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Numerical investigation of gas flow rate in shale gas reservoirs with nanoporous media

Hongqing Song [a,c,*], Mingxu Yu [a], Weiyao Zhu [a], Peng Wu [b], Yu Lou [a], Yuhe Wang [c], John Killough [c]

[a] School of Civil and Environmental Engineering, University of Science and Technology Beijing, Beijing 100083, China
[b] State Development Investment Corp, Beijing 100034, China
[c] Department of Petroleum, Texas A&M University, Texas 77843, USA

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ABSTRACT

Theoretical analysis of transport mechanism of gas flow in shale gas reservoirs with nanoporous media was carried out on the basis of molecular kinetic theory. The motion equation and mathematical model of shale gas transport in multi-scale medium are established in this article. The pressure distribution equation of radial flow was derived, and the computing method of the control area of gas well was presented. Additionally, the volume flow rate equations of vertical and horizontal fractured wells were obtained. Through Newton iterative method, volume flow rate was analyzed, considering various factors such as production pressure drawdown, fracture half-length, fracture conductivity, fracture spacing and diffusion coefficient. According to the numerical results, the volume flow rate of the gas well increases when the diffusion coefficient grows. Consequently diffusion in shale gas reservoirs with nanoporous media plays an important role. With increase of fracture half-length, the volume flow rate increases first and then tends towards stability. Moreover, for certain length of the horizontal wellbore, when fracture spacing increases and the number of the fractures lessens, the control area and the volume flow rate of the gas well decreases. Therefore, there is an optimum allocation among these factors to achieve maximum volume flow.

1. Introduction

With the development of science and technology, more and more attention has been paid to nanoporous [1–3] flow which plays a central role in the field of underground energy development, including shale gas. Shale gas, a kind of unconventional gas resources, which relieves the resources shortage efficiently, has become the hotspot of energy investigation [4–6]. There is a wide range of pore sizes in shale. The kerogen pores are primarily nanoporous and the permeability ranges from tens nD to hundreds nD [7–9]. The measurement of 152 cores from 9 shale reservoirs indicates that the average permeability is about 54nD ($5.43 \times 10^{-20}\,\mathrm{m}^2$) [10]. The ultra-low permeability in shale gas reservoir leads to quite different a flow pattern compared with conventional gas reservoir [11,12]. Consequently, clear gas transport mechanism, motion equation and volume flow rate will contribute a lot to the shale gas reservoir mining.

The present research on fluid flow mainly focuses on millimeter, micron porous media [13–18]. Pore diameters in shale gas reservoirs are mostly between 0.1 and 100 nm. Many researchers use the electron scanning microscope to observe the pore structure in shale [19–21]. In addition, with the help of FIB and SEM technology, Curtis M.E. made a study and comparison of the shale pores from 9 different reservoirs in 2010 [22–24], which provides the theoretical foundation to study the gas flow in nanoporous reservoirs and to establish gas motion equation.

Many researchers distinguish the transport mechanisms in porous media by Knudsen number and then establish gas kinematic equations. Knudsen number refers to the ratio of mean free path of the gas molecules to pore radius [25–27]. According to the Knudsen number, there are four types of gas flow mechanisms. As shown in Fig. 1, when Knudsen number is under 0.01, gas flow is continuum, and Darcy's law and Euler equation are available to describe the flow characteristics. When it ranges from 0.01 to 0.1, gas flow displays slippage effect which is quite different from flow phenomenon of oil, water et cetera. Navier–Stokes equation can be used to represent the gas flow features [28,29]. Klinkenberg discovered slippage phenomenon and studied slippage effect [30]. Subsequently, a lot of researchers study gas slippage effect in

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* Corresponding author at: School of Civil and Environmental Engineering, University of Science and Technology Beijing, Beijing 100083, China. Tel.: +86 10 82376239.

E-mail address: songhongqing@ustb.edu.cn (H. Song).

