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A new seepage model for shale gas reservoir and productivity analysis of fractured well

Jia Deng *, Weiyao Zhu, Qian Ma

School of Civil and Environmental Engineering, University of Science and Technology Beijing, Beijing 100083, China

HIGHLIGHTS

- The diffusion, slippage and desorption effect are considered in the seepage model.
- The influences of sorption and poromechanical properties are discussed.
- The productivity equations of fractured well are obtained.
- The fracture penetration ratio, conductivity and fracture numbers are optimized.
- The desorbed gas contributes 10–15% to the total gas production.

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ABSTRACT

The shale gas reservoirs are rich in nano-micro scale pores. The flow regime and gas flow state are not clearly understood and applied to the hydraulic fractured wells, which is crucial for economic production of shale gas. Beskok and Karniadakis equation can describe the relationship between flow velocities and pressure gradient, which considers the molecular collisions with the pore walls. But the equation is too complex to be applied. In this paper, the Beskok and Karniadakis equation is simplified. Based on this, we establish the multi-scale seepage model considering of diffusion, slippage and desorption effect. Considering on the influence of sorption and the poromechanical response to the permeability, by use of elliptical flow model considering on the coupling of the matrix and the fractures, the productivity equation of vertical and horizontal fractured well in consideration of diffusion, slip and desorption absorption is obtained. Furthermore, we numerically study the influencing factors such as fracture conductivity, fracture penetration ratio and the status of the gas and obtain critical parameters that control this process. Compared with the field production data, this model is verified effectively and practically. It is concluded that the desorbed gas contributes 10–15% to the total gas production. The paper provides a better model for shale gas production prediction.

1. Introduction

Core analyses show that the porosity and pore volume in shale gas reservoirs are nano-scale. The flow in ultralow permeability shale gas reservoirs is non-linear, which undergoes a transition from a Darcy regime to other regimes where molecular collisions with the pore walls have a significant effect on transport. Therefore the Darcy formula is not applicable in shale gas reservoirs. Analysis of lithological properties of shale gas reservoir showed that, the sizes of main nanopores are in a range of 5–200 nm, and the permeability is in a range of 1×10^{-9}–1×10^{-3} μm^2. The flow regime in tight shale gas reservoirs, which not only includes seepage, but also diffusion, slippage, desorption and absorption is different from conventional reservoirs obviously. Therefore, it is necessary to establish a new seepage theory to describe the flow law in nanopores and the multi-scale coupled flow in shale gas reservoirs.

Some studies have suggested that the model of gas flow in nanopores is a non-Darcy type. Javadpour et al. put forward the conclusion that gas flow in nanopores is different from the Darcy flow, and had a test on the mean free path of gas and Knudsen number [1]. Wang and Reed showed free gas flow can be a non-Darcy type in matrices, but a Darcy type in natural and hydraulic fractures [2]. Freemanindicated pore throat diameters on the order of molecular mean free path lengths will create non-Darcy flow conditions, where permeability becomes a strong function of pressure [3]. Michel et al. developed a model to describe the transport

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* Corresponding author. Tel./fax: +86 01062332778.
E-mail addresses: dengjia_123@126.com (J. Deng), weiyaook@sina.com (W. Zhu), maqian0428@163.com (Q. Ma).

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of gas in tight nanoporous media by modifying the original Beskok and Karniadakis equation through Knudsen number [4,5]. However, the previous model was built based on the premise that the slip coefficient b is assigned a theoretical value of negative one corresponding to full-slip under slip regime conditions. And the model can not apply for the entire range of flow regimes. Hence, a comprehensive and brief model for shale gas reservoir is still necessary.

In our paper, a new motion model was established based on Beskok and Karniadakis equation in regard of different slip coefficients. Then the multi-scale seepage model considering diffusion, slippage and desorption effect was established. By means of conformal transformation and equivalent flow resistance method, the productivity formula of vertical and horizontal fractured well considering diffusion, slip and desorption absorption was obtained, which could predict production rate of fractured wells, and provide the theoretical basis of production optimization.

2. Multi-scale flow regimes of shale gas reservoirs

Flow in the reservoir was modeled macroscopically based on continuous assumption. Molecular interaction was not considered in general gas seepage models. Tight shale gas reservoir is constituted by micron- and nano-scale pores, in which continuum hypothesis is no longer valid under some conditions. Then, the flow regime in shale gas reservoir should be modeled based on continuum mechanics and molecular kinematics theory. Gas flow regime in porous media is dependent on lithological properties and the average free path of gas molecules Liu et al. [6]. According to the research of Liepmann [7], Stahl [8] and Kaviany [9], gas flow regimes could be grouped into three categories based on Knudsen Number: (1) continuum flow; (2) slip flow; (3) transition flow; (4) Knudsen flow. At a low Knudsen number ($K_n \leqslant 0.001$), no-slip boundary condition in the continuum flow regime is valid, and Darcy's law remains suitable. At a higher Knudsen number ($0.001 < K_n \leqslant 0.1$), the slip boundary condition in the slip flow regime is valid, and Knudsen equation is suitable model. At a high Knudsen number ($0.1 < K_n \leqslant 10$), the continuum approach breaks down, slip boundary condition in transition flow is valid, and Burnett equation is suitable. When $K_n > 10$, the gas flow is free molecule flow, and diffusion is the main transport mechanism.

