CSCanada
Advances in Petroleum Exploration and Development
Vol. 9, No. 1, 2015, pp. 9-12
DOI:10.3968/6405

ISSN 1925-542X [Print]
ISSN 1925-5438 [Online]
www.cscanada.net
www.cscanada.org

A New Waterflooding Characteristic Curve for Naturally Fractured Sandstone Reservoirs

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Supported by Science Foundation of China University of Petroleum, Beijing (ZX20120204).

Received 23 January 2015; accepted 14 March 2015

Abstract

Characteristic curves have found wide applications to analysis and prediction of waterflooding behavior for sandstone reservoirs. Based on the theory of water-oil two-phase flow in dual porous media and taking advantage of the relative permeability curve for naturally fractured sandstone reservoirs, a new waterflooding characteristic curve was derived with an explicit mathematical expression. Verified by physical simulation, numerical simulation and field case, the curve for fractured reservoirs will upwarp at high watercuts, rarely seen in that of non-fractured sandstone reservoirs. In order to improve the quality of analysis and prediction, it is suggested to utilize the new characteristic curve for naturally fractured sandstone reservoirs rather than the conventional curves for non-fractured sandstone reservoirs.

Key words: Fractured sandstone reservoir; Waterflooding characteristic curve; Relative permeability curve; Physical simulation; Numerical simulation

Han, S. G., & Zhao, C. F. (2015). A new waterflooding characteristic curve for naturally fractured sandstone reservoirs. *Advances in Petroleum Exploration and Development*, *9*(1), 9-12. Available from: URL: http://www.cscanada.net/index.php/aped/article/view/6405
DOI: http://dx.doi.org/10.3968/6405

INTRODUCTION

Waterflooding characteristic curves are statistically found to predict cumulative oil production and recoverable oil reserves for waterflooding sandstone reservoirs[1-3]. A great number of expressions have been put forward for characteristic curves to cater to different kinds of reservoirs. Characteristic curves with the character of being straight in part are commonly utilized. Among them, the relationship curves between cumulative water production or water-oil ratio and cumulative oil production or recovery are representative. However, the being-straight part will not be found at high watercut for naturally fractured sandstone reservoirs, which makes the common characteristic curves not applicable any more. What causes this phenomenon is still an enigma. The new characteristic curve developed for naturally fractured reservoirs on the basis of the theory of oil-water two-phase flow in dual porous media is expected a possible answer to this enigma.

1. DERIVATION OF A NEW CHARACTERISTIC CURVE

Injected water is apt to channel along fracture toward production wells due to the low flow resistance in fracture. As a result, the production wells will be extremely waterflooded and the watercut will soar. This phenomenon is not expected to happen in conventional sandstone reservoirs. The water and oil production performance of production wells in a fractured reservoir depends on the water-displacing-oil character in the fracture system.The relative permeability curve of the fracture system can be adjustably used for the whole fractured reservoir[4-5]. The relative permeability curve of an ideal fracture system can be expressed as:

$$\frac{K_{ro}}{K_{rw}}=\frac{1-S_w}{S_w}\ . \tag{1}$$

Where S_w is the water saturation; K_{rw} is the relative permeability to the water phase; K_{ro} is the relative permeability to the oil phase.

In this paper a reservoir model including one injection well and one production well was employed to derive the waterflooding characteristic curve for fractured sandstone reservoirs. In the model, the injection well was set in one end and the production well was set in the other end. The production well will produce oil at the beginning, and then both water and oil, and finally only water. According to the water-displacing-oil theory put forward by Buckley-Leveret, the relationship between the average water saturation and the water saturation at the production end after the water front arrives can be expressed by Welge Equation[6]:

$$\overline{S_w}=S_{we}+\frac{1-f_w(S_{we})}{f_w{}'(S_{we})}. \tag{2}$$

Where $\overline{S_w}$ is the average water saturation, S_{we} is the water saturation at the production end, $f_w(S_{we})$ is the watercut of the production well, and $f_w{}'(S_{we})$ is the one-order derivative of $f_w(S_{we})$ to S_{we}.

It is well known that the irreducible water saturation is negligibly small for a fracture-dominant sandstone reservoir[7]. Therefore, the initial oil saturation is assumed as 1.0 and the irreducible water saturation 0.0. The recovery percentage of oil reserves can be expressed as:

$$R_o=\frac{1-S_{wi}-\overline{S_o}}{1-S_{wi}}=\overline{S_w}. \tag{3}$$

Where R_o is the recovery percentage of reserves, S_{wi} is the irreducible water saturation, $\overline{S_o}$ is the average oil saturation.

The following expression can be obtained with Leveret Function:

$$f_w(S_{we})=\frac{\mu_r}{\mu_r+\frac{K_{ro}}{K_{rw}}}=\frac{\mu_r S_{we}}{\mu_r S_{we}+(1-S_{we})}. \tag{4}$$

Where μ_r is the ratio of oil viscosity to water viscosity.

