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SCIENTIFIC AND STRATEGIC ENVIRONMENTAL CONSULTING

Benchmarking tailored formulations of multiphase flow in porous media

Álvaro Sáinz-García, E. Abarca, A. Nardi, F. Grandia

COMSOL CONFERENCE
2015 GRENOBLE

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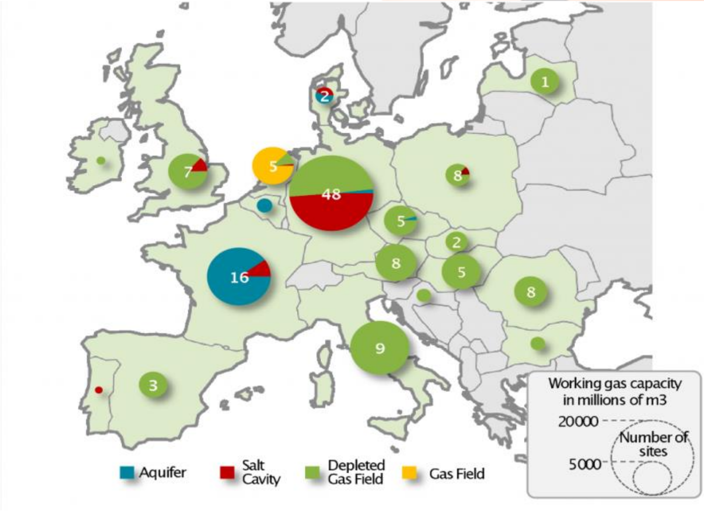
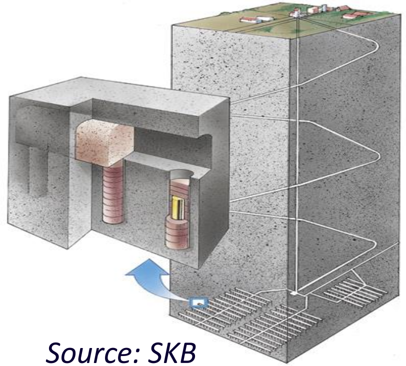
Multiphase flow situations

New uses of the underground

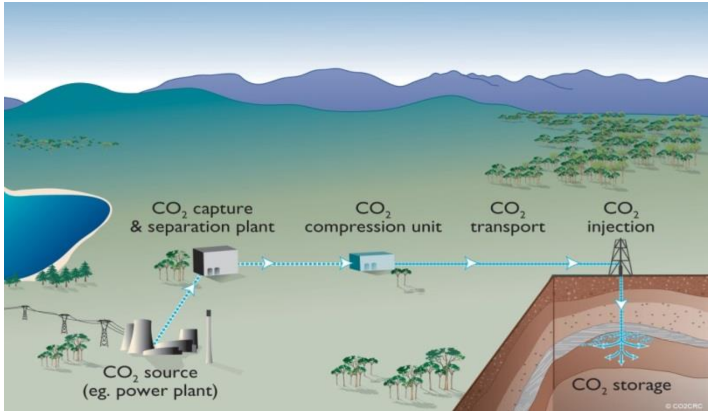
- Geological gas storage
  - Hydrogen storage
  - Carbon capture and storage
- Oil and gas industry
  - Enhance Oil Recovery
- Nuclear waste storage



Source: GSE 2013



Source: SKB



Source:
CRC for GHG (CO2CRC)

Multiphase flow formulation

ADE system

Component mass conservation

$$\partial_t(\phi S_\alpha \rho_\alpha m_\alpha^\kappa M^\kappa) = -\nabla(\boldsymbol{q_\alpha}\rho_\alpha m_\alpha^\kappa M^\kappa - \phi S_\alpha \rho_\alpha \boldsymbol{D_\alpha}\nabla(m_\alpha^\kappa M^\kappa)) + Q_\alpha^\kappa + T_\alpha^\kappa$$

$$\boldsymbol{q_\alpha} = -\frac{k k_{r,\alpha}}{\mu_\alpha}(\nabla P_\alpha - \rho_\alpha \boldsymbol{g})$$

