Journal of Natural Gas Science and Engineering 35 (2016) 593–604

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

journal homepage: www.elsevier.com/locate/jngse

A fractal permeability model for shale gas flow through heterogeneous matrix systems

Lidong Geng [a], Gensheng Li [a, *], Pacelli Zitha [b, c], Shouceng Tian [a], Mao Sheng [a]

[a] State Key Laboratory of Petroleum Resources and Prospecting, (China University of Petroleum, Beijing), Beijing 102249, PR China
[b] Delft University of Technology, Delft 2628CN, The Netherlands
[c] Geo-Energy Research Institute, Qingdao University of Science and Technology, Qingdao 266042, PR China

ARTICLE INFO

Article history:
Received 19 June 2016
Received in revised form
10 August 2016
Accepted 12 August 2016
Available online 15 August 2016

Keywords:
Shale gas
Fractal
Heterogeneous
Shale matrix

ABSTRACT

Natural gas flow in shale matrices consisting of both organic and inorganic components was modeled using fractal concepts. The expression of the apparent permeability (AP) of such shale systems was derived following three main steps: (a) modeling real gas flow in a single pore by generalizing our previously reported Extended Navier-Stokes Equations method, then (b) using fractal theory concepts to obtain the apparent permeability for both the organic and inorganic-matter cells, and finally (c) upscaling the AP model to the sample scale, accounting for the heterogeneous distribution of the organic matter. The up-scaled AP model is more realistic, because it considers not only the varying cross-section shapes and tortuosity of the pores, but also the characteristic flow mechanisms and multi-scale pore size distribution in heterogeneous shale matrix systems. The model was successfully validated with experimental data from real samples. The effects of the organic matter and shape of the pores on the AP are investigated. The sensitivity of the AP to the total organic carbon (TOC), porosity, pore shape, and structural parameters of both organic and inorganic systems is studied. The results indicated that the AP would be overestimated by up to 24.1% if the characteristics of the organic matrix are ignored, and the AP proves more sensitive to the effect of the pore shape in the inorganic matrix. In addition, the top three key parameters affecting the AP are pore shape, maximum pore diameter in the inorganic matrix, and porosity. The AP is more sensitive to the pore size within the inorganic matrix than within the organic matter. The proposed model provides some theoretical and technical support for shale gas simulations.

1. Introduction

Currently, shale gas reservoirs are intensely explored and developed worldwide as a source of clean fossil fuel. Horizontal drilling, combined with multi-stage hydraulic fracturing, has been the key to the remarkably successful exploitation of shale gas resources (Mattar et al., 2008). Accurate determination of the permeability of the shale matrix is the basis for numerical simulation, providing theoretical and technical support for the evaluation of productivity, fracture parameter optimization, and efficient exploitation of shale gas reservoirs (Wu et al., 2014, 2015a,b,c; Civan et al., 2013).

The shale matrix is a complex mixture of an organic and inorganic matrix. An abundance of non-circular and tortuous pores exist in both organic and inorganic parts of the shale matrix, as illustrated in Fig. 1 (Ren et al., 2016; Javadpour et al., 2015). Pores in the organic matter fall within the nanometer scale, whereas the inorganic-matrix pore size varies widely from the nano-meter to micron scale (Loucks et al., 2010). This complex and multi-scale pore structure is a significant difference from conventional reservoirs in terms of the transport mechanisms (Guo et al., 2015). The conventional Darcy's Law breaks down when the mean free path of the gas molecules and the characteristic pore diameter have the same order of magnitude, causing the molecules to “slip” along the pore wall.

Many attempts have been made to describe gas transport in shale pores under various regimes. Beskok and Karniadakis (1999) extended Maxwell's slip model and developed a second-order permeability correlation for a single-pipe flow. Several scholars modified the rarefaction coefficient and the gas slippage

* Corresponding author.
E-mail address: ligs@cup.edu.cn (G. Li).

http://dx.doi.org/10.1016/j.jngse.2016.08.033
1875-5100/

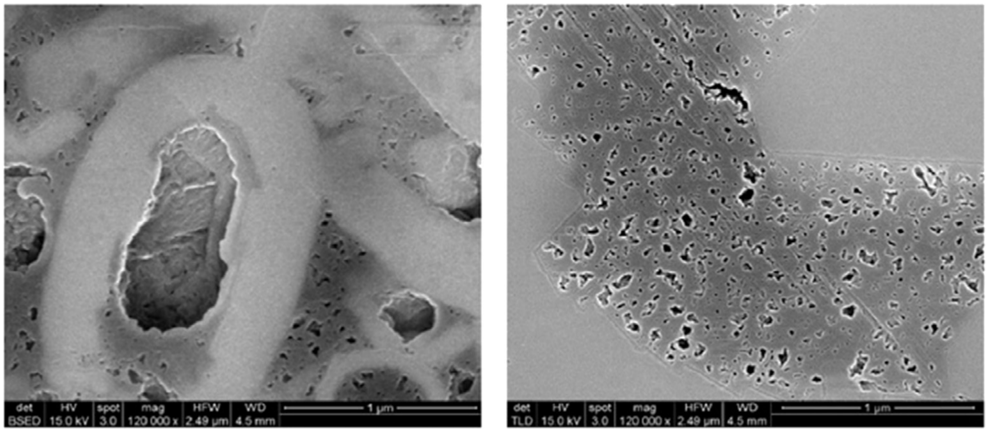

Fig. 1. Two exemplary SEM images of the pores in a shale matrix (Javadpour et al., 2015).

