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An analytical model for shale gas transport in circular tube pores

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ABSTRACT

An analytical model for gas transport in shale media is proposed on the basis of the weighted superposition of slip flow, bulk diffusion and Knudsen diffusion. The model takes account of slip effect and real gas effect, and is successfully validated by experimental data and Lattice Boltzmann simulation results. The contribution of each transport mechanism to the total flow is investigated. The effect of porosity, diameter and pressure on the apparent permeability is studied and a sensitivity analysis is performed to evaluate the significance of the parameters for gas transport. The results show: (1) the present model can reasonably describe the process of the mass transform of all different gas transport mechanisms; (2) As pressure and pore diameter decrease, the number of molecule-wall collisions gradually predominates over the number of intermolecular collisions, Knudsen diffusion contributes more to the total flow; and (3) the apparent permeability increases with porosity, pore diameter, and decreases with pressure. It is more sensitive to pressure in rarefied gas flow regime, and pore diameter has a significant impact under high pressure. The present model can provide some theoretical support in numerical simulation of shale gas production.

1. Introduction

The commercial shale gas production is being achieved in North America, due to the improved horizontal drilling and hydraulic fracturing technologies, which has received a great of attention around the world [1–3]. The accurate description of shale gas transport in shale media is the basis for gas predicting the production, optimizing the fracture parameters and efficiently exploiting shale gas [4]. Understanding gas transport in shale media is an enormous challenge. This causes a significant necessity for a deeper understanding of gas transport in shale media.

Due to the nanoscale phenomena and complex microstructure of shale media, the study of gas transport properties in shale media is facing challenges and always hard to resolve [5]. Shale is referred to as extraordinarily fine-grained sediments that mainly consist of nanopores [6,7]. Diameters of shale nanopores ranging from a few to several hundred nanometers are abundant in the shale media [8], which causes that gas mass transport is significantly different from that in conventional gas reservoirs [9]. The gas transport process is governed by different mechanisms, including continuum flow regime ($Kn < 10^{-3}$), slip flow regime ($10^{-3} < Kn < 10^{-1}$), transition flow regime ($10^{-1} < Kn < 10$) and free molecular flow regime ($Kn > 10$), which can be determined based on the different range of Knudsen number [10]. Knudsen number refers to the ratio of the molecular mean free path to a representative physical length scale, which quantifies the rarefaction of fluid. Gas molecules not merely have intermolecular collisions, but also collide with the wall in shale nanopores. The state of the gas is referred to as rarefied, which causes deviation from continuum flow [11]. The conventional method, based on the Navier–Stokes (NS) equation, describes the continuum flow regime well. However, it is inadequate for other flow regimes.

Several studies have been performed in an effort to build a unified model for shale gas transport covering the various flow regimes. Generally, the researches can be divided into two categories: microscopic methods based on dilute gas kinetic theory and modified continuum approaches. For the microscopic methods, it mainly includes a direct simulation Monte Carlo method (DSMC) [12], a molecular dynamics simulation (MD) method [13] and a lattice Boltzmann method (LBM) [14]. The molecular simulation considers the attributes of gas molecules accurately [15–17], but it consumes huge computational time and memory, which could not be feasible for gas transport simulation in shale media [18,19].

Continuum models based on NS equations is applicable to continuum flow regime fairly easily under some simplified assumptions. However, the NS equations with no-slip boundary

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Nomenclature

b	gas slip constant, dimensionless
D	pore diameter, m
J_b	bulk diffusion mass flux, kg/(m^2 s)
J_k	Knudsen diffusion mass flux, kg/(m^2 s)
J_t	total mass flux, kg/(m^2 s)
J_{vs}	slip flow mass flux, kg/(m^2 s)
$J_{\omega b}$	weighting bulk diffusion mass flux, kg/(m^2 s)
$J_{\omega k}$	weighting Knudsen diffusion mass flux, kg/(m^2 s)
$J_{\omega vs}$	weighting slip flow mass flux, kg/(m^2 s)
k_k	the Knudsen diffusion apparent permeability, m^2
k_B	the Boltzmann constant, J/K
K_n	Knudsen number, dimensionless
k_{vs}	the slip flow apparent permeability, m^2
k_{bulk}	the bulk diffusion apparent permeability, m^2
M	gas molar weight, kg/mol
N_A	Avogadro constant, mol^{-1}
n_V	the number of molecules per unit volume, m^{-3}
p	pressure, MPa
p_c	critical pressure of gas, MPa
p_t	reduced pressure of gas, dimensionless
r	pore radius, m
R	universal gas constant, J/(mol k)
S	the reduced mass flow rate, dimensionless
t_t	the average time consumed for one collision of overall gas molecules, s
$t_{vs\text{-}b}$	the average time required for one collision between the gas molecules, s
t_k	the averaged time required for one collision between a nanopore wall and gas molecule, s
T	reservoir temperature, K
T_c	critical temperature of gas, K
T_r	reduced temperature of gas, dimensionless
Z	gas compressibility factor, dimensionless