α = *wetting & non-wetting phase*

k = *components*

Typically 4 equations

Constitutive equations

Total saturation $S_n + S_w = 1$

Capillarity pressure $P_{cap} = P_n - P_w$; $P_{cap} = P_{cap}(S_w)$

Relative permeability $k_l^r, k_g^r = f(S_w)$

Gas volume $V_g = V_g(p_g, T, m_l^{CO_2}, m_S^{NaCl})$

Liquid density $\rho_b = \rho_b(p_l, T, m_l^{CO_2}, m_S^{NaCl})$

Viscosity $\mu_g = \mu_g(p_g, T, m_l^{CO_2}, m_S^{NaCl})$

…

Multiphase flow formulation

Modeler alternatives

- How to represent the **capillary pressure**
  - Van Genuchten
  - Brooks & Corey
  - Specific interfacial area
- Which **unknowns** will be solved
  - Phase pressure & Phase saturation ($S_\alpha, P_\alpha\}$)
  - “Global” variables (total pressure or capillary pressure)
- Which **combination of governing equations** will be solved
  - Global equation, phase equation, linear combinations,…
- Which **state variables** will be used
  - Thermodynamic relations

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Multiphase flow formulation

COMSOL Implementation

Non-wetting + wetting eq.

$$0 = \nabla\left(k\lambda_n\left(\nabla P_w + \frac{dP_{cap}}{dS_n}\nabla S_n - \rho_n \boldsymbol{g}\nabla z\right)\right) + \nabla\left(k\lambda_w(\nabla P_w - \rho_n \boldsymbol{g}\nabla z)\right) + q_n + q_w$$

Non-wetting eq.

$$\phi\, \partial_t(S_n) = \nabla\left(k\lambda_n\left(\nabla P_w + \frac{dP_{cap}}{dS_n}\nabla S_n - \rho_n \boldsymbol{g}\nabla z\right)\right) + q_n$$

Matrix form:

$$\begin{pmatrix} 0 & 0 \\ 0 & \phi \end{pmatrix}\frac{\partial}{\partial t}\begin{pmatrix} P_w \\ S_n \end{pmatrix} + \nabla\cdot\left[-k\begin{pmatrix} \lambda & \lambda_n \frac{dP_{cap}}{dS_n} \\ \lambda_n & \lambda_n \frac{dP_{cap}}{dS_n} \end{pmatrix}\nabla\begin{pmatrix} P_w \\ S_n \end{pmatrix} - kg\begin{pmatrix} \lambda_w\rho_w + \lambda_n\rho_n \\ \lambda_n\rho_n \end{pmatrix}\right] = \begin{pmatrix} q_n + q_w \\ q_n \end{pmatrix}$$

COMSOL Coefficient Form PDE

$$e_a\frac{\partial^2 \mathbf{u}}{\partial t^2} + d_a\frac{\partial \mathbf{u}}{\partial t} + \nabla\cdot(-c\nabla \mathbf{u} - \alpha \mathbf{u} + \gamma) + \beta\cdot\nabla \mathbf{u} + a\mathbf{u} = f$$

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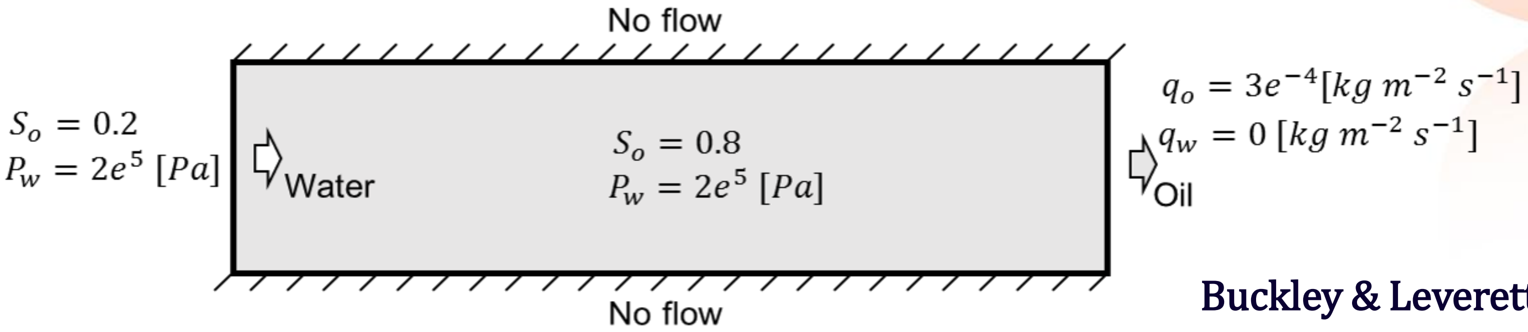
Multiphase flow

