



Research Article

A new model for calculating the apparent permeability of shale gas in the real state[☆]Zhang Yanyu^a, Li Dongdong^{a,*}, Sun Xiaofei^a, Song Zhaoyao^a, Shi Dayou^b & Su Yuliang^a^a School of Petroleum Engineering, China University of Petroleum (East China), Qingdao, Shandong 266580, China^b College of Energy, Chengdu University of Technology, Chengdu, Sichuan 610059, China

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Abstract

In all the existing apparent permeability calculation models used for shale gas, the effect of surface diffusion of adsorbed gas is neglected and shale gas is assumed to be in an ideal state, so the calculation results may not reflect the real situations. In this paper, a new apparent permeability model suitable for the shale gas of real state was developed by seepage mechanics method. In this model, the influential factors (e.g. the viscous flow and Knudsen diffusion of free gas and the surface diffusion of adsorbed gas) are taken into account to present the real flowing situations of shale gas in nanopores. Then, the accuracy of this new apparent permeability model was verified by comparing its calculation results with the experimental data. Finally, all factors influencing the apparent permeability of shale gas were analyzed in this new model. It is shown that the apparent permeability of shale gas is most affected by pressure and pore radius, and less by relative molecular mass and blockage coefficient. Langmuir maximum adsorption capacity, Langmuir pressure and isothermal adsorption heat mainly affect the fraction of permeability contributed by surface diffusion. Besides, the effects of each factor on apparent permeability and permeability fraction under low pressure are different from those under high pressure. Under low pressure, the effects of temperature and pore radius on apparent permeability are more obvious, and the effects of temperature, pore radius, Langmuir maximum adsorption capacity, Langmuir pressure and isothermal adsorption heat on the fraction of permeability are also more obvious. Finally, when the pressure is low and the pore radius is small, the surface diffusion is dominant. When the pressure is high and the pore radius is large, the viscous flow is dominant. In the case of small pore radius or low pressure, the surface diffusion shall not be neglected.

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Shale gas reservoirs are characterized by the development of nano-scale pores [1], with a porosity of less than 6% [2], and a permeability of less than 0.001 mD. Among the current models for calculating the apparent permeability of shale gas,

the Besick–Karniadakis [3], Javadpour [4,5] and Klinkenberg [6] models are based on the percolation mechanics method, while the Jones–Owens [7], Florence [8], Ertekin [9], Michel [10], Sakhaee–Bryant [11] and Civan [12] models are based on the Klinkenberg model, which are different in the methods for calculating slip coefficients. The Beskok–Karniadakis, Javadpour, and Klinkenberg models all assume that shale gas is an ideal gas, but don't consider the size of shale gas molecules and the intermolecular interaction forces. Moreover, they only consider the viscous flow of free gas and Knudsen diffusion, but not consider the phenomenon of surface diffusion of adsorbed gas.

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The authors studied the flow of shale gas in the nanopores in real conditions, with consideration to the viscous flow of free gas in the pores, the Knudsen diffusion and the surface diffusion of the adsorbed gas. Thus, a new suitable model for calculating the apparent permeability of shale gas in a real state was deduced. Based on the experimental data, this model was verified for its accuracy. Finally, this model was used to analyze the effects of pressure, temperature, pore radius, relative molecular weight, Langmuir adsorption, Langmuir pressure, isothermal heat of adsorption and blocking coefficient on apparent permeability, permeability fraction of viscous flow, Knudsen diffusion permeability and the fraction of surface diffusion permeability.

1. Apparent permeability model of shale gas in the real state

As to shale gas flow in nanopores, the total flow is the sum of the viscous flow of free gas and the Knudsen diffusion flow, if the surface diffusion of adsorption gas is considered [5,13,14], and it is the sum of the flow of free gas and the surface diffusion flow of adsorbed gas if the surface diffusion of adsorbed gas is considered [14,15]. Therefore, the total flow of shale gas in nanopores is the sum of the viscous flow of free gas, the Knudsen diffusion flow, and the surface diffusion flow of adsorbed gas, that is

$$J = J_{vs} + J_K + J_S \quad (1)$$

where, J_{vs} is the viscous flow mass flow of free flow, $\text{kg}/(\text{m}^2 \cdot \text{s})$; similarly, J_K : the Knudsen diffusion mass flow of free flow, $\text{kg}/(\text{m}^2 \cdot \text{s})$; J_S : the surface diffusion mass flow of adsorbed gas, $\text{kg}/(\text{m}^2 \cdot \text{s})$.

