

## The Research on Evaluation of Areal Sweep Efficiency in Low Permeability Reservoir with Streamline Numerical Simulation Method

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**Abstract**—Since nature fracture develops in the low permeability reservoir, the anisotropy has a great impact on areal sweep efficiency of water flooding, however most of the current methods don't consider and describe the influence of anisotropy. This paper introduces the frontal water equisaturation interface, defines the concept of areal sweep efficiency and calculates the breakthrough areal sweep efficiency of geometric well pattern by using streamline simulation technique. Meanwhile, we compare and verify the calculating results with reservoir engineering method. Based on the waterflood frontal movement, we have mapped out the plates of areal sweep efficiency of various aeolotropies both in quadrade inverted nine-spot pattern and in rhombus inverted nine-spot pattern with fractured vertical well. The method and plates could provide a good reference for calculation and evaluation of areal sweep efficiency of the low permeability reservoir.

**Keywords**- Low Permeability Reservoir; Areal Sweep Efficiency; Aeolotropies, Streamline Numerical Simulation; Evaluation Method

### I. INTRODUCTION

To the water flooding as in [1], the areal sweep efficiency is theoretically defined as the ratio of the swept area by injected water to the area the well pattern controls as in [2]. However, this definition fails to offer an exact definition of areal sweep efficiency. Some scholars define the swept area as its difference of oil saturation at some certain time exceeding some certain value ( $\Delta S = S_{oi} - S_{ot} > n$ , normally  $n=0$ ), but the value of difference  $\Delta S$  is difficult to obtain as in [3] and [4]. It's because many factors could contribute to the decrease of oil saturation, such as the change of formation pressure, which could induce to the

release of elastic energy as in [5]. Some other scholars use the stream tubing method to research the areal sweep efficiency as in [6] and [7], however these methods didn't consider the impact of natural fractures and anisotropy for the low permeability reservoir, so that the current definition and method of areal sweep efficiency are not suitable to evaluate the water flooding efficiency for the low permeability reservoir as in [8].

This paper introduces the frontal water equisaturation interface, defines the concept of areal sweep efficiency and calculates the breakthrough areal sweep efficiency of geometric well pattern by using streamline simulation technique. Meanwhile, we compare and verify the calculating results with reservoir engineering method. Based on the water flood frontal movement, we map out the plates of areal sweep efficiency of various aeolotropies both in quadrade inverted nine-spot pattern and in rhombus inverted nine-spot pattern with fractured vertical well as in [9] and [10]. The method and plates could provide a good reference for calculation and evaluation of areal sweep efficiency of the low permeability reservoir.

### II. THE CALCULATION METHOD OF AREAL SWEEP EFFICIENCY

#### A. THE DEFINITION OF AREAL SWEEP EFFICIENCY

In streamline simulation, the areal sweep is defined as the flowing path of frontal water interface along the streamline. The areal sweep efficiency is defined as the ratio of the area enclosed by the frontal water interface to the well pattern control area (Fig. 1).

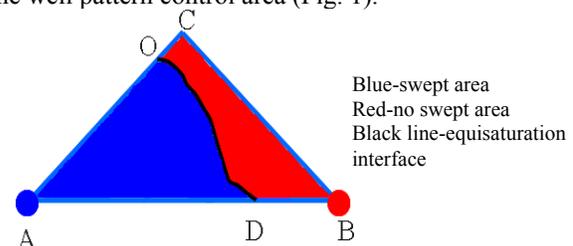


Figure 1 Sketch Map of Areal Sweep in 1/8 unit of nine spot well pattern

The formula of areal sweep efficiency is defined as,

$$E_A = \frac{S_{ADO}}{S_{ABC}}$$

### B. THE CALCULATION OF AREAL SWEEP EFFICIENCY

Before calculating the areal sweep efficiency, we need confirm the position of frontal water equisaturation interface, and there are three steps:

(1) According to the relative permeability curves and the definition of water cut, we get the relationship between water cut and water saturation.

