



Assessing relative contributions of transport mechanisms and real gas properties to gas flow in nanoscale organic pores in shales by pore network modelling



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ABSTRACT

It is well-known that the movement of gas in organic nanoscale pores of typical shales must be modelled by capturing real gas flow behaviours in the full range of flow regimes, gas ad-/de-sorption and its effect on the flow, and surface diffusion while properly accounting for real gas PVT and viscosity changes as affected by the confined pore space. So far, no comprehensive model has been developed to enable the evaluation of the relative contributions of each of these physical aspects in a realistic organic pore space. In this work, a steady-state pore-network gas flow model that accounts for all of the listed aspects is developed to allow an assessment of their flow contributions in organic pores. The gas flow model is applied to three pore/throat network models, which are constructed from the same realistic pore network but with different average pore radii at 15.6, 3.2 and 1.56 nanometres, respectively, to calculate apparent gas permeability for each model at gas pressures ranging from 5 to 70 MPa. Analytical solution is applied to calculate the apparent gas permeability at the same gas pressures for three cylindrical pores with pore radii equal to the average pore radii of respective pore networks. For both the single pores and the pore networks, results show that when the average or single pore radius is larger than 10 nm, there is little influence on apparent gas permeability no matter what gas property, either real or ideal gas, is considered, nor is the surface diffusion, in the full pressure range. However, when the pore radius is smaller than 5 nm, the apparent gas permeability is notably influenced by the gas property and the surface diffusion. Furthermore when the pore radius is less than 2 nm, the gas permeability will be significantly underestimated if the surface diffusion is neglected. It is found that the influence of both critical temperature and pressure in the confined pore space, which deviate from the expected values in wide space, is insignificant and negligible on shale gas permeability. The relative contributions of the gas property and the surface diffusion, respectively, are shown to follow different trends for the single pores and the pore networks within the range of the pressures. An analysis shows that the differences can be attributed to the mixture of large and small pores and throats in a pore network that effectively suppresses the stronger effects of the gas property and the surface diffusion in the smaller pores and throats. This indicates the importance to consider spatial pore size distribution and pore connectivity when seeking to estimate effective properties.

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1. Introduction

Gas shales contain predominantly submicron-sized pores with large specific surface areas [1,2]. In such pores, the pore size

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approaches the molecular mean free path, and therefore gas flow cannot be modelled as a continuum process [3–5] beyond the slip flow regime within the full range of flow regimes (Fig. 1). Note that the Knudsen number, the ratio of molecular mean free path to the average pore radius, is conventionally used to demarcate the flow regimes. In an organic-rich pore, its large specific surface area is likely to adsorb a significant amount of gas molecules [6]. This gives rise to two phenomena (Fig. 2) [7,8]: the adsorbed gas mole-

