

Numerical Analysis of Micellar-Polymer Displacement of Oil from Flooded Strata

التحليل العددي لإزاحة البوليمر-السيلوري لفيض طبقات الزيت

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Abstract: Mathematical modeling of the process of flooding of an oil-bearing bed by a micellar-polymer mixture is developed. A model of the process is developed in the framework of isothermal flow of a multiphase, multicomponent incompressible fluid. The model takes into account nonequilibrium effects in the multiphase flow associated with the presence of the relaxation times needed for rearrangement of the flow structure, when the hydrodynamic forces change and the adsorption of the components ; it also takes into account the inaccessibility of part of the pore space for flow of multicomponent systems, the freeing of the trapped part of the oil and the decrease in the mobility of the water under the influence of the active components. In this solution represented in this paper, the breakup of the micellar solution slug was simulated only by retention, nevertheless, the numerical solution agrees satisfactorily with the experimental data which confirms the conclusion that the retention of the micellar solution in the porous medium plays the predominant part in the breakup of the micellar slug.

Keywords: Mathematical model, Micellar-polymer, oil.

المستخلص: لقد تم تطوير النمذجة الرياضية الخاصة بفيض الزيت عن طريق مزيج البوليمر-السيلوري. وتم تحسين الأنموذج أيضاً في إطار الدفع الحراري المتساوي متعدد المراحل ومتعدد الوحدات للمائع غير قابل للانضغاط. كلمات مدخلية: النمذجة الرياضية، البوليمر-السيلوري، بفيض الزيت، الدفع الحراري.

Introduction

The micellar-polymer method of increasing the oil recovery from strata (Surguchev *et. al.*, 1977) is currently regarded as promising. The method of a micellar-polymer recovery of oil remaining after the oil has been displaced by regular water consists of a successive pumping into the bearing bed of fairly small volumes of a micellar solution (5-10% of the pore volume) and a highly viscous buffer fluid (aqueous solution of polymer). The role of micellar solution consists of "dissolving" immobile petroleum on account of a significant reduction of surface tension, thereby making it mobile. The buffer liquid, because of its high viscosity, protects the advanced micellar solution from being broken through by water which presses through the system

of these slugs. Thus so affected, some admixtures (e.g., surfactants soluble in petroleum), in petroleum and water may produce a micellar solution in the form of a mixture between petroleum and very small micelles (microdrops) of water. The main components of micellar solutions are : a hydrocarbon fluid (oil or its fractions), water, and surface-active substances.

The micellar solution considered here dissolves oil but does not mix with water : the relationship between the components in it are characteristic for the solutions used to increase oil recovery from strata. The displacement of the oil that remains after flooding in the stratum is achieved by a decrease in the coefficient of surface tension at the boundaries of the micellar solution with the oil and the water to the value $10^{-2} - 10^{-3} \text{ dyn/cm}$.

The Mathematical Model

Taking into account the data on the mechanism of the process given in (Surguchev *et. al.*, 1977; Healy *et. al.*, 1976; Larsen and Stenmark; 1976), we list below the liquid phases that participate in the flow and the components that can be contained in them (Table 1).

The hydrocarbon liquid is divided into mobile and immobile phases, each consisting of three components : oil, water and surface-active admixtures. The aqueous phases (both mobile and immobile) contain three components too : water, a thickening polymer and salt.

The division into mobile and immobile parts makes it possible to describe in more detail the motion of the fluid in the porous medium.

Further, as a simplification, we assume that the concentrations of the components in the mobile and immobile phases are equal. In Table 1 we give in this connection the concentrations of the components for the hydrocarbon fluid and the water as a whole.

Since α_i is the volume fraction of the pore space occupied by phase i , the reduced density of phase i is determined by

$$\rho_i = \rho_i^0 \alpha_i \quad (1)$$

where m is the porosity of the medium, and ρ_i^0 is the true density of phase i .

Since the true densities of the components that participate in the process are nearly equal to each other, the true densities of the phases are virtually constant.

In the interest of simplifying the calculations, we assume that the diffusion motion of components may be ignored.

The conservation equations for the masses of the incompressible phases and the components participating in the process of micellar-polymer flooding have the following form in the absence of deformations of the stratum:

$$\frac{\partial \alpha_1}{\partial t} = -J_{12}, \quad \frac{\partial \alpha_3}{\partial t} = -J_{34}$$

$$\frac{\partial \alpha_2}{\partial t} + \nabla \alpha_2 V_2 = J_{12} - J_{24}$$

$$\frac{\partial \alpha_4}{\partial t} + \nabla \alpha_4 V_4 = J_{34} + J_{24}$$

$$\frac{\partial S_p C_{p1}}{\partial t} + \nabla \alpha_2 C_{p1} V_2 = 0$$

$$\frac{\partial S_p C_{p2}}{\partial t} + \nabla \alpha_2 C_{p2} V_2 = -J_{24}$$

$$\frac{\partial S_p C_{p3}}{\partial t} + \nabla \alpha_2 C_{p3} V_2 = -J_{03}$$

$$\frac{\partial S_w C_{w2}}{\partial t} + \nabla \alpha_4 C_{w2} V_4 = J_{24}$$

$$\frac{\partial S_w C_{w4}}{\partial t} + \nabla \alpha_4 C_{w4} V_4 = -J_{04}$$

$$\frac{\partial S_w C_{w5}}{\partial t} + \nabla \alpha_4 C_{w5} V_4 = -J_{05}$$

$$\frac{\partial a_5}{\partial t} = J_{05}, S_p = \alpha_1 + \alpha_2, S_w = \alpha_3 + \alpha_4$$

Here S_p and S_w are the total dynamical saturation of the porous medium by hydrocarbon fluid and water respectively, J_{ji} is the rate of the phase transitions from the j -th phase to the i -th phase, J_{0k} is the rate of adsorption of the component k is the mass velocity of phase and i ; a_5 is the concentration of the adsorbed polymer.

The inertialess motion of the mobile phases in the porous medium is described by Darcy's law:

$$V_i = -\frac{k \alpha_i}{m \mu_i} \nabla p \quad (i = 2, 4) \quad (3)$$

where k is the absolute permeability of the porous medium, and μ_i is the viscosity of phase i . It is assumed here that the phase permeability of the i -th mobile phase is equal to its volume concentration.

For the rates of the phase transitions, we assume

TABLE 1

Phases	Volume of phases in unit volume of pores	Concentration of components
Immobile hydrocarbon	α_1	C_{p1} : oil
Mobile hydrocarbon	α_2	C_{p2} : water C_{p3} : surface active substance
Immobile water	α_3	C_{w2} : water
Mobile water	α_4	C_{w4} : salt C_{w5} : polymer

linear kinetics determined by the relaxation times and the equilibrium concentrations of the phases, α_{ie} , and the adsorbed components, a_{ke}

$$J_{21} = -J_{12} = \frac{\alpha_2 - \alpha_{2e}}{t_{12}}, \quad J_{43} = -J_{34} = \frac{\alpha_4 - \alpha_{4e}}{t_{34}}$$

$$J_{ok} = \frac{a_k - a_{ke}}{t_{ok}}, \quad k = 3, 4, 5 \quad (4)$$

The phase transition rate J_{24} determines the release of the water from the micellar solution due to the depletion of the solution of the surface-active substances through their adsorption, and it can be specified in the form (C_{p3^*} is the critical concentration of micelle formation):

$$J_{24} = \begin{cases} 0, & C_{p3} > C_{p3^*} \\ C_{p2}/t_{24}, & C_{p3} \leq C_{p3^*} \end{cases}$$

The equilibrium concentrations α_{2e} and α_{4e} of the mobile phases can be determined from the condition of transition in the equilibrium case of the system of equations (2) to the classical theories (Bedrikovetsky P., 1993). These concentrations are equal to the phase permeabilities for hydrocarbon fluid and water determined from a series of experiments on steady two-phase flow in porous media. In accordance with the recent experimental data (Larseon and Hirasaki, 1978; Vakhitov *et. al.*, 1980), we have:

$$\alpha_{4e} = \alpha_{4e}(S_w, a_5) = S_w^{N_1} / R(a_5)$$

$$\alpha_{2e} = \alpha_{2e}(S_p, C_{p3}), \quad \alpha_{2e}(S_p, C_{p3}^0) = S_p^{N_2}$$

$$\alpha_{2e}(S_p, 0) = \begin{cases} 0, & S_p < S_{pr} \\ \left(\frac{S_p - S_{pr}}{1 - S_{pr}} \right)^{N_2}, & S_p \geq S_{pr} \end{cases} \quad (5)$$

Here S_{pr} is the residual oil saturation of the medium; C_{p3}^0 is the initial concentration of the surface-active substances in the micellar solution; R is a residual resistance factor due to the clogging of the porous medium by the adsorbed polymer (Dawson and Lantz, 1972), and N_1 and N_2 are constants that characterize the porous medium. Thus, the influence of the surface-active substances (C_{p3}) reduces to the setting in motion of almost all the hydrocarbon fluid, while the adsorbed polymer (α_5) reduces the fraction of mobile water. In what

follows, the dependence of the equilibrium concentration α_{2e} of the mobile hydrocarbon fluid on the concentration C_{p3} of the surface-active substances will be approximated by a linear form.

