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A workflow to estimate shale gas permeability variations during the production process

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ABSTRACT

Gas flow behavior in the tight shale porous matrix is complex due to the involvement of multiple physical processes. Pore size reduces as the effective stress increases during the production process, which will reduce the intrinsic permeability of the porous media. Slip flow and pore diffusion enhance gas apparent permeability, especially under low reservoir pressure. Adsorption not only increases original gas in place (OGIP) but also influences gas flow behavior because of the pore size reduction when the molecule size is comparable with the pore size along with the induced surface diffusion. Surface diffusion between the free gas phase and adsorption phase enhances gas permeability. Pore size reduction and the adsorption layer both have complex impacts on gas apparent permeability, plus the non-Darcy flow component make shale gas permeability look mysterious. These physical processes are difficult to couple with fluid flow, and previous research is generally incomplete. This work proposes a methodology to take these various effects into account simultaneously. Our results show that the geomechanical effect significantly reduces the intrinsic permeability of shale gas. However, slip flow and pore diffusion begin to overwhelm the geomechanical effect at reservoir pressure of 500 psi and below. As for the adsorption layer, it changes little of shale gas permeability but its induced surface diffusion might increase gas flow capacity significantly at low pressure, and the influence depends on the value of surface diffusivity. The workflow proposed in this study is considered to be useful to describe shale gas permeability evolution considering these physics together.

1. Introduction

Despite the rapid growth of non-fossil fuels, fossil energy still is expected to account for 78% of the global energy consumption in 2040 [1]. Natural gas is probably the most promising fossil fuel, and shale gas is a major component of natural gas supplies. Horizontal drilling and multi-stage hydraulic fractured wells provide great momentum for shale gas production. However, the production behavior of shale gas wells are not well understood due to the complex non-Darcy flow behaviors in the porous and fractured reservoir [2–4].

Before digging into the production behavior, it is imperative to understand gas flow behavior in nanopores because the produced gas accounts for most of the volume in the matrix. Non-Darcy is a frequently used term to describe flow process deviated from Darcy flow. In shale reservoirs, non-Darcy flow in the fracture refers to the flow phenomenon with inertial effects caused by high flow velocity. The Forchheimer equation [5] and the Barree and Conway models [6,7] can be used to describe this phenomenon in both single phase and multiphase flow [8]. Differently, non-Darcy flow in the matrix is caused by the multi physics occurred in nano-sized pores, and the term “gas apparent permeability” is frequently used to account for that.

Gas apparent permeability is related to Knudsen number and intrinsic permeability. Knudsen number is defined as the ratio of gas molecule mean free path over the representative physical length of the porous media [9], which is the pore diameter if a circular cross section is assumed. Physics in the nanopores affect gas flow behavior by changing either Knudsen number or intrinsic permeability, or both of them. Based on a comprehensive literature review, four physics include the effective stress on the matrix, slip flow, Fickian diffusion and Knudsen diffusion and surface diffusion. Fickian diffusion and Knudsen diffusion are also termed together as pore diffusion to distinguish from surface diffusion [10]. Surface diffusion occurs between the free gas and adsorption phase in tiny pores.

It is difficult to understand the overall effect of these physics since they occur simultaneously during the process of gas production. As gas is depleted, pressure decrease will cause mean free path growth, which increases the Knudsen number. The effective stress is increasing because gas is depleted, leading to a smaller pore size, which reduces

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Nomenclature

C	Gas compressibility, 1/psi
C_{ad}	Adsorption amount in a unit volume of rock, kg/m^3
d	Pore size, nm
d_{ad}	Pore size with adsorption, nm
d_{eff}	Effective pore diameter, nm
d_{mol}	Molecule diameter, nm
D	Gas molecule size, m
D_{s-d}	Surface diffusivity, m^2/s
E	Characteristic adsorption energy of the porous media, kcal/mol
F	Ratio between k_{s-d} and $k_{\infty eff}$, dimensionless
$f(Kn)$	Ratio of gas apparent permeability over intrinsic permeability, dimensionless
$f(Kn)_{ad}$	$f(kn)$ with adsorption, dimensionless
$f(Kn)_{eff}$	Effective $f(kn)$, dimensionless
$f(Kn)_{tot}$	Final $f(kn)$ considering all the physics, dimensionless
J_D	Mass flux of Darcy flow, kg/(m^2·s)
J_{s-d}	Mass flux of surface diffusion, kg/(m^2·s)
k_0	Constant in the equation of the Langmuir pressure
k_∞	Intrinsic permeability, nD
$k_{\infty eff}$	Effective intrinsic permeability, nD
k_a	Apparent permeability, nD
k_{aeff}	Effective apparent permeability, nD
k_{atot}	Apparent permeability considering all the physics, nD
k_B	Boltzmann constant, J/K
k_b	Klinkenberg term, psi
k_{eff}	Effective permeability, nD
k_f	Fracture permeability, mD
k_m	Matrix permeability, nD
Kn	Knudsen number, dimensionless
k_{s-d}	Effective permeability for surface diffusion, nD
l	Mean free path, m
M_g	Molecular weight, kg/mol
P	Pressure, psi or Pa
p_L	Langmuir pressure, psi
q	Adsorption amount, scf/ton
q_m	Maximum adsorption amount, scf/ton
R	Gas constant, J/(K·mol) or kcal/(K·mol)
T	Temperature, °F or K
v_{std}	Standard volume of gas, L/mol
α_1	Coefficient of permeability enhancement, dimensionless
θ	Adsorption coverage on the pore surface, dimensionless
μ_g	Viscosity, Pa·s
ρ_g	Gas density, kg/m^3
ρ_r	Rock density, kg/m^3
σ_e	Effective stress, psi
σ_{tot}	Total stress, psi
α	Biot coefficient

