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Anomalous diffusion performance of multiple fractured horizontal wells in shale gas reservoirs

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ABSTRACT

Shale gas reservoirs are naturally fractured reservoirs which mainly consist of organic matrix and natural fracture system. The disordered distribution of natural fractures results in anomalous diffusion taking place in shale gas reservoirs, and thus the classical Darcy's law is no longer suitable for simulating gas flow under this condition. This paper introduces fractional Darcy's law to establish a novel model for multiple fractured horizontal wells (MFHWs) in shale gas reservoirs with consideration of desorption and anomalous diffusion. As a result the resulting seepage equations are differential equations with fractional calculus. Laplace transform, point source function, numerical discrete method, and Gaussian elimination method are applied to obtain the semi-analytical solution in Laplace space. Duhamel's principle is then applied to consider the effects of the wellbore storage and skin on the pressure responses. Stehfest numerical inversion method is finally used to invert the pressure responses from Laplace space to real space. Type curves of the pressure responses are plotted, and a detailed analysis of the pressure characteristics is presented. The model presented here can be applied to accurately interpret the pressure data of an MFHW in a shale gas reservoir.

1. Introduction

Shale gas reservoirs have recently attracted significant attention because they become enormous sources of hydrocarbon, while extremely low permeability usually results in no natural production capacity in shale gas reservoirs (Javadpour et al., 2007). Currently, multiple fractured horizontal wells (MFHWs) have been proven to be the most successful well type to develop shale gas reservoirs (Wang, 2014).

In general, the interpretation of wellbore-pressure or production data is the best means to obtain the reservoir properties, and thus interest in the development of models for studying pressure behaviors in shale gas reservoirs has grown strikingly. Although a great deal of work has been devoted to the simulations of the pressure behaviors for a shale gas reservoir (Bumb and McKee, 1988; Javadpour et al., 2007; Freeman et al., 2011; Akkutlu and Fathi, 2012; Huang et al., 2015), little attention has been focused on the MFHW in the shale gas reservoir. Ozkan et al. (2011) established a seepage model to study the pressure behaviors of an MFHW in a shale gas reservoir based on the trilinear-flow assumption, while the effects of diffusion and desorption in the matrix were ignored. Guo et al. (2012) presented a well test model for an infinite-conductivity MFHW in a shale gas reservoir, which could consider the effects of diffusion and desorption in the matrix on the pressure behaviors. However, their model is based on the assumption that the hydraulic fractures are perpendicular to the horizontal well and gas flow in the natural fracture system follows the classical Darcy's law, which may not always be the case under actual conditions. Zhao et al. (2013) established a tri-porosity model to study the pressure behaviors of an MFHW in a shale gas reservoir. Nevertheless, the effects of the fracture-azimuth angle and anomalous diffusion in the natural fracture system are neglected. Wang (2014) proposed a seepage model for an MFHW in a shale gas reservoir with considering the effects of multiple mechanisms, especially the effect of the stress-sensitivity permeability. The Darcy's law, however, is also applied to describe the gas flow in the natural fracture system, which may not be always true for the complex natural fracture system. Tian et al. (2014) recently presented a tri-porosity model for an MFHW in a shale gas reservoir with considering the effects of dual diffusion in the matrix,

