Journal of Petroleum Science and Engineering 108 (2013) 52–63

Contents lists available at SciVerse ScienceDirect

Journal of Petroleum Science and Engineering

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

A new rod source model for pressure transient analysis of horizontal wells with positive/negative skin in triple-porosity reservoirs

Haitao Wang*, Liehui Zhang, Jingjing Guo

State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu, Sichuan 610500, China

ARTICLE INFO

Article history:
Received 21 April 2012
Accepted 19 March 2013
Available online 12 June 2013

Keywords:
triple-porosity reservoir
horizontal well
pressure transient analysis
negative skin factor
sphere-surface source
rod source
effective wellbore radius

ABSTRACT

Although the concept of triple-porosity system has been introduced to describe naturally-fractured reservoirs, few models have been reported for horizontal wells in triple-porosity reservoirs; meanwhile, horizontal well is usually considered as a line source in conventional methods for the purpose of pressure transient analysis, but theoretically it is more like a rod source rather than a line source considering the radius of horizontal well. In this paper, the pressure transient behavior is obtained for horizontal wells with non-negligible well radius in triple-porosity reservoirs, which is achieved by utilizing source function method, substituting rod source for line source and sphere-surface source for point source. The concept of effective radius of horizontal wells is introduced after the similarity has been identified by comparing the early-stage flow characteristics of horizontal wells with vertical wells. Based on the concept, a new method is developed to calculate the pressure transient behavior and to plot the type curves for horizontal wells with negative skin factors. This method finally solves the problem of calculating pressure transient behavior of horizontal wells with negative skin factors which cannot be solved by conventional methods in the past 30 years. At last, the comparison of calculated results from both conventional and proposed method is presented in this paper, which indicates that the method proposed in this paper is correct and more applicable than conventional methods.

1. Introduction

Well testing theory for horizontal wells has been studied for 30 years. Various models of pressure transient analysis for horizontal wells were proposed to plot type curves. Also, lots of simplified formulas were derived, which greatly improved the calculation efficiency for the well testing theories to become practical for field applications.

In 1973, Source Function and Green Function were introduced to the petroleum literature by Gringarten and Ramey (1973). Though this method is very powerful in solving 2D and 3D unsteady flow problems as in the case of fractured wells, slanted wells, and horizontal wells, etc., difficulties will be encountered while incorporating the influence of factors like storage, skin effects and variable production rate. After that, to analyze the transient pressure behavior of horizontal wells, several research works were carried on (Clonts and Ramey, 1986; Goode and Thambynayagam, 1987; Daviau et al., 1988).

Ozkan and Raghavan (1991a, 1991b, 1994) proposed a new source function approach to study transient pressure behaviors of horizontal wells in dual-porosity reservoirs. By adopting the method proposed by Ozkan and Raghavan, one can get the solutions in Lapace-transform domain, which makes it easier to incorporate the effects of wellbore storage and skin. This method has been and remains one of the primary solving methods in well testing domain.

In order to better describe natural fractured reservoirs, Abdassah and Ershaghi (1986) proposed the concept of triple-porosity system. In their model, two matrix system which have different properties flow to a single fracture under unsteady state interporosity flow. The signature of a triple-porosity response has been observed by Kabir et al. (2011) in the field, and they found there exist two dips in the derivative signature from a group of buildup test data obtained in October 2003.

Though there are many studies on transient pressure behaviors of vertical wells in triple-porosity reservoirs (Freddy et al., 2004; Yang et al., 2005; Li et al., 2006; Mirshekari et al., 2007; Wang and Zhang, 2008; Zhao et al., 2010; Al-Ghamdi et al., 2011), few studies have been seen on pressure transient analysis of horizontal wells in triple-porosity reservoirs but Alahmadi (2010). Alahmadi (2010) developed a triple-porosity (dual fracture) model for fractured horizontal wells, and the model consists of three contiguous porous media: the matrix, less permeable micro-fractures and more permeable macro-fractures.

In theory, well testing analysis for horizontal wells is more complicated than vertical wells in the triple-porosity reservoir.

* Corresponding author. Tel.: +86 28 830 32052.
E-mail addresses: 907088352@qq.com (H. Wang), zhangliehui@vip.163.com (L. Zhang), jingjing8622@126.com (J. Guo).

