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Impact of micro- and macro-scale consistent flows on well performance in fractured shale gas reservoirs

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A B S T R A C T

Shale gas revolution comes from the skillful combination of horizontal drilling and hydraulic fracturing technology that can create a fractured gas reservoir for gas production. The well performance in the fractured shale gas reservoir is significantly impacted by the complicated gas flow regimes in both fracture network and shale matrix. The consistency between the macro-flow in fracture network and the micro-flow in shale matrix determines the gas production curve, thus being a key issue to gas well design. This paper proposes a numerical model to investigate the impact of micro- and macro-scale consistent gas flows on well performance in fractured shale gas reservoirs. In this numerical model, the macro-scale gas flow follows the Darcy law in the fracture network and the micro-flow in the shale matrix is described by a diffusion-controlled gas transport model. Two apparent diffusion coefficients or models are then obtained. They incorporate viscous flow with slip boundary, molecular diffusion (i.e. molecular self-diffusion), Knudsen diffusion, and surface diffusion in the adsorption layer. The performances of these two diffusion models for the gas transport within shale matrix are investigated and compared with two apparent permeability models proposed by Singh and Javadpour (2013) and Darabi et al. (2012). Furthermore, the pressure-dependent anisotropy of fracture permeability and compressibility is incorporated into the numerical model. This numerical model is verified by an analytical solution and history matching for a Barnett shale gas well. Finally, a fractured gas reservoir with different scenarios is numerically simulated and the shapes of production curves are analyzed through parametric study. It is found that the enhancement of gas recovery efficiency and the life of a shale gas well can be effectively designed if the consistency of micro- and macro-flows can be well designed.

1. Introduction

Shale gas is playing an increasingly critical role in the world's natural gas production due to the advancement of enormous reserves, exploration technology, and the demand for cleaner energy such as crude oil and natural gas (Lee and Sohn, 2014; Guo et al., 2015; Kang et al., 2015; Sharma et al., 2015; Zhang et al., 2015). Shale gas reservoirs usually have extremely low permeability, thus the flow behaviors in shale gas reservoirs are different from conventional gas reservoirs. The commercial development of shale gas has been driven by following three key advances: (1) horizontal well plus multi-staged hydraulic fracturing, (2) understanding of gas storage mechanism in shale matrix, (3) understanding of gas flow mechanism in shale matrix (Li et al., 2014). Therefore, the investigation on the shale gas flow in the shale matrix with rich nanopores is a vital procedure for the commercial development of shale gas reservoirs.

The gas flow in the nanopores within shale matrix is considerably complicated (Singh and Javadpour, 2016). Based on Knudsen number,Kn, which is the ratio of molecular mean free path to space characteristic dimension, the gas flow regime can be classified into viscous flow, slip flow, transition flow, and free molecular flow, respectively (Roy et al., 2003; Dongari et al., 2009; Darabi et al., 2012; Hashemifard et al., 2013; Deng et al., 2014; Li et al., 2014; Ren et al., 2015; Zhang et al., 2015). In the viscous flow and slip flow regimes, the Navier-Stokes equation is applicable to the

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description of gas flow. In the transitional flow regime, continuum approximation is not suitable for gas flow. The Knudsen layer, where gas molecules collide with the wall, occupies a significant fraction of the flow domain. In the free molecular flow regime, the Knudsen number is significantly greater than unity. The mean free path is therefore much greater than the length of the flow channel and molecules collide with surfaces bounding the flow wall more frequently than they collide with one another. A lot of mathematical models expressed by apparent permeability have been proposed for the gas flow within shale matrix (Javadpour, 2009; Civan, 2010; Civan et al., 2011; Darabi et al., 2012; Singh and Javadpour, 2013; Wu et al., 2014; Guo et al., 2015). However, no gas transport model is available in expression of apparent diffusion coefficient.

The mechanisms of gas flow in shale matrix have been studied through both numerical simulations and experimental measurements. Micro-scale flow simulations have been conducted to investigate the mechanisms of gas desorption and transport within shale matrix (Zhai et al., 2014; Ren et al., 2015; Sharma et al., 2015; Zhang et al., 2015). For example, Zhang et al. (2015) investigated the transport mechanisms and influence factors through Lattice Boltzmann method (LBM). They found that net desorption, diffusion, and slip flow are very sensitive to pore scale. Pore pressure and temperature have also impacts on the mass flux of gas (Teng et al., 2016). Ren et al. (2015) studied the effect of surface diffusion and gas slippage on the velocity of free gas and the mass flux in a kerogen pore via LBM. The simulation results show that the surface diffusion is a more important factor than gas slippage, but it can be negligible in large-size pores. Due to the significant advantages of multi-scale times, LBM became a prevailing numerical simulation approach for the investigation of gas transport mechanisms. In addition, Zhai et al. (2014) used grand canonical Monte Carlo (GCMC) simulation to investigate the adsorption of shale gas in a shale matrix model at different geological depths up to 6 km. They adopted molecular dynamics (MD) simulation to examine the diffusion of shale gas in shale matrix. The GCMC configurations were used as initial input in their MD simulation. Similarly, Sharma et al. (2015) investigated the adsorption and diffusion characteristics of methane and ethane in montmorillonite slit pores via GCMC and MD simulations. Micro-flow simulations can deepen our understandings on the flow mechanisms within shale matrix, but are difficult to be incorporated into a large-scale simulation for a well performance in a fractured gas reservoir.

