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Apparent gas permeability in an organic-rich shale reservoir

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HIGHLIGHTS

- New gas permeability models for organic and inorganic pores were built.
- Effective stress, phase behavior and multiple transport mechanisms were considered.
- Effects of real gas, stress, and adsorption on gas transport were discussed.

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ABSTRACT

Accurate models of gas transport in shale gas reservoirs must consider complex gas transport mechanisms and phase behavior in nanopores, as well as different pore types. The gas transport mechanisms in shale gas reservoirs include viscous flow, Knudsen diffusion, surface diffusion, adsorption and desorption. In this study, a unified model of nanopore gas transport in shale gas reservoirs is presented. Gas storage patterns are different in organic pores and inorganic pores. Therefore, we develop two fully coupled apparent permeability models to describe gas transport in organic pores and inorganic pores separately. The apparent permeability model of organic pores considers the gas transport mechanisms of viscous flow, Knudsen diffusion, surface diffusion, adsorption and desorption. The apparent permeability model of inorganic pores considers the gas transport mechanisms of viscous flow and Knudsen diffusion. In both models, stress dependence, real gas effects and phase behavior are taken into account. Then, the influences of pore pressure, effective stress, real gas effects, pore radius, phase behaviors and transport properties on apparent gas permeabilities in organic pores and inorganic pores are analyzed based on the proposed models.

1. Introduction

With the rapid decline in conventional reserves, unconventional resources such as tight gas and shale gas reservoirs have played an increasingly important role in the North American energy industry in recent years and have gradually become a key component of the world energy supply. In shale gas reservoirs, gas is stored in organic pores and inorganic pores with nm-scale pore size and extremely low matrix intrinsic permeability. Zou et al. [1] reported pore sizes in shale gas reservoirs ranging from 1 to 200 nm and shale matrix intrinsic permeabilities ranging from 10^{-9} to $10^{-3} \times 10^{-15}$ m^2 [2,3]. Organic pores are usually smaller than 10 nm in diameter [3–5]. For macro-scale numerical simulations and productivity forecasts, existing multi-continuum medium models [6] are divided into inorganic matrix and organic matrix components; however, gas transport differences in the two different matrices are often neglected. The consequences of neglecting this difference indicate that apparent gas permeability in shale nanopores should be studied based on different pore types.

The size of shale nanopores approaches the molecular mean free path. Therefore, the continuity assumption becomes invalid [7,8]. Knudsen number is defined as the ratio of the molecular mean free path to the average pore diameter. At different Knudsen numbers, the corresponding gas flow regime differs, as is shown in Fig. 1. Zheng et al. [9,10] derived a fractal model for gas diffusivity in porous media using fractal theory and an analytical expression for gas permeability in dual-porosity media. A fractal predictive model of the gas slippage factor and gas permeability in porous media with low permeability in the slip flow regime was proposed by Zheng et al. [11] based on the combination of bulk diffusion and Knudsen diffusion. Zheng et al. [12] studied the effective gas

