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Sizing Conformance Control Treatment Based on Law of Gel Transportation Through Porous Media[1]

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Abstract: Treatment volume sizing is quite indispensible to conformance control project design. The sizing methods used currently suffer from such disadvantages as oversimplifying the law of gel transportation through porous media or completely neglecting it, and give calculation results far from optimal. A new sizing method is presented to take the transportation law into account. First, theoretical analysis, physical simulation and numerical simulation are employed to conduct qualitative analysis on how gel transports between one injector and one producer. It was found that most of gel injected into formation would migrate through the effective water-swept region toward the producer. This region, low in flow resistance, can be approximately deemed as the overlap of two equirotal circles. The intersection angle of the two circles is called water-swept angle and dominates the area of this region. Water-cut performance of the producer, mobility ratio and relative permeability-saturation relation can be used to compute this angle. Given the optimal treatment distance, the area of the gel distribution region will be determined. Then treatment volume can be determined by multiplying the area by the water-swept thickness. Its consideration of fluid properties, rock properties and well performance allows this new method to gain an advantage over other sizing methods. In a field case, this method yielded much smaller treatment volume and saw good response to treatment.

Keywords: water channelling; conformance control; treatment volume; physical simulation; numerical simulation; effective water-swept region

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1. INTRODUCTION

Conformance control is one EOR technique for mature waterflooding oilfields, especially effective for treating water channeling caused by a high permeability thief zone. Treatment volume sizing is quite indispensible to conformance control project design. Too large a treatment size will lead to prohibitive costs and cause damage to non-target zones. Too small a size will lead to an ineffective treatment. There are currently several kinds of sizing methods. Numerical reservoir simulation was sometimes used for conformance control treatment sizing (Bai, 1999; Jiang, 1994; Shi, 2005; Wang, 2007). The use of this method is limited for its long duration and high cost despite its high reliability. Treatments sizing were also based on treatment volume per unit pressure index (Zhao, 1994; Wang, 1999; Wang, 2005), or per unit injection pressure difference (HE, 2000), or per unit water injectivity index (Feng, 1999; Huang, 2001), or per unit perforated interval thickness (Giangiacomo, 2001; Philip, 2007). Methods of this kind may be the most convenient for use but simultaneously the lowest in reliability for their full neglect of the law of gel transportation in porous media. The third kind of methods was to determine treatment volumes according to production wells' response to waterflooding (Smith, 1999), but had the problem common to the second kind. The problem was overcome in the fourth kind of methods for they did take account of the gel transportation law. But this consideration seemed inadequate for they over-simply the gel transportation region as an circle, a part of circle, a rectangle or a diamond (Fan, 2002; Han, 2003; Fu, 2007; Yuan, 2007). The oversimplification was not based on solid background. Theoretical analysis, physical simulation and numerical simulation are employed to determine the law of gel transports in porous media in this paper and on this basis a new treatment sizing method is suggested. It should be pointed out that this method is presented for channeling caused by a high permeability thief zone rather than by vertical permeability contrast.

2. QUALITATIVE CHARACTERIZATION OF LAW OF GEL TRANSPORTATION THROUGH POROUS MEDIA

2.1 Theoretical analysis

Suppose there are one injector and one producer in an infinite reservoir. According to the theory of flow through porous media (Ge, 2003), the injected water prefers to approach the producer along the main streamlines than along other streamlines, thus causing the tonguing phenomenon (Fig 1) and then gradually evolving a water-swept region (Fig.2). One part of this region (the shaded region in Fig. 3) is exposed to increasing erosion and its permeability becomes higher and higher. As a result, most of the injected water will advance along this shaded region, which is called effective water-swept region (hereinafter referred to as effective region). The blank region in Fig.3 is called ineffective water-swept region (hereinafter referred to as ineffective region). It can be inferred that most of the plugging agent should migrate toward the producer through the effective region for its lower flow resistance, and that only a fraction of agent should enter the ineffective region.

