Analysis of Textile Filter Media and Simulation of Filtration Processes Based on µCT Scans

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How can simulations help to improve a filter?

Step 1: Understand the existing filter material
- CT Scan
- Simulations on CT Scan
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Step 2: Create a model of the existing material
- Analyze CT Scan
- Create structure model
- Simulations on Structure model
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Step 3: Modify the structure model
Sample Structure: Cabin Air Filter

- Commercially available filter
- CT scan by service provider RJL Micro&Analytic
Step 1:
Understand the existing filter material
Determine Flow Rate or Pressure Drop

Stationary Navier-Stokes flow:

\[-\mu \Delta \vec{u} + \rho (\vec{u} \cdot \nabla) \vec{u} + \nabla p = 0\]  
\[\nabla \cdot \vec{u} = 0\]  
\[\vec{u} = 0 \text{ on } \Gamma\]  
\[P_{in} = P_{out} + \text{const}\]

\(\vec{u}\): velocity  
\(p\): pressure  
\(\mu\): dynamic viscosity  
\(\rho\): fluid density
Result for Clean Cabin Air Filter Media (Flat Sheet): Pressure drop of 7.35 Pa at 0.1 m/s mean velocity
1. Filter media model
Efficiency of Clean Filter Media: Method

1. Filter media model
2. Determine flow field
Efficiency of Clean Filter Media: Method

1. Filter media model
2. Determine flow field
3. Track particles (filtered or not?)
Efficiency of Clean Filter Media: Method

1. Filter media model
2. Determine flow field
3. Track particles (filtered or not?)
4. Result: percentage of filtered particles of each size
Movement of Particles in a Flow Field: Balance of Forces Equation

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

- \( \vec{v} \): 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]
- \( d\overrightarrow{W} \): 3D Wiener process
Movement of Particles in a Flow Field: Balance of Forces Equation

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

Cunningham Corrected Particle Radius

\[\vec{v}\]: particle velocity [m/s]  \quad \mu\]: dynamic viscosity [kg/m⋅s]
\[\vec{u}\]: fluid velocity [m/s]  \quad Q\]: particle charge [C]
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Impulse  Stokes Drag  Electrostatic Force  

Cunningham Corrected  Particle Radius  

Brownian Motion
Particle Adhesion Models

What happens when a particle touches a fiber?

Caught on first touch  Compare Kinetic and Adhesive Forces  Sieving
Particle Adhesion Models

What happens when a particle touches a fiber?

Air Filtration

Caught on first touch

Compare Kinetic and Adhesive Forces

Oil Filtration

Sieving
Cabin Air Filter
Fractional Efficiency (w/o Electrostatic Attraction)

![Graph showing the fractional efficiency of a cabin air filter with particle size vs. efficiency at two different velocities (V = 0.01 m/s and V = 0.1 m/s).](image-url)
Filter Life Time Simulation - Method

1. Filter Model
Filter Life Time Simulation - Method

1. Filter Model

2. Flow Field
Filter Life Time Simulation - Method

1. Filter Model
2. Flow Field
3. Track Particles
Filter Life Time Simulation - Method

1. Filter Model
2. Flow Field
3. Track Particles
4. Deposit Particles
Filter Life Time Simulation - Method

1. Filter Model
2. Flow Field
3. Track Particles
4. Deposit Particles
5. Recompute Flow
Filter Life Time Simulation - Method

1. Filter Model
2. Flow Field
3. Track Particles
4. Deposit Particles
5. Recompute Flow
6. Repeat ...
Cabin Air Filter - Life Time Simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Initial pressure drop</td>
<td>7 Pa</td>
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<tr>
<td>Pressure drop after 1000s</td>
<td>101 Pa</td>
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<tr>
<td>Total deposited dust after 1000s</td>
<td>93 g/m²</td>
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<tr>
<td>Total filter efficiency</td>
<td>93% (weight)</td>
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Pressure Drop [Pa] vs. Time [s]

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GEO DICT

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Step 2:

Create a model of the existing material
Why create a filter model?

- A CT scan is an image!
  - It can only be changed voxel-by-voxel.
  - It is not possible to remove a fiber
  - It is not possible to change diameters or shape

=> We need to “understand” the image!
GeoDict Workflow

1. **μCT image**
2. **FiberGuess**
3. **Fiber parameters**
4. **FiberGeo**
5. **Virtual material**
6. **FilterDict**
7. **Material properties**
8. **Compare**
9. **Desired material properties**
10. **Modified Fiber Parameters**
Geometric Analysis I: Media Thickness, Porosity, Pore Sizes, Fiber Diameter

Average fiber diameter: 33.6 µm  
Porosity: 80.4 %  
Thickness: 605 µm
How is fiber orientation measured?

Orientation tensor describes probability of direction component.

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</table>
Orientation analysis – Method 1: Principal Component Analysis (PCA)

1. PCA subdivides domain into windows of given size
   - Automatic window size estimates about 2x fiber diameter
2. For each window, finds fiber fragments and analyzes direction tensor
3. For each block, averages direction tensors over windows in that block

![Diagram showing orientation analysis using PCA](image)
Orientation analysis – Method 2: Star Length Distribution (SLD)

- For each voxel, SLD analyzes chord lengths through it for fixed set of directions
- The relative length of the chords gives per-voxel orientation tensor
- The tensors are averaged over all voxels in the block (similar to PCA)

Comparison of CT Scan and Model

CT Scan

Model
Comparison of CT Scan and Model

Input parameters found by CT-Scan analysis:
- media thickness
- porosity
- fiber diameter
- in-plane anisotropy

Input parameters taken from assumptions:
- straight fibers
- fibers oriented in-plane
- homogeneous distribution
- circular cross section
Filter Life Time
Filter Life Time
Filter Life Time Simulation
Comparison CT Scan vs Model

![Graph showing pressure over time for CT Scan vs Model comparison. The red line represents the CT Scan, and the gray line represents the Model. The x-axis represents time in seconds (0 to 1000), and the y-axis represents pressure in Pascals (0 to 120).]
Filter Life Time Simulation
Comparison CT Scan vs Model

CT Scan

Model

~ 10% deviation!
Step 3: Modify the structure model
Possibilities in GeoDict to Vary the Structure Model

- Fiber diameter
- Fiber orientation
- Fiber cross sectional shape
- Curved fibers instead of straight fibers
- Density gradient in through-plane direction
- Porosity
- Media thickness
Summary and Outlook

Overall goal of this work:

- get from CT-Scan to Model structure automatically

Current state:

- works for straight fibers with circular cross section

Work in progress: curved fibers with circular cross section

- Determine curvature distribution from CT
- Realize given curvature distribution in a model
Visit us @ www.geodict.com