The oil and water relative permeability curves could be obtained by (1),

$$K_{ro} = \alpha_1(1 - S_{wD})^m \quad K_{rw} = \alpha_2 S_{wD} \quad (1)$$

$$\text{Here, } S_{wD} = \frac{S_w - S_{wr}}{1 - S_{or} - S_{wc}}$$

Based on the definition of water cut and (1), we get the relationship between of water cut  $f_w$  and water saturation  $S_{wD}$ ,

$$f_w = \frac{S_{wD}^n}{S_{wD}^n + A(1 - S_{wD})^m} \quad (2)$$

(2) On the basis of the derivative expression of frontal water cut to water saturation and step (1), we could get the calculation expression of frontal water saturation,

$$\left( \frac{\partial f_w}{\partial S_w} \right)_{S_{wf}} = \frac{f_w(S_{wf})}{S_{wf} - S_{wc}} \quad (3)$$

Based on (2) we get,

$$\frac{\partial f_w}{\partial S_w} = \frac{AB[nS_{wD}^{n-1}(1 - S_{wD})^m + mS_{wD}^n(1 - S_{wD})^{m-1}]}{[S_{wD}^n + A(1 - S_{wD})^m]^2} \quad (4)$$

Combined with (3) and (4), we get,

$$S_{wDf}^n + A(1 - S_{wDf})^m = An(1 - S_{wDf})^m + AmS_{wDf}^n(1 - S_{wDf})^{m-1} \quad (5)$$

(3) Calculate the frontal water saturation in (5) with iteration method and locate the position of the frontal water saturation interface of each streamline at some certain time with streamline simulation, then draw a line with the frontal water saturation interface of each streamline, we can get the frontal water equisaturation interface.

After obtaining the frontal water equisaturation interface, the sweep area could be calculated with numerical software. As defined in this paper, the areal sweep efficiency at any time can be calculated.

The suitability of the method to be used to calculate the areal sweep efficiency can be verified with the established theoretical five-spot well pattern model. Fig.2 is the sketch map of the breakthrough areal sweep performance.

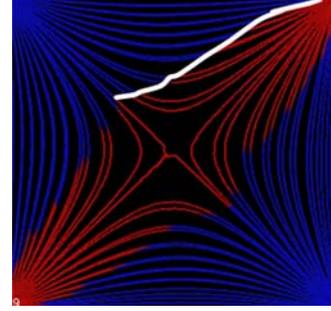


Figure 2 Sketch Map of the Breakthrough Areal Sweep Performance

The frontal water saturation value calculated with (5) is 0.664, then we can get the areal sweep efficiency which is 0.682. In order to verify the reasonability of the definition, we compare the value with the result gained with the stream tubing model of five-spot well pattern whose value is 0.71 as in [11]. Based on B. Danilov's research, the result of breakthrough areal sweep efficiency is 0.702 as in [12]. According to Dyes empirical formula, the value of breakthrough areal sweep efficiency is 0.697 as in [13].

Table.1 The Correlation of Areal Sweep Efficiency

Method & Result	Streamline simulation	Stream tubing simulation	Formula 1	Formula 2
The breakthrough areal sweep efficiency	0.682	0.71	0.702	0.697

The results calculated with the above four methods is shown in Table.1, it is obviously seen that the streamline simulation result is smaller. It is because it takes the viscosity and gravity difference into account to the influence of areal sweep efficiency. However, the stream tubing method ignores these factors, Formula 1 and 2 do not consider the gravity difference. Moreover, the dead oil area phenomenon in the flow event contributes to a smaller value, hence, the streamline simulation method is closer and more suitable to the actual reservoir.

### III. AREAL SWEEP EFFICIENCY CHARACTERISTICS OF DIFFERENT ANISOTROPY

For low permeability reservoir, the matrix permeability is relatively low and natural fracture has a marked impact, thus low permeability has an obviously anisotropy. Now quadrate inverted nine-spot and rhombus inverted nine-spot are the most widely used well pattern to those water flooding low permeability reservoir.

