Journal of Hydrology 554 (2017) 155–172

Contents lists available at ScienceDirect

Journal of Hydrology

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

Research papers

Nonlinear flow model of multiple fractured horizontal wells with stimulated reservoir volume including the quadratic gradient term

Junjie Ren [a,*], Ping Guo [b]

[a] School of Sciences, Southwest Petroleum University, Chengdu 610500, Sichuan, China
[b] State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu 610500, Sichuan, China

ARTICLE INFO

Article history:
Received 28 May 2017
Received in revised form 27 July 2017
Accepted 5 September 2017
Available online 8 September 2017
This manuscript was handled by P. Kitanidis, Editor-in-Chief, with the assistance of Jean-Raynald de Dreuzy, Associate Editor

Keywords:
Nonlinear model
Multiple fractured horizontal well
Quadratic gradient term
Stimulated reservoir volume
Transient pressure

ABSTRACT

The real fluid flow in porous media is consistent with the mass conservation which can be described by the nonlinear governing equation including the quadratic gradient term (QGT). However, most of the flow models have been established by ignoring the QGT and little work has been conducted to incorporate the QGT into the flow model of the multiple fractured horizontal (MFH) well with stimulated reservoir volume (SRV). This paper first establishes a semi-analytical model of an MFH well with SRV including the QGT. Introducing the transformed pressure and flow-rate function, the nonlinear model of a point source in a composite system including the QGT is linearized. Then the Laplace transform, principle of superposition, numerical discrete method, Gaussian elimination method and Stehfest numerical inversion are employed to establish and solve the seepage model of the MFH well with SRV. Type curves are plotted and the effects of relevant parameters are analyzed. It is found that the nonlinear effect caused by the QGT can increase the flow capacity of fluid flow and influence the transient pressure positively. The relevant parameters not only have an effect on the type curve but also affect the error in the pressure calculated by the conventional linear model. The proposed model, which is consistent with the mass conservation, reflects the nonlinear process of the real fluid flow, and thus it can be used to obtain more accurate transient pressure of an MFH well with SRV.

1. Introduction

The multiple fractured horizontal (MFH) well is considered as the most effective well type for the ultra-low permeability reservoirs to increase production at a low cost. Massive hydraulic fracturing can not only generate a few of highly conductive hydraulic fractures intersected with the horizontal wellbore, but also create an induced fracture network named as stimulated reservoir volume (SRV) (Mayerhofer et al., 2006; Clarkson, 2013; Zhao et al., 2014). The permeability of the SRV is much higher than that of the reservoir formation, and so the existence of the SRV region can significantly improve the well performance (Mayerhofer et al., 2010; Guo et al., 2016).

A great deal of work has been conducted to develop flow models of MFH wells in different reservoir scenarios, but most of them focus on the models without considering the effect of the SRV (Wan, 1999; Wan and Aziz, 2002; Luo et al., 2014; Wang, 2014; Ren and Guo, 2015a,b). Recently, as the massive-hydraulic-fracturing technology is widely applied to develop the ultra-low permeability reservoirs, especially shale gas reservoir, the seepage models of MFH wells with SRV have attracted great attention. The seepage models of MFH wells with SRV fall into three main types (Chen et al., 2015): (1) analytical models, mainly including the tri-linear flow model (Ozkan et al., 2011) and its improved models (Stalgorova and Mattar, 2012; Tian et al., 2014; Zheng et al., 2017), have been successfully used to simulate the early linear flow of MFH wells with SRV, but it cannot capture some flow characteristics such as the radial flow and the interferences between the hydraulic fractures; (2) numerical models with different numerical simulation methods, such as the finite element method (Fan et al., 2015) and boundary element method (Zhao et al., 2016), have been employed to investigate the performance of MFH wells with different shaped SRV. However, time-consuming and the difficult of gridding make numerical models less attractive (Chen et al., 2015); (3) semi-analytical models (Zhao et al., 2014; Jia et al., 2015, 2016; Xu et al., 2015; Guo et al., 2016) not only capture the complete flow characteristics of MFH wells with SRV but also have much higher computational efficiency than numerical models. Therefore, semi-analytical models have recently gained much attention. However, to our knowledge, almost all models of MFH wells with SRV, especially the analytical/semi-analytical models,

* Corresponding author.
E-mail address: renjunjie1900@126.com (J. Ren).