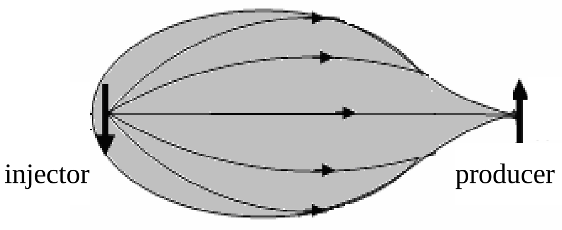

Figure 1: A schematic figure of the tonguing phenomenon

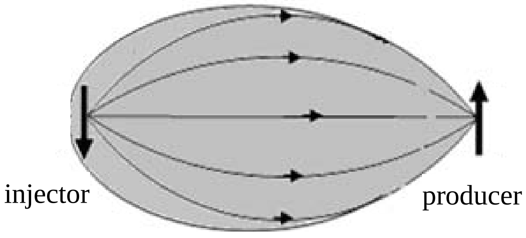

Figure 2: Water–swept region based on theoretical analysis

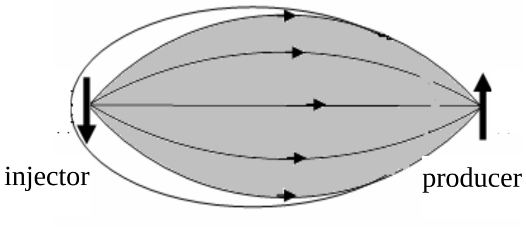

Figure 3: Effective region based on theoretical analysis

2.2 Physical simulation

A visible sand-packed plate model with dimension of 30cm×20cm×1cm was prepared. An injector and a producer were respectively positioned about 7.0cm away from the model sides (Fig. 4). According to the dimensional similarity analysis, the injection rate of 1.0 ml/min was selected. After the model was water-saturated, the water injection process commenced. When the production rate approached the injection rate, the gel injection process succeeded.

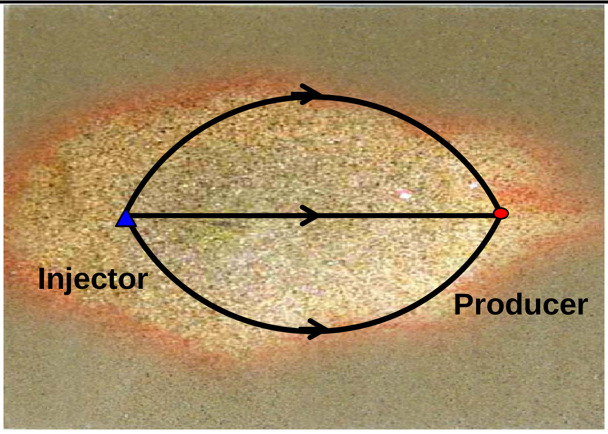

Figure 4: Water–swept region and effective region based on physical simulation

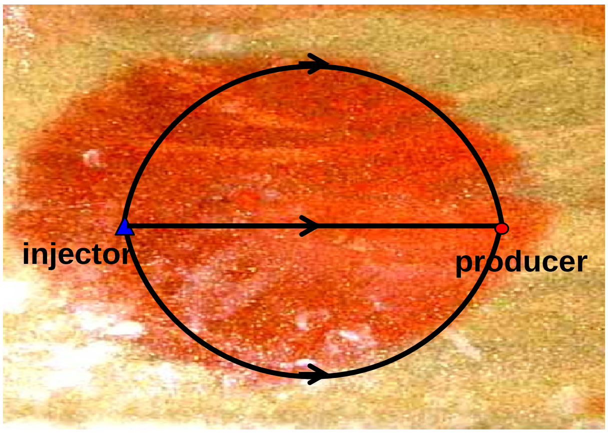

Figure 5: Gel distribution region based on physical simulation

A water-swept region (the whole bright area in Fig.4) formed during water injection. The region between the two intersecting arcs was the effective region. Both the water-swept region (the whole red region in Fig.5) and the effective region (the region between the two intersecting arcs in Fig.5) became a little larger in area during gel injection, but this increase was negligible. It was obviously seen that most of the gel entered the effective region except a fraction of gel migrating into the ineffective region. The phenomenon coincided with the results of the theoretical analysis.

2.3 Numerical simulation

Numerical simulation was conducted to verify the findings in the physical simulation. In order to truly simulate the law of gel transportation through porous media, it is necessary not to neglect the permeability alternation in the effective water-swept region. The permeability distribution field was dynamically changed during the numerical simulation to observe gel transportation.