In this paper, we simulated areal sweep law of quadrate inverted nine-spot and rhombus inverted nine-spot pattern of different anisotropy by using reservoir streamline simulation technique. The production well will be fractured and the half fracture length is 80m. The sketch map is shown as Fig.3, the model parameters are listed in Table.2 and Table.3.

Well spacing of quadrate inverted nine-spot pattern: 300m×300m; Matrix permeability:  $1.8 \times 10^{-3} \mu\text{m}^2$ ; Hydraulic fracture permeability:  $150 \times 10^{-3} \mu\text{m}^2$ ; Porosity: 12.5%; Initial oil saturation: 57%; Production regime: the injection rate of injectors:  $24 \text{m}^3/\text{d}$ ; the flow pressure of producers: 13.5MPa.

Table 2 Statistical List of Model Parameters in Quadrate Inverted Nine-spot Pattern

Well pattern	quadrate inverted nine-spot	Average porosity	12.5%
Well spacing	300m×300m	Initial oil saturation	57%
Matrix permeability	$1.8 \times 10^{-3} \mu\text{m}^2$	The injection rate	$24 \text{m}^3/\text{d}$
Hydraulic fracture permeability	$150 \times 10^{-3} \mu\text{m}^2$	The flow pressure	13.5MPa

Table 3 Statistical List of Model Parameters in Rhombus Inverted Nine-spot Pattern

Well pattern	rhombus inverted nine-spot	Average porosity	12.0%
Well spacing	500m×180m	Initial oil saturation	62%
Matrix permeability	$1.49 \times 10^{-3} \mu\text{m}^2$	The injection rate	$32 \text{m}^3/\text{d}$
Hydraulic fracture permeability	$150 \times 10^{-3} \mu\text{m}^2$	The flow pressure	9MPa

Well spacing of rhombus inverted nine-spot pattern: 500m×180m; Grid:  $101 \times 73 \times 1$ ; Matrix permeability:  $1.49 \times 10^{-3} \mu\text{m}^2$ ; Hydraulic fracture permeability:  $150 \times 10^{-3} \mu\text{m}^2$ ; Porosity: 12.0%; Initial oil saturation: 62%; Production regime: the injection rate of injectors:  $32 \text{m}^3/\text{d}$ ; the flow pressure of producers: 9MPa.

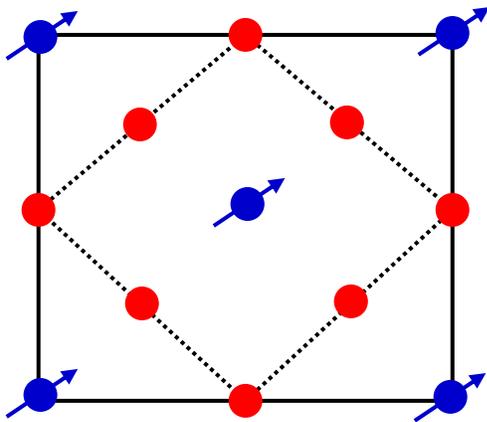


Figure 3 Sketch Map of Quadrate and Rhombus Inverted Nine-spot Well Pattern

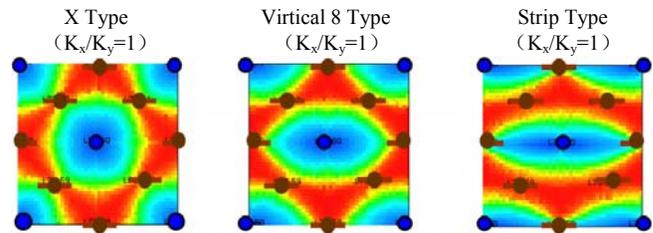


Figure 4 Field Pattern of Oil Saturation

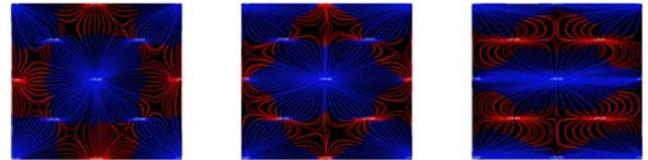


Figure 5 Field Pattern of Areal Sweep Performance

For quadrate inverted nine-spot well pattern, we simulated different anisotropy ( $K_x/K_y=1, 3, 5$ ), then we get the remaining oil distribution pattern shown as the above Fig.4 and Fig.5. It is obvious that a strong anisotropy will gain a bigger accumulation trend in x direction, the pattern of remaining oil are named x type, vertical 8 type and Strip Type. Under the weak anisotropy condition ( $K_x/K_y=1$ ), the frontal water interface is like a circle, with the anisotropy becoming stronger, the frontal water interface is acceleratingly changing to ellipse from circle.

