A Flow And Transport Model In Porous Media For Microbial Enhanced Oil Recovery Studies Using COMSOL Multiphysics® Software

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Background

- The oil fields at the initial stage of operation produce using basically its natural energy which is known as *primary recovery*.
- As the reservoir loses energy it requires the injection of gas or water in order to restore or maintain the pressure of the reservoir, this stage is called *secondary recovery*.
- When the secondary recovery methods become ineffective it is necessary to apply other more sophisticated methods such as steam injection, chemicals, microorganisms, etc. These methods are known as *tertiary or enhanced oil recovery* (EOR).
- Some important oil fields in Mexico are entering the third stage.

Motivation

- For the optimal design of enhanced oil recovery methods it is required to perform a variety of laboratory tests under controlled conditions to understand what are the fundamental recovery mechanisms for a given EOR method in a specific reservoir.
- The laboratory tests commonly have a number of drawbacks, which include among others, that they are very sophisticated, expensive and largely unrepresentative of the whole range of phenomena involved.
- A proper modeling of the laboratory tests would be decisive in the interpretation and understanding of recovery mechanisms and in obtaining the relevant parameters for the subsequent implementation of enhanced recovery processes at the well and the reservoir scale.

Aim

- In this work we present a model of flow and transport which was implemented using COMSOL Multiphysics® Software to numerically simulate, analyze and interpret biphasic oil-water displacement and multicomponent transport processes in porous media at laboratory scale.
- From the methodological point of view the (conceptual, mathematical, numerical and computational) development stages of the model will be shown.
- This model will be exploded as a research tool to investigate the impact on the flow behavior of the porosity-permeability dynamic variation due to the clogging/declogging phenomena that occur during microbial enhanced oil recovery (MEOR) processes.

Metodology

The general procedure for a model development includes the following four stages:

- **Conceptual Model:** The hypothesis, postulations and conditions to be satisfied by the model.
- **Mathematical Model:** The mathematical formulation of the conceptual model in terms of equations.
- **Numerical Model:** The discretization of the mathematical model by the application of the appropriate numerical methods.
- **Computational Model:** The computational implementation of the numerical model.

Conceptual Model

- There are three phases: **water** (W), **oil** (O) and **solid** (S).
- There are five components: **water** (w), only in the water phase, **oil** (o), only in the oil phase, **rock** (r), only in the solid phase, **microorganisms** (m) in the water phase (*planktonic*) and in the solid phase (*sessile*), and **nutrients** (n) in the water phase (*fluents*) and in the solid phase (*adsorbed*).
- The rock (*porous matrix*) and the fluids are slightly compressible.

Conceptual Model

- No diffusion between phases.
- The porous medium is fully saturated.
- The fluid phases are separated in the pores.
- All phases are in thermodynamical equilibrium.
- The porous medium is considered homogeneous and isotropic
- Dynamic porosity and permeability variation due to clogging/declogging processes is allowed.

Conceptual Model

- The microorganisms and nutrients dispersive fluxes follow the Fick's law: $\boldsymbol{\tau}_\gamma^W(\mathbf{x}, t) = \phi S^W \mathbf{D}_\gamma^W \cdot \nabla c_\gamma^W; \gamma = m, n$, where S^W is the water saturation (volume fraction of water in the porous space), c_γ^W is the concentration of the component γ in water (mass of the component γ per volume of water), and $\mathbf{D}_\gamma^W$ is the hydrodynamic dispersion tensor [2].
- Microorganisms and nutrients have biological interaction, as growth Monod equation [3]: $\mu = \mu_{\max}\left(\frac{c_n^W}{K_{m/n}+c_n^W}\right)$, where $\mu_{\max}$ is the maximum specific growth rate, $K_{m/n}$ is the Monod constant for nutrients, c_n^W is the nutrients concentration in water.

Conceptual Model

- Linear decay model for planktonic ($\kappa_d \phi S^W c_m^W$) and sessile ($\kappa_d \rho_m^S \sigma$) microorganisms are used, here κ_d is the specific decay rate of cells, ρ_m^S is the microorganisms density, σ is the volume fraction of sessile microorganisms, and c_m^W is the concentration of planktonic microorganisms.
- The clogging/declogging process is modelled as a quasilinear adsorption $\kappa_a^m \phi c_m^W$ [4] and an irreversible limited desorption $\kappa_r^m \rho_m^S (\sigma - \sigma_{irr})$ processes [5], for $\sigma \geq \sigma_{irr}$ and 0 for $\sigma < \sigma_{irr}$, where κ_a^m and ${}_r^m$ are the adsorption and desorption rate coefficients, respectively, and σ_{irr} is the minimum sessile concentration.