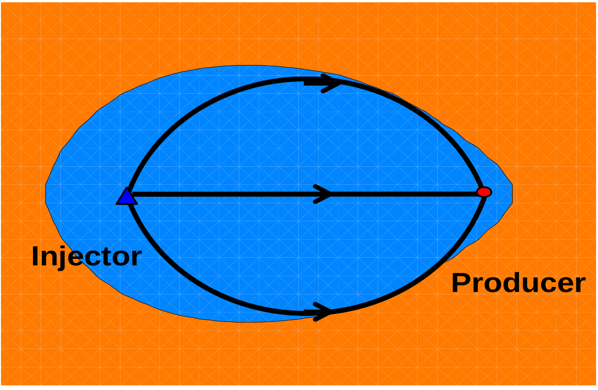

Figure 6: Water–swept region and effective region based on numerical simulation

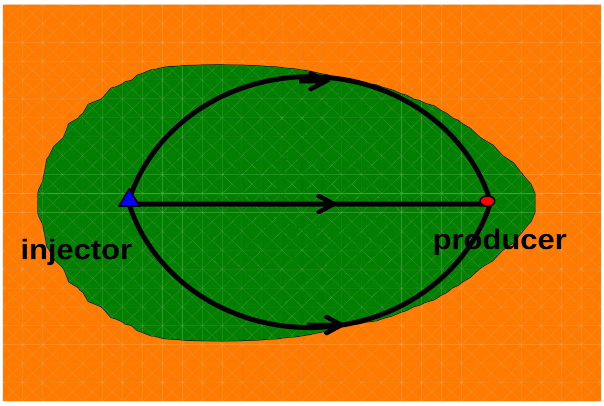

Figure 7: Gel distribution region based on numerical simulation

A water-swept region (the whole blue area in Fig.6) formed during water injection. The region between the two intersecting arcs was the effective region. Both the water-swept region (the whole green region in Fig.7) and the effective region (the region between the two intersecting arcs in Fig.7) became a little larger in area during gel injection, but this increase was also negligible. Common to the physical simulation, most of gel entered the effective region except a fraction of gel moving into the ineffective region.

3. QUANTITATIVE DETERMINATION OF TREATMENT VOLUME

3.1 Calculation of the area of gel distribution region

Indicated by theoretical analysis, physical simulation and numerical simulation, most of gel will migrate through the effective water-swept region. This region can be approximately deemed as the overlap of two equirotal circles (Fig.8). θ, the intersection angle of the two circles, is called water-swept angle. Suppose piston-like gel transportation in the effective water-swept region. If the area of the gel distribution region (the shaded area in Fig.8) can be computed, then the treatment volume can be sized by multiplying the area by the water-swept thickness that can be determined according to injection profile.

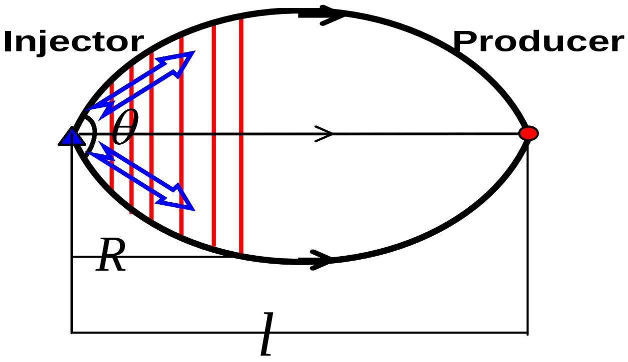

Figure 8: Gel distribution region in the effective water–swept region

For convenience, the upper half (Fig.9) of the effective region is extracted to derive the equation computing the area of the region. In Fig.9, Point *A*, the origin of coordinates, is on behavior of the injector, Point *F* the producer, Chord *AF* the interwell distance l, and Segment *AD* the treatment distance *R*. $\angle PAF = \theta / 2$. Point *O* is the center of a virtual circle, and Curve *AEF* is an arc of this circle. Its radius *OA* is $r = \dfrac{l/2}{\sin(\theta/2)}$.