Using the above method combined with the front water saturation interface determination formula and streamline simulation technique, we get the areal sweep efficiency plate of different water cut, shown in Fig.6. We notice that under the same water cut, the stronger anisotropy will contribute to a smaller water flooding areal sweep efficiency, but with the increasing of water cut, the difference the anisotropy induced is becoming smaller. This is because the numerical model used is half theoretical model, it just takes the permeability areal anisotropy into account but ignored the areal heterogeneity. When the research unit has a higher water cut, the final areal sweep efficiency is 1 with the continuing injection of water.

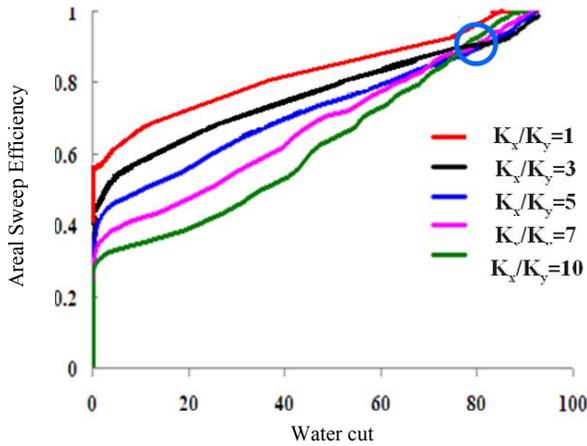


Figure 6 The Areal Sweep Plate of Quadrate Inverted Nine-spot Well Pattern

We also make research on the sweep characteristics of rhombus inverted nine-spot pattern. The remaining oil distribution pattern is respectively Horizontal 8 Type, Vertical 8 Type and Strip Type when the anisotropy ( $K_x/K_y$ ) is 2, 4 and 6, as Fig.7 and Fig.8. Obviously, when  $K_x/K_y$  is smaller than 3, the areal sweep efficiency gain an increase with the increase of anisotropy. However, when  $K_x/K_y$  is bigger than 5, the areal sweep efficiency will decrease with the increase of anisotropy. When  $K_x/K_y$  equals to 3, the areal sweep performance is the best, as Fig.9.

