MODELAGEM DO MÉTODO MICROBIOLÓGICO DE MELHORIA DA RECUPERAÇÃO DE ÓLEO

MODELLING OF MICROBIOLOGICAL METHOD OF OIL RECOVERY IMPROVEMENT

МОДЕЛИРОВАНИЕ БИОХИМИЧЕСКИХ ПРОЦЕССОВ ПОВЫШЕНИЯ НЕФТЕОТДАЧИ ПЛАСТОВ.

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RESUMO

O problema do suprimento de energia tem sido uma das questões mais urgentes para a humanidade em todos os momentos. O petróleo é uma das fontes de energia mais desejadas. No entanto, as reservas de petróleo estão se esgotando e quantidades substanciais de óleo residual subterrâneo não podem ser extraídas com o uso dos métodos tradicionais, portanto, exigindo a implementação de novas tecnologias. O presente artigo sugere dois modelos matemáticos destinados a descrever e prever as implicações do método microbiológico de recuperação da recuperação de petróleo com base nos dados atualmente disponíveis, bem como avaliar a eficiência deste método. O primeiro modelo consiste em equações diferenciais parciais que descrevem o processo de expansão da população microbiana através da formação de petróleo. O segundo modelo inclui equações diferenciais ordinárias, descrevendo o crescimento e o metabolismo de culturas bacterianas dentro da zona do fundo do poço de produção. Os modelos foram estudados com o uso de métodos de grade numérica e Euler. Os parâmetros de modelagem foram avaliados pelo método dos mínimos quadrados. O trabalho atual inclui os resultados dos cálculos realizados com base nos modelos propostos. Foram obtidos e estudados perfis de distribuição da população bacteriana e dos produtos metabólicos ao longo do reservatório; forneceu recomendações para a implementação prática do método microbiológico.

Palavras-chave: Formações produtoras de óleo, substrato, metabolito, porosidade, permeabilidade.

ABSTRACT

The problem of energy supply has been one of the most pressing issues for the humanity at all times. Oil is one of the most desired sources of energy. However, oil reserves are being depleted, and substantial amounts of subterranean residual oil cannot be extracted with the use of traditional methods, therefore requiring implementation of new technologies. The current paper suggests two mathematical models aimed to describe and predict implications of microbiological method of oil recovery improvement based on the currently available data, as well as to assess the efficiency of this method. The first model consists of partial differential equations that describe the process of expansion of microbial population through oil formation. The second model includes ordinary differential equations, describing growth and metabolism of bacterial cultures within the bottom-hole zone of the production well. The models were studied with the use of numerical grid and Euler methods. The modeling parameters were evaluated using the least squares method. The current paper includes the results of calculations performed on basis of the proposed models. Distribution profiles of the bacterial population and the metabolic products along the reservoir were obtained and studied; provided recommendations for practical implementation of the microbiological method.

Keywords: *oil-producing formations, substrate, metabolite, porosity, permeability.*

АННОТАЦИЯ

Проблема энергоресурсов всегда была одной из наиболее актуальных для человечества. Нефть один из наиболее востребованных источников энергии. Тем не менее, запасы нефти истощаются, и значительное количество подземной остаточной нефти, на данный момент, невозможно извлечь с использованием традиционных методов, поэтому требуется внедрение новых технологий. В настоящей статье предлагаются две математические модели, призванные описать и прогнозировать последствия микробиологического метода повышения нефтеотдачи пластов на основе имеющихся в настоящее время данных, а также для оценки эффективности этого метода. Первая модель состоит из дифференциальных уравнений, описывающих процесс расширения микробной популяции за счет образования нефти. Вторая модель включает в себя обыкновенные дифференциальные уравнения, описывающие рост и метаболизм бактериальных культур в призабойной зоне добывающей скважины. Модели были изучены с использованием численной сетки и методов Эйлера. Параметры моделирования были оценены с использованием метода наименьших квадратов. В статье отражены результаты расчетов, выполненных на основе предложенных моделей. Распределение профилей популяции бактерий и продукты метаболизма вдоль водохранилища были получены и изучены; даны рекомендации для практической реализации микробиологического метода.

Ключевые слова: нефтеносные пласты, субстрат, метаболит, пористость, проницаемость.