Conceptual Model

- Nutrients and rock have physico-chemical interaction as a linear adsorption isotherm $\hat{c}_n^S = \kappa_a^n c_n^W$, where $\hat{c}_n^S$ is the adimensional nutrient concentration adsorbed within the porous medium.

Conceptual Model

Phase (α)	Component (γ)	Intensive Properties (ψ_{γ}^{α})
Water (W)	Water (w)	$\phi S^{W} \rho_{w}^{W}$
	Microorganisms (m)	$\phi S^{W} c_{m}^{W}$
	Nutrients (n)	$\phi S^{W} c_{n}^{W}$
Oil (O)	Oil(o)	$\phi S^{O} \rho_{o}^{O}$
Solid (S)	Microorganisms (m)	$c_{m}^{S} \equiv \rho_{m}^{S} \sigma$
	Rock (r)	$\rho_{r_b}^{S} \equiv (1-\phi)\, \rho_{r_p}^{S}$
	Nutrients (n)	$c_{n}^{S} \equiv \rho_{r_b}^{S} \hat{c}_{n}^{S}$

Table : Intensive properties associated with the mass of the components by phases

Mathematical Model

- For deriving the equations of the mathematical model the **axiomatic formulation of continuum mechanic systems** is applied [6].
- This axiomatic formulation adopts a macroscopic approach, which considers that the material systems are fully occupied by particles.
- A continuum system is made of a particle set known as material *body*, see figure 1.
- The continuum system approach works with the volume average of the body properties and consequently there is a volume called *representative elementary volume* (REV) over which the property averages are valid.

Axiomatic Formulation of Continuum Mechanic Systems

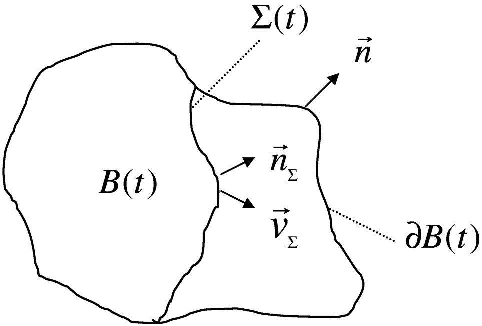

Figure : General scheme of a material body: $B(t)$ is the body with boundary $\partial B(t)$, where $\mathbf{n}$ is the outer normal vector, $\Sigma(t)$ is the discontinuity surface with a normal vector $\mathbf{n}_\Sigma$ and velocity $\mathbf{v}_\Sigma$.

Axiomatic Formulation of Continuum Mechanic Systems

- The continuum approach formulation basically consists in to establish a one to one correspondence between the *extensive properties* $E(t)$, which are the volume integrals of the intensive properties, for example: the mass, and the *intensive properties* $\psi(\mathbf{x}, t)$, which are the physical properties by unit of volume, for example: the mass density. Both properties are related by the following expression:

$$E(t) \equiv \int_{B(t)} \psi(\mathbf{x}, t)\, d\mathbf{x}, \tag{1}$$

Axiomatic Formulation of Continuum Mechanic Systems

- **Global Balance Equation**

$$\frac{dE(t)}{dt} = \int_{B(t)} g(\mathbf{x},t)\,d\mathbf{x} + \int_{\Sigma(t)} g_{\Sigma}(\mathbf{x},t)\,d\mathbf{x} + \int_{\partial B(t)} \boldsymbol{\tau}(\mathbf{x},t)\cdot\mathbf{n}\,dx \quad (2)$$

where $g(\mathbf{x},t)$ is the source term in $B(t)$; $g_{\Sigma}(\mathbf{x},t)$ is the source term at $\Sigma(t)$; and $\boldsymbol{\tau}(\mathbf{x},t)$ is the vector flux through the boundary $\partial B(t)$.

