Effects of Sweep Efficiency and Displacement Efficiency During Chemical Flooding on a Heterogeneous Reservoir*

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Abstract

The processes of flooding—water flooding, polymer flooding and ternary combination flooding—were simulated respectively on a 2-D positive rhythm profile geological model by using the ASP numerical modeling software developed by RIPED [1]. The recovery coefficient, remaining oil saturation, sweep efficiency and displacement efficiency were calculated and correlated layer by layer. The study shows that the displacement efficiency and sweep efficiency play different roles in different layers for such highly heterogeneous reservoirs. The displacement efficiency contributes mainly to the high permeable zones, the sweep efficiency to the low permeable zones, both of which contribute to the middle permeable zones. To improve the sweep efficiency in the low permeable zones is of significance for enhancing the whole recovery of the reservoir. It points to an important way for improving the effectiveness of chemical flooding in the highly heterogeneous reservoirs by injecting a ternary combination slug after profile control.

Introduction

Among the numerous factors influencing the recovery efficiency, displacement efficiency and sweep efficiency are two key elements. Alkali/Surfactant/Polymer Flooding chemical system can not only produce an ultra-low interfacial tension but also a high apparent viscosity, so it can improve both displacement efficiency and sweep efficiency. Thus, the ultimate recovery can be enhanced greatly. The sweep efficiency and displacement efficiency take different effects on different layers in the seriously heterogeneous reservoirs in China. Which is the main factor? Which is more important to improve the sweep efficiency or the displacement efficiency? How to quantitatively describe the effects of the sweep efficiency and the displacement efficiency during Alkali/Surfactant/Polymer chemical flooding? In this paper, the processes of flooding, including water flooding, polymer flooding and ternary combination flooding, are simulated respectively on a positive rhythm 2-D profile geological model (Fig. 5) by using

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the ASP (Alkali/Surfactant/Polymer) numerical modeling software developed by RIPED. The recovery coefficient, remaining oil saturation, sweep efficiency and displacement efficiency were calculated and correlated layer by layer. It has significant implications to further enhance the ultimate recovery [2].

The concept and theoretic analysis of displacement efficiency and sweep efficiency

In order to study the effect of the displacement efficiency and the sweep efficiency quantitatively, this paper presents the calculation methods of the displacement efficiency and the sweep efficiency.

The residual saturation for each phase depends on the Capillary Number, Nc, defined as follows:

$$Nc=|\sum_j \mu_j V_j|/\sigma \quad (1)$$

$$Srj=Srj(Nc) \quad (2)$$

Where Nc-- Capillary Number;

μ_j—Viscosity for phase j;

V_j—Darcy velocity;

Srj-- The residual saturation for phase j;

and σ--Interfacial tension.

The displacement efficiency and the sweep efficiency for each layer and each grid can be calculated in the following steps.

1) Calculate interface tension for each grid

Interfacial tension is a function of the concentrations of the injected alkali, the surfactant and the polymer for a given oil and water salinity:

$$\sigma=\sigma\ (C_{OH}, C_S, C_P) \quad (3)$$

where C_{OH}-- alkali concentration; C_S-- surfactant concentration; C_P-- polymer concentration.

2) Calculate residual oil saturation for each grid

The ternary combination flooding: calculated by the interpolation with the chart of interface tension and residual oil saturation;

The water flooding: employing Sor, the endpoint value of the phase-permeability curve.

Thus the residual oil saturation for each grid can be calculated.

3)calculate displacement efficiency Ed

$$Ed=(Soi-Sor)/Soi \quad (4)$$

4)calculate recovery efficiency R

$$R=(Soi-So)/Soi \quad (5)$$

5)calculate sweep efficiency Ev

$$Ev=R/Ed \quad (6)$$

Calculate the sweep efficiency Ev and the displacement efficiency Ed of the whole and of each layer by the weighted averages.