Benchmarking – Buckley-Leverett problem

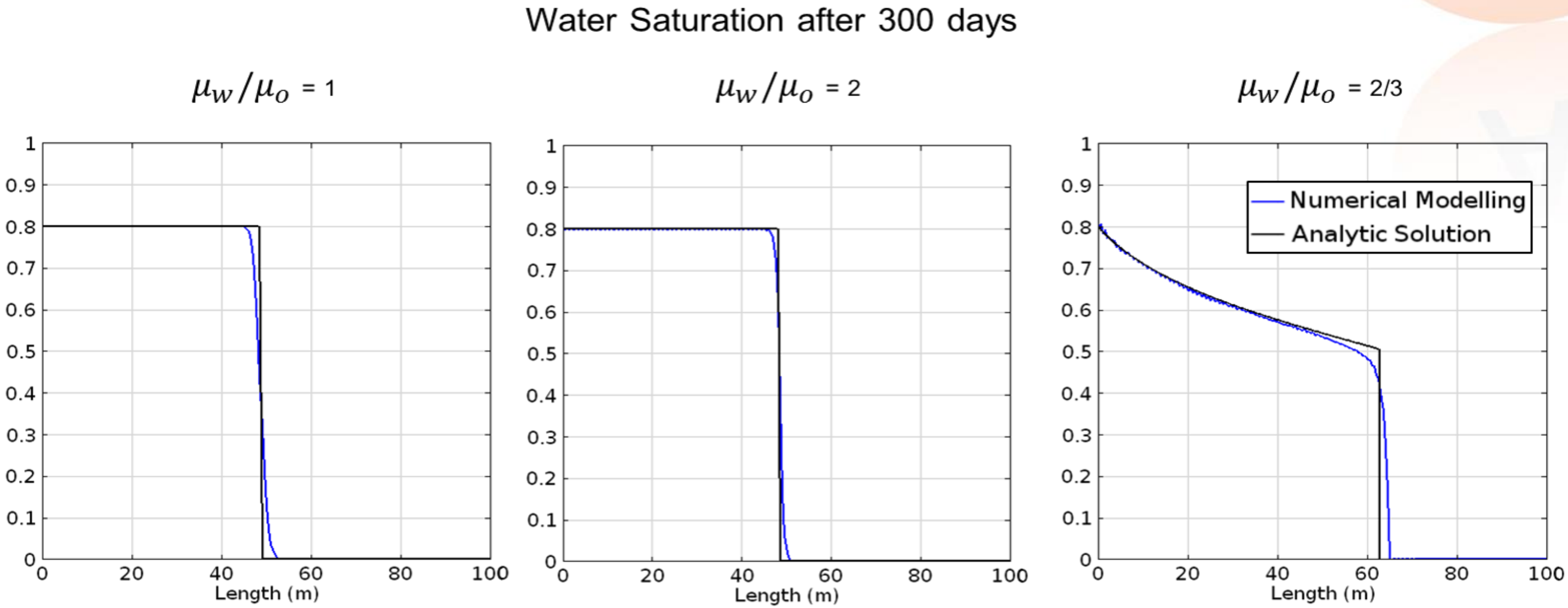


Buckley & Leverett, 1942

- 1D displacement of oil by water
- Immiscible fluids
- No capillary pressure
- Various fluid viscosities
- Gravity effects neglected
- Homogeneous porous media