On the other hand, micro-flow experiments on gas flow have also been conducted. Compared to micro-flow simulations, corresponding micro experiment is insufficient due to its difficulty. Guo et al. (2015) presented an experiment for nitrogen flow through nano membranes and derived an apparent permeability based on an advection-diffusion model. In order to investigate the characteristics of nonlinear gas flow in shale matrix, Kang et al. (2015) conducted a core-flooding experiment under the net confining stress at reservoir conditions. They found that the nonlinear flow behavior has a huge difference between nitrogen and methane as a driving fluid. This is because nitrogen and methane have significantly different adsorption properties on organic matter. Therefore, the adsorption property of gas on shale matrix is an important issue to affect the micro-flow of gas within shale matrix.

Further, the estimation of gas content in a shale reservoir is a vital issue for gas production. It is known that gas is stored as free gas in tiny spaces of shale matrix or absorbed on the surfaces of organic matter and clays (Sharma et al., 2015). Free gas also exists in fracture network and this free gas is transported to the wellbore driven by the difference between the bottom-hole pressure and the reservoir pressure. The gas pressure difference in matrix pores and fracture network drives the free gas in matrix pores to flow into the fracture network. This process is slow and usually diffusive. It changes the pressure profile and causes the adsorbed gas on the surface of organic matter to adsorb into pore spaces. This desorption supplies free gas to the pore channel and increases its pore pressure (Zhang et al., 2015). In addition, the adsorbed gas can be migrated in the sorption layer by surface diffusion without any desorption (Sheng et al., 2014; Wu et al., 2015). Therefore, any gas transport model for the gas diffusion in shale matrix should systemically consider these mechanisms.

The above-mentioned gas transport mechanisms can be described by two possible types of conceptual models: (1) molecular dynamics model considering the details of gas molecular nature; (2) macro-scale model ignoring the details of gas molecular nature (Wu et al., 2014). The molecular dynamics model can accurately simulate the gas flow in high Knudsen number ranges within nanopores, but its computational time and memory requirement limit its implementation for large-scale problems such as the well performance in fractured shale gas reservoirs. Therefore, molecular dynamics model can only simulate some small-scale problems. Macro-scale model is practical, although it is cannot take all the mechanisms in a shale gas reservoir into considerations.

This paper proposes a dual-porosity numerical model to simulate the well performance in a fractured shale gas reservoir. The gas reservoir is regarded as a composite body of fracture network and shale matrix. The formation matrix with low permeability is intersected by fractures with high hydraulic conductivity. In such a fractured shale gas reservoir, the micro- and macro-consistent flows play a crucial role in the performance of shale gas wells. In this paper, the gas flow in fracture network satisfies the Darcy flow and the gas transport in a shale matrix block follows a nonlinear diffusion process. Then, a diffusion-controlled gas transport model is proposed and two new apparent diffusion coefficients are obtained. These two diffusion coefficients incorporate viscous flow considering slip boundary, molecular diffusion (i.e. molecular self-diffusion), Knudsen diffusion, and surface diffusion together in different ways. They are then applied to the modeling of the gas transport in shale matrix. The superiority and reliability of this diffusion-controlled gas transport model is verified through the comparisons with an analytical solution and the history matching of well production data in Barnett shale reservoirs. Subsequently, the gas production of a horizontal well is numerically simulated and the shapes of production curves are analyzed through parametric study. Finally, the effects of fracture anisotropic permeability and compressibility on gas production rate are explored.

This paper is organized as follows. Section 2 presents the diffusion-controlled gas transport model and two apparent diffusion coefficients. Section 3 discusses the gas exchange rate between matrix and fracture network. Section 4 describes the macro-flow in fracture network. The pressure-dependent anisotropy of fracture permeability and compressibility is introduced into the macro-flow. Section 5 validates the numerical model with an analytical solution and history matching. The two diffusion models for the gas transport in shale matrix are also compared with two apparent permeability models proposed by other researchers. Section 6 conducts parametric study on the numerical model for a fractured shale gas reservoir. The shapes of production curves and the effect of fracture anisotropy are investigated. The conclusions are given in Section 7.

2. Diffusion-controlled gas transport model

In previous studies, seepage-controlled transport models are prevailing for the gas flow in shale matrix. The apparent permeability is the focus (Javadpour, 2009; Civan, 2010). However, no diffusion-controlled gas transport model is available. This section

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