Geological modeling and fundamental parameters

Fundamental physical and chemical parameters

We adopt a pre-studied optimum chemical compound ingredient with 1.2% of alkali(A), 0.3% of surfactant (S) and 1500mg/L of polymer (P). With the surfactant concentration variation, the interfacial tension changes accordingly under different alkali concentrations. (Fig. 1) It also changes along with the residual oil saturation. (Fig. 2) The polymer viscosity changes with its concentration under different alkali concentrations. (Fig. 3)

The other parameters are listed as follows:
Percentage of the pore volume swept by polymer flooding: 0.9
Diffusion coefficient of the components such as polymer and surfactant (cm2/sec): 3.4E-4;
Alkali consumption rate during a long period:1.0E-7mg/g/day;
Adsorption holdup of the polymer: 34μg/g sand adsorption with a 1,000ppm of concentration;
Adsorption holdup of the surfactant: 0.3mg/g sand adsorption with a 0.4% of concentration.

Basic fluid parameters

The relative permeability curve of water flooding is shown in Fig. 4. Other parameters are shown in Table 1.

Mathematical model of chemical flooding

The mathematical model employed in this paper is a 3-D numerical compositional model, which takes into consideration comprehensively the main displacement mechanisms and all physics and chemical phenomena of the alkali/surfactant/polymer (ASP) flooding. All phenomenological parameters in this simulation have a definite physical sense and are obtainable from experimental data without extra assumption, so that it is more practical to simulate real problems.

The model has the following basic assumptions: The reservoir is isothermal; local equilibrium exists; generalized Darcy Law is applicable to multiphase flow; and generalized Fick Law is applicable to multi-component dispersion. Three phases (w, s, o) are considered in the model. Owing to a low concentration of surfactant (generally $C_s<1\%$) in ASP flooding, two phases (w, o) are essentially taken into consideration in most cases. N components are designed mainly as follows: w, o, s, Na^+; Ca^{++}; Mg^{++}; OH^-; CO_3^{2-}; (SiO_3^{2-}, SiO_4^{4-}); CO_2; HA; crosslinking agent and rock components, etc.

A comparison of experimental results vs. numerical simulation

It is shown in Fig. 5 that the numerical simulation results have good match with experimental results. The experiment was classified into three steps. First, water is injected until its water-cut reaches 95%. At this moment, inject 0.3PV chemical compound and continue to inject water until the water water-cut reaches 98%. The experimental data were described in Table 2.

Numerical modeling method

We used the ASP numerical modeling software developed by RIPED [1]. We aim to investigate the effectiveness of the chemical flooding at a high water-bearing stage. A typical reservoir profile model was designed in order to correlate the effectiveness of each grid and each layer (Fig. 6). It was classified into three layers in the vertical direction, with a thickness of 5m for each and a permeability variation coefficient of 0.75. First, water is injected until its water-cut reaches 90%. The geological model shows that the production zone under this condition still has a feature of high oil saturation because the high permeable zone was flooded by water preferentially, while the low permeable zone was flooded slightly[3]. At this moment, inject 0.3PV chemical compound and continue to inject water until the water water-cut reaches 98%. Then the effectiveness of the chemical flooding in each layer can be correlated.

Correlation between the calculation results of each zone

Here we begin to analyze the contributions of the sweep efficiency and displacement efficiency of the ASP flooding, the polymer flooding and the water flooding respectively in each zone. Fig. 7-9 give the curves of sweep efficiency, displacement efficiency and recovery efficiency of the ASP flooding, the polymer flooding and the water flooding respectively in each zone.

It is shown in Fig. 7 that the recovery efficiency by using the polymer flooding in the top zone is obviously higher than those by the water flooding and the ASP flooding, and the recovery efficiency is a little enhanced by ASP flooding than the water flooding. The displacement efficiencies of these three flooding methods are about the same. So, the recovery efficiency under this condition depends mostly on the sweep efficiency. From the sweep efficiency curves, we can see that the sweep efficiency by using the polymer flooding in the top zone is obviously higher than those by the water flooding and the ASP flooding, and the sweep efficiency is a little enhanced by ASP flooding than the water flooding. Thus we can draw a conclusion that the sweep efficiency plays the most important role in the recovery efficiency of the low permeable zone.

