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A dynamic predictive permeability model in coal reservoirs: Effects of shrinkage behavior caused by water desorption

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ABSTRACT

Forecasting production in coal reservoirs accurately has been of growing interest in the industry. Permeability of coal reservoirs is a key parameter affecting coalbed methane production. In terms of current literature, the dynamic variation of coal permeability mainly depends on the effect of effective stress, coal matrix shrinkage caused by gas desorption and gas slippage during coalbed well drainage. The volume occupied by water in coal matrix was overlooked and its effect on matrix desorption-shrinkage-effect has not been investigated ever. In this work, on the basis of S-D stress-permeability model (Shi and Durucan, 2004), a dynamic prediction model of coal permeability fully considering the effect of effective stress, coal matrix shrinkage caused by gas desorption, gas slippage and coal matrix shrinkage caused by water desorption was established. The dynamic variation of permeability in coalbed methane development was revealed. The reliability of proposed model for permeability variation was successfully verified through the excellent agreements compared with experimental results. In addition, comparisons among the commonly utilized models and the new model indicated that the predicted permeability from the new model is overestimated than other models, such as P-M, S-D, and C-B models. The large differences between the new model and traditional models explicitly stress the necessity and significance of considering the matrix shrinkage effect caused by water desorption on coal permeability, which should not be neglected. Furthermore, based on the proposed permeability model, the influence of relative humidity in coal matrix was seriously paid attention. The four effects for the dynamic permeability of coalbed methane well were compared and analyzed. Results illustrated that relative humidity has an important effect on coal permeability performance, which will increase the dynamic permeability in coal reservoirs. Accordingly, the effect of coal matrix shrinkage caused by water desorption will increase the dynamic permeability in coal reservoirs. The gas slippage has a little effect on dynamic permeability in coal reservoirs.

1. Introduction

In the past two decades, coalbed methane resources have provoked worldwide attention because coalbed methane reservoirs are showing the potential to be commercially exploited around the world. Coalbed methane reservoirs have undergone the process of drainage, depressurization, desorption, diffusion, seepage and production (Mccourt et al., 2017; Freij-Ayoub, 2012; Zhao et al., 2017; Miao et al., 2018a, 2018b; Meng et al., 2018; Sun et al. 2017a, 2017b, 2018), which can be divided into three stages: with the decrease of pore pressure, the adsorbed gas is desorbed from the pore surface of the coal matrix to form a free gas stage; The free gas diffuses through the pores of coal matrix to the coal cleat stage; The free gas moves through the cleat system to the wellbore production stage. The permeability of coal reservoirs is a key parameter affecting the productivity of a coalbed methane well, which determines the seepage and production of coalbed methane well. Compared with permeability models for conventional gas reservoirs, coal permeability is more complicated since it can vary significantly during gas production in response to decreases in pore pressure and gas desorption-induced coal matrix shrinkage (Agarwal et al., 2013; Sevket et al., 2014; Kumar et al., 2015). Therefore, the study of dynamic permeability is of great significance to illustrate the fluid flow behavior

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in coal reservoirs.

