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Transient pressure analysis of fractured well in bi-zonal gas reservoirs

Yu-Long Zhao *, Lie-Hui Zhang *, Yong-hui Liu, Shu-Yong Hu, Qi-Guo Liu

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

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SUMMARY

For hydraulic fractured well, how to evaluate the properties of fracture and formation are always tough jobs and it is very complex to use the conventional method to do that, especially for partially penetrating fractured well. Although the source function is a very powerful tool to analyze the transient pressure for complex structure well, the corresponding reports on gas reservoir are rare. In this paper, the continuous point source functions in anisotropic reservoirs are derived on the basis of source function theory, Laplace transform method and Duhamel principle. Application of construction method, the continuous point source functions in bi-zonal gas reservoir with closed upper and lower boundaries are obtained. Sequentially, the physical models and transient pressure solutions are developed for fully and partially penetrating fractured vertical wells in this reservoir. Type curves of dimensionless pseudo-pressure and its derivative as function of dimensionless time are plotted as well by numerical inversion algorithm, and the flow periods and sensitive factors are also analyzed. The source functions and solutions of fractured well have both theoretical and practical application in well test interpretation for such gas reservoirs, especial for the well with stimulated reservoir volume around the well in unconventional gas reservoir by massive hydraulic fracturing which always can be described with the composite model.

1. Introduction

Hydraulic fracturing has been proved to be an efficient technique to develop gas reservoirs and enhance gas production rate recently, which has been widely used in tight gas reservoirs. From laboratory experiments and rock mechanics analysis, it has been found that the fracture height is often determined by the existence and position of rock barriers in pay zone, and sometimes these barriers are local scale. If the hydraulic pressure cannot fracture these limited scale hard interlayers, the partially penetrating fractured well will be formed. Furthermore, during the fracturing process, the fracturing fluid pumped into the formation through the tubing with a high pressure always flow into the porous medium surrounding the well as a damaged zone. The damage zone and the outer intact zone can be treated as a radial composite system. Not only that, the fractured radial composite system can also occur naturally. Formation with two different permeabilities and oil and water regions or gas and oil regions with different fluid properties in a reservoir are the examples of naturally occurring. Besides the above, secondary and tertiary recovery projects for oil reservoir and formation produced water reinjection for water carrying gas reservoir can also formed the composite gas reservoir for the different properties of fluid.

Now that the transient pressure analysis is a vital method to analyze the reservoir characteristics (such as permeability and control radius), and also can evaluate the efficiency of the fracturing operation (such as fracture length, radial of damage zone and the well completion skin). With the help of these parameters, reservoir engineers can analyze reservoir performance and forecast future production rate under various modes of operation, which will have a significant effect on the oil/gas recovery. For the edge water drive gas reservoirs, the engineers always care about the distance of the water front to the well. If the water front advances too fast, the field engineers will reduce the production rate because of the water flooded may abandon the gas well. So, it is very important to analyze the transient pressure response of the fractured wells in such bi-zonal gas reservoirs. Although, there are many papers and methods have been published to analyze fluid flow in porous media (Gringarten et al., 1973; Ozkan, 1988; Cheng et al., 2005; Chen and Chau, 2006; Chau, 2007; Taormina et al., 2012), the transient pressure method and type curves are still the most popular methods used in the petroleum engineering.

The source function method has played an important role in well test interpretation for reservoirs with complex geometries (Lord Kelvin, 1881; Carslaw and Jaeger, 1959; Ozkan, 1988). Gringarten et al. (1973) has made further efforts to solve problems

* Corresponding authors.
E-mail addresses: 373104686@qq.com (Y.-L. Zhao), zhangliehui@vip.163.com (L.-H. Zhang).