From Fig.8 we can see that for the mid-zone, the sweep efficiency of the ASP and polymer flooding tends to be the same, which is 20% higher than that of the water flooding.

At the same time, the displacement efficiency of the ASP flooding is 20% higher than that of the polymer and water flooding, while the latter two have the same values. Among the three flooding methods, the recovery efficiency of the ASP flooding is the highest, the polymer flooding lower, and the water flooding the lowest. So, the recovery efficiency of the mid-permeable zone is influenced by both the sweep efficiency and the displacement efficiency.

From Fig. 9 we can see that the recovery efficiency of the ASP flooding in the bottom zone is much higher than those of the other two methods. The displacement efficiency plays the most important part in the recovery efficiency because the sweep efficiencies of these three methods are almost the same. The displacement efficiencies of the polymer and water flooding are equivalent, which is much lower than that of the ASP flooding. So the recovery efficiency of the bottom high permeable zone is mostly influenced by the displacement efficiency.

To summarize the above analyses, the displacement efficiency play principle roles in the high permeable zones while the sweep efficiency in the low permeable zone. The mid-zone depends on the both. Due to the fairly high residual oil saturation in the low permeable zone at the high water-bearing stage, the recovery efficiency in the low permeable zone should be enhanced in order to enhance the whole recovery efficiency of the ASP flooding. We should work on special methods to improve the sweep efficiency of the low permeability layer. It is shown from the figure that the recovery efficiency of the low permeable zone is only about 40% by using the ASP flooding. So the low permeable zone, especially the top low permeable layer, still has relatively large potential to be developed.[4]

Conclusions

1. The development program of the chemical flooding should be planned on the basis of a research of the reservoir geological features. It is of significance for further enhancing the oil recovery efficiency of the chemical flooding to analyze the effects of the displacement and sweep efficiencies quantitatively.

2. On the basis of the research on the 2-D positive rhythm geological model, for a highly heterogeneous reservoir model, the sweep efficiency plays the most important role in the recovery efficiency of the low permeable zone, and the recovery efficiency of the bottom high permeable zone is mostly influenced by the displacement efficiency while the mid-permeable zone is influenced by both the sweep and the displacement efficiencies.

3. For such a heterogeneous positive rhythm reservoir, the polymer flooding improves

the sweep efficiency of the top to mid-zones and the ASP flooding improves the displacement efficiency of the mid to bottom zones. So, how to enhance the recovery efficiency of the low permeable zones by the ASP flooding is the key challenge for improving the total recovery efficiency of the chemical flooding the sweep efficiency of the top to mid-zones and the ASP flooding improves the displacement efficiency of the mid to bottom zones. So, how to enhance the recovery efficiency of the low permeable zones by the ASP flooding is the key challenge for improving the total recovery efficiency of the chemical flooding.

References

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Fundamental parameters	value
simulative well spacing	250m
porosity	30%
Primary oil saturation	0.7
reservoir pressure	12.9MPa
formation oil density	0.86g/cm3
formation water viscosity	0.5 MPa.s
formation water density	1.002g/cm3
formation oil viscosity	6.8 MPa.s

Table 1 Fundamental parameters for simulation model

Fundamental parameters		physical model
Model size		length=50cm
		wide=50cm
		highness=10cm
formation oil viscosity (MPa·s)		10
formation water density (g/cm^3)		0.84
formation water viscosity (MPa.s)		0.61
Primary information: oil saturation (%)		64
porosity %	1□ top zone□	40.7
	2□ mid-zone □	42.8
	3□ bottom zone □	44.9
permeability $10^{-3}\mu m^2$	1□ top zone □	150
	2□ mid-zone □	550
	3□ bottom zone □	2100
Thickness(cm)	1(top zone)	17.76
	2(mid-zone)	17.96
	3□ bottom zone □	15.1

Table 2 Fundamental parameters for experiment

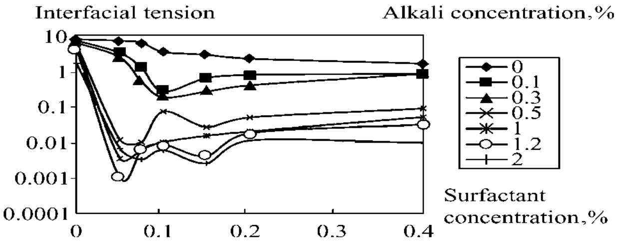

Fig. 1 The interfacial tension changes with the surfactant concentration variation under different alkali concentrations

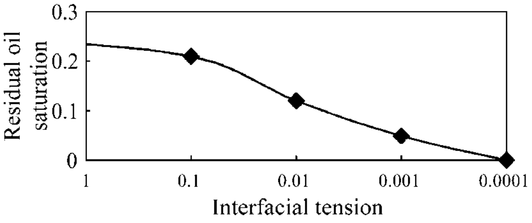

Fig.2 Relation curve of residual oil saturation and interfacial tension

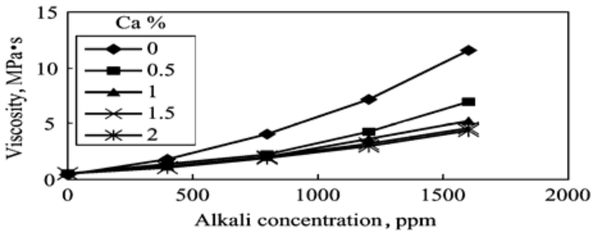

Fig. 3 The polymer viscosity changes with its concentration under different alkali concentrations

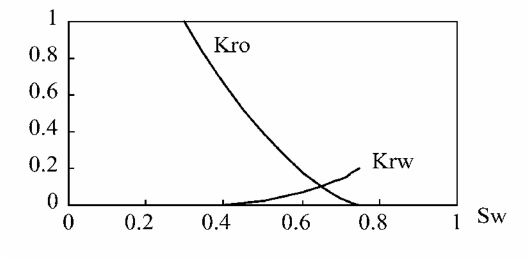

Fig. 4 Relative permeability curve while water flooding

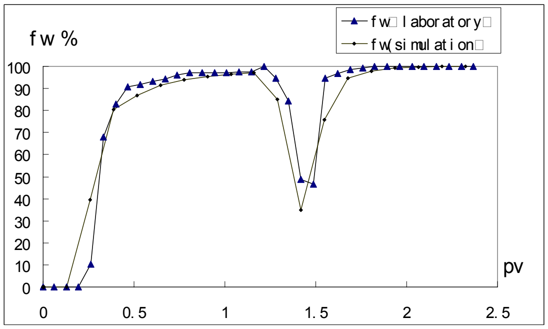

Fig.5 The comparison of experimental water-cut vs. numerical simulation water-cut