Multiphase flow

Benchmarking – Buckley-Leverett problem



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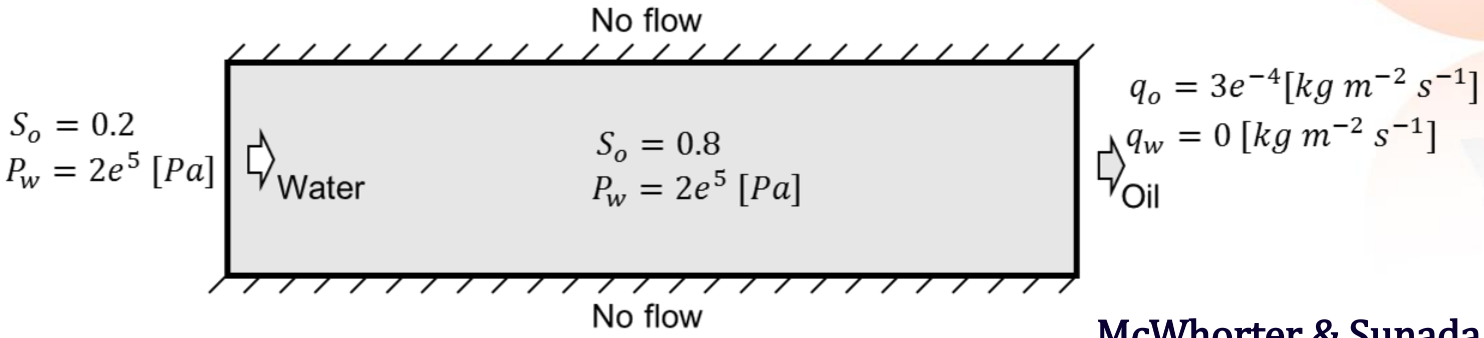
Multiphase flow