Nomenclature

A	vdW energy parameter ($\text{Pa}\cdot\text{m}^6\cdot\text{mol}^{-2}$)	p_L	Langmuir pressure (Pa)
A	area of the 3D model cross section (m^2)	P_{pr}	pseudo reduced pressure
B	vdW energy parameter ($\text{dm}^3\cdot\text{mol}^{-1}$)	p_i	pore pressure in pore i
C_a	adsorbed gas concentration (mol/m^3)	p_j	pore pressure in pore j
C_{max}	maximum adsorbed gas concentration (mol/m^3)	q	volumetric gas flow flux through a single pipe (m^3/s)
d_m	gas molecular diameter (m)	q_{inlet}	gas flux in inlet pores (m^3/s)
D_{s0}	surface diffusion coefficient when gas coverage is zero (m^2/s)	Q_{ij}	gas flux between pore i and pore j (m^3/s)
D_s	surface diffusion coefficient (m^2/s)	Rel_{sd}	relative contribution from considering surface diffusion, dimensionless
G	shape factor of the pore cross section, dimensionless	Rel_{ig}	relative contribution from considering T_c , P_c change and real gas effect, dimensionless
g_{Darcy}	Darcy flow conductance ($\text{m}^3/\text{Pa}\cdot\text{s}$)	r	pore radius (m)
g_{free}	free gas flow conductance ($\text{m}^3/\text{Pa}\cdot\text{s}$)	r_i	radius of pore i (m)
$g_{surface}$	adsorbed gas flow conductance ($\text{m}^3/\text{Pa}\cdot\text{s}$)	r_j	radius of pore j (m)
g_{or}	gas flow conductance in organic pores ($\text{m}^3/\text{Pa}\cdot\text{s}$)	r_{eff}	effective capillary radius (m)
g_{ij}	gas flow conductance between pore j and pore i ($\text{m}^3/\text{Pa}\cdot\text{s}$)	r_t	original throat radius distribution (m)
g_i	gas flow conductance of pore i ($\text{m}^3/\text{Pa}\cdot\text{s}$)	r_{t1}	throat size distribution when $\gamma = 1$ (m)
g_j	gas flow conductance of pore j ($\text{m}^3/\text{Pa}\cdot\text{s}$)	r_{t2}	throat size distribution when $\gamma = 0.2$ (m)
g_t	gas flow conductance of the throat that connect pore i and pore j ($\text{m}^3/\text{Pa}\cdot\text{s}$)	r_{t3}	throat size distribution when $\gamma = 0.1$ (m)
$H(1 - \kappa)$	Heaviside function, dimensionless	T	formation temperature (K)
ΔH	isosteric adsorption heat at the gas coverage of “0” (J/mol)	T_c	critical temperature (K)
J_a	molar flow rate per unit area ($\text{mol}/(\text{m}^2\cdot\text{s})$)	T_{pr}	pseudo reduced temperature
J_A	molar flow rate in the adsorbed layer (mol/s)	u_{ave}	mean speed of a molecule (m/s)
k_{app}	gas permeability through pore network (μm^2)	V_A	adsorbed gas volumetric flow rate (m^3/s)
k_{or}	gas permeability of a capillary with a given pore radius	V_L	Langmuir volume (m^3/kg)
$k_{dfr+gc+rg}$	gas permeability based on Darcy flow regime considering T_c , P_c change and real gas effect (μm^2)	Z	gas compressibility factor, dimensionless
$k_{ffr+gc+rg}$	gas permeability based on full flow regimes considering T_c , P_c change and real gas effect (μm^2)	α	rarefaction coefficient dimensionless
$k_{ffr+gc+sd+rg}$	gas permeability based on full flow regimes and surface diffusion considering T_c , P_c change and real gas effect (μm^2)	β	slip coefficient, dimensionless
$k_{ffr+sd+rg}$	gas permeability based on full flow regimes and surface diffusion considering real gas effect (μm^2)	γ_i	scaling factor, $i = 1, 2, 3$
K_B	Boltzmann constant (J/K)	σ	Lennard-Jones size parameter (m)
Kn	Knudsen number, dimensionless	ρ_s	rock density, kg/m^3
L	length of the 3D model (m)	ρ	gas density, kg/m^3
L_i	pore body length of pore i (m)	ε	Lennard-Jones energy parameter, dimensionless
L_j	pore body length of pore j (m)	ε_{ks}	total organic grain volume per total grain volume, dimensionless
L_t	the length of throat that connects pore i and pore j (m)	θ_i	gas coverage of ideal gas, dimensionless
l	cylindrical capillary length/m	θ	gas coverage of real gas, dimensionless
M	gas molecular weight (g/mol)	μ	viscosity ($\text{Pa}\cdot\text{s}$)
N_{inlet}	number of the inlet pores	μ_{inlet}	gas viscosity in inlet pores ($\text{Pa}\cdot\text{s}$)
P_c	critical pressure (Pa)	λ	mean free path length of molecules (m)
P_d	the perimeter of the pore cross section (m)	ρ_{grain}	rock density (kg/m^3)
P	pore pressure (Pa)	$\rho_{sc,gas}$	gas density at standard condition (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
		ΔP	pressure drop on the 3D model (Pa)

cules reduce the pore space available for non-adsorbed or free gas molecules to move/flow, while surface diffusion may take place within the adsorbed gas to enhance the transport of gas molecules along molecular concentration gradients. These phenomena become important in nanoscale pores and must be considered in full. In addition, it has been shown [9–11] that in confined pores, the critical pressure (P_c) and temperature (T_c) of natural gas, including shale gas, depend on the sizes of pores, and therefore these issues must be accounted for using an appropriate Equation of State for the determination of in-situ properties of the gas.

Two types of models of gas flow in confined pore space have been developed. Beskok and Karniadakis [12] developed a unified Hagen–Poiseuille-type model valid in all flow regimes. This model

has been adapted and expanded by Civan et al. [13–15] to consider the effect of the intrinsic permeability, porosity, and tortuosity of porous media. Another type of model is based on superposing slip flow and Knudsen diffusion on top of the Darcy flow approach [16–20] by Javadpour et al., in a linear fashion, with pre-defined weighting coefficients. Zheng et al. [21] 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 and Yu [22] based on the combination of bulk diffusion and Knudsen diffusion. Wu et al. [23] proposed to determine those weighting coefficients based on

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