factor based on the Beskok and Karniadakis model (Florence et al., 2007; Civan, 2010; Civan et al., 2011). Javadpour (2009) proposed a formulation for shale gas flow in a single straight pore based on Knudsen diffusion and slip flow and derived an AP term to describe the complexity of gas flow. Wu et al. (2015a,b,c) developed a real gas transport model in nano-pores based on the weighted superposition of slip flow and the Knudsen diffusion for circular pores. Singh et al. (2014) assumed that pores are composed of either tortuous circular cylindrical tubes or rectangular channels and developed an apparent permeability model based on the statistical sum of the individual permeability of variably shaped pores. Nevertheless, the majority of the models were derived based on the assumption that pores have a circular cross-section. More significantly, the multi-scale pore size distribution of a shale matrix system was unreasonably simplified to a certain mean value, which causes an error in the predictions of the apparent permeability (Sheng et al., 2016).

Several authors represented the shale media as bundles of capillary tubes that have a log-normal pore size distribution (Michel et al., 2011; Civan, 2002; Xiong et al., 2012). Naraghi and Javadpour (2015) developed a stochastic permeability model for shale systems based on a bimodal pore-size distribution. The model investigated the multi-scale flow characteristics based on

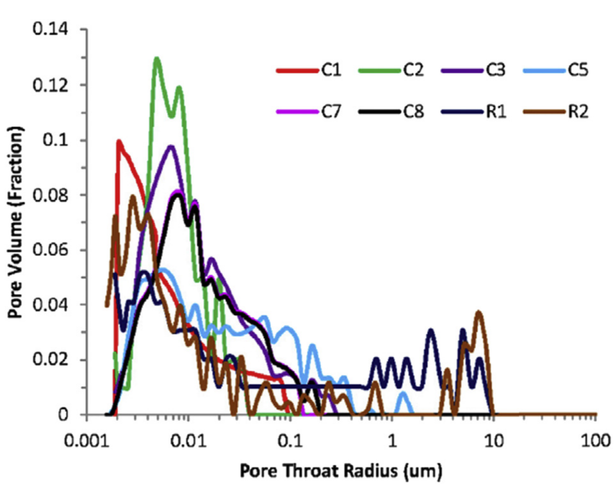

Fig. 2. Pore size distribution of eight shale gas samples from the Western Australian Formation (Hinai et al., 2014).

a mixture of Gaussian assumptions. However, in many cases, the pore-size distribution of the shale matrix is more complex and irregular, which can be seen in high resolution (down to 10 nm) Scanning Electron Microscopy (SEM) images, as shown in Fig. 2. Using the SEM, several authors found that the pore networks of the shale matrix exhibit self-similar fractal properties (Klaver et al., 2012; Hassanpoor et al., 2013). Currently, the fractal theory has proven to be a powerful tool for investigating irregularity and heterogeneity in nature (Mandelbrot, 1983; Li and Horne, 2009). Yang et al. (2014) discussed the impact of a fractal dimension on the gas adsorption capacity based on the physical description of the fractal surfaces. Yuan et al. (2016) developed an analytical model for the AP for tight rocks and studied the effect of fractal dimensions on the AP. Sheng et al. (2016) built a shale-gas permeability model and investigated various transport regimes that occur in multi-scale pores. However, most existing models do not distinguish between the organic and inorganic components of the shale matrix and thus do not account for the impact of the organic matter.

In this study, a single pore model for real gas transport accounting for the effect of the pore cross-section shape is proposed. Then, the AP model is developed separately for the organic and inorganic components of the shale matrix using fractal theory concepts. Next, we upscale the AP models to the sample scale using the incomplete layer method. We also draw different realizations to show the validity of the method. Moreover, the modified AP model for a shale sample is validated with different experimental results. Finally, we investigate the effect of the organic matter and pore shape on the AP. The sensitivity of the AP to the total organic carbon (TOC), porosity, pore shape, and structural parameters of organic and inorganic systems is also discussed.

2. Model development

In this section, an AP model for a real shale sample is established, accounting for the effect of the pore cross-section shape, tortuosity, TOC, and pore size distribution of both the organic matter and inorganic matrix (as shown in Fig. 3).

2.1. Real gas transport model for variably shaped pores

2.1.1. Gas transport in nanopores

Recently, we proposed a unified model for the convective and diffusive transport of free gas in a straight, cylindrical nanopore based on the Extended Navier-Stokes Equations (Geng et al., 2016).