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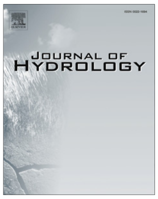

Performance of multiple fractured horizontal wells in shale gas reservoirs with consideration of multiple mechanisms

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SUMMARY

Gas flow in shales is believed to result from a combination of several mechanisms, including desorption, diffusion, viscous flow and the effect of stress-sensitivity of reservoir permeability. However, little work has been done in literature to simultaneously incorporate all these mechanisms in well testing models for shale gas reservoirs. This paper presents a new well testing model for multiple fractured horizontal wells (MFHW) in shale gas reservoirs with consideration of desorption, diffusive flow, viscous flow and stress-sensitivity of reservoir permeability. Comparing with current well testing models for MFHW, the model presented here takes into consideration more mechanisms controlling shale gas flow, which is more in line with the actual reservoir situation. Laplace transformation, point source function, perturbation method, numerical discrete method and Gaussian elimination method are employed to solve the well testing model. The pressure transient responses are then inverted into real time space with Stehfest numerical inversion algorithm. Type curves are plotted, and different flow regimes in shale gas reservoirs are identified. The effects of relevant parameters are analyzed as well. The presented model can be used to interpret pressure data more accurately for shale gas reservoirs and provide more accurate dynamic parameters which are important for efficient reservoir development.

1. Introduction

There are multiple types of pores in shale gas reservoirs. According to Wang et al. (2009), four different types of pores are present in shale gas reservoirs: pores in organic matrix, pores in nonorganic matrix, natural fractures and hydraulic fractures. Organic-matter pores, ranging from a few nanometers to a few micrometers, are especially important because they can adsorb shale gas, as well as store free gas. Compared to the pores in conventional gas reservoirs, for the same pore volume, the exposed surface area in organic-matter pores is larger, thus they can absorb more shale gas.

Generally speaking, pores in shale gas reservoirs can be classified as two major types like Warren–Root model (Warren and Root, 1963): (1) pores in shale matrix whose diameter is very small. Shale gas in this kind of pore space is mainly stored by adsorption, and gas flow is believed to be diffusive flow driven by concentration difference and (2) fracture which is not only storage space for free shale gas, but also connection between different pores. Like conventional gas reservoirs, shale gas flow in fractures is seepage flow driven by pressure difference.

Kucuk and Sawyer (1980) first studied the pressure transient behavior of shale gas reservoirs by using analytical method and numerical simulation method. However, the analytical model presented in their paper did not take into account the effects of desorption and diffusion; the numerical model took into consideration the effect of desorption, but the effect of diffusive flow was still ignored.

Some researchers (Bumb and McKee, 1988; Lane et al., 1989; Gao et al., 1994; Spivey and Semmelbeck, 1995) represented by Bumb and McKee (1988) proved that the desorption behavior of shale gas could be described by Langmuir isotherm theory based on experimental data.

Carlson and Mercer (1991) investigated the behavior of gas flow in shale gas reservoir by coupling conventional dual-porosity model and the effects of desorption and diffusion. However, in this paper the hydraulic fractured vertical well in shale gas reservoirs was treated as a non-fractured vertical well with magnified well radius, thus pressure responses calculated by this model could not reflect characteristic flow regime for fractured wells, such as linear flow regime. In addition, the proposed model did not take into account the stress-sensitivity of natural fracture system.

Ozkan et al. (2010) established a dual-mechanism dual-porosity model for shale gas reservoirs, taking into account the diffusive flow in shale matrix and the stress-sensitivity of natural fracture system. However, desorption of shale gas, which is an important

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Nomenclature

B_g	volume factor, dimensionless
C	wellbore storage coefficient, $m^3\ Pa^{-1}$
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	permeability of natural fracture system, m^2
k_i	permeability of natural 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
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 natural fracture system, Pa
p_i	initial pressure of shale gas reservoirs, Pa
p_{sc}	pressure at standard condition, Pa
$\hat{q}(t)$	surface production rate of the line sink, m^3/s
q^*	mass flow rate per unit reservoir between shale matrix and fracture, $kg/(m^3\ s)$
q_{ij}	flux density of the jth segment in the ith fracture, $m^3/(s\ m)$
$\overline{q_{ij}}(s)$	Laplace transformation of q_{ij}
q_{sc}	constant surface production rate of the multiple fractured horizontal well, m^3/s
q_{sf}	sandsurface flow rate, m^3/s
$\hat{q}_D$	dimensionless production rate of the line sink, dimensionless
r	radial distance, $r = \sqrt{x^2 + y^2}$, m
r_m	radial distance in spherical matrix blocks, m
r_w	well radius of horizontal well, m
r_D	dimensionless radial distance, $r_D = \sqrt{x_D^2 + y_D^2}$, 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 natural 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
Δy_i	difference between y_i and y_{i-1}, $\Delta y_i = y_i - y_{i-1}$
X_{fLi}	length of left wing of ith fracture, m
X_{fRi}	length of right wing of ith fracture, m
$\Delta X_{fi,j}$	length of discrete segment (i,j), m
$\Delta X_{fDi,j}$	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, fraction
μ	gas viscosity, Pa s
μ_i	gas viscosity at initial condition, Pa s
σ	adsorption index, dimensionless
α_j	angle between jth fracture and y-axis, degree
β	a parameter related to permeability modulus, Pa^{-1} 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
Λ	total storage capacity, Pa^{-1}
γ_D	dimensionless permeability modulus, dimensionless

Subscript

D	dimensionless

Superscript

$^{-}$	Laplace transform

source of production in shale gas reservoirs, was ignored in their model.

Freeman (2010) and Cipolla et al. (2010) employed a numerical simulator to study the flow regimes for shale gas reservoirs incorporating the effect of gas desorption, but the diffusive flow in shale matrix and stress-sensitivity of natural fracture system were not taken into account.

Guo et al. (2012) established a well testing model for multi-stage fractured horizontal wells in shale gas reservoirs. In their model, the diffusion and desorption effects were considered, but the stress-sensitivity effect was not considered. The permeability of shale is ultralow, thus the stress-sensitivity of shale gas reservoirs should not be ignored. In addition, in Guo's paper, hydraulic fractures were assumed to be perpendicular to the horizontal well, which is not always true in actual reservoirs because the minimum principal stress may not be parallel to the horizontal well.

Multiple fractured horizontal well is proved to be the most effective well type for the development of shale gas reservoirs, and some work has been done to study the pressure transient dynamics of this kind of well type. Based on linear flow assumption, many researchers (Aboaba and Cheng, 2010; Bello and Watenbargen, 2010; Al-Ahmadi et al., 2010; Brohi et al., 2011; Ozkan et al., 2011) proposed linear flow model, linear composite model or tri-linear flow model to study production from a multiple fractured horizontal well in a shale gas reservoir. These models are easy to solve, however, they did not take into account desorption or diffusive flow which is typical in shale gas reservoirs. In addition, these models can only calculate the pressure responses of certain regime, such as early-time linear-flow regime; they can not reflect the complete pressure dynamics and flow regimes through the production of multiple fractured horizontal wells, such as pseudo-radial flow regime and interference between fractures.

In view of this, this paper presents a semi-analytical model for multiple fractured horizontal wells in shale gas reservoirs which takes into consideration multiple flow mechanisms of shale gas,