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Modeling and application of coalbed methane recovery performance based on a triple porosity/dual permeability model

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ABSTRACT

The triple porosity/dual permeability (TPDP) model is an advanced coalbed methane (CBM) model for recovery simulation, which processes CBM flows via desorption and diffusion into permeation pores and moves sequentially via Darcy flow through permeation pores and cleats, and, finally, into the wellbore. Based on this theory, this paper describes the mathematical models of desorption, diffusion and permeation during CBM drainage; conducts the measurements of routine core analyses to obtain fluid characteristics, rock mechanics, coal seam domain, diffusion pore property and fracturing property, and nuclear magnetic resonance to acquire porosity and permeability of permeation pores and cleats; and, finally, takes a typical CBM well named QSDU01, located in the Qinshui basin in China, as an example to simulate its recovery performance. The following conclusions are reached. Compared with a dual porosity/single permeability (DPSP) model, the TPDP model is more advanced and can effectively eliminate the slight nonconformities caused by the DPSP model. Reservoir pressure, gas content, porosity and permeability initially decrease rapidly and subsequently slow during the CBM drainage process. The decreased amplitudes of parameters become larger as the distance to the wellbore decreases. Variations of parameters can be divided into two stages, corresponding with the stages of free gas drainage and desorbed gas drainage. The decreased amplitudes of parameters are quite small in the first stage and relatively larger in the second stage. Gas peaks lead to the turning points of the variation curves and cause the variation curves to exhibit a type of multisection.

1. Introduction

As an unconventional gas reservoir, a coalbed methane (CBM) reservoir serves as both reservoir rock and source rock for methane. In the past few decades, a dual porosity/single permeability (DPSP) model has been adopted as a typical geological model in many areas of CBM simulation, including recovery performance (Aminian et al., 2005; Law et al., 2002; Wei et al., 2007; Young, 1998), carbon dioxide injection and sequestration (Perera et al., 2011; Perera and Ranjith, 2012; Perera et al., 2012, 2013), nitrogen displacement (Pini et al., 2011; Zhou et al., 2013), and others (Zou et al., 2013a, 2014). This model suggests that there are two locations in CBM reservoirs, which are matrix and cleat, and assumes that CBM first desorbs from the matrix, then diffuses to the cleat system via the matrix, and finally flows to the wellbore through cleats.

In recent years, some researchers have found that the historical matching and production prediction simulated by the DPSP model may frequently be in error, and laboratory tests show that there is another porosity and permeability within the coal matrix (Reeves and Pekot, 2001). To solve these problems, Reeves and Pekot (2001) developed a triple porosity/dual permeability (TPDP) model, which proposed that there were two types of pores in the matrix; one was a diffusion pore controlling CBM desorption and diffusion, and the other was a permeation pore dominating CBM permeation. Therefore, for the TPDP model, CBM flows via desorption and diffusion into permeation pores, then moves sequentially via Darcy flow through permeation pores and cleats, and finally into the wellbore (Wei and Zhang, 2010).

Since then, the TPDP model has been extensively studied. However, many studies have focused on conventional reservoirs, including Al-shaalan et al. (2003), Ayala et al. (2005), Fung and Al-Shaalan (2005) and Gong et al. (2006). Studies on CBM reservoirs can only be found in two papers, written by Wei and Zhang (2010) and Thararoop et al. (2012). Wei and Zhang (2010) described a

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mathematical model, and simulated gas and water productions and parameter variations by assuming a set of reservoir parameters. Thararoop et al. (2012) amended Langmuir equations and developed a CBM modeling software based on the TPDP model, and then used the software to simulate the recovery performance of a well.

As a result, studies on the TPDP model mainly focus on two aspects of the model (Zou et al., 2013b). One is the development and improvement of the mathematical model, and the other is the verification of the model's advantages. However, another two aspects still need to be solved. One is to determine how to obtain the reservoir parameters of permeation pores and cleats because CBM can flow through them. The other one is the application on real CBM wells. Zou et al. (2013b) classified coal pore systems into diffusion pore, permeation pore and cleat systems, and then estimated porosity and permeability for each pore system. This method can be used to solve the first unsolved aspect.

To solve the second aspect, this paper gives a mathematical description of the TPDP model in detail, calculates reservoir parameters based on laboratory experiments and mathematical methods, and selects a typical CBM well at Qinshui basin of China as an example to simulate its recovery performance.

2. Mathematical model description

2.1. Desorption and diffusion

The desorption process can be described by the Langmuir equation,

$$C(P) = V_L P/(P_L + P) \tag{1}$$

where V_L is the Langmuir volume; P_L is the Langmuir pressure; P is the reservoir pressure; and $C(P)$ is the gas content under pressure P.

