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Triple-continuum modeling of shale gas reservoirs considering the effect of kerogen

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A B S T R A C T

Shale gas storage and transport mechanisms are notably different in kerogen systems and inorganic matrix systems. Based on these complex shale gas transport mechanisms, including viscous flow, Knudsen diffusion, surface diffusion and gas adsorption/desorption on the internal kerogen grain surfaces, a kerogen – inorganic matrix – fracture triple-continuum model is established. There are two transfer terms in the triple-continuum model in this paper. The kerogen – inorganic matrix transfer flow is simulated by the Warren-Root pseudo-steady state (PSS) transfer model, while the inorganic matrix – fracture transfer flow is simulated by the Vermeulen transient transfer model.

To investigate the impact of the kerogen continuum on shale gas reservoir performance, a comparison between the matrix – fracture dual-continuum model and kerogen – inorganic matrix – fracture triple-continuum model is conducted. The matrix – fracture transfer flow in the dual-continuum model is also simulated by the Vermeulen transient transfer model. In addition, two triple-continuum models with different inorganic matrix – fracture transfer models are compared to investigate the impact of the transfer model. One triple-continuum model uses the Warren-Root PSS transfer model. The other uses the Vermeulen transient transfer model. The mathematical model is solved by the PDE module of COMSOL Multiphysics. A sensitivity analysis of parameters affecting shale gas production, including kerogen pore volume, kerogen permeability, inorganic matrix permeability, fracture permeability and Langmuir parameters, is conducted.

The results indicate that dividing the matrix system into a kerogen continuum and inorganic matrix continuum significantly influences shale gas reservoir performance. Not considering the kerogen continuum could lead to an overestimate in cumulative gas production of approximately 8%. The triple-continuum model that uses the Vermeulen transient transfer model yields a higher recovery than that which uses the Warren-Root PSS transfer model. Moreover, natural fractures are the main permeable channels in shale gas reservoirs and play a more important role than the kerogen and inorganic matrix in shale gas recovery. Langmuir pressure and Langmuir volume also have significant effects on the cumulative production of desorbed gas, free gas and total gas, with the effect of Langmuir volume being relatively larger. In conclusion, a triple-continuum model with a transient transfer term should be incorporated into the numerical simulators of shale gas reservoirs to predict shale gas production more accurately.

1. Introduction

It is widely considered that conventional resource shortage has become a bottleneck of global economic development. As an important class of unconventional natural gas resources (EIA, 2013), shale gas reservoirs significantly contribute to the growing energy demand. In the past decade, shale gas resources

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have received additional attention and become a major focus of the petroleum industry, as well as energy resource industries worldwide (Wu et al., 2013). Compared to conventional reservoirs, shale has a relatively low porosity and ultra-low permeability at the nanoscale (Javadpour et al., 2007; Loucks et al., 2009). These characteristics mean that the traditional governing equation, Darcy's law, is no longer applicable. In addition, shale is a complex unconventional reservoir with coupled storage and transport mechanisms (Freeman et al., 2011; Hill and Nelson, 2000; Yao et al., 2013). Therefore, the simulation of shale gas reservoirs is far more difficult than that of conventional resources.

Shale is a complex mixture of organic matter (i.e., porous kerogen pockets), inorganic matrix and natural fractures (Killough et al., 2013). The organic matter is a nanoscale porous medium that mainly consists of micropores (<2 nm) and mesopores (2–50 nm) (Kang et al., 2011), while inorganic pores with a much larger size (>100 nm) (Wasaki and Akkutlu, 2014). Because the organic material has a strong affinity (large molecular interaction) for the hydrocarbon fluids and large surface area associated with the pore walls, the organic pores are the ideal places for storage of shale gas in the adsorbed phase (Wasaki and Akkutlu, 2014). Due to the minor molecular interaction between the inorganic material and hydrocarbon fluids, and relatively larger pores in the inorganic material, the amount of gas adsorbed by the inorganic walls is considered negligible. In conclusion, free gas and adsorbed gas exist in the kerogen system, while only free gas exists in the inorganic matrix system. In addition, the transport mechanisms of shale gas are different in the kerogen and inorganic matrix. The transport mechanisms in the kerogen system include viscous flow, Knudsen diffusion, the surface diffusion and desorption mechanism of adsorbed gas. However, only viscous flow and Knudsen diffusion exist in the inorganic matrix system. Because the shale gas storage and transport mechanisms in the kerogen system and inorganic matrix system are notably different, it is necessary to divide the matrix system into a kerogen continuum and inorganic matrix continuum (Akkutlu and Fathi, 2012).

