Foam flooding reservoir simulation algorithm improvement and application

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Abstract

As one of the important enhanced oil recovery (EOR) technologies, Foam flooding is being used more and more widely in the oil field development. In order to describe and predict foam flooding, experts at home and abroad have established a number of mathematical models of foam flooding (mechanism, empirical and semi-empirical models). Empirical models require less data and apply conveniently, but the accuracy is not enough. The aggregate equilibrium model can describe foams' generation, burst, coalescence from mechanism, but it is very difficult to describe. The research considers the effects of critical water saturation, critical concentration of foaming agent and critical oil saturation on the sealing ability of foam and considers the effect of oil saturation on the resistance factor for obtaining the gas phase relative permeability and the results were amended by laboratory test, so the accuracy rate is higher. Through the reservoir development concepts simulation and field practical application, the calculation is more accurate and higher.

Keywords: foam flooding, numerical simulation of reservoir, EOR method, laboratory experiments

1 The mechanism and application of foam flooding

Foam flooding as a new EOR method to develop high water cut, heterogeneous, after polymer flooding fields and enhance oil recovery is so significant [1, 2].

The mechanism of foam flooding mainly has four aspects: 1) selective plugging, plugging water but not oil, plugging high but not low, plugging high permeability layer, profile control effect; 2) The foam increase the gas phase viscosity and effectively reduce the gas phase flow and inhibit gas channeling to enlarge swept volume; 3) foaming agent is strong surfactant which can reduce the oil-water interfacial tension and improve the cleaning ability; 4) Gas in the bubble is high dilatability fluid which can increase reservoir elastic properties (Figure 1, Figure 2).

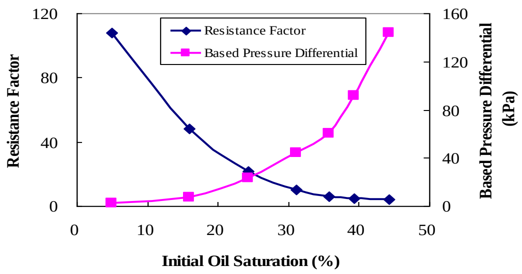

FIGURE 1 The relation curve between initial oil saturation and resistance factor of foam flooding reservoir

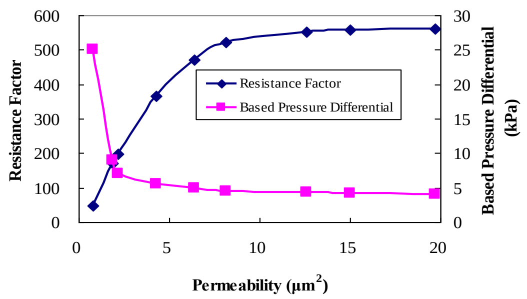

FIGURE 2 The relation curve between permeability and resistance factor of foam flooding reservoir

Whether Roche foaming method or the method of airflow, study on this two kinds of foaming method have shown that surfactant types, molecular structure, medium pore size, surfactant concentration, the gas injection rate and the addition of polymers can affect the foam bubbles' generation and size. Therefore, it is necessary to have an accurate description of the bubble absorption and attenuation, and of the influence of the oil-water two-phase permeability, in order to carry out the reservoir numerical simulation of foam flooding [3, 4].

2 The improvement of foam composite flooding model

2.1 NUMERICAL SIMULATION ACTIVE MODEL OF FOAM FLOODING

Foam flooding is an important one of EOR techniques, which is being used more and more widely in the oil field development. In order to describe and predict foam flooding, experts at home and abroad has established a number of mathematical models of foam flooding (mechanism, empirical and semi-empirical models). Including: PBM model, empirical model, semi empirical relation model, the critical capillary pressure model, bubble aggregate equilibrium model, seepage and network model, Fractal flow theory model, resistance coefficient model, component model, semi general equilibrium model and so on. Diversity of foam models also reflects the immaturity of foam flooding simulation [5-8].

Currently, empirical model is most widely used and it describes the properties of foam from the foam adsorption, attenuation and the effect of foam on relative permeability of gas. Empirical model requires less data and in the laboratory experiments data support which can correctly simulate bubble propulsion, so it is widely used in foam flooding simulation presently [9, 10]. While the general equilibrium model is the future development direction which has a better description from mathematics and physics, it can describe the bubbles formation, burst, coalescence, but the disadvantage of general equilibrium model is difficult to describe and not easy to solve (Table 1).

