Journal of Petroleum Science and Engineering 137 (2016) 250–257

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

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

Modified analytical equations of recovery factor for radial flow systems

He Zhang [a,*], Kegang Ling [b], Guoqing Han [c]

[a] Ryder Scott Company, United States
[b] University of North Dakota, United States
[c] China University of Petroleum, China

ARTICLE INFO

Article history:
Received 30 April 2015
Received in revised form
24 September 2015
Accepted 30 November 2015
Available online 2 December 2015

Keywords:
Radial water flooding
Volumetric reserve evaluation

ABSTRACT

Buckley–Leverett displacement equations have been derived strictly from linear flow systems, and have been verified by linear flow experiments only. This paper presents analytical algorithms to calculate recovery factors for radial flow systems, which is expected to be more accurate for peripheral water-flooding reservoirs.

The proposed equations have been verified with field data. The original Buckley–Leverett equation generally results in much lower recovery factors that barely match the well cumulative production at interest. Consequently, the estimated ultimate recovery (EUR) by volumetric methods tends to be low. As a result, the production projection according to volumetric EUR is not reasonable in comparing to the historical performance. The proposed analytical model improves the prediction of reservoir performance.
© 2015 Elsevier B.V. All rights reserved.

1. Introduction

The volumetric method is one of the most important methods used for reserve estimation when combined with the waterflood frontal advance equation from Buckley–Leverett (1942) to calculate recovery factor. Welge (1952) proposed a tangent construction method to supplement Buckley–Leverett to estimate the water saturation, water fraction at the water front, and recovery factor. Stiles (1949) investigated multilayer-reservoir displacements assuming the displacement velocity in a layer to be proportional to its absolute permeability. Dykstra and Parsons (1950) developed a multi-permeability model for non-communicating layers without cross-flow. Hearn (1971) derived expressions for communicating stratified reservoirs using the pseudo-relative permeability functions. Smith (1992) analyzed the impact on fractal flow and frontal displacement under various mechanisms of pressure support, gas saturation control, mixed phase flow, errors, and voidage calculations. El-Khatib (1999a, 1999b) advanced the closed-form analytical solution for communicating stratified systems with log-normal permeability distributions. Aziz (2011) performed a study to investigate the impact of wettability alternation on recovery factor. Fassihi et al. (1997) presented a study on the improved recovery by air injection, and asserted the produced-gas analysis can be used to estimate NGL capture efficiency. Research pioneers have improved the methodology to estimate the performance for waterflooded reservoirs, and numerous textbooks (Green and Willhite, 1998, 1986; Lake, 1994, 2007) have summarized and highlighted those methods.

Since 1950's, industry has tried various water injection patterns whose displacements are non-linear. Kimbler and Caudle (1964) and Watson et al. (1964) have investigated nine-spot injection pattern. Caudle et al. (1968) studied four-spot injection pattern. Recently, Jones et al. (1997) performed sensitivity analysis on the waterflooding patterns in a giant carbonate oil reservoir in North Kuwait by numerical simulation. El-Khatib (1999) developed a new mathematical model for waterflooding performance calculation in five-spot pattern reservoirs. Zakirov et al. (2012) developed an approach for pattern optimization of water injection and applied it in a viscous oil field. Besides those cited works, many papers have discussed various waterflooding in non-linear patterns. However, to the best of our knowledge, all these practices are based on the linear displacement theory. Undoubtedly, the Buckley–Leverett method has been well recognized and successfully verified by experiments conducted in linear displacement systems, but this method has also shown major limitations in predicting the performance of multiple water injectors drilled to enhance oil recovery around the producers, especially for mature fields. The modified analytical equations proposed herein address radial flow patterns to more appropriately model these operations.

This paper presents a modified set of equations to calculate the waterflood frontal advance for peripheral waterflooding systems, which uses parallel derivation approaches of Buckley–Leverett method. This modified radial displacement model generally provides higher recovery factors and supplements conventional methods in the determination of reservoir performance.

* Corresponding author.
E-mail address: he_zhang@ryderscott.com (H. Zhang).

http://dx.doi.org/10.1016/j.petrol.2015.11.034
0920-4105/© 2015 Elsevier B.V. All rights reserved.

