Concepts for Modeling Filter Media and Simulating Filtration Processes

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# Math2Market GmbH
## Promoted Industries

<table>
<thead>
<tr>
<th>Industry</th>
<th>Description</th>
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<tbody>
<tr>
<td><strong>Filtration</strong></td>
<td>Mostly automotive, filter media &amp; filters for water, sludge, oil, air and fuel</td>
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<tr>
<td><strong>Electrochemistry</strong></td>
<td>Fuel cell media &amp; battery materials, catalyst materials</td>
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<td><strong>Composites</strong></td>
<td>CFRP, GFRP, mostly automotive, lightweight materials</td>
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<tr>
<td><strong>Oil and Gas</strong></td>
<td>Digital rock physics, digital sand control</td>
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</tbody>
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The function of porous and composite materials results from the choice of raw materials and their microstructure, i.e., the distribution of the constituents, e.g., fibers, in space.

The power of simple models to predict the effects of the microstructure is limited.

μCT and FIB-SEM provide 3D images of existing materials with unprecedented resolution.

From these, one can compute the material's properties to match measured properties.

Models also convert into 3D images. From these, material properties can be determined without the need to manufacture the new materials first.

GeoDict is the complete software solution for multi-scale 3D image processing, visualization, simulation-driven property characterization, material development, and process optimization.

11 of the top 100 market capitalized companies are M2M clients, including Shell and P&G, who introduced the concept of open innovation about 2 decades ago.

In the future, companies will need to be on top of their materials. The days of trial and error are coming to an end as powerful research tools deliver scientific data of unprecedented depth. [http://www.economist.com/technology-quarterly/2015-12-05/new-materials-for-manufacturing]

At M2M, we believe this is true in particular for filter media – the future has already begun!
Simulate filtration at different scales
Medium models and property simulations
Simulate on μCT scans

(+) Allows simulations on real filter structures
(-) Modifications of the filter structure are not possible

Aim: create a model that mimics the tomography first, then modify it to find structures with even better properties!
Input parameters needed (straight fibers):
- Porosity
- Fiber type: cross sectional shape, diameter, length
- Fiber orientation tensor
- Thickness (height) of the filter media

Parameters might be
- known from manufacturing process
- measured experimentally
- measured from CT image
Fiber Curvature

Segment image → Identify fibers → Analyze every fiber individually and combine
Fiber Curvature

Segment image

Identify fibers

Analyze every fiber individually and combine
Estimated parameters used to generate a model of the gas diffusion layer
Create an oil filter model

- Ellipsoidal cross section, diameter distribution
- Curved fibers
- Fibers oriented in xy-plane
- 500 x 500 x 650 grid cells, 1 µm voxel length
Create cellulose and layered media scale models

Cellulose nonwoven

Layered filter medium
Create woven, foam and sintered media scale models

Metal wire mesh
Open-cell foam
Sintered ceramics
Model a desalination membrane from a SEM image

http://www.geodict.com/Showroom/structures.php
µCT scan and models of a felts

Forming fabric and dewatering felt
Woven Metal Wire Meshes: Complex weave models

Left: Model of a two-layer weave based on a CT-scan.
Right: Model of a complex one-layer twill Dutch-weave.
Flow Simulation
Stationary Navier-Stokes flow

\[-\mu \Delta \vec{u} + \rho (\vec{u} \cdot \nabla) \vec{u} + \nabla p = 0\]
\[\nabla \cdot \vec{u} = 0\]

\(\vec{u} = 0\) on \(\Gamma\)
\(P_{in} = P_{out} + \text{const}\)

\(\vec{u}\): velocity
\(p\): pressure
\(\mu\): dynamic viscosity
\(\rho\): fluid density
Basic idea:
1. Filter media model
2. Determine flow field
3. Track particles (filtered or not?)

Result:
- Percentage of filtered particles
Filter life-time simulations
Filter Capacity and Life Time
Pleat models and property simulations
Pleat model

- Pleat Generator accounts for
  - Height
  - Width
  - Inner support
  - Outer support
  - Layered media
  - Angeled pleats
  - Etc.
Hydraulic filter with supported pleat

Two effects lead to pressure loss:

1. Across the filter media
2. Along the outflow channels

A support mesh prevents the collapse of the outflow channel

Source: webpage
Argo-Hytos
Optimized hydraulic filter

- Same pleat count
- Vary channel width by weave pattern & wire diameter

Trying different parameters, the pressure drop could be lowered by more than 35%, by reducing the pressure loss along the outflow channel.

The optimized filter element ...

The optimized filter element ...

A new design for hydraulic filter lowers the pressure drop by 40-50 %

Patent granted to Argo-Hytos in 2009
First, compute the flow in the pleat. Then, track the particles and find the trajectories following the flow field without obstacles. Locations where particles cross the media are found and the probability of particles being captured in the media is determined.
Compare with experimental data
The particle deposition with time
Agreement with experimental data

- Pressure drop vs. load of a pleated filter
- Rescale to constant flow rate, what the pump was asked to do but did not do
- Simulation results compared with experimental measurements (rescaling done w.r.t. fluctuations in the volumetric flow rate)

Conclusions
Conclusions

- We saw 3d models for filter media, pleats and whole filters, where the media models could also result from µCT scans of existing media
  - Cellulose, glass and synthetic fibers
  - Ceramics
  - Open cell foams
  - Weaves
- On the models one can predict
  - Pore Size measures
  - Pressure drop, flow resistivity, permeability,
  - Filter Efficiency
  - Filter Life Time / Dust Holding Capacity
- Simulations, combined with experiments, can lead to
  - New knowledge, such as more detailed information, parameter study
  - Quantification of phenomena such as different filtration stages
  - And also patents and long term commercial benefits
Thank you!
Tracking Particles in a Flow Field

\[ m \frac{d\vec{v}}{dt} = 6\pi\mu \frac{R}{C_c} \left( \vec{u} - \vec{v} + \sqrt{2D} \frac{d\vec{W}(t)}{dt} \right) + Q \vec{E} \]

- \( \vec{v} \): particle velocity [m/s]
- \( \vec{u} \): fluid velocity [m/s]
- \( R \): particle radius [m]
- \( C_c \): Cunningham correction
- \( m \): particle mass [kg]
- \( \mu \): dynamic viscosity [kg/m \cdot s]
- \( Q \): particle charge [C]
- \( E \): electric field [V/m]
- \( D \): Diffusivity [m²/s]
- \( d\vec{W} \): 3D Wiener process

Impulse
Stokes Drag
Electrostatic Force
Cunningham Corrected
Particle Radius
Brownian Motion
Filtration Effects I

A: direct interception
B: inertial impaction
C: diffusional deposition

D: clogging
E: sieving
Filtration Effects II and modes of particle motion

F: electrostatic attraction

G: Slide
H: Bounce
Collision model

Caught on first touch

Hamaker

Sieving