



Modeling transient flow behavior of a multiscale triple porosity model for shale gas reservoirs



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ABSTRACT

Gas flow in shales is a complex process from nanoscale to macroscale which includes diffusion of dissolved gas molecules in kerogen bulk, desorption from the pore walls, Knudsen diffusion and slip flow in nanopores, and conventional flow in natural fracture network according to recent studies. However, little work has been done in literature to simultaneously incorporate all these complex storage and flow mechanisms in well testing models for shale gas reservoirs. This paper presents a new tri-porosity model for shale gas reservoirs to describe that gas flows from formation to wellbore with consideration of all the mechanisms mentioned above. Compared with current well testing models for shale gas reservoirs, this model will be more close to the actual reservoir situation by simulating the physics behind the actual process. Partial differential equations of this tri-porosity model are derived and Laplace transform is employed to solve these equations analytically. The analytical solution of the transient pressure is obtained in real space with Stehfest numerical inversion method, and standard bi-logarithmic type curves are plotted. The characteristics of transient pressure behavior are analyzed thoroughly and different flow regimes are observed in type curves for shale gas reservoirs. Effects of relevant parameters are analyzed as well, which has important significance to understand the transient flow behavior for shale gas reservoirs.

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1. Introduction

As the conventional source of energy are dwindling, shale gas has attracted attention throughout the world and is perceived as the energy supplement for decades to come owing to its abundance. Shale gas is not only stored in pores and natural fractures, adsorbed on the surface of pores (Hill and Nelson, 2000), but also dissolved in solid organic materials (Chalmers and Bustin, 2007; Ross and Bustin, 2009). Abundant nanoscale pores were found in shale, and gas flow in shales cannot be simply represented by Darcy equation anymore (Javadpour et al., 2007). Therefore, considerable efforts should be undertaken to improve the knowledge of the physics behind the actual storage and seepage mechanisms.

Gas dissolved in organic materials cannot be ignored in shale gas reservoirs. Chalmers and Bustin (2007) claimed that the solubilization of methane is responsible for higher gas capacities of liptinite-rich coals (bituminite and gilsonite) with lower micropore volume. Ross and Bustin (2009) obtained the similar experimental

results which indicate a solute gas for organic-rich Jurassic shales, and the linear correlation between pressure and methane sorption declares that solution process follows Henry's Law. Javadpour et al. (2007) proposed that quantities of gas can be stored either in liquid hydrocarbons as a dissolved phase or adsorbed on other materials within kerogen bulk (Fig. 1e), and observed the process that gas diffusing from kerogen bulk or clays to the exposed surfaces from the results of canister desorption tests. Mathematical models of dissolved gas diffusing from kerogen bulk to the surface had been studied by some researchers (Swami and Settari, 2012; Shabro et al., 2012; Moghanloo et al., 2013; Mi et al., 2014) as well.

Besides, gas flow in shales cannot be simply represented by Darcy equation anymore due to abundant nanopores in shale matrix. Roy and Raju (2003) used Knudsen coefficient which was first proposed by Knudsen (1909) to model gas flow in nanopores and validated with presented experimental data. Brown et al. (1946) introduced a theoretical dimensionless coefficient F to correct for slip velocity in tubes. Javadpour (2009) verified that mass flux equation which combines Knudsen diffusion and slip flow matches well with the experiment data presented by Roy and Raju (2003). And the major difference in shale gas reservoirs is that desorption

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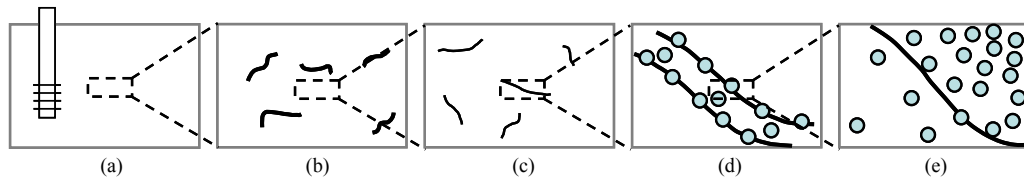


Fig. 1. Process of gas flowing from nano to macro scale (modified from Javadpour et al., 2007): (a) Macroscale (reservoir); (b) Mesoscale (micro fracture network); (c) Microscale (nanopores network); (d) Nanoscale (gas desorption from nanopore walls); (e) Molecular scale (mass transfer from kerogen/clay bulk to pore surface).

