Journal of Petroleum Science and Engineering 143 (2016) 26–34

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

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

A direct method for property estimation from analysis of infinite acting production in shale/tight gas reservoirs

M. Heidari Sureshjani [a,*], H. Behmanesh [b], M. Soroush [b], C.R. Clarkson [b]

[a] IOR Research Institute, Iran
[b] University of Calgary, Alberta

A R T I C L E I N F O

Article history:
Received 26 April 2015
Received in revised form
18 January 2016
Accepted 14 February 2016
Available online 20 February 2016

Keywords:
Shale gas
Linear flow
Production data
Hydraulic fracture

A B S T R A C T

Infinite acting linear flow is a dominant flow regime in many multi-fractured horizontal wells completed in shale/tight gas reservoirs. A well-accepted methodology for analysis of this flow regime in systems without aquifer influence is the square-root of time plot. For reservoirs producing single phase oil, fracture half-length can be estimated from the slope of this plot, provided reservoir permeability is known. However, for gas reservoirs, pseudovariables are required to account for the pressure-dependence of gas properties. For example, the pseudotime function must be used to account for the strong dependence of gas viscosity and compressibility on pressure. As has been previously noted, for tight reservoirs, the pseudotime function must be evaluated at average pressure in the region of influence, which in turn is calculated from the material balance equation. Therefore, the linear flow equation should be coupled with the material balance equation so that fracture half-length can be estimated. This solution methodology is implicit and may require iterative procedures.

This paper introduces an explicit solution methodology for estimating fracture half-length. As in the case of implicit solution methodology, the assumptions of no aquifer influence and infinite acting flow are considered. Because of no aquifer support, we can use material balance equation of volumetric reservoirs. We propose an appropriate correlation between viscosity–compressibility product and the material balance equation. This correlation helps to simplify pseudotime calculations and remove the implicit and iterative nature of the previous solution methodology. Accordingly, we have developed simple semi-analytic solutions that provide a methodology for direct estimation of fracture half-length. The solutions were developed for constant rate, constant pressure, and variable pressure/rate production from wells. We used numerical simulation to generate many synthetic production examples with wide ranges in reservoir properties to validate the introduced equations. We further used our approach for analysis of field cases (multi-fractured horizontal wells completed in shale reservoirs) to demonstrate its practical applicability to real data.

1. Introduction

With the development of advanced hydraulic fracturing technologies, shale/tight gas reservoirs have become a viable source of energy. In recent years, numerous horizontal wells with multiple hydraulic fractures have been drilled in these formations. Stimulation effectiveness is the key to produce economic rates from these plays. Therefore, the knowledge of stimulation parameters such as fracture half-length is of great value. These parameters can be also used to forecast the well production. A well-accepted methodology for deriving stimulation parameters and production forecast is production data analysis on the basis of appropriate models.

In 1944, Arps (1945) presented empirical correlations for production analysis which are exponential, hyperbolic, and harmonic. Later, Fetkovich (1980) extended Arps decline relations in type curve format using new dimensionless rate and time functions. Blasingame and Lee (1986, 1988) introduced the concept of material balance time and material balance pseudotime for oil and gas reservoirs to account for variable well rate/pressure data. Since then, type curves (e.g. Blasingame type curves) and also type-curveless methods (Agarwal et al., 1999) were published. Because transient linear flow is the dominant flow regime in many shale/tight gas reservoirs and may last for several years, recently many researchers have focused on analyzing production data of transient linear flow period. The full pressure transient solutions including the linear flow approximations for vertically fractured wells were reported by Prats et al. (1962) for the constant-rate and constant-pressure inner-boundary conditions. Gringarten et al.

