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Analyzing the production data of fractured horizontal wells by a linear triple porosity model: Development of analysis equations

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ABSTRACT

Tight reservoirs stimulated by multistage hydraulic fracturing are commonly described by a dual porosity model. This model consists of homogeneous matrix blocks separated by vertical hydraulic fractures. This work hypothesizes that the production data of some fractured horizontal wells may also be described by a triple porosity model. The third medium can be either reactivated natural fractures or thin horizontal beds of higher permeability. We test this hypothesis by extending the existing triple porosity models to develop an analytical procedure to determine the reservoir parameters. We derive simplified equations for different regions of the rate-time plot including linear and bilinear flow regions. These equations can be used to calculate the effective fracture half-length, matrix permeability and length of micro-fractures. We use the proposed model to analyze the production data of two wells drilled in Barnett shale. The results show that a dual porosity model is more appropriate for describing Barnett shale data. Even if the micro-fractures are present they are not inter-connected and the length scale is much smaller than the hydraulic fracture spacing.

1. Introduction

Recent advances in horizontal drilling and multistage hydraulic fracturing have unlocked the tight formations such as shale gas and tight oil. Modeling hydrocarbon flow in these fractured systems is challenging since there is a big contrast between matrix and fracture permeability, and also the flow geometry is different from the conventional reservoirs.

The previous dual porosity models (Warren and Root, 1963; Kazemi, 1969; Carlson and Mercer, 1991) have been extended for analyzing fractured horizontal wells. Bello (2009) applied the linear dual porosity model developed by El-Banbi and Wattenbarger (1998) to do rate transient analysis of fractured shale reservoirs. This model includes slab matrix blocks separated by vertical hydraulic fractures, which can estimate the half length of the hydraulic fractures by history matching of the measured well production data.

However, the induced hydraulic fractures may reactivate possibly existing natural fractures which in turn may result in a complex fracture network (Gale et al., 2007; Dahi-Taleghani, 2009). Under these conditions, the reservoir should be described by a triple porosity model. Mathematical formulations of flow through triple porosity media were first introduced three decades ago (Liu, 1981). Abdassah and Ershaghi (1986) developed a triple porosity model to describe the well test data of fractured reservoirs with a dual matrix structure. Liu et al. (2003) proposed a triple porosity model to describe the well test data of a reservoir which consists of fractures, rock matrices, and cavities. Wu et al. (2004) used the same model to describe flow in a reservoir, which consists of matrices, large fractures, and small fractures.

The linear dual porosity models have been recently extended to account for both hydraulic fractures, and microfractures in horizontal wells. Ozkan et al. (2010) presented a transient dual-porosity model for the inner shale reservoir and extended the previous tri-linear model presented by Brown et al. (2009). The combination of these two models is the first triple porosity model proposed for linear fractured systems. Recently, Al-Ahmadi (2010) extended the dual porosity model of Bello (2009) and presented a triple porosity model for the linear systems. Their fully unsteady state model is essentially similar to the model presented by Ozkan et al. (2010), except they assumed slab matrix blocks whereas Ozkan et al. (2010) assumed spherical matrix blocks to derive the transfer functions. Dehghanpour and Shirdel (2011) extended Ozkan et al. (2010) transient model and presented a triple porosity model for the inner shale reservoir. The combination of this model and the tri-linear model presented by Brown et al. (2009) represents a quadruple porosity model which includes a triple fracture system and one matrix system.

The existing triple porosity models for fractured horizontal wells assume sequential flow. This means that they ignore fluid

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Nomenclature

A_{cm}	total matrix/micro-fracture surface drainage area, ft^2
A_{cw}	well-face cross-sectional area to flow, ft^2
c_t	total compressibility, psi^{-1}
$f_f(s)$	fracture function for matrix-micro-fracture fluid transfer
$f(s)$	fracture function for micro-fracture–macro-fracture fluid transfer
h	matrix block thickness, ft
k_f	permeability of micro-fracture, md
k_F	permeability of macro-fracture, md
k_m	permeability of matrix block, md
$\mathscr{L}^{-1}$	inverse Laplace operator
L_f	micro-fracture spacing, ft
L_F	macro-fracture spacing, ft
m_r	slope of region
$m(pi)$	gas pseudo-pressure at initial conditions, psi^2/cp
$m(pwf)$	gas pseudo-pressure at well-bore, psi^2/cp
n_{fxe}	number of micro-fractures in the direction of well length
n_{fye}	number of macro-fractures in the direction of macro-fracture length
q_{DL}	dimensionless flow rate
q_g	gas rate, MScf/day
s	Laplace space variable
t	time, days
t_{dac}	dimensionless time
T	absolute temperature, °R
x_D	dimensionless distance along micro-fracture spacing
x_e	length of horizontal well, ft
y_{De}	dimensionless length of reservoir
y_e	macro-fracture half length, ft
z_D	dimensionless distance along macro-fracture spacing

