



Fractal models for gas slippage factor in porous media considering second-order slip and surface adsorption



Wenhui Song^a, Jun Yao^{a,*}, Yang Li^b, Hai Sun^a, Yongfei Yang^a

^a Research Centre of Multiphase Flow in Porous Media, China University of Petroleum (East China), Qingdao 266580, China

^b Department of Oilfield Exploration & Development, Sinopec, Beijing 100029, China

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ABSTRACT

Fluid flow in porous media with multi-scale pore size is known to be affected by fluid transport mechanisms, fluid properties and pore structure properties. Literatures have reported that gas slippage factor plays an essential role in determining apparent gas permeability. In this study, analytical models for gas slippage factor in porous media are proposed based on the fractal theory. The gas flow channels within porous media are modeled by tortuous capillaries with different diameters. For porous media with no adsorption capacity such as tight sandstone, gas flow in single capillary is solved by Navier-Stokes (N-S) equation associated with second-order slip. Adsorbed gas and bulk gas coexist in porous media with strong adsorption capacity like coal and shale. Adsorbed gas flows in the form of surface diffusion and the bulk gas transport is governed by N-S equation associated with Langmuir slip to incorporate boundary condition change because of the existence of adsorbed gas on the pore wall. Analytical solutions for gas slippage factor in aforementioned two different types of porous media are established using the fractal theory. The predictions of developed models are in good agreement with the molecular simulation and experimental data. Key analysis results show that gas slippage factor is closely related to porous media structural parameters, adsorption capacity, reservoir properties and gas properties.

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1. Introduction

Due to recent advances in unconventional gas reservoir development and manufacturing technology for microfluidic devices, gas flow through porous media beyond continuum flow regime has drawn considerable attention [1–7]. For highly permeable porous media, Darcy's law can be applied to describe the relationship between gas flux and pressure gradient. However, for low permeable porous media with nano-micro pore size, the measured gas permeability from experiments is always larger than the intrinsic permeability [8–11]. This phenomenon is defined as the slip effect that the velocity of gas molecules in the vicinity of pore wall is not equal to zero and is also named as the Klinkenberg effect [12]. The Klinkenberg effect can be attributed to the gas rarefaction phenomenon, where the mean free path of the gas molecules is comparable to the pore size [13]. Knudsen number is conventionally used to demarcate the flow regimes which is defined as the ratio of molecular mean free path to the pore radius [14,15]. In a basic sense, flows are generally classified as four regimes: continuum,

slip, transition and free molecular flows, depending on the magnitude of the Knudsen number as shown in Fig. 1.

To analyze such microscale gas flow, various analytical and numerical works have been conducted. Maxwell first proposed a first-order slip model to calculate the slip velocity at the wall for atomically smooth walls and the Maxwell type first-order slip can be applied to calculate the slip velocity [16]. In transition flow regime, second-order and higher-order slip boundary conditions can be used to compute slip velocity [17–21]. Beskok and Karniadakis [22] developed a unified Hagen–Poiseuille-type model valid in all flow regimes and this model has been adopted by Civan et al. [23–25] to consider the effect of the intrinsic permeability, porosity, and tortuosity of porous media. Zheng et al. [26] proposed a fractal model for gas slippage factor based on the simplified Beskok et al. model. Javadpour [27] proposed a model for gas flow in a nanopore duct based on the Knudsen diffusion and slip flow. Darabi et al. [28] incorporated Knudsen diffusion and surface roughness into the gas flow model in addition to slip flow using Maxwell theory. Wang et al. [29] proposed a non-empirical gas slippage model within micro- and nano-flow channels for low to moderate Knudsen numbers in ideal gas condition. Wu et al. [30] solved the Bhatnagar–Gross–Krook equation in simplified porous media and showed that the tortuous flow path and the coexistence

* Corresponding author.

E-mail address: rcogfr_upc@126.com (J. Yao).

Nomenclature

A	cross sectional area of a unit cell (m^2)	q_{ads}	adsorbed gas flux for a single capillary (m^3/s)
A_{ads}	pore area occupied by the adsorbed gas molecules with the thickness of d_m	q_{bulk}	bulk gas flux for a single capillary (m^3/s)
A_1	first-order slip coefficients, dimensionless	Q	gas flux in porous media (m^3/s)
A_2	second-order slip coefficients, dimensionless	Q_c	gas flux in porous media based on continuum flow regime (m^3/s)
b	gas slippage factor (psi)	R	capillary of radius (m)
C_a	adsorbed gas concentration (mol/m^3)	R_{eff}	effective capillary radius (m)
C_{amax}	maximum gas concentration inside the organic pores (mol/m^3)	r	pore radius (m)
C_{max}	maximum gas concentration inside the total core sample (mol/m^3)	T	temperature (K)
d_m	gas molecular diameter (m)	T_c	critical temperature (K)
D_{s0}	surface diffusion coefficient when gas coverage is zero (m^2/s)	T_{pr}	pseudo reduced temperature
D_s	surface diffusion coefficient (m^2/s)	U	velocity (m/s)
D_p	pore fractal dimension, dimensionless	$U_{sec r=R_{eff}}$	second-order slip velocity when the pore radius reduces because of the adsorbed gas coverage on the boundary (m/s)
D_t	tortuosity fractal dimension, dimensionless	U_{surf}	velocity of surface diffusion (m/s)
k_∞	intrinsic permeability (μm^2)	$U_{gl r=R_{eff}}$	slip velocity at the interface of bulk gas and adsorbed gas (m/s)
k	apparent permeability (μm^2)	U_{bulk}	bulk gas velocity distribution (m/s)
$H(1 - \kappa)$	Heaviside function, dimensionless	Z	gas compressibility factor, dimensionless
$\Delta H(0)$	isosteric adsorption heat at the gas coverage of “0” (J/mol)	$\bar{\tau}$	average tortuosity, dimensionless
ΔH	isosteric adsorption heat (J/mol)	ρ	gas density, kg/m^3
J_a	molar flow rate per unit area ($mol/(m^2 s)$)	φ	porosity, dimensionless
J_A	molar flow rate in the adsorbed layer (mol/s)	ϵ_{ks}	total organic grain volume per total grain volume, dimensionless
N	number of capillaries	θ	gas coverage of real gas, dimensionless
L	length scale (m)	μ	viscosity (Pa s)
L_0	straight length of capillary pathways along the flow direction (m)	δ	mean free path length of molecules (m)
K_B	Boltzmann constant (J/K)	λ	pore diameter (m)
Kn	Knudsen number, dimensionless	λ_{max}	maximum pore diameter (m)
M	gas molecular weight (g/mol)	λ_{min}	minimum pore diameter (m)
P_c	critical pressure (Pa)	κ	ratio of the rate constant for blockage to the rate constant for forward migration, dimensionless
p	pore pressure (Pa)	κ_b	rate constant for blockage (m/s) in surface diffusion
p_L	Langmuir pressure (Pa)	κ_m	rate constant for forward migration in surface diffusion
P_{pr}	pseudo reduced pressure	γ	fitting coefficients of isosteric adsorption heat (J/mol)
q	gas flux for a single capillary (m^3/s)	ΔP	pressure drop on the porous media (Pa)
q_c	gas flux in continuum flow regime for a single capillary (m^3/s)		

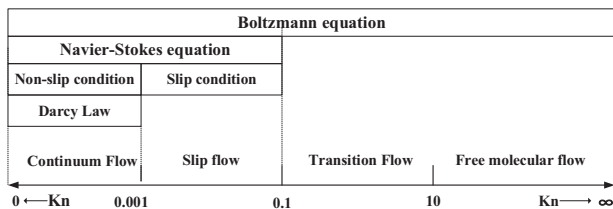


Fig. 1. Transition of flow regimes based on the Knudsen number.

of the diffuse and specular scatterings of the gas molecules when impinging on solid surfaces are the main cause of the Klinkenberg effect. Nevertheless, Wu et al. model doesn't consider the real gas equation of state because the gas viscosity is strongly dependent on the pore pressure [31]. Geng et al. established a fractal model for real gas transport but the boundary condition change because of the existence of adsorbed gas on the pore wall is neglected [32]. In addition, adsorbed gas and bulk gas coexist in porous media with adsorption capacity such as coal and shale [33]. To account for the influence of adsorbed gas on bulk gas flow, Singh and Javadpour established the Langmuir slip-Langmuir sorption

permeability model [34]. Wu et al. [35] combined bulk gas transport with surface diffusion of the adsorbed gas. Lu et al. [36] proposed a non-isothermal gas flow model based on the dusty-gas model and considered the conversion between the free gas and the adsorbed gas. Song et al. developed fully coupled apparent permeability models to describe gas transport in two types of pores based on the effective hydraulic radius assumption [37]. Recent advances in high-resolution imaging technology have made it possible to characterise the pore structures of the porous material [38–42]. Numerical simulation methods like lattice Boltzmann model and pore network modeling can be carried out to predict macro-scale phenomena, expressed in terms of transport and mechanical properties [43–46] based on such pore-structure models. Ma et al. [47–50] developed a 3D pore network flow model that captures gas flow from slip flow regime to Knudsen diffusion. This model was expanded further by Song et al. to consider the effect of adsorbed layers on the free gas flow with modeling the surface diffusion [44]. Tang et al. [51] and Chen et al. [43] established a generalized lattice Boltzmann model that includes gas slippage effect and simulated fluid flow within the reconstructed 3D shale porous media [52]. Later Christopher and Masa et al. [53] presented a local-effective-viscosity multi-relaxation-time lattice Boltzmann

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