



Full Length Article

Effects of nano-pore wall confinements on rarefied gas dynamics in organic rich shale reservoirs



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ABSTRACT

The advancements in horizontal well drilling and multistage hydraulic fracturing technology enabled us to unfold major sources of hydrocarbon trapped in ultra-tight formations such as organic rich shales. Tremendous gas production from these reservoirs has transformed today's energy landscape [1]. Even though multi-stage hydraulic fracturing stimulation provides high permeability paths to transfer gas to the wellbore, however, most of the gas is stored in nano-organic pores of the ultra-low permeability shale matrix that needs to be transferred to the hydraulic fractures to be able to be produced. Studies using advanced imaging technologies such as FIB/SEM and low temperature adsorption measurements show that in the organic rich shale gas reservoirs, Kerogen, the finely dispersed organic nano-porous material with an average pore size of less than 10 nm holds bulk of the total gas in place (GIP). The molecular level interactions between fluid–fluid and fluid–solid organic pore walls govern the transport and storage in these organic nano-pores.

To understand the high gas production rates from these ultra-tight formations, the objective of this study is to advance our understanding of non-ideal gas dynamics in multiscale pore structure of organic rich shale matrix (i.e., gas storage and transport influenced by adsorption and adsorbed gas transport) and develop a model to quantify these effects under wide range of reservoir conditions. Among different methods used to model gas dynamics in organic nano-pores such as the multi-continuum, molecular dynamics and Monte Carlo, the lattice Boltzmann method (LBM) is more effective method with much less computational cost relative to other techniques. In this study we focus on rarefied gas dynamics in Kerogen organic nano-tubes under wide range of reservoir pressure and temperature conditions using a two dimensional LBM model.

In this model the Langmuir-slip boundary condition at capillary walls, convection or darcy flow and diffusive transport (slippage of free gas molecules and surface transport of adsorbed molecules combined) are considered to model gas transport. Different transport mechanisms and their contribution in gas transport is investigated in a large range of Knudsen numbers from continuum flow to transition flow regime under different reservoir conditions. The deviation from classical theory of fluid flow in micro channels such as Knudsen's minimum in the mass flow rate is investigated and the effect of gas slippage and double slippage on Knudsen minimum is discussed in details. Finally the results are compared with analytical, and semi analytical solutions available in the literature.

The LBM model results displays a clear indication that the gas transport in the capillary tube is highly depends on the pore width size, pressure and temperature. The relative impact of pore size, pressure and temperature on maximum gas velocity and gas wall velocity differs at different flow regime conditions. A critical Knudsen number exists at different reservoir conditions, where the anticipated parabolic fluid velocity profile in organic nano-pores alters and shows higher flow rate as capillary widths reduces due to the underlying effect of molecular phenomena of double slippage and the wall confinement. The comparison with traditional continuum Hagen-Poiseuille law, Klinkenberg slip theory, and recent modified versions of Klinkenberg slip flow equations show that the previous models are valid only in the continuum flow regime, however, they fail to capture high gas flow rates at high Knudsen number and transition flow regimes which is the case in most of the shale organic nano-pore conditions [2].

This work is not only important for the advancement of shale gas flow simulators, but also for organic rich shale characterization.

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Nomenclature

a	channel half width
c	proportionality constant
C	free gas density
C_1	first-order slip coefficient
C_2	second-order slip coefficient
C_μ	adsorbed gas density
$C_{\mu s}$	maximum monolayer adsorption capacity
D_k	Tortuosity-corrected coefficient of molecular diffusion
D_s	surface diffusion coefficient
e	lattice Velocity
f	single-particle distribution function
f^{eq}	equilibrium distribution function
f^{neq}	non-equilibrium distribution function
F	long range fluid interaction force
G	interaction strength
G	pressure gradient
H	width of capillary tube
J_{ads}	adsorbed-gas flux
J_{free}	free-gas flux
K	langmuir partition coefficient
Kn	Knudsen number
L	length of capillary tube
L	length of capillary tube
m	molecular mass
M	molar mass/Molecular weight of the gas
N_R	Avogadro number
P	pore pressure
P_L	Langmuir pressure
r	distance from the center of the capillary
r_0	capillary Half-width