Greek symbols

$\varnothing$	porosity, fraction
μ	viscosity of a gas, cp
σ_i	shape factor, $1/ft^2$
ω_i	storativity ratio
λ_{Ac}	dimensionless interporosity flow

Subscripts

f	micro-fracture
F	macro-fracture
m	matrix
i	f, F, and m
r	regions

transfer between matrix and hydraulic fractures. In this work, we test the performance of such models to analyze the production data of two fractured horizontal gas wells. We simplify the triple porosity transfer function, developed by Al-Ahmadi (2010), and develop analytical equations describing the different regions observed on the rate-time plot.

2. Transient triple-porosity model for sequential linear flow

The constant pressure solution for linear fluid flow in fractured reservoirs is given by El-Banbi and Wattenbarger (1998)

$$\frac{1}{q_{Dl}}=\frac{2\pi s}{\sqrt{sf(s)}}\left[\frac{1+e^{-2\sqrt{sf(s)}y_{De}}}{1-e^{-2\sqrt{sf(s)}y_{De}}}\right] \quad (1)$$

where s is the Laplace operator, and $f(s)$ is the interporosity transfer function. Al-Ahmadi derived $f(s)$ for transient linear flow through the triple porosity media schematically demonstrated in Fig. 1.

$$f(s)=\omega_F+\frac{\lambda_{AcFf}}{3s}\sqrt{sf_f(s)}\tanh\sqrt{sf_f(s)} \quad (2)$$

and $f_f(s)$ is given by

$$f_f(s)=\frac{3\omega_f}{\lambda_{AcFf}}+\frac{\lambda_{Acfm}}{s\lambda_{AcFf}}\sqrt{\frac{3s\omega_m}{\lambda_{Acfm}}}\tanh\sqrt{\frac{3s\omega_m}{\lambda_{Acfm}}} \quad (3)$$

The fluid sequentially flows from matrix to micro-fractures, macro-fractures, and finally to the horizontal well. This model is an extension of the transient dual porosity model proposed by Kazemi (1969). The dimensionless variables in Eqs. (1)–(3) are defined as

$$\frac{1}{q_{Dl}}=\frac{k_F\sqrt{A_{cw}}[m(p_i)-m(p_{wf})]}{1422q_gT} \quad (4a)$$

$$t_{dac}=\frac{0.00633k_Ft}{(\varnothing\mu c_t)_tA_{cw}} \quad (4b)$$

$$\lambda_{AcFf}=\frac{12\,k_f}{L_F{}^2k_F}A_{cw} \quad (4c)$$

$$\lambda_{Acfm}=\frac{12\,k_m}{L_f{}^2\,k_F}A_{cw} \quad (4d)$$

$$\omega_i=\frac{(\varnothing\mu c_t)_i}{(\varnothing\mu c_t)_t} \quad (4e)$$

where i=F, f and m.

$$(\varnothing\mu c_t)_t=(\varnothing\mu c_t)_F+(\varnothing\mu c_t)_f+(\varnothing\mu c_t)_m \quad (4f)$$

$$y_{De}=\frac{y}{\sqrt{A_{cw}}} \quad (4g)$$

$$z_D=\frac{z}{L_f/2} \quad (4h)$$

$$x_D=\frac{x}{L_F/2} \quad (4i)$$

3. Triple porosity type curve

The Laplace-space solution of dimensionless flow rate is obtained by substituting Eqs. (2) and (3) in Eq. (1). The Laplace solution can be inverted to time domain by using a numerical method such as Stehfest algorithm (Stehfest, 1970).

Fig. 2 shows an example type curve developed by solving Eq. (1). Six different flow regimes are observed at different time scales. A negative quarter-slope identifies the bi-linear transient flow region and a negative half-slope identifies the linear transient flow region. Region 1 represents the linear flow through the hydraulic fractures. Region 2 represents the bi-linear flow due to simultaneous depletion