- **Local Balance Equations**

$$\frac{\partial\psi}{\partial t} + \nabla\cdot(\psi\mathbf{v}) = g + \nabla\cdot\boldsymbol{\tau}; \qquad \forall\mathbf{x}\in B(t) \quad (3)$$

$$[\![\psi(\mathbf{v}-\mathbf{v}_{\Sigma}) - \boldsymbol{\tau}]\!]\cdot\mathbf{n}_{\Sigma} = g_{\Sigma}; \qquad \forall\mathbf{x}\in\Sigma(t), \quad (4)$$

where $[\![f]\!] \equiv f_{+} - f_{-}$ is the jump of the function f across $\Sigma(t)$.

Axiomatic Formulation of Continuum Mechanic Systems

- It is necessary to apply the previous procedure to each component in each phase, obtaining as many equations as components by phases we have.
- For the resulting system of equations it is required to specify certain *constitutive laws* which are related with the nature of the problem, for example, the Darcy law in the case of a model of flow in porous media. These constitutive relationships allow to link the intensive properties among them and define the flux and source terms.
- Even after this operation it is usually necessary to add some complementary relationships to obtain a determined system.
- Finally, the model is completed when sufficient *initial* and *boundary conditions* are specified. In this manner we get a well posed problem, which means that there exists one and only one solution.

The flow model

The flow model is based on the oil phase pressure and total velocity formulation given by Chen Z. [7]

- **Pressure equation**

$$
\begin{aligned}
&-\nabla \cdot \left\{ \lambda \mathbf{k} \cdot \nabla p^O - \left(\lambda^W \frac{dp_c^{OW}}{dS^W} \right) \mathbf{k} \cdot \nabla S^W \right\} \\
&-\nabla \cdot \left\{ \left(\lambda^O \rho^O + \lambda^W \rho^W \right) \gamma \mathbf{k} \cdot \nabla z \right\} = q^O + q^W - \frac{\partial \phi}{\partial t}
\end{aligned}
\tag{5}
$$

- **Saturation equation**

$$
\begin{aligned}
&\phi \frac{\partial S^W}{\partial t} - \nabla \cdot \left\{ \lambda^W \mathbf{k} \cdot \nabla p^O - \left(\lambda^W \frac{dp_c^{OW}}{dS^W} \right) \mathbf{k} \cdot \nabla S^W \right\} \\
&-\nabla \cdot \left\{ \left(\lambda^W \rho^W \gamma \right) \mathbf{k} \cdot \nabla z \right\} + \left(\frac{\partial \phi}{\partial t} \right) S^W = q^W
\end{aligned}
\tag{6}
$$

The flow model

- **Phase velocities**

$$\mathbf{u}^W = -\lambda f^W \mathbf{k}\cdot\nabla p^O + \lambda f^W \left(\frac{dp_c^{OW}}{dS^W}\right)\mathbf{k}\cdot\nabla S^W - \lambda f^W \rho^W \gamma \mathbf{k}\cdot\nabla z;$$
$$\mathbf{u}^O = -\lambda f^O \mathbf{k}\cdot\nabla p^O - \lambda f^O \rho^O \gamma \mathbf{k}\cdot\nabla z; \tag{7}$$

Here, $\mathbf{u}^\alpha$ is the Darcy velocity

$$\mathbf{u}^\alpha = -\frac{k_r^\alpha}{\mu^\alpha}\mathbf{k}\cdot(\nabla p^\alpha + \rho^\alpha \gamma \nabla z)\,;\alpha = O,W \tag{8}$$

where ϕ - porosity, $\mathbf{k}$ - absolute permeability tensor, S^α - saturation, ν^α - viscosity, ρ^α - density, p^α - pressure, k_r^α - relative permeability, and q^α - source term, for each phase $\alpha = O, W$, $|\mathbf{g}|$ - absolute value of the gravity acceleration, p_c^{OW} - capillary oil-water pressure and z - vertical coordinate.

The flow model

- **Brooks-Corey's relative permeability equation**[8]:

$$k_r^W = S_e^{\frac{2+3\theta}{\theta}} \; k_r^O = (1 - S_e)^2 \left(1 - S_e^{\frac{2+\theta}{\theta}}\right); \qquad (9)$$

where S_e is the effective or normalized saturation, which is defined as:

$$S_e = \frac{S^W - S_r^W}{1 - S_r^W - S_r^O}$$

Here, S_r^W and S_r^O are the residual saturations for water and oil, respectively. As long as θ characterizes the pore size distribution.

The flow model

- **Brooks-Corey's oil-water capillary pressure equation**:

$$p_c^{OW}\left(S^W\right) = p_t \left(\frac{S^W - S_r^W}{1 - S_r^W - S_r^O}\right)^{(-1/\theta)} \tag{10}$$

where p_t is the entry or left threshold pressure assumed to be proportional to $(\phi/k)^{1/2}$.

The transport model

- **Planktonic microorganisms equation (in water)**(c_m^W):

$$\frac{\partial\left(\phi S^W c_m^W\right)}{\partial t} + \nabla\cdot\left(c_m^W \mathbf{u}^W - \phi S^W \mathbf{D}_m^W \cdot \nabla c_m^W\right) = \left(\mu - \kappa_d - \kappa_a^m\right)\phi S^W c_m^W + \kappa_r^m \rho_m^S \left(\sigma - \sigma_{irr}\right) \quad (11)$$

- **Sessile microorganisms equation (in solid)**(σ):

$$\frac{\partial\left(\rho_m^S \sigma\right)}{\partial t} = \left(\mu - \kappa_d\right)\rho_m^S \sigma + \kappa_a^m \phi S^W c_m^W - \kappa_r^m \rho_m^S \left(\sigma - \sigma_{irr}\right) \quad (12)$$

- **Nutrients equation (total)**(c_n^W):

$$\frac{\partial\left\{\left(\phi S^W + (1-\phi)\rho_{r_b}^S \kappa_a^n\right) c_n^W\right\}}{\partial t} + \nabla\cdot\left(c_n^W \mathbf{u}^W - \phi S^W \mathbf{D}_n^W \cdot \nabla c_n^W\right) = -\frac{\mu}{Y_{m/n}}\left(\phi S^W c_m^W + \rho_m^S \sigma\right) \quad (13)$$

Complementary relationships

- **Porosity modification:** The porosity modification due to the clogging/declogging processes is taking in account by the following expression given in Chang et al. in 1992 [9]:

$$\phi = \phi_0 - \sigma \tag{14}$$

where ϕ - actual porosity, ϕ_0 - initial porosity and σ - volume fraction occupied by sessile microorganisms.

- **Permeability modification:** The permeability modification is expressed as a porosity function by the Kozeny-Carman equation [1]:

$$k = k_0 \frac{(1-\phi_0)^2}{\phi_0^3} \frac{\phi^3}{(1-\phi)^2} \tag{15}$$

where k and k_0 are the actual and initial permeability, respectively.

Initial and boundary conditions

- **Initial conditions:**

$$\begin{aligned} p^{O}\left(t_0\right) = p_0^{O},\ S^{W}\left(t_0\right) = S_0^{W};\\ c_m^{W}\left(t_0\right) = c_{m0}^{W},\ \sigma\left(t_0\right) = \sigma_0,\ c_n^{W}\left(t_0\right) = c_{n0}^{W}; \end{aligned} \tag{16}$$

- **Boundary conditions**
  1. Inlet conditions (constant rate)

$$\begin{aligned} \mathbf{u}^{O}\cdot\mathbf{n} = \mathbf{u}^{W}\cdot\mathbf{n} = \mathbf{u}_{in}^{W}\cdot\mathbf{n};\\ -\left[c_\gamma^{W}\mathbf{u}_{in}^{W} - \phi S^{W}\mathbf{D}_\gamma^{W}\cdot\nabla c_\gamma^{W}\right]\cdot\mathbf{n} = c_{\gamma_{in}}^{W}\mathbf{u}_{in}^{W}\cdot\mathbf{n},\ \gamma = m, n; \end{aligned} \tag{17}$$

  2. Outlet conditions (constant pressure)

$$\begin{aligned} p^{O} = p_{out}^{O},\ \frac{\partial S^{W}}{\partial \mathbf{n}} = 0;\\ \frac{\partial c_\gamma^{W}}{\partial \mathbf{n}} = 0,\ \gamma = m, n; \end{aligned} \tag{18}$$

Numerical Model

For the numerical solution we applied the following methods:

- For the temporal derivatives a backward finite difference discretization of second order resulting a full implicit scheme in time.
- For space derivatives a standard finite element discretization with quadratic Lagrange polynomials.
- For the linearization of the non linear equation system the iterative Newton-Raphson method.
- For the solution of the resulting algebraic system of equations a variant of the LU direct method for non symmetric and sparse matrices implemented in the UMFPACK library.