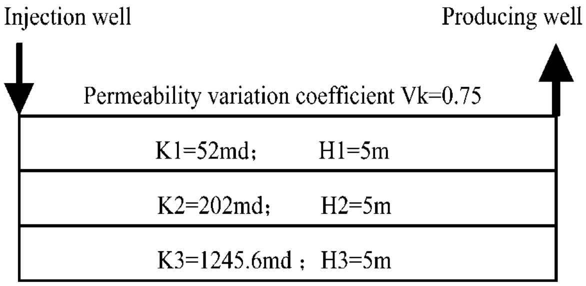

Fig. 6 Geological model

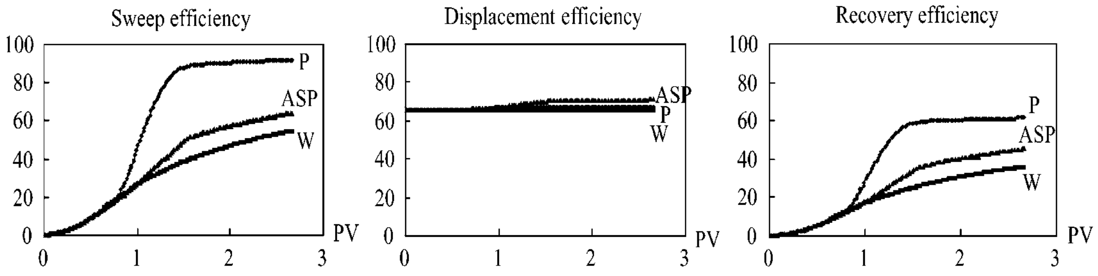

Fig. 7 Curves of sweep efficiency, displacement efficiency and recovery efficiency of the ASP flooding, the polymer flooding and the water flooding respectively in the top zone

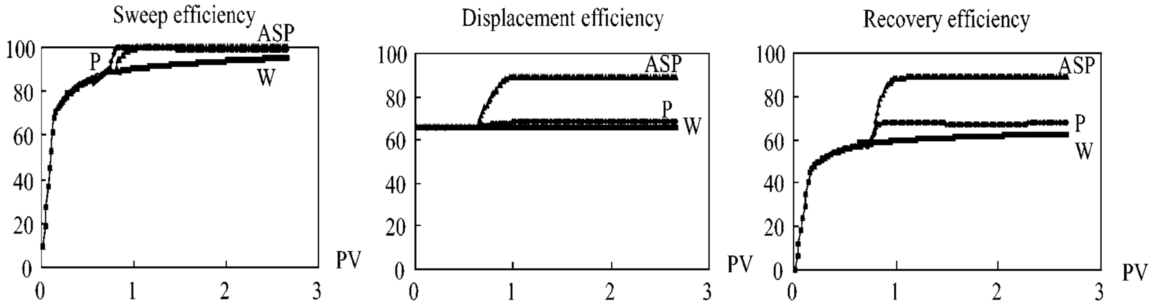

Fig. 8 Curves of sweep efficiency, displacement efficiency and recovery efficiency of the ASP flooding, the polymer flooding and the water flooding respectively in the mid-zone

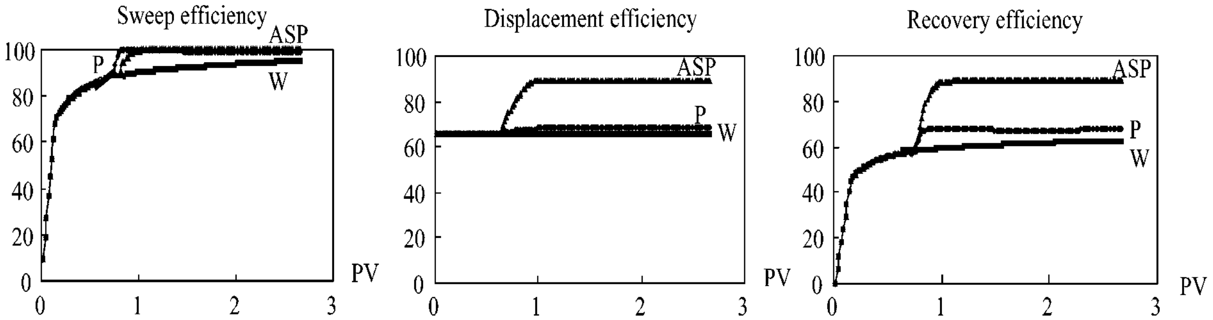

Fig. 9 Curves of sweep efficiency, displacement efficiency and recovery efficiency of the ASP flooding, the polymer flooding and the water flooding respectively in the bottom zone