International Journal of Heat and Mass Transfer 126 (2018) 1007–1018

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Transport capacity of gas confined in nanoporous ultra-tight gas reservoirs with real gas effect and water storage mechanisms coupling

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ARTICLE INFO

Article history:
Received 12 September 2017
Received in revised form 24 April 2018
Accepted 16 May 2018

Keywords:
Nanoporous ultra-tight gas reservoirs
Water storage mechanisms
Monte Carlo sampling method
Geostatistical method
Real gas effect

ABSTRACT

It is a well-established fact that mineral matter in actual ultra-tight gas reservoirs presents a strong affinity for water. However, the presence of water within nanopores has not drawn due attention and is generally overlooked by previous literature. Furthermore, the other key physics required to be captured is how to upscale the gas conductance from a single nanopore to a core scale, which greatly aggravates the complexity of the issue. To date, the comprehensive apparent permeability model considering the aforementioned features is still lacking and the intent of this research is to achieve this goal. Firstly, the Beskok's model is utilized to characterize bulk-gas transport behavior through nanotubes. And Li's model is employed to quantify water storage mechanisms, which are based on thermodynamic equilibrium theory between liquid and vapor. More features, such as stress dependence and real gas effect are incorporated. Thus, the apparent permeability model for a single nanopore is developed. Secondly, actual core sample is discretized to numerous little cells and the pores within each cell are assumed to possess uniform pore size, which are assigned by Monte Carlo sampling from pore size distribution (PSD). Thus, the transport capacity of each cell can be quantified by utilizing the aforementioned established model for a single nanopore. Finally, based on apparent permeability of each cell, a reliable geostatistical method is employed to calculate the effective permeability of the core sample. And the proposed apparent permeability model for actual ultra-tight gas reservoirs is successfully verified against experimental data collected from published documents. Subsequently, we identify the effect of PSD, relative humidity, real gas effect and stress dependence on the apparent permeability of actual ultra-tight gas reservoirs. Results show that the presence of heterogeneity in 2D will contribute to the increase of effective permeability and the influence of water condensation only works when the relative humidity is relatively high (>0.8). Moreover, the real gas effect has little effect on the gas transport behavior at a certain pressure and can be neglected.

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1. Introduction

With the rapid decline in conventional reserves and increase in energy demand, the unconventional resources have become the research focus, including ultra-tight gas reservoirs [1–4,57–59]. Core samples from so-called ultra-tight gas reservoirs possess nanoscale pore size and extremely low matrix intrinsic permeability [5,6,51]. As the most important petro-physical property in ultra-tight gas reservoirs, the determination of permeability will significantly contribute to the development and production from them. However, despite much effort and considerable advances over the last few decades, it remains challenging to precisely characterize the gas transport behavior through nanoporous ultra-tight gas reservoirs, in which the assumptions of classical Navier-Stokes equation break down [7–10]. Moreover, the heterogeneity and anisotropy exhibit in actual core samples further aggravate the complexity of quantifying the permeability of ultra-tight gas reservoirs. The most conventional methods utilized to obtain the apparent permeability are various laboratory-based measurement techniques, involving unsteady-state methods, such as pressure-decay method, or steady state method [11–15]. However, these experiments are generally expensive and time-consuming. The other commonly used methods combine a detailed understanding of gas transport regimes at nanoscale with a faithful representation of the actual pore space topology to generate physically-based pore scale models, including X-ray computed tomography (CT), nano-CT imaging and so on [16–19]. However, although computational performance of nowadays computer has been significantly enhanced, the numerical construction process of the actual core sample is still

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.05.078
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Nomenclature