Computational Model

- Once we have established the numerical model for the solution of the mathematical model its computational implementation is required.
- The realization of the flow model was performed using the COMSOL Multiphysics ® software by the PDE mode in general coefficient form for the time-dependent analysis [10].

Reference case study: a waterflooding test in a core

- The reference case study is a waterflooding test in a core that can be conventionally divided in two injection steps that are sequentially performed.
- In the first step the oil is displaced by water injection.
- While, in the second one the water is injected with microorganisms and nutrients.
- The data used here to simulate both injection steps are taken from the published literature [11, 12].

First injection step: secondary recovery by water injection

- Initially, a Berea sandstone core of 0.25 m of length and 0.04 m of diameter with homogeneous porosity (ϕ_0=0.2295) and isotropic permeability ($k_0 = 326$ md) set in vertical position, is fully saturated with water.
- The water is displaced by oil injection until the residual saturation of water is achieved.
- The water is injected from the lower side of the core with a constant velocity of one foot per day (3.53×10^{-6} m/s), while the oil and water are produced at a constant pressure (10 kPa) in the opposite side of the core during 200 hours until a steady state is obtained.
- A summary of the data is given in table 2 which are taken from [11] and [12].

Data for the flow and transport model

Parameter	Value	Parameter	Value
Core length	$L = 0.25$ m	Core diameter	$d = 0.04$ m
Porosity	$\phi_0 = 0.2295$	Permeability	$k_0 = 326$ md
Water viscosity	$\nu^W = 1.0 \times 10^{-3}$ Pa.s	Oil viscosity	$\nu^O = 7.5 \times 10^{-3}$ Pa.s
Water density	$\rho^W = 1.0$ g/cm^3	Oil density	$\rho^O = 0.872$ g/cm^3
Residual water saturation	$S_r^W = 0.2$	Residual oil saturation	$S_r^O = 0.15$
Production pressure	$p_{out}^O = 10$ kPa	Brooks-Corey parameter	$\theta = 2$
Entry pressure	$p_t = 10$ kPa	Injection velocity	$u_{in}^W = 1$ ft/day
Nutrients dispersion	$D_n^W = 0.0083$ ft^2/day	Microorganisms dispersion	$D_m^W = 0.0055$ ft^2/day
Injected nutrients conc.	$c_{n_{in}}^W = 2.5$ lb/ft^3	Injected microorganisms conc.	$c_{m_{in}}^W = 1.875$ lb/ft^3
Microorganisms density	$\rho_m^B = 1000$ kg/m^3	Irreducible biomass fraction	$\sigma_{irr} = 0.003$
Maximum specific growth	$\mu_{\max} = 8.4$ day^{-1}	Affinity coefficient	$K_{m/n} = 0.5$ lb/ft^3
Production coefficient	$Y_{m/n} = 0.5$	Decay coefficient	$\kappa_d = 0.22$ day^{-1}
Adsorption coefficient	$\kappa_a^m = 25$ day^{-1}	Desorption coefficient	$\kappa_r^m = 37$ day^{-1}

Table : Data for the flow and transport model taken from [11] and [12].

A 3D view of the finite element discretization mesh

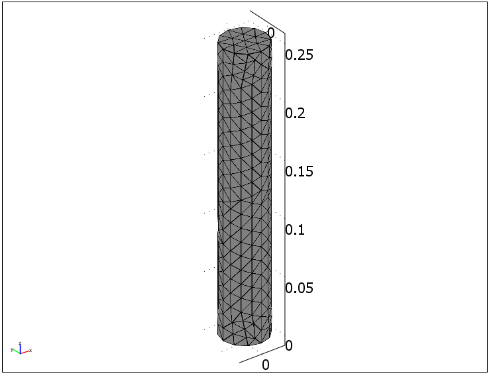

Figure : 1,702 tetrahedral elements, 6,232 degrees of freedom, execution time: 170.179 seg, in a PC with CPU Intel Core2 Duo @2.66 GHz and 4Gb of RAM @1.97 GHz.

Water saturation

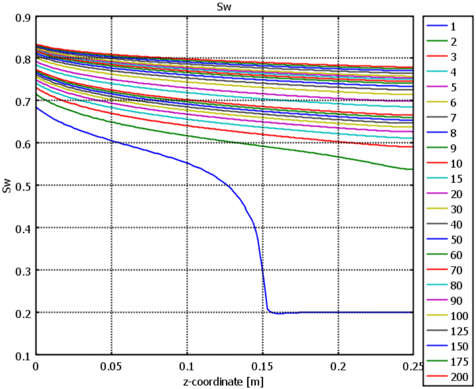

Figure : Water saturation distribution during 200 hours of water flooding.

Oil pressure drop

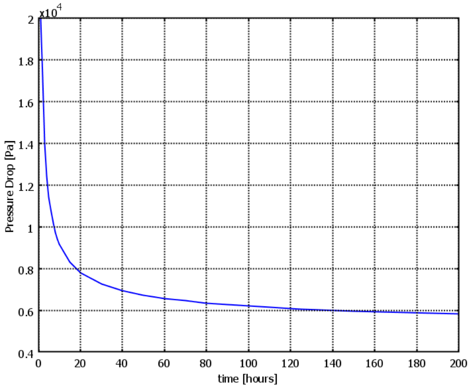

Figure : Oil pressure drop curve during 200 hours of water flooding.

Oil recovery

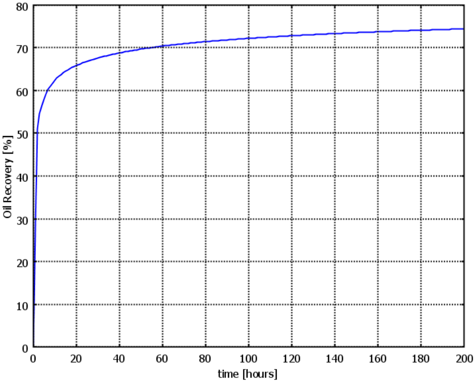

Figure : Oil recovery curve during 200 hours of water flooding.

Interpretation of results

- It is shown that a water front through the porous medium is formed. The oil displaced by the water front is recovered at the upper end of the core.
- The head of water breaks through the top of the core just before the two hours. It can be observed that the oil pressure drop ($\delta p \equiv p_{in}^{O} - p_{out}^{O}$) downfalls drastically from 20 kPa to 8 kPa during the first 20 hours, whereas in the next 180 hours the oil pressure drop continues downfalling but slowly up to a value of 5,770 Pa, approximately.
- It is worth to note that the oil recovery curve represents a typical behavior of a recovery process where the porous medium is strongly oil wet.
- The total recovery of oil is approximately 74%.

Second injection step: EOR by water injection with microorganisms and nutrients

- In the second step of the test, microorganisms and nutrients are injected simultaneous and continuously to the Berea sandstone core through the water phase during 24 hours until a steady state is obtained.
- The intention of this test consists in evaluating the additional oil production that can be recovered by mechanical effects because of the microbial activity (MEOR).
- As in the first step of the test data are taken from [11] and [12].

A 3D view of the finite element discretization mesh

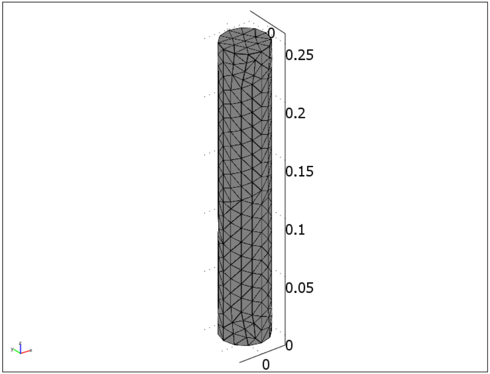

Figure : 1,702 tetrahedral elements, 15,577 degrees of freedom, execution time: 216.906 seg, in a PC with CPU Intel Core2 Duo @2.66 GHz and 4Gb of RAM @1.97 GHz.

Water saturation

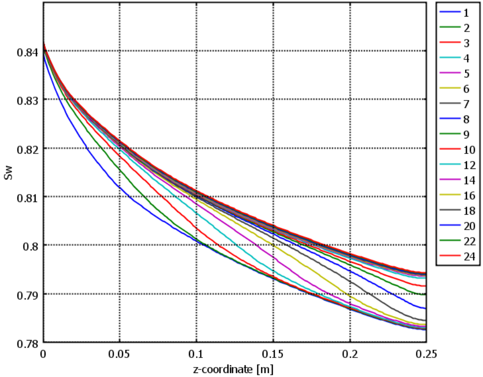

Figure : Water saturation distribution during 24 hours of water flooding with microorganisms and nutrients.

