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Study on gas flow through nano pores of shale gas reservoirs

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HIGHLIGHTS

- Experiments were carried out to study gas flow behavior in nano membranes.
- Apparent discrepancy which different from conventional flow were observed.
- A new model for gas transfer through nanopores was established.
- Model got verified using experimental data for different pore size and gas type.
- Proposed model shows better matching results compared with existing models.

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ABSTRACT

Unlike conventional gas reservoirs, gas flow in shale reservoirs is a complex and multiscale flow process which has special flow mechanisms. Shale gas reservoirs contain a large fraction of nano pores, which leads to an apparent permeability that is dependent on pore pressure, fluid type, and pore structure. Study of gas flow in nano pores is essential for accurate numerical simulation of shale gas reservoirs. However, no comprehensive study has been conducted pertaining to the gas flow in nano pores. In this paper, experiments for nitrogen flow through nano membranes (with pore throat size: 20 nm, 55 nm, and 100 nm) have been done and analyzed. Obvious discrepancy between apparent permeability and intrinsic permeability has been observed; and the relationship between this discrepancy and pore throat diameter (PTD) has been analyzed. Then, based on the advection-diffusion model, a new mathematical model has been constructed to characterize gas flow in nano pores. A new apparent permeability expression has been derived based on advection and Knudsen diffusion. A comprehensive coefficient for characterizing the flow process was proposed. Simulation results were verified against the experimental data for gas flow through nano membranes and published data. By changing the comprehensive coefficient, we found the best candidate for the case of argon with a membrane PTD of 235 nm. We verified the model using experimental data with different gases (oxygen, argon) and different PTDs (235 nm, 220 nm). The comparison shows that the new model matches the experimental data very closely. Additionally, we compared our results with experimental data, the Knudsen/Hagen–Poiseuille analytical solution, and existing models available in the literature. Results show that the model proposed in this study yielded a more reliable solution. Shale gas simulations, in which gas flowing in nano pores plays a critical role, can be made more accurate and reliable based on the results of this work.

1. Introduction

With the growing shortage of domestic and foreign energy, producing gas from shale strata recently has become increasingly important in the volatile energy industry in North America and is gradually becoming a key component in the world's energy supply [1]. As more attention is given to these unconventional gas resources, understanding the rock and its permeability is crucial. The dynamics of gas in small pore throats in shale and other tight formations has become an important research topic during the current decade in the oil and gas industry [2]. Shale gas reservoirs are characterized by an organic-rich deposition with extremely low matrix permeability and clusters of mineral-filled "natural" fractures (Fig. 1). Through an experimental analysis of 152 cores of nine reservoirs in North America, Javadpour [3,4] found that the average permeability of shale bedrock is 54 nd, and approximately

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Nomenclature

b	Klinkenberg coefficient [1/P$_a$]
C	gas mole concentration [mol/m^2]
D_k	Kundsen diffusion coefficient [m^2/s]
J	mass flux [kg/(m^2)]
M_g	gas mole weight [kg/mol]
N_v	mass flux caused by viscous flow [kg/(m^2)]
N_k	mass flux caused by Knudsen diffusion [kg/(m^2)]
k_i	intrinsic permeability of the nano capillary [m^2]
k_{app}	apparent permeability [m^2]
Kn	Knudsen number, which equals the ratio of free length to PTD [dimensionless]
p	pressure of the nano capillary [P$_a$]
$\bar{p}$	average gas pressure [P$_a$]
P_{in}	inlet pressure [P$_a$]
P_{out}	outlet pressure [P$_a$]
r	pore radius [m]
R	universal gas constant [8.314474 J/(K mol)]
T	temperature [K]
Z	compression factor
α	slip coefficient
ρ_g	gas density [kg/m^3]
ϕ	the porosity of a single nano capillary, which is equal to 1
σ	comprehensive coefficient
μ_g	gas viscosity [mPa s]

90% have permeabilities less than 150 nd. Most pore throat diameters (PTD) are concentrated in the range of 4–200 nm (10^{-9} m) [5].

Loucks et al. [6] found that gas shale strata is composed of micro and nano pores, with the majority being nano pores. These findings emphasize the importance of studying how gas flows in nano pores or nanotubes, which is critical for shale gas simulation and effective commercial production.