The equilibrium concentrations of the adsorbed components are determined by the equilibrium adsorption isotherms (Dawson and Lantz, 1972; Irogus *et. al.*, 1977).

$$a_{3e} = a_{3e}(S_p, C_{p3}), \quad a_{4e} = a_{4e}(S_w, C_{w4})$$

$$a_{5e} = a_{5e}(S_w, C_{w5}) \quad (6)$$

The viscosity of the water is determined basically by the concentration in it of the polymer (Dawson and Lantz, 1972); the viscosity of the hydrocarbon fluid (the micellar solution and the oil), and by the concentration in it of the water (Surguchev, *et. al.*, 1977).

$$\mu_2 = \mu_2(C_{p2}), \quad \mu_4 = \mu_4(C_{w5}) \quad (7)$$

and in the absence of inversion of the micellar solution, its viscosity depends monotonically on the concentration of the disperse component, the water, and therefore

$$\mu_2(0) = \mu_p, \quad \mu_2(C_{p2}^0) = \mu_m$$

$$\mu_4(0) = \mu_w, \quad \mu_4(C_{w5}^0) = \mu_b \quad (8)$$

Here, C_{p2}^0 are μ_m the initial concentration of the water and viscosity of the micellar solution; C_{w5}^0 and μ_b are the initial concentration of the polymer and viscosity of the buffer fluid. In the calculations, these dependences were approximated linearly.

The Results of Calculations

In what follows, we shall restrict ourselves to considering the plane one-dimensional case. The system of equations (2) was solved numerically by an explicit finite difference scheme of first order of accuracy with orientation along the characteristics. The number of cells was chosen to ensure not less than 20 cells for the slug.

Micellar-polymer displacement of residual oil is regarded as effective when the complete breakup of the slug of the micellar solution occurs at the end of the stratum, i. e., after extraction of the main oil reserves. Thus, the main aim of the investigation is to determine the effective size of the propelled slugs and the influence of the main parameters of the process on this size.

We estimate the influence of nonequilibrium effects. The characteristic relaxation times of the adsorption of the components and the redistribution of the fractions of the mobile and immobile phases can be determined by comparing numerical solutions that take into account nonequilibrium effects with the results of experiments and the selection of appropriate times, ensuring agreement between the calculated and the experimental data. The adsorption relaxation times of various surface-active substances were estimated in this manner in (Irogus *et al.*, 1977). These results give the following estimate: $t_{03} \sim 1-3h$.

A similar method was used to estimate the relaxation times t_{12} and t_{34} .

Qualitative comparison of the numerical solutions and the experimental data of (Ogadzhanlyants, 1973) showed that the J_{12} phase transition takes place almost in equilibrium even in the case of small-size porous models of the stratum, i.e., $t_{12} \ll t_{34}$. Comparison with the experimental results of (Ogadzhanlyants, 1973) on the determination of the time of waterless oil recovery during displacement of oil by water from samples of a porous medium of different sizes give the estimate $t_{34} \sim 0.5-2h$, $t_{12} \ll t_{34}$.

In the micellar-polymer flooding of real strata, the slug of micellar solution will be broken up mainly by the retention of the solution and the adsorption of the surface-active substances in the porous medium.

Experimentally, the amount of retained micellar solution and adsorbed surface-active substances can be determined by two methods: In the first, after micellar-polymer flooding, the porous medium is washed out with hydrocarbon fluid and water. The mass of the components of the micellar solution displaced in this stage determines the amount of retained solution. Then the porous medium is washed out with alcohol, which removes the surface-active substances adsorbed on the skeleton of the porous medium. The second method of determining the amount of adsorbed surface-active substances lags behind the front of the nonadsorbed alcohol also contained in the solution. Both methods indicate that retention of the micellar solution plays the predominant part in the breakup of the micellar slug (Healy, *et al.*, 1976; Davis and Jones, 1968).

To test the adequacy of the mathematical description of the process and to determine more precisely the mechanism of retention of the micellar solution in the porous medium, we simulated numerically experiments on micellar-polymer

displacement of residual oil from Berea sandstone for different sizes of the micellar solution slugs (Larsen and Hirasaki, 1978). The calculations were made for the system of equations (2) without allowance for the disequilibrium of the interphase transfer, and the adsorption of the surface-active substances from the micellar solution. The phase permeabilities of the water and the hydrocarbon fluid for the given medium have the form (5) with the following values of the constants (Larsen and Hirasaki, 1978):

$$S_{wr}^0 = 0.2; S_{pr}^0 = 0.33; N_1 = 3.75; N_2 = 1.5 \quad (9)$$

Here S_{wr}^0 is the saturation of the porous medium by the bound water. The degree sign as superscript is used to denote the true values of the quantities.

The viscosities of the fluids at their initial compositions were

$$\mu_p = 7; \mu_w = 1; \mu_m = 25.2 \text{ cp} \quad (10)$$

The buffer fluid was simulated by an aqueous solution of polyacrylamide with concentration 0.0008 which corresponds to a mobility of it in the porous medium of $\lambda = 1/\mu_b R = 0.033 \text{ cp}^{-1}$.

Variations of phase flow rates for water, petroleum, and components at the oil-bearing bed outlet as functions of time are generally measured in experiments on a core sample. It is for these particular values that the numerical and experimental results are compared in Fig. 1 and Fig. 2.

Fig. 1 relates to a thick micellar solution (MS)

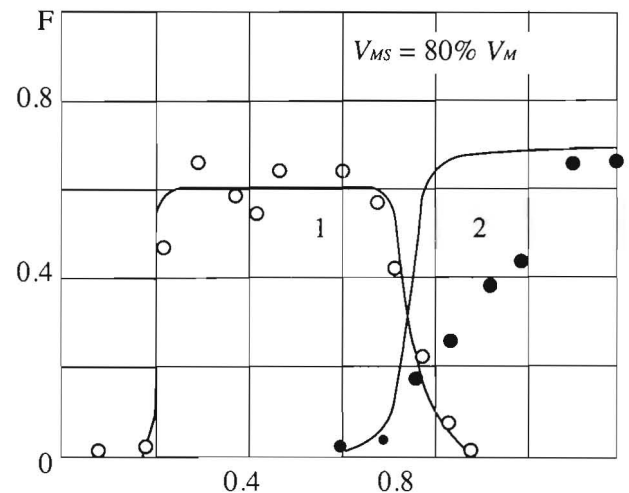


Fig. 1. Variation of the volumetric share of both oil (1) and micellar solution (2) at the outlet of the oil-bearing bed with time (or as a function of growth of relative volume V/V_m of pumped liquid). Volume of MS layer: $V_{ms} = 0.8V_m$. Lines 1 and 2 correspond to predicted analytical data; dots 1 and 2 correspond to experimental data (S. Davis and C. Jones, 1968).

layer ($V_{ms} = 0.8 V_m$). In this case oil is displaced out of the bed in the form of a fixed-saturation wave, which breaks through near the bed outlet after a volume of liquid equal to 0.2 of the volume of voids V_m is pumped through the bed U_p to a point in time $t=0.8$ (which corresponds to a volume of liquid of $0.8 V_m$ pumped through the oil-bearing bed) the oil recovery (in terms of its part of the volume in the total flow of liquid) becomes constant.

Fig. 2 relates to a real regime with a thin layer of edging MS ($V_{ms} = 0.1 V_m$) when the formation of the petroleum wave of variable oil-saturation takes place; namely, the share of oil in the flow of discharged liquid grows $F_p \approx 0.6$ immediately after the arrival of the petroleum wave followed by a sharp decrease at time as distinct from the regime depicted in Fig. 1. From Fig. 2, it is seen that intensity of adsorption of thickening polymer determined by Henry's law constant significantly affects the dynamics of the process. Note that the

