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Characterization of gas transport behaviors in shale gas and tight gas reservoirs by digital rock analysis

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ABSTRACT

Due to the extremely tiny pore size of tight gas and shale gas reservoir, the modified Darcy's law in which the intrinsic permeability is replaced by the apparent permeability that can be obtained by a function of three transport parameters (intrinsic permeability, porosity and tortuosity), is used to describe the combined mechanisms of viscous flow, Knudsen diffusion, the effect of the adsorbed layer thickness and surface diffusion through the adsorbed layer. A new apparent permeability estimation method based on digital rock was proposed in this paper. The digital rock with nanopores could be constructed by 3D pore structure images obtained from micro/nano CT and FIB-SEM images directly or reconstructed with Markov Chain Monte Carlo (MCMC) method from the 2D SEM images of pore structure; then Lattice Boltzmann method can be applied to calculate the intrinsic permeability, porosity and tortuosity of 3D digital rock. These parameters are used to calculate the apparent permeability under consideration of different combined gas transport mechanisms. This method is applied to samples from the shale gas reservoir in Silurian Longmaxi Formation of Sichuan Basin and from the tight gas reservoir in the Wenchang Formation of Huizhou Sag. The results show that all considered transport mechanisms greatly impact the shale apparent permeability and cannot be ignored in shale samples. In tight gas reservoirs, Knudsen diffusion is an important mechanism at low pressures of less than 1 MPa. However, Knudsen diffusion could be ignored when pressure is greater than 1 MPa due to its smaller impact.

1. Introduction

Unconventional energy resources such as tight gas and shale gas reservoirs play an increasingly important role in the energy industry over recent years in North America. In the future, such gas resources will become more important to the global energy supply due to the huge quantity of reserves, the extensive distribution of tight reservoirs and the rapid decline of conventional reserves [1].

Most gas in shale gas and tight gas reservoirs is stored in extremely small matrix pores. The distribution of pore sizes is in the 40–700 nm range in tight gas reservoirs and the 1–200 nm range in shale gas reservoirs [2]. Both free and adsorbed gas are found stored in shale reservoirs, but only free gas is found in tight gas reservoirs [3,4].

Gas transport in nanopores involves both conventional viscous flow which can be described by Darcy's law generating from the collision between gas molecules, and Knudsen diffusion which is generated from the collision between gas molecules and the pore wall surface [5,6] (as shown in Fig. 1). Viscous flow and Knudsen diffusion occur in all porous media. Which of these two mechanisms is dominant depends on the pore scale of the porous media [7,8]. When the pore diameters are very large compared to the mean free path of the gas molecules, the probability of collisions between molecules is much higher than the collisions between molecules and the pore walls; thus gas transport is primarily governed by viscous flow and is less influenced by Knudsen diffusion. As the pore diameters become smaller, and reach the same order of magnitude as the gas's mean free path, the collisions between molecules and the pore walls become more important, gas transport is primarily governed by Knudsen diffusion and not viscous flow. Therefore, gas transport mechanism in nanopores includes both viscous flow and Knudsen diffusion. In large pores, Knudsen diffusion can be ignored and Darcy's law alone accurately describes viscous flow [5]. Because the smallest chambers in shale gas reservoirs and tight gas reservoirs are nanopores, both viscous flow and Knudsen diffusion must be considered.

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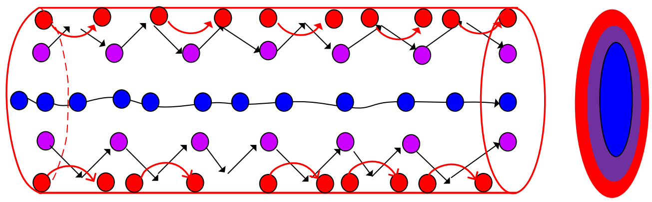

Fig. 1. Schematic map of individual gas transport in porous media.

In shale gas reservoirs, an additional transport mechanism may exist, namely, surface diffusion of adsorbed molecules along the pore wall surface [9,10]. Keliu Wu [11] investigated the impact of the surface diffusion on the gas transport in shale gas reservoirs; in their study, they found that: in micropores (pore radius of <2 nm), the contribution of surface diffusion to the gas mass transfer is dominant, up to 92.95%; in macropores (pore radius of >50 nm), the contribution is less than 4.39%, which is negligible; in mesopores (2 nm < pore radius < 50 nm), the contribution is between micropores and macropores.

Several gas transport models have been developed to describe the combined mechanisms in tight porous media with nanopores. A modified Darcy's law using apparent permeability could describe the combination of viscous flow and Knudsen diffusion [12–15]. The apparent permeability which is valid over all flow regimes has been proposed using the Knudsen correction function and the intrinsic permeability [12,14,16]. When an appreciable fraction of the pore-volume is occupied by an adsorbed gas layer, surface diffusion through the adsorbed layer should be considered in the calculation of the apparent permeability. For shale gas reservoirs, a gas transport model that considers all of the gas transport mechanisms has been previously proposed using the equivalent hydraulic radius [9].

The models of gas transport in tight porous media proposed in previous studies are based on the equivalent hydraulic radius of porous media [12,17]. The equivalent hydraulic radius can be calculated by three transport parameters: intrinsic permeability, porosity and tortuosity [18]. In previous work [7], we proposed a new model based on these three transport parameters to describe the combined mechanisms of gas transport and to calculate the apparent permeability in tight porous media [7].

