Two-phase Flow Calculations in Pore Unit-cells Implementing Mixed FEM/Lattice-Boltzmann Simulators

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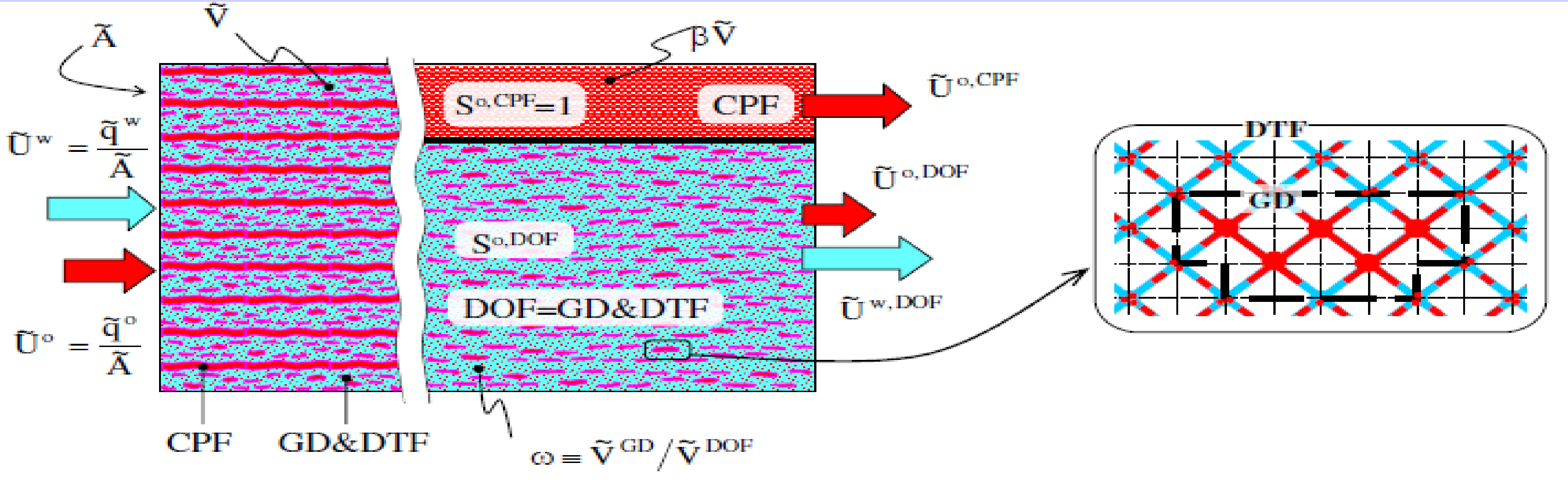
OBJECTIVES

- Macroscopic two-phase flow in porous media is a mixture of connected (COF) and disconnected oil flow (DOF)
- DOF is expressed as
  - ganglion dynamics
  - drop traffic flow
- with flow patterns observed experimentally in
  - pore network models
  - real porous media
- This characteristic was adversely not taken into account in previous modeling approaches.
- Mechanistic model *DeProF* for immiscible, two-phase flow in pore networks developed by Valavanides & Payatakes (2001)
  - predicts steady-state relative permeabilities
  - implementing concept of decomposition in prototype flows
- Common macroscopic pressure gradient for wetting and non-wetting phase is computed for each set of imposed flowrates

BASIC CONCEPTS



The DeProF model of the macroscopic 2ph flow and its conceptual decomposition into connected pathway flow (CPF) and disconnected-oil flow (DOF), comprising ganglion dynamics (GD) and drop traffic flow (DTF).

OBJECTIVES

Computational effectiveness of *DeProF* algorithm (~15 mins per complete simulation on a standard PC) is based on an inherent hierarchical theoretical modeling approach

- At pore scale level, the different configurations of two-phase flow within unit cells
  - imbibition & drainage, invoking larger non-wetting blobs (ganglia & large droplets) within pores,
  - core annular flow of tiny non-wetting droplets within pore throats,

  modeled by implementing relatively simple computational schemes
  - lubrication approximation of Stokes flow,
  - Young-Laplace law for the interfacial tension,
  - to derive the corresponding unit cell conductances.
- Fractional distribution of conductances are scaled-up:
  - using effective medium theory
  - mass & flowrate balances

  into a macroscopic description of flow.
- Canonical ensemble of physically admissible flow configurations is integrated into a corresponding average (or effective) configuration of the macroscopic flow

