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A model for multiple transport mechanisms through nanopores of shale gas reservoirs with real gas effect–adsorption-mechanic coupling

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ABSTRACT

Multiple transport mechanisms coexist in nanopores of shale gas reservoirs with complex pore size distribution and different gas-storage processes, including continuum flow, slip flow and transition flow of bulk gas and surface diffusion for adsorbed gas. The force between gas molecules and the volume of the gas molecules themselves cannot be negligible in shale gas reservoirs with high pressure and nanoscale pores, influences gas transport and must be taken into account as a real gas effect. During depressurization development of shale gas reservoirs, the adsorbed gas desorption and a decrease in an adsorption layer influence gas transport. Meanwhile, due to the stress dependence, decreases in intrinsic permeability, porosity and a pore diameter also influence gas transport. In this work, a unified model for gas transport in organic nanopores of shale gas reservoirs is presented, accounting for the effects of coupling the real gas effect, stress dependence and an adsorption layer on gas transport. This unified model is developed by coupling a bulk gas transport model and an adsorbed gas surface diffusion model. The bulk gas transport model is validated with published molecular simulation data, and the adsorbed gas surface diffusion model is validated with published experimental data. The results show that (1) in comparison with the previous models, the bulk gas transport model developed on the basis of a weighted superposition of slip flow and Knudsen diffusion can more reasonably describe bulk gas transport, (2) surface diffusion is an important transport mechanism, and its contribution cannot be negligible and even dominates in nanopores with less than 2 nm in diameter, and (3) the effect of stress dependence on fluid flow in shale gas reservoirs is significantly different from that in conventional gas reservoirs, and is related to not only the shale matrix mechanical properties and the effective stress but also the gas transport mechanisms.

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1. Introduction

Recoverable reserves of shale gas in the United States are estimated to be 24.409×10^{12} m^3 [1]. Over the past years, profitable production in shale gas reservoirs is a result of technological advancement in horizontal drilling and hydraulic fracturing [2]. Even with significant progress made in production of shale gas reservoirs, gas recovery remains very low, estimated at 10–30% of original gas in place [3]. One of the issues yet to be addressed is the lack of a valid predictive tool for shale-gas production [4]. A model for gas transport in nanopores of shale gas reservoirs is the fundament for numerical simulation and production forecast [5,6].

Typical organic-rich shale has low porosity (less than 10%) and permeability (ranging from nano Darcy to micro Darcy) [7]. According to the International Union of Pure and Applied Chemistry (IUPAC), classification of a pore size in shale can be divided into ultramicropores (pore diameter <0.7 nm), micropores (0.7 nm ∼ 2 nm), mesopores (2 nm ∼ 50 nm) and macropores (>50 nm). Small-scale nanopores dominate in shale. The pore volume with a pore radius of less than 10 nm accounts for the total pore volume up to 42% [8]. Some of the pores and the paths connecting the pores have a pore radius of even less than 2 nm and only a small amount of macropores distributes [9]. The effective pore size estimated by Kang et al. shows that shale could be considered as a microporous-mesoporous material [10]. According to a general classification, shale pores can be divided into organic pores and inorganic pores; organic pores account for a significant portion [9]. Shale gas is self-generating and self storage, and free gas, adsorbed gas and dissolved gas coexist in shale gas reservoirs

