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### ABSTRACT

Water shutoff is an effective way to enhance oil recovery and lower water production. It is crucial to select target wells and target zones properly, otherwise, the effect of water shutoff may be disturbed. Traditionally, the job to select target wells and target zones is always done artificially and imprecisely, as a result, water shutoff does not perform as good as it can. This paper proposes a fuzzy method capable of optimizing the selection of target wells and target zones for water shutoff. This study plays a significant role in the technique of water shutoff.

### FUNCTION OF WATER SHUTOFF

An effective water shutoff treatment can lead to the following good results [2].

1. Water shutoff conducted in the stage of low or intermediate water cut will be able to prolong water-free oil production period.

2. Water shutoff is able to improve oil displacement efficiency and thus enlarge recoverable oil reserves.

3. By plugging zones of high water cut, liquid production from these zones is controlled at a desirable level, water cut of the treated oil well is successfully controlled and water output of it is decreased. Correspondingly, the utilization efficiency of injected water is enhanced and thus more oil can be recovered with the same amount of water injection.

4. Water shutoff performed on high water cut zones will result in an increase of the liquid output from low water cut zones not plugged. As a result, oil production of the treated well is stimulated. Indirectly, water shutoff weakens the decline rate of oil production.

5. For commingled production wells, certain amount of crude oil still exists in some zones when water cut of some other zones already exceeds the economic limit. Plugging high water cut zones makes it possible to recover the residual oil in these zones.

### DETERMINATION OF THE WATER CUT LIMIT FOR WATER SHUTOFF

Water cut limit for water shutoff means the optimum water cut to conduct the treatment of water shutoff. For different oilfields, water shutoff should be adopted at different level of water cut. Two aspects of facts must be considered comprehensively.

1. For zones without alternative production wells or for zones tending to form some stagnant area inside them, premature water shutoff will cause a substantial loss of recoverable oil reserves. Therefore, higher water cut of the plugged zones is more helpful to increase recoverable oil reserves and maintain oil production.

2. Determination of the water cut limit for water shutoff should make certain considerations of the price system. Both investment and output should be considered economically [2].

### PRINCIPLES FOR SELECTING TARGET WELLS AND TARGET ZONES

To efficiently choose target wells and target zones to be treated with water shutoff, the following principles must be well weighted.

1. Target zone should qualify the water cut limit water shutoff required.

2. Zones with sharp plane contradictions caused by unreasonable injection-production relationship or reservoir heterogeneity should be preferentially considered.

3. Wells containing zones with very different water cut should be preferentially selected.

4. Wells having relatively capable alternative pay zones should be preferentially considered.

5. Wells with higher flowing pressure should be preferentially considered.

6. If dynamic parameters of every zone can not be determined through separate zone test, then wells with water cut higher than 90% or mean value should be preferentially considered and zones with higher liquid production should be preferentially selected.

7. For wells satisfying (1), enhancement of liquid production should be preferentially considered. Otherwise, water shutoff should be applied.

$$(P_{wf1} - P_{wf2})/(P_r - P_{wf1}) \times [(1 - f_{wf2})(1 - R) + (1 - f_{wf1})R]Q_L \geq S_c / [P_c - (36.6 + 3.04 f_w / (1 - f_w))] \quad (1)$$

Where,

$P_{wf1}$ and $P_{wf2}$ = flowing pressure before and after liquid production enhancement respectively, MPa

$P_r$ = formation pressure, MPa

$f_{wf1}$ and $f_{wf2}$ = water cut of high water cut zone and that of low water cut zone respectively, fraction

$Q_L$ = liquid production rate of the well, t/d

R = the ratio of the liquid production from the high water cut zone, fraction

$f_w$ = water cut of the well, fraction

$P_c$ = price of crude oil, yuan/t

$S_c$ = the cost to change the pump, yuan/t

8. Income created by water shutoff should be greater than the total cost, i.e., either (2) or (3) should be satisfied. Otherwise, water shutoff should not be adopted.

$$(1 - f_w)Q_L R_{oi}(P_c - S_v) + f_w Q_L R_{wd} B \geq S_{pl} / (E_{pl} T_e) \quad (2)$$

$$\{(P_{wf1} - P_{wf2})/(P_r - P_{wf1})[(1 - f_{wf2})(1 - R) + (1 - f_{wf1})R]Q_L\} \times (P_c - S_v) + [f_{wf1} R Q_L - (P_{wf1} - P_{wf2})/(P_r - P_{wf1}) f_{wf2}(1 - R)Q_L]B \geq S_{pl} / (E_{pl} T_e) \quad (3)$$

