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Status Report

MODELING OF MICROBIAL TRANSPORT PHENOMENA IN POROUS MEDIA

Project BE3, FY91 Annual Research Plan, Milestone 4

by

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MODELING OF MICROBIAL TRANSPORT PHENOMENA IN POROUS MEDIA

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ABSTRACT

The purpose of this status report is to summarize results obtained for the mathematical modeling research conducted to date on NIPER project BE3 - Development of Improved Microbial Flooding Methods. Many of these results from this study have previously been published.[1] The progress made on development of a three-dimensional, three-phase, multiple-component numerical model to describe microbial transport phenomena in porous media is presented.

The governing equations in the mathematical model include the net flux of microbes by convection and dispersion, the decay and growth rates of microbes, and the deposition of microbes on rock grain surfaces. The decay of microbes is assumed to be a first-order reaction, and the growth of microbes is assumed to follow the Monod equation. Porosity and permeability reductions due to cell clogging have been considered, and the release of gas from microbial metabolism has been incorporated in this model. The governing equations for microbial transport and nutrient transport are coupled with the continuity and flow equations under conditions appropriate for a black oil reservoir. The nonlinear transport equations are solved by use of the Crank-Nicolson finite difference method. The model can accurately describe the observed transport of microbes, nutrients, and metabolites in coreflooding experiments. It can be used to predict the propagation of microbes and nutrients to optimize injection strategies and to design laboratory protocols for microbial enhanced oil recovery.

INTRODUCTION

Development of the methodology for applying microbial technology for improving oil recovery requires an integrated laboratory and field research effort to identify and understand the mechanisms of oil recovery, to determine the relative importance of these mechanisms in oil mobilization by laboratory experimentation, to develop mathematical correlations and models to describe the physical phenomena, and to develop and apply a mathematical computer reservoir simulator to match laboratory coreflooding results and ultimately match and predict oil recovery performance in field applications.

The relationships between transport of microbes, nutrients, metabolic products, and mobilized crude oil need to be clarified and interpreted with mathematical models for fluid flow in porous media. Physical phenomena that affect the microbial oil recovery process include: (1) dynamic growth of microorganisms; (2) mass transfer and transport of microorganisms, nutrients, metabolic chemical products, oil and brine; (3) changes in microscopic properties such as interfacial tension, wettability, and adsorption that govern oil mobilization and affect fractional flow and relative permeabilities; (4) changes in rheology of the flowing phases; and (5) certain other physical phenomena that are peculiar to microorganisms. The phenomena that affect oil mobilization by microorganisms must be understood, and mathematical models and correlations must be developed to relate the phenomena to oil recovery efficiency.

Although several attempts have been made to modify existing reservoir simulators to describe microbial processes, no model has yet fully incorporated all of the complex phenomena that are believed to be important. The unusual complexity of oil recovery by microbial formulations will obviously require close coordination between laboratory mechanistic studies and oil displacement experiments under carefully controlled conditions to develop and validate a computer model. The accuracy of a simulator that is designed for MEOR processes will be strongly dependent upon the accuracy of the equations that are used to describe the important phenomena. It is also important to recognize the unique constraints and variation in conditions that occur in actual field applications but are not always accounted for in controlled laboratory experiments. Thus, an accurate reservoir simulator for MEOR methods can best be developed through an integrated program of acquisition of laboratory and field data with the feedback loop being the reservoir simulation model. This report describes work on the development of a three-dimensional, three-phase, multiple-component numerical model to describe the microbial transport phenomena in porous media. Initial efforts have focused on incorporating the most important phenomena for which mathematical models or correlations are available or can be available in a reasonably brief period of time.