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Nomenclature

b gas slippage constant, dimensionless
C_g gas compressibility factor, 1/MPa
C_k Knudsen diffusion conductance considering real gas effect, s
C_{kad} Knudsen diffusion conductance considering real gas effect and adsorption layer, s
C_{ki} Knudsen diffusion conductance when gas is considered as ideal gas, s
$C_{knon\text{-}ad}$ Knudsen diffusion conductance with considering real gas effect and without adsorption layer, s
$C_{knon\text{-}str}$ Knudsen diffusion conductance with considering real gas effect and without stress dependence, s
C_{kstr} Knudsen diffusion conductance considering real gas effect and stress dependence, s
C_s adsorbed gas surface diffusion conductance, s
C_{sc} adsorbed gas concentration when gas is considered as real gas, kg/m^3
C_{sci} adsorbed gas concentration when gas is considered as ideal gas, kg/m^3
C_{si} adsorbed gas surface diffusion conductance when gas is considered as ideal gas, s
$C_{snon\text{-}str}$ adsorbed gas surface diffusion conductance with considering real gas effect and without stress dependence, s
C_{sstr} adsorbed gas surface diffusion conductance considering real gas effect and stress dependence, s
C_t total flow conductance when gas is considered as real gas, s
C_{tad} total flow conductance considering real gas effect and adsorption layer, s
C_{ti} total flow conductance when gas is considered as ideal gas, s
$C_{tnon\text{-}ad}$ total flow conductance with considering real gas effect and without adsorption layer, s
$C_{t\text{-}non\ influence\ factor}$ total flow conductance without considering real gas effect, or stress dependence, or adsorption layers, s
$C_{tnon\text{-}str}$ total flow conductance with considering real gas effect and without stress dependence, s
C_{tstr} total flow conductance considering real gas effect and stress dependence, s
C_v slip flow conductance when gas is considered as real gas, s
C_{vad} slip flow conductance considering real gas effect and adsorption layer, s
C_{vi} slip flow conductance when gas is considered as ideal gas, s
$C_{vnon\text{-}ad}$ slip flow conductance with considering real gas effect and without adsorption layer, s
$C_{vnon\text{-}str}$ slip flow conductance with considering real gas effect and without stress dependence, s
C_{vstr} slip flow conductance with considering real gas effect and stress dependence, s
D_f fractal dimension of the pore surface, dimensionless
D_s surface diffusion coefficient, m^2/s
D_s^0 surface diffusion coefficient when gas coverage is “0”, m^2/s
d_m gas molecular diameter, m;
$H(1-\kappa)$ Heaviside function, dimensionless
ΔH isosteric adsorption heat at the gas coverage of “0”, J/mol
J_b total mass flux for bulk real gas, kg/(m^2·s)
J_{bi} total mass flux for bulk ideal gas, kg/(m^2·s)
J_{ci} continuum mass flux for ideal gas, kg/ (m^2·s)
J_k Knudsen diffusion mass flux for real gas, kg/(m^2·s)
J_{ki} Knudsen diffusion mass flux for ideal gas, kg/(m^2·s)
J_s surface diffusion mass flux for real gas, kg/(m^2·s)
J_{si} surface diffusion mass flux for ideal gas, kg/(m^2·s)
J_t total mass flux for real gas, kg/(m^2·s)
J_v slip mass flux for real gas, kg/(m^2·s)
J_{vi} slip mass flux for ideal gas, kg/(m^2·s)
K intrinsic permeability of shale under effective stress condition, m^2
Kn Knudsen number for real gas, dimensionless
Kn_i Knudsen number for ideal gas, dimensionless
K_o intrinsic permeability of shale at atmospheric pressure, m^2
l distance along the gas transport direction, m
M gas molar mass, kg/mol
N_A Avogadro’s constant, 6.0221415×10^{23}/mol
p gas pressure, MPa
p' gas pressure at certain time during depressurization, MPa
p_c overburden pressure, MPa
p_e effective stress, MPa
p_L Langmuir pressure, MPa
q shale porosity coefficient, dimensionless
q_a standard adsorbed gas volume per unit weight, m^3/kg
q_L Langmuir volume, m^3/kg
R gas universal constant, J/(mol·k)
r pore radius under effective stress condition, m
Δr decreased pore radius due to stress dependence, m
r' pore radius under effective stress condition at certain time during depressurization, m
r_{ad} adsorption layer for real gas, m
r'_{ad} adsorption layer for real gas at certain time during depressurization, m
r_{adi} adsorption layer for ideal gas, m
r_o pore radius under atmospheric pressure, m
s shale permeability coefficient, dimensionless
T reservoir temperature, K
t_M the average time required for one collision between the gas molecules, s
t_S the averaged time required for one collision between a nanopore wall and gas molecule, s
t_T the average time consumed for one collision of overall gas molecules, s
Z gas deviation factor, dimensionless
α rarified effect coefficient for real gas, dimensionless
α_1 fitting constant, dimensionless
α_i rarified effect coefficient for ideal gas, dimensionless
α_o rarified effect coefficient when $Kn \to \infty$, dimensionless
β fitting constant, dimensionless
ξ_{mb} the correction factor for bulk gas transport in shale, dimensionless
ξ_{ms} surface diffusion coefficient in shale, dimensionless
η gas viscosity, p_a·s
θ gas coverage on nanopores wall for real gas, dimensionless
θ_i gas coverage on nanopores wall for ideal gas, dimensionless
κ the ratio of the rate constant for blockage to the rate constant for forward migration, dimensionless
κ_b the rate constant for blockage, m/s
κ_m the rate constant for forward migration, m/s;
λ molecular mean free path for real gas, m
λ_i molecular mean free path for ideal gas, m
λ_T molecular mean free path of the overall gas molecules, m
σ the ratio of normalized molecule size to local average pore diameter, dimensionless
τ tortuosity, dimensionless

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