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Full Length Article

A theoretical study on the permeability of tight media; effects of slippage and condensation

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HIGHLIGHTS

- The gas permeability is presented by combinations of dusty gas model and gas kinetic theory.
- The gas permeability is studied from macro-scale to nano-scale.
- Effects of pore size, grain surface roughness on the gas permeability are studied.
- Presented approach helps to study the influence of condensed phase on gas permeability.
- The effective gas permeability is well predicted by presented approach.

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ABSTRACT

Slippage and phase change are important factors which are affected on the permeability of gas in tight media. When dealing with micro/nano-scale media, conventional equations breaks down and can not be used to characterize gas transport in tight media. In this paper, we study gas transport in tight porous media to explore effects of the condensation and different types of gas molecule surface scattering on the permeability. Using the kinetic theory of gases and with an analogy between heat transfer and mass transfer, we derive first a formula for the effective mass diffusion coefficient in tight porous media. In particular, effects of the pore size, condensed phase saturation and grain surface roughness are determined. Then, the introduced model for the effective mass diffusion coefficient is implement to the dusty gas method to make it applicable for our investigation purposes. The well-known Kozeny–Carman equations and the fractal techniques are used to predict the absolute permeability of tight porous media. Our predictions for both self-diffusivity coefficient and the permeability are in good agreement with experimental data and numerical simulations.

1. Introduction

Permeability, as a representation of the ability of a formation to transmit fluids, is a fundamental rock property that controls the directional movement and the flow rate of the reservoir fluids in the formation. Fine grained matrix, low permeability and porosity are the main characteristics of shale gas reservoirs. Gas flow in tight reservoirs is significantly affected by the slippage phenomenon. Thus, applicability of the conventional form of Darcy's law has been challenged. It has been observed that CFD based calculations do not predict accurately gas permeability in tight reservoirs [1–6]. If the pore size is in the order of the mean free path of the gas molecule, the continuum assumption breaks down and the well-known Darcy's and Fick's laws can not be used to study the transport mechanisms in tight reservoirs. Several methods have been introduced to predict shale gas reservoir permeability [1–5,7–10]. For instance, the effect of gas slippage on the permeability in tight porous media can be presented by the Klinkenberg equation. According to the Klinkenberg equation the permeability is related to the inverse of pressure [11].

$$k = k_0\left(1 + \frac{b_k}{p}\right) \quad (1)$$

k_0 is the permeability of the conduit to liquid under the no slip boundary condition, p is the pressure and b_k is the Klinkenberg's slippage factor. Several correlations for Klinkenberg's slippage factor can be found in the literature [1,12–15]. The liquid phase permeability k_0 can be measured experimentally or predicted by the classical Kozeny–Carman equation [16–20]. The Kozeny–Carman

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equation is generally applied in various engineering fields including oil/water reservoirs, membranes, medicine, biochemicals and electrochemicals. The fractal technique is another approach which can be used to predict the permeability of a porous medium. The disordered and irregular nature of pore structures confirm the fractal characters of porous media. It has been observed that the fractal theory is able to predict the transport properties of porous media. This approach has been previously used to investigate mass diffusivity, permeability [21–24] and thermal conductivity [25,26] of porous media.

In this article, a phenomenological model is introduced to predict gas permeability in tight reservoirs. The diffuse and specular natures of the gas molecule–grain surface collisions are included in the proposed model. Results of the presented model are compared against available experimental data. Then the model is further extended to study the permeability of the gas phase when condensation occurs. A liquid hydrocarbon phase may be found in tight gas reservoirs (i.e. due to the pressure reduction below dew point pressure in gas condensate reservoirs). The existence of this phase results in a decrease in the gas permeability and consequently severe loss of gas recovery [27,28]. It is due to the fact that some of pore spaces can be either partially or completely blocked by the condensate phase (the condensate phase remains immobile until its critical saturation value). Therefore, effective pathways belonged to the gas phase are occupied by the immobile liquid phase and consequently the reduction of permeability is observed [29].