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Nomenclature

Variables

- C Wellbore storage coefficient, m^3/Pa.
- C_D Dimensionless wellbore storage coefficient.
- c_g Compressibility, Pa^{-1}.
- D Diffusion factor, m^2/s.
- h Reservoir thickness, m.
- k Permeability of natural fracture system without the influence of the anomalous diffusion, See Eq. (4), m^2.
- k_α Permeability of natural fracture system under the influence of the anomalous diffusion, See Eq. (1), $m^2/s^{\alpha-1}$.
- $K_0(x)$ Modified Bessel function of second kind of order zero.
- L_a Reference length, here the average half-length of hydraulic fractures, $L_a = \sum_{i=1}^{m} \frac{L_{fLi}+L_{fRi}}{2m}$, is chosen, m.
- L_{fLi} Length of the left wing of the i th fracture, m.
- L_{fLDi} Dimensionless length of the left wing of the i th fracture.
- ΔL_{fLDi} Dimensionless length of discrete segment in the left wing of the i th fracture.
- L_{fRi} Length of the right wing of the i th fracture, m.
- L_{fRDi} Dimensionless length of the right wing of the i th fracture.
- ΔL_{fRDi} Dimensionless length of discrete segment in the right wing of the i th fracture.
- m Number of hydraulic fractures, integer.
- p Pressure of natural fracture system, Pa.
- p_0 Reference pressure, Pa.
- p_{sc} Pressure at standard condition, Pa.
- q Flow rate from point source, m^3/s.
- q_D Dimensionless flow rate from point source.
- q_f Flow rate per unit length, m^2/s.
- q_{fD} Dimensionless flow rate per unit dimensionless length.
- $q_{fDi,j}$ Dimensionless flow rate per unit dimensionless length of the j th segment in the i th fracture.
- $q_{fi,j}$ Flow rate per unit length of the j th segment in the i th fracture, m^2/s.
- Q_{sc} Total production rate under surface conditions, m^3/s.
- r Radial distance, $r = \sqrt{x^2+y^2}$, m.
- r_D Dimensionless radial distance, $r_D = \sqrt{x_D^2+y_D^2}$.
- R Radius of shale matrix block, m.
- s Laplace transform variable.
- S_f Skin factor.
- t Time, s.
- t_D Dimensionless time.
- T Temperature of shale gas reservoir, K.
- T_{sc} Temperature at standard condition, K.
- v Velocity, m/s.
- V Gas concentration, m^3/m^3.
- V_D Dimensionless gas concentration.
- V_E Gas concentration at equilibrium, m^3/m^3.
- V_{ED} Dimensionless gas concentration at equilibrium.
- V_i Gas concentration at initial condition, m^3/m^3.
- V_L Langmuir volume, m^3/m^3.
- x,y Space coordinates in x,y Cartesian coordinate system, m.
- x_D,y_D Dimensionless space coordinates in x_D,y_D Cartesian coordinate system.
- x_{wi},y_{wi} Space coordinates of the intersection of the i th fracture and the horizontal wellbore, m.
- Δy_i Difference between y_{wi} and y_{wi-1}, $\Delta y_i = y_{wi} - y_{wi-1}$, m.
- $x_{i,j},y_{i,j}$ Space coordinates of the j th end point in the i th fracture, m.
- $x_{Di,j},y_{Di,j}$ Dimensionless space coordinates of the j th end point in the i th fracture.
- $x_{mi,j},y_{mi,j}$ Space coordinates of midpoint of the j th segment in the i th fracture, m.
- $x_{mDi,j},y_{mDi,j}$ Dimensionless space coordinates of midpoint of the j th segment in the i th fracture.
- x_{wDi},y_{wDi},z_{wDi} Dimensionless space coordinates of the intersection of the i th fracture and the horizontal wellbore.
- Z Z-factor of shale gas.
- α Anomalous diffusion exponent.
- ρ Gas density, kg/m^3.
- ρ_{sc} Gas density at standard condition, kg/m^3.
- μ Gas viscosity, Pa•s.
- Φ Porosity, fraction.
- ω Storativity ratio.
- λ Inter-porosity flow coefficient.
- σ Adsorption index.
- θ_i Angle between the i th fracture and the horizontal well, degree.
- ψ Pseudo-pressure of natural fracture system, Pa/s.
- ψ_D Dimensionless pseudo-pressure of natural fracture system.
- ψ_i Pseudo-pressure at initial condition, Pa/s.
- ψ_L Langmuir pseudo-pressure, Pa/s.
- $\Delta\psi_s$ Additional pseudo-pressure drop, Pa/s.
- ψ_{wD} Dimensionless pseudo-pressure in horizontal wellbore with consideration of wellbore storage and skin factor.
- ψ_{wDH} Dimensionless pseudo-pressure in horizontal wellbore without consideration of wellbore storage and skin factor.
- DFP Diffusive flow period.
- ETLFP Early-time linear flow period.
- ITLFP Intermediate-time linear flow period.
- ITPRFP Intermediate-time pseudo-radial flow period.
- LTPRFP Late-time pseudo-radial flow period.
- MFHW Multiple fractured horizontal well.
- PWSP Pure wellbore storage period.

Superscript

- $-$ Laplace space.

Subscript

- D Dimensionless.

whereas, the anomalous diffusion in the natural fracture system is also not considered.

In fact, shale gas reservoirs are naturally fractured reservoirs which mainly consist of organic matrix and natural fracture system. In general, adsorbed gas in the matrix desorbs from the pore surfaces of the matrix, and then diffuses from the matrix to the natural fracture system, and then flows (or diffuses) to the MFHW. Previous studies usually focus on the improvement of the seepage models for accurately describing desorption and diffusion in the matrix, and neglect the development of the seepage models for