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RESEARCH PAPER

A new method for calculating volumetric sweep efficiency in a water-flooding oilfield

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Abstract: On the basis of Zhang Jinqing's water drive characteristic curve and the basic principle of material balance, and using displacement efficiency expressions of water flooding, volumetric sweep efficiency expressions of water drive and the relationship between average water saturation and exit-end water saturation, this paper deduce the theoretical relationship formulae between displacement efficiency, volumetric sweep efficiency and water cut in a water-flooding oilfield, and puts forward a new method to calculate displacement efficiency and volumetric sweep efficiency with dynamic data in a water-flooding field. A case study shows when water cut is 100%, the volumetric sweep efficiency calculated with Zhang's water drive characteristic curve is 99.7%, and that calculated with Sipachev's water drive characteristic curve is 100%, which proves that the method with Zhang's water drive characteristic curve can more accurately reflect the actual field situation, and is more rational. Study shows the method is simpler, more efficient and cost-saving than conventional core test, reservoir engineering and numerical simulation methods, moreover, it overcomes the narrow application scope of the aforementioned methods.

Key words: water-drive oilfield; water drive curve; volumetric sweep efficiency; water cut

Introduction

Volumetric sweep efficiency is an important parameter to evaluate the effect of water-flooding oilfield development. Methods to obtain sweep efficiency include laboratory test, reservoir engineering and numerical simulation[1–13], but these methods cannot avoid the following disadvantages: (1) Laboratory test is high in coring cost, low in efficiency, and difficult to track continuously, and the core can hardly reflect heterogeneity in reservoir scale[1–4]. (2) The calculation accuracy of numerical simulation heavily depends on dynamic and static data quality and history match accuracy of reservoir, among which static data comes mainly from laboratory test[5,6], so numerical simulation has the same limitations as laboratory test. (3) With respect of reservoir engineering, the water-drive characteristic curve method and the combination method of water-drive characteristic curve and Weibull proposed by Chen Yunqian et al.[7,8], have made great progress in resevoir scale, data quality and quantity, but only the volumetric sweep efficiency of water flooding at the highest oil displacement efficiency can be calculated because Sipachev water drive curve selected can only describe this kind of f_w-R^* curve. These methods are applicable in a narrow scope and can not be promoted in a wide range.

In this paper, we propose a new method to calculate the oil displacement efficiency and volume sweep efficiency in water flooding oilfield on the basis of Zhang's water drive curve. This new method is suitable for different water-cut stages of water-flooding oilfields because Zhang's water drive curve can reflect different kinds of f_w-R^* curves.

1 Formula derivation

A new water drive curve proposed by Zhang Jinqing and its theoretical derivation are given in reference [14]. It is expressed as follows:

$$\frac{W_p}{N_p} = -a + b\frac{W_p}{{N_p}^2} \tag{1}$$

where, the relationship of cumulative oil production and water cut is:

$$N_p = b\left[1 - \sqrt{\frac{a(1-f_w)}{f_w + a(1-f_w)}}\right] \tag{2}$$

Formation pore volume is:

$$V_p = 100Ah\phi \tag{3}$$

Cumulative oil production of oilfield is:

$$N_p = NR \tag{4}$$

Oil-in-place and recovery percent of reserves of oilfield are

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expressed as:

$$N=\frac{V_{\rm p}\left(1-S_{\rm wi}\right)}{B_{\rm oi}} \tag{5}$$

$$R=E_{\rm D}E_{\rm V} \tag{6}$$

The oil displacement efficiency of water drive oilfield is:

$$E_{\rm D}=\frac{S_{\rm w}-S_{\rm wi}}{1-S_{\rm wi}} \tag{7}$$

Average water saturation of a known stratum at a certain moment, derived from material balance equation, is expressed as:

$$\overline{S_{\rm w}}=S_{\rm wi}+\frac{B_{\rm o}\left(1-S_{\rm wi}\right)}{B_{\rm oi}}R \tag{8}$$

The theoretical relationship between average water saturation in oil-water mixture and water saturation at exit end in the well-known Welge equation [15] can be expressed as

$$\overline{S_{\rm w}}=S_{\rm w}+\frac{1-f_{\rm w}}{\dfrac{{\rm d}f_{\rm w}}{{\rm d}S_{\rm w}}} \tag{9}$$

An ordinary differential equation can be obtained on the bases of simultaneous equations (2), (4), (8), (9)

$$\frac{{\rm d}S_{\rm w}}{{\rm d}\left(1-f_{\rm w}\right)}+\frac{\dfrac{B_{\rm o}b\left(1-S_{\rm wi}\right)}{NB_{\rm oi}}\left[1-\sqrt{\dfrac{a\left(1-f_{\rm w}\right)}{f_{\rm w}+a\left(1-f_{\rm w}\right)}}\right]+S_{\rm wi}}{1-f_{\rm w}}-\frac{S_{\rm w}}{1-f_{\rm w}}=0 \tag{10}$$