In conventional porous media with large pores, the permeability, porosity and tortuosity can be measured by experiment. However, laboratory experiments are extremely difficult to perform on tight porous media, such as tight gas and shale gas reservoirs, due to the very small pore sizes [19]. FIB-SEM and Nano CT can obtain images of the pore structures of porous media with nanopores [20–22]. After a 3D digital rock reconstructed, pore-scale simulation can estimate these three transport parameters [23–28]. Therefore, the apparent permeability of porous media can be calculated using digital rock as a proxy.

This work follows our previous study [7], to develop a digital rock analysis workflow for characterizing the gas transport behaviors in shale gas and tight gas samples, while taking into consideration all gas transport mechanics. This paper is organized as follows. First, formulae of apparent permeability in terms of the intrinsic permeability, porosity and tortuosity as well as other state parameters, are introduced. Second, a digital rock analysis workflow is proposed. Finally, this workflow is applied in a digital rock model reconstruction, the apparent permeability calculation and the gas transport pattern analysis of the gas shales in the Silurian Longmaxi Formation of Sichuan Basin in China and the tight gas in the Wenchang Formation of the Huizhou Sag in China. The effect of pore-volume occupied by the adsorbed layer and the surface diffusion through adsorbed layer were considered in the shale gas reservoir only.

2. Apparent permeability method based on digital rock

2.1. Gas transport model based on transport parameters in tight porous media

In tight porous media, the primary gas transport mechanisms are viscous flow and Knudsen diffusion, assuming that there is no adsorbed gas on the pore surface. A transport model [7,9,12,14] that is valid for all flow regimes based upon viscous flow and Knudsen diffusion is given below.

$$N_t = -\frac{\rho_g k_a}{\mu_g}(\nabla p_g) \tag{1}$$

where N_t is the mass flux of gas transport in porous media in kg/(m^2·s), ρ_g is the gas density in kg/m^3, k_a is the apparent permeability of porous media in m^2, p_g is the pressure in Pa, μ_g is the gas viscosity in Pa·s.

Civan [14] obtained the expression of k_a considering only viscous flow and Knudsen diffusion using Knudsen number, as shown in Eq. (2).

$$k_a = k_\infty f(K_n) = k_\infty(1+\alpha(K_n)K_n)\left(1+\frac{4K_n}{1-bK_n}\right) \tag{2}$$

where k_∞ is the intrinsic permeability of porous media in m^2, K_n is Knudsen number, $\alpha(K_n)$ is the rarefaction coefficient and given by Eq. (3) [7], b is the slip coefficient and equal to -1 (for slip flow).

$$\alpha(K_n) = \frac{128}{15\pi^2}\tan^{-1}\left[4.0K_n^{0.4}\right] \tag{3}$$

By the definition of K_n, we obtained another expression of k_a from Eq. (2) in our previous paper [7] and given by Eq. (4).

$$\begin{aligned} k_a = k_a = k_\infty f(K_n) = k_\infty f\left(\frac{k_BT}{4\pi\delta^2 P_g}\sqrt{\frac{\phi}{k_\infty\tau}}\right) \\ = k_\infty\left(1+\alpha\left(\frac{k_BT}{4\pi\delta^2 P_g}\sqrt{\frac{\phi}{k_\infty\tau}}\right)\frac{k_BT}{4\pi\delta^2 P_g}\sqrt{\frac{\phi}{k_\infty\tau}}\right) \\ \times\left(1+\frac{4\frac{k_BT}{4\pi\delta^2 P_g}\sqrt{\frac{\phi}{k_\infty\tau}}}{1-b\frac{k_BT}{4\pi\delta^2 P_g}\sqrt{\frac{\phi}{k_\infty\tau}}}\right) \end{aligned} \tag{4}$$

where T is the temperature in K, δ is the collision diameter of the gas molecular in m, k_B is the Boltzmann constant in J/K, ϕ is the porosity of the porous media, and τ is the tortuosity of the porous media. In the derivation of Eq. (4), the gas is supposed to ideal gas, therefore Eq. (4) is only suitable if the gas is ideal gas. When the gas is real gas, we should revise the expression.

From Eq. (4) we can see that the apparent permeability, considering viscous flow and Knudsen diffusion, is a function f of temperature, the gas collision diameter, the pressure and the transport properties of the porous media (intrinsic permeability, porosity and tortuosity). $\frac{k_a}{k_\infty}$ can be used to quantify the impact of Knudsen diffusion in porous media [7].

Ignoring surface diffusion through the adsorbed layer, but including the fact that some of the pore volume is occupied by the adsorbed layer, the apparent permeability is then given by [7,24]:

$$\begin{aligned} k_a' = k_\infty\left(1-\frac{d_m}{2\sqrt{2\tau}\sqrt{\frac{k_\infty}{\phi}}}\frac{P_g/P_L}{1+P_g/P_L}\right)^4 \\ \times f\left(\frac{k_BT}{\sqrt{2}\pi\delta^2 P_g 2\sqrt{2\tau}\sqrt{\frac{k_\infty}{\phi}}}\frac{1}{1-\frac{d_m}{2\sqrt{2\tau}\sqrt{\frac{k_\infty}{\phi}}}\frac{P_g/P_L}{1+P_g/P_L}}\right) \end{aligned} \tag{5}$$