



Gas transport behaviors in shale nanopores based on multiple mechanisms and macroscale modeling



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ABSTRACT

The combined action of multiple transport mechanisms and reservoir characteristics makes gas transport behaviors in nanoporous shale complicated. Accurate apparent gas permeability (AGP) characterization for gas transport in nanopores is crucially essential for macroscale modeling in shale gas reservoirs development. In this study, a new unified AGP model for gas transport in the organic and inorganic nanoporous shale (OM and IM) is presented, incorporating multiple mechanisms, such as real gas effect, viscous-slip flow, Knudsen diffusion, surface diffusion, stress dependence and especially the organic nanopores content. Besides, the effect of multilayer adsorption on gas transport is included. The model is validated by experimental and linearized Boltzmann results and compared with the published AGP models. After that, sensitivity analysis and the contribution of each mechanism to the total AGP are conducted. Moreover, a numerical model for the fractured well in shale based on the presented AGP model and discrete fracture model (DFM) is derived. The finite element method (FEM) is applied to solve the model and then influence factors of gas transport behaviors are discussed. The results show that different transport mechanisms exist in organic and inorganic nanopores respectively. The larger pore radius or pressure causes a smaller ratio of the AGP over the intrinsic permeability. Moreover, the contribution of surface diffusion to the total AGP is significantly influenced by the OM nanopores radius and surface diffusion coefficient. In addition, gas transport is governed by Knudsen diffusion in nanopores with a small radius and low pressure and is controlled by viscous flow under the large pore radius and high-pressure conditions. Then, the presented AGP model is introduced into the macroscale numerical model for a fractured well in shale. Larger hydraulic fracture half-length, OM nanopores content and matrix pore radius as well as smaller natural fracture spacing cause higher gas production. The study provides a new unified AGP model considering gas transport behaviors in nanopores and applies the AGP model to macroscale modeling.

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1. Introduction

Shale gas with rich reserves, great potential and especially the efficient development in North America and China, has gained an increasing amount of worldwide attention [1]. The distinguishing characteristics of shale gas from conventional resources are mainly caused by the hydrocarbon accumulation mechanism and reservoir space types. Multiple mechanisms and reservoir features make gas transport behaviors complicated. Therefore, accurate characterization methods of the apparent gas permeability (AGP) are very significant for the macroscale modeling and productivity predict-

ing in shale reservoirs development. Experimental studies [2,3] (such as AFM and SEM) show that nanopores range in size from 1 to 200 nm ($1 \text{ nm} = 10^{-9} \text{ m}$), and most frequent pore radii are generally smaller than 5 nm. It indicates that the molecular mean free path approaches the shale nanopore size, which makes the gas transport complex and leads to describing it based on Knudsen number (Kn) instead of continuity assumption [4]. Meanwhile, typical components of shales including organic matter (OM) and inorganic matter (IM) have been observed. Up to now, the methane transport behaviors in nanoporous shale have been studied by experts using experimental [5–7] and numerical methods [8,9], such as molecular dynamics simulation (MDS) [10,11] and the lattice Boltzmann method (LBM) [12]. Several types of AGP models based on Kn and microscale pores have been presented for the macroscale flow simulation [4,13–17].

