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A semi-analytical model for the relationship between pressure and saturation in the CBM reservoirs

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ABSTRACT

At present, analyzing and predicting CBM production performance remains challenging, which can be attributed to the complex gas-water two phase flow and dynamic nature of petro-physical properties. For the sake of simplicity, the saturation distribution in coal seams is generally overlooked and characterized by average water saturation in previous literature, which one can easily handle analytically, semi-analytically, and numerically. However, average water saturation is inadequate to obtain the precise value of pseudo pressure for water/gas phase, which may generate large deviation compared with actual production behavior. To our best knowledge, the relationship between pressure and saturation in coal seams is still lacking in the petroleum industry. Thus, the main objective of this research is to gain a clear understanding of this issue.

In this work, on the basis of rigorous derivation, a semi-analytical model for the relationship between pressure and saturation is developed, which comprehensively accounts for the presence of free gas at the early production stage, matrix shrinkage and gas desorption. Notably, the stress dependence effect is incorporated during the entire production process of CBM wells. Subsequently, employing the gas-water two phase relative permeability data, we present an iterative numerical algorithm to solve the model. Moreover, the proposed semi-analytical model is successfully verified against a numerical reservoir simulator. After that, we shed light on the influences of physical parameters upon the saturation distribution versus pressure and achieve a variety of new insights.

This research, for the first time, presents a semi-analytical model to quantify the relationship between pressure and saturation, which fills the gap for the theory of gas-water two phase flow in CBM reservoirs. The proposed model is less data-intensive than performing a numerical simulation and turns out to be simple and powerful in the application. In addition, the new model can significantly contribute to the obtainment of precise pseudo pressure for water/gas phase, therefore lays the theoretical basis for the accurate production prediction for CBM wells.

1. Introduction

Recently, as one of the most promising potential alternatives for the conventional natural gas, the exploration and exploitation of coal-bed methane reservoirs (CBM) attract a great deal of attention (Clarkson and McGovern, 2005; Karacan, 2013; Lou et al., 2013; Wang et al., 2014; Bao et al., 2016). Apparently different from conventional gas reservoirs, coal seams possess unique methane storage and transport mechanisms due to the complex dual porosity: matrix system (micropores and macropores) and cleat system (micro fractures). Under the initial formation condition, the majority of gas store in micropores within the matrix system by adsorption mechanism, while the cleat network system is considered saturated with water (Gray, 1987; Xu et al., 2013). During the depressurization development process of CBM wells, the gas transport mechanism in a matrix system is assumed as diffusion dominated by gas desorption process and the cleats provide the relatively high permeability pathway from matrix to wellbore (Mora and Wattenbarger, 2009; Aminian and Ameri, 2009; Chen et al., 2013). As a result, analyzing and predicting production performance for CBM wells remain challenging. Moreover, water-gas two phase flow expects to occur in the cleats at the early production stage, which significantly aggravates the complexity of the aforementioned issue (Ma et al., 2017; Sun et al., 2017a). The most accurate way to predict production performance is to employ a calibrated full-physics reservoir

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simulator (Gentzis and Bolen, 2008; Pan and Wood, 2015). However, although recent advances have significantly enhanced computational performance, the numerical simulation is still challenging to simulate the well performance because of the considerable time-consuming gridding issues and expensive computation cost (Wu et al., 2016; Sun et al., 2017b). Hence, it will be attractive to establish an analytical or semi-analytical model to simulate production performance of CBM wells.

The entire production life of typical CBM wells can be divided into three stages. At the early production stage, the formation pressure decreases in terms of the dewatering operation. Notably, numerous previous literature assumed that there only exhibited single water phase flow in the cleats at this stage (Seidle, 1999; Firanda, 2011; Xu et al., 2013; Shi et al., 2014). However, the assumption cannot agree with the actual production performance that the CBM well yields a little gas once the production starts. The presence of lithological heterogeneity in the actual CBM reservoirs results in the existence of a small amount of free gas, which is generally overlooked. Thus, the actual coal cleats experience water-gas two phase flow once the gas well put into production. When the bottom-hole pressure (BHP) is lower than the critical desorption pressure, the CBM well enters into the negative decline stage, in which gas can desorb from the coal matrix. At this stage, the gas saturation will increase rapidly which will result in substantial enhancement of gas production. Moreover, the stage will end once the gas production reaches its maximum value and transitions to the decline stage. As the production process and gas desorption continue, the gas saturation will further increase and the gas flow will gradually dominate the flow features in the cleats. Through the analysis of the production life of CBM wells, it can be demonstrated that the key issue required to be captured is how to reasonably handle the water-gas two phase flow. Also, the production behavior of CBM wells is subject to the influence of stress dependence when the pressure is higher than critical desorption pressure, and the effects of stress dependence and matrix shrinkage simultaneously when the pressure is lower than the critical desorption pressure (Harpalani and Schraufnagel, 1990; Ibrahim and Nasr-El-Din, 2015; Clarkson and Qanbari, 2015).