TABLE 1 Comparison table of numerical simulation model of foam flooding reservoir

Models	Components	Main features	Shortcomings
Empirical model	Oil, gas, water, surfactant	Introduce the mobility correction coefficient to modify the relative permeability of the gas phase and can reflect the effect of foam on gas flow and flow channel and need less data.	Without considering the mechanism about foam generation, flow and coalescence
The aggregate equilibrium model	Oil, gas, water, surfactant, liquid film	There is a perfect description on mathematics and physics and it descript the bubble burst, description and coalescence from mechanism.	Difficult to describe and to solve.

2.2 IMPROVED FOAM FLOODING MODEL

The new foam flooding model is achieved by the mainly following steps.

2.2.1 The main physical and chemical parameters

Foam description: bubble absorption, bubble attenuation, the impact on the gas relative permeability of the foam, the impact on foam stability of the oil phase and so on.

Polymer description: concentration description, viscosity description, adsorption, shearing, inaccessible pore volume, the impacts of residual resistance to aqueous phase and so on.

Surfactants (foaming agents) description: concentration description, interfacial tension changes, relative permeability changes, adsorption and so on.

The influence of description: the effect of polymer on the foam stability, the effect of surfactant concentration on bubble.

2.2.2 Assumed condition

1) The three-phase seven components: the oil phase, water phase (water, polymer, foaming agent, salt), gas (nitrogen, liquid film); 2) No mass exchange between oil and water phase; 3) Ignore the loss of water phase because the water and foaming agent generate foam; 4) Ignore the influence of water and the foaming agent on water phase because bubble burst.

2.2.3 Mathematical equations

The basic equations including seepage equations, convection diffusion equation, physicochemical parameters equation, kinetic equation. The auxiliary equation including phase saturation equation, capillary force equation between phases, the conservation equations of each component [11-14].

1) The continuity equation (based on the material balance principle)

Phase continuity Equation:

$$-\nabla\cdot\left(\rho_l\vec{v}_l\right)+\rho_l q_l=\frac{\partial}{\partial t}\left(\rho_l\phi S_l\right)\quad l=o,g,w6\,. \tag{1}$$

Convection diffusion equation:

$$-\nabla\cdot\left(\vec{v}_w c_i\right)+\nabla\cdot\left(\vec{d}_i\phi f_i S_w\nabla c_i\right)+q_w c_i =\frac{\partial\left(\phi f_i S_w c_i\right)}{\partial t}+\frac{\partial\left[f_i\rho_r\left(1-\phi\right)\hat{c}_i\right]}{\partial t}\quad ,\ i=p,sa,s. \tag{2}$$

The bubble general equilibrium model:

$$-\nabla\cdot\left(n_f\vec{v}_g\right)+\phi S_g\left(G_f-C_f\right)+n_f q_g =\frac{\partial}{\partial t}\left(\phi S_g x_f n_f+\phi S_g x_t n_t\right) \tag{3}$$

"The number of liquid film inflow unit" – "The number of liquid film outflow unit" + "The number of generated liquid film" – "the number of coalescence liquid film" + "Sources and sinks" = "The variation in the number of liquid film in unit".

2) Flow equation (based on seepage law and considering the Starting pressure of bubbles)

$$v_l=f_l(\nabla\Phi_l)\frac{kk_{rl}}{\mu_{la}R_{lk}}\nabla\Phi_l\,. \tag{4}$$

$$f_l(\nabla\Phi_l)=\frac{\left|\nabla\Phi_l\right|-\lambda_1 G_l}{\lambda_2 G_l+\sqrt{\lambda_3 G_l^2+\left|\nabla\Phi_l\right|^2}}\,. \tag{5}$$

2.2.4 Physicochemical parameters model

Physicochemical parameters model is built based on the following principles: 1) Bubble does not affect the relative permeability of oil and water; 2) Polymer components in the aqueous phase increase the viscosity and have diffusion, adsorption, and inaccessible volume with water phase flow; 3) Considering the phenomenon of starting pressure gradient of oil phase and the bubble; 4) Considering the non-Newtonian characteristics of fluid foam, its apparent viscosity was affected by foaming agent concentration, foam structure and gas flow rate; 5) Considering oil effect on the production of foam; 6) Considering porous medium permeability, foaming agent concentration, foam dry (gas liquid ratio) effect on foam resistance factor; 7) The presence of surfactants on the effect of residual oil saturation decreases.

1) The general equilibrium model of flowing bubble.

The correlation function between bubble generation rate and water and gas phase flow rate

$$G_f = k_1 \left|u_g\right|^{1/3} \left|u_w\right| \tag{6}$$

Bubble coalescence rate is a function of gas phase flow rate and movable foam density

$$C_f = k_2^0 \left(\frac{p_c}{\beta(c_p)\cdot p_c^* - p_c} \right)^2 \left|u_g\right| n_f \tag{7}$$

The balance between the flow bubble and the stationary bubble

$$x_f + x_t = 1 \tag{8}$$

$$n_t = \frac{k_f A_f n_f x_f}{(1-x_f)(1+k_f n_f x_f)} \tag{9}$$

$$x_t = x_{t,\max} \frac{\beta n_t}{1+\beta n_t} \tag{10}$$

2) Foam plugging property-foam inhibiting gas channeling model (considering the mechanism of bubble generation in water but rupture in oil)

$$k_{rg} = \begin{cases} k_{rg} = k_{rg}^0 & \text{When } S_w < (S_w^* - \varepsilon) \text{ or } C_{ws} < C_{ws\lim} \text{ or } S_o \ge S_{o\lim} \\ \dfrac{k_{rg}^0}{1+\dfrac{(R-1)(S_w - S_w^* + \varepsilon)}{2\varepsilon}} & \text{When } (S_w^* - \varepsilon) < S_w < (S_w^* + \varepsilon) \text{ and } C_{ws} \ge C_{ws\lim} \text{ and } S_o < S_{o\lim} \\ k_{rg} = \dfrac{k_{rg}^0}{R} & \text{When } S_w > (S_w^* + \varepsilon) \text{ and } C_{ws} \ge C_{ws\lim} \text{ and } S_o < S_{o\lim} \end{cases}$$

The establishment of the gas phase relative permeability correction relationship previously without considering the critical oil saturation effect on the change of relative permeability, but now it considers the influence of critical water saturation, the critical concentration of foaming agent and critical oil saturation on the sealing ability of foam and it can amend gas phase relative permeability by considering the effect of oil saturation on resistance factor, so the factors are considered more comprehensive.

3) Foam plugging property--foam resistance factor calculation model (based on the experimental results)

$$R = A_R \cdot R(K)\cdot R(C_s)\cdot R(\eta)\cdot R(S_O), \tag{11}$$

where: R - Foam resistance factor; K - Absolute permeability; C_S - Foaming agent concentration; η – Foam quality; S_O -—Oil saturation.

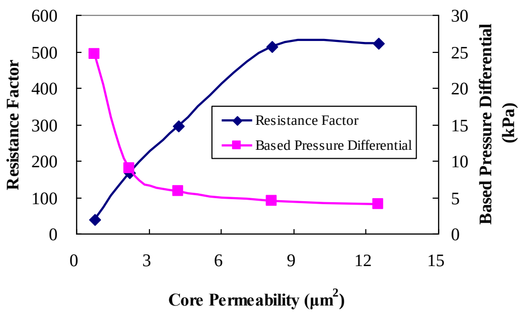

FIGURE 3 The relation curve between core permeability and resistance factor of foam flooding

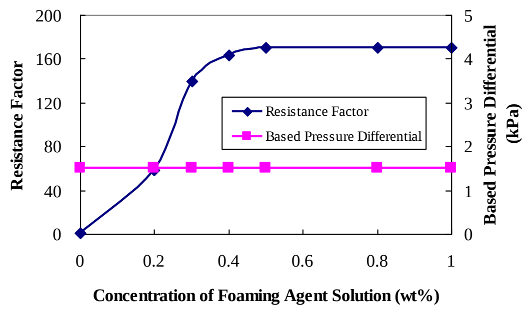

FIGURE 4 The relation curve between foaming agent concentration and resistance factor of foam flooding

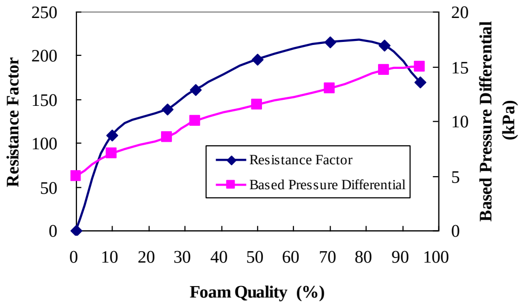

FIGURE 5 The relation curve between foam quality and resistance factor of foam flooding

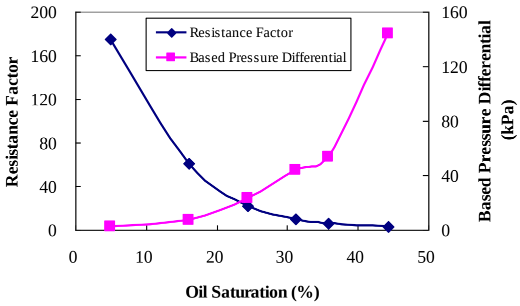

FIGURE 6 The relation curve between oil saturation and resistance factor of foam flooding

From the rules based on the above factors affect the resistance factor, the resistance factor increased with the increase of K, Cs, η and decreased with the increase of So, but it is proportional with R(K), R(Cs), R(ETA), R(So). Therefore, it should consider the expression of foam resistance factor R with K, Cs, η, So [15-16].

2.3 THE RESULTS OF MODEL VALIDATION

We establish a foam flooding model based on the aforementioned results, and substitute with physical models parameters, so that we can solve the differential equation and compare the results with that of sand packed oil displacement experiment model. (Table 2, Figure 7 & Figure 8.

TABLE 2 The Parameter table of foam flooding sand packed test model

Experimental temperature	**The sand packed model**	**Porosity**
60℃	30cm×2.5cm	0.32
Permeability	Injection rate	Injection concentration
1.51μm^2	0.5ml/min	0.5wt%
Crude oil viscosity	Initial oil saturation	Gas-liquid ratio
84mPa·s	0.86	1:30

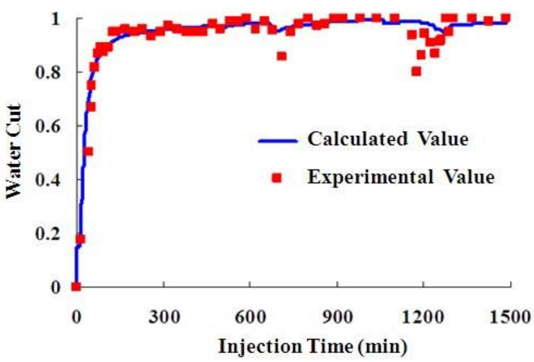

FIGURE 7 The fitting results of water cut

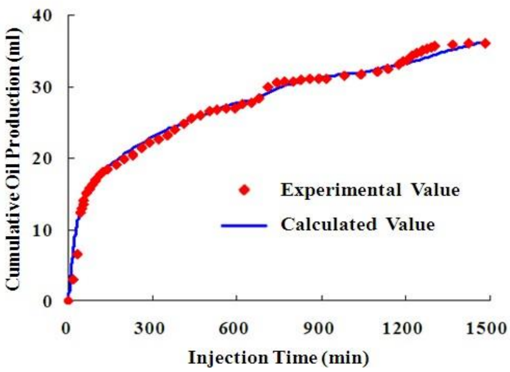

FIGURE 8 The fitting results of cumulative oil production

3 The result of field application and analysis

3.1 FIELD RESERVOIR GEOLOGICAL SITUATION AND MODEL ESTABLISHMENT

Foam flooding test area of a reservoir was put into operation in April 1976 and was developed by water flooding in May 1977, now it exists 4 injection wells and 15 production wells. In the numerical study, in order to reduce the adverse effects of open boundary, the numerical simulation model expanded a well spacing, including 42 production wells and 21 injection wells (include 18 converted-injector wells). The grid size is 25m×25m and the scale is 79×77×3=18249.(Table 3, Figure 9).

TABLE 3 The basic geological reservoir parameter table of Foam flooding test area

Oil-bearing area	**Geological reserves**	**Reservoir temperature**	**Formation water salinity**	**Number of production wells**
0.9km^2	119×10^{4}t	65℃	6227mg/L	26
Number of injection wells	Water cut before injecting	Recovery percent before the injection	Water injection multiples before the polymer injection	Water injection rate
11	97.1%	39.5%	3.0PV	0.3PV/a

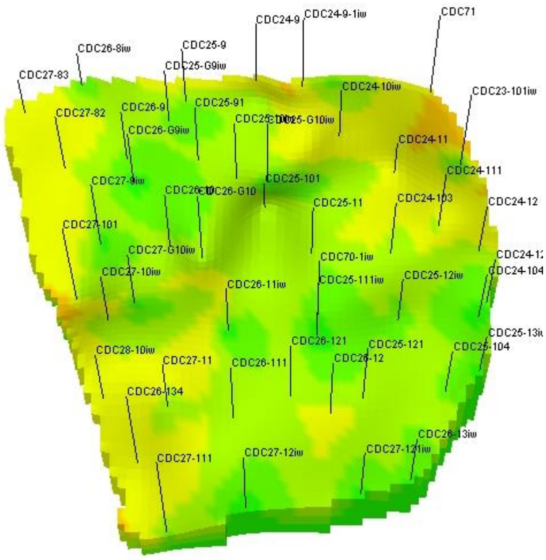

FIGURE 9 The basic geological reservoir mode of foam flooding test area

3.2 PHYSICOCHEMICAL PARAMETERS OPTIMIZED OF FOAM FLOODING

The key of foam flooding reservoir simulation technology is dependent on the experimental data, the foam flooding is a complex process which can be easily influenced by outside factors and the mechanism of flooding is difficult to describe by mathematical. The characteristic of empirical mathematical model is that in order to determine model parameters it needs according to the experimental data.

Researchers through the indoor experiment and other methods have determined the critical gas saturation, polymer adsorption capacity, polymer residual resistance factor, foam concentration threshold, bubble flow attenuation factor etc.

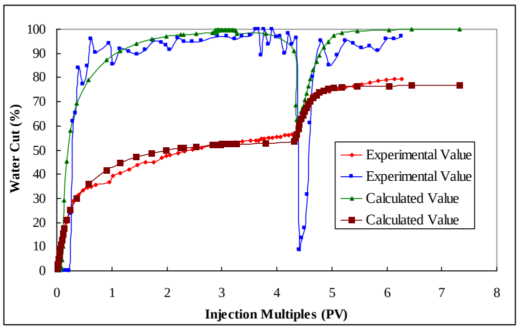

FIGURE 10 The results comparison between core displacement test and simulation

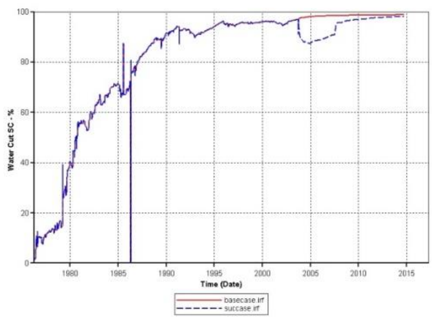

FIGURE 11 The water cut comparison between based scheme and foam flooding scheme of test area

According to the calculation model after being amended by laboratory test data which match the results of core flooding experiments well (Figure 10), using the amended calculation model to calculate in reservoir numerical simulator and getting the development index of foam flooding test area (Figure 11).

3.3 IMPLEMENTATION EFFECT

Through the actual development curve of test area (Figure 12) and the production curve of central well (Figure 13), it shows the results of using improved foam flooding reservoir numerical simulation and the actual production effect have a higher degree of matching, so the method is credible.

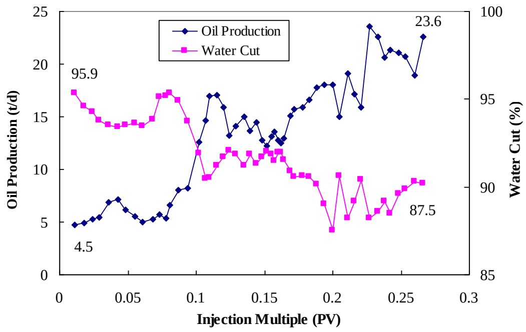

FIGURE 12 The development curve of test area

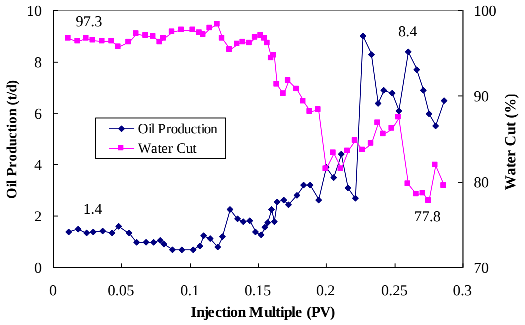

FIGURE 13 The production curve of central well

4 Conclusions and suggestions

During foam flooding process, foam adsorption, attenuation and foam have an effect on gas phase relative permeability. Foam seepage mathematical model needs to consider the effect of surfactant concentration, gas phase flow rate, oil saturation and rheological characteristic.

The foam flooding mathematical model is a multiphase and multicomponent model. It reasonably considers the components of convection, dispersion, surfactant distribution and surfactant loss. The model is more reasonable and the simulation results are more accurate.

Foam injection parameters have an effect on the displacement effect. The crude oil production increased with the increase of foam concentration, but there was an optimum injection concentration; Foam injection timing and gas-liquid ratio should be optimized according to the reservoir conditions.

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