The dynamic change of coal permeability depends on multiple factors. So far, significant efforts have been devoted to characterize the permeability variation associated with the influencing parameters and prediction models (McKee et al., 1988; Harpalani and Schraufnagle, 1990; Levine, 1996; Enever et al., 1998; Zhou and Lin, 1999; Dennis et al., 2015; Connell, 2009; Meng et al., 2011; Pan and Connell, 2012). The permeability variation models can be classified into two categories: porosity-based and stress-strain based permeability models (Meng et al., 2018). For the porosity-based models, the permeability was correlated with porosity through cubic laws (Palmer and Mansoori, 1998; Palmer, 2009; Wei et al., 2015). For the stress-strain based models, the permeability was related to the effective stress variation through the exponential function (Somerton et al., 1975; Shi and Durucan, 2004, 2005). It should be noted that the S-D model (2004) is one of the most popular prediction model of coal reservoir permeability, which is based on matchstick representation of coalbed. The cleat permeability is impacted by the prevailing effective horizontal stresses acting normal to the cleats. The variation in effective horizontal stress under uniaxial strain condition is expressed as a function of pore pressure, which included a cleat mechanical compression term and a matrix shrinkage term that have competing effects on cleat/fracture permeability (Liu and Harpalani, 2013a, 2013b). On this basis, dynamic models of permeability evolution around the coalbed methane wells were established considering the effective stress effect and matrix shrinkage effect to explain the permeability variation law. Harpalani and Chen (1995) conducted a numerical simulation to estimate the variation of cleat porosity and permeability with matrix shrinkage. Depending on the matchstick geometry, a permeability variation model was developed assuming constant reservoir volume. This model can be applied to the cases where permeability change is close related to pore pressure change and swelling/shrinkage strain. Seidle and Huitt (1995) proposed a permeability model taking into account permeability changes as a result of the sorption-induced strain, where permeability was expressed as a function of the initial porosity, Langmuir strain constants and pressure. It is limited to be employed for cases where only the impact from coal swelling/shrinkage is considered. Levine (1996) developed a novel model to estimate the variation in permeability with depletion where the new cleat aperture width is assumed as the previous cleat aperture with plus the closure because of cleat compressibility and opening owing to matrix shrinkage, then sensitivity study were conducted and indicated that the matrix shrinkage coefficient had the strongest influence on coal permeability. Gu and Chalaturnyk (2005) developed a coupled permeability model to predict dynamic changes in permeability, where gas pressure, gas production, adsorbed gas volume, etc. were estimated by employing the simulator. In this model, firstly, a coal mass is regarded as an equivalent elastic continuum and the anisotropy of coalbeds in permeability. Secondly, matrix shrinkage/swelling caused by gas desorption/adsorption, thermal expansion induced by temperature change are incorporated. Thirdly, matrix spacing and cleat apertures for the cleats are various. The Pan and Connell (2007) established a mathematical model to calculate the strain of coal matrix with the assumptions that the surface energy change duo to adsorption equals to the elastic energy change of the coal solid, which represents different gases' coal swelling depending on one set of coal property parameters and adsorption isotherms. Robertson and Christiansen (2008) proposed a permeability model for coal and other media. The cubic geometry model was employed as the basis instead of the matchstick model, which is under the conditions of variable stress commonly employed during permeability data determination in the laboratory. Connell (2009) proposed a new model by incorporating flow and geomechanics for a coalbed with the assumption of isotropic sorption-induced strain, uniaxial strain condition and constant vertical stress. Based on this model, it can be concluded that constant overburden stress may bring some inaccuracy near wellbore. Liu and Harpalani (2013a, 2013b) established a mathematical model of adsorption-induced strain of coal matrix, taking into account the physical-mechanical and adsorption parameters based on the variation of surface energy caused by adsorption. This model is depending on the principles of physics and chemistry of a surface and the interface theory. The volumetric strain of coal matrix for sorbing gas includes sorption-induced and mechanical-induced strain. The sorption-induced strain is directly proportional to the decrease in surface energy and mechanical-induced strain is calculated by the Hooke's law (Liu and Harpalani, 2013a, 2013b). These models have been widely utilized to predict the variation of coal permeability and gas well production.

Compared with the conventional gas reservoirs, the coal reservoirs have obvious characteristics of elastic-plastic deformation and stress sensitivity (Meng et al., 2018). In the process of coalbed methane development, the pore pressure decreases and effective stress increases with the extraction of underground fluids, which results in the decrease of coal porosity and permeability. However, many existing permeability models didn't incorporate the three effects of effective stress, matrix shrinkage and gas slippage in one formula. Later, Meng et al. (2018) established a dynamic prediction model of coal reservoir permeability considering the effective stress, coal matrix shrinkage caused by gas desorption and gas slippage effect. However, Meng's model failed to take the desorption-induced-shrinkage effect caused by water in coal matrix material into account. It is noticeable that the water exists in mesopores and macropores and gas exists in micropores. Water present in coal seams is of profound importance in relation to coalbed methane production since this effect directly influences pore and cleat apertures (Liu et al., 2011; Bergen et al., 2006, 2009; White et al., 2005; Wang et al., 2017). First, the presence of water in coal reduces gas diffusivity (Pan et al., 2010). It also reduces the sorption capacity of coal to gas, such as CH_4 and CO_2, as coal has a greater affinity for adsorbing water (Busch and Gensterblum, 2011; Day et al., 2008; Gensterblum et al., 2013, 2014; Merkel et al., 2015). More importantly, desorption of water by coal matrix material leads to several percent of shrinkage (Fry et al., 2009; Suuberg et al., 1993). As a result, the comprehensive permeability model for coal is still lacking in the petroleum industry, which highlights the urgent requirement to develop fully coupled permeability models for coal reservoirs.

In this work, on the basis of Shi-Durucan (S-D) stress-permeability model, a dynamic predictive model of coal permeability was established, which incorporated the effective stress effect, coal matrix shrinkage effect caused by gas desorption, gas slippage effect, and coal matrix shrinkage effect caused by water desorption. In addition, the proposed permeability model was validated with the experimental data, and sensitivity analysis of the model was further conducted. Because the proposed permeability model in this research accounts for nearly all influential factors, the model turns out to be powerful in the application. Furthermore, this work can lay the theoretical basis for the next generation numerical simulator for coalbed methane reservoirs.

2. Methodology

The dynamic variation of coal reservoir permeability during coalbed methane well drainage accounts for the effective stress effect, coal matrix shrinkage effect caused by gas desorption, gas slippage effect, and coal matrix shrinkage effect caused by water desorption.

2.1. Effective stress effect

During the development of coalbed methane, with the extraction of water and gas, the reservoir pressure declines gradually, which leads to the micro-pores and fractures in coal be compressed. Before the dewatering, coalbed methane reservoir is in a virgin equilibrium state and the reservoir pressure is termed as initial reservoir pressure. For the undersaturated reservoirs, in the beginning of production, reservoir pressure is higher and desorption of adsorbed gas does not occur. When the reservoir pressure reduces to the time that desorption of adsorbed