas sorption capacity. Also, the coal shrinkage and swelling effects are caused by the two conflicting mechanisms including rock expansion and the release of methane from the coal surface as pressure decreases. Ignoring these two phenomena could result in inaccurate reserve estimation and production performance predictions.

Formulation

The development of a new material balance equation for CBM systems is explained here. The proposed MBE accounts for water in the coal matrix and coal shrinkage–swelling effects, which are ignored by the existing material balance equations. The development of the proposed material balance equation involves the derivation of the gas and water flow equations in the fracture and matrix domains of CBM systems used in developing the multi-phase, dual-porosity, dual-permeability, multi-mechanistic numerical flow model accounting for the water presence in the coal matrix and coal shrinkage and swelling effects (Thararoop, 2010). The derivation of the proposed material balance equation follows a transformation technique used in demonstrating the existing relationship between numerical-simulation and material-balance approaches. This technique was proposed by Ertekin et al. (2001). The derivation assumes that (1) the reservoir is holding an average pressure with no pressure gradients, (2) there is no capillary effect, (3) the potential gradients are negligible and (4) the reservoir exhibits homogeneous and isotropic properties. The development of the proposed material balance equation as presented in Appendix A yields the following equation:

$$\begin{aligned} G_p + \frac{B_w W_p}{B_g} - R_{sw}W_p = &-7758\frac{Ah}{B_g}\left[\phi_{F,i}\left(e^{c_{p,F}(p-p_i)} - 1\right)\right. \\ &\left.+\phi_{M,i}\left(e^{c_{p,M}(p-p_i)} - 1\right) + \tilde{f}\beta\rho_b V_L\left(\frac{p_i}{p_L + p_i} - \frac{p}{p_L + p}\right)\right] \\ &- 1359.7Ah\tilde{f}\rho_b V_L\left[\left(\frac{p}{p_L + p}\right) - \left(\frac{p_i}{p_L + p_i}\right)\right] \\ &+ 7758Ah[\phi_{F,i}(1 - S_{w,F,i}) + \phi_{M,i}(1 - S_{w,M,i})]\left(\frac{1}{B_{g,i}} - \frac{1}{B_g}\right) \\ &- 7758\frac{Ah}{B_{w,i}}(\phi_{F,i}S_{w,F,i} + \phi_{M,i}S_{w,M,i})(R_{sw} - R_{sw,i}) \\ &+ 7758\frac{Ah}{B_g}c_w(\phi_{F,i}S_{w,F,i} + \phi_{M,i}S_{w,M,i})(p_i - p) \end{aligned} \tag{6}$$

Eq. (6)can be expressed as a straight-line equation in the following form:

$$y = mx + c \tag{7}$$

where