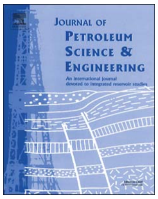
Journal of Petroleum Science and Engineering (xxxx) xxxx–xxxx

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

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



The physical process and pressure-transient analysis considering fractures excessive extension in water injection wells

Yang Wang, Shiqing Cheng*, Naichao Feng, Youwei He, Haiyang Yu

China University of Petroleum, Beijing, China

ARTICLE INFO

Keywords:
Waterflood-induced fracture
Fracture extension
Pressure-transient analysis
Water injection well

ABSTRACT

It is well established within the industry that waterflooding almost takes place in the low permeability reservoir. In order to meet the multiple objectives of pressure maintenance, voidage replacement and sweep optimization, the waterflood-induced fractures can be reactivated when the formation pressure above fracture opening pressure. In general, this is a risky operation, which may lead undesired performance, i.e. pre-matured water breakthrough in producers, steep rise in oilfield overall water-cut profiles, unpredictable flood pattern, poor sweep and so on. However, neither the existed mathematical models nor current commercial softwares could simulate the bottom-hole pressure behaviors of the dynamic process of fractures propagation.

The main objective of the study is to provide a dedicated methodology to analyze the pressure responses considering the dynamic process of the extension of waterflood-induced fractures. First, the physical mechanism of the mini-fractures initiation, communication, and propagation is presented. Next, we define the water injection flow coefficient, whose physical meaning is the characterization of the flow ability from fractures into matrix, with unit of $m/d^{0.5}$. Several mathematical models are put forward to analyze the bottom-hole pressure behaviors considering the complex process of continuous evolution of main and secondary fractures. After that, parameter sensitivity, model comparison and verification are conducted. Finally, we apply the proposed models in a case derived from Changqing oilfield.

Based on the proposed models, the pressure-transient behavoirs of wells with waterflood-induced fractures are obtained and type curves are plotted. The shape of these type curves is studied as a function of different relevant parameters, i.e. water injection volume, fracture area exponent, flow coefficient for main and secondary fractures, fracture surface area, secondary fracture initiation time and so on. It is concluded that the bottom-hole pressure is consisted of two parts: one is the increase of pressure caused by water injection while the other is pressure relief caused by fractures extension. Calculations indicate that the relationship between pressure logarithmic derivative and fractured injection time still meet the linearity approximately in log-log plot even considering fracture extension if constant fracture height is assumed. The slope of the curve is largely controlled by flow coefficient from fracture into matrix and fracture area exponent. Compared with the model of fixed fracture length (in the shut-in moment), the slope of pressure logarithmic derivative of this model proposed is smaller. The initiation of secondary fractures lowers the pressure derivative value. The results show pretty good agreements between our model and the fall-off analysis after shut-in period, with the relative error of 3.6%, which indicates our new models are reasonable.

1. Introduction

Fracturing pressure analysis offers one of the cheapest ways to determine the parameters related to reservoir and fractures (Van den Hoek, 2002, 2003; 2005). Based on the different stages of fracture evolution, the fracturing pressure analysis can be reduced to three distinct types of analysis (Benelkadi and Tiab, 2004): fracturing pressure analysis for injection period, closing period and closed period.

Until now, vast amount of work has been conducted in the fracture closing period and closed period in Mini-Frac Test analysis (Van den Hoek, 2002, 2003; Soliman et al., 2009; Marongiu-Porcu et al., 2011; Liu, 2015, 2016a, 2016b). The pioneer contributor to the pressure falloff analysis is Nolte (1979, 1986, 1988), who introduced a methodology to determine the key parameters in fracture calibration test. Meyerhofer and Economides (1993, 1997) and Mayerhofer et al. (1995) provided a before-closure straight-line technique for determi-

---

* Corresponding author.
E-mail address: chengsq973@163.com (S. Cheng).

http://dx.doi.org/10.1016/j.petrol.2017.01.006
Received 3 July 2016; Received in revised form 8 November 2016; Accepted 4 January 2017

Please cite this article as: Wang, Y., Journal of Petroleum Science and Engineering (2017), http://dx.doi.org/10.1016/j.petrol.2017.01.006

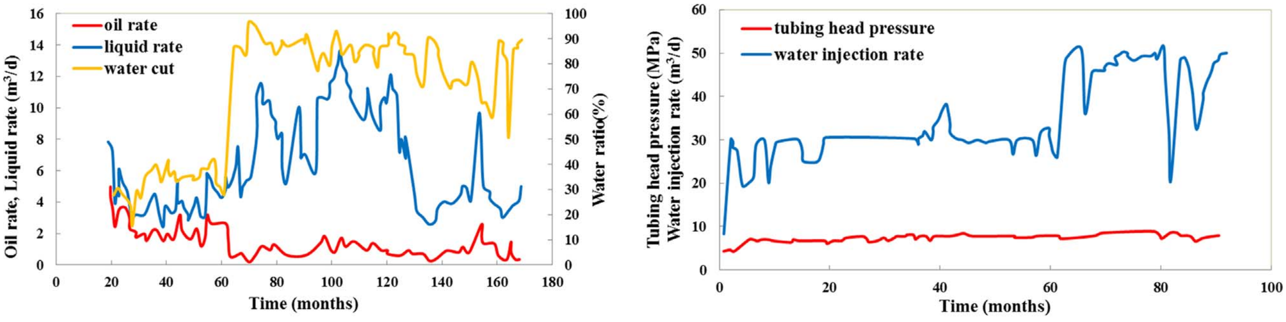
Nomenclature

A	fracture surface area, m^2
A_f	fracture surface area at the end of injection, m^2
A_{fb}	surface area of secondary fracture at the end of injection, m^2
A_{fm}	surface area of main fracture at the end of injection, m^2
A_1	surface area of main fracture, m^2
A_2	surface area of secondary fracture, m^2
c_f	fracture compliance, m/MPa
C_L	water flow coefficient, $m/d^{0.5}$
C_{Lb}	water flow coefficient of secondary fracture, $m/d^{0.5}$
C_{Lm}	water flow coefficient of main fracture, $m/d^{0.5}$
C_{L2}	equivalent flow coefficient, $m/d^{0.5}$
E	plane strain modulus, MPa
h_f	fracture height, m
k	reservoir permeability, 10^{-3} μm^2
k_f	fracture permeability, 10^{-3} μm^2
L	fracture length, m
p_b	fracture opening pressure of secondary fracture, MPa
p_i	initial reservoir pressure, MPa
p_{net}	net pressure on fracture face, MPa
p_{open}	opening pressure of mini-fracture, MPa
p_{tip}	fracture extension pressure, MPa
p_w	bottom-hole pressure, MPa
q	water injection rate, m^3/d
q_i	constant flow rate into fracture, m^3/d
q_l	water flow rate from fracture into matrix, m^3/d
r_1, r_2, r_3	radius of inner region, m
r_p	ratio of permeable fracture surface area to the gross fracture area, dimensionless
R_f	fracture radius in radius fracture model, m
t	fractured injection time, d
t_b	time when secondary fracture initiates, d
t_{open}	time when main fracture initiates, d
t_p	fractured injection time at the end of injection, d
t_{shutin}	shut-in time, d
x_f	fracture half-length, m
v	flow rate from fracture into matrix, m/d
V_l	flow volume from fracture into matrix, m^3
V_{lb}	flow volume from secondary fractures into matrix, m^3
$V_{l\ m}$	flow volume from main fracture into matrix, m^3
V_s	flow from injection well directly to matrix, m^3
$\overline{w}$	fracture width, m
x, y	coordinate, dimensionless
x_{f1}, x_{f2}, x_{f3}	fracture half length, m
Δt	time interval, d
Δt_D	dimensionless fracture injection time, dimensionless
α	area exponent, dimensionless
α_1	area exponent of main fracture, dimensionless
α_2	area exponent of secondary fracture, dimensionless
$\sigma_{resistant}$	confining stress on the fracture face, MPa
ξ	variable of integration, dimensionless
μ	viscosity of water, mPa·s
η	diffusivity coefficient, 10^{-3} μm^2·MPa/mPa·s
c	coefficient which control the increase rate of flow coefficient, dimensionless
i	time node, dimensionless
τ	the time when the fracture area was created, h

nation of reservoir permeability and fracture face resistance. But the proposed techniques to calculate the leakoff rates require information not realistically available. Barree et al. (2009) introduced an empirical relationship for reservoir permeability derived from numerical simulations. However, the relation between reservoir permeability and leakoff coefficient is not obvious, which limits the use of this method. Gu et al. (1993) proposed a method to determine reservoir permeability by impulse-fracture test. However, since the test time is short, the radius of investigation is rather smaller than conventional well testing. Soliman et al. (2004); Soliman and Kabir (2012) included the change in flow rate into inner boundary condition, and solved the drawdown-buildup problem. He found that a plot of pressure change versus time yields a straight line whose intercept on the y-axis is a function of reservoir permeability while the slope of the curve is a function of flow regime. Unfortunately, the methods above are both require much longer shut-in time compared with fractured injection period.

As for the few work related to the fractured injection period, Hall (1963), Daniel (1976) and Ojukwu (2004) presented a system of analyzing the performance of injection wells known as Hall Plots. However, its only use is for recognizing any formation damage or fracturing as evident by the accompanying drop or increase in injectivity, which can be shown in the slope of the curve. Izgec and Kabir (2007) proposed a reformulated Hall analysis to diagnosis the injection well's performance. They conclude that no separation between Hall integral and the derivative curve occurs for matrix injection while fracturing is indicated by downward separation between the two curves. On the whole, the current analysis method on fractured injection period, they did not consider the influence of fractures in the main equation, but meets radial fluid flow and qualitatively diagnose whether fracturing occur. In other words, they did not grasp the actual mechanism of fractures evolution.

All above methods mainly aimed at Mini-Frac, which is generally performed prior to the main hydraulic treatment in order to determine critical parameters required for the stimulation design (Marongiu-Porcu 2011). As for waterflooding, the water injectors are usually at high rates in order to meet the multiple objectives of pressure



(a) W21-08 Production Well (b) W20-06 Injection Well

Fig. 1. Production performance curves in oil and water well (Xie et al., 2015) (a) W21-08 Production Well (b) W20-06 Injection Well.