Where,

B = constant related to cost of water injection, yuan/t

$S_v$ = ambulatory cost of crude oil, yuan/t

$E_{pl}$ = ratio of success of water shutoff, fraction

$T_e$ = valid period of water shutoff, day

$R_{oi}$ = ratio of enhanced oil production by water shutoff, fraction

$R_{wd}$ = ratio of weakened water production by water shutoff, fraction

$S_{pl}$ = operation cost, yuan/well

## TO SELECT TARGET WELLS AND TARGET ZONES USING FUZZY METHOD

### Indexes

A. Water Cut

If water cut of every zone can not be determined, combined water cut of the whole well is often used as an index to select zones to be plugged. A larger difference between the combined water cut ( $f_w$ ) and the water cut limit for water shutoff always necessarily means a better result.

$$\Delta f_w = f_{w,well} - f_{w,\lim it} \geq 0 \quad (4)$$

$$f_{w,\lim it} = (f_{w,ultimate} - A) \quad (5)$$

Where,

$\Delta f_w$ = the difference between combined water cut of the whole well and the water cut limit of water shutoff, %

$f_{w,well}$ = combined water cut of the whole well, %

$f_{w,\lim it}$ = water cut limit for water shutoff, %

$f_{w,ultimate}$= economic limit of water cut, %

A = scope of water cut

B. Difference of Water Cut Between Different Zones, $\Delta f_w'$

The difference of water cut between different zones should be greater than 50%. The larger it is, the better the result is.

$$\Delta f_w' = \frac{f_{w,high} - f_{w,low}}{f_{w,low}} * 100\% \quad (6)$$

Where,

$\Delta f_w'$ = the largest relative difference of water cut between different zones, $a \leq \Delta f_w' < b$

$f_{w,high}$ = the highest water cut among all zones, %

$f_{w,low}$ = the lowest water cut among all zones, %

C. Alternative Productivity of Tthe Plugged Zone, $\Delta Q_L$

The productivity loss at the plugged zone should be compensated by the alternative producing zones in the same well.

$$\Delta Q_L = \frac{Q_L - Q_L'}{Q_L} \quad (7)$$

Where,

$Q_L'$ = productivity of alternative producing zones

$Q_L$ = productivity loss caused by water shutoff

$\Delta Q_L$ = relative difference

D. Flowing Pressure, $\Delta P_w$

$$\Delta P_w = (P_w - \overline{P_w}) / \overline{P_w} \times 100\% \geq 10\% \quad (8)$$

Where,

$\Delta P_w$ = relative difference between flowing pressure of the plugged well and average flowing pressure of the whole tract, %

$P_w$ = flowing pressure of the plugged well, MPa

$\overline{P_w}$ = average flowing pressure of the whole tract, MPa

The larger $\Delta P_w$ is, the better the effect is.

E. Index for Comparing Liquid Production Enhancement and Water Shutoff, $\Delta D$

Usually, if conditions permitted, liquid production enhancement should be preferentially adopted. Nevertheless, water shutoff should be applied if sales profit created by liquid production enhancement is smaller than the total cost, i.e., a bigger $\Delta D$ suggests water shutoff be applied.

$$\Delta D = \{S_c / [P_c - (36.6 + 3.04 f_w / (1 - f_w))] - A[B(1 - R) + (1 - f_{wf1})R]Q_L\} / \{A[B(1 - R) + (1 - f_{wf1})R]Q_L\} \times 100\% \quad (9)$$

*Where,* $A = \frac{P_{wf1} - P_{wf2}}{P_r - P_{wf1}}$

$B = 1 - f_{wn1}$

While $\Delta D \geq 10\%$, water shutoff should be selected.

F. Profit Obtained Through Water Shutoff, $\Delta D'$

Water shutoff will increase oil production and decrease water production. Certain income will be produced by this way. The income $\Delta D'$ should be larger than the total cost. The larger $\Delta D'$ is, the better water shutoff is.

$$\Delta D' = [(1 - f_w)Q_L R_{oi}(P_c - S_v) + f_w Q_L R_{wd} B - S_{pl} / (E_{pl} T_e)] / [S_{pl} / (E_{pl} T_e)] \quad (10)$$

G. Plane Contradiction of The Target Zone, M

For the reason that water shutoff is able to weaken plane contradiction, so water shutoff is a preferential choice for zones with sharp plane contradiction.

