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Real gas transport in shale matrix with fractal structures

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ABSTRACT

A real gas transport model in shale matrix with fractal structures is established to bridge a pore size distribution and multiple transport mechanisms. This model is well validated with experiments. Results indicate that different pore size distributions lead to various transport efficiencies of shale matrix. A larger fractal dimension of the pore size and a smaller minimum pore size yield higher frequency of occurrence of small pores and a lower free gas transport ratio, which further results in lower transport efficiency. Gas transport efficiency due to pore size distribution parameters (a fractal dimension and a minimum pore size) varies with different porosities and pressures. Increasing fractal dimension and decreasing minimum pore size result in a higher contribution of Knudsen diffusion to the total gas transport. Decreased pressure and increased porosity enhance the sensitivity of gas transport efficiency to a pore size distribution. The relationship between apparent permeability and porosity based on different pore size distributions is also established for industrial application.

1. Introduction

As one of the clean energy resources, shale gas significantly reduces greenhouse gas emissions [1]. Owning to technological advancements in horizontal drilling and hydraulic fracturing, the shale gas is developing very fast in North America [2], which has received much attention from all over the world. However, there are still many challenges regarding the development of shale gas sources [3]. For instance, the gas transport behavior varies considerably in pores of shale matrix [4]. Studies on gas transport in shale matrix indicate the mechanisms of the transport behavior and provide a basis for evaluating well productivity, which contributes to the research on the development of shale gas resources.

Shale rocks are formed by compaction and solidification under high pressure in deep underground over a long time [5]. The shale matrix consisting of pores exhibits low porosity (1%–15%) and low permeability (nanodarcy to microdarcy) [6]. Chalmers et al. (2012) [7] investigated a range of pore sizes based on samples from the Barnett, Marcellus, Woodford, and Haynesville gas shales in the United States and the Doig Formation of northeastern British Columbia, Canada. They claimed that the pore size in shale matrix ranges from 1 nm to 100 µm. Experimental observations reported by Utpalendu and Prasad (2013) [8], Ye et al. (2015) [9], Zhang et al. (2015) [10], Chalmers and Bustin (2017) [11] and Wu et al. (2017) [12] also indicated a wide range of pore size distributions in shale matrix.

Fractal model is an effective method to describe the pore size distribution, and advantages are concluded as follows: (1) the fractal theory has been an effective method to study a wide range of pore size distributions in experimental studies. Clarkson et al. (2013) [13] studied the pore size data from currently active shale gas plays including the Barnett, Marcellus, Haynesville, Eagle Ford, Woodford, Muskwa, and Duvernay shales. Their study indicated a fractal geometry (power law scattering) for a wide range of pore sizes. Further studies by Lee et al. (2014) [14], Bahadur et al. (2015) [15] and Wang et al. (2015) [16] also showed that the fractal geometry is suitable to describe a pore size distribution for Baltic Basin in United Kingdom, Second White Specks and Belle Fourche formations in Canada, and Songliao Basin in China; (2) fractal theory is able to bridge the pore size distribution and gas transport mechanisms based on link of porosity. Effects of pore size distribution on gas transport behavior and efficiency can thus be studied. We thus select fractal model as part of our models.

In industry, different kinds of experimental methods may be performed to test the porosity of shale samples[17]. Mercury intrusion (MICP), low-pressure adsorption, and small-angle and ultra-small-angle neutron scattering (SANS/USANS) techniques have been wide used to measure porosity in experiments. MICP cannot access the porosity with pore diameter less than 3 nm in shale gas reservoir, and the risk to damage the pore structure exists. Low-pressure adsorption method must be combined with MICP to investigate the pore size spectrum due to the variable access of the probe molecules. SANS/USANS is able to detect a