Benchmarking – McWorther problem

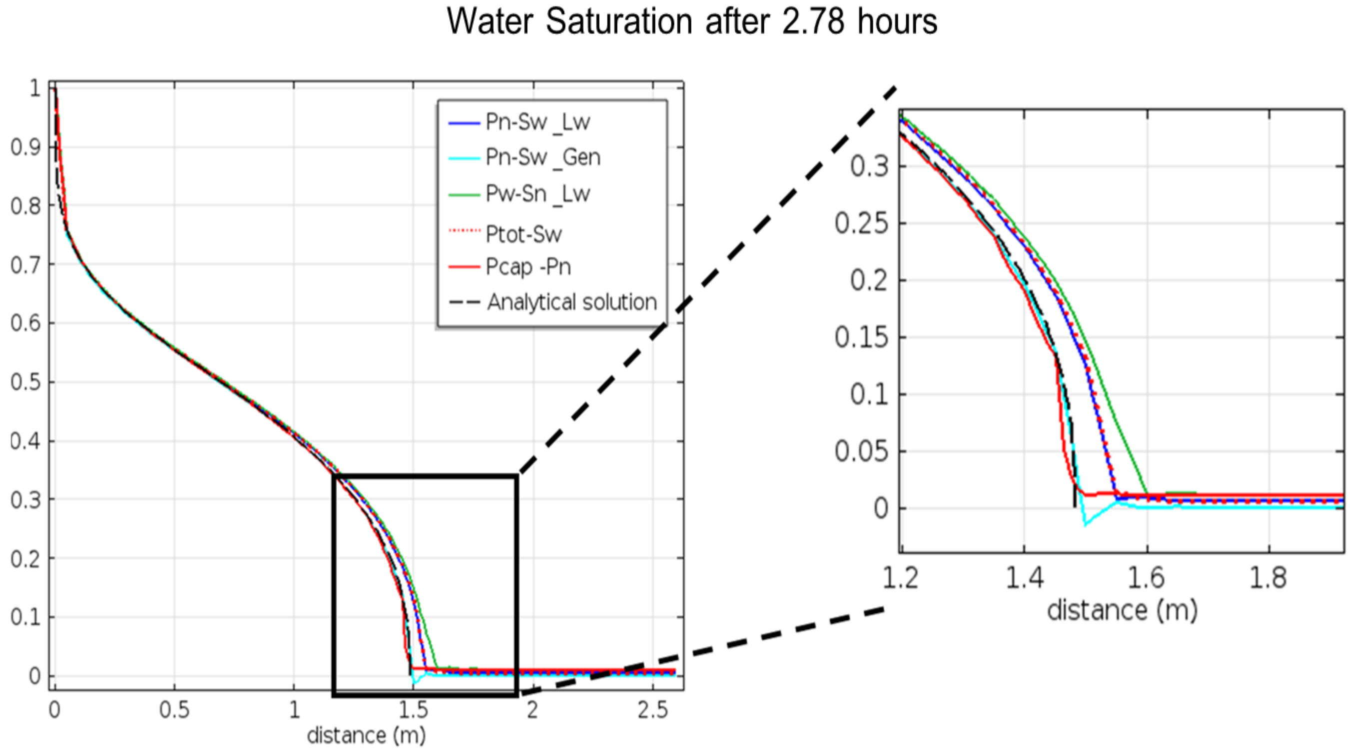


McWhorter & Sunada, 1990

- 1D displacement of oil by water
- Immiscible fluids
- Capillary pressure
- Equal fluid viscosities
- Gravity effects neglected
- Homogeneous porous media