The most critical issue faced when using a dual-continuum model is the handling of the matrix–fracture transfer, which couples the matrix continuum with the fracture continuum. Generally, there are 3 ways to do so in a reservoir simulator framework (Azom and Javadpour, 2012). The first is the boundary condition approach, which is acceptable for near wellbore studies, such as well testing, but quite impractical for full field simulations. In addition, numerical instabilities will occur for large time steps when this method is used in a numerical simulator. The second approach is the Warren-Root method, which assumes that the transfer term between the matrix block and surrounding fractures is a pseudo-steady state transfer and directly proportional to the difference between the matrix pressure and fracture pressure (Warren and Root, 1963). However, the Warren-Root PSS transfer model only holds for large times when the flow in matrix block can be represented by a pseudo-steady state flow regime. The errors will generally be quite large at small times (Zimmerman et al., 1993). The third method is the Vermeulen model, which provides a good approximation at all time scales. Additionally, the transient shape factor is not a constant, but a function of the reservoir pressure (Azom and Javadpour, 2012).

In this study, the shale gas reservoir is simulated as a triple-continuum (kerogen – inorganic matrix – natural fractures) system and the transport of shale gas takes place in the following sequence: kerogen → inorganic matrix → natural fractures (Akkutlu and Fathi, 2012; Kang et al., 2011). Therefore, there will be two transfer terms in the triple-continuum model. One term defines the transfer between the kerogen and inorganic matrix, and the other term defines the transfer between the inorganic matrix and natural fractures. Because the Warren-Root PSS transfer model is relatively simple when compared to the Vermeulen model, which uses a nonlinear transfer formula, the present numerical simulations of the shale gas reservoirs typically use the Warren-Root PSS transfer model (Chawathe et al., 2014; Fathi and Akkutlu, 2014; Sun et al., 2013; Swami et al., 2013).

However, due to the ultra-low matrix permeability and large fracture spacing, the transient shale gas flow from the inorganic matrix to natural fractures can take years in the triple-continuum model (Zimmerman et al., 1993). That is, it will take years for shale gas flow in the inorganic matrix block to reach a pseudo-steady state flow regime. Hence, if we use the Warren-Root PSS transfer model for the entire inorganic matrix – natural fractures transfer period, the error will be quite large. Therefore, in this work we use the Vermeulen model for the inorganic matrix – fracture transfer. For the kerogen – inorganic matrix transfer, the permeability difference between the kerogen and inorganic matrix is very small (often one order of magnitude) when compared to the large permeability difference between the inorganic matrix and natural fractures. Moreover, the inorganic matrix spacing is quite small compared to fracture spacing. Therefore, the transient flow from the kerogen to inorganic matrix takes little time, and the shale gas flow in finely dispersed kerogen pockets will reach a pseudo-steady state flow regime relatively quickly. Hence, the Warren-Root PSS transfer model can be used to approximate the kerogen – inorganic matrix transfer period. This treatment of these two transfer terms in the triple-continuum model is justifiable and saves both computation time and memory.

The mathematical model is solved by COMSOL Multiphysics. First, we compare a dual-continuum (matrix – fracture) model and triple-continuum (kerogen – inorganic matrix – fracture) model. Next, a comparison of two triple-continuum models with different inorganic matrix – fracture transfer models is conducted. Finally, a detailed sensitivity analysis of the impacts of parameters, including kerogen pore volume, kerogen permeability, inorganic matrix permeability, fracture permeability and Langmuir parameters, on the shale gas reservoir performance is conducted.

2. Triple-continuum model and numerical solution

The assumptions are as follows: (1) the organic matter (kerogen pockets), inorganic matrix and natural fractures can be considered as continua in space; (2) only free gas exists in the inorganic matrix and natural fractures, while both free gas and adsorbed gas exist in kerogen; (3) the transport mechanisms in kerogen include viscous flow, Knudsen diffusion, surface diffusion and gas adsorption/desorption on the internal kerogen grain surfaces, while those in the inorganic matrix are viscous flow and Knudsen diffusion, and only viscous flow is considered in natural fractures; (4) the gas contains CH_4 only; (5) shale gas flow in the reservoir is an isothermal process, with shale gas adsorption on the internal kerogen solid surfaces obeying the Langmuir isotherm equation.

2.1. Transport mechanisms and continuity equation of kerogen system

2.1.1. Viscous flow

Viscous flow is the dominant transport mechanism in shale gas reservoirs, and the net flux generated by very small pressure gradients will exceed that caused by very large gradients in concentration (Freeman et al., 2011). The gas flux caused by viscous flow can be modeled by Darcy's law: