A Study of the Displacement Efficiency and Swept Efficiency to Enhance Oil Recovery

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***Abstract* — Taking the offshore heterogeneous reservoirs in Suizhong 36-1 oilfield as the subject of our study, the work in this paper has: i) prepared a 2-D tri-laminar heterogeneous physical model, ii) combined the oil mass data at the macroscopic level, iii) used the method of saturation monitoring in rock-electric experiment to monitor the conditions of: iii-a) swept efficiency and iii-b) displacement efficiency during the stage of: iii-c) polymer flooding, and iii-d) binary combination flooding, for heterogeneous reservoirs, iv) deduced the calculation formula for increasing the value of oil recovery, v) split the contribution into enlarging swept volume and enhancing displacement efficiency, vi) calculated the displacement efficiency and swept efficiency of every layer during the different stages, vii) quantized the contribution value of displacement efficiency and swept efficiency to enhance oil recovery, and finally viii) analyzed the contribution of every layer to enhance oil recovery. The results show that: i) increasing enhanced oil recovery in the stage of polymer flooding and binary combination flooding mainly comes from the contribution of swept volume, ii) the contribution of enhanced oil recovery in high permeability layer during the stage of polymer flooding is the biggest, iii) the contribution of enhanced oil recovery in low permeability layer during the stage of binary combination flooding is the biggest, and iv) the middle permeability layer is second biggest. The potential after binary combination flooding is mainly still in the low and middle permeability layers.**

Keyword - Oil recovery*; *swept efficiency*; *displacement efficiency*; *contribution

Ⅰ. INTROUCTION

The sustained growth of offshore oil production has become an important part of oil production capacity to replace, it is imperative to develop the enhanced oil recovery technology of offshore with the increasing difficulty of exploration and efficient development of oil and gas resources in offshore[1,2]. All kinds of chemical flooding technology have become more mature because of the successful implementation of chemical flooding in onshore oilfield, especially the large-scale industrial application of polymer flooding [3,4,5]. Chemical flooding technology has been gradually developed to offshore oilfield whose reservoir is complex and injection conditions are harsh and risk characteristics is high [6,7]. As the most potential chemical flooding technology, polymer flooding and binary flooding have become the first displacement way after water flooding in the offshore oil field [8,9,10]. Aim at the present conditions of reservoir and the situation of exploitation in Suizhong 36-1 oilfield, this paper has used AP-P5 polymer and BHM2 surfactant to formulate the binary multisystem, compared and analyzed the contribution of swept efficiency and displacement efficiency during the polymer flooding and binary combination flooding after polymer flooding through the comparative experiments of physical simulation by the tri-laminar heterogeneous and thickness physical model.

Ⅱ. EXPERIMENT DETAILS

A. Experimental conditions

- The experimental water is the simulated formation water of Offshore oil whose salinity is 9374mg/L; The experimental oil is the simulation oil which is mixed with crude oil and kerosene oil and the viscosity is 70mPa·s when the temperature is 65 ℃.
- The physical model which are used in the experiment are quartz sand epoxy cemented heterogeneous saturation monitoring cores whose specifications are 300 ×300 × 45mm and electrodes are arranged different permeable layer and permeability of each layer is respectively 4800, 2200, 500×10^{-3}μm^2.
- The polymer used in the experiments during polymer flooding stage is AP-P4 hydrophobic associated polymer whose concentration is 2000 mg/L and the viscosity is 42 mPa·s.
- The polymer used in the experiments during binary combination flooding stage is AP-P5 hydrophobic associated polymer whose concentration is 1750 mg/L and mass concentration of BHM2 surfactant is 0.2% and the viscosity is 34.5 mPa·s, the viscosity of the binary multisystem is 34.5 mPa·s.
- The experiment are conducted under the temperature condition of 65 ℃; The injection speed is 3 ml/min. The experiment scheme is that water flooding is conducted until the water cut is 95%, then the polymer whose volume is 0.3 multiples of pore volume injected is injected, next the binary combination flooding are conducted and injection of

binary multisystem is 0.3 multiples of pore volume injected, finally the further water flooding is conducted until the water cut is 95%.

B. The introduction of monitoring method

The literatures about saturation monitoring show that rock-electric experiment is the most extensive method to monitor the oil saturation, whose theoretical base is Archie's formulas, whose core thought is that there is a function relationship between the electrical resistivity and oil saturation for the two points on the rock of reservoirs, if the relationship can be found, the oil saturation can be judged by electrical resistivity.

The monitoring technology of oil saturation in this paper has taken above theories as the theoretical basis, used real-time monitoring system to monitor the oil saturation of the electrode points which is laid on the two-dimensional physical model during the experiments, the laid electrode points divide the two-dimensional physical model into different grids, the swept condition of the monitoring points could be grasped by the change of oil saturation, the monitoring points are swept when the oil saturation is lower than the initial value at the end of a stage of displacement, the data of displacement efficiency could be calculated by combining the swept condition with the condition of oil recovery in macroscopic.

Ⅲ. THE CALCULATION OF SWEPT VOLUME

In order to study the swept conditions of the every layer, the two-dimension heterogeneous physical models were divided into the uniform grids whose size was 2.5×2.5cm according to the different permeability, a couple of electrode points were laid in every grid, and the setting map is as shown as Fig.1.

Considering the influence of electrodes to seepage, the oil saturation of the grid without the laid electrodes was calculated according to the interpolation results, there has conducted many interpolations and production matching to ensure the veracity of the interpolation results in the experiments.

Draw the distribution map of every layer during the every stage after mesh generation, calculate the swept condition for every grid, if a certain grid is swept, which means that oil saturation is lower than initial oil saturation and the oil saturation of the grid at a testing time point and next changes substantially, it is swept completely for the certain grid; if the certain grid has already been swept but the range ability of oil saturation a testing time point and next is not big, it is swept half for the certain grid. The finally calculation formula is as shown as Formula 1.

$$E_v = \frac{\sum a}{b} \tag{1}$$

Fig.1-1

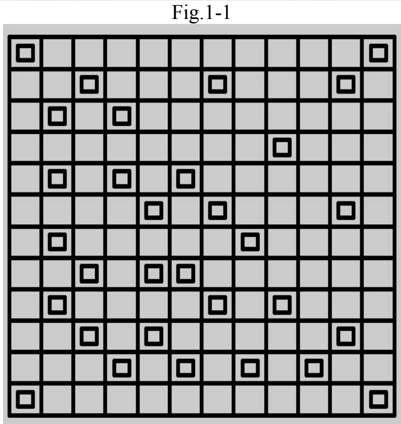

Fig.1-2

Fig.1 The picture and mesh generation for the two-dimensional heterogeneous planar model

TABLEⅠ. THE SWEPT EFFICIENCY OF EVERY LAYER FOR THE TWO-DIMENSIONAL HETEROGENEOUS PHYSICAL MODEL AT EVERY DISPLACEMENT STAGE

Layer	The swept efficiency (%)				
	Water flooding	Polymer flooding	Increasing value	Binary combination flooding	Increasing value
High permeability layer	80.56	93.75	13.19	98.61	4.86
Middle permeability layer	71.53	75.69	4.17	93.40	17.71
Low permeability layer	20.83	45.14	24.31	85.42	40.28
Overall the model	57.64	71.53	13.89	92.48	20.95

Among the above formula, a represents for the number of swept grid, b represents for the number of all grids.

The swept efficiency of the two-dimensional heterogeneous model in every stage was calculated through the above method, the result is as shown as Table Ⅰ.

The ultimate swept efficiency of polymer flooding in middle and low permeability layer for the two-dimensional heterogeneous physical model respectively is 75.69%, 45.14%, which respectively is 93.40%, 85.42% after binary combination flooding. The above shows that the binary multisystem has enlarged the swept volume of middle and low permeability layer, and mainly enlarged the swept volume of low permeability layer.

Ⅳ. THE CALCULATION OF DISPLACEMENT EFFICIENCY

The degree of reserve recovery can't be calculated by measuring produced liquid of every layer for two-dimensional heterogeneous model, so the experiments used monitoring the variation of oil saturation of monitoring point to calculate it, the calculation formula is as shown as Formula 2.

$$E_i = \frac{\sum_{k=1}^{b}(S_{ok} - S_{ohk}) \cdot V_{bi}}{\sum_{k=1}^{b}(S_{ok} \cdot V_{bi})} = \frac{\sum_{k=1}^{b}(S_{ok} - S_{ohk})}{\sum_{k=1}^{b} S_{ok}} \tag{2}$$

Among the above formula, V_{bi} represents for the pore volume of the grid, S_{ok} represents for the initial oil saturation of the *k*th monitoring point at the *i*th layer of the model, S_{ohk} represents for the oil saturation of the *k*th monitoring point at the *i*th layer of the model at the end of displacement.

The data of displacement efficiency is as shown as Table Ⅱ.

TABLE II. THE DISPLACEMENT EFFICIENCY OF EVERY LAYER FOR THE TWO-DIMENSIONAL HETEROGENEOUS PHYSICAL MODEL AT EVERY DISPLACEMENT STAGE

Layer	The displacement efficiency (%)				
	Water flooding	Polymer flooding	Increasing value	Binary combination flooding	Increasing value
High permeability layer	63.50	65.20	1.70	70.50	5.30
Middle permeability layer	47.60	50.60	3.00	63.50	12.90
Low permeability layer	22.80	28.60	5.80	54.00	25.40
Overall the model	56.59	61.43	4.84	68.81	7.38

Ⅴ. THE CONTRIBUTION OF DISPLACEMENT EFFICIENCY AND SWEPT EFFICIENCY TO ENHANCED OIL RECOVERY DURING THE BINARY COMBINATION FLOODING

A. The contribution of displacement efficiency and swept efficiency to enhanced oil recovery

The contribution of swept volume (or displacement efficiency) to enhanced oil recovery is the percentage between the extraction of oil because of the increasing of swept volume (or displacement efficiency) and the overall extraction of oil at a certain stage in a certain reservoir. The enhanced oil recovery called ΔR is the difference value between ultimate recovery efficiency and the recovery efficiency before taking measures, and the recovery efficiency called R is the product between swept efficiency called E_{V} and displacement efficiency called E_{D}, so the Formula 3 could be deducted which is as shown as following.

$$\begin{aligned}\Delta R &= (E_{\mathrm{V}} + \Delta E_{\mathrm{V}}) \cdot (E_{\mathrm{D}} + \Delta E_{\mathrm{D}}) - E_{\mathrm{V}} \cdot E_{\mathrm{D}} \\ &= E_{\mathrm{V}} \cdot \Delta E_{\mathrm{D}} + E_{\mathrm{D}} \cdot \Delta E_{\mathrm{V}} + E_{\mathrm{V}} \cdot \Delta E_{\mathrm{D}} \\ &= (E_{\mathrm{D}} + A \cdot \Delta E_{\mathrm{D}}) \cdot \Delta E_{\mathrm{V}} + \\ &\quad \left[E_{\mathrm{V}} + (1-A) \cdot \Delta E_{\mathrm{V}}\right] \cdot \Delta E_{\mathrm{D}}\end{aligned} \tag{3}$$

Among the above formula, ΔE_{V} is the increased value of swept efficiency, ΔE_{D} is the increased value of displacement efficiency, A is the percentage.

It can be seen from formula 3 that the enhanced oil recovery can be divided into two parts, one is $(E_{\mathrm{D}} + A \cdot \Delta E_{\mathrm{D}}) \cdot \Delta E_{\mathrm{V}}$ which the change value of the recovery efficiency caused by the change of swept efficiency, the other is $\left[E_{\mathrm{V}} + (1-A) \cdot \Delta E_{\mathrm{V}}\right] \cdot \Delta E_{\mathrm{D}}$ which the change value of the recovery efficiency caused by the change of displacement efficiency. The value of A can't ensure in the experiments, but the contribution of swept

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efficiency and displacement efficiency to enhanced oil recovery during the stages of polymer flooding and binary combination flooding can be sure under the condition of different splits by ensuring the range of values for A as shown as Fig.2, Fig.3 and Fig.4.

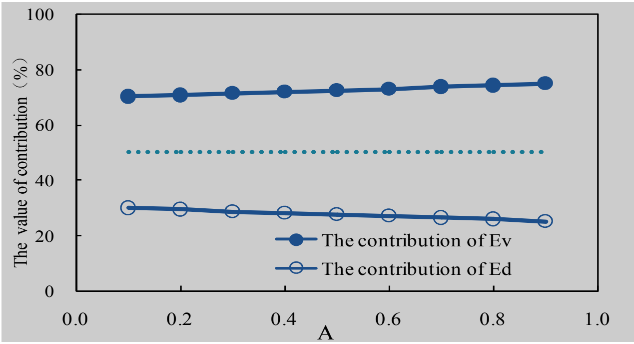

Fig.2 The contribution at polymer flooding stage for two-dimensional heterogeneous physical model

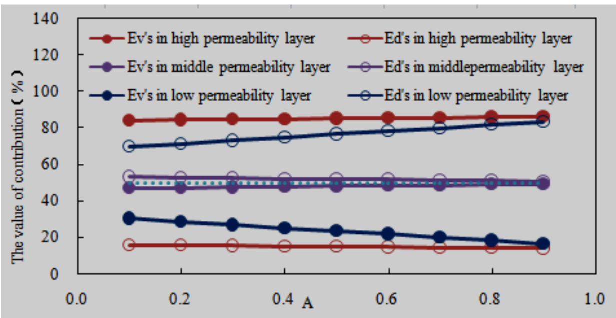

Fig.3 The contribution of each layer at polymer flooding stage for two-dimensional heterogeneous physical model

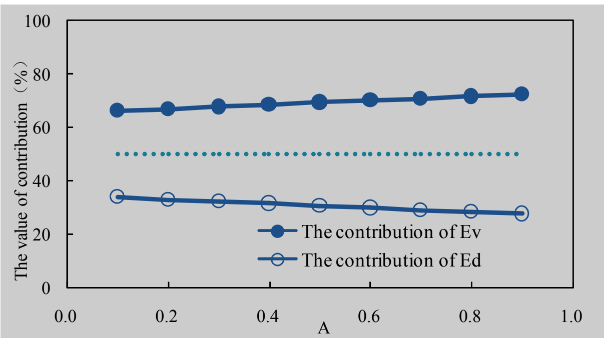

Fig.4 The contribution at binary combination flooding stage for two-dimensional heterogeneous physical model

It can be seen from Fig.2, Fig.3 and Fig.4 that the contribution of swept efficiency and displacement efficiency to enhanced oil recovery is influenced by the value of A, which is because that compared with polymer flooding, the binary combination flooding can not only enlarge swept volume but also enhance displacement efficiency, but it mainly enlarges swept volume on the whole.

The contributions are calculated according to the monitoring results of single layer for the two-dimensional physical model at the stage of binary combination flooding, which is as shown as Fig.5.

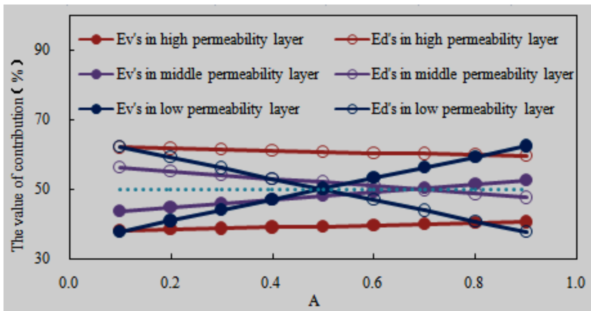

Fig.5 The contribution of each layer at binary combination flooding stage for two-dimensional heterogeneous physical model

It can be seen from Fig.5 that the contribution of displacement efficiency to enhanced oil recovery for the high permeability layer during combination flooding is influenced less by the value of A, which shows that the binary combination flooding mainly enhanced the displacement efficiency of high permeability layer; the contribution of displacement efficiency to enhanced oil recovery for the middle and low permeability layer during combination flooding is influenced significantly by the value of A, which shows that the binary combination flooding can not only enhance the displacement efficiency of middle and low permeability layer but also enlarge the swept efficiency of the two layers.

B. The contribution of each layer to enhanced oil recovery

Through the experimental results of cores with different sizes and permeability, the displacement efficiency and swept efficiency for each layer is used to calculate the contribution of each layer to enhanced oil recovery, the calculation results are as shown as TableⅢ. It can be seen from TableⅢ. that the contribution of middle permeability layer to enhanced oil recovery reaches to 61.79% because the polymer flooding mainly enlarged the swept volume of middle permeability layer, the degree of enlarged swept volume for low permeability layer at the stage of binary combination flooding is lower, but the contribution of low permeability layer to enhanced oil recovery which is 46.43% is bigger because the binary multisystem enhanced the displacement efficiency.

The data from Table □ shows that though the polymer flooding mainly enlarged the swept volume of every layer, its contribution to enhanced oil recovery mainly came from middle and low permeability layers, and the middle and high permeability layers are the main contribution layer for enhanced oil recovery; Compared with polymer flooding, the binary combination flooding has enhanced the displacement efficiency of each layer, and mainly acts on low permeability layer.

