Innovative design, analysis and optimization of woven filter media through experimental and computational methods

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Abstract

Type of weave, wire diameter, and mesh counts are geometrical characteristics with an enormous impact on the specific flow and filtration properties of a wire cloth. HAVER & BOECKER uses GeoDict (Math2Market GmbH) to input these parameters and depict the structure of single-layer and multiple-layer cloths as a real 3D model (Fig. 1). Geometric parameters such as pore size distribution and bubble point are determined with GeoDict. The cloth or cloth laminate behaviour in various fluids (air, water, fuel) is predicted by GeoDict as a function of flow rate or differential pressure. Wire diameter, pore sizes, and permeability of the structure are changed by the calibration process, which can be simulated by digitally compressing the media. GeoDict predicts the change in these properties before and after the calibration process.

Filtration experiments, carried out at the IUTA (Duisburg) with the single-pass filtration test rig MFP 1000 (Palas GmbH), used ISO A2 fine test dust particles for roughly 60 seconds. The pressure drop of the clean media is found by measuring only under air flow and, later, particles are injected with it. To define the standard deviation, the particle size distribution in the air was measured four times in the upstream flow and three times in the downstream flow of the filter media.

Filter life-time simulations of the filtration of solid particles were carried out using single-pass parameters, i.e. with a constant contaminant concentration by HAVER & BOECKER in consultation with Math2Market. Pressure drop, filter efficiency, and count/mass of the deposited solid particles are computed as a function of time and can be shown in an animation. The solid particles are simulated as spheres. One of the challenges is to find a precise distribution for the restitution coefficient of different particle sizes when impacting the surface. Since the restitution coefficient is a function of material properties, impact velocity and angle, particle size and shape, it can have a considerable effect on the filtration results when considering it in the collision models.

The results, namely the filter efficiency and pressure drop, obtained from the simulations are compared and validated with the experimental data. Using the proposed modeling and simulation technique, it is possible to predict the flow and filtration behavior of woven media and to optimize the micro-structure best suited for the specific applications.

Keywords:
Modeling and simulation, pressure drop, filter lifetime, filter efficiency, micro-structure
1 Introduction

Besides the know-how and experience existing in HAVER & BOECKER OHG, the GeoDict software from Math2Market GmbH is intensively used to determine which wire cloth configuration suits the best for the specific field of application. By simulating different cases, it is possible to optimize existing wire cloth specifications and develop new ones.

Geometrical characteristics such as type of weave, wire diameter and mesh counts have an enormous impact on the specific flow and filtration properties of a wire cloth. Using specific cloth parameters resulting from the type of weave, aperture width, pitch and wire diameter, HAVER & BOECKER can depict the structure of single-layer and multiple-layer wire cloths as a real 3D model (Fig. 1) using WeaveGeo module of GeoDict.

![Fig. 1: Three different woven filter media of HAVER & BOECKER modelled with GeoDict](image)

The WeaveGeo module can be used to design and generate 3D models of regular woven structures, including textiles, carbon fiber reinforced plastics and wire meshes within minutes.

Material properties can then be simulated using one of the GeoDict modules for Digital Material Analysis and design parameters can be optimized based on the results, often within a few days.

WeaveGeo supports both mono- and multifilament yarns, including ropes and random fiber bundles. Mutual deformation of weft- and wrap-yarns can be controlled by assigning a stiffness to materials. WeaveGeo contains several sub-modules for designing different types of weaves. For the most common types of weave-patterns, simplified user interfaces are provided which allow for the rapid design of these types of structures. These include Plain, Twill and Satin Weaves.

More complex (including multi-layer) designs can be realized using the FreeWeave sub-module, which allows you to enter custom bindings using weave diagrams.

2 Method

Several pre-defined settings are included which highlight the capabilities of WeaveGeo and can be used as a starting point for the user own designs.

If the input data for modelling the weave is unavailable or very difficult to measure from an unknown micro-woven media, an appropriate μCT-scan or SEM can also help extract this information from images and use it to create a digitalized model. With these data and the WeaveGeo module of GeoDict, such geometries can be modeled and analyzed.