INTRODUCTION

Gradual decrease in oil reserves is being observed throughout the world over the recent years. At the same time, their substantial part remains unextracted due to different reasons. Specifically, it is well known that water encroachment of productive formations increases at the final stages of oil recovery. For example, at Tatarstan oil fields the proportion of water in extracted fluid goes up to 90 % and sometimes to 95 %. It poses a threat to the environment and leads to economic losses. One of the known solutions to this problem is the implementation of microbiological technologies: microorganisms and culture medium are added to the water pumped into oil reservoirs. The evolution of the microbial population leads to changes in physical conditions, which results in easier displacement of oil from the reservoirs. Additional displacement of residual oil is induced by the following events:

- forming biopolymers and surfactants of biological origin improve oil and water mobility ratio;
- microbiological gas synthesis restores local pressure in the reservoir;
- oil stream viscosity decreases due to biosynthesis of bacterial solvents;
- highly permeable zones are selectively plugged due to rapid growth of clogging bacterial biomass;

- pore channels significantly expand and new routes for filtration flows are formed, as the synthesis of organic acids within the formation causes dissolution of mineral deposits in the container rock.

Active laboratory and experimental field tests involving microbiological technologies are carried out in Russia and other countries. International researchers including Zobell, Zajic, Moses (Moses and Springham, 1982; Moses, 1987; Zajic *et al.*, 1983; Zo Bell, 1947), and Russian scientists – S. Kuznetsov, M. Ivanov, E. Rozanova and others (Ivanov *et al.*, 1986; Rozanova and Kuznetsov, 1974; Rozanova *et al.*, 1997) have contributed greatly to the study of this issue.

The current paper presents the results of the studies, conducted by researchers from I.M. Gubkin Russian State University of Oil and Gas and St. Petersburg State Technological Institute (Technical University). These studies included stating and solving the problem of the microbial population expansion in the porous medium of oil formation under the conditions of continuous or recurrent pumping of culture fluid into the well. The purpose of the study was to specify the impact factors of concentrations of certain microorganisms on the reservoir porosity, as well as the influence of biochemical processes on the formation permeability due to dissolution of carbonate deposits, that clog certain parts of the formation, by the products of microbial synthesis.

Other processes mentioned above were left out of scope due to the lack of experimental data that prevents the development of a plausible model of the process, however, they are scheduled for further consideration.

The current study is relevant, as it provides an opportunity to assess the virtues and drawbacks of this technology without any expensive field tests.

MATERIALS AND METHODS

In the course of this research, a simulation experiment was performed, which included development and analysis of two different mathematical models. The first model governs migration and development of microbial population from the injection well towards the producing well. The problem of microbial population expansion in porous medium is represented as a set of nonlinear inhomogeneous differential second-order partial equations (1).

The fluid flow was considered rectilinear and parallel. In this case the distributions of all system components at the initial instant of time are considered to be linear. Unknown functions are: N — concentration of microorganisms; S — concentration of the active component of culture medium, kg/m^3 ; C — concentration of microbial synthesis product, kg/m^3 ; P — internal reservoir pressure, Pa; x — coordinate, m; t — time, s; L — length of productive formation, m; μ_f — viscosity of culture fluid, $\text{Pa}\cdot\text{s}$; ρ_0 — fluid density under $P = P_0$, kg/m^3 ; β_H — fluid volume compressibility coefficient, Pa^{-1} .

The current problem includes the following parameters: m — porosity, k — permeability, ρ — fluence of bacterial suspension; D_1 , D_2 , D_3 — coefficients of diffusion for bacterial cells, substrate and metabolite, respectively; $\mu_{\max}$ — maximum specific growth rate of microorganisms; α — economic coefficient of the metabolite synthesis; K_1 — factor of decrease in microbial population due to natural lysis and intraspecific competition $1/(\text{cell/m}^3\text{s})$; K_2 — specific substrate consumption rate; K_s — substrate saturation constant, kg/m^3 ; K_c — metabolic product inhibition constant kg/m^3 ; F_1 — factor of the reproduction rate of microorganisms; V_{cell} , ρ_{cell} — volume and density of a single cell unit, respectively.

The first equation of the system describes the dynamics of microbial population expansion over the formation. The second and third equations describe the dynamics of the culture medium active component and the microbial synthesis product, respectively. The fourth equation represents Darcy's law.

Initial and boundary conditions depend on the mode of pumping the bacterial suspension into the reservoir (recurrent or continuous).

In the case of continuous process, initial and boundary conditions are as Equation 2.

In the case of recurrent process, initial and boundary conditions are as Equation 3.

Functional relations, governing the changes of medium porosity and permeability in the presence of microorganisms, were obtained from the results of statistical analysis of the experimental data (Azizov *et al.*, 1994; Milovanovich, 1990) concerning three bacterial cultures: *Pseudomonas aeruginosa*, *Micrococcus roseus*, and *Proteus vulgaris*.

The experiments showed that the most prominent decrease in porosity is observed in *Micrococcus roseus* culture, whereas the least prominent — in *Pseudomonas aeruginosa* culture. It can probably be explained by the fact that *Pseudomonas aeruginosa* is the smallest, while *Micrococcus roseus* cells are able to form large conglomerates. Therefore, *Micrococcus roseus* and other similar cultures are the most suitable for partial isolation of water influx to production wells, and *Pseudomonas aeruginosa* — for bottom-hole treatment.

Similar results were obtained for the other two bacterial cultures. For every bacterial culture studied, the following regression estimators were proposed:

$$\bar{m}(N) = m_0(\bar{a}_0 + \bar{a}_1 e^{-\bar{a}_2 N}) \quad (\text{Eq. 4})$$

$$\bar{m}(N) = \frac{m_0}{\bar{a}_0 + \bar{a}_1 N} \quad (\text{Eq. 5})$$

$$\bar{m}(N) = m_0 e^{-\alpha N} \quad (\text{Eq. 6})$$

where $\bar{a}_0, \bar{a}_1, \bar{a}_2$ are estimated coefficients.

Function parameters were identified through the least squares method. The constructed regression functions were then used to formulate the problem of microbial population expansion in porous medium. Fisher's criterion was used to estimate the fitness of proposed regression equations.

The simultaneous equations were solved by the grid method. Coordinate increment in the constructed difference scheme was 0.25 m, time increment was 2 hours. The difference scheme was proved to be correct, stable and to have the second order of approximation.

RESULTS

In the course of solving, distribution profiles for the constituents of biocenosis were obtained, including concentrations of microorganisms, substrate and metabolite (substrate is the active component of culture medium, metabolite is the product of biochemical reaction) along the formation under recurrent or continuous pumping of culture fluid into the reservoir. The cultivation period was considered 30 days.

DISCUSSION

1) In the case of continuous process, the distribution of microorganisms concentration along the formation is wave-like, gradually attenuating towards the production wells. This phenomenon can probably be explained by gradually increasing plugging of the pore channels.

2) The decay of biochemical processes depends on the morphological and biochemical features of the culture: shape and size of bacterial cells, their growth and reproduction rate, their ability to form conglomerates.

3) In the case of recurrent process, the components of biocenosis are distributed along the formation more evenly than in the case of continuous process. However, all metabolic processes in the reservoir will be active for approximately one month after the end of

pumping. Therefore, in case of need for further continuation of these processes, it is necessary to re-pump the bacterial suspension in small doses every 30–40 days.

Let us now pass on to setting up the problem of quantitative estimation of the enhanced oil recovery due to dissolution of carbonate deposits, which plug certain parts of the reservoir space, by the products of microbial synthesis.

Some products of biochemical reactions that take place in oil reservoirs can cause dissolution of certain mineral deposits that plug some pores and fractures (Milovanovich, 1990; Andreev *et al.*, 2000; Ametov and Entov, 1981).

Let us assume that acetic acid is the product of microbial synthesis and the pore walls are covered with lime deposits. Then the following chemical reaction will take place inside the pore:

The formed calcium acetate is soluble. Because of this chemical reaction, the lime scale will be decreasing, and, consequently, the pore diameter will be increasing. In turn, pore widening will lead to higher rock permeability and subsequent increase in the reservoir output (Ametov and Entov, 1981; Basniev *et al.*, 1993; Kotenev *et al.*, 2004).

Let us consider a small element of porous medium and calculate the change in the lime mass due to the chemical reaction (7). For the sake of simplicity, let us presume that all pores in the chosen element have the same diameter and are parallel.

The mass of lime within the considered element of the porous medium at the initial moment of time may be expressed in the following way:

$$m = \frac{\pi L}{4} \rho (d_2^2 - d_1^2) n \quad (\text{Eq. 8})$$

where ρ is the lime density, kg/m³; L — specimen length, m; d_2 — outer pore diameter,

m ; d_1 — inner pore diameter, m; n — number of pores within the considered element of the porous medium.

Equation (8) contains only two values that will be changing in course of time, m and d_1 . Hence it can be rewritten:

$$m(t) = \frac{\pi L}{4} \rho (d_2^2 - d_1(t)^2) n \quad (\text{Eq. 9})$$

Then the rate of lime mass change is:

$$\frac{dm}{dt} = -\frac{\pi L \rho n}{2} d_1 \frac{dd_1}{dt} \quad (\text{Eq. 10})$$

At the same time, the change in the lime mass will depend on the concentration of acetic acid, as follows (Ostrovskiy, 2004):

$$\frac{dm}{dt} = -K S C^\alpha(t) n e^{-E/RT} \quad (\text{Eq. 11})$$

where S is the surface area of the lime deposit, m^2 ; C is the acetic acid concentration, kg/m^3 ; α — the order of chemical reaction ($\alpha = 2$); K — reaction rate constant; E — activation energy, J; T — temperature, K; R — molar gas constant, $\text{J} \cdot (\text{mole} \cdot \text{K})^{-1}$.

The surface area of the lime deposit can be considered as the surface area of the side of the cylinder of diameter d_1 .

$$S(t) = \pi L d_1(t). \quad (\text{Eq. 12})$$

Therefore:

$$\frac{dm}{dt} = -K c^2(t) n \pi d_1(t) L e^{-E/RT} \quad (\text{Eq. 13})$$

By making (11) equal to (13), it turns out that the change of the inner pore diameter over time can be calculated with the help of the following differential equation:

$$\frac{dd_1(t)}{dt} = \frac{2Kc^2(t)e^{-E/RT}}{\rho} \quad (\text{Eq. 14})$$

In our case, the filtration process is considered isothermal, therefore $e^{-E/RT}$ can be considered constant.

Let us set

$$K = \frac{2Ke^{-E/RT}}{\rho} \quad (\text{Eq. 15})$$

Then

$$\frac{dd_1}{dt} = Kc^2(t) \quad (\text{Eq. 16})$$

Now one can formulate the problem of the impact of the biochemical processes within the reservoir on the oil recovery rate. It should be kept in mind that two effects will influence the change in the formation permeability. On the one hand, the permeability will be decreasing due to bacterial plugging, as follows:

$$k(N) = k_0(b_0 + b_1 e^{-b_2 N}) \quad (\text{Eq. 17})$$

where k_0 is the initial permeability coefficient, N — microorganisms concentration, b_0 ; b_1 — constant factors characterizing the rate of permeability decrease due to biomass plugging.

On the other hand, permeability will be increasing, as the pores will be widening. Hence, the final problem statement should include both factors.

Let us consider:

$$k(t) = k(N) \cdot k(d_1), \quad (\text{Eq. 18})$$

$$k(d_1) = ad_1^2, \quad (\text{Eq. 19})$$

where a is a proportionality factor.

Then

$$\frac{dk(t)}{dt} = k(d_1) \frac{dk(N)}{dt} + k(N) \frac{dk(d_1)}{dt}. \quad (\text{Eq. 20})$$

Let us also take into account that oil flow, in the case of rectilinear and parallel filtration, is expressed as follows:

$$Q = \frac{k}{\mu} \frac{P_k - P_0}{L} Bh, \quad (\text{Eq. 21})$$

where k is permeability, m^2 ; μ — oil viscosity, $\text{Pa}\cdot\text{s}$; P_k — formation pressure, Pa ; P_0 — bottom-hole pressure, Pa ; L — formation length, m ; B — formation breadth, m ; h — formation height, m .

Finally,

$$\frac{dN}{dt} = \mu_{\max} \frac{S}{K_s + S} N - K_1 N^2 \quad (\text{Eq. 22})$$

$$\frac{dS}{dt} = -K_2 \mu_{\max} \frac{S}{K_s + S} N \quad (\text{Eq. 23})$$

$$\frac{dc}{dt} = \alpha \mu_{\max} \frac{KcSN}{(K_s + S)(K_c + C)} - b(1 - \omega) \quad (\text{Eq. 24})$$

$$\frac{dd_1}{dt} = Kc^2 \quad (\text{Eq. 25})$$

$$\frac{dk}{dt} = k(d_1) \frac{dk(N)}{dt} + k(N) \frac{dk(d_1)}{dt} \quad (\text{Eq. 26})$$

$$\frac{dQ}{dt} = \frac{(P_k - P_0)Bh}{\mu L} \frac{dk}{dt} \quad (\text{Eq. 27})$$

where N is the microorganisms concentration, S — substrate concentration, $\mu_{\max}$, K_1 , K_s , K_c , α — coefficients characterizing the kinetics of biochemical reactions. $B(1 - \omega)$ of the equation (24) characterizes the decrease in acetate concentration due to the lime dissolution, ω is the proportion of undissolved lime, b — the decrease in acetate concentration, when the lime is fully dissolved, $\omega = m / m_0$, where m is the lime mass at the current time.

$$\omega = \frac{m}{m_0} = \frac{\frac{\pi L}{4} \rho (d_2^2 - d_1^2)}{\frac{\pi L}{4} \rho (d_2^2 - d_0^2)} = \frac{d_2^2 - d_1^2}{d_2^2 - d_0^2}, \quad (\text{Eq. 28})$$

where d_0 is the inner pore diameter at the initial time.