DESCRIPTION OF MODEL

Modeling Microbial Transport in Porous Media

Mathematical models for MEOR processes were developed in two steps. The first step was to develop a mathematical model to predict the propagation and distribution of microorganisms and nutrients in a one-dimensional core. The transport of microbes in porous media is governed by many complicated physical, chemical, and biological aspects such as adsorption, interaction between microbes and nutrients, and growth and decay of the cells. Based on available information, the decay of microbes was assumed to be a first-order reaction, and the growth of microbes was assumed to follow the Monod equation.[2] The governing equation for microbial transport was coupled with a transport equation for microbial nutrients. Porosity reduction due to cell clogging has been considered in this model. The nonlinear coupling equations were solved by the Crank-Nicolson finite difference method.[3] This model can be used to predict the concentration distributions for injected nutrients and microorganisms with various injection modes.

The second step was to incorporate the transport equations for microorganisms and microbial nutrients into a three-dimensional, three-phase (oil, water, and gas) black oil simulator.[4] Distributions of pressure and oil/water/gas saturation in a reservoir were first calculated according to the injection/production strategy. The fluid flow due to the pressure gradient in a reservoir was then used in the transport calculation for microorganisms and microbial nutrients. Using this simulator, the transport of microorganisms can be investigated, and the effect of the microbial system on oil recovery can be studied.

Mathematical Formulation

The microbial transport in porous media is described by the following equations:

$$\vec{\nabla} \cdot \vec{\vec{D}} \cdot \vec{\nabla}(\phi SC) - \vec{\nabla} \cdot (\vec{u}C) - k_m \vec{\nabla} \cdot (C \vec{\nabla} \ln C_f) + \phi S(\mu - k_d)C + QC/V = \frac{\partial(\phi SC)}{\partial t} + \phi S k_c C - k_y \rho \sigma \left(\frac{\sigma}{\phi}\right)^h \quad (1)$$

where σ is solved from

$$\frac{\partial \sigma}{\partial t} = (\mu - k_d)\sigma + k_c \frac{\phi SC}{\rho} - k_y \sigma \left(\frac{\sigma}{\phi}\right)^h \quad (2)$$

where

C = microbial concentration

C_f = nutrient concentration

$\vec{\vec{D}}$ = effective dispersion coefficient tensor for microbes

Q = well rate

S = aqueous saturation

V = bulk volume of well block

h = declogging parameter

k_m = chemotaxis coefficient
k_d = decay rate
k_c = clogging rate
k_y = declogging rate
u = Darcy velocity
ρ = microbial density
μ = growth rate
ϕ = porosity
σ = volume of deposited microbes / volume of porous medium

The growth of microbes was assumed to follow the Monod equation.[2] The decay rate was assumed to be a first-order reaction. The chemotactic flow of microbes, which was induced by the presence of nutrients, was assumed to follow an exponential gradient of nutrient concentration.[5-6] The porosity of the porous medium was changed by the deposition of microbes:

$$\phi = \phi_o - \sigma \tag{3}$$

where ϕ_o is the original porosity of the porous medium. Based on the Hagen-Poiseuille and Darcy equations[6], the permeability reduction due to the deposition of microorganisms to the rock pore space can be predicted by:

$$\frac{k}{k_o} = \left(\frac{\phi}{\phi_o}\right)^3 \tag{4}$$

The transport of nutrient is described by the following equations:

$$\vec{\nabla} \cdot \vec{\vec{D}}_f \cdot \vec{\nabla} (\phi S C_f) - \vec{\nabla} \cdot (\vec{u} C_f) - \mu(\phi S C + \rho \sigma)/Y + Q C_f/V = \frac{\partial(\phi S C_f)}{\partial t} \tag{5}$$

where

$\vec{\vec{D}}_f$ = dispersion coefficient tensor for nutrient
Y = yield coefficient

The functional relationship between μ in equations 1, 2 and 5 and C_f was proposed by Monod:

$$\mu = \frac{\mu_m C_f}{K_s + C_f} \tag{6}$$

where μ_m is the maximum growth rate achievable and K_s is that value of the concentration of the substrate where the specific growth rate has half its maximum value. Values of μ_m and K_s can be obtained from experimental results. The yield coefficient Y is defined as the mass of cells produced per unit of substrate removed.

Numerical Solution

The governing equations exhibit a high degree of complexity. With non-linearity and coupling, it is impossible to obtain analytical solutions for C, σ, and C_f even for a one-dimensional space. The Crank-Nicolson finite difference method was used in the numerical solution. The Crank-Nicolson finite difference method is more stable than other methods such as forward difference or backward difference methods. This numerical method has been tested with reported results for other models.

Dimensions and properties of the core, fluid characteristics, and values of parameters used are listed in table 1. The dispersion coefficient determined from this simulation match was 8.93E-5 cm^2/sec. This number was used in the following simulation runs.

TABLE 1. Model parameters

Parameter	Value
Model length (L)	122 cm (4 ft)
Porosity (ϕ)	0.20
Flow velocity (u)	1.27 cm/hr (1 ft/day)
Density of microorganisms (ρ)	1 mg/mL
Dispersion coefficients:	
microbes (D)	0.775 cm^2/hr
nutrients (D_f)	0.775 cm^2/hr
Injection microbe conc. (C_o)	30 mg/mL
Injection nutrient conc. (C_{fo})	40 mg/mL
Cell yield coefficient (Y)	0.53
Monod half growth constant (K_s)	100 mg/mL
Maximum growth rate (μ_m)	0.38 hr^{-1}
Clogging rate constant (k_c)	0.234 hr^{-1}
Declogging rate constant (k_y)	1.566 hr^{-1}
Specific decay constant (k_d)	0.0036 hr^{-1}

SIMULATION OF MEOR PROCESSES USING A THREE-DIMENSIONAL THREE-PHASE SIMULATOR

Simulator Description

Model Equations and Numerical Solution Methods

A three-dimensional, three-phase simulator for MEOR processes was developed by incorporating the above mathematical equations into a black oil simulator. Sources (injectors) and sinks (producers) at various strengths were assigned in the three-dimensional reservoir model. Note the well rate (Q) term in equations 1 and 5. The boundary condition is the no-flow boundary of the reservoir. No flow means there is no fluid flow across the boundary and is implemented by setting pressure gradients at boundary interfaces to zero. In contrast with the one-dimensional, laboratory model, where the velocity of the aqueous phase was constant in each grid block, the velocities in the x, y, and z directions in the three-dimensional reservoir model were determined from the pressure distribution obtained from solving the flow equations of the black oil reservoir model. The Crank-Nicolson method was used in setting up the finite difference formulation of transport equations. For simplicity, the numerical solutions of transport equations of the microorganisms and the nutrient were decoupled and solved separately. Component concentrations were solved implicitly in space using a direct solution method. The amount of deposition of microorganism was then calculated, and the permeability was adjusted for pressure calculations for the next time step.

Experiments are being conducted to obtain data in order to validate or improve the numerical model. An experiment was completed to determine the dispersion coefficient of microbial cells without nutrient in a Berea sandstone core. A chemical tracer, fluorescein, was first injected into a brine-saturated 10-in. long core. After tracer injection, a slug containing microbial cells with no nutrient present was injected. The tracer data was matched using the simulator (fig. 1).

Capability and Limitations

The newly developed MEOR reservoir simulator is able to model oil, water, and gas flow in a three-dimensional reservoir with heterogeneous distributions of permeability, porosity, and

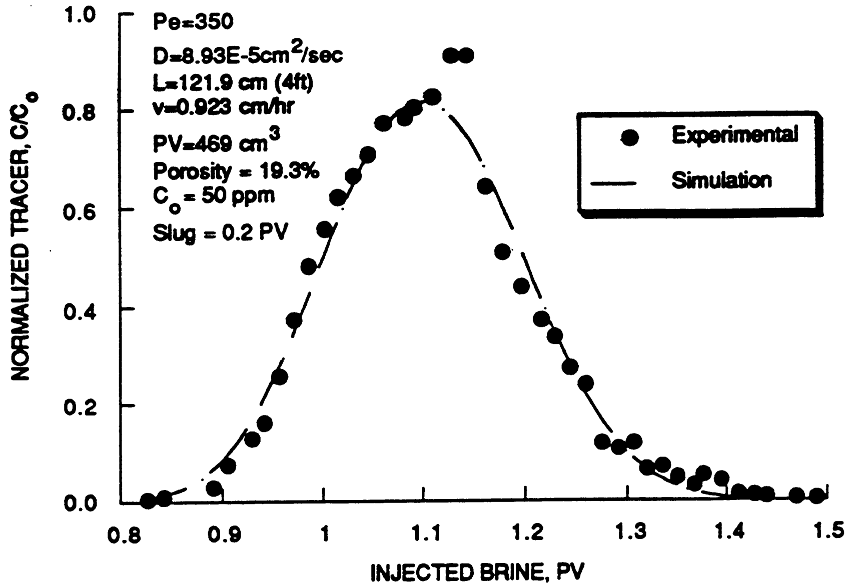

FIGURE 1. – Experimental and simulated effluent tracer concentration profiles.

saturation. It allows a flexible assignment of well locations in the model and a study of different injection and production strategies for various microbial systems. This MEOR reservoir simulator models the transport process and the permeability reduction resulting from the microbial system. However, effects of gas, surfactant, and other products released by the microorganisms on oil recovery are not included in this first phase of development. Effects of microbes and their products on relative permeability will be incorporated into this model in the near future.

Because of decoupling of transport equations of microorganisms and nutrients in solving the concentration profiles, the numerical solution might require small time steps when large values of certain interaction parameters between microorganisms and nutrients are used.

Simulation Results

Field-scale simulation runs were conducted on (1) a one-dimensional, one-layer reservoir model; and (2) a two-dimensional, two-layer reservoir model with the developed three-dimensional microbial simulator. Table 2 shows the reservoir model and the microbial system parameters used in the test runs. In the one-dimensional simulation run, only the top layer was used as the reservoir model. Injection rates used were 100 bbl/day in the one-dimensional simulation run and 300 bbl/day in the two-dimensional simulation runs. Figure 2 shows one-dimensional simulated results of the concentration profiles for microbes and nutrient at 0.23 and 0.94 PV after initiation of the injection of the microbial system into the reservoir. Because of continuous injection of nutrient, a high concentration of microbes was found near the injection wellbore. As injection continued, microbes moved into the formation. Because of a high consumption rate of the nutrient, the nutrient was close to zero at a distance beyond 30 ft from the injection wellbore. Figure 3 shows two-dimensional simulated results on the effect of microbial concentration in the injection fluid on the porosity of the high-permeability layer (bottom layer). As shown in the figure, the porosity decreased with an increase in the microbial concentration in the injection fluid. A reduction in the porosity will result in a reduction in the permeability; hence, the injection profile will be modified, and oil recovery will be increased.

TABLE 2. Reservoir model and microbial system parameters used in field-scale simulation runs

Parameter	Value
Reservoir:	
length, ft	200
width, ft	200
thickness (top/bottom layers), ft	15 and 15
Porosity, ϕ, %	20
Permeability:	
kx, ky, kz (top layer), md	100, 100, 10
kx, ky, kz (bottom layer), md	1,000, 1,000, 100
Initial oil saturation, %	75
Initial water saturation, %	25
Injected microbial conc., mg/mL	30
Injected nutrient conc., mg/mL	40
Diffusion coefficient	
microbes, ft^2/day	5.5×10^{-3}
nutrient, ft^2/day	8.3×10^{-3}
Clogging rate constant, day^{-1}	0.00234
Declogging rate constant, day^{-1}	0.01
Cell yield coefficient (Y)	0.53
Monod half growth constant, lb/cu ft	100
Maximum growth rate, day^{-1}	0.38

FUTURE WORK

The microbial parameters incorporated into the microbial transport model include: (1) microbial growth and decay; (2) microbial deposition (clogging and declogging); (3) chemotaxis; (4) diffusion; (5) convective dispersion; (6) tumbling; and (7) nutrient

