Generalized network modelling of two-phase flow

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Outline

- **Background**
  - Direct simulation and conventional network modelling

- **Generalized network modelling**
  - Network extraction
  - Flow simulation
  - Validation

- **Conclusion and future work**
Single-phase flow computations

Simulation time: 12 hours on a single workstation (16 processors)
Direct simulations are computationally expensive

- Simulations on 1 million cells took \( \sim 1 \) week on 24 processors, for a relatively high capillary number of \( 10^{-5} \)
- Simulation time increases as we decrease the capillary number
- Two-phase flow REV-size is about 1 billion grid-blocks
Background:
upscaleing from pore-scale to Darcy-scale:

Network extraction
Flow simulation

Reservoir simulation

Rock image

(a) 3 mm

Conventional network elements

Drainage

(b)

Water

Oil

Imbibition

(c) Water-wet

(d) Oil-wet

Background – conventional network model drawbacks

Igor Bondino (Total) et al. SCA (2012):
- different network extraction algorithms give significantly different results for the same fluid/rock system

Source of the problem:
Oversimplification of the pore-space

Summary: **conductances** and **volumes** may not be assigned correctly to **capillary radii** and hence causing uncertainty in the flow modelling predictions
**Background: Sources of uncertainty**

### Description of the pore space:

<table>
<thead>
<tr>
<th>Discretization</th>
<th>Resolution</th>
<th>Error</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Segmentation / noise</strong></td>
<td>stair-case</td>
<td>high</td>
<td>$O(\delta x)$ to $O(\delta x^2)$</td>
</tr>
<tr>
<td><strong>Conventional pore network</strong></td>
<td>stair-case</td>
<td>low</td>
<td>$O(\delta x)$, Refinement not possible</td>
</tr>
<tr>
<td><strong>Direct simulations</strong></td>
<td>linear</td>
<td>high</td>
<td>$O(\delta x^2)$</td>
</tr>
<tr>
<td><strong>Generalised networks</strong></td>
<td>linear</td>
<td>medium</td>
<td>$O(\delta x^2)$, Refinement not implemented</td>
</tr>
</tbody>
</table>

**Fluid/rock properties:**

- Contact angle distribution
- Clay / micro-porosity identification
Mathematics behind network extraction

There is a one-to-one relationship between any 3D geometry and its medial surface → no information loss → no additional uncertainty due to oversimplification of the pore space

Generalized pore network can be viewed as a coarse medial-surface representation of the pore space
Background – generalised network model

Half-throat corners
Flow simulation: interface tracking + post-processing

There is a one-to-one relationship between capillary radius and interface location for each half throat

→ allowing the interface location to be recorded and tracked as a single scalar variable
Generalized network modelling - summary

➢ The necessary parameters are extracted directly from the micro-CT image as tabulated functions and used in a generalized network flow simulator:

✔ MS-P theory is used to relate $P_c$ to Volume ($S_w$) for each pore/throat
  ✔ The necessary parameters: pore/throat radius and corner angles.
    → extracted directly from the micro-CT image

✔ Direct simulation is used to compute throat conductivities

✔ Effect of contact angle and other fluid properties is added during flow simulation.
Generalised pore-network **extraction**

**Parametrisation of pore space**

Pore-space converted into voxelated (micro-CT) format, on which Navier-Stokes equations are solved: and converted into generalised network format.
Parametrisation of pore space

Step 2.
2.1. Extract ball hierarchy (medial surface),
2.2. find local maxima of the radius and
2.3. Assign a pore index to each of the local maxima
Parametrisation of pore space

Step 3.0. Find pore-to-pore connections (throats)
Step 3.1. Identify and label individual corners on the throat medial axis
Parametrisation of pore space

Step 3.1. Map corner labels to the original image and analyse direct simulation results for each corner at Level 0
Parametrisation of pore space

Step 3.3. More balls from throat centres are deleted from corners to analyse direct simulations at Level 2
Comparison - generalized network extraction

Corner conductivities are calculated from tabulated functions extracted from direct single-phase flow simulations.