The set of Eq. (23)–(27) was numerically solved by the Runge-Kutta fourth-order method. Time integration interval was 100 days, integration step $\Delta t = 2$ hours. Figures 1 and 2 show the dynamics of the pore channel diameter increase and the residual oil extraction.

In Figure 1 N is microbial concentration, units/m^3 ; x is reservoir length, m .

In Figure 2 d_1 is pore diameter, mm ; t is time, hours.

In Figure 3 Q is oil volume flow rate, l/hour ; t is time, hours.

The obtained results lead to the following conclusions:

1) In course of the chemical reaction involving the microbial synthesis product and the lime deposits in the reservoir, cross-sectional area of the pore channel significantly increases;

2) The increase in the pore cross-sectional area leads to enhanced oil influx at the producing well, which provides significantly higher ultimate oil recovery.

In the case under study, the estimated increase in the oil yield is two or three fold over

90 days, which is compatible with the experimental data.

CONCLUSIONS

In the course of current research, two mathematical models describing the behavior of the microbial population within the porous medium were developed and studied. During the analysis of the first model, we obtained distribution profiles of the metabolic components along the reservoir and examined their dynamics. Solving the differential equations of the second model allowed us to assess the rate of enhancement of the reservoir filtration parameters influenced by the microbial metabolites and to predict the increase in residual oil yield.

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Equations

$$\left\{ \begin{array}{l} \frac{\partial}{\partial t}(mN) = \frac{\partial}{\partial x} \left[\frac{K}{\mu} \frac{\partial P}{\partial x} N \right] + D_1 \frac{\partial^2 N}{\partial x^2} + \mu_{\max} \frac{S}{K_s + S} N - K_1 N^2 \\ \frac{\partial}{\partial t}(mS) = \frac{\partial}{\partial x} \left[\frac{K}{\mu} \frac{\partial P}{\partial x} S \right] + D_2 \frac{\partial^2 S}{\partial x^2} - K_2 \mu_{\max} \frac{S}{K_s + S} N \\ \frac{\partial}{\partial t}(mC) = \frac{\partial}{\partial x} \left[\frac{K}{\mu} \frac{\partial P}{\partial x} C \right] + D_3 \frac{\partial^2 C}{\partial x^2} + \alpha \mu_{\max} K_c \frac{SN}{(K_s + S)(K_c + C)} \\ \frac{\partial}{\partial t}(m\rho) = \frac{\partial}{\partial x} \left[\frac{K}{\mu} \frac{\partial P}{\partial x} \rho \right] + F_1 V \rho \\ \rho = \rho_0 (1 + \beta (P - P_0)) \end{array} \right.$$

(Eq. 1)

$$\left\{ \begin{array}{l} x=0: UN - D_1 \frac{\partial N}{\partial x} = A; S = S_0; C = 0; P = P_0 \\ x=L: \frac{\partial N}{\partial x} = 0; \frac{\partial S}{\partial x} = 0; \frac{\partial C}{\partial x} = 0; P = P_k \\ t=0: N = 0; S = S_0; C = 0; P = P_0 - \frac{P_0 - P_k}{L} x \end{array} \right.$$

(Eq. 2)

$$\left\{ \begin{array}{l} x=0: \frac{\partial N}{\partial x} = 0; \frac{\partial S}{\partial x} = 0; \frac{\partial C}{\partial x} = 0; P(t, 0) = P_0 \\ x=L: \frac{\partial N}{\partial x} = 0; \frac{\partial S}{\partial x} = 0; \frac{\partial C}{\partial x} = 0; P(t, L) = P_k \\ t=0: N(0, x) = N_0 - \frac{N_0}{L} x \\ S(0, x) = S_0 - \frac{S_0}{L} x \\ C(0, x) = C^* - \frac{C^*}{L} x \\ P(0, x) = P_0 - \frac{P_0 - P_k}{L} x \end{array} \right.$$

(Eq. 3)

Figures

Figure 1. Distribution of microbial concentrations along the reservoir length in case of continuous pumping of culture fluid.

Figure 2. Changes in the pore channel diameter over time

Figure 3. Dynamics of the oil volume flow rate