2. Gas flow regime

2.1. Continuum regime

In classical fluid mechanics and heat transfer and from the macroscopic point of view, the medium is treated as a continuum (medium is continuous and indefinitely divisible). In other words, medium properties such as mass diffusivity, viscosity, electrical conductivity and thermal conductivity are defined as the average over elements of the medium which are larger than the microscopic structure of the medium but much smaller than the macroscopic scale. The continuum assumption is not always valid, particularly when the interactions between molecules and solid surfaces become important. The continuum assumption breaks down and subsequently transport phenomena do not belong to the macroscale regime [30,31]. In fact, contribution of molecule–solid surface collision on transport phenomena becomes more significant than molecule–molecule collision.

In order to determine whether a given phenomenon falls in the macroscopic regime or otherwise belongs to the microscopic regime, the Knudsen number Kn is defined as the ratio of the mean free path Λ of the molecule to the characteristic size L of the medium.

$$Kn = \frac{\Lambda}{L} \tag{2}$$

Continuum transport phenomena are valid when the Knudsen number is very small ($Kn \ll 0.001$) [30]. In this regime and for a porous medium, transport properties can be determined by the conventional expressions, correlations such as Kozeny–Carman and the fractal method. On the other hand, when the Knudsen number increases the scenario is different and non-continuum regime dominates.

2.2. Slip flow regime

The condition of $0.001 \leqslant Kn \leqslant 0.1$ generally corresponds to the slip flow regime. In this regime, the Navier–Stokes equations can still be applicable for the flow by including the slip boundary condition (the influence of molecule–solid surface collision) [30]. It was reported that the gas slippage at the surface of the solid phase can impact the effective permeability [2,4,32]. Heid et al. [13] explained that in the absence of chemical or electro-kinetic reactions the difference between permeabilities of liquids and gases rise from the slip of gas molecules at the solid surface. Thus, in porous tight formations gas transport depends on both the viscous flow and the Knudsen diffusion. The dusty gas model can be applied to predict the overall flow in the slip flow regime [4,33]. In this approach the overall flow J_t is presented as a linear combination of viscous J_{visc} and Knudsen J_{Kn} gas transport mechanisms and written as follows [4,32,33]:

$$J_t = J_{visc} + J_{Kn} = -\left(\frac{k_0 p}{\mu} + D_{self}\right)\frac{\nabla p}{RT} \tag{3}$$

where ∇p is the pressure gradient, μ is the gas viscosity, R is the gas constant, and T is the absolute temperature. Note that D_{self} stands for the self-diffusivity coefficient. This relation can be equivalent to the gas permeability as

$$J_t = -\left(\frac{k_0 p}{\mu} + D_{self}\right)\frac{\nabla p}{RT} = -\frac{k_g p}{\mu}\frac{\nabla p}{RT} \tag{4}$$

where k_g is the permeability of the gas under the slip boundary condition. Using Eq. (4), the gas permeability is expressed by

$$k_g = k_0\left(1 + \frac{D_{self}\mu}{k_0 p}\right) \tag{5}$$

2.3. Transition and free molecular regimes

The rarefaction effects are dominant when $0.1 \leqslant Kn \leqslant 10$. In this condition, the continuum assumption starts breaking down. Transport phenomena fall in the free molecular regime when $Kn \gg 10$. Ballistic collision between molecule and solid surface is the main characteristic of this regime. The continuum assumption totally breaks down and the medium properties are predicted by molecular-based models, such as the Boltzmann transport equation, the direct simulation Monte Carlo method, or molecular dynamics [30].

3. Determination of the effective permeability with condensation

In order to obtain a phenomenological expression to predict the effective permeability of the porous medium while condensation is occurring, dusty gas model should be modified as follows:

$$k_{eff} = F(S_l)k_0\left(1 + \frac{D_{eff}\mu}{k_0 p}\right) \tag{6}$$

where S_l is the condensed phase saturation. We use the correlation factor $F(S_l)$ to show the role of condensation on the effective permeability. There are different models available in the literature for $F(S_l)$ [34–37]. As an illustration, we take the Brooks–Corey correlation [35].

$$F(S_l) = (1 - S_l)^2\left(1 - S_l^{\frac{2+N_l}{N_l}}\right) \tag{7}$$

The empirical N_l parameter which is related to pore size distribution (greater than 2 for narrow distributions and less than 2 for wide distributions) can be obtained from experimental data.

For mass transfer process inside the tight porous medium when phase change occurs both Knudsen diffusion and binary diffusion