Deformable porous media saturated by three immiscible fluids: Constitutive modeling and core flooding simulations

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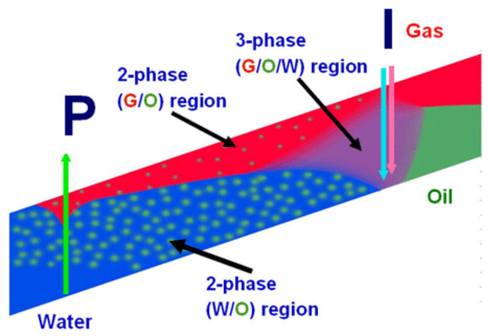
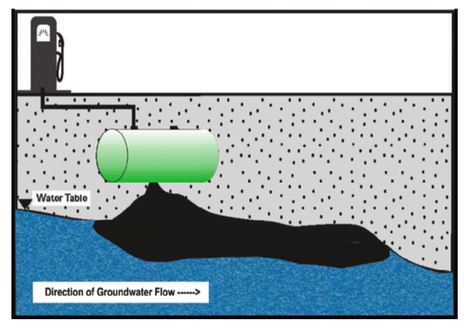
INTRODUCTION

- The coexistence of three non-miscible fluids, typically water, a gaseous and an oily phase, is typical of (e.g.)
  - **soil decontamination**, such as air sparging techniques
  - **enhanced hydrocarbon recovery** (EOR) processes, such as gas or steam injection and water-alternating-gas (WAG) injection.
- In such cases, **three fluid phase modelling** is required.
- A comprehensive framework based on the finite element method to simulate **fluid injection/imbibition processes in deformable rocks** saturated by three immiscible fluids is developed, without resorting to specific simplifications.
- The proposed model is then used to simulate different types of **core flooding experiments**.



Example of EOR: schematic of Water-Alternated-Gas injection. Image from statoil.com



Schematic of groundwater pollution with hydrocarbons, that may be treated with (e.g.) air sparging. Image from wrd.org

MODEL FORMULATION

Mass and momentum balances

$$\frac{1}{J}\frac{dm_k}{dt} = -\mathrm{div}\,\mathbf{M}_k + n_k\,\hat{\rho}_k \qquad \mathrm{div}\,\boldsymbol{\sigma} + \rho\,\mathbf{g} = \mathbf{0}$$

Constitutive equations of the solid grains and skeleton

$$\frac{dv_s}{dt} = \frac{K}{K_s}\frac{d}{dt}\mathrm{tr}\,\boldsymbol{\epsilon} + \frac{n-\kappa}{K_s}\frac{d\overline{p}}{dt}$$

$$-\frac{dn}{dt} = (n-\kappa)\frac{d}{dt}\mathrm{tr}\,\boldsymbol{\epsilon} + \frac{n-\kappa}{K_s}\frac{d\overline{p}}{dt}$$

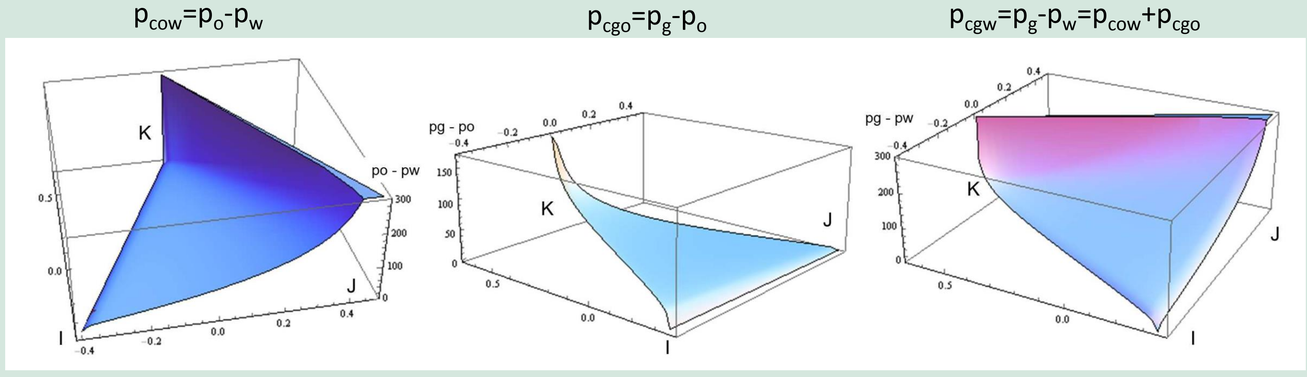
Constitutive equations of fluid transport

$$\mathbf{M}_k \equiv n_k\,\rho_k\,(\mathbf{v}_k - \mathbf{v}_s) = -D_k\,(\boldsymbol{\nabla} p_k - \rho_k\,\mathbf{g}), \quad D_k \equiv \rho_k\,k_{rk}\,\frac{k_{in}}{\eta_k}$$