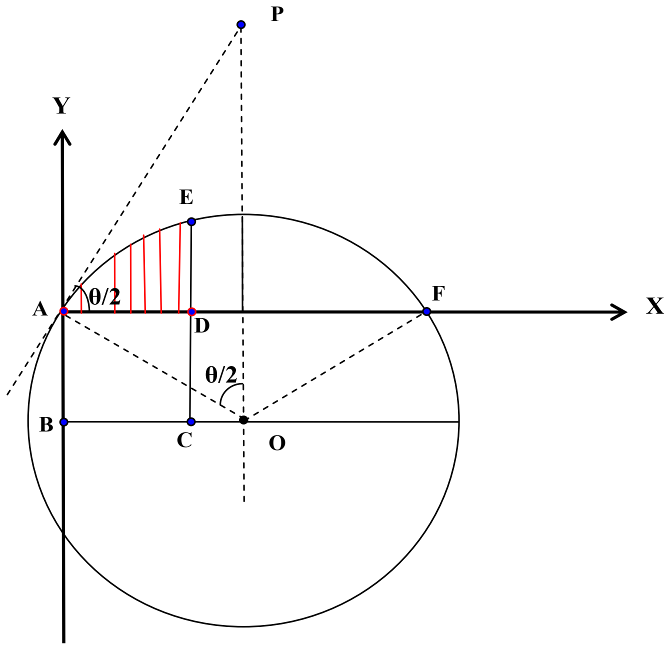

Figure 9: The upper half of gel distribution region in a Cartesian coordinate

According to the Inscribed angle theorem, $\angle PAF = \angle AOF / 2 = \angle POA = \theta / 2$.

Suppose $\alpha = \theta / 2$. The ordinate *y* of any point in the virtual circle can be expressed as

$$y = \sqrt{r^2 - (r\sin\alpha - x)^2} - r\cos\alpha \qquad (1)$$

The area S_1 of the shaded region can be calculated through Eq.(2).

$$\begin{aligned} S_1 &= \int_0^R y dx \\ &= \int_0^R (\sqrt{r^2 - (r\sin\alpha - x)^2} - r\cos\alpha) dx \end{aligned} \qquad (2)$$

There are two cases for calculation of S_1.

(1) The treatment distance is less than or equal to half the interwell distance, $R \le l/2 = r\sin\alpha$

$$\begin{aligned} S_1 &= \int_0^R y dx = \int_0^R (\sqrt{r^2 - (r\sin\alpha - x)^2} - r\cos\alpha) dx \\ &= \frac{1}{2}\alpha r^2 + \frac{1}{4} r^2 \sin 2\alpha - Rr\cos\alpha \\ &\quad - \frac{1}{2} r^2 \arcsin(\sin\alpha - \frac{R}{r}) \\ &\quad - \frac{1}{4} r^2 \sin(2\arcsin(\sin\alpha - \frac{R}{r})) \end{aligned} \qquad (3)$$

(2) The treatment distance is more than half the interwell distance, $R > l/2 = r\sin\alpha$

$$\begin{aligned} S_1 &= \int_0^{r\sin\alpha} y dx + \int_{r\sin\alpha}^{R - r\sin\alpha} y dx \\ &= \frac{1}{2}\alpha r^2 - \frac{1}{4} r^2 \sin 2\alpha \\ &\quad + \int_{r\sin\alpha}^{R - r\sin\alpha} (\sqrt{r^2 - (x - r\sin\alpha)^2} - r\cos\alpha) dx \\ &= \frac{1}{2}\alpha r^2 + \frac{1}{4} r^2 \sin 2\alpha - Rr\cos\alpha \\ &\quad + \frac{1}{2} r^2 \arcsin(\frac{R}{r} - \sin\alpha) \\ &\quad + \frac{1}{2} r^2 \sin(2\arcsin(\frac{R}{r} - \sin\alpha)) \end{aligned} \qquad (4)$$

The area of the gel distribution region is expressed as

$$S = 2S_1 \qquad (5)$$

It can be seen that R and θ are the only two unknown parameters. R can be determined according to physical simulation, experience or gel breakthrough pressure gradient (Cai, 2005; Li, 2005; Luo, 2007;

Wu, 2002). θ can be computed through Eq.(6) and Eq.(7) (Chen, 1982; Chen, 1990).