- *Valavanides, M.S. "Steady-State Two-Phase Flow in Porous Media: Review of Progress in the Development of the DeProF Theory Bridging Pore- to Statistical Thermodynamics- Scales" Oil & Gas Science and Technology* ***67****(5) (2012) pp. 787-804*

OBJECTIVES

- In order to harness the *DeProF* model algorithm with more realistic pore-scale two-phase flow modules:

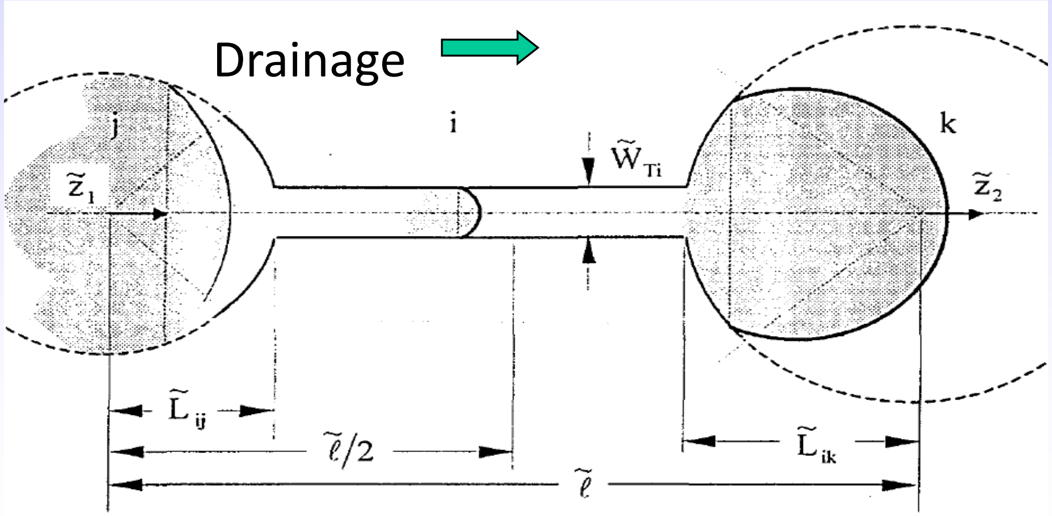
- Calculations of the flow conductance in both
  - typical cells,
  - more complex pore configurations, and
  - for various flow configurations
    - Single-phase of oil or water flow
    - Two-phase oil-water interfaces

  have been performed.

- Numerically calculated values of the simple pore conductivities have been compared with the conventional approaches (lubrication approximation) already used in the basic versions of the *DeProF* algorithm

CORRELATIONS & PARAMETERS

- The cells in which CFD calculations were performed were of the chamber-and-throat type unit-cells.
- Each unit-cell consist of two short cylinders of class (j, k), linked together with a rectilinear cylindrical throat of elliptical cross section of class i ("blister-and-flat-stick" type u.c.). All cylindrical chambers have parallel axes, perpendicular to the macroscopic flow direction.



Geometric unit-cell parameters

$$\xi_{ij} = \frac{W_{Ti}}{D_{Cj}}$$

$$u_{0ij} = \cosh^{-1}\left(\frac{1}{\xi_{ij}}\right)$$

$$x_{0ij} = \frac{D_{Cj}}{2}\frac{\sqrt{1-\xi_{ij}^2}}{1+\xi_{ij}}$$

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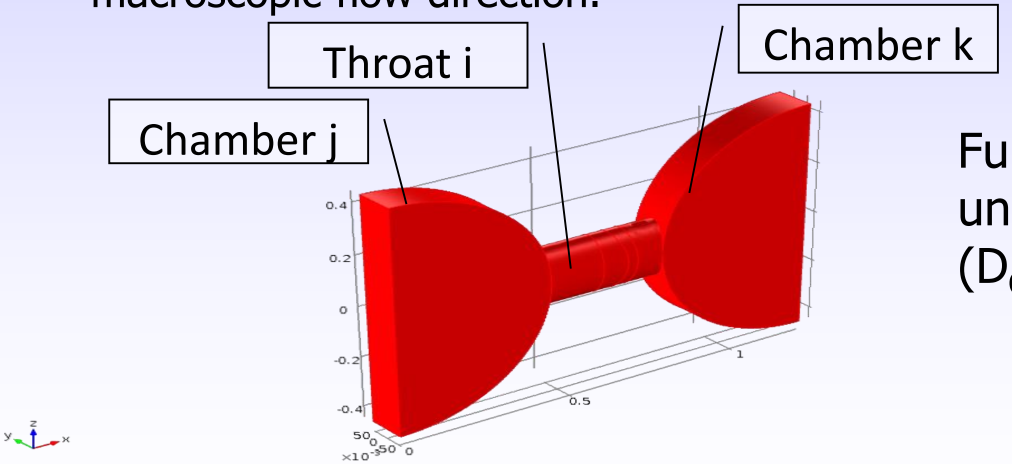
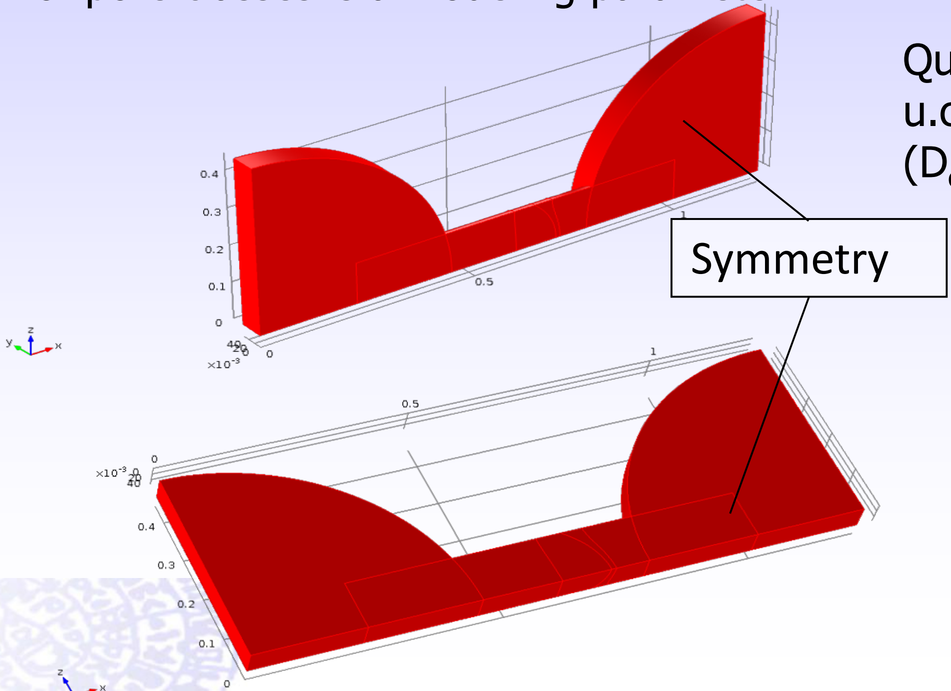


Full geometry view of a typical jik unit cell
(D_{Cj}= D_{Ck}=880μm, W_{ti}=222μm)

CORRELATIONS & PARAMETERS

- There are *N* classes of throats and chambers (*i*, *j*, *k*, = {1, 2, …, *N*}), forming N^3 classes of *jik*-unit-cells. Similarly, in the 3D network, each elementary unit-cell is composed of two sixths-spherical chambers of class *j*, *k*, interconnected with a straight cylinder of diameter class i. In the present work, *N*=5, however the number of pore classes is a modeling parameter.



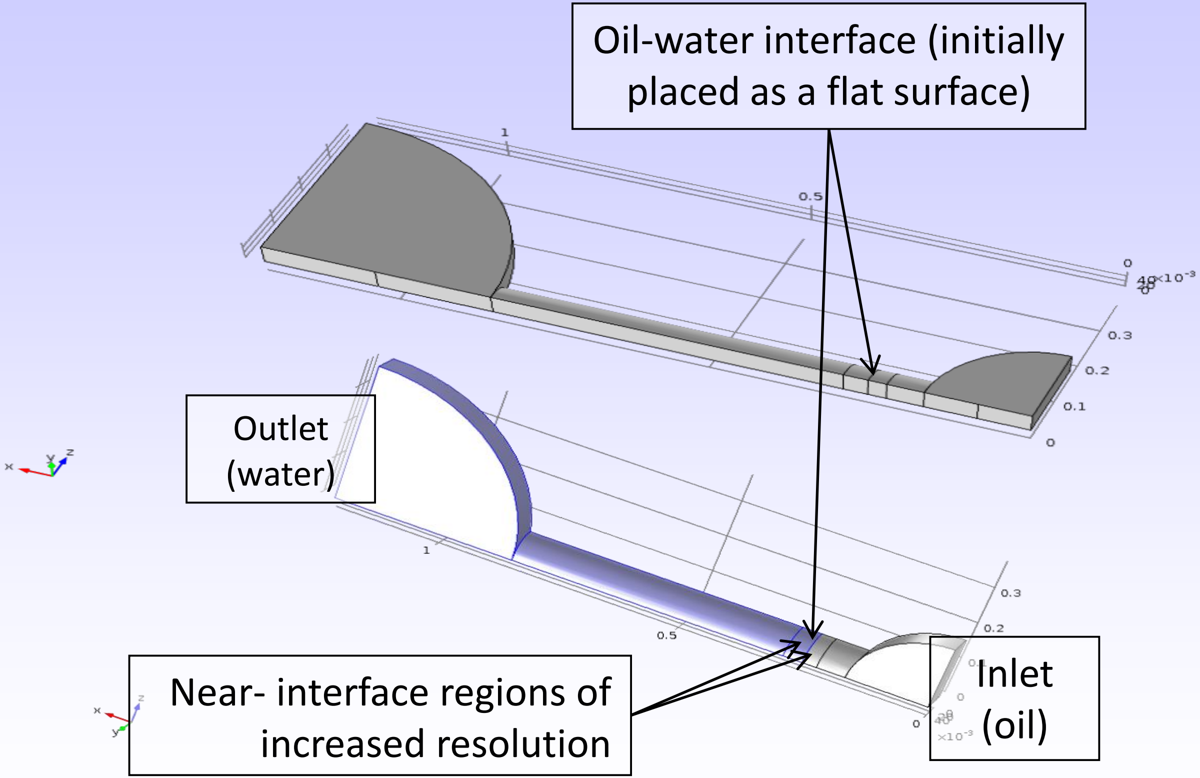
Quarter-geometry view of jik-class u.c.
(D_{cj}=880μm, W_{ti}=222μm)

- Basic configuration uses all available symmetries to minimize computational burden.
- Volume of Fluids method
- Computational mesh is moving (adapted) with the oil-water interface

FLOWFIELD & BOUNDARY CONDITIONS

- Precise geometry, nominal dimensions of chambers & necks, and their occurrence frequency on the network are described in [Valavanides & Payatakes, 2001].
- Two-phase flow conductances (absolute permeabilities) of *jik*-class unit cells were studied
  - with sophisticated transient Level-Set multiphase FEM methods with moving mesh at the interfaces [Olson & Kreiss, 2005], and
  - Lattice-Boltzmann two-phase flow with the BGK approximation [Kalarakis *et al.*, 2002] simulators

2Φ Simulations



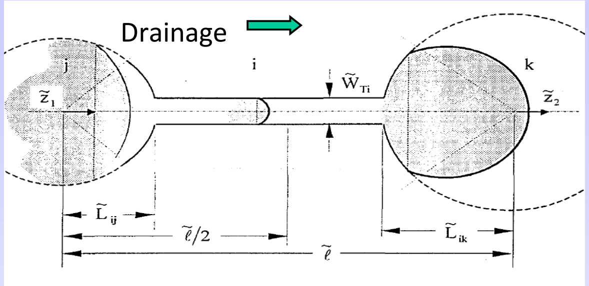
Quarter geometry view (D_{cj}=330μm, D_{ck}=750μm, W_{ti}=111μm).

3. FLOWFIELD & BOUNDARY CONDITIONS

- Results are delivered for the following configurations:
  - (i) Single-phase water and oil flow
  - (ii) Two-phase wetting/non-wetting (immiscible) flow with the w/n-w interface contacting –at fixed angle- the pore conduit walls for cases:
    - (ii.a) Receding w/n-w interface across a jik unit-cell (gradual drainage)
    - (ii.b) Advancing w/n-w interface across a jik unit-cell (gradual imbibition)
- Conductivities were calculated for predefined values of velocities or pressure gradients, and appropriate look-up tables (maps) were delivered
- Results are compared with typical analytical estimations using lubrication theory used in current *DeProF* implementations