http://dx.doi.org/10.1016/j.jhydrol.2017.09.005
0022-1694/

Nomenclature

Roman symbols

B	volume factor, m^3/m^3
C_f	rock compressibility, Pa^{-1}
C_t	total compressibility, Pa^{-1}
C_{t1f}	total compressibility of the fracture system in the SRV region, Pa^{-1}
C_{t1m}	total compressibility of the matrix system in the SRV region, Pa^{-1}
C_{t2}	total compressibility in the outer region, Pa^{-1}
C_ρ	fluid compressibility, Pa^{-1}
h	formation thickness, m
k	formation permeability, m^2
k_{1f}	fracture-system permeability in the SRV region, m^2
k_{1m}	matrix-system permeability in the SRV region, m^2
k_2	formation permeability in the outer region, m^2
L	horizontal well length, m
L_{fLDi}	dimensionless length of the left wing of the i th hydraulic fracture, dimensionless
L_{fLi}	length of the left wing of the i th hydraulic fracture, m
L_{fRDi}	dimensionless length of the right wing of the i th hydraulic fracture, dimensionless
L_{fRi}	length of the right wing of the i th hydraulic fracture, m
m	fracture number, integer
M_{12}	mobility ratio of the SRV region to the outer region, dimensionless
p	formation pressure, Pa
p_{1f}	fracture-system pressure in the SRV region, Pa
p_{1m}	matrix-system pressure in the SRV region, Pa
p_2	formation pressure in the outer region, Pa
p_i	initial formation pressure, Pa
p_w	wellbore pressure, Pa
p_{wD}	dimensionless wellbore pressure, dimensionless
p_{wDl}	dimensionless wellbore pressure calculated by the linear model, dimensionless
p_{wDnl}	dimensionless wellbore pressure calculated by the nonlinear model, dimensionless
q	flow rate from point source, m^3/s
q_D	dimensionless flow rate from point source, dimensionless
q_D^*	flow-rate function of q_D, defined in Eq. (42)
q_f	flow-rate density, m^2/s
q_{fD}	dimensionless flow-rate density, dimensionless
q_{fD}^*	flow-rate function of q_{fD}, $q_{fD}^* = q_{fD}(\xi_w + 1)$, dimensionless
$q_{fDi,j}$	dimensionless flow-rate density of the j th segment in the i th hydraulic fracture, dimensionless
$q_{fDi,j}^*$	flow-rate function of $q_{fDi,j}$, $q_{fDi,j}^* = q_{fDi,j}(\xi_w + 1)$, dimensionless
$q_{fi,j}$	flow-rate density of the j th segment in the i th hydraulic fracture, m^2/s
Q_{sc}	total production rate under surface conditions, m^3/s
r	radial distance in reservoir formation, $r = \sqrt{x^2 + y^2}$, m
r_m	radial distance in a spherical matrix block, m
r_1	radius of a spherical matrix block, m
r_f	SRV radius, m
s	Laplace transform variable, dimensionless
t	time, s
W_{12}	storability ratio of the SRV region to the outer region, dimensionless
x, y	Cartesian x, y coordinates, m
x_D, y_D	dimensionless Cartesian x, y coordinates, dimensionless
$x_{Di,j}, y_{Di,j}$	dimensionless coordinates of the j th end point in the i th hydraulic fracture, dimensionless
$x_{i,j}, y_{i,j}$	coordinates of the j th end point in the i th hydraulic fracture, m
$x_{mi,j}, y_{mi,j}$	coordinates of midpoint of the j th segment in the i th hydraulic fracture, m
$x_{mDi,j}, y_{mDi,j}$	dimensionless coordinates of midpoint of the j th segment in the i th hydraulic fracture, dimensionless
x_{wDi}, y_{wDi}	dimensionless coordinates of the intersection of the i th hydraulic fracture and the horizontal wellbore, dimensionless
x_{wi}, y_{wi}	coordinates of the intersection of the i th hydraulic fracture and the horizontal wellbore, m

Greek Symbols

α	dimensionless nonlinear flow coefficient, dimensionless
ΔL_{fLDi}	dimensionless discrete-segment length of the left wing of the i th hydraulic fracture, dimensionless
ΔL_{fRDi}	dimensionless discrete-segment length of the right wing of the i th hydraulic fracture, dimensionless
Δy_i	difference between y_{wi} and y_{wi-1}, $\Delta y_i = y_{wi} - y_{wi-1}$, m
δ_p	relative difference between the pressures calculated by the nonlinear and linear models, dimensionless
λ_1	interporosity flow coefficient in the SRV region, dimensionless
μ	fluid viscosity, $Pa \cdot s$
ξ_{1f}	transformed pressure for p_{1fD}, defined in Eq. (28)
ξ_{1m}	transformed pressure for p_{1mD}, defined in Eq. (29)
ξ_2	transformed pressure for p_{2D}, defined in Eq. (30)
ξ_w	transformed pressure for p_{wD}, defined in Eq. (31)
ρ	fluid density, kg/m^3
υ	velocity, m/s
ϕ	formation porosity, fraction
ϕ_{1f}	fracture-system porosity in the SRV region, fraction
ϕ_{1m}	matrix-system porosity in the SRV region, fraction
ϕ_2	formation porosity in the outer region, fraction
ω_{1f}	storability ratio of fracture system in the SRV region, dimensionless

Superscript

$-$	Laplace space

Subscript

D	dimensionless

are established and solved by ignoring the quadratic gradient term (QGT) in the governing equation, which makes the models be inconsistent with material balance and may lead to significant errors in the predicted pressure. Unfortunately, there is no work to investigate the effect of such approximation with ignoring the QGT on the predicted pressure of MFH wells with SRV.

During the last decades, much attention has been paid to the nonlinear flow models with the QGT. Finjord (1986) first introduced a functional transformation to linearize the nonlinear governing equation including the QGT. Chakrabarty et al. (1993) proposed a radial flow model with the QGT to quantitatively analyze the impact of the QGT on the pressure distribution during constant-rate or constant-pressure injection. Bai et al. (1994) developed a flow model for vertical wells in dual-porosity reservoirs including the QGT. Braeuning et al. (1998) investigated a nonlinear model for partially penetrating vertical wells with