Generalised network simulation results - validation in progress
Comparison - conventional network extraction

Corner conductivities are calculated using correlations, from the shape of the corner.

Conventional network extraction, Only throat corners are visualised.
Network extraction demonstration – Berea sandstone

Element Indices

✔ High resolution

➜ Important for detecting and analysing corners accurately
Generalised network in flow simulator, a primitive visualization
Relative permeability predictions – **water-wet**
Bentheimer sandstone (from IC-PSM website, 1000^3 @ 3um)
Relative permeability predictions – oil-wet Bentheimer sandstone (from IC-PSM website, 1000^3 @ 3um)
Relative permeability predictions – mix-wet
Bentheimer sandstone (from IC-PSM website, 1000 m @ 3um)
Capillary heterogeneity at core scale

Krevor et al (2012)
Experimental relative permeability measurement

Reynolds and Krevor (2015)
Experimental relative permeability measurement

Different rocks, CO2-brine

Berea sandstone, CO2-brine

Effect of wettability

Effect of capillary number

Credit: GCCSI report no. 2 relative permeability (2013)
Validation with direct simulations - **star-shaped pore-throat system**

**Star-shaped geometry parameters:**
Corner Angle : 45 degrees

\[
\frac{R_{\text{pore}}}{R_{\text{throat}}} = 2.25 \\
\frac{R_{\text{pore}}}{L_{\text{throat}}} = 1.25
\]

**Direct simulation**
simulations run on 12 processors
Simulation time:

- 3-4+ hours for \( \frac{R_{\text{throat}}}{\delta x} = 5 \)
- 2-3+ days for \( \frac{R_{\text{throat}}}{\delta x} = 10 \)

**Network model**
Simulation time: **less than 1 second**

Note: network model visualization is primitive, the actual calculations are done based on a fixed 4-segment linear interpolation scheme for each half corner.
Improvements to direct simulations:

- Mesh quality improvements:

- Improved surface tension model using explicit interface reconstruction

Thanks to Mosayeb Shams for sharing his code, Arthur Moncorgé and Stephane Zaleski for their feedback and advice
Post-processing direct simulations

Corner Indices from network extraction are used directly as input control-volumes during direct simulations,

The code that is used for computing relative permeability curves is used to analyse individual corners extracted from rock images.

Each throat (pore-to-pore connection) is divided to 8 half throat corners during network extraction stage
Validation of network flow simulator code saturation/conductivity computations

Layer saturation/conductivities depend on:

- Corner cross-sectional shape
- Variation of the cross-sectional area along the pore-to-pore connection
- Flow pattern / rates
Direct simulations, star-shaped, drainage, piston-like invasion followed by layer flow,
Parameters to be studied:
(Compute their Pc-volume-conductivity relationship)

- Contact angle
- Corner angle
- Longitudinal interface curvature
- Different pore geometries

- More Complex test cases to verify cooperate-pore filling algorithm
- Run direct simulations on small, but high resolution micro-CT images
Curvature and contact angle measurements using high resolution micro-CT imaging

Singh et al, WRR 2016
Validation using experimental measurements

Multi-phase micro-CT imaging experiments
each experiment repeated 5 times → uncertainty quantification

(Andrew et al, 2014)
Simulations on High resolution micro-CT images

Small sample taken from the larger-scale image:

Direct simulation (Lingru Zheng, MSc thesis, July 2016):

Network model

Multi-phase micro-CT image:
The computations are comparable in accuracy with direct simulations and in speed with network models (a gain of about 6 orders of magnitude in performance).

Corner extraction and connectivity-tracking provides richer computations and predictions and gives us the opportunity to have a pore-by-pore comparison on complex micro-CT images.

Further work is needed to quantify the range of uncertainties/variations in experimental measurements and compare them with network model predictions.
Thanks to Total for providing the financial support

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Thank you for your attention