TABLEⅢ. THE CONTRIBUTION OF EACH LAYER AT BINARY COMBINATION FLOODING STAGE FOR TWO-DIMENSIONAL HETEROGENEOUS PHYSICAL MODEL

Layer	The contribution of each layer to enhanced oil recovery	
	Polymer flooding compared with water flooding (%)	Binary combination Flooding compared with polymer flooding (%)
High permeability layer	50.97	16.58
Middle permeability layer	18.77	35.83
Low permeability layer	30.26	47.59

Synthesizing the analysis of contribution at every stage for different reservoirs, the polymer flooding mainly acts on middle and high permeability layers and employs the remaining oil of the middle and high permeability layers in the plane, and takes enlarging the swept volume of every layer as the principle thing in the longitudinal; binary combination flooding has enlarged the swept volume of every layer by a large margin and enhanced the degree reserve recovery of high and middle permeability layers in plane and longitudinal, and mainly acts on low permeability layer and displaces the remaining oil of low permeability layer by a large margin; synthesizing the swept laws in the plane and longitudinal, it can be seen that the potential of polymer flooding mainly shows on the middle and high permeability layers and reduces the remaining oil of middle and high permeability layers in the plane, but the binary combination flooding mainly acts on the low permeability layer.

C. The relative potential of swept efficiency and displacement efficiency

In conclusion, the main function of polymer of offshore oilfield is enlarging the swept volume, and the function of binary combination flooding takes enlarging the swept volume as the principle thing and takes enhancing the displacement efficiency as a supplement, so once the main purpose whether enlarging the swept volume or enhancing the displacement efficiency in the further production is ensured, the following displacement measures could be ensured. This research has calculated the relative potential of swept efficiency and displacement efficiency, on this basis, has provided a lot of suggestions for offshore oil field after binary combination flooding. Difference value between the final swept efficiency and swept efficiency at a certain stage is defined as ΔE_{V}, difference value between the final displacement efficiency and displacement efficiency at a certain stage is defined as ΔE_{D}, the relative potential called i of swept efficiency and displacement efficiency is defined as shown as Formula 4.

$$i = \frac{\Delta E_{\mathrm{V}}}{\Delta E_{\mathrm{D}}} \tag{4}$$

If the value of i is bigger than 1, the further measures should take enlarging swept volume as the principle thing and the potential is bigger relatively; if the value of i is equal or lower than 1, the potential of enhancing displacement efficiency is bigger at the next stage; $i = 1$ is the turning point of development method, the value of i can be reduced appropriately considering the economic factors. The calculation results of the value of i for every layer is as shown as TableⅣ.

TABLEⅣ. THE CALCULATION RESULTS OF THE VALUE OF I FOR EVERY LAYER

Layer	The value of i after binary combination flooding
High permeability layer	0.31
Middle permeability layer	0.89
Low permeability layer	1.28
The whole	1.72

It can be seen from the TableⅣ that the value of i for high permeability layer after binary combination flooding is 0 or nearly, the middle and low permeability layer's is bigger than 1 or nearly, so in order to enhance the oil recovery in high permeability layer, the measure of enhancing displacement efficiency should be put on the first place; for the middle and low permeability layer, the measure of enlarging swept efficiency should be put on the first place.

Aim at the heterogeneous reservoirs in offshore oilfield, in order to make further improvement on enhanced oil recovery, putting the infill wells on the two sides of mainstream in low and middle permeability layers should be considered, and the position of low permeability layer's potential is bigger, considering the polymer is taking enlarging swept volume as the principle thing, economic benefits and other factors, the polymer should be injected into the infill wells to increase the drawdown pressure, and then enlarge the swept volume in low and middle permeability layers to reach the purpose of enhanced oil recovery.

Ⅵ. CONCLUSIONS

For the two-dimensional physical model, the overall enlarging swept efficiency at the stage of polymer flooding increased by 13.89%, the binary combination flooding's increased by 20.95%, the binary combination flooding has further enlarged the swept volume of heterogeneous reservoirs by a large margin; the overall enhancing displacement efficiency at the stage of polymer flooding increased by 4.84%, the binary combination flooding's increased by 7.38%, the binary combination flooding could further displace the residual oil after polymer flooding. For the contribution to the reservoirs during the chemical flooding, polymer flooding's mainly came from high permeability layer, binary combination flooding's mainly came from low and middle permeability layer. For the relative potential, the potential acts on the low and middle permeability layers after binary combination flooding. On the whole, for the conditions of Suizhong 36-1 reservoir in offshore oilfield, the contribution of swept efficiency to enhanced oil recovery is bigger than displacement efficiency's at the stage of polymer and binary combination flooding.

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