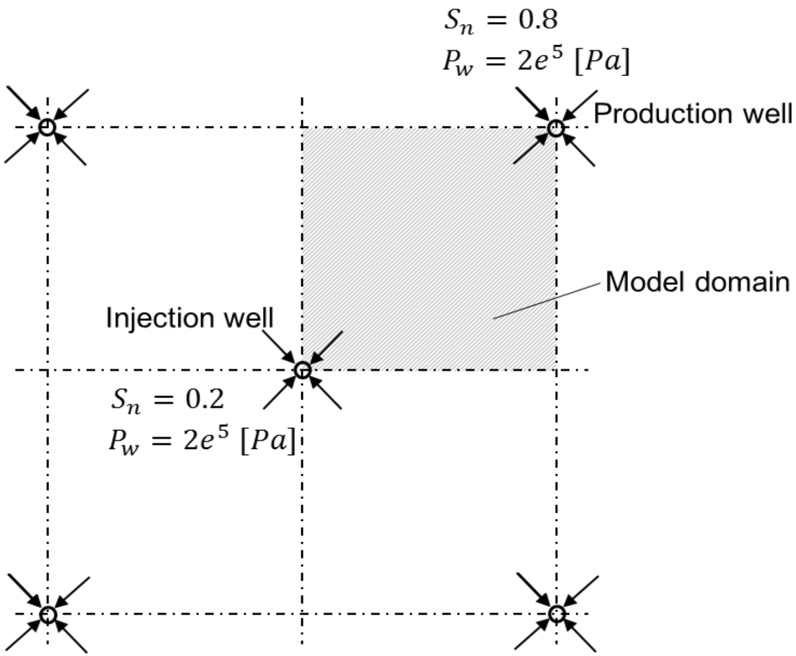
Multiphase flow

Benchmarking – McWorther problem



Multiphase flow

Benchmarking – Five spot problem

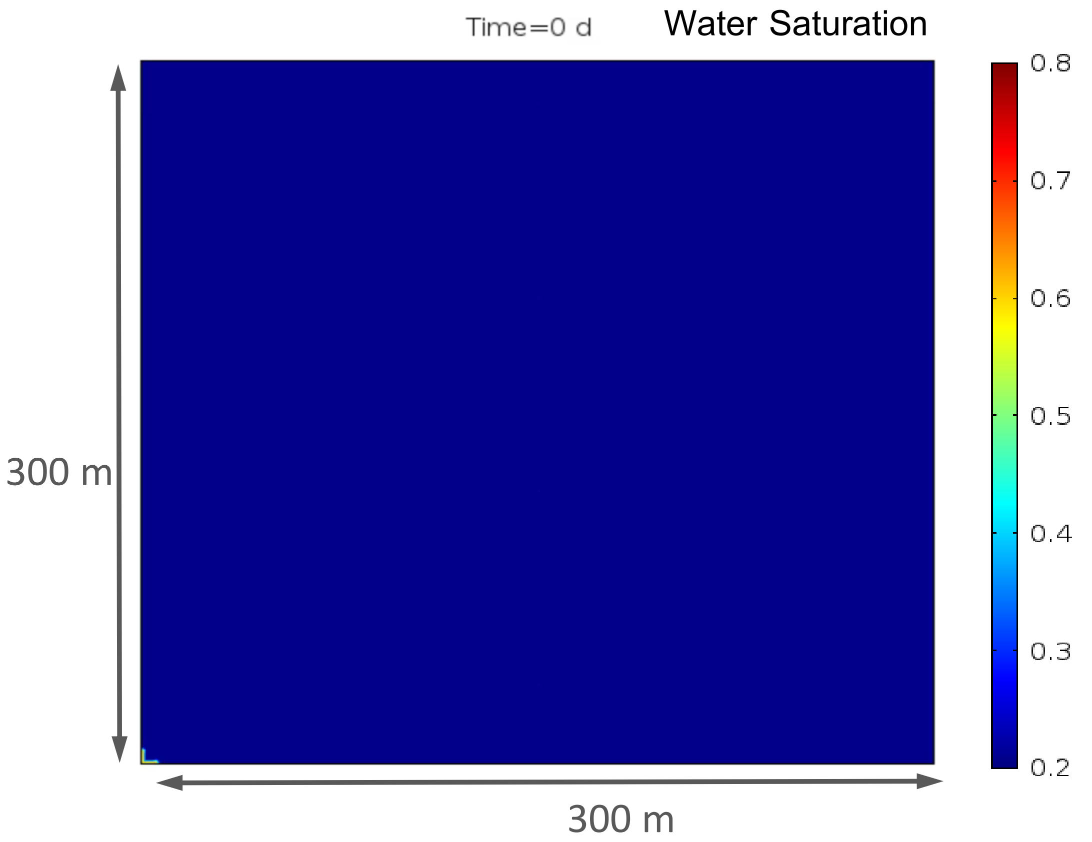


Chen, et al., 2006

- 2D displacement of oil by water
- Immiscible fluids
- No capillary pressure
- Equal fluid viscosities
- Gravity effects neglected
- Homogeneous porous media