Oil pressure drop

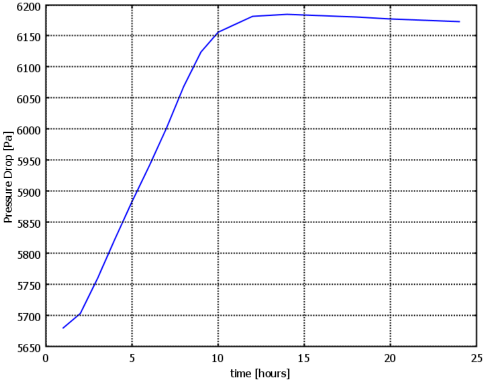

Figure : Oil pressure drop curve during 24 hours of water flooding with microorganisms and nutrients.

Oil recovery

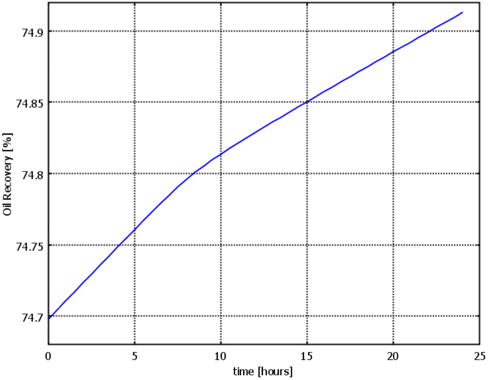

Figure : Oil recovery curve during 24 hours of water flooding with microorganisms and nutrients.

Nutrients and planktonic microorganisms concentrations

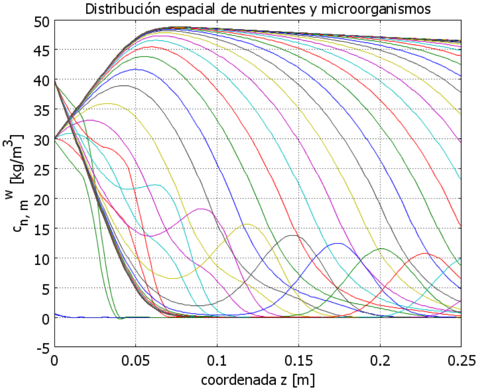

Figure : Nutrients (rising from 40 kg/m^3) and planktonic microorganisms (rising from 30 kg/m^3) concentrations, given every hour, along the vertical axis during 24 hours of water flooding with

Sessile microorganisms concentration

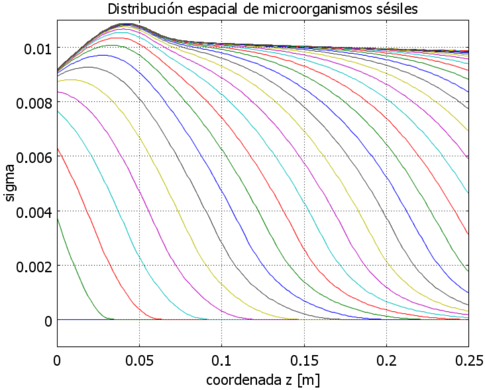

Figure : Sessile microorganisms concentrations, given every hour, along the vertical axis during 24 hours of water flooding with microorganisms and nutrients.

3D porosity distribution

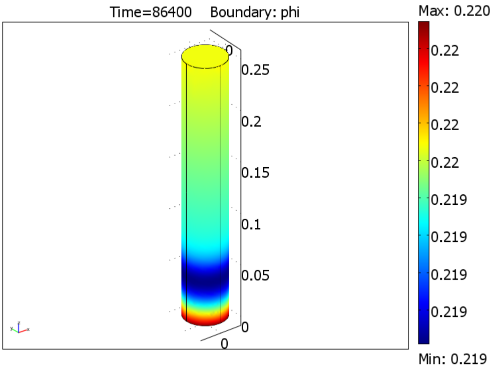

Figure : 3D porosity distribution after 24 hours of water flooding with microorganisms and nutrients.