Geometric parameters such as the pore size distribution and bubble point are then determined with the PoroDict module [1] of GeoDict. PoroDict is used to calculate pore-structure characteristics of 3D models obtained from CT, μCT, or FIB/SEM-image data or generated with GeoDict.
3 Simulation Results

The bubble point and the percolation path were calculated here to find the largest bubble or particle that can pass through the geometry. The cut point (d97%) of Whitehouse Scientific suspension challenge test was also measured and compared with our simulation results (See Fig. 2). As long as the geometry is correctly modelled and the resolution (voxel length) is good enough, the simulation results should be very close to the experimental values.

As a background information, GeoDict software is specified in the latest ASTM-E2814-18 [1], as a standard way of evaluating the quality of wire meshes.

![Fig. 2: Max. particle diameter passable computed with PoroDict module of GeoDict](image)

**Table 1: Comparison of simulated max. particle diameter passable and the Cut Point (d97) measurement of suspension challenge testing (Whitehouse Scientific)**

<table>
<thead>
<tr>
<th>Weave</th>
<th>max. particle diameter passable (GeoDict)</th>
<th>Cut Point (d97) by suspension challenge testing (Whitehouse Scientific)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DTW 14 S</td>
<td>14.3 +/- 0.5 µm</td>
<td>15.43 +/- 0.6 µm</td>
</tr>
<tr>
<td>RPD HiFlo 15 S</td>
<td>13.0 +/- 0.5 µm</td>
<td>15.03 +/- 0.6 µm</td>
</tr>
<tr>
<td>HiFlo 15 S</td>
<td>14.0 +/- 0.5 µm</td>
<td>14.50 +/- 0.6 µm</td>
</tr>
</tbody>
</table>

The behaviour of the respective cloth or cloth laminate in various fluids such as air, water and fuel as a function of flow rate or differential pressure is predicted by the FlowDict module.

The FlowDict module predicts effective material properties (flow velocity, flow permeability, and flow resistivity) by simulating flow experiments and post-processing the simulation results. A flow experiment in FlowDict requires the input of a 3D representation of a structure or material, considering a Newtonian fluid (gas or liquid) with constant density (incompressible), and providing experimental process parameters, such as mass flow rate, pressure difference and flow direction.

FlowDict can perform three categories of calculations. Prediction of mean flow velocity for a given pressure drop, prediction of the pressure drop for a given mean flow velocity, and prediction of the full or partial permeability tensor.
As shown in Fig. 3, the air permeability of the three media shown in Fig. 1 is calculated according to ASTM standard (125 Pa) and European standard (200 Pa) with the FlowDict module of GeoDict. Navier-Stokes equations were solved because the flow regime is not laminar. The velocity distribution through the medium can be observed (here only the left half of the velocity distribution is visualized).

![Air Flow Simulation Results](image)

**Table 2: Comparison of simulated air permeability and the measurement data by Haver & Boecker**

<table>
<thead>
<tr>
<th>Weave</th>
<th>Thickness</th>
<th>Air permeability at 125 Pa (GeoDict)</th>
<th>Air permeability at 200 Pa (GeoDict)</th>
<th>Air permeability at 200 Pa (Measurement by H&amp;B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DTW 14 S</td>
<td>153 µm</td>
<td>0.151 m³/(m² s)</td>
<td>0.240 m³/(m² s)</td>
<td>0.233 m³/(m² s)</td>
</tr>
<tr>
<td>RPD HiFlo 15 S</td>
<td>230 µm</td>
<td>0.259 m³/(m² s)</td>
<td>0.415 m³/(m² s)</td>
<td>0.395 m³/(m² s)</td>
</tr>
<tr>
<td>HiFlo 15 S</td>
<td>69 µm</td>
<td>0.618 m³/(m² s)</td>
<td>0.971 m³/(m² s)</td>
<td>0.961 m³/(m² s)</td>
</tr>
</tbody>
</table>

The deviation between experimental data and simulation result is only 3% for DTW 14S, about 5% for RPD HiFlo 15S, and 1% for HiFlo 15S, which is indeed a very good agreement between the simulations and experimental data.

The calendering process of the media can also be simulated by compressing the media in a specified direction of deformation. The wire diameter, pore sizes and the permeability of the structure will change by calibration. The simulations predict the difference of these properties before and after the calibration process. Furthermore, various analyses can be performed to determine the geometric properties and to simulate the flow and filtration through such media.