intrinsic permeability but increases the Knudsen number. Gas desorbs from the pore surface as gas is depleted, which enlarges pore size but decreases the Knudsen number. Surface diffusion near the pore surface increases gas transport capacity throughout the process.

Experimentally, the pulse-decay method is a feasible way to study gas flow behavior in tight porous media [10–16]. However, the permeability obtained from a pulse-decay experiment is gas apparent permeability of the porous media depending on the gas type, temperature and pressure [13]. In the literature, these effects are usually studied separately in gas shales. For example, Heller et al. [17] measured the Marcellus shale matrix apparent permeability under a range of pore pressure and effective stress, based on which the stress-dependent pore size is estimated. Sakhaee-Pour and Bryant [18] investigated gas apparent permeability considering slip flow and pore diffusion with a constant pore diameter. Inspired by them, we combined the experimental results by Heller et al. [17] and the theory by Sakhaee-Pour and Bryant [18] in this study to couple the geomechanical effect, adsorption and the slip flow with pore diffusion effect.

Surface diffusion has been recently reported to be an important flow mechanism in organic-rich shale reservoirs. Kang [19] reported values of diffusivity in kerogen by pulse-decay experiments. Fathi and Akkutlu [20] used Lattice Boltzmann Method to describe this phenomenon. Wu et al. [21] investigated the importance of surface diffusion in pores with various sizes. Sheng et al. [22] coupled surface diffusion with slip flow, viscous flow and Knudsen diffusion using different values of surface diffusivity. They all reached the conclusion that surface diffusion contribution to shale gas flow is significant in micro and meso pores and under low pressure.

In summary, most previous studies overlook the simultaneous effects of surface diffusion and the effective stress for gas flow in nanopores. What's more, all the physics are dynamically changing from the initial reservoir pressure to the pressure at the end of production, making it more difficult to describe gas permeability evolution. Accordingly, we propose a workflow and demonstrate how the procedure proceeds to consider the multi physics together during gas production in the tight porous shale matrix.

2. Knudsen number and gas permeability

Knudsen number (Kn) has been used widely to define flow regimes in the porous media with a small pore size [23] (Table 1) which is defined as the ratio of the mean free path over pore diameter (Eq. (1)). Eq. (2) describes the formula calculating mean free path in this study.

$$Kn = \frac{l}{d} \tag{1}$$

$$l = \frac{k_B T}{\sqrt{2} Z \pi d_{mol}^2 p} \tag{2}$$

where l is mean free path, in the unit of m, k_B is the Boltzmann constant, $1.38065\mathrm{E}-23$, in the unit of J/K; T is temperature in the unit of K, d is pore diameter and d_{mol} is the molecule diameter, in the unit of m, p is pressure, in the unit of Pa, and Z is gas compressibility factor, a dimensionless number. Table 2 lists the classification for the level of "small" in pore size by the International Union of Pure and Applied Chemistry (IUPAC).

Using properties of methane [24], Fig. 1 plots Knudsen number values as a function of pore pressure. Pore diameter is set to be 5 nm, 50 nm and 1000 nm, which covers a wide range of pore size in organic matters reported by Wang and Reed [25]. Temperature is set to be from 100 °F to 400 °F which covers the temperature in most reservoirs. It shows that for most pores, from the initial pore pressure (usually below 10,000 psi) to the pore pressure at the end of production, flow regimes are in transition and slip flow regions. When the pore size is on the order of micrometer scale (> 1 μm), flow regime will shift to continuum flow when the reservoir pressure is higher than 1,000 psi. It also

Table 1
Classification of flow regimes by Knudsen number.

Knudsen number range	$< 10^{-3}$	$10^{-3} < Kn < 0.1$	$0.1 < Kn < 10$	$Kn > 10$
Flow regime	continuum	slip flow	transition flow	free molecular flow