Differentiating $f_w(S_{we})$ gives:

$$f_w{}'(S_{we})=\frac{\mu_r}{[\mu_r S_{we}+(1-S_{we})]^2}\ . \tag{5}$$

Putting Equations (3), (4) and (5) into (2) gives:

$$S_{we}=1-\frac{\sqrt{(1-R_o)}}{\sqrt{(1-\mu_r{}^{-1})}}\ . \tag{6}$$

Putting Equation (6) into (4) gives:

$$f_w(S_{we})=1-\frac{\sqrt{(1-R_o)}}{\sqrt{\mu_r(\mu_r-1)}-(\mu_r-1)\sqrt{(1-R_o)}}. \tag{7}$$

The water-oil ratio at the production end can be expressed as:

$$\mathrm{WOR}=\frac{f_w(S_{we})}{1-f_w(S_{we})}=\frac{\sqrt{\mu_r(\mu_r-1)}}{\sqrt{(1-R_o)}}-\mu_r. \tag{8}$$

The common logarithm of Equation (8) is:

$$\lg(\mathrm{WOR})=\lg[\frac{\sqrt{\mu_r(\mu_r-1)}}{\sqrt{(1-R_o)}}-\mu_r]. \tag{9}$$

We can also get Equation (10) from Equation (8):

$$Q_w=Q_o[\frac{\sqrt{\mu_r(\mu_r-1)}}{\sqrt{(1-R_o)}}-\mu_r]\ . \tag{10}$$

Where Q_w is the water production; Q_o is the oil production.

Q_o can also be expressed as:

$$Q_o=\frac{\mathrm{d}N_p}{\mathrm{d}t}=N\frac{\mathrm{d}R_o}{\mathrm{d}t}. \tag{11}$$

Where N_p is the cumulative oil production; N is the original oil in place.

The cumulative water production can be expressed as:

$$W_p=\int_0^t Q_w\mathrm{d}t. \tag{12}$$

Where W_p is the cumulative water production; t is the production time.

The dimensionless W_p can be defined as:

$$\begin{aligned}\frac{W_p}{N}&=[-\mu_r R_o-2\sqrt{\mu_r(\mu_r-1)(1-R_o)}\\&+2\sqrt{\mu_r(\mu_r-1)}]\end{aligned}\ . \tag{13}$$

Finding the common logarithm of Equation (13) gives:

$$\begin{aligned}\lg\frac{W_p}{N}&=\lg[-\mu_r R_o-2\sqrt{\mu_r(\mu_r-1)(1-R_o)}\\&+2\sqrt{\mu_r(\mu_r-1)}]\end{aligned}\ . \tag{14}$$

The ratio of cumulative water production to cumulative oil production can be expressed as:

$$\begin{aligned}\mathrm{CWOR}&=\frac{W_p}{N_p}=\frac{W_p}{NR_o}\\&=\left[-\mu_r R_o-2\sqrt{\mu_r(\mu_r-1)(1-R_o)}\right.\\&\left.+2\sqrt{\mu_r(\mu_r-1)}\right]/R_o\end{aligned}\ , \tag{15}$$

$$\begin{aligned}\lg\mathrm{CWOR}&=\lg\{\left[-\mu_r R_o-2\sqrt{\mu_r(\mu_r-1)(1-R_o)}\right.\\&\left.+2\sqrt{\mu_r(\mu_r-1)}\right]/R_o\}\end{aligned}\ . \tag{16}$$

If μ_r is a known parameter, the characteristic curvesfor a fractured sandstone reservoir can be plotted in semi-log coordinates for the relationship between R_o and WOR, CWOR as well as W_p (Figure 1 and Figure 2).

2. DISCUSSION

The following features can be seen from the curves in Figure 1 and Figure 2.

(a) After the production well begins to produce water, WOR rises rapidly at first and then moderately and rapidly at high watercut.

(b) At the middle watercut stage, a straight part can still be found in the curves. For this stage, the conventional waterflooding characteristic curves are still applicable to future performance prediction for a fractured reservoir.

(c) At the high watercut stage, the waterflooding characteristic curve for a fractured reservoir upward rapidly (Figure 1 and Figure 2). Extremely large recoverable reserves will be obtained if the conventional characteristic curves are employed for calculation.