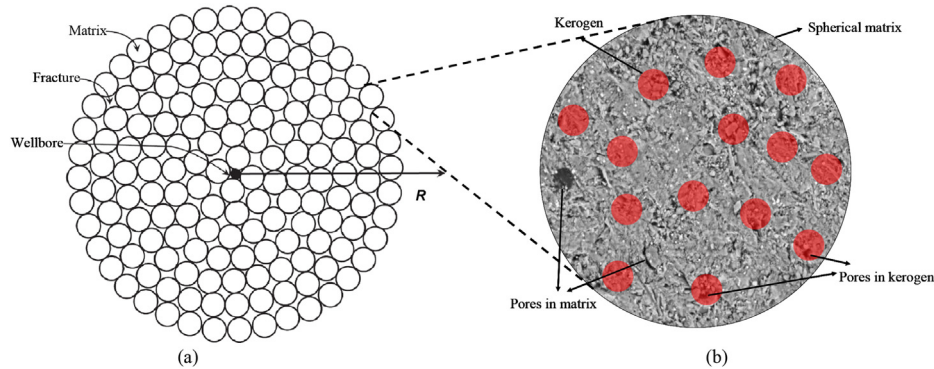


Fig. 2. Sketch map of relationship between matrix system and fracture system. (a) Fracture system (Ozkan et al., 2010); (b) Matrix system.

takes place from the surface of nanopores (Bumb and McKee, 1988; Swami and Settari, 2012). Numerical models which focus on desorption, Knudsen diffusion and slip flow in nanopores for shale gas reservoirs had been studied by many scholars (Ozkan et al., 2010; Alharthy et al., 2012; Swami and Settari, 2012; Swami et al., 2013; Azom and Javadpour, 2012; Shabro et al., 2011, 2012).

However, little work has been done to simultaneously incorporate all these complex storage and flow mechanisms in well testing models for shale gas reservoirs. In this work, a multiscale comprehensive model is established, which considers dissolved gas diffusing in kerogen bulk, desorption from the pore walls, Knudsen diffusion and slip flow in nanopores, and conventional flow in natural fracture network towards the wellbore (Fig. 1). Gas dissolved in kerogen bulk is proposed as an additional gas storage mechanism (Ross and Bustin, 2009; Swami and Settari, 2012; Moghanloo et al., 2013) apart from adsorbed gas and free gas, so kerogen bulks within matrix are considered as the “third porosity” to supply dissolved gas to matrix (Fig. 2b, Fig. 3). A new triple porosity model (Fig. 4) comprising kerogen system, matrix system and natural fracture system is first presented to describe that gas

flows in shale gas reservoirs from nanoscale to macroscale compared with other triple porosity models (Table 1).

2. Physical modeling

In this paper, shale gas reservoir is composed of kerogen system, matrix system and fracture system with relatively independent physical properties. Dissolved gas diffuses from kerogen bulk to nanopores within matrix, and then flow to natural fractures, which displays a triple-porosity flow behavior (Fig. 4).

To make this mathematical model more tractable and easy to understand, the following assumptions and descriptions are given:

- (1) Matrix block is assumed as sphere (Fig. 2a) as it is easier to derive the mass balance equation considering the effects of nanopores by using spherical matrix blocks, and insignificant differences were found in the solutions for the transient model compared with other matrix block models (slabs, match-sticks and cubes) according to El-Banbi (1998). The radius of matrix takes an average value of r_m ;

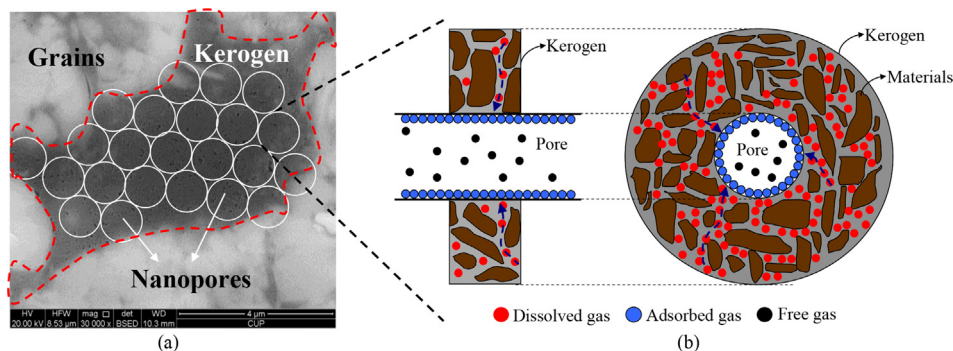


Fig. 3. Sketch map of kerogen system. (a) SEM image of nanoscale pores in kerogen within matrix of shale (Well M64 in Sichuan basin, section in red irregular curve is kerogen, and outside the curve are grains). (b) Microscopic schematic of gas diffusion from kerogen to pores in matrix system (modified from Mi et al., 2014). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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