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Study on the steady and transient pressure characteristics of shale gas reservoirs

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ABSTRACT

The flow law was obtained by combining the mechanics of continuous media and molecular kinematics method for shale gas reservoirs with nano/micropores. The new non-linear seepage model considering the diffusion, slippage and desorption effects was established and simplified. The steady and transient governing equations were constructed on the basis of the non-linear model. The pressure characteristic analytical solution was then obtained. The permeability adjustment factor changes largely when the pore throat radius is less than 100 nm. Therefore, the flow law in nano/micropore departs significantly from Darcy's law. Numerical simulation results show that the flux of gas changes significantly with the permeability of the pore throat radius, and the flow in nano/micropore reservoir shows the microscale effect. Compared with the pressure distribution calculated by Darcy's law, the pressure distribution calculated by the new model decreases slowly because of the diffusion and desorption effect. The results provide a theoretical foundation for developing shale gas reservoirs.

The production of natural gas from shale formations has restored the natural gas industry in China. Shale gas refers to natural gas that is trapped within shale formations. Shales are finely grained sedimentary rocks with ultra-low porosity and permeability and can be rich sources of petroleum and natural gas (Loucks et al., 2009). The pore structure was measured, and the cores were from the Lower Silurian Longmaxi Shale, Sichuan Basin, South China (Nie and Zhang, 2010). The reservoir mainly consists of nanopores with 2–40 nm diameter, 88.39% volume and 1×10^{-9}–1×10^{-3} μm^2 permeability (Chen et al., 2011; Long et al., 2012; Zou et al., 2012). The flow regime in tight shale gas reservoirs is significantly different from conventional reservoirs because this reservoir not only includes seepage but also consists of diffusion, slippage, desorption and absorption.

Javadpour et al. (2007) considered that the flow in nano/micropores does not follow Darcy's law completely. Freeman et al. (2009) argued that molecular collision on pore walls can result in non-linear flow. Beskok and Karniadakis (1999) described the gas flow in nano/micropores by using the Knudsen model. Freeman (2010) found that pore throat diameters with molecular mean-free-path lengths will create non-Darcy flow conditions, wherein permeability becomes a strong function of pressure. Michel et al. (2011) developed a model to describe the transport of gas in tight nanoporous media by modifying the original Beskok–Karniadakis equation by using the Knudsen number. Deng (2014) developed a novel seepage model to describe the flow law in nanopores and multi-scale coupled flow in shale gas reservoirs on the basis of the Beskok–Karniadakis model. However, the adsorption term was ignored in the previous models, particularly for the calculation of transient flow pressure distribution.

In this paper, we considered that the adsorption term changes with time. Moreover, we simplified the model to study the multi-scale effect and pressure distribution characteristics. The model will be convenient and helpful for predicting production and pressure control in gas fields.

1. Non-linear gas flow model in nano/micropores considering diffusion, slippage and seepage

Molecule collision can result in momentum and mass transmission. Thus, the time and length scale parameters, such as the mean free path related to the molecule collision, are important. The mean free path λ is the average distance travelled by a moving molecule between successive collisions.

For the micro-flow, the Knudsen number (Kn) is a dimensionless number defined as the ratio of the molecular mean-free-path

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length to a representative physical length scale. The Knudsen number is related to the Reynolds number and Mach number, and this relation is shown in the following equation:

$$Kn = \frac{\lambda}{r} = \sqrt{\frac{\gamma\pi}{2}} \times \frac{Ma}{\mathrm{Re}}, \tag{1}$$

where $\lambda$is the gas-phase molecular mean free path (m) and r is the pore throat diameter (m).

When the Knudsen number increases, the rarefied effect becomes more important and the model based on gas dynamics theory cannot be used. Schaaf and Chambre (1961) classified different flow areas: if $Kn \leq 10^{-2}$, the fluid is considered a continuous medium; if $Kn \geq 10$, the fluid is considered a free molecule movement. The other two flows include slip flow ($10^{-2} < Kn < 0.1$) and transition flow ($0.1 < Kn < 10$). This classification has been certified in the experiment by the American National Standards Institute.

The Beskok–Karniadakis equation shows an expression between flow velocities and pressure gradient, and the equation is expressed as follows:

$$v = -\frac{k_0}{\mu}(1 + \alpha K_n)\left(1 + \frac{4K_n}{1 - bK_n}\right)\left(\frac{dp}{dx}\right) = K\left(\frac{dp}{dx}\right). \tag{2}$$

where K_n is the Knudsen number, α is the rarefied factor, b is the slippage factor, λ is the mean free path of molecule collision, and K is the apparent permeability.

