Deformation and the Change of Filtration Properties of Weaves - A Computational Approach

S. Rief, E. Glatt, A. Wiegmann, M. Kabel, H. Andrä

Fraunhofer-Institut Techno- und Wirtschaftsmathematik,
Fraunhofer-Platz 1, 67663 Kaiserslautern, Germany

ABSTRACT

Virtual performance tests of filter media help to speed up development cycles and to quