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Pseudo-steady state analysis in fractured tight oil reservoirs

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ABSTRACT

The log–log plots of normalized rate versus material balance time of two fractured horizontal wells completed in the Cardium and Bakken formations show three distinct regions of quarter, half and unit slopes. The first two regions can be interpreted by the existing semi-analytical models for bi-linear and linear transient flow. This study develops a pseudo-steady state (PSS) model for linear dual porosity reservoirs that describes the third region (unit slope). The application of this PSS model on field production data from two tight oil wells yields reasonable estimates of hydraulic fracture half-length and average matrix permeability. Also, this paper demonstrates how the proposed PSS analysis complements the transient linear analysis commonly used in industry.

1. Introduction

Unconventional (tight oil, tight gas, shale gas and coal-bed methane) resources have emerged as important sources of energy supply in the United States and Canada (Franz and Jochen, 2005). These resources have low matrix permeability and require large reservoir contact area per well to achieve economic production (Ning et al., 1993). A combination of horizontal drilling and hydraulic fracturing stimulation provides the required reservoir contact area to justify economic production from these tight reservoirs (Wang et al., 2008; Medeiros et al., 2010).

In contrast to conventional vertical wells, fractured horizontal wells demonstrate a complex rate and pressure transient behavior. Analyzing the production data of various fractured tight reservoirs indicates the development of extended linear flow regimes. Linear flow may occur when a square geometry reservoir drains into hydraulic fractures or a tight layer drains into a high permeability layer (Wattenbarger, 2007; Bello and Wattenbarger, 2010; Clarkson and Pedersen, 2010; Al-Ahmadi et al., 2010).

El-Banbi (1998) presented a linear dual porosity model to describe flow in various naturally and artificially fractured reservoirs. Bello (2009) extended this linear dual porosity model to describe gas depletion in hydraulically fractured shale gas reservoirs. He identified five possible flow regimes, and developed approximate analytical solutions for the transient linear and bi-linear regions, excluding the fifth pseudo-steady depletion region. Similar models have been developed to describe transient flow through more complicated systems composed of hydraulic fractures, reactivated natural fractures and matrix blocks (Ozkan et al., 2010; Al-Ahmadi, Wattenbarger, 2011; Dehghanpour and Shirdel, 2011; Ali et al., 2013).

Although linear transient flow regime is dominant in most of the multifractured horizontal wells, recent studies indicate the occurrence of a pseudo-steady state (PSS) flow regime after late linear transient region (Clarkson and Pedersen, 2010, 2011;Kabir et al., 2011; Samandarli et al., 2011; Song et al., 2011). During PSS (boundary dominated) flow, virtual no-flow boundaries develop between adjacent hydraulic fractures and the average pressure in the stimulated reservoir volume drops with time at a constant rate. However, due to the existence of possible fluid influx beyond the fracture tip, the change in pressure is not quite linear with time. As a result the derivative plot may show a slope which is slightly less than one (Samandarli et al., 2012).

Most of the existing analytical models capture the transient regions (Bello and Wattenbarger, 2010; Ali et al., 2013) and there is a need for an approximate analytical model for quick analysis of PSS data observed in hydraulically fractured tight oil reservoirs. In this paper, we combine the continuity and linear diffusivity equations and arrive at a linear relationship between rate normalized pressure (RNP) and material balance time (MBT) for the flow region 5 from the linear dual porosity model (Bello, 2009). This paper applies the linear relationship to analyze the PSS data of two fractured horizontal wells completed in Cardium and Bakken Formations. Also, it shows how the combined analysis of production data related to linear transient and pseudo steady state regions gives reasonable estimates of average matrix permeability and fracture half length.

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Nomenclature

A_{cw}	well-face cross-sectional area to flow, m^2
B	formation volume factor, $m^3/s\ m^3$
c	compressibility of rock, kpa^{-1}
h	reservoir thickness, m
k	permeability, m^2
L_f	fracture spacing, m
N_p	cumulative oil production, STB
N_f	number of fractures
P	pressure, kPa
q_o	oil rate produced from one fracture, m^3/s
Q_o	daily oil rate, STB/day
MBT	material balance time, day
V_m	matrix control volume, m^3
X_e	length of horizontal well, m
y_e	fracture half-length, m
φ	porosity
ρ	density, kg/m^3
μ	viscosity, cP

Subscript

i	initial
m	matrix
f	fracture
o	oil
wf	bottom-hole flowing
t	total
r	rock

2. Field data

Figs. 1 and 2 show the log–log plot of normalized rate versus material balance time for two tight oil wells completed in Cardium and Bakken formations. The data show three distinct flow regions. Region 1 with an approximate negative quarter slope represents bi-linear transient flow (Xu et al., 2012; Bello, 2009). Region 2, with a negative half slope, represents linear transient flow, and is the dominant flow regime. Although material balance time successfully eliminates the effect of variable-rate production on field data (Medeiros et al., 2010), its application for analyzing transient flow regimes has not been proved mathematically. However, it has been shown recently (Samandarli et al., 2012) that bi-linear and linear transient regions keep their characteristic slopes when plotted versus material balance time (as shown in Figs. 1 and 2).

This paper focuses on Region 3 (negative unit slope). Based on previous works (Song et al., 2011; Clarkson and Pedersen, 2011; Song and Ehlig-Economides, 2011; Samandarli et al., 2012), we hypothesize that this region represents PSS flow due to the pressure interference between the consecutive hydraulic fractures, and insufficient fluid influx from the formation beyond the fracture tip.

3. Model geometry and assumptions

Fig. 3 and 4 shows the conceptual linear dual porosity model which comprises hydraulic fractures and matrix blocks. The key assumptions include (i) equally spaced hydraulic fractures, (ii) which are perpendicular to the horizontal well, (iii) this well is located at the center of rectangular drainage area, (iv) simultaneous occurrence of pressure interference at the center of all matrix blocks, (v) single phase flow perpendicular to fractures (vi) negligible flow from matrix to well, (vii) negligible stress, temperature and secondary fracture effects on reservoir depletion.

4. Mathematical solution

The PSS model for analyzing flow region 5 from linear dual porosity model (Bello, 2009) is derived by combining material balance and linear diffusivity equations. The control volume (V_m) shown in Fig. 5, represents a fraction of reservoir volume feeding one fracture. When the pressure interference occurs between adjacent fractures, the no-flow boundaries appear at the distance of $L_f/2$ from the fracture faces (Song et al., 2011), where L_f is the fracture spacing. Applying mass balance on V_m, the change in

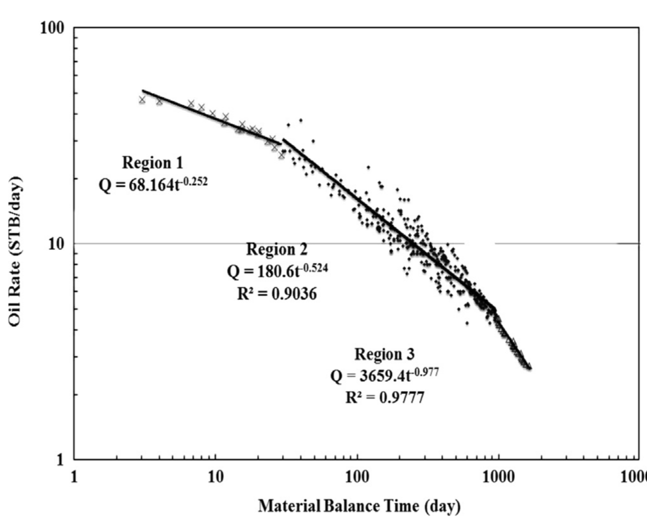

Fig. 1. Log–log plot of daily normalised oil rate versus material balance time for Cardium well (flow regions are based on constant pressure draw-down assumption).

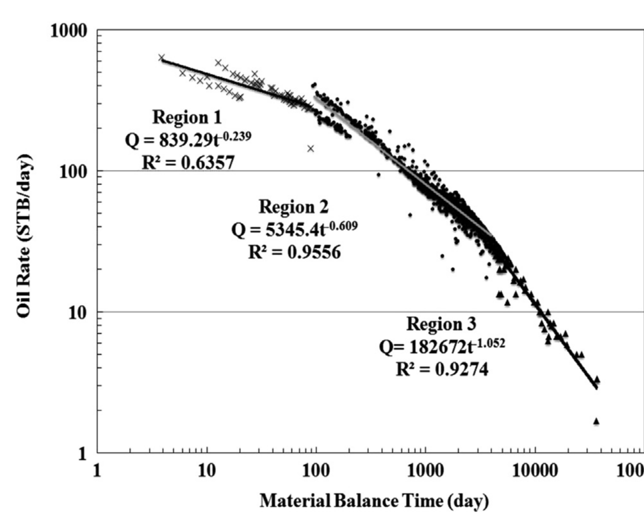

Fig. 2. Log–log plot of daily normalised oil rate versus material balance time for Bakken well (flow regions are based on constant pressure draw-down assumption).