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Transient linear flow analysis of constant-pressure wells with finite conductivity hydraulic fractures in tight/shale reservoirs

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ABSTRACT

Transient linear flow is the dominant flow regime in many multi-fractured horizontal wells completed in very low permeability reservoirs. Therefore, development of reliable methods for analyzing production data from this flow regime is of great value. The common methodology for production analysis of this flow period is use of square-root-time plot in which normalized pressure (or pseudopressure for gas) is plotted vs. square-root-time. This method has been proved to be acceptable for systems with infinite conductivity hydraulic fractures. The square-root-time plots for such systems exhibit a zero intercept.

When analyzing production histories of real examples, we observe cases for which the square-root-time plot exhibits a straight-line trend with a positive intercept. We demonstrate that this behavior can be attributed to systems with finite conductivity hydraulic fractures. For constant-pressure systems with finite conductivity hydraulic fractures, the square-root-time plot methodology overestimates fracture half-length. This has been shown using synthetic examples. To solve this problem, we have developed a new inverse solution methodology which is based on an analytical formulation. We have defined new plotting functions and illustrated that a plot of these functions against each other in the formation linear flow period exhibits a linear trend. From the slope of this plot, the true value of fracture half-length can be estimated. Also, fracture conductivity can be determined from the intercept. The proposed methodology has been verified using synthetic tight oil examples. We have also applied it for several tight gas examples.

We have analyzed production data for two field examples using the conventional square-root-time plot methodology and the new inverse solution methodology. Our analysis reveals that the square-root-time plot methodology considerably overestimates the fracture half-length for these examples.

1. Introduction

Production from tight/ultra-tight reservoirs is increasing with the emergence of advanced hydraulic fracturing technologies. A successful fracturing job is crucial to produce economic rates from these reservoirs. A well-accepted methodology for evaluation of stimulation effectiveness is analysis of production data with the aid of rate transient analysis techniques. These methods are helpful for estimation of the distance of fracture penetration into the reservoir as well as in the generation of production forecasts.

Transient linear flow is often the dominant flow regime in many low permeability reservoirs. This flow regime may be the only available regime for analysis. Consequently, development of reliable methods to estimate stimulation properties from production analysis of this flow regime is quite important.

A common methodology for estimating fracture half-length is the use of square-root-time plots. In these plots, normalized pressure (or pseudopressure for gas) is plotted vs. square-root-time (or pseudotime for gas) which forms a straight-line trend during transient linear flow. From the slope of best-fit line to these data, fracture half-length can be determined, if reservoir permeability is known (Wattenbarger et al., 1998). This technique was originally developed for a system with infinite conductivity hydraulic fracture(s) (ICHF). For a system with finite conductivity hydraulic fracture(s) (FCHF), investigators use the same technique. Although the technique is applicable for production analysis of constant-rate FCHF systems, it introduces considerable error when used for constant-pressure systems with FCHFs. It is noted that in low permeability reservoirs, constant-pressure production is observed more frequently than constant-rate production. Therefore, a reliable technique for analysis of constant-pressure FCHF systems is of great interest.

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Nomenclature

Variables

a	a parameter defined by Eq. (13)
b	intercept term in Eq. (5)
b'	a constant parameter used in Eq. (14)
B	formation volume factor
c	compressibility
C_1	conversion factor
C_2	conversion factor
F_{CD}	dimensionless fracture conductivity
F_g	a parameter used in Eq. (31)
G_p	produced gas
G_{pa}	a parameter defined by Eq. (17)
h	formation thickness
k	permeability
m	pseudopressure
M_{cp}	a parameter defined by Eq. (4)
M_{cr}	a parameter defined by Eq. (3)
M'	a parameter defined by Eq. (31)
N_p	produced oil
p	pressure
p_n	normalized pressure
q	production rate
q_n	normalized rate
r_w	wellbore radius
s	Laplace variable
S_C	convergence skin
S_{FC}	skin due to finite conductivity of fracture
S_o	other skins
S_{wi}	initial water saturation
t	time
t_a	pseudotime
T	temperature
w	fracture width
X_f	fracture half length

Greek symbols

μ	viscosity
ϕ	porosity

Subscripts

g	gas
f	fracture
i	initial
wf	well flow

Superscripts

–	Laplace transform operator

2. Background

For systems with ICHFs producing during transient linear flow, the following equations are used for constant-rate and constant-pressure production, respectively (El-Banbi and Wattenbarger, 1998):

$$p_n = M_{cr}\sqrt{t} \tag{1}$$

$$p_n = M_{cp}\sqrt{t} \tag{2}$$

where p_n is $(p_i\text{-}p_{wf})/q$ (normalized pressure) and parameters M_{cr} and M_{cp} are defined as:

$$M_{cr} = C_1\frac{B}{2hX_f}\sqrt{\frac{\mu}{\pi\phi ck}} \tag{3}$$

$$M_{cp} = C_1\frac{\sqrt{\pi}}{4}\frac{B}{hX_f}\sqrt{\frac{\mu}{\phi ck}} \tag{4}$$

Parameter C_1 is the unit conversion factor which is 70.19 for field units. As seen from Eqs (1) and (2), from the slope of plot of normalized pressure (or pseudopressure) vs. square-root of time (or pseudotime), one can estimate $X_f\sqrt{k}$ and therefore X_f if k is known. Fig. 1 shows an idealized physical model for a hydraulically-fractured horizontal well.

When the plot of normalized pressure vs. square-root-time exhibits positive intercept, it may indicate the presence of low conductivity hydraulic fractures. For constant-rate production from systems with FCHF, the square-root-time plot is parallel to the case of ICHF. In another words, we can use square-root-time plots to estimate fracture half-length for such systems. This has been verified by Agarwal et al. (1979), Raghavan (1993) and

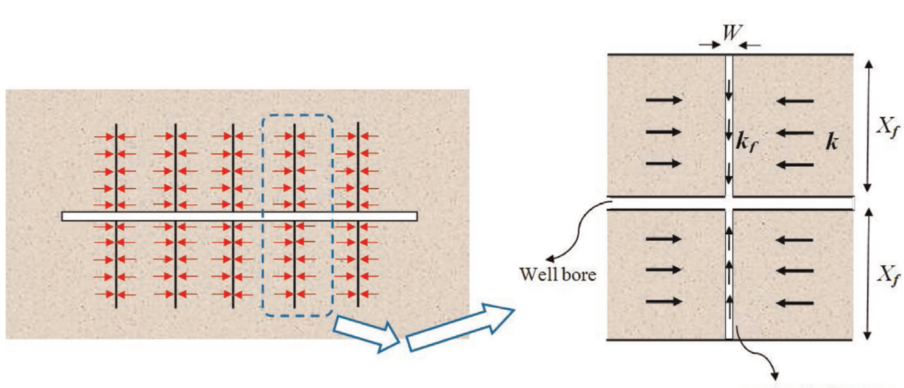

Fig. 1. Top view of an idealized multi-fractured horizontal well with planar, bi-wing, hydraulic fractures. The right hand side picture is magnified representation of one of the fractures.