On the basis of the Beskok–Karniadakis model, Deng (2014) proposed a uniform law to describe the flow from nanoscale to macroscale by coupling molecular dynamics with continuous medium:

$$v = -\frac{K_0}{\mu}\left(1 + \frac{3\pi}{16K_0}\frac{\mu D_K}{p} + \frac{\mathrm{b}}{4}\left(\frac{3\pi}{16K_0}\frac{\mu D_K}{p}\right)^2\right)\left(\frac{dP}{dx}\right). \tag{3}$$

Darcy's flow law is expressed as follows:

$$v = -\frac{k_0}{\mu}\left(\frac{dp}{dx}\right). \tag{4}$$

By comparing Equations (2) and (4), the permeability adjustment factor ς can be defined as follows:

$$\varsigma = K/k_0. \tag{5}$$

By introducing the polynomial coefficients, the Beskok–Karniadakis model was simplified to a binomial equation. The flow rate equation in nano/microporous media was developed on the basis of the simplified model.

$$\varsigma = 1 + 4aK_n. \tag{6}$$

For different flow state regions, three different approximate linear functions were obtained as follows:

$$\begin{aligned} g_1(Kn) &= 1 + 4a_1Kn \quad 0 < Kn \leq 0.001, \\ g_2(Kn) &= 1 + 4a_2Kn \quad 0.001 < Kn \leq 0.1, \\ g_3(Kn) &= 1 + 4a_3Kn \quad 0.1 < Kn \leq 10. \end{aligned}$$

Table 1
Value of polynomial correction coefficient a.

Kn	a
0–0.001	0
0.001–0.1	1.2
0.1–10	1.34

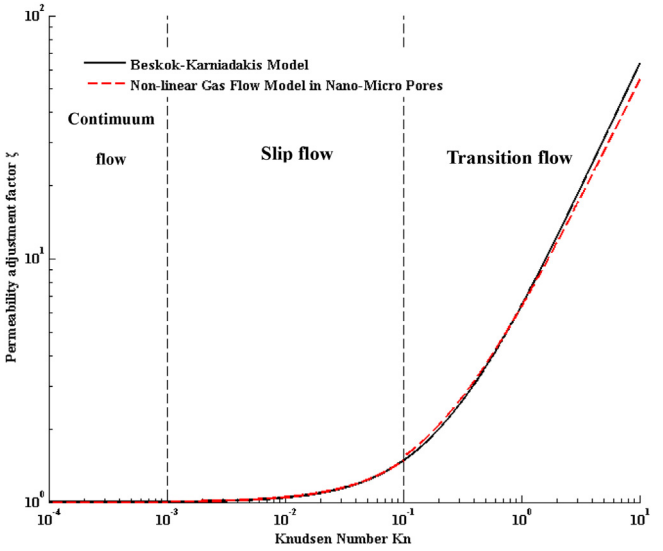

Fig. 1. Comparison between the non-linear gas flow model in nano/micropores and the Beskok–Karniadakis model.

The polynomial correction coefficient a was obtained by segmentation fitting (Table 1).

Fig. 1 shows the comparison between the non-linear gas flow model in nano/micropores and the Beskok–Karniadakis model. The results show that the fitting error is small and that the model shows great accuracy. Furthermore, the model provides a convenient method for the efficient development of theories.

Hence, the non-linear gas flow model in nano/micropores considering diffusion, slippage and seepage is rearranged as follows:

$$v = -\frac{k_0}{\mu}(1 + 4aK_n)\left(\frac{dp}{dx}\right). \tag{7}$$

On the basis of the non-linear gas flow model in nano/micropores considering diffusion, slippage and seepage, the flux equation was obtained by using math substitution and transformation.

The mean free path was given by Guggenheim (1960), and the Knudsen diffusion coefficient (D_k) was given by Michel et al. (2011); these two equations are expressed as Equations (8) and (9), respectively.

$$\lambda = \sqrt{\frac{\pi zRT}{2M_w}}\,\frac{\mu}{P}, \tag{8}$$

$$D_K = \frac{4r}{3}\sqrt{\frac{2zRT}{\pi M_w}}, \tag{9}$$

where R is the universal gas constant, μ is the gas viscosity, T is the temperature, M_w is the molecular weight, Z is the gas compression factor, λ is the mean free path of the gas molecule (m), and D_k is the diffusion coefficient.

By combining Equations (7)–(9), the flow model is modified as Equation (10).

$$v = -\frac{k_0}{\mu}\left(1 + \frac{3\pi}{2}\frac{\mu a}{r^2}D_K\frac{1}{p}\right)\left(\frac{dp}{dx}\right). \tag{10}$$

Given that