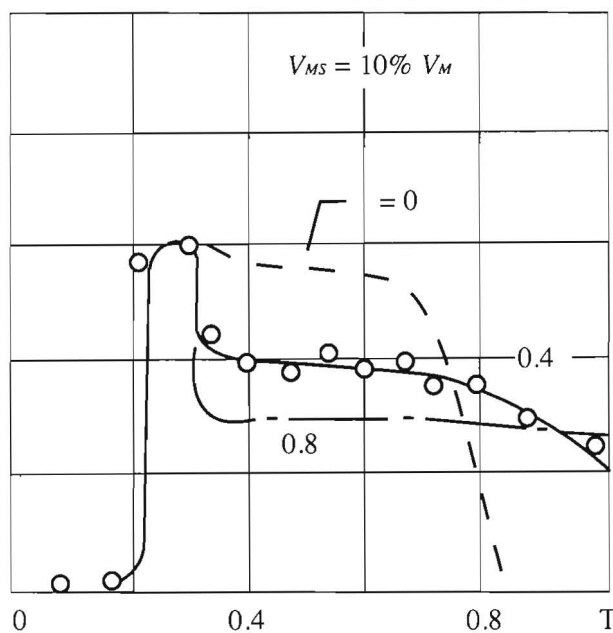


Fig. 2. The same as in Fig. 1, but for the volume of the MS solution equal to $V_{ms} = 0.1 V_m$, and with variation of Henry's coefficient Γ in the polymer (thickener) adsorption law used in analytical calculations.

value relates to polyacrilamides.

Fig. 3 shows the results of calculations of the dependence of the efficiency of oil displacement (is the volume of displaced oil as a percentage of the residual oil) on the volume of the micellar solution slug that is used (V_{ms}). All the remaining parameters apart from the size of the slug were fixed. The volume of the slug of buffer fluid was 40% of the pore volume. Thus in the solution represented in Fig. 3 the breakup of the micellar solution slug was

simulated only by retention; nevertheless, the numerical solutions agree satisfactorily with the experimental data, which confirms the conclusion that the retention of the micellar solution in the porous medium plays the predominant part in the breakup of the micellar slug. The effective size of the micellar solution slug in the considered cases is characterized by 5% of the pore volume.

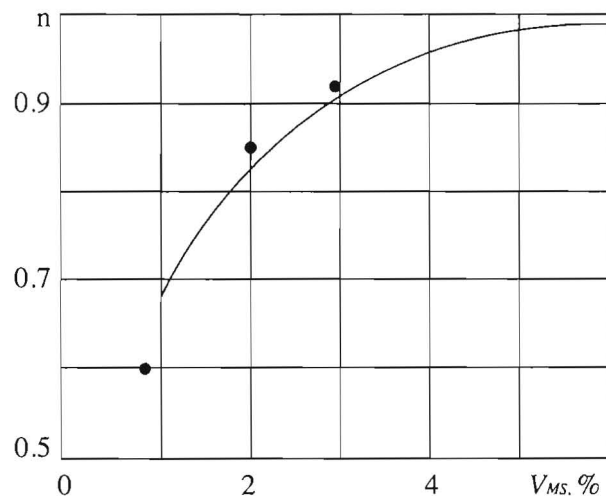


Fig. 3. Effectiveness of oil recovery as a function of the MS-solution volume determined by the percentage of displaced oil (η) relative to the total volume of petroleum in a homogeneous bore-core sampled in the Berea sandstone. The size of the buffer liquid layer is $V_{BL} = 0.4 V_m$. Solidline represent prediction, dots represent experiment (Davis and Jones, 1968).

A review of new methods of improved oil recovery was done in (Farouq, 1995). The details of numerical method used for calculations are described in (Burden, *et. al.*, 1981).

Conclusion

The mathematical model of a micellar-polymer flooding based on the implementation of equations of mechanics of a multiphase, multicomponent percolation in porous medium permits the satisfactory description of the principal features of the process. The discussed model in its one-dimensional variant may be used for analysis of the process and its optimization directly in industry. It should be remembered that it is in laboratory experiments on relatively small lengths ($L = 0.1 - 1.0$ m), when duration of the process is short ($t = 0.1 - 1.0$ hour), that the nonequilibrium effects of the transition from immobile to mobile phases may play a certain role.

The method of micellar-polymer flooding of

strata makes it possible, by variation of the initial concentrations of the active components of the solution and the buffer fluid, to achieve optimal conditions of oil extraction (optimal slug size, viscosity, etc.) under given physico-geological conditions. The proposed model of the process makes it possible to particularize its mechanism, predict the results of application of the method under real conditions, and to solve a number of optimization problems associated with the choice of the size and properties of the employed slug of chemical reactance.

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