Equation (10) belongs to a nonhomogeneous differential equation:

$$y_1+f_1(x)y_1^{a_1}+g_1(x)y_1^{b_1}=0 \tag{11}$$

where,

$$a_1=0 \tag{12}$$

$$f_1(x)=\frac{\dfrac{B_{\rm o}b\left(1-S_{\rm wi}\right)}{NB_{\rm oi}}\left[1-\sqrt{\dfrac{a\left(1-f_{\rm w}\right)}{f_{\rm w}+a\left(1-f_{\rm w}\right)}}\right]+S_{\rm wi}}{1-f_{\rm w}} \tag{13}$$

$$b_1=1 \tag{14}$$

$$g_1(x)=-\frac{1}{1-f_{\rm w}} \tag{15}$$

Equation (11) can be solved as follows according to handbook of ordinary differential equations[16] :

$$u+(a_1-1)f_1u^2+(a_1-1)g_1u^{\frac{a_1+b_1-2}{a_1-1}}=0 \tag{16}$$

where,

$$u(x)=y_1^{a_1-1} \tag{17}$$

Substituting equations (12)-(15) into equation (16) gives:

$$u-\frac{\dfrac{B_{\rm o}b\left(1-S_{\rm wi}\right)}{NB_{\rm oi}}\left[1-\sqrt{\dfrac{a\left(1-f_{\rm w}\right)}{f_{\rm w}+a\left(1-f_{\rm w}\right)}}\right]+S_{\rm wi}}{1-f_{\rm w}}u^2+\frac{1}{1-f_{\rm w}}u=0 \tag{18}$$

Equation (18) is a Bernoulli style equation

$$y_2+f_2(x)y_2^2+g_2(x)y_2=0 \tag{19}$$

According to the handbook of ordinary differential equations[16], equation (19) can be solved as:

$$\frac{1}{y_2}=E(x)\int\frac{f_2(x)}{E(x)}{\rm d}x \tag{20}$$

where,

$$E(x)={\rm e}^{\int g_2(x){\rm d}x} \tag{21}$$

The following equations can be obtained from equations (18) and (19)

$$f_2(x)=\frac{\dfrac{B_{\rm o}b\left(1-S_{\rm wi}\right)}{NB_{\rm oi}}\left[1-\sqrt{\dfrac{a\left(1-f_{\rm w}\right)}{f_{\rm w}+a\left(1-f_{\rm w}\right)}}\right]+S_{\rm wi}}{1-f_{\rm w}} \tag{22}$$

$$g_2(x)=\frac{1}{1-f_{\rm w}} \tag{23}$$

From equations (11), (12), (17), (18) and (19), we will obtain:

$$y_2^{-1}=u^{-1}=y_1^{1-a}=S_{\rm w} \tag{24}$$

Then consolidating equation (20) by substituting equations (21)-(24) into equation (20) gives the following results

$$S_{\rm w}=S_{\rm wi}+\frac{B_{\rm o}b\left(1-S_{\rm wi}\right)}{NB_{\rm oi}}\times\left\{1-2\sqrt{a\left[1-f_{\rm w}+(a-1)\left(1-f_{\rm w}\right)^2\right]}\right\}-(1-f_{\rm w})c \tag{25}$$

As $S_{\rm w}$=$S_{\rm wi}$ when $f_{\rm w}$=0, from equation (25), we can deduce:

$$c=\frac{B_{\rm o}b(1-S_{\rm wi})}{NB_{\rm oi}}-\frac{2B_{\rm o}b(1-S_{\rm wi})a}{NB_{\rm oi}} \tag{26}$$

Consolidating equation (25) by substituting equation (25), we obtain:

$$S_{\rm w}=S_{\rm wi}-\frac{B_{\rm o}b\left(1-S_{\rm wi}\right)}{NB_{\rm oi}}\left[2\sqrt{a}\sqrt{1-f_{\rm w}+(a-1)\left(1-f_{\rm w}\right)^2}-2a\left(1-f_{\rm w}\right)-f_{\rm w}\right] \tag{27}$$

Equation (27) is the relational expression of the characteristics of oil-water flow ($S_{\rm w}$-$f_{\rm w}$) deduced from Zhang jinqing's water drive curve. Then substitute equation (27) into equation (7), the theoretical relational expression of water cut and oil displacement efficiency can be obtained as follows:

$$E_{\rm D}=-\frac{B_{\rm o}b}{NB_{\rm oi}}\left[2\sqrt{a}\sqrt{1-f_{\rm w}+(a-1)\left(1-f_{\rm w}\right)^2}-2a\left(1-f_{\rm w}\right)-f_{\rm w}\right] \tag{28}$$

Theoretical relational expression of water cut and volumetric sweep efficiency of water flooding can be deduced by simultaneous equations (2), (4), (6) and (28):

$$E_{\rm V}=\frac{B_{\rm oi}\left[1-\sqrt{\dfrac{a\left(1-f_{\rm w}\right)}{f_{\rm w}+a\left(1-f_{\rm w}\right)}}\right]}{B_{\rm o}\left[2a\left(1-f_{\rm w}\right)+f_{\rm w}-2\sqrt{a}\sqrt{1-f_{\rm w}+(a-1)\left(1-f_{\rm w}\right)^2}\right]} \tag{29}$$

If water content and volume of crude oil are known, the volumetric sweep efficiency at this water content can be calculated from equation (29).

2 Example

The normal rhythm reservoir of the 4th small layer of 3