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Nomenclature

Roman Symbols

A_t	cross-sectional area of the sample, m^2;
A_p	total cross-sectional area of pores, m^2;
C	conductance, (mol·m)/(Pa·s);
D_p	fractal dimension of the pore size, dimensionless;
D_τ	fractal dimension of the tortuosity, dimensionless;
d_p	equivalent pore diameter, m;
d_m	gas molecular diameter, m;
F_p	cumulative probability of pore size distribution, dimensionless;
f_p	probability density function of pore size;
ΔH	isosteric adsorption heat at $\theta = 0$, J/mol;
$H()$	Heaviside step function;
K_A	apparent permeability, m^2;
k	Boltzmann constant, $= 1.38 \times 10^{-23}$J/K;
L	straight length of the pore, m;
L_t	tortuous length of the pore, m;
M	gas molecular weight, kg/mol;
N_p	total number of pores with the equivalent pore diameter larger than d_p in shale matrix, dimensionless;
N_A	Avogadro constant, $= 6.02 \times 10^{23}$mol^{-1};
n	molecular number density, m^{-3};
o_1	fitting coefficient, = 7.9;
o_2	fitting coefficient, $= 9 \times 10^{-6}$;
o_3	fitting coefficient, = 0.28;
P	pressure, Pa;
P_c	critical pressure, Pa;
P_L	Langmuir pressure, Pa;
P_r	reduced pressure, dimensionless, $= \frac{P}{P_c}$;
Q	transport molar rate, mol/s;
q	transport molar rate in a single pore, mol/s;
T	temperature, K;
T_c	critical temperature, K;
T_r	reduced temperature, dimensionless, $= \frac{T}{T_{cz}}$;
V_m	molar volume, m^3/mol;
Z	gas compressibility factor, dimensionless.

Greek Symbols

α	function of gas properties and temperature in the SRK EOS, dimensionless;
β	fracture dip, dimensionless;
γ	aspect ratio, dimensionless;
χ	repulsion parameter in the SRK EOS, (Pa·m^3)/mol;
Ψ	ratio between the blockage rate constant and the forward migration rate constant, dimensionless;
Γ	gas transport ratio, dimensionless;
$\varkappa$	attraction parameter in the SRK EOS, m^3/mol;
ω	acentric factor, dimensionless;
ξ	taper ratio, dimensionless;
ϕ	porosity, dimensionless;
$\mathscr{D}_s$	surface diffusion coefficient, m^2/s;
θ	gas coverage, dimensionless;
ρ	gas density, kg/m^3;
μ	gas viscosity, Pa·s;
μ_0	gas viscosity at P = 1.01325 × 105 Pa and T = 423 K, $= 2.31 \times 10^{-5} Pa{\cdot}s$;
η	ratio between d_{pmin} and d_{pmax} in shale matrix, dimensionless, $= d_{pmin}/d_{pmax}$.

Subscripts

a	adsorbed gas;
b	free gas;
p	pore;
min	minimum;
max	maximum;
k	Knudsen diffusion;
s	surface diffusion;
t	total;
v	viscous flow.

wide range of pore sizes and good to be used at reservoir pressure and temperature conditions [17]. The theoretical relationship between porosity and permeability based on pore size distribution benefits in improving efficiency of estimating porosity or permeability. The mechanisms of change of transport efficiency with pore size distribution and porosity are also need to be indicated to better understand production optimization.

Many models have been proposed in the past decade to study the gas transport behavior in shale matrix. Javadpour (2009) [18] and Rahmanian et al. (2013) [19] proposed an ideal free gas transport model based on the sum of viscous flow and Knudsen diffusion in single pores. Sheng et al. (2015) [20] further took the surface diffusion into

Table 1
Review of existing gas transport models in shale rocks [18–25].

Model	Description	Comments
Javadpour, 2009 [18]	Ideal gas EOS; Linear superposition of viscous flow and Knudsen diffusion based on the slip boundary condition	Only for ideal gas in single pores; Neither adsorption nor surface diffusion
Rahmanian et al., 2013 [19]	Ideal gas EOS; Weighted superposition of viscous flow and Knudsen diffusion based on slip boundary condition	Only for ideal gas in single pores; Neither adsorption nor surface diffusion
Sheng et al., 2015 [20]	Ideal gas EOS; Weighted superposition of viscous flow, Knudsen diffusion and surface diffusion based on slip boundary condition	Only for ideal gas in single pores
Miao et al., 2015 [22] Li et al., 2016 [23]	Ideal gas transport model for a bundle of pores in fractal rocks	Only for ideal gas; Knudsen diffusion and surface diffusion are not considered
Wu et al., 2016 [21]	Consideration of real gas effect based on empirical equation of methane; Weighted superposition of viscous flow, Knudsen diffusion and surface diffusion based on the slip boundary condition	Empirical equation to describe real gas effect; single pores (elliptical cross section is omitted); Compressibility factor is always larger than 1 which is not real under low pressure
Ren et al., 2016 [24]	Consideration of real gas effect based on empirical equation of methane; Linear supervision of viscous flow and Knudsen diffusion based on non-slip boundary	Empirical equation to describe real gas effect; Single pores; Neither adsorption nor surface diffusion
Xu et al., 2017 [25]	Real gas transport for tapered non-circular pores in shale rocks	Only apply for single pores