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Nomenclature

A_{1i}	intersection area between fracture i and fracture $i+1$ in Zone I (m^2)
A_{2i}	intersection area between fracture i and fracture $i+1$ in Zone II (m^2)
d_{pore}	the diameter of porous media (m)
h	reservoir thickness of shale gas (m)
D_{ij}^{e}	effective gas diffusivity of species i in species j (m^2/s)
$D_{i,k}$	Knudsen diffusivity of species i (m^2/s)
D_k	diffusion coefficient (m^2/s)
k	absolute permeability of porous media (m^2)
k_f	absolute permeability in fracture (m^2)
K_n	Knudsen number (λ/r_{pore})
K_B	Boltzmann constant (J/k)
M	gas molecules molar mass (g/mol)
n	number of components present in system
N_i	the molar flux of component i
N_j	the molar flux of component j
p	reference pressure (Pa)
p_e	boundary pressure (Pa)
p_m	pressure at the junction of Zone I and Zone III (Pa)
p_w	buttonhole pressure (Pa)
p_{sc}	standard state pressure (Pa)
Q_{m1}	mass flow rate of Zone I (m^3)
Q_{m2}	mass flow rate of Zone II (m^3)
Q_m	mass flow rate of Zone III (m^3)
Q_{v1}	volume flow rate of Zone I of fractured vertical well (m^3/s)
Q_{v2}	volume flow rate of Zone II of fractured vertical well (m^3/s)
Q_v	volume flow rate of Zone III of fractured vertical well (m^3/s)
Q_{f1}	volume flow rate of Zone I of fractured horizontal well (m^3/s)
Q_{f2}	volume flow rate Zone II of fractured horizontal well (m^3/s)
Q_f	volume flow rate of Zone III of fractured horizontal well (m^3/s)
Q_{fmax}	maximum flow rate of horizontal well

Q_i	intersection area between fracture i and fracture $i+1$ of fractured horizontal well' total flow (m^3/s)
r_c	control radius (m)
r_w	radius of gas well (m)
r_e	boundary radius (m)
r_{pore}	radius of porous media (m)
R	universal gas constant (m^3 Pa/mol k)
S	total control area of fractures
$\widetilde{S}_f$	effective control area of fractures
T_{sc}	temperature in standard of gas reservoir (K)
T	temperature of gas reservoir (K)
v	gas motion velocity (m/s)
w_f	fracture width (m)
x_f	fracture half-length (m)
x_i	component i proportion
x_j	component j proportion
Z_{sc}	gas compressibility factor under standard state (dimensionless)
Z	gas compressibility factor under normal state (dimensionless)

Greek symbols

λ	molecular mean free path (m)
μ	viscosity of the gas (Pa s)
φ	porosity (dimensionless)
ρ_g	gas density (m^3/kg)
ρ_{gsc}	gas density under standard state (m^3/kg)

Subscripts

f	horizontal wells
m	vertical wells (mass)
v	vertical wells (volume)

Operators

Δ	increment
∇	gradient
∂	partial differential

microtubule by means of theoretical analysis, numerical simulation and experimental observation methods [31,32]. When the Knudsen number lies between 0.1 and 10, slippage and diffusion coexist in gas flow. When Knudsen number is over 10, gas flow is treated as Knudsen flow, which could be modeled with Boltzmann equation [33,34]. From the four transport mechanisms we mentioned above, percolation mechanism in nanoporous media involves not only concentration-driven diffusion and pressure-driven convection, but also pressure-driven diffusion. However, the existing shale gas kinematic equation does not take gas diffusion driven by pressure into consideration [11,25,35].

During the gas production process in shale, precise evaluation of volume flow, clear knowledge of effect of various control factors play an important role in mining of shale gas reservoirs. Because of the particularity and complexity of unconventional shale gas reservoirs, there is few research about shale gas volume flow. Mayerhoffer used numerical simulation of explicit fracture networks created in a stimulated reservoir volume (SRV) to model the physics of flow within a fractured shale reservoir [36]. Mattar et al. presented analytical and empirical methods for production data analysis and forecasting [37], according to the power-law exponential model [38]. Cipolla et al. illustrates the impact of gas desorption on production profile and ultimate gas recovery in shale reservoirs by mathematical simulation and the impact of changing closure stress distribution in the fracture network on well volume flow rate and gas recovery [39].

According to molecule kinetic theory and gas transport characteristics in shale gas reservoir with nanoporous, the motion equation and mathematical model of shale gas transport in multi-scale medium are established in this article. Furthermore, pressure distribution formula of radial flow is obtained as well as the calculation method of control region of shale gas well. Volume flow rate equation of fractured well is obtained. In addition, gas well volume flow rate considering main control factors are analyzed. What is done provides the theoretical foundation for efficient shale gas energy mining.

2. Mathematical models for shale gas transport

2.1. The motion equation of shale gas transport

According to molecular kinematic theory, diffusion theory and the four types of gas transport mechanisms in nanoporous media, shale gas pressure-driven transport contains two main parts: gas diffusion and gas convection. The smaller the pressure, the more the gas diffusion. When there is enough pressure, gas diffusion