Different modeling approaches have been adopted to simulate the flow of gas in nanotubes. Hornyak et al. [7] used the Lattice-Boltzmann (LB) method to study gas flow_ENREF_4; Bird [8] and Bhattacharya et al. [9] both tried the molecular dynamics (MD) method; Tokumasu [10] and Karniadakis [11] used Direct Simulation Monte Carlo (DSMC) to study gas flow characteristics; and Burnett [12] introduced the Burnett equation type method in 1935. However, all of these modeling methods consume excessive space and time when systems are larger than a few microns, rendering them impracticable. The situation worsens when attempting to make accurate simulations with very small time steps and grid sizes, as convergence becomes a significant problem. Some researchers have attempted to derive an equation to characterize the law of gas flow. Beskok and Karniadakis [13] derived a unified Hagen–Poiseuille-type equation for volumetric gas flow through a single pipe, and Klinkenberg [14] introduced the Klinkenberg coefficient to consider the slip effect when gas flows in nano pores. However, the applicability of these methods requires further investigation, and these modeling results have not yet been compared to real experimental data.

The concept of apparent permeability was first proposed by Javadpour [4] to simplify simulation work. In 2009, he proposed the concept of apparent permeability, considering Knudsen diffusion and advection flow. Using this method, the flux vector term can be expressed simply in the form of a Darcy equation, which greatly reduces the computational complexity. Then, Shabro et al. [15,16] applied the concept of apparent permeability further in pore scale modeling for shale gas. Civan [17] and Ziarani and Aguilera [2] derived the expression for apparent permeability in the form of Knudsen number based on a unified Hagen–Poiseuille equation [13].

In this paper, utilizing the advection diffusion model (ADM) [18] and considering the slip flow together with the Knudsen diffusion, we theoretically derived a new formula for the apparent permeability and the flux with a comprehensive coefficient to be determined from the experiment data. Different from what Javadpour [4] proposed, we assumed that the slip flow is part of Knudsen diffusion and proposed a new idea with the comprehensive coefficient in the Knudsen diffusion term instead of adding a theoretical dimensionless coefficient to correct for slip velocity in the Darcy term [4]. A comparison among the experimental data, the results of the proposed method, the K/HP analytical solution [19], and Javadpour's solution [4] shows that the proposed model produces simulation results that better match the experimental data provided by Cooper et al. [20].

2. Experiments for gas flow through nano membranes

2.1. SEM imaging of nano membranes

Experiments for gas flow through nano membranes have been done in Missouri S&T. Nitrogen was used as the test gas. Three kinds

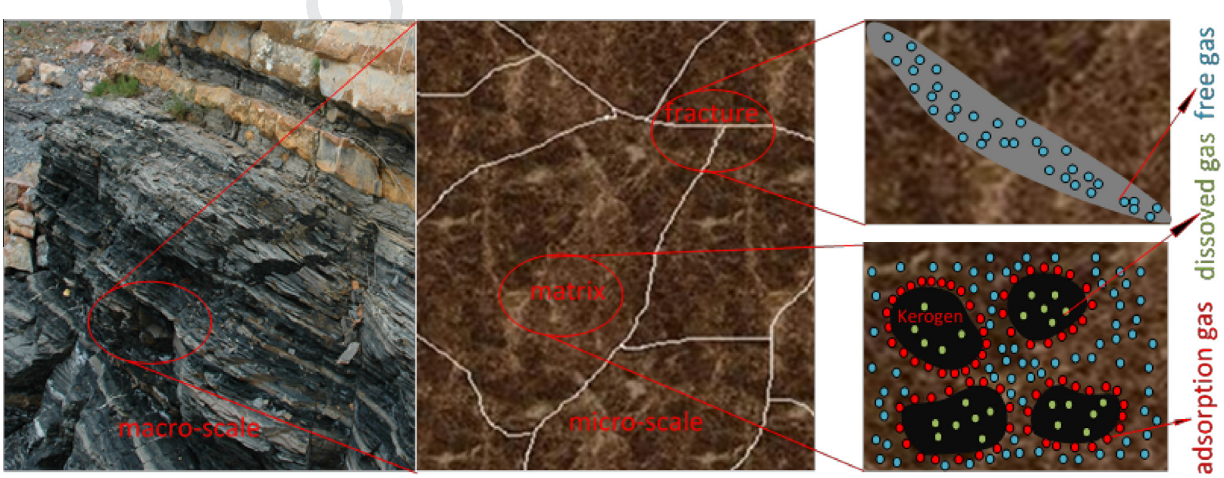

Fig. 1. Gas distribution in shale strata from macro-scale to micro-scale. In the fracture, there exists free gas; in the matrix, free gas and adsorption gas co-exist.

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