Determination of Two-Phase Flow Properties with SatuDict

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Case Study

Input:
- Tomogram of Palatine Sandstone (Pfälzer Buntsandstein)

Aim: Determine (saturation dependent) permeability

Steps:
- Segmentation (ImportGeo)
- Pore size distribution (PoroDict)
- Capillary pressure curve (SatuDict)
- Permeability, fully saturated (FlowDict)
- Relative permeability, partially saturated (SatuDict)
Tomogram

- F. Enzmann, Inst. for Geosciences, Uni Mainz
- Pfälzer Buntsandstein
- resolution 0.7 µm
- 1024³ voxels
Segmentation

- Porosity 25.7 %
- Downscaled to $512^3$ voxels
Pore Size Distribution

Pore space: \( X \)

Opening of radius \( r \):

\[
O_r(X) = \bigcup_{B_r,x \subset X} B_{r,x}
\]

Volume of pores with radius \( r_1 \leq r \leq r_2 \):

\[
O_{r_1}(X) - O_{r_2}(X)
\]

(PoroDict - Geometric Pore Size Distribution)

- dark grey: \( r \geq 20 \)
- light grey: \( 16 \leq r < 20 \)
Pore Size Distribution (Sandstone)
Capillary Pressure / Pore Morphology Method

- Young – Laplace equation

\[ p_c = \frac{2\sigma}{r} \cos \beta \]

(pore radius <-> cap. pressure)

- => Pore size distribution gives saturation at given cap. pressure
- But: connectivity of pores?

Pore Morphology Method:
- adds connectivity checks to Young-Laplace
- low numerical cost
Drainage I

- Hilpert / Miller 2001
- SatuDict 2010R2
- Guarantees connectivity of NWP to reservoir
- Idea: move in spheres
  - Start: completely wet
  - Start: large radius (i.e. small $p_c$)
  - Steps: smaller radius (higher $p_c$)
- No residual water

Non-wetting phase (air) reservoir

Wetting phase (water) reservoir
Drainage II

- Ahrenholz et al. 2008
- Additionally: WP must be connected to reservoir
- Residual water (orange)
Drainage (Sandstone Sample)

Drained pores (r = 14 µm)  Drained pores (r = 8.4 µm)
Drainage - Sandstone Sample

- Slice of the 3D result
- Residual water: 8.6%

- black: air
- red: residual water
- white: matrix material
Capillary Pressure Curve (Drainage, Sandstone)

- Drainage II
- contact angle 0°

Water Saturation

Cap. Pressure [Pa]
Imbibition I

- Hilpert / Miller 2001
- SatuDict 2010R2
- No connectivity checks
- No residual air
  - Start: completely dry
  - Start: small radius (i.e. large $p_c$)
  - Steps: larger radius (smaller $p_c$)

Distribution by pore radius (Young-Laplace)
Imbibition II

- Ahrenholz et al. 2008
- WP must be connected to reservoir
- No residual air

Non-wetting phase (air) reservoir

Wetting phase (water) reservoir
Imbibition III

- Ahrenholz et al. 2008
- WP must be connected to reservoir
- NWP must be connected to NWP reservoir
- Residual air (orange)
Drainage & Imbibition (Sandstone)

- Drainage
- Drainage (res)
- Imbibition
- Imbibition (res)

- Small pores are connected
- Large pores are not connected
Permeability

Macroscopic description (homogenized porous media model)

Darcy’s law: \[ u = \frac{1}{\mu} \kappa \nabla p \]

- \( u \): average flow velocity
- \( \kappa \): permeability tensor \textit{unknown}
- \( \mu \): viscosity
- \( p \): pressure

Microscopic description (pore structure model)

Stokes equation: \[ -\mu \Delta u + \nabla p = 0 \]

Boundary conditions: no-slip on surface, pressure drop \( \kappa \) can be determined from the solution!
Permeability (Sandstone)

FlowDict Result (EJ-Stokes): 0.966 e-12 m²
Relative Permeability

Idea:
- Combine
  - phase distributions from pore morphology
  - single-phase flow

Advantage:
- low computational costs
- stability
Relative Permeability (Sandstone)

- Choose saturation level, choose wetting model
- Use PM to find air distribution (here: yellow)
- Solve Stokes equation in remaining pore space
Relative Permeability (Sandstone)
Summary: Case Study

Input:
- Tomogram of Palatine Sandstone (Pfälzer Buntsandstein)

Calculated properties:
- Pore size distribution
- Capillary pressure curve
- Permeability
- Relative permeability
Comments

- Same ideas can be used for diffusivity or conductivity

- Applications:
  - Gas diffusion layer of fuel cells
  - Hygiene products
  - Paper dewatering felts

Thank you!