Combining Pore Morphology and Flow Simulations to Determine Two-Phase Properties of 3D Tomograms


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Case Study

Input:
- Tomogram of Palatine Sandstone (Pfälzer Buntsandstein)

Aim: Determine (saturation dependent) permeability

Steps:
- Segmentation
- Pore size distribution
- Capillary pressure curve
- Permeability (fully saturated)
- Relative permeability (partially saturated)
Tomogram

- F. Enzmann, Inst. for Geosciences, Uni Mainz
- Pfälzer Buntsandstein
- resolution 0.7 µm
- $1024^3$ voxels
Segmentation

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

Pore space: $X$

Opening of radius $r$:

$$O_r(X) = \bigcup_{B_{r,x} \subseteq X} B_{r,x}$$

Volume of pores with radius $r_1 \leq r \leq r_2$

$$O_{r_1}(X) - O_{r_2}(X)$$

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

- Young – Laplace equation
  \[ p_c = \frac{2\sigma \cos \beta}{r} \]
  (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

- Hilpert / Miller 2001
- 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 (+)

- 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 Model (incl. residual water)
- Contact angle 0°
Imbibition

- Hilpert / Miller 2001
- 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

- Ahrenholz et al. 2008
- WP must be connected to reservoir
- No residual air
Imbibition (+)

- 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

Water Saturation vs. Cap. Pressure [Pa]
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)

Result: $0.966 \times 10^{-12} \text{ m}^2$
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 (Pfalzer Buntsandstein)

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

Software used: www.geodict.com
Other Options

- Virtually generated 3D models instead of tomograms
  - Fibrous nonwovens
  - Wovens
  - Sintered ceramics
- Consider relative diffusivity instead of relative permeability
Other Industrial Applications

- Fuel cell: gas diffusion layer
- Diapers and hygiene products
- Filtration
- Paper dewatering felts
- Sintered ceramics
- Woven metal wire meshes
Thank You!

Geometry generator, property predictor and virtual material designer

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