* Corresponding author.
E-mail address: m.heidari.su@gmail.com (M. Heidari Sureshjani).

http://dx.doi.org/10.1016/j.petrol.2016.02.007
0920-4105/

Nomenclature

Variables

A	a parameter defined by Eq. (10)
A'	a parameter defined by Eq. (18)
b	intercept term in Eq. (12)
B	formation volume factor
c	compressibility
C	conversion factor
G_p	produced gas
G	gas in place
h	formation thickness
k	permeability
k_{eff}	effective permeability
m	pseudopressure
m_n	normalized pseudopressure
M_{cp}	a parameter defined by Eq. (6)
M_{cr}	a parameter defined by Eq. (4)
M'	slope of the plot of m_n versus t_{LST}
p	pressure
q	production rate
S_{wi}	initial water saturation
t	time
t_a	pseudotime
t_{LST}	linear superposition time
t_{LSTa}	pseudo linear superposition time
X_f	fracture half length
X_e	reservoir length in fracture direction
Y_e	reservoir length perpendicular to fracture
z	deviation factor

Greek symbols

α	coefficient of distance of investigation
μ	viscosity
ϕ	porosity

Subscripts

g	gas
f	fracture
i	initial
l	last production data
m	mean
w	water
wf	well flow

(1972) further presented more compact solutions for constant-rate infinite-conductivity vertically fractured wells. For multi-fractured horizontal wells, Brown et al. (2011), Stalgorova and Mattar (2013), and Heidari Sureshjani and Clarkson (2015a) have reported full pressure transient analytical solutions. If there is no pressure interference between adjacent hydraulic fractures, a single fracture model can be used to model infinite acting linear flow and estimate stimulation properties. The square-root-time plot is commonly used for production analysis of transient linear flow in shale/tight reservoirs. There are, however, modified methods for special cases (Heidari Sureshjani and Clarkson, 2015b). The square-root-time plot may result in overestimation of fracture half-length in gas reservoirs (Ibrahim and Wattenbarger 2006a, 2006b). Use of pseudovariables in the plot can improve the analysis; however, for tight reservoirs, pseudotime should be evaluated at average pressure in the region of influence, as discussed by Anderson and Mattar (2007). Nobakht and Clarkson (2012a, 2012b) applied this approach to transient linear flow in tight/shale gas reservoirs. In their approach, material balance equation is coupled with the transient linear flow equation to implicitly estimate average pressure so that pseudotime can be calculated. This requires an iterative procedure.

In the present work, we introduce simple flow equations applicable for transient linear flow so that fracture half-length can be directly estimated. Using these equations, the need for iteration is removed and the implicit nature of the calculations is eliminated. We have validated the proposed solutions against synthetic numerical examples across a range of reservoir and fluid parameters. We further applied the proposed solutions for production analysis of two field examples and demonstrated their applicability.

The structure of this paper is as follow. First, a background for linear flow analysis in hydraulically fractured wells in presented. Next, semi-analytic solutions for direct property estimation are developed for constant-rate, constant-pressure, and variable rate/pressure cases. In the subsequent section, the solutions are verified using synthetic numerical examples. Finally, field examples are practiced to demonstrate the applicability of proposed solutions.

2. Background

Problems of fluid flow in gas reservoirs are commonly solved using solutions based on those developed for liquids. This is possible through the use of special functions such as pseudopressure and pseudotime which are used instead of pressure and time, respectively. These pseudovariables are designed to account for the pressure-dependent properties of the fluid (gas), which are not considered in the solutions for liquids. Pseudopressure was first introduced by Al-Hussainy et al. (1966) and pseudotime was later introduced by Agarwal (1979):

$$m = \frac{\mu_i z_i}{p_i}\int_{p_0}^{p}\frac{p}{\mu z}\,dp \tag{1}$$

$$t_a = \int_0^t \frac{\mu_i c_{gi}}{\mu c_g}\,dt \tag{2}$$

where m is pseudopressure and t_a is pseudotime. The transient linear flow solutions are reported by El-Banbi and Wattenbarger (1998) for both constant rate and constant pressure production. The solution for constant-rate gas wells during infinite acting flow period is expressed as

$$m_n = M_{cr}\sqrt{t_a} \tag{3}$$

$$M_{cr} = C\frac{B_{gi}}{2hX_f}\sqrt{\frac{\mu_{gi}}{\pi\phi c_{gi}k}} \tag{4}$$

where m_n is normalized pseudopressure, which is $(m_i - m_{wf})/q$. For the constant flowing pressure condition the solution is

$$m_n = M_{cp}\sqrt{t_a} \tag{5}$$

$$M_{cp} = C\frac{\sqrt{\pi}}{4}\frac{B_{gi}}{hX_f}\sqrt{\frac{\mu_{gi}}{\phi c_{gi}k}} \tag{6}$$

Parameter C is the unit conversion factor, which is 12.5 for field