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Nomenclature

AGP	apparent gas permeability	V_L	maximum adsorbed gas volume (m^3/kg)
AFM	atomic force microscopy	Γ	gas coverage (dimensionless)
SEM	scanning electron microscopy	V	adsorption volume of real gas in OM nanopores (m^3/kg)
OM	organic matter	C	constant related to the net heat of adsorption (dimensionless)
IM	inorganic matter	p_0	saturated adsorption pressure of gas (MPa)
MDS	molecular dynamics simulation(s)	n	adsorbed layer number (dimensionless)
LBM	lattice Boltzmann method	p_L	Langmuir pressure (MPa)
Kn	Knudsen number (dimensionless)	θ	ratio of adsorbed volume to V_L (dimensionless)
λ	mean free path of gas molecule (m)	D_s	surface diffusion coefficient (m^2/s)
r_{e_in}	effective inorganic pore radius (m)	D_s^0	surface diffusion coefficient at $\Gamma = 0$ (m^2/s)
κ_B	Boltzmann constant, ($\text{MPa}\cdot\text{m}^3/\text{K}$)	ρ_r	rock density (kg/m^3)
T	pore temperature (K)	C	adsorbed gas concentration (kg/m^3)
Z	gas deviation factor (dimensionless)	\dot{m}_s^t	mass flux of surface diffusion in an organic tube ($\text{kg}/(\text{m}^2\cdot\text{s})$)
p	pore pressure (MPa)	\dot{m}_s^O	mass flux of surface diffusion in OM nanopores ($\text{kg}/(\text{m}^2\cdot\text{s})$)
δ	molecular collision diameter (m)	A	cross-sectional area of porous media (m^2)
p_{pr}	pseudo reduced pressure (dimensionless)	n^t	nanopores number (dimensionless)
p_c	critical pressure (MPa)	ϕ	porosity (dimensionless)
T_{pr}	pseudo reduced temperature (K)	L_t	tortuous length of the nano-capillary tube (m)
T_c	critical temperature (K)	\dot{m}_t	total mass flux of a nanoporous medium ($\text{kg}/(\text{m}^2\cdot\text{s})$)
μ	gas viscosity ($\text{MPa}\cdot\text{s}$)	\dot{m}^O	total mass flux of organic nanopores ($\text{kg}/(\text{m}^2\cdot\text{s})$)
ρ	gas density (kg/m^3)	β	content of organic nanopores (dimensionless)
\dot{m}_{vs}^l	viscous and slip flow mass flux in IM nanopores ($\text{kg}/(\text{m}^2\cdot\text{s})$)	k	permeability (m^2)
\dot{m}_v^l	viscous flow mass flux in IM nanopores ($\text{kg}/(\text{m}^2\cdot\text{s})$)	k_0	intrinsic permeability of a nanoporous medium (m^2)
\dot{m}_s^l	slip flow mass flux in IM nanopores ($\text{kg}/(\text{m}^2\cdot\text{s})$)	p_e	effective stress (MPa)
ϕ_e^l	effective porosity of IM (dimensionless)	r_{0_in}	radius of an inorganic nanopore (m)
M	gas molar mass (kg/mol)	r_{0_or}	radius of an organic nanopore (m)
τ	tortuosity (dimensionless)	r_0	original radius of the nanopore (m)
R	gas universal constant, ($\text{J}/(\text{mol}\cdot\text{K})$)	q	porosity coefficient (dimensionless)
μ_e	effective gas viscosity ($\text{MPa}\cdot\text{s}$)	s	permeability coefficient (dimensionless)
b	slip coefficient (dimensionless)	k_a	apparent permeability of nanopores (m^2)
α	rarefaction coefficient (dimensionless)	k_a^O	apparent permeability of OM nanopores (m^2)
\dot{m}_k^l	Knudsen diffusion mass flux in IM nanopores ($\text{kg}/(\text{m}^2\cdot\text{s})$)	k_a^l	apparent permeability of IM nanopores (m^2)
∇p	gas pressure gradient (MPa/m)	k_s^O	apparent permeability of surface diffusion in OM (m^2)
D_m	methane molecule diameter (m)	k_k^{I+O}	apparent permeability of Knudsen diffusion in nanopores (m^2)
d_f	fractal dimension of the pore surface (dimensionless)	k_{vs}^{I+O}	apparent permeability of viscous and slip flow in nanopores (m^2)
\dot{m}^l	mass flux in IM nanopores ($\text{kg}/(\text{m}^2\cdot\text{s})$)	a_f	hydraulic fracture aperture (m)
ω_{vs}	weighting coefficient of viscous and slip flow (dimensionless)	f_{-a}	natural fracture spacing (m)
ω_k	weighting coefficient of Knudsen number (dimensionless)	f_{-b}	natural fracture aperture (m)
r_{e_or}	effective organic pore radius (m)		
\dot{m}_b^O	bulk gas mass flux in OM nanopores ($\text{kg}/(\text{m}^2\cdot\text{s})$)		
ϕ_e^O	effective porosity of OM (dimensionless)		
σ_m	pseudo-steady-state shape factor ($1/\text{m}^2$)		
L_0	linear length of the nano-capillary tube (m)		
\dot{m}	mass of nano-capillary tube (kg/m)		
r_{or}^l	organic pore radius except first adsorption layer (m)		
		Subscripts	
		F	hydraulic fracture
		f	natural fracture

As mentioned above, Knudsen number (Kn) represents the relative degree of gas molecules collisions with molecules and pore walls, defined as the ratio of a molecular mean free path to the average pore diameter [18]. Different flow regimes are classified based on Kn as shown in Fig. 1. For continuum flow ($Kn < 10^{-3}$), the continuum assumption and Darcy's law are valid for describing the gas transport. For slip flow ($10^{-3} < Kn < 10^{-1}$), gas molecules are affected by pore walls, which causes gas velocity along the pore wall no longer zero, and Darcy's law is invalid. For transition flow ($10^{-1} < Kn < 10$), gas molecules collisions with each other and pore walls result in complex transport behaviors. If pore sizes are small enough ($Kn > 10$), the flow regime should be focused on the molec-

ular scale [19]. Since the Knudsen number ranges from 2×10^{-4} to 6 under shale gas reservoirs conditions [18], continuum flow, slip flow and transition flow coexist for the bulk gas transport. However, depending on the organic nanopores content, adsorbed gas and dissolved gas constitutes about 20–80% of the total gas-in-place in a typical organic-rich shale gas reservoir [20]. Adsorbed gas reduces the effective volumes of organic nanopores and causes the surface diffusion of adsorbed gas molecules under a concentration gradient [21]. Therefore, due to the differences between IM and OM in gas transport mechanisms, a comprehensive AGP model coupling multiple transport mechanisms and pore types should be paid more attention.

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