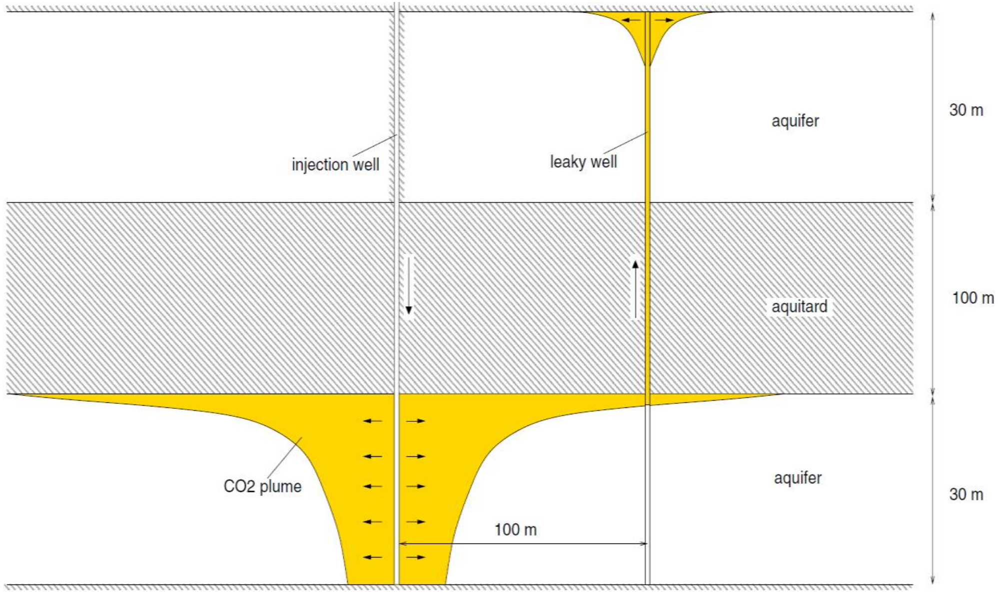
Multiphase flow

Benchmarking – Five spot problem



Multiphase flow

Benchmarking – CCS well leakage

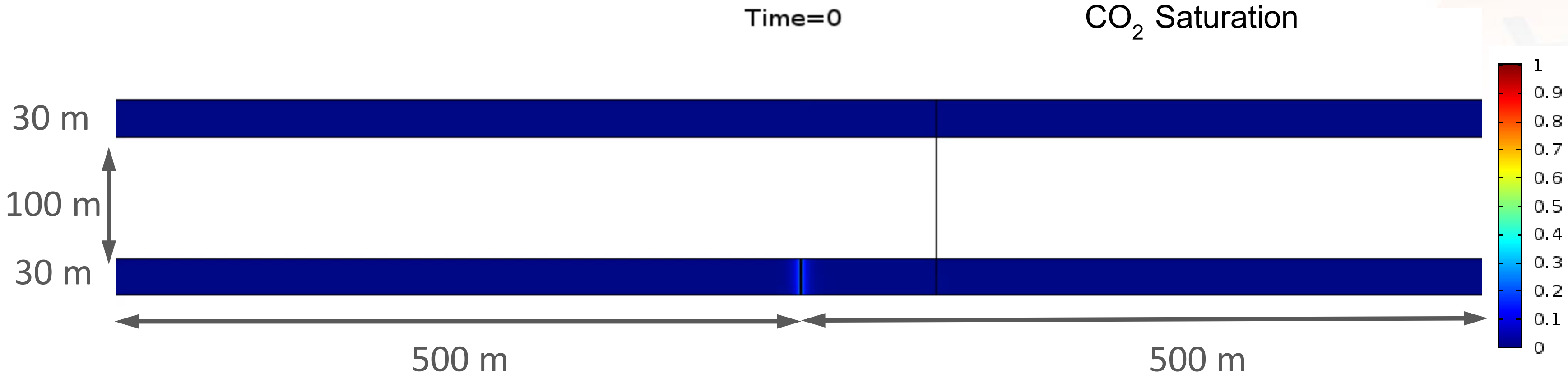


Ebigbo et al., 2007

- 2D model simplification of the 3D problem
- Immiscible fluids
- No capillary pressure
- ρ, μ are constant
- isothermal

Multiphase flow

Benchmarking – CCS well leakage



Multiphase flow

Summary

- Formulations reproduced multiphase physical processes
- equations of state of oil, water, brine and CO_2sup
  - easily extended to any other fluid

- The manner the equations are combined matters
- **Each formulation has its own benefits and drawbacks**
- The preferred may vary depending on the physics and numerical methods

ESPAÑA
AMPHOS 21 CONSULTING S.L.
Paseo de García Faria, 49-51
08019 BARCELONA
Tel.: +34 93 583 05 00
Fax : +34 93 307 59 28

CHILE
AMPHOS 21 CONSULTING CHILE Ltda.
Av. Nueva Tajamar 481 of. 1005 (Torre Sur)
Las Condes 7550099
SANTIAGO DE CHILE
Tel.: +562 27991630

PERÚ
AMPHOS 21 CONSULTING PERU S.A.C.
Av. del Parque Sur 661, San Borja
Lima 41
Tel.: +511 5921275

FRANCE
AMPHOS 21 CONSULTING FRANCE S.A.R.L.
14 Avenue de l'Opéra
75001 PARIS
Tel.: +33 1 69345030

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