λ	the molecular mean free path, nm
r_e	the effective radius of nanopores, nm
μ	gas viscosity, MPa·s
T	the formation temperature, K
p	formation pressure, Pa
R	the universal gas constant, dimensionless
Z	the gas compressibility factor, dimensionless
M	the gas molar mass, g/mol
ϕ_e	the effective porosity, dimensionless
τ	the touristy of the single nanopore, dimensionless
b	the slip constant, dimensionless
α	the rarefaction coefficient, dimensionless
α_o	the rarified effect coefficient when $Kn \to \infty$, dimensionless
α_1	the fitting constant, dimensionless
β	the fitting constant, dimensionless
$\phi(p)$	the porosity considering stress dependence, dimensionless
ϕ_r	the porosity under high effective stress, dimensionless
ϕ_i	the initial porosity, dimensionless
σ_e	the effective stress, Pa
η	the porosity stress-dependence factor, Pa^{-1}
$k(p)$	the permeability considering stress dependence, m^2
k_i	the intrinsic absolute permeability, m^2
ψ	the permeability stress-dependence factor, Pa^{-1}
r_s	the pore radius considering stress dependence, m
$\Pi(h_w)$	the disjoining pressure inside nanotubes, MPa
$\Pi_f(h_w)$	the disjoining pressure of liquid film on flat surface, MPa
h_w	the thickness of adsorption water film, m
γ	the gas-water surface tension, mN/m
$\Pi_m(h_w)$	the molecular component of disjoining pressure, MPa
$\Pi_e(h_w)$	the electrostatic component of disjoining pressure, MPa
$\Pi_s(h_w)$	the structural component of disjoining pressure, MPa
A_{gws}	the Hamaker constant in gas-water-solid system, J
l	the London Wavelength, nm
ε_r	the relative permittivity of media, dimensionless
ε_o	the vacuum permittivity of media, dimensionless
κ_B	the Boltzmann constant, J/K
e	the electron charge, C/number
ξ	the ion valence, dimensionless
ω	parameter related to the surface charge density and film thickness, nm^{-1}
χ	the coefficient for the strength of structural force, N/m^2
ζ	the characteristic decay length, nm
$h*$	the critical thickness of water film at a given pore size, m
V_m	molar volume of water, cm^3/mol
p_0	the saturated vapor pressure of water, MPa
p_v	the critical water vapor pressure in gaseous phase, MPa
P_r	the pseudo pressure, dimensionless
T_r	the pseudo temperature, dimensionless
p_c	the critical pressure, MPa
T_c	the critical temperature, K
s	the pore size, nm
σ	the standard deviation of the LGD function, nm
θ	the mean deviation of the distribution function, nm
$f(s)$	the proportion of the nanopores when the pore size is s, dimensionless
N_r	the number of cells in the vertical direction, dimensionless
N_c	the number of cells in the horizontal direction, dimensionless
$k_{i,j}$	the apparent permeability of the cell in row i and column j, m^2
k_e	the effective permeability of the actual core sample, m^2

time-consuming, with each study case requiring a separate modeling [20,21]. In contrast, an analytical or semi-analytical model, based on some reasonable assumptions, not only provides instantaneous results but also facilitates identifying the effect of each key physical parameter. Hence, it will be quite attractive to develop a practical mathematical model for gas transport through actual nanoporous ultra-tight gas reservoirs.

Due to the diverse nanoscale pores in the ultra-tight gas reservoirs, the gas transport features are apparently different from that in conventional gas reservoirs [22–24]. Generally, there are three flow regimes in porous media based on the pressure gradient (or the velocity), including: Pre-Darcy, Darcy, and Post-Darcy (or Non-Darcy) [60,61]. Because of the ultra-tight nature, the flow mechanism of gas confined in ultra-tight gas reservoirs cannot be described by Darcy or Post-Darcy flow regimes. On the basis of Knudsen number (K_n) which refers to the ratio of gas mean free path to the characteristic dimension, the gas transport regimes in a single nanopore can be classified as continuum flow ($K_n < 10^{-3}$), slip flow ($10^{-3} < K_n < 10^{-1}$), transition flow ($10^{-1} < K_n < 10$) and free molecular diffusion ($K_n > 10$) [25,26]. Numerous scholars have performed comprehensive researches to investigate the gas transport capacity through a single nanopore and several robust models which can describe all the aforementioned bulk-gas transport mechanisms have been established [7,23,27,50,54]. In addition, it is a well-established fact that the mineral matter in actual ultra-tight gas reservoirs presents a strong affinity for water [28–31]. However, water storage mechanisms in nanopores have not drawn due attention and are generally overlooked by previous published literature [32–35]. Experiments implemented by Li directly demonstrated the evidence of water condensation in hydrophilic clay samples, in which the pores <6–7 nm will be totally blocked by capillary water. Furthermore, the water tends to store within the other pores >6–7 nm in the form of adsorbed water film [28,29]. That is to say that, at a given relative humidity, the presence of water will significantly influence the effective pore size of a single nanopore and subsequently affect the gas transport capacity through the actual core sample. Thus, it highlights the urgent need to seriously consider the water storage mechanisms within nanopores. Moreover, during the depressurization development process of ultra-tight gas reservoirs, the stress dependence effect will decrease the pore size and become more obvious with lower formation pressure [36–38]. Notably, the force between gas molecules and the volume of the gas molecules themselves cannot be neglected in the nanoscale pores, and must be taken into account as the real gas effect [39,40]. In summary, gas transport capacity through a single nanopore from ultra-tight gas reservoirs is influenced by bulk-gas transport regimes, water storage mechanisms, stress dependence and real gas effect. After that, the other key physics required to be captured is how to upscale the gas conductance from a single nanopore to a core sample scale, which greatly aggravates the complexity of the issue. To my best knowledge, the practical model considering the aforementioned features for gas transport through actual nanoporous ultra-tight gas reservoirs is still lacking.

A great deal of effort has been devoted to investigate the gas transport behavior through actual nanoporous media [2,6–10,16,17,22–27,32–41,52,56]. However, these proposed models in previous literature generally neglect the presence of water within the

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