LUBRICATION THEORY APPROXIMATION

Total pressure drop across any *jik*-class unit cell



$$\Delta\tilde{p}_{jik} = \Delta\tilde{p}_{jik}^{1\Phi} + \Delta\tilde{p}_{jik}^{ow}$$

$$= \left(\tilde{\mu}_o \frac{\tilde{z}}{\tilde{\ell}} + \tilde{\mu}_w \frac{\tilde{\ell}-\tilde{z}}{\tilde{\ell}}\right)\frac{\tilde{q}_{uc}}{\tilde{\ell}^3} A_{jik}^{1\Phi} + 2\frac{\tilde{\gamma}_{ow}}{\tilde{\ell}} H_j^{1\Phi}(\tilde{z})$$

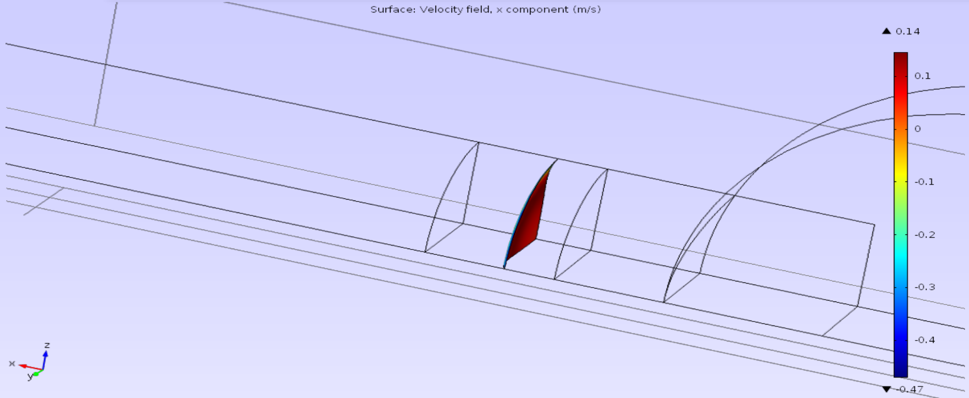
Contribution of the mean o/w interface surface curvature (Laplace law)

$$H_j^{1\Phi}(\tilde{z};\theta) = \frac{\cos\theta}{D_T} + \frac{1}{D_{Cj}}\left(\cos\theta - \sin\theta \frac{\tilde{z}}{\sqrt{\left(\tilde{D}_{Cj}/2\right)^2 - \tilde{z}^2}}\right)$$

Contribution of bulk phases
(creeping + Hele-Shaw flow conditions)

$$A_{jik}^{1\Phi} = 12\frac{1}{D_T}\left(u_{0ij} + u_{0ik} - 2u_1\right) + \frac{64}{\pi}\frac{{W_{Ti}}^2 + {D_T}^2}{{W_{Ti}}^3 {D_T}^3}\left(1 - x_{0ij} - x_{0ik}\right)$$

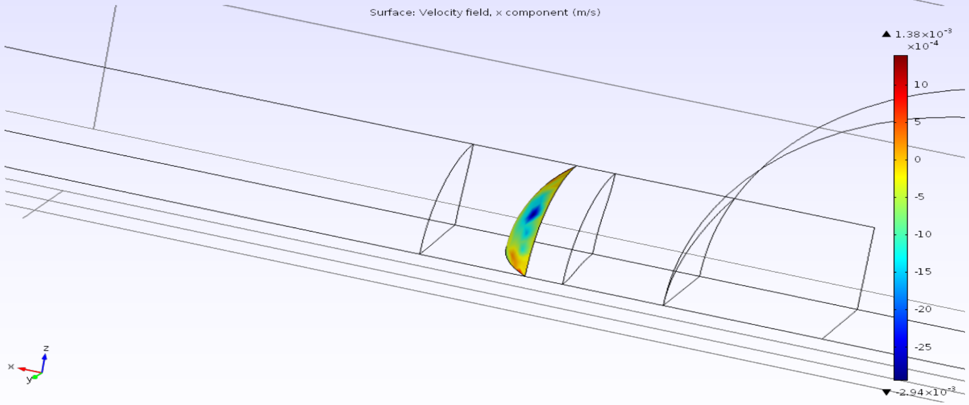
TRANSIENT CFD SIMULATION RESULTS



<u>Quarter geometry view</u>

(D_{Cj}=330μm, D_{Ck}=750μm, W_{ti}=111μm):