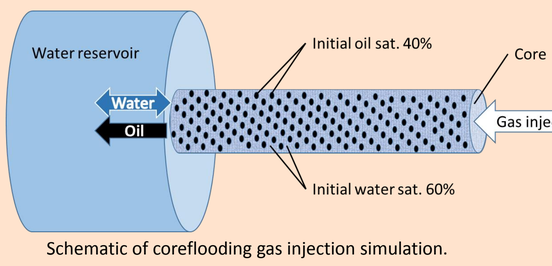
Capillary pressures for a three-fluid phase porous medium

Original relations are proposed, to provide more realistic curves over the irreducible saturation triangle

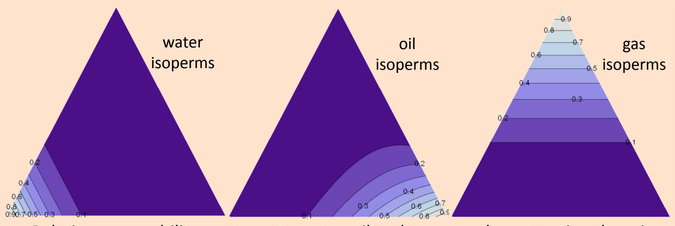
$p_{cow}=p_o-p_w$ $\quad$ $p_{cgo}=p_g-p_o$ $\quad$ $p_{cgw}=p_g-p_w=p_{cow}+p_{cgo}$



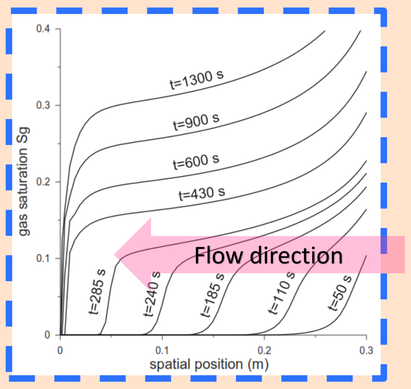
GAS INJECTION USING BROOKS-COREY TYPE PERMEABILITY MODEL



Schematic of coreflooding gas injection simulation.

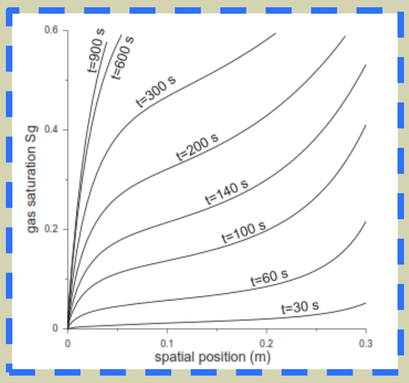


Relative permeability contours to water, oil and gas over the saturation domain.

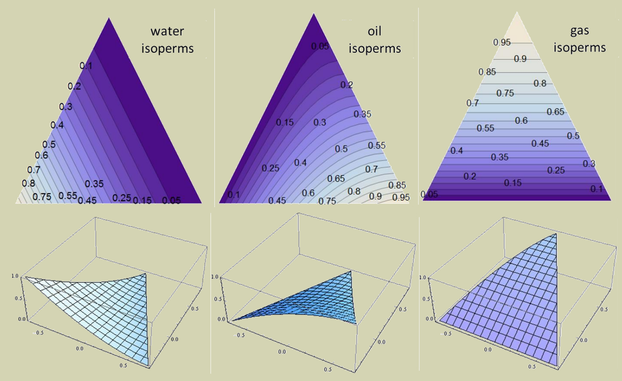


Gas saturation spatial profiles during gas injection simulation.

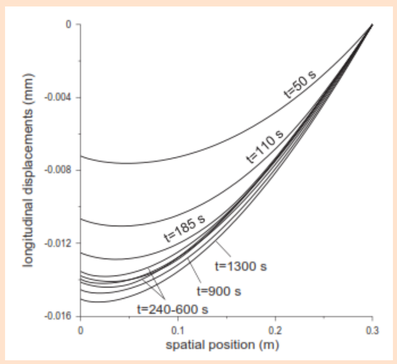
GAS INJECTION USING ALTERNATIVE PERMEABILITY MODELS



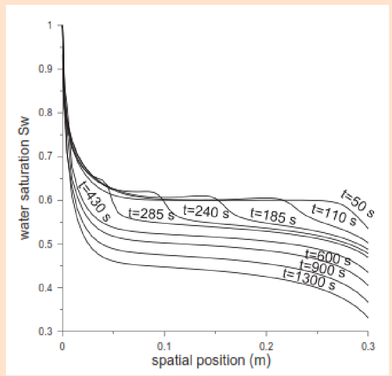
Gas saturation spatial profiles during gas injection simulation using the bundle model.