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http://dx.doi.org/10.1016/j.petrol.2013.03.005

Nomenclature

B formation volume factor, m^3/m^3
C wellbore storage coefficient, m^3/Pa
C_D dimensionless wellbore storage coefficient defined by well radius r_w [Eq. (5)]
C_{DL} dimensionless wellbore storage coefficient defined by reference length L [Eq. (3)]
C_t total compressibility, Pa^{-1}
dV the volume of fluid instantaneously removed from the sphere-surface source, m^3/s
h reservoir thickness, m
h_D dimensionless reservoir thickness, dimensionless
$\tilde{k}_f$ permeability tensor for the fracture system, m^2
k_{fj} fracture permeability in the j-direction, $j= x, y$, or z, m^2
k_{fh} horizontal permeability of the fracture system, m^2
k_f geometric average permeability of the fracture system defined by Eq. (A-32), m^2
k_m geometric average permeability of the matrix system, m^2
k_v geometric average permeability of the vug system, m^2
L reference length, m
L_D dimensionless horizontal well half length, dimensionless
L_h horizontal well length, m
p pressure, Pa
Δp pressure drop from initial pressure, Pa
p_i initial pressure, Pa
p_D dimensionless pressure of fracture system, dimensionless
p_{wD} dimensionless wellbore pressure without wellbore storage and skin effects, dimensionless
p_{wDH} dimensionless wellbore pressure with wellbore storage and skin effects, dimensionless
Δp_s extra pressure drop, Pa
q^*_{mf} interporosity flow rate from matrix system to fracture system per unit volume of rock, s^{-1}
q^*_{vf} interporosity flow rate from vug system to fracture system per unit volume of rock, s^{-1}
q^*_{mv} interporosity flow rate from matrix system to vug system per unit volume of rock, s^{-1}
$\hat{q}(t_D)$ production rate from the small continuous sphere-surface source, m^3/s
q_{sf} the fluid flux from formation to bottom hole, m^3/s
r_w wellbore radius, m
r_{wD} dimensionless wellbore radius [Eq. (A-33)], dimensionless
r_D dimensionless radial distance, dimensionless
r_{we} effective wellbore radius, m
r_{weD} dimensionless effective wellbore radius [Eq. (8b)], dimensionless
s Laplace transform variable with respect to t_{DL}
S' skin factor defined by the horizontal permeability k_{fh} [Eq. (4)], dimensionless
S skin factor defined by the geometric average permeability $\sqrt{k_{fh}k_{fz}}$ [Eq. (9)], dimensionless
t time, s
t_{DL} dimensionless time defined by the reference length [Eq. (A-11)], dimensionless
t_D dimensionless time defined by the wellbore radius [Eq. (14)], dimensionless
V relative volume with respect to the bulk volume
x distance in the x-direction, m
y distance in the y-direction, m
z distance in the z-direction, m
x_D dimensionless distance in the x-direction, dimensionless
y_D dimensionless distance in the y-direction, dimensionless
z_D dimensionless distance in the z-direction, dimensionless
α_{mf} shape factor between matrix system and fracture system, m^{-2}
α_{vf} shape factor between vug system and fracture system, m^{-2}
α_{mv} shape factor between matrix system and vug system, m^{-2}
ϕ porosity, fraction
μ fluid viscosity, Pa.s
η diffusivity constant, m^2/s
π circular constant, and it is equal to 3.1415926…, dimensionless
ω_f dimensionless fracture storativity [Eq. (A-12a)], dimensionless
ω_m dimensionless matrix storativity [Eq. (A-12b)], dimensionless
ω_v dimensionless vug storativity [Eq. (A-12c)], dimensionless
λ_{mf} dimensionless interporosity flow coefficients between matrix system and fracture system [Eq. (A-13a)], dimensionless
λ_{vf} dimensionless interporosity flow coefficients between vug system and fracture system [Eq. (A-13b)], dimensionless
λ_{mv} dimensionless interporosity flow coefficients between matrix system and vug system [Eq. (A-13c)], dimensionless
δ Dirac function

Subscript

f fracture system
m matrix system
v vug system
D dimensionless
h horizontal

Superscript

— Laplace transform

Operator

$\nabla\cdot$ divergence operator
∇ gradient operator
l Laplace transform operator

Horizontal well is usually simplified as a line source in conventional methods; however, radius of any horizontal well does not equal to zero; therefore it is more appropriate to consider horizontal well with finite radius as a rod source theoretically. In this paper, the source function method is employed and the pressure transient behavior of horizontal wells with non-negligible radius in triple-porosity reservoirs is obtained by substituting rod source for conventional line source and sphere-surface source for conventional point source.

Nowadays, more and more stimulation treatments, such as acidizing and fracturing, have been utilized. The value of the skin factor reflects the effects of treatments, for example, a negative