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Full Length Article

A new approach to model shale gas production behavior by considering coupled multiple flow mechanisms for multiple fractured horizontal well

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ABSTRACT

Production decline analysis of multiple fractured horizontal wells (MFHW) is crucial for long-term shale gas development. Analytical solutions of production decline model accounting for sorption, diffusion (slip flow and Knudsen diffusion) and non-static (stress-dependent) permeability can precisely predict the long term production behavior, especially for the late time production period. However, little work has simultaneously incorporated all these mechanisms into production decline analysis for shale gas wells. In this work, a new production decline model for MFHW in shale gas reservoirs incorporating multiple flow mechanisms is established. To weaken the strong nonlinearities of seepage mathematical equation caused by combining multiple mechanisms, perturbation technology is employed to establish the point source solution considering stress-dependent permeability of MFHW and little effort has been done on this before. Besides, Laplace transformation, numerical discrete method, Stehfest numerical inversion algorithm and Gaussian elimination method are employed to solve the new model's mathematical problem. Estimated inversion values of reservoir parameters are consistent with the reported data from Barnett shale. Further, comparisons between production behaviors with and without multimechanics flows were made in three flow periods and the production discrepancy increases with continuous depletion, which is attributed that desorption and diffusion is increasingly important as pressure depleting. Finally, the effects of major parameters on production decline curves are analyzed by using the proposed model and it was found that different parameters have their own influence period and sensitivity intensity.

1. Introduction

The conventional natural gas productions are depleting at an alarming rate and the gas production from shale becomes one of the primary energy sources for United State. The shale gas revolution is only possible because of the technology advancements including multistage fracturing and horizontal drilling [1]. Gas production in transient flow regime of multiple fractured horizontal well (MFHW) is known to be extensively elongated because of the ultra-low porosity and permeability of gas shale formation. This extended transient flow period in shale reservoirs makes production decline analysis and prediction become a challenging task, but the detailed knowledge on the production decline will be required for the gas shale production planning.

It is widely reported that the pore characterization of shales is challenging because of the wide spectrum of pore sizes and types within shales [2]. It can be widely classified as two major types according to Warren-Root fractured reservoir model [3]: (1) micro-/mesco-pores within shale matrices serving as gas storage house by adsorption and the gas transport is defined by diffusive flow due to concentration gradient; (2) macropores and/or fractures at which the gas can be stored as compressed free gas and the gas transport is dominant by pressure gradient. As a dual/triple porosity reservoir, the shale fracture will provide the gas pathways with Darcian flow and the mass transport [4]. Because of the multiscale pore structure in shale, the overall gas deliverability of shale falls into a multimechanics flow regime including Darcy flow, Knudson diffusion, slippage flow and sorption [5,6]. In addition to the complex pore structure, the shale formation also involves the stimulated fractures which will provide main fluid flow pathway during both the flowback and production stages. Therefore,