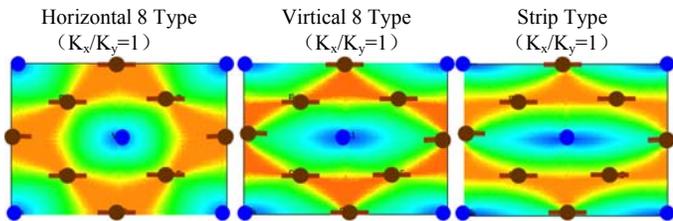


Figure 7 Field Pattern of Oil Saturation

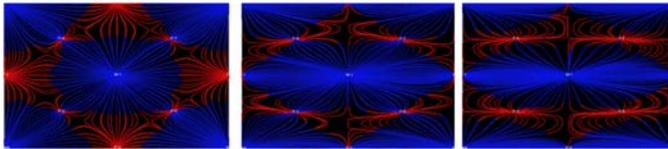


Figure 8 Field Pattern of Areal Sweep Performance

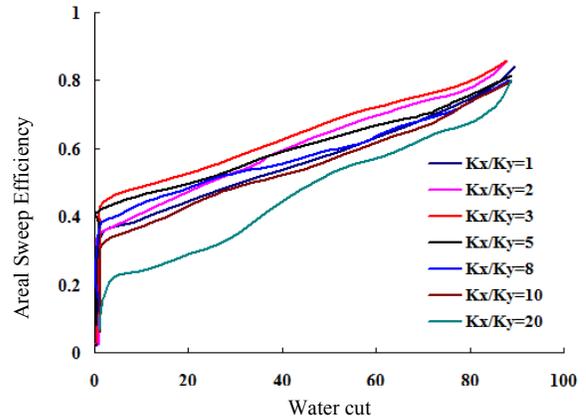


Figure 9 The Areal Sweep Plate of Rhombus Inverted Nine-spot Well Pattern

Make a comparison of the rhombus areal sweep performance with the quadrate, we find that the quadrate inverted nine-spot pattern is not suitable for the oilfield anisotropy exists. Moreover, the stronger the anisotropy is, the poorer the sweep performance. It also provides evidence that the development performance of rhombus inverted nine-spot pattern is better than that of quadrate inverted nine-spot pattern in low permeability reservoir micro fractures develop.

#### IV. CONCLUSION

- (1) This paper introduces the frontal water equisaturation interface, defines the concept of areal sweep efficiency and calculates the breakthrough areal sweep efficiency of five-spot well pattern, thus has verified the suitability of the defined calculation method.
- (2) Established areal sweep plates of different anisotropy quadrate inverted nine-spot pattern and rhombus inverted nine-spot pattern in low permeability reservoir.
- (3) The comparison of quadrate inverted nine-spot pattern with rhombus inverted nine-spot pattern shows that the rhombus inverted nine-spot pattern is more suitable for stronger anisotropic low permeability reservoir.

#### ACKNOWLEDGMENTS

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#### REFERENCES

- [1] Wang Junkui. Water-Oil Displacement Mechanism and Waterflooding Method in Fractured Reservoir [J].P.G.O.D.D, 1997, 16(15):35-38.
- [2] Cheng Linsong. Flow in Porous Media[M].Beijing: Petroleum Industry Press, 2011.

- [3] C.I.Bargas, J.I.Yanosik, The Effects of Vertical Fractures on Areal Sweep Efficiency in Adverse Ratio Floods. SPE Reservoir Engineering, 1988, 611-620.
- [4] De Swan O A. Analytic solutions for determining naturally fractured reservoir properties by well testing[R].SPE5346, 1976.
- [5] Kazemi H, Seth M S, Thomas G W. Pressure transient analysis of naturally fractured reservoir with uniform fracture distribution[R].SPE2156, 1969.
- [6] Gao Chuqiao, Zhang Chaomo. Watercut Calculation and Classification of Waterflooded Grades in L Oilfield [J].Well Logging Technology.2004,(1):75-77.
- [7] Ji Bingyu. Oil production calculation for areal well pattern of low-permeability reservoir with non-Darcy seepage flow [J].ACTA PETROL EI SINICA.2008,(2):256-261.
- [8] Li Songquan, Tang Zengxiong. The Reasonable Well Pattern for Developing Low Permeability Oilfield[J]. ACTA PETROL EI SINICA,1998,19(3):52-56.
- [9] Li Daopin, Luo Diqiang. Rational Well Pattern and Injection-Production Principle of Low Permeability Oilfield [J].Fault-Block Oil & Gas Field,1994,1(4):12-20.
- [10] Wang Shouping. Fracture Distributional Laws and Well Pattern Adjustment in Low Permeability Reservoir in North Block of Wen 13. Journal of Jiangnan Petroleum Institute. [J].Journal of Jiangnan Petroleum Institute, 2004, 26(1):82-85.
- [11] Nie Jun. Computing Method Research on Sweep Efficiency of Polymer Flooding for Five-Spot Pattern [D]. China University of Geosciences (Beijing),2010/2011.
- [12] Jiang Hanqiao. Principle and Method of Reservoir Engineering [M]. China University of Petroleum Press,2006.
- [13] M.R. Fassihi. New Correlation for Calculation of Vertical Coverage and Areal Sweep Efficiency. SPE ARCO Resources Technology, November 1986, pages: 604-606.