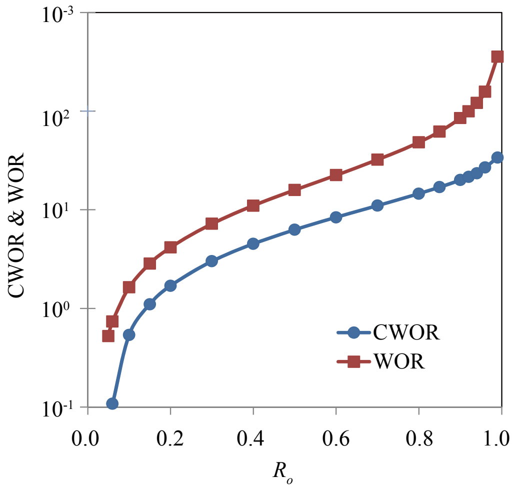

Figure 1
Theoretical CWOR & WOR ~ R_o Characteristic Curve

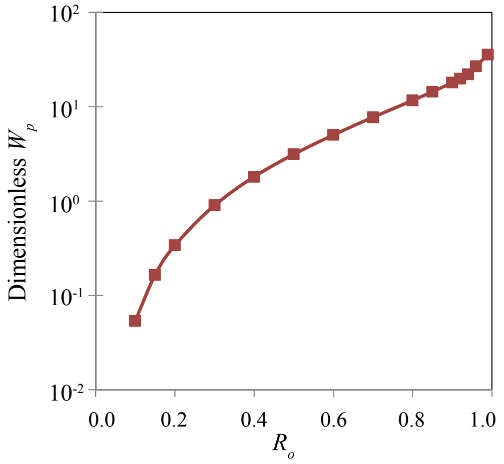

Figure 2
Theoretical Dimensionless W_p ~ R_o Characteristic Curve

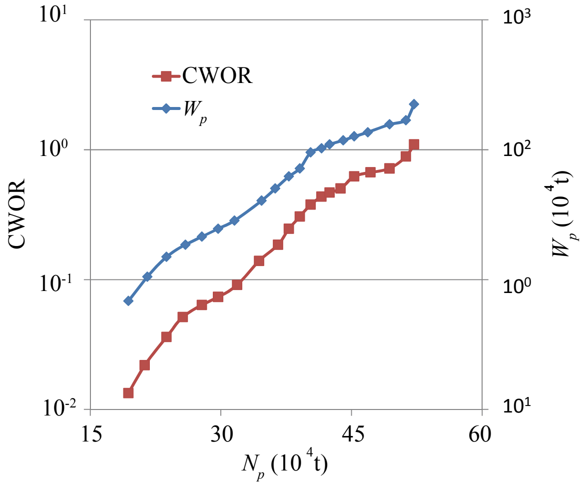

Figure 3
Real CWOR & W_p ~ N_p Characteristic Curve

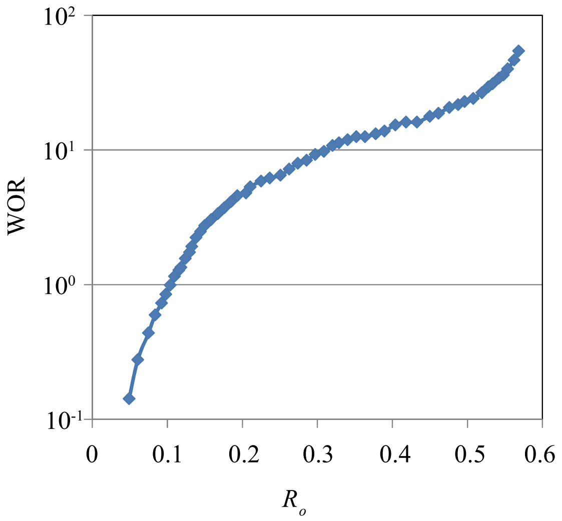

Figure 4
Synthetic WOR ~ R_o Characteristic Curve

3. VERIFICATION BY FIELD CASE AND SYNTHETIC CASE

Jilin Oilfield in Northeast China is an oilfield composed of fracture-dominant sandstone reservoirs[8]. Seen from the waterflooding characteristic curves for one reservoir in Jilin oilfield, end-upwarping exists at both CWOR~N_p and W_p~N_p semi-log coordinates (Figure 3). It should be noted that a secondary upwarping can be seen in the curves after the first upwarping was offset by the stimulation measures.

A numerical simulation model was set for one reservoir of Jilin Oilfield to run reservoir simulation. A characteristic curve was plotted using the result of synthetic case (Figure 4). Seen from Figure 4, the end-upwarping phenomenon exists without exception at the high watercut stage, consistent with the findings of the new characteristic curve for fractured sandstone reservoirs.

CONCLUSION

(a) The end-upwarping phenomenon exists in the new waterflooding characteristic curve for fractured sandstone reservoirs at the high watercut stage.

(b) The straight part of the characteristic curve at the moderate watercut stage can still be used to predict the future recoverable oil reserves. However, it is not applicable any more at the high watercut stage.

(c) Stimulation measures like acidizing or hydraulically fracturing may offset the end-upwarping tendency.

(d) The end-upwarping feature can be used to distinguish fractured reservoirs and non-fractured reservoirs.

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