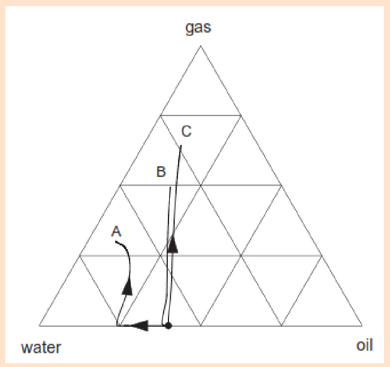
Relative permeabilities to water, oil and gas over the saturation domain represented both in 2D and 3D using the bundle model.



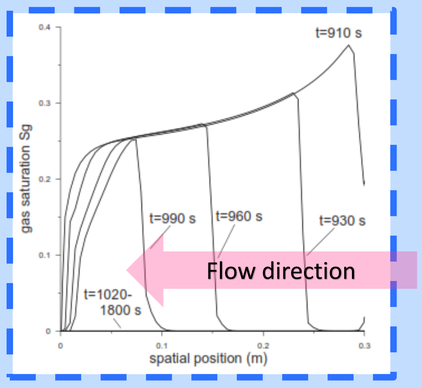
Spatial profiles of displacement during the injection process.



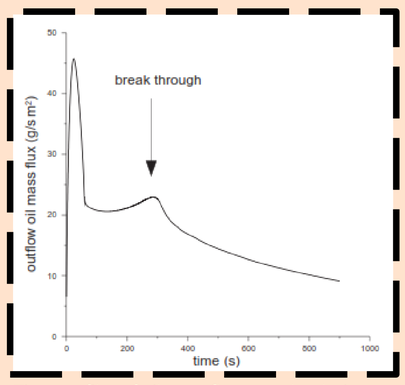
Water saturation spatial profiles during gas injection simulation.



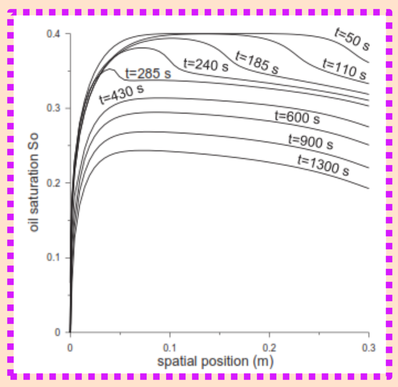
Saturation paths at points A close to outlet, B at core center, and C close to inlet, during gas injection for 900 s.



Gas saturation spatial profiles during water-alternated-gas simulation (water injection phase).

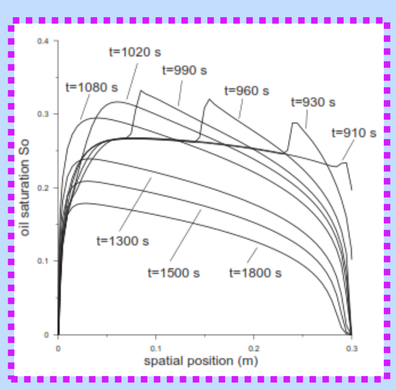


Time profiles of oil mass flux at outlet during gas injection simulation.

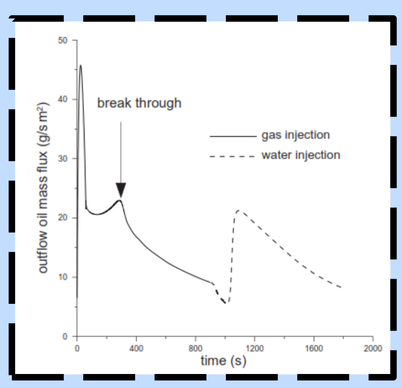


Oil saturation spatial profiles during gas injection simulation.

WAG INJECTION USING BROOKS-COREY TYPE PERMEABILITY MODEL



Oil saturation spatial profiles during water-alternated-gas simulation (water injection phase).



Time profiles of oil mass flux at outlet during water-alternated-gas simulation (water injection phase).

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References:

Gajo, A., Cecinato, F. and Loret, B. (2016), Deformable Porous Media Saturated by Three Immiscible Fluids: Constitutive Modelling and Simulations of Injection and Imbibition Tests. Transport in Porous Media. DOI 10.1007/s11242-016-0763-2

Gajo, A., Cecinato, F. and Loret, B. (2016), A general computational framework for immiscible three phase flow in deformable porous media, submitted for publication.