A large number of scholars have devoted significant research efforts to investigate and predict the dynamic production behavior of CBM wells (King, 1993; Spivey and Semmelbeck, 1995; Clarkson and McGovern, 2001, Clarkson et al., 2007; Aminian and Ameri, 2009; Firanda, 2011; Chen et al., 2013; Ibrahim and Nasr-El-Din, 2015; Clarkson and Qanbari, 2016). However, the majority of these models only consider the single gas phase flow, which cannot satisfy the application requirement of the petroleum industry. In addition, for the sake of simplicity, the saturation distribution in coal seams is either overlooked or represented by average water saturation in the other published literature considering the water-gas two phase flow, which one can easily handle analytically, semi-analytically, and numerically. Unfortunately, the average water saturation is inadequate to capture the key physics of transient flow behavior in coal seams and cannot achieve the precise value of pseudo pressure for water/gas two phase, which may generate large deviation compared with actual production behavior. Assuming the water saturation remained unchanged throughout the production life of CBM wells, Seidle (1993) utilized the flow equations that described dry gas wells to investigate the long-term gas deliverability of a dewatered CBM wells. Incorporating stress dependence and matrix shrinkage, Spivey and Semmelbeck (1995) developed a production prediction model based on material balance equation. However, the average water saturation was employed in Spivey's model. Similar with Spivey, Ibrahim and Nasr-El-Din, 2015 presented a generalized material balance equation utilizing the concept of average water saturation. Xu et al. (2013) established a simple analytical model to quantify the expansion principle of desorption area by combining material balance equation and pressure approach or pressure squared approach. However, the water saturation was neglected in Xu's model. Clarkson and Salmachi (2017) modified the flowing material balance equations for gas and water two phases by accounting for effective permeability changes above and below critical desorption pressure. However, Clarkson made a simplification that there were negligible saturation and pressure gradients within the high permeability CBM reservoirs (10–100 md). For low permeability (< 1 md), under-saturated coal seams, Clarkson and Qanbari (2016) obtained the relationship between pressure and water saturation from a rigorous numerical simulator. Subsequently, Clarkson established a production prediction model on the basis of this relationship and achieved excellent agreements compared with actual production performance. In summary, the main limitation of Clarkson's model is the requirement to implement a numerical simulator, which is considered as time-consuming and is not appropriate for the field application. Considering the saturation distribution in the coal seams, Sun et al. (2017a) established a semi-analytical model for drainage and desorption area expansion during coal-bed methane production. However, different water saturation will correspond to the same water-gas mobility ratio in Sun's model, which is conflict with the well-established fact. To our best knowledge, the relationship between pressure and saturation in coal seams has not correctly reported yet. To date, a model to characterize the relationship between pressure and saturation is still lacking in the petroleum industry and thus this research intends to gain a clear understanding of this issue.

In this work, on the basis of rigorous derivation, a semi-analytical model for the relationship between pressure and saturation is developed according to the partial differential equations of gas-water two phase flow, which comprehensively accounts for the free gas saturation at early production stage, matrix shrinkage and gas desorption. Notably, the stress dependence effect is incorporated during the entire production process of CBM wells. After that, employing the gas-water two phase relative permeability data, we present an iterative numerical algorithm to solve the model. This research effort, for the first time, presents a semi-analytical model to quantify the relationship between pressure and saturation, which fills the gap for the theory of gas-water two phase flow in CBM reservoirs. Furthermore, it will serve as a simple, applicable and powerful tool to modify the current production prediction models, rate transient analysis methods and pressure transient analysis methods for CBM reservoirs (Nie et al., 2012; Williams-Kovacs et al., 2012).

2. Model assumptions and establishment

In this section, firstly, we make some reasonable assumptions in order to achieve a simple semi-analytical model. Secondly, the relationships between pressure and saturation are developed when the pressure is above and below the critical desorption pressure respectively. Finally, calculation formulas for the petro-physical properties are given in detail, encompassing porosity, gas viscosity (μ_g), compressibility factor (Z), and gas compressibility (C_g).

2.1. Assumptions

Considering the lithological heterogeneity exhibited in the actual CBM reservoirs, in this work, we assume that the initial water saturation is less than unity. Also, we ignore the kinetics of the process in gas-flow transport formulation by assuming desorption time to be zero. Moreover, following assumptions and simplifications are made to generate a practical model.

(1) The CBM reservoir is assumed to be a dual-porosity and single permeability model with homogeneous and isotropic properties and uniform thickness. Furthermore, the gas-water two phase flow in the cleats obeys Darcy's law;
(2) In the derivation process for the relationship between pressure and saturation in coal seams, the gravity and capillary effects are neglected;