Moreover, filtration experiments are carried out at the IUTA (Institut für Energie- und Umwelttechnik e. V.) in Duisburg using the single-pass filtration test rig MFP 1000 from Palas GmbH (See Fig. 4, left side). On the right side of Fig. 4, a schematic representation of a single pass test with constant flow is shown.

![Filtration Experiments](image)

**Fig. 4:** left: Single-pass filtration test rig MFP 1000 from Palas GmbH, right: Schematic of single-pass life-time filtration simulation in GeoDict
Test dust concentration, average flow rate, and some important fluid and particle properties are listed in Table 3.

Table 3: Fluid and particle properties

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>22 °C</td>
</tr>
<tr>
<td>Flow velocity</td>
<td>0.1 m/s (60l/min)</td>
</tr>
<tr>
<td>Particles</td>
<td>ISO A fine test dust (0.255 - 16.6 µm)</td>
</tr>
<tr>
<td>Test dust concentration</td>
<td>9.26 g/m³</td>
</tr>
<tr>
<td>Particle density</td>
<td>2650 kg/m³</td>
</tr>
<tr>
<td>Particle shape</td>
<td>Spherical</td>
</tr>
</tbody>
</table>

To find the pressure drop of the clean media, the samples are measured only under air flow, i.e. without injection of dust particles. Afterwards, the particles are injected with the air flow. For defining the standard deviation, the particle size distribution in the air was measured four times in the upstream flow and three times in the downstream flow of the filter media. In other words, three samples for each kind of filter media were used in the experiments to ensure the accuracy confidence of the results.

In the following diagram (Fig. 5), the particle number concentration for each medium is shown at different particle sizes between 4 and 16.5 µm.

Fig. 5: Measured particle number concentration versus particle diameter size

Based on the particle number concentration as a function of particle size, the fractional filtration efficiency curves for the three media are shown and compared in Fig. 6.

Fig. 6: Measured fractional filtration efficiency versus particle diameter size
The filtration tests are conducted for roughly 60 seconds. The accuracy of this filtration time may vary due to the time the user needs to adjust the sample and later to take the sample out of the apparatus.

The filtration of solid particles from the fluid is also simulated. Filter life-time simulations were carried out using single-pass filtration parameters, i.e. with a constant contaminant concentration. The simulated quantities are the pressure drop, filter efficiency and count/mass of the deposited solid particles as a function of time. Furthermore, the deposited volume of particles and the pressure drop are animated as a function of time. In these simulations, the solid particles are spherical. One of the challenges is to find out a precise distribution for the restitution coefficient of different particle sizes when impacting the surface. As restitution coefficient is a function of material properties, impact velocity and angle, particle size and shape, it can have a considerable effect on the filtration results when considering it in the collision models.

The results, namely the filter efficiency and pressure drop, obtained from the simulations are compared and validated with the experimental data. Using the proposed modeling and simulation technique, it is possible to predict the flow and filtration behavior of woven media and to optimize the micro-structure which suits the best for the specific applications.

In Fig. 7, a screenshot of the filtration simulation through the HiFlo 15S is shown as an example. Gray particles show the already deposited particles of the previous batches and green particles show the injected particles through the current batch.

Since the filtration test duration is 60 s, the particles are injected by 4 batches, each batch 15 s in simulations. Flow field through the clean media and also after every batch is calculated. The Sieving collision model was applied here.

Here, important results such as pressure drop development, filtration efficiency as a function of time and fractional filtration efficiency are calculated.

By defining a distribution for the restitution coefficient (RC), smaller RC for smaller particles and larger RC for larger particles, the filter efficiency can be computed in very good agreement with the experimental data. In Fig. 8 left side, the computed values for cut point d97 and air permeabilities for the three media are listed once more. On the right side, the simulated filtration efficiency values are compared and validated with the measurement data of IUTA.
<table>
<thead>
<tr>
<th>Weave</th>
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<th>Air Perm. at 200 Pa</th>
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<td>15.43 +/- 0.6 µm</td>
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<td>0.971 m/s</td>
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</table>

Fig. 8: Comparison of simulated filtration efficiency by GeoDict with the measurement data by IUTA

References