**Selection of Target Wells and Target Zones Using Fuzzy Theory** [1]

The method involves the following three steps.

A. The First Step

Firstly, wells and zones obviously unfit for water shutoff should be artificially picked and thrown away. These wells and zones are mainly the following ones.

1. those very different from the aforementioned indexes
2. those fit for other measures
3. those fit for neither mechanical water plugging nor chemical water plugging

Except for the three cases, water shutoff is available.

B. The Second Step

In the second step, first level judgement is conducted using fuzzy method.

Give points to every index for all wells according to the value. If value of the ith index of the jth well is $D_j$ and the upper and the lower limit of it are $D_{up}$ and $D_{down}$ respectively, then the following two parameters can be calculated.

$$a = 0.5(d_{up} + d_{down})$$

$$b = [-(d_{up} - d_{down})/(4l \times n \times 0.5)]^{1/2}$$

Then tij and rij can be calculated respectively, as shown in (11) and (12).

$$t_{ij} = (d_i - a)^2 - b^2 \times \ln x \qquad (11)$$

$$r_{ij} = \exp(-t_{ij}/b^2) \qquad (12)$$

Then we obtain the fuzzy analogous matrix.

$$R_1 = \begin{bmatrix} r_{11}, r_{12}, \dots\dots\dots, r_{1n} \\ r_{21}, r_{22}, \dots\dots\dots, r_{2n} \\ r_{31}, r_{32}, \dots\dots\dots, r_{3n} \\ r_{41}, r_{42}, \dots\dots\dots, r_{4n} \end{bmatrix} \begin{matrix} K \\ Ö \\ S \\ K_f \end{matrix}$$

$$R_2 = \begin{bmatrix} r_{11}, r_{12}, \dots\dots\dots, r_{1n} \\ r_{21}, r_{22}, \dots\dots\dots, r_{2n} \\ r_{31}, r_{32}, \dots\dots\dots, r_{3n} \\ r_{41}, r_{42}, \dots\dots\dots, r_{4n} \end{bmatrix} \begin{matrix} H \\ N_p \\ S_w \\ Kh/u \end{matrix} \qquad (13)$$

$$R_3 = \begin{bmatrix} r_{11}, r_{12}, \dots\dots\dots, r_{1n} \\ r_{21}, r_{22}, \dots\dots\dots, r_{2n} \\ r_{31}, r_{32}, \dots\dots\dots, r_{3n} \\ r_{41}, r_{42}, \dots\dots\dots, r_{4n} \end{bmatrix} \begin{matrix} P_e \\ Q \\ ç \\ \Delta P \end{matrix}$$

Apply $B_i = A_i \times R_i$ to calculate $B_i$.

Reservoir property is $B_1 = (b_{11}, b_{12}, b_{13}, \dots\dots\dots \;\dots, b_{1n})$.

Oil related property is $B_2 = (b_{21}, b_{22}, b_{23}, \dots\dots, b_{2n})$.

Productivity related property is $B_3 = (b_{31}, b_{32}, b_{33}, \dots\dots b_{3n})$.

Where, $b_{ij} = \sum_{k=1}^{4} A_{ik} r_{kj}$.

C. The Third Step

The third step is to execute the second level fuzzy judgement.

The fuzzy analogous matrix here can be formulated through the first level judgement.

$$R = \begin{bmatrix} B_1 \\ B_2 \\ B_3 \end{bmatrix} \qquad (14)$$

Where,

$B_1$ = reservoir property

$B_2$ = oil related property

$B_3$ = productivity property

At last, based on the formula $B = A \times R$ (Matrix multiplication), we can obtain (15).

$$B = \{b_1, b_2 \dots\dots, \quad b_n\} \qquad (15)$$

Where, $b_i = \sum_{k=1}^{B} A_k b_{ki}$.

Then $\bar{b_i}$ can be obtained through (16).

$$\bar{b_i} = b_i / \sum_{i=1}^{N} b_i \qquad (16)$$

Final choice can be made according to the calculated $\bar{b_i}$ and its standard distribution.

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