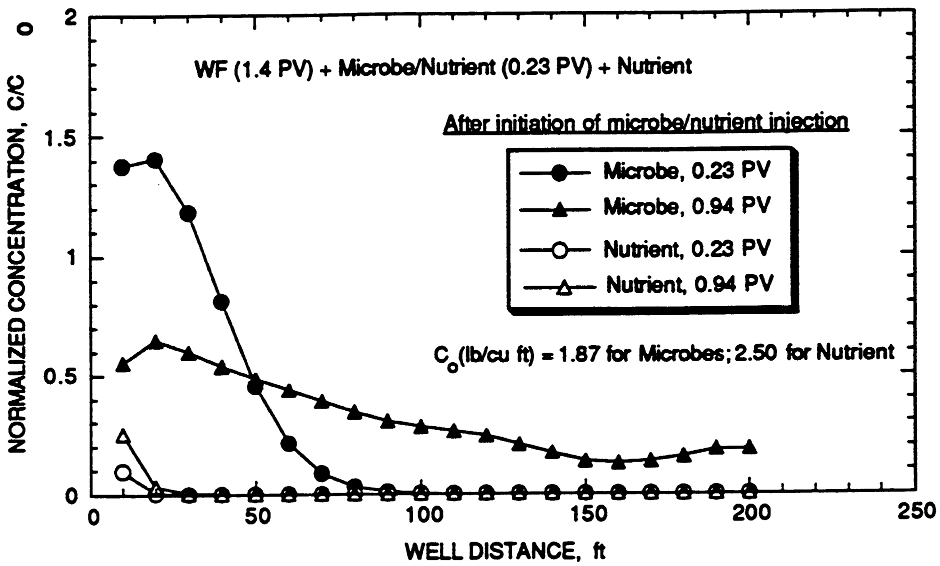

FIGURE 2. – Microbe and nutrient concentration profiles from a one-dimensional simulation run.

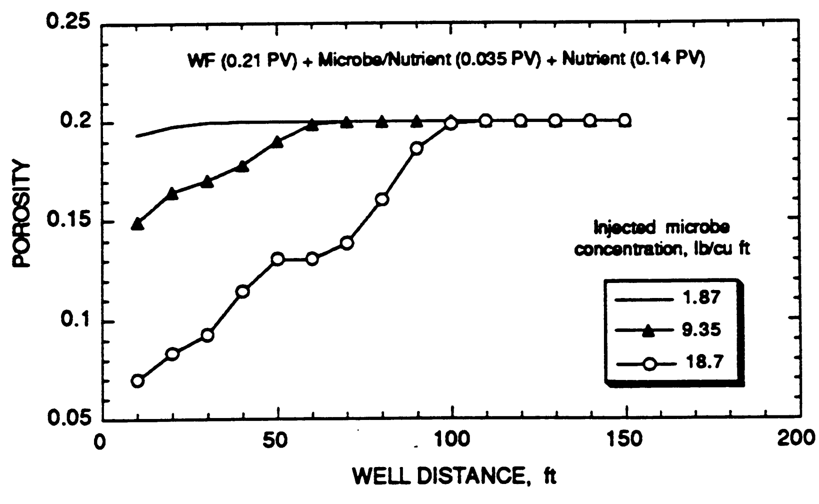

FIGURE 3. – Effective porosity profiles in the high-permeability layer.

consumption. During FY91 laboratory experiments were conducted to obtain actual data for the simulator regarding microbial growth and decay, nutrient consumption, microbial deposition, convective dispersion, and diffusion. Work for FY92 will continue to develop laboratory experiments to refine the model, not only with the above parameters, but also for obtaining data to incorporate microbial oil recovery mechanisms. Mechanisms considered to be important for oil recovery include changes in microscopic properties such as interfacial tension, wettability, and adsorption that govern oil mobilization and affect fractional flow and relative permeabilities. Other oil recovery mechanisms traditionally associated with fluid flow changes include polymer and biomass production by microorganisms.

CONCLUSIONS

1. A three-dimensional, three-phase, multiple-component simulator that includes all required mechanisms and transport phenomena of microbial systems in porous media has been developed.

2. The simulator can be used to predict the propagation of microbes and nutrients to optimize injection strategies for improving oil recovery.

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