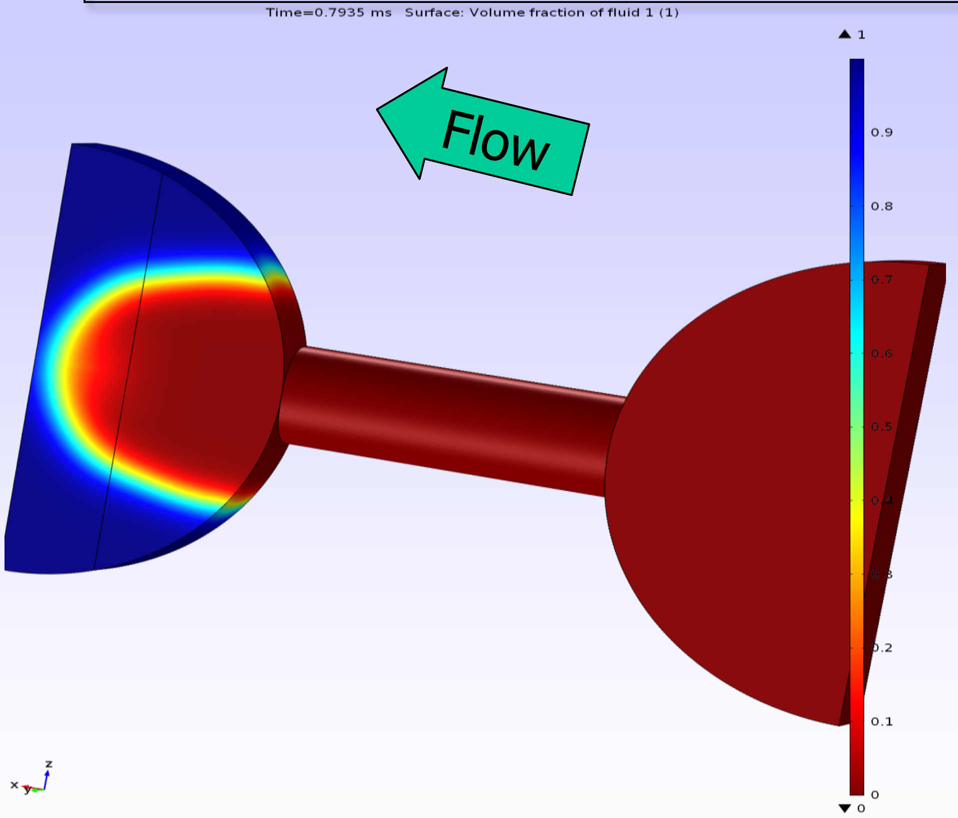
Interface at time t=0 s



(D_{Cj}=330μm, D_{Ck}=750μm, W_{ti}=111μm):

Interface 3 seconds after equilibrium and pressure gradient applied

TRANSIENT CFD SIMULATION RESULTS

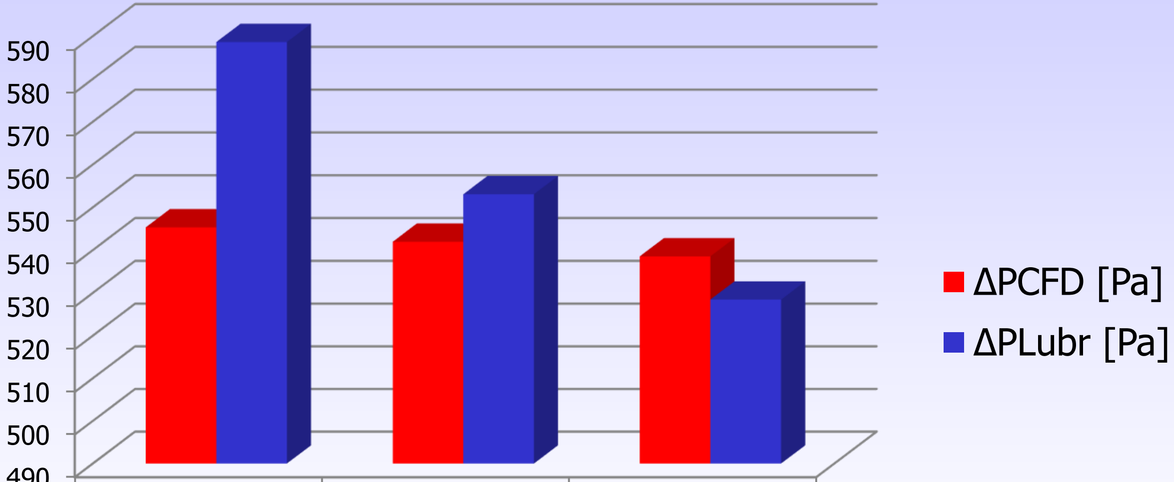


Full geometry view ($D_{Cj}=D_{Ck}=750\mu m$, $W_t=1169\mu m$):

- Interface in the interior of the exit chamber.
- Color coding depending on the volume fractions. (red: 100% oil, blue:100% water

RERFORMANCE

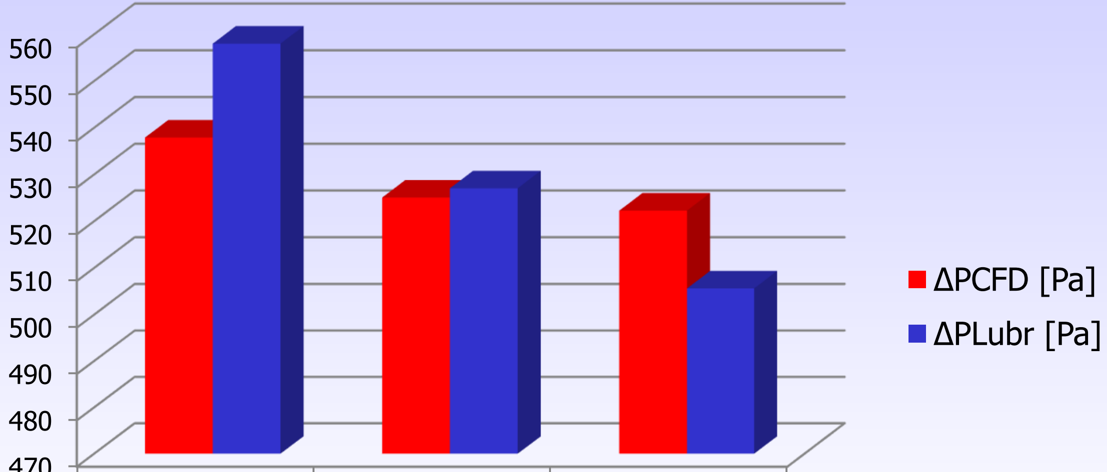
$D_{Cj}=D_{Ck}=750\mu m$



W_t [μm]	169	195	222
ΔPCFD [Pa]	545.314301	541.9475988	538.5309251
ΔPLubr [Pa]	588.6127637	553.039695	528.4330998

RERFORMANCE

D_{Cj}=750μm, D_{Ck}=890μm



W_t [μm]	169	195	222
ΔPCFD [Pa]	537.8951646	525.0536196	522.2619472
ΔPLubr [Pa]	557.9893235	527.0271912	505.5990007

CONCLUSIONS

- ✓ The absolute permeabilities of two-phase flow in *jik*-class unit cells were calculated with sophisticated transient Level-Set multiphase FEM methods using moving mesh at the water-oil interfaces.

- ✓ Results were delivered for single- and two-phase water and oil flow, either wetting/non-wetting (immiscible) flow with the w/n-w interface contacting the pore conduit walls, for receding and advancing w/n-w interface across a *jik* unit-cell (gradual drainage or imbibition, respectively)

- ✓ Conductivities were calculated for predefined values of velocities or pressure gradients, and appropriate look-up tables (maps) were delivered.

- ✓ Comparison of results with typical analytical estimations using lubrication approximation used in current *DeProF* implementations.presented errors up to 7%, a value well within the expected range given the assumptions used for the extraction of the analytical solutions.

REFERENCES

- Valavanides, M.S. 2012 "Steady-State Two-Phase Flow in Porous Media: Review of Progress in the Development of the DeProF Theory Bridging Pore- to Statistical Thermodynamics- Scales" *Oil & Gas Science and Technology* **67**(5) 787-804
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  - Kalarakis, A.N., Burganos, V.N., and Payatakes A.C. 2002 "Galilean-invariant lattice-Boltzmann simulation of liquid-vapor interface dynamics" *Phys. Rev. E* **65**, 0567021–05670213

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