The flow mechanism and characteristics of shale gas under different lithological properties were different. Through the above analysis, flow regime could be distinguished by Knudsen number.

In 1934, Knudsen dimensionless numbers K_n was defined by Knudsen as

$$K_n = \frac{\bar{\lambda}}{r}$$

$$\lambda = \frac{K_B T}{\sqrt{2}\pi\delta^2 P}$$

where $\bar{\lambda}$ is the gas phase molecular mean free path, m; r is the pore throat diameter, m; K_B is the Boltzmann constant, 1.3805×10^{-23} J/K. δ is the collision diameter of the gas molecule; P is pressure and T is temperature.

Table 1 presents properties of typical gas mixture in shale. Fig. 1 presents the Knudsen number as a function of pressure under different pore sizes ranging from 10 nm to 50 μm. The flow regimes can be distinguished between transition flow, slip flow and continuum flow under different pore and pressure conditions. Conventional seepage model remains valid in continuum flow. In nano-scale pores the gas flow regime is mainly transition flow or slip flow. In micron-scale pores the gas flow regime is mainly continuum flow or slip flow, dependent on pressure. When pore size $r > 50$ μm, the flow can be modeled by continuum flow. For example, in the shale gas reservoir, when the pressure was 10–20 MPa, the pore was 10–30 nm, the gas flow was slip flow. So for the shale gas reservoir, the flow in the pore was slip flow.

Table 1
Gas molecule collision diameter of different components.

Gas components	Mole (%)	Collision diameter (δ, nm)	Molar mass (kg/kmol)
CH_4	87.4	0.4	16
C_2H_6	0.12	0.52	30
CO_2	12.48	0.45	44

For instance, the following cited the Long maxi reservoir, which the nanopore was mainly 2–40 nm, accounting for 88.39% of the total pore volume, 98.85% of the specific surface area; the 2–50 nm mesopore provides the main pore volume space, the micropore and mesopore less than 50 nm provides the main specific surface area [10].

The simulation results were shown in Fig. 2, and shale gas flow mechanism can be distinguished under different pore size combination. Under the condition of 10–20 MPa, in the sentiment combined with pores of 70 nm pore diameter which account for 80%, and pores of 3 μm pore diameter which account for 20%, the flow was continuum flow. While in the sentiment combined with pores of 10 nm pore diameter which account for 70%, and pores of 1 μm pore diameter which account for 30%, the flow could be continuum flow or slip flow, and was determined by pressure. Therefore for different combination of pore sizes, the flow mechanism of shale gas was different.

3. Multi-scale seepage non-linear model in shale gas reservoir

3.1. Non-linear model considering diffusion and slippage effect

Seepage model: Slippage effect and molecular collisions with the pore wall are not considered in Darcy's law. Gas flow in ultra-low permeability shale gas reservoirs undergoes a transition from a Darcy regime to other regimes where molecular collisions with the pore walls have a significant effect on transport. Beskok and Karniadakis equation shows a relational expression between flow velocities and pressure gradient:

Beskok and Karniadakis equation:

$$v = -\frac{K_0}{\mu}(1 + \alpha K_n)\left(1 + \frac{4K_n}{1 - bK_n}\right)\left(\frac{dP}{dx}\right) \tag{1}$$

Darcy's law describes the flow velocities by:

$$v = -\frac{K}{\mu}\frac{dP}{dx} \tag{2}$$

By comparing Eqs. (1) and (2), permeability adjustment factor can be defined as:

$$K = K_0 \varsigma \tag{3}$$

$$\varsigma = (1 + \alpha K_n)\left(1 + \frac{4K_n}{1 - bK_n}\right) \tag{4}$$

where K_n is the Knudsen number given by: $K_n = \lambda / r$, α is the rarefication coefficient, which is the correction of the bulk viscosity μ, b is the slip coefficient and λ is the mean free-path of a molecule covered between the molecular collisions.

The rarefication coefficient by Beskok and Karniadakis (1999) is

$$\alpha = \frac{128}{15\pi^2}\tan^{-1}(4K_n^{0.4}) \tag{5}$$

Permeability adjustment factor gained by Eq. (6) is