Nomenclature

A	=flow area in radial flow system, ft^2
A'	=flow area in linear flow system, ft^2
A_x	=flow area regardless flow system, ft^2
f_w	=fractional flow of water at reservoir, dimensionless
f_{w1}	=fractional flow of water at radius r_1, dimensionless
f_{w2}	=fractional flow of water at radius r_2, dimensionless
f_{ws}	=fractional flow of water at surface, dimensionless
h	=payzone thickness, ft
k	=reservoir permeability, md
k_{ro}	=relative permeability to oil, dimensionless
k_{rw}	=relative permeability to water, dimensionless
P_c	=capillary pressure, psia
p_o	=oil pressure, psia
p_w	=water pressure, psia
Q_i	=dimensionless injection volume, dimensionless
q_o	=oil rate, bbl/D
q_t	=total liquid rate, bbl/D
q_w	=water rate, bbl/D
r	=radius from wellbore, ft
r_D	=dimensionless radius, dimensionless
r_e	=reservoir radius, ft
r_f	=displacement front position in radial system, ft
r_{Sw}	=position of any water saturation in radial system, ft
r_w	=wellbore radius, ft
S_w	=water saturation, dimensionless
t	=time, days
t_{bt}	=waterflood breakthrough time, days (or years)
x_f	=displacement front position in linear system, ft
Z	=elevation (positive upward), ft
μ_o	=oil viscosity, cp
μ_w	=water viscosity, cp
ρ_o	=oil density, lbm/cu-ft
ρ_w	=water density, lbm/cu-ft
$\rho_o/144$	=oil hydrostatic gradient, psia/ft
$\rho_w/144$	=water hydrostatic gradient, psia/ft
Δr	=radius incremental, ft
Δt	=time period, days
ϕ	=porosity, dimensionless
θ	=dip angle, degrees

2. Derivation of fractional flow in a radial reservoir system

Fig. 1 shows a circular reservoir with a well located in the center. A strong peripheral water drive is created by surrounded injectors or strong side aquifer supports, so the water displaces oil as peripheral fractional flow. Fig. 2 illustrates the actual flow line and pressure distribution in reservoir. The following assumptions are made in our derivations:

1) A circular reservoir with constant height.
2) Homogeneous reservoir rock properties.
3) Oil and water two-phase flow in the reservoir.
4) Constant reservoir temperature.
5) All rock properties are independent of pressure.
6) Constant oil and water viscosities during the displacement.

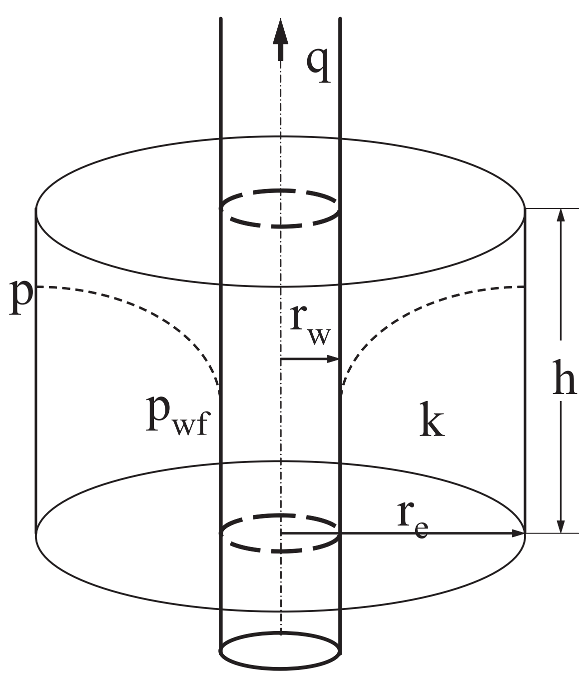

Fig. 1. A circular reservoir with a well located in the center.

Darcy´s equation (Ertekin et al., 2001) gives,

$$q_o = \frac{kk_{ro}}{\mu_o}\frac{\partial\left(A\left(p_o + \frac{\rho_o}{144}Z\sin\theta\right)\right)}{\partial r} \tag{1}$$

$$q_w = \frac{kk_{rw}}{\mu_w}\frac{\partial\left(A\left(p_w + \frac{\rho_w}{144}Z\sin\theta\right)\right)}{\partial r} \tag{2}$$

where

A=flow area, ft^2
k=reservoir permeability, md
k_{ro} =relative permeability to oil, dimensionless
k_{rw} =relative permeability to water, dimensionless
p_o =oil pressure, psia
p_w =water pressure, psia
q_o =oil rate, bbl/D
q_w =water rate, bbl/D
r=radius from wellbore, ft
Z=elevation (positive upward), ft
μ_o =oil viscosity, cp
μ_w =water viscosity, cp
ρ_o =oil density, lbm/cu-ft
ρ_w =water density, lbm/cu-ft
$\rho_o/144$=oil hydrostatic gradient, psia/ft (1/144 is the conversion factor from square ft to square inch)
$\rho_w/144$=water hydrostatic gradient, psia/ft (1/144 is the conversion factor from square ft to square inch)
θ=dip angle, degrees

Recalling the concept of capillary pressure we have

$$P_c = p_o - p_w \tag{3}$$

where P_c=capillary pressure, psia

Replacing water-phase pressure in Eq. (2) by Eq. (3), we have

$$q_w = \frac{kk_{rw}}{\mu_w}\frac{\partial\left[A\left(p_o - P_c + \frac{\rho_w}{144}Z\sin\theta\right)\right]}{\partial r} \tag{4}$$

Expressing in pressure gradient, Eqs. (1 and 4) are changed to

Download English Version:

https://daneshyari.com/en/article/1754654

Download Persian Version:

https://daneshyari.com/article/1754654

Daneshyari.com