3D permeability distribution

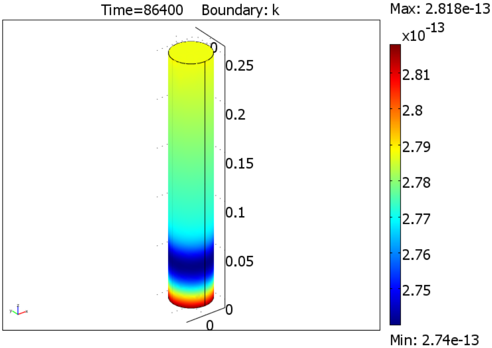

Figure : 3D permeability distribution after 24 hours of water flooding with microorganisms and nutrients.

Interpretation of results

- It is observed that water continues displacing the oil through the core during the 24 hours of water flooding with microorganisms and nutrients.
- It can be seen that there is a slightly increase in the oil pressure drop from 5680 to 6185 Pa. This repressurization phenomenon is associated with the modification of porosity and, consequently, with the modification of the permeability due to the biomass growth.
- A marginal additional oil recovery of about 0.2% is obtained.

Interpretation of results

- Stationary state is established around the 6 hours, where nutrients are almost completely consumed, while at the 24 hours approximately an asymptotic value in the concentration of microorganisms is reached.
- The maximum planktonic and sessile microorganisms concentration values are achieved in $c_m^W = 48.85$ kg/m^3 and $\sigma = 1.1\%$ at 0.074 m and 0.041 m, respectively.
- The variations in σ are reflected directly in porosity and permeability changes, where the minimum values are achieved in a zone around 0.041 m from the core bottom.

Final remarks

- In this work a quite general flow and transport model in porous media was implemented using the standard formulation of the finite element method to simulate laboratory tests at core scale and under controlled conditions.
- This model was successfully applied to a reference case study of oil displacement by the injection of water follows by the injection of water with microorganisms and nutrients, using data taken from the published literature.

Final remarks

- In this paper, the porosity and permeability modification due to the variation in the biomass distribution along the core was investigated.
- The resemblance of the porosity (ϕ) and permeability (k) spatio-temporal distributions of the form of the sessile microorganisms concentration (σ), can be attributed to the simplicity of the porosity and permeability relationships applied.
- The application of more realistic dependence functions is an open issue.

Final remarks

- The observed repressurization phenomenon associated with the modification of porosity and permeability due to the biomass growth could be used to plug highly permeable zones to redirect the flow and to increase the oil sweep efficiency.
- Regarding the marginal additional recovery produced during the EOR microbial process, less than 1%, it can not be directly attributed to the mechanical effects such as the pressure increase due to microbial growth.

Future work

- To model other effects such as: rock wettability, viscosity ν, relative permeability k_r and capillary pressure p_c curves modification because of the bioproducts action over fluids and rock, further experimental investigation is required, to quantify in terms of constitutive relationships the interaction between petrophysical and fluid properties as a function of bioproducts concentrations.

References

P. C. Carman, *Flow of gases through porous media*, Butterworth, London, (1956).

Jacob Bear, *Dynamics of fluids in porous media*, Dover, USA, (1972).

Gaudy, A.F., Jr. and E.T. Gaudy, *Microbiology for environmental scientists and engineers*, McGraw-Hill Book Co., USA, (1980).

Corapcioglu M.Y. and A. Haridas, "Transport and fate of microorganisms in porous media: A theoretical investigation", *Journal of Hydrology*, **72**, 149-169, (1984)

Lappan, E.R. and Fogler, H.S., "Reduction of porous media permeability from in situ Leuconostoc mesenteroides growth and dextran production", *Biotechnol. Bioeng.*, **50** (1), 6-15, (1996)

M. B. Allen, I. Herrera and G. F. Pinder, *Numerical modeling in science and engineering*, John Wiley & Sons., USA, (1988).

Z. Chen, G. Huan and Y. Ma, *Computational methods for multiphase flows in porous media*, SIAM, USA, (2007).

R. Brooks and A. Corey, "Hydraulic Properties of Porous Media", *of Colorado State University Hydrology Paper*, **3**, Colorado State University, (1964).

M.M.Chang, R. S. Bryant, A.K. Stepp and K.M. Bertus, "Modeling and Laboratory Investigations of Microbial Oil Recovery Mechanisms in Porous Media", **DE/93 000105, NIPER-629**, (1992).

COMSOL Multiphysics, *Modeling Guide Version 3.4*, COMSOL AB, USA, (2007).

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Thank you

¿Questions , comments?