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Nomenclature

B_g	volume factor, dimensionless
C	wellbore storage coefficient, m^3Pa^{-1}
C_D	dimensionless wellbore storage coefficient, dimensionless
C_g	gas compressibility, Pa^{-1}
C_{gi}	gas compressibility at initial condition, Pa^{-1}
D	diffusion coefficient, m^2/s
h	reservoir thickness, m
k_m	permeability of matrix system, m^2
k_{fi}	permeability of fracture system at initial condition, m^2
$I_0(x)$	modified Bessel function of first kind, zero order
$K_0(x)$	modified Bessel function of second kind, zero order
$K_1(x)$	modified Bessel function of second kind, first order
L_{ref}	reference length, m
L_h	length of horizontal well
M	number of hydraulic fractures
M_g	apparent molecular weight of shale gas, kg/kmol
n	molar quantity of shale gas, kmol
p	pressure of fracture system, Pa
p_i	initial pressure of shale gas reservoirs, Pa
p_{sc}	pressure at standard condition, Pa
$\tilde{q}(t)$	surface production rate of the line sink, m^3/s
q^*	mass flow rate per unit reservoir between shale matrix and fracture, $kg/(m^3{\cdot}s)$
q_{ij}	flux density of the jth segment in the ith fracture, $m^3/(s{\cdot}m)$
$\bar{q}_{ij}(s)$	Laplace transformation of q_{ij}
q_{sf}	sandsurface flow rate, m^3/s
$\tilde{q}_D$	dimensionless production rate of the line sink, dimensionless
r	radial radius, m
r_m	radial radius in spherical matrix blocks, m
r_w	well radius of multiple fractured horizontal well, m
r_D	dimensionless radius, dimensionless
R	gas constant, J/(mol·K)
R_m	external radius of matrix block, m
s	variable of Laplace transformation, dimensionless
S	skin factor, dimensionless
t	time, s
t_D	dimensionless time, dimensionless
T	reservoir temperature, K
T_{sc}	temperature at standard condition, K
v	flow velocity of shale gas in fracture system, m/s
V	volumetric gas concentration, sm^3/m^3
V_D	dimensionless gas concentration, dimensionless
V_E	equilibrium volumetric gas concentration, sm^3/m^3
V_i	volumetric gas concentration at initial condition, sm^3/m^3
V_L	Langmuir volume (at standard condition), sm^3/m^3
x, y	x- and y-coordinates, m
y_i	y-coordinate of the intersection of the ith fracture and y-axis, m
L_{fUi}	length of upper wing of ith fracture, m
L_{fLi}	length of lower wing of ith fracture, m
ΔL_{fij}	length of discrete segment (i, j), m
ΔL_{fDij}	dimensionless length of discrete segment (i, j), dimensionless
Z	Z-factor of shale gas, dimensionless
ρ	shale gas density, kg/m^3
ρ_{sc}	shale gas density at standard condition, kg/m^3
ϕ	porosity, dimensionless
μ_g	gas viscosity at current condition, Pa·s
μ_{gi}	gas viscosity at initial condition, Pa·s
σ	adsorption index, dimensionless
β	a parameter related to permeability modulus, $Pa^{-1}{\cdot}s$
ψ	pseudo-pressure, Pa/s
ψ_L	Langmuir pseudo-pressure, Pa/s
ψ_i	pseudo-pressure at initial condition, Pa/s
$\Delta\psi$	pseudo-pressure difference, Pa/s
$\Delta\psi_s$	additional pseudo-pressure drop, Pa/s
ψ_D	dimensionless pseudo-pressure, dimensionless
ω	storativity ratio, dimensionless
λ	interporosity flow coefficient, dimensionless
γ_D	dimensionless permeability modulus, dimensionless

the gas production behavior characterization and prediction is expected to be a multimechanistic flow process. The multimechanistics flow model will be required to define the unique production behavior of shale reservoirs.

The pore structures of natural rocks are known to be fractal and gas flow for real state gas(es) through rocks is very complex [7]. Especially in shale, the properties of single-component diffusion of hydrocarbons in zeolites were known to be a concentration gradient drive diffusive flow [8]. It was proposed by previous researchers that the gas flow in nanopores of shale can be modeled with a diffusive transport regime with a constant diffusion coefficient [9]. A formulation was presented [9] for gas flow in the nanopores of mudrocks based on Knudsen diffusion and slippage flow and pointed out that the contributions of Knudsen diffusion increase as pores become smaller and smaller. The permeability of tight/shale gas reservoir ($k < 0.1$ md) is commonly pressure dependent [10,11]. With consideration of diffusive flow in shale matrices and the stress-sensitivity of fracture system, a dual-mechanism dual-porosity model was established [12] for gas transport in shale reservoirs. However, desorption of shale gas was ignored in the proposed model. It's [13] firstly proved that the desorption phenomenon of shale gas could be described by Langmuir isotherm theory based on experimental data. Other scholars [14–21] also arrived at the similar conclusion that the gas sorption in shale can be described by the Langmuir model.

MFHW has been proved to be the most effective well type and completion technique for the economical shale gas development. Numerical simulator (dusty-gas model) with an adjusted Knudsen diffusion coefficient [22] was used to characterize the flow regimes for tight and shale gas reservoirs, but desorption in matrix and stress-sensitivity of fracture system were ignored. Incorporating gas adsorption, stress dependence, non-Darcy flow and surface diffusion, an integrative model for shale-gas-reservoir simulation was proposed [23]. Meanwhile various semi-analytical models have been proposed to diagnose the pressure and production for MFHW shale wells. Amongst these semi-analytical methods, linear flow model is widely used. Many previous studies [23–32] focused on linear gas flow modeling. These proposed linear models are simple and they can be practically used to identify the linear flow regime. However, these models ignore the fracture interference effect which could be a major decline driving parameter at low reservoir pressures. To overcome the shortcomings of linear models, other researchers [33–36] proposed improved semi-analytical models combining point source function which can obtain transient pressure solution of MFHW easily. Even though these improved models are capable of matching a portion of gas production accurately, some of the