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Nomenclature

B_g	gas volume factor (sm^3/sm^3)
C	wellbore storage coefficient (cm^3/atm)
C_D	dimensionless wellbore storage coefficient, $C_D = \frac{C}{2\pi h\phi C_{gi} x_f^2}$
C_{ti}	total compressibility for homogeneous reservoir at initial condition (atm^{-1})
C_{ti1}	total compressibility for inner zone at initial condition (atm^{-1})
C_{ti2}	total compressibility for outer zone at initial condition (atm^{-1})
dV	production rate from the point source (cm^3/s)
h	formation thickness (cm)
h_f	fracture height (cm)
h_{fzm}	the mid-point height of the fracture (cm)
k	the equivalent permeability, $k = \sqrt[3]{k_x k_y k_z}$ (D)
$k_x/k_y/k_z$	permeability in the $x/y/z$ directions (D)
k_{r1}, k_{r2}	radial permeability of the inner and outer regions respectively (D)
k_{z1}, k_{z2}	vertical permeability of the inner and outer regions respectively (D)
k_1, k_2	the effective permeability of the inner and outer regions respectively (D)
L_{re}	reference length in system, cm, for fractured well, $L_{re} = x_f$ (fracture half-length)
p	reservoir pressure (atm)
p_{sc}	pressure at standard condition, p_{sc} = 1 atm
$\tilde{q}(t)$	continuous point source strength (cm^3/s)
q_{sc}	the production rate under the standard conditions (cm^3/s)
r	radial in the cylindrical coordinate system (cm)
r_m	the radius of the inner region (cm)
R	radial in the spherical coordinate system (cm)
t	production time (s)
T	reservoir temperature (K)
T_{sc}	temperature in standard condition, T_{sc} = 293 K
s	Laplace transform variable with respect to t_D
S_k	skin factor, $S_k = \frac{\pi k_r h T_{sc}}{p_{sc} q_{sc} T}\Delta\psi_s$
S_c	the instantaneous point source in real space, $S_c = \mathbf{L}^{-1}\left[\frac{e^{-\sqrt{s}R_D}}{4\pi L^3 R_D}\right]$
W_{12}	storability ratio, which defined as $W_{12} = \frac{\phi_1 C_{ti1}}{\phi_2 C_{ti2}}$
$x/y/z$	coordinates (cm)
x', y', z'	the location of the continuous point source (cm)
x_f	half fracture length (cm)
$x_{wD}/y_{wD}/z_{wD}$	the dimensionless coordinates of the source point
Z_g	gas deviation factor (m^3/sm^3)

Greek

μ	gas viscosity at current reservoir pressure p (cp)
μ_{gi}	gas viscosity at initial reservoir pressure and temperature (cp)
$\psi()$	pseudo-pressure, defined in Eq. (4)
$\Delta\psi_1$, $\Delta\psi_2$	the pseudo-pressure difference in region 1 and region 2 respectively, $\Delta\psi_l = \psi_l(p_i) - \psi_l(p),\ l = 1,2$
λ_{rD}	transmissivity ratio between the inner region with the outer region, dimensionless
$\varnothing$	porosity for homogeneous reservoir, fraction
$\varnothing_1$	porosity of inner region for bi-zonal gas reservoir, fraction
$\varnothing_2$	porosity of outer region for bi-zonal gas reservoir, fraction
η_{r1}, η_{r2}	the conductivity of the inner and outer regions respectively (D/(cP atm^{-1}))
η_{rD}	the conductivity ratio of the inner region with the outer region, dimensionless
$\delta(t)$	Dirac delta function
$K_0()$	modified Bessel function of the second kind, zero order
$K_0'()$	the derivative of the Bessel function to radius
$I_0()$	modified Bessel function of the first kind, zero order
$I_0'()$	the derivative of the Bessel function to radius
a, b, u, τ	variables

Subscripts

1	inner region
2	outer region
D	dimensionless
wD	wellbore dimensionless
Δ	differential operator

Superscripts

–	Laplace transform

Operator

$L^{-1}[\ ]$	Laplace inverse transform operator

of transient flow by exploring the use of source functions and Newman product method. In Laplace space, Ozkan (1988) derived the point source solutions for anisotropic oil reservoir in order to obtain pressure distributions for various well configurations, and they also gave some computational considerations and algorithms for the high efficient calculation. In his paper, he only gave the source functions in homogeneous reservoirs and he also did not analyze the performance of fractured well.

Han and Hasebe (2002) reviewed Green's functions for point heat source in various thermoelastic boundary value problems for an infinite plane with an inhomogeneity, which includes external force, displacement and mixed boundaries. Chao et al. (2006) derived the Green's functions of heat conduction and thermo-elastic problems for a three-phase multilayered cylinder for a heat point source. Pan et al. (2007) developed a methodology to obtain the source functions using flow rates and pressure responses obtained from transient pressure tests.

For fractured well in composite reservoir, Chu and Shank (1993) presented a mathematical model for a vertically fractured well with either finite conductivity or uniform flux in a composite system. Chen and Raghavan (1995) developed a model for a fractured well in a composite reservoir, they also addressed computational issues to obtain fine results of $I_n(x) \cdot K_n(x)$. Feng et al. (2009) proposed a seepage flow model for fractured heterogeneous composite reservoir using equivalent flow resistance method. Although, the above scholars had conducted some researches related on the well pressure response in bi-zonal gas reservoir, all of them did not take into account the wellbore storage and skin effect, and another limitation is that their researches did not involve any partially penetrating fractured vertical well model. Using the source function, Zhang et al. (2014a) analyzed the fully and partially penetrating vertical wells in bi-zonal gas reservoir. But in this paper, they just listed the source functions and plotted a set of type curves, and they did not mention how to derive these functions and the pressure response of fractured well. Thereafter, Zhao et al. (2014b) used the line source function to analyze the pressure response of fractured horizontal well in unconventional gas reservoir. Because of they just derived the fully continuous line source