$$\theta = \frac{f_w}{f_w + M(1 - f_w)} \quad (6)$$

$$M = \frac{K_{rw}(S_{or}) / K_{ro}(S_{wc})}{\mu_w / \mu_o} \quad (7)$$

Where S is the area of the gel distribution region, m^2; l is the interwell distance, m; R is the treatment distance, m; θ is the water-swept angle, in radian; r is the radius of the virtual circle, m; f_w is he water-cut of the producer, percentage; M is the water-oil mobility ratio, dimensionless; $K_{rw}(S_{or})$ is the relative permeability to water at the residual oil saturation, fraction; $K_{ro}(S_{wc})$ is the relative permeability to oil at the connate water saturation, fraction; μ_w is water viscosity, mPa·s; μ_o is oil viscosity, mPa·s. S_{wc} is the connate water saturation, fraction; S_{or} is the residual oil saturation, fraction.

3.2 Treatment volume sizing

Given the area of the gel distribution region, the treatment volume can be computed through Eq.(8).

$$W = \beta \cdot S \cdot h \cdot \lambda_\phi \cdot \phi \cdot (1 - S_{wc} - S_{or}) \quad (8)$$

Where W is the treatment volume, m3; β is the area factor for compensation of the ineffective water-swept region, usually 1.2 ~ 1.5, dimensionless; h is the water-swept thickness, m; λ_ϕ is the effective pore utilization factor, fraction; ϕ is the porosity, fraction; S_{wc} is the connate water saturation, fraction; S_{or} is the residual oil saturation, fraction.

4. FIELD CASE

Well +13-9.2 is an injector in Fuyu Block of Jinlin Oilfield in Jilin Province, China. It began injecting water into Formation *12+13* in August 2003. The neighboring producer +13-010.4 began producing oil from the same formation in September 2003, with the initial water-cut of 77.2%. Its water-cut rose to 98% in April, 2004 and maintained at this level since then.

It was inferred according to the injection and production performance and the injection profile that severe water channeling happened between the two wells through a thin high-permeability thief zone. In order to improve oil recovery, conformance control treatment was planned for the injector. The designed treatment distance was 35.6m, about one third of the interwell distance of 106.8m. Table 1 showed the parameters involved treatment sizing. Based on the relative permeability curve, the producer's water-cut performance and the injection profile, a treatment size of 117m^3 was determined with the sizing method presented in this paper. If gel was expected to move uniformly like a circle around the injector, the treatment volume was 830.0m^3 with the same treatment distance. The treatment was conducted from 1~7 July 2005. After the treatment, Well +13-9.2 saw a uniform injection profile and Well +13-010.4 saw large oil increment. This result continued about 10 months. The water-cut of Well +13-010.4 declined from 98.3% to 85.5%. The cumulative incremental oil production was 163.8t. And the base daily oil production of this producer was only 0.4t. The increment ratio of cumulative oil production amounted to 136.5%.

Table 1: Values of parameters involved in treatment sizing

Parameters	R (m)	f_w	$K_{rw}(S_{or})$	$K_{ro}(S_{wc})$	μ_w (mPa·s)	μ_o (mPa·s)	β	h (m)	λ_ϕ	S_{wc}	S_{or}
Values	36.5	98%	0.069	0.755	1.0	50.0	1.2	2.5	0.8	0.256	0.327

5. CONCLUSIONS

1) Among the conformance control treatment sizing methods used currently, the application of numerical simulation is restricted for its high time cost despite its high accuracy, and other sizing methods for their neglecting or oversimplifying the law of gel transportation through porous media.

2) It was indicated from theoretical analysis, physical simulation and numerical simulation that an effective water-swept region would be evolved during waterflooding and that most of gel subsequently injected would move through the effective region.

3) The effective water-swept region can be approximately deemed as the overlap of two equirotal circles at the water-swept angle. The angle can be determined according to fluid property, relative permeability function and producer water-cut performance.

4) It was shown by the field case that the treatment sizing method suggested in this paper would yield smaller treatment sizes than the conventional methods used currently, but this would not damage the treatment effect for it takes account of the law of gel transportation through porous media.

5) In compensation for the gel entering the ineffective water-swept region, an area factor is introduced into the treatment sizing equation. It is suggested to determine the magnitude of this factor according to injection and production performance or through physical simulation.

6) For the assumption of piston-like gel transportation reduces the precision of the sizing equation suggested in this paper and this method applies only to channeling caused by a high permeability thief zone rather than by vertical permeability contrast, further improvements are needed.

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