R	universal Gas constant
t	time
T	reservoir temperature
U	macroscopic velocity
$U_{g,slip}$	velocity of gas which is one mean free path distance away from the wall i.e. slip velocity
U_{slip}	slip Velocity
$\frac{U_{slip}}{U_0}$	normalized Slip Velocity
U_{surf}	local wall velocity due to the adsorbed-phase transport
U_W	fluid velocity by the wall
V_a	adsorbed gas volume
V_{amax}	maximum monolayer adsorbed gas volume
x	lattice space
z	compressibility factor

Greek symbols

α	equilibrium Langmuir isotherm coefficient
k_B	Boltzmann constant
λ	mean free path of gas molecules
μ	gas dynamic viscosity
ν	gas Kinematic viscosity
Ω	collision Operator
ρ	macroscopic fluid density
ρ_{ads}	average adsorbed gas density
ρ_g	gas density
ρ_0	arbitrary constant
ψ	interaction potential function
τ	relaxation time
τ^*	effective relaxation time
w	weighing factor

1. Introduction

Shale gas formations increase the total gas production by accessing the trapped natural gas within organic rich shale sedimentary rocks, comprising of organic porous material (kerogen), and inorganic matrix. To effectively develop shale gas reservoirs, it is essential to understand the gas transport and storage in these ultra-tight formations. Previous studies have investigated different couplings between shale matrix organic and inorganic components, natural fractures and hydraulic fractures [1–5,6]. These studies suggest that the kerogen organic pores are the main source of the gas and gas transport in shale is mostly follows the series coupling, where gas flows from organic pores to non-organic pores of the matrix to the natural fractures and hydraulic fractures. Therefore, the gas dynamics in organic pores of the kerogen are the major controlling factor that impacts gas production rates throughout the life of the reservoir. The kerogen organic pores generally extends between macro-pores ($h \geq 50$ nm), meso-pores ($2 \leq h < 50$ nm), and micro-pores ($h < 2$ nm) having an average pore size of 10 nm, h being the pore size [2].

In recent years, to study the micro-scale flow characteristics of shale gas, laboratory measurement techniques and numerical simulation methods have been incorporated [7–9,10]. A dimensionless number, Knudsen Number ($Kn = \lambda/h$), defined as the ratio of mean free path of gas molecules (λ) to hydraulic pore diameter of conduit (h) is used to differentiate different gas flow regimes, namely – Continuum flow ($Kn \leq 0.001$), Slip flow ($0.001 < Kn \leq 0.1$), Transition flow ($0.1 < Kn \leq 10$), and Free molecule flow ($Kn > 10$) [11]. The continuum flow is governed by the Navier-Stokes equations, dominated by the viscosity effects; the slip flow is characterized by the inclusion of a slip parameter to the Navier-Stokes equations; the transition flow is described by Burnett equation and modeled using molecular

simulations, such as Direct Simulation Monte Carlo (DSMC); the free molecular flow is depicted as the flow where the molecular collisions are ignored, and is represented by the Boltzmann equation.

Kang et al. [2] showed that the gas flowing in the kerogen pores of shale matrix is generally in the slip flow or transition flow regimes, under initial shale gas reservoir conditions that involves strong molecular interactions between gas and kerogen, i.e., sorption phenomena. In addition to gas adsorption/desorption behavior, studies showed that adsorbed-gas molecules can move along the pore wall due to surface diffusion, leading to more complex gas dynamics in the kerogen organic nano-pores [12–14,15]. During the last few years, the Lattice Boltzmann method (LBM) is used as a prime alternative numerical approach for modeling physical phenomena in fluid flows combining microscopic and macroscopic physical mechanisms [16–19]. According to the kinetic theory of gases, equilibrium phase behavior of gases is a function of gas pressure, temperature and volume, where the effect of container is ignored. Therefore, the phase behavior of gas in a bulk system or in a nano-capillary tube is treated likewise for the same pressure, temperature and gas volume. But as the system volume shrinks to meso- and micro-scales the phase equilibrium becomes pore size dependent where the wall confinement effect changes the hydrodynamic behavior of fluid [20–22]. Yuan and Schaefer [23] in 2006 incorporated various equations of state into the single-component multiphase lattice Boltzmann model and conclude that more realistic equation of state is required to quantify non-ideal gas dynamics. This can be achieved using short and long range intermolecular forces between fluid particles and container [24].

In this study we assume the fluid flow in organic pores as single phase single component methane gas, where a two-dimensional LBM is employed to evaluate the velocity profiles across the single organic nano-capillary tube under different initial and boundary conditions.

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