Greek letters

φ	porosity, decimal
τ	tortuosity, dimensionless
μ	gas viscosity, pa s
α	rarefication coefficient, dimensionless
λ	molecular mean free path, m
λt	molecular mean free path of the overall gas molecules, m
$\omega_{vs\text{-}b}$	weighting coefficient for slip flow and bulk diffusion
σ_m	the molecular diameter, m;
ω_k	weighting coefficient for Knudsen diffusion
δ	weighting coefficient for bulk diffusion

condition are not valid for Knudsen numbers increases to 10^{-3} [20]. Therefore, to resolve this limitation, several models were proposed for gas mass transport under the slip flow regime, in which the NS equations are combined with slip flow boundary. They include the first-order, second-order, and Beskok-Karniadakis slip models [21–23]. For transition flow, due to the coupling of slip flow, bulk diffusion and Knudsen diffusion, it is the most difficult regime for modeling which the slip modifications did not always match the experimental results [24]. However, gas mass flow in many shale reservoirs falls under this regime [25]. Gas mass transport calculated by the first-order slip flow equation is underestimated [26], and the lack of a universally accepted coefficient is a major problem when the second-order slip flow equation is applied to transition flow [22]. Hence, a single constitutive equation can't describe all the gas mass transport mechanisms in shale media. Several researchers have attempted to build a unified model for gas mass transport under various flow regimes to overcome this problem, as summarized in Table 1. Many gas transport models were proposed. However, some models contain unreasonable weight coefficients, while the other models contain empirical coefficients. Hence, a unified model that covers all transport mechanisms is still required. Such a model is of practical significance to the development of shale gas reservoirs.

Slip effect is a common physic phenomenon under a low pressure condition in gas transport through nanopores in shale media [27]. The real gas effect refers to that the gas intermolecular force and molecules themselves volume both significantly affect gas transport [28]. Due to an extremely high reservoir pressure, the real gas effect on gas transport in shale media is also need to be resolved. On the other hand, slip flow, bulk diffusion and Knudsen diffusion are the different gas transport mechanisms in shale media. The slip flow occurs when the intermolecular collision dominates, whereas the diffusion takes place due to the increased frequency of the wall-molecule collision. When the Knudsen number becomes large ($Kn \gg 1$), diffusion is describe by Knudsen diffusion rather than bulk diffusion [29,30]. Based on the slip flow, bulk diffusion and Knudsen diffusion, a gas transport model in shale gas reservoirs is proposed by coupling these transport mechanisms together using the weighted coefficients based on the ratios of intermolecular collision frequency and wall molecule collision frequency to the total collision frequency. The schematic diagram of individual transport in shale media is showed in Fig. 2. This model

Table 1
Comparison of the existing gas transport models.

Model	Description	Limitation
Ertekin et al. [31]	Model developed based on weighted superposition of convective flow and Fick diffusion	Constant weighted factors; without consideration of real gas effect
Besk and karniadakis [23]	Model developed based on Hagen-poiseuille type equation to describe various flow regimes	The correlation is complex; ideal gas
Javadpour [32]	Model developed based on linear superposition of slip flow and Knudsen diffusion	Linear superposition; without consideration of real gas effect
Darabi et al. [33]	Model developed based on the Javadpour model; The effect of surface roughness on Knudsen diffusion is considered	Linear superposition; without consideration of real gas effect
Rahmanian et al. [34]	Model developed based on weighted superposition based on continuum flow and Knudsen diffusion	Empirical parameters in determining weighted factors
Wu et al. [35]	Model developed based on weighted superposition of slip flow and Knudsen diffusion	Without consideration of bulk diffusion
Geng et al. [36]	Model developed based on superposition of convective flow, bulk diffusion and Kundsen diffusion	Linear superposition of convective flow and diffusion