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Nomenclature

a	vdw energy parameter (Pa dm^6/mol^2)
b	vdw energy parameter (dm^3/mol)
C_{max}	maximum adsorbed gas concentration (mol/m^3)
d_m	gas molecular diameter (m)
D_{s0}	surface diffusion coefficient when gas coverage is zero (m^2/s)
D_s	surface diffusion coefficient (m^2/s)
$H(1-\kappa)$	Heaviside function (dimensionless)
ΔH	isosteric adsorption heat at the gas coverage of "0" (J/mol)
k_0	permeability at zero effective stress (μm^2)
k_B	Boltzmann constant (J/K)
k_m	matrix permeability in Gangi's model (μm^2)
k_{ins}	intrinsic permeability (μm^2)
Kn	Knudsen number (dimensionless)
k_{free}	free gas transport permeability (μm^2)
$k_{surface}$	surface diffusion permeability (μm^2)
k_{app_or}	organic pores apparent permeability (μm^2)
k_{app_in}	inorganic pores apparent permeability (μm^2)
M_g	gas molecular weight (g/mol)
m	associated with the surface roughness of pores
Pc	critical pressure (Pa)
p	pore pressure (Pa)
p_1	effective stress when pores are closed completely (Pa)
p_c	confining pressure (Pa)
p_L	Langmuir pressure (Pa)
P_{pr}	pseudo reduced pressure
r	pore radius (m)
r_0	initial effective hydraulic radius (m)
r_c	critical radius (m)
r_{eff_stress}	effective hydraulic radius in consideration of stress dependence (m)
r_{eff_in}	effective hydraulic radius in inorganic pores (m)
T_c	critical temperature (K)
T_{pr}	pseudo reduced temperature
V_L	Langmuir volume (m^3/kg)
V_m	molar volume of gas (m^3)
Z	gas compressibility factor (dimensionless)
α	rarefaction coefficient (dimensionless)
β	slip coefficient (dimensionless)
σ_{eff}	effective stress on the matrix (Pa)
σ	Lennard-Jones size parameter (m)
ρ_s	rock density (kg/m^3)
Φ	porosity (dimensionless)
Φ_{0_or}	initial porosity in organic matrix (dimensionless)
Φ_{0_in}	initial porosity in inorganic matrix (dimensionless)
ε	Lennard-Jones energy parameter (dimensionless)
θ_i	gas coverage of ideal gas (dimensionless)
θ	gas coverage of real gas (dimensionless)
μ	viscosity (Pa s)
λ	mean free path length of molecules (m)
ρ_s	rock density (kg/m^3)
κ	ratio of the rate constant for blockage to the rate constant for forward migration (dimensionless)
κ_b	rate constant for blockage (m/s) in surface diffusion
κ_m	rate constant for forward migration in surface diffusion
τ	tortuosity (dimensionless)

diffusion coefficient in dry porous media with a fractal-like tree network. Beskok and Karniadakis [13] and Civan et al. [5,14,15] developed apparent permeability models based on the Knudsen number flow regime. Apparent permeability models based on superposition of Knudsen diffusion and slip flow were developed by Javadpour et al. [16–20]. Ma et al. built a pore network model for simulating gas flow in micro- and nano-porous materials [21] based on the Javadpour model [17]. Additional studies have analyzed viscous flow generated from collisions between gas molecules and Knudsen diffusion due to collisions between gas molecules and pore walls [22,23] (as shown in Fig. 2). Of these two mechanisms (viscous flow and Knudsen diffusion), the dominant mechanism depends on the pore scale of the porous media. When the pore diameters are very large compared to the mean free path of gas molecules, the probability of collisions between molecules is much higher than that of collisions between molecules and pore walls. Thus, gas transport is mainly governed by viscous flow due to collisions between molecules and is less influenced by Knudsen diffusion. As the pore diameters decrease, reaching the same order of the mean free path of gas molecules, the collisions between molecules and pore walls become more important, with gas transport mainly governed by Knudsen diffusion.

Javadpour et al. [16] described gas flow in nanopores using a diffusive transport regime with a Knudsen diffusion coefficient and negligible viscous effects. He later [17] presented a formulation for gas flow in mudrock nanopores based on linear superposition of Knudsen diffusion and viscous flow using the Maxwell theory. Based on the Javadpour model [17], Azom and Javadpour [24] proposed a gas transmission model for real gas in nanopores. Additionally, the effect of wall roughness on Knudsen diffusion in nanopores was considered by Darabi et al. [18]. However, the Javadpour [17] model includes one empirical coefficient known as the tangential momentum accommodation coefficient (TMAC). An accurate value of TMAC is hard to define for different shale

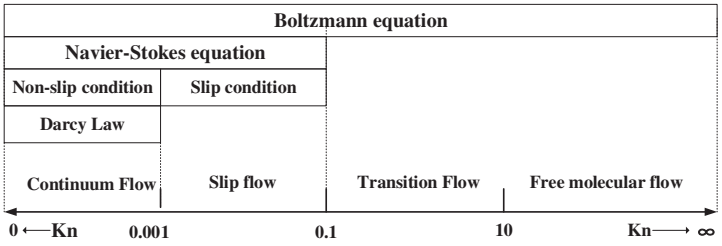

Fig. 1. Transition of flow regimes based on the Knudsen number.