1.1. Viscous flow of free gas

According to the Hagen–Poiseuille equation [8], when shale gas flows in the nanopores in a real state, the mass flow of viscous flow is:

$$J_{vs} = -\frac{r^2}{8} \frac{M}{\mu RT} \frac{p}{Z} \frac{dp}{dz} \quad (2)$$

where, r is the pore radius, m ; similarly, M : the relative molecular mass of the gas, kg/mol ; μ : the viscosity of the shale gas, $\text{Pa} \cdot \text{s}$; R : the universal gas constant, $8.314 \text{ J}/(\text{mol} \cdot \text{K})$; T : the temperature, K ; p : the pressure, Pa ; Z : the compression factor of shale gas; z : the distance, m .

1.2. Knudsen diffusion of free gas

Considering the molecular size and molecular interaction, assuming that the pore is circular, the inner wall is smooth and the gas is moving in a positive direction, then the Knudsen diffusion equation of gas in a real state is [4,16]:

$$J_K = -\frac{MD_K}{RT} C_g \frac{p}{Z} \frac{dp}{dz} \quad (3)$$

In which,

$$D_K = \frac{2r}{3} \sqrt{\frac{8ZRT}{\pi M}}$$

$$C_g = \frac{1}{p} - \frac{1}{Z} \frac{dZ}{dp}$$

where, D_K is the Knudsen diffusion coefficient, m^2/s ; C_g is the isothermal compression coefficient of shale gas, $1/\text{Pa}$.

1.3. Surface diffusion of adsorbed gas

The mass flow of the surface diffusion of adsorbed gas is calculated by Fick's diffusion law [15,17]:

$$J_S = -MD_S \frac{dC_S}{dz} \quad (4)$$

The calculation method of the adsorption concentration C_S of shale gas in Equation (4) is related to the adsorption type of shale gas. A large amount of literature shows that methane in shale is monolayer adsorption, which satisfies the Langmuir isotherm adsorption law [18–20], so

$$C_S = \frac{C_L p}{p_L + p} \quad (5)$$

Substituting Equation (5) into Equation (4), the surface diffusion equation of adsorbed gas can be deduced as follows:

$$J_S = -MD_S C_L \frac{p_L}{(p_L + p)^2} \frac{dp}{dz} \quad (6)$$

where, D_S is the surface diffusion coefficient, m^2/s ; similarly, C_S : the adsorption concentration of shale gas, mol/m^3 ; C_L : the maximum adsorption concentration of Langmuir, mol/m^3 ; p_L : the Langmuir pressure, which means the pressure corresponding to the 1/2 of the maximum adsorption concentration.

The surface diffusion coefficient D_S is calculated by the Chen–Yang model [21]:

$$D_S = D_{S0} \frac{1 - \theta + \frac{\gamma}{2}\theta(2 - \theta) + H(1 - \gamma)\frac{\gamma}{2}\theta^2}{(1 - \theta + \frac{\gamma}{2}\theta)^2} \quad (7)$$

In which,

$$H = \begin{cases} 0 & \gamma \geq 1 \\ 1 & 0 \leq \gamma < 1 \end{cases}, \quad \gamma = \frac{k_b}{k_m}$$

where, γ is the blocking constant, dimensionless (when $\gamma = 0$, the model can be simplified to the HIO model); similarly, H : the step function; k_b : the blocking rate constant, m/s ; k_m : the advancing rate constant, m/s ; θ : the surface coverage of Langmuir isothermal adsorption and dimensionless, where the surface coverage is defined as:

$$\theta = \frac{p}{p_L + p} \quad (8)$$

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