After desorbing from diffusion pores, CBM will flow via diffusion pores to permeation pores, and its gas quantity can be described by Fick's first law, as follows:

$$q_m = \frac{V_m}{r}(C(t) - C(P)) \tag{2}$$

where V_m is the bulk volume of the matrix; q_m is the gas desorption rate; $C(t)$ is the average gas rate at time t; and r is the desorption time.

2.2. Permeation in the permeation pore system

For the permeation pore system, the source item of gas is the quantity of gas diffused from diffusion pore to permeation pore, the source item of water equals zero, and the sink items of gas and water are the gas and water quantities permeated from the permeation pore to the cleat system, defined as E_g and E_w, respectively.

The final permeation description can be described using mass conservation and Darcy's law as expressed in Eq. (3):

$$\begin{cases} \nabla\cdot\left[\dfrac{\rho_w k_p k_{rwp}}{\mu_w}(\nabla P_{wp} - \rho_w g \nabla h)\right] - E_w = \dfrac{\partial}{\partial t}(\varphi_p \rho_w S_{wp}) \\ \nabla\cdot\left[\dfrac{\rho_g k_p k_{rgp}}{\mu_g}(\nabla P_{gp} - \rho_g g \nabla h)\right] + q_m - E_g = \dfrac{\partial}{\partial t}(\varphi_p \rho_g S_{gp}) \end{cases} \tag{3}$$

where ρ_g and ρ_w are the gas and water densities, respectively; k_p is the absolute permeability of the permeation pore; k_{rgp} and k_{rwp} are the relative permeabilities of gas and water in the permeation pore system, respectively; μ_g and μ_w are the viscosities of gas and water, respectively; P_{wp} and P_{gp} are the reservoir pressures of water and gas, respectively; h is the reservoir thickness; S_{wp} and S_{gp} are the water and gas saturations of the permeation pore system, respectively; φ_p is the porosity of the permeation pore system; and ∇ is the Hamilton operator.

In Eq. (3), P_{wp}, P_{gp}, S_{wp} and S_{gp} satisfy

$$\begin{cases} P_{cp} = P_{gp} - P_{wp} \\ S_{wp} + S_{gp} = 1 \end{cases} \tag{4}$$

where P_{cp} is the capillary pressure of the permeation pore system and is always set to zero.

Eqs. (3) and (4) are the final permeation descriptions of the permeation pore system.

2.3. Permeation in the cleat system

For the cleat system, the source item of gas is the quantity of gas permeated from permeation pore to cleat, the source item of water is the quantity of water permeated from permeation pore to cleat, and the sink items of gas and water are the gas and water quantities produced from the wellbore, defined as q_g and q_w, respectively. Similar to Eq. (3), the permeation equations of the cleat system can be expressed as

$$\begin{cases} \nabla\cdot\left[\dfrac{\rho_w k_c k_{rwc}}{\mu_w}(\nabla P_{wc} - \rho_w g \nabla h)\right] + E_w - q_w = \dfrac{\partial}{\partial t}(\varphi_c \rho_w S_{wc}) \\ \nabla\cdot\left[\dfrac{\rho_g k_c k_{rgc}}{\mu_g}(\nabla P_{gc} - \rho_g g \nabla h)\right] + E_g - q_g = \dfrac{\partial}{\partial t}(\varphi_c \rho_g S_{gc}) \end{cases} \tag{5}$$

where the subscript c represents that the values are for the cleat system.

The additional equations are

$$\begin{cases} P_{cc} = P_{gc} - P_{wc} \\ S_{wc} + S_{gc} = 1 \end{cases} \tag{6}$$

where P_{cc} is the capillary pressure of the cleat system.

Eqs. (5) and (6) are the final permeation equations for the cleat system.

2.4. Solutions of E_g and E_w

E_g and E_w are both generated by pressure differences between permeation pore and cleat systems. Hence, they can be expressed by Darcy's law as

$$\begin{cases} E_g = \sigma\dfrac{\rho_g k_{rgc} k_c}{\mu_g}(P_{gp} - P_{gc}) \\ E_w = \sigma\dfrac{\rho_w k_{rwc} k_c}{\mu_w}(P_{wp} - P_{wc}) \end{cases} \tag{7}$$

where σ is the shape factor.

As a commercial and special simulator for CBM, COMET3 software, developed by Advanced Resources International of America, has all of the above equations in its built-in equations. All of the equations can be found in the COMET3 user manual.

2.5. Geomechanical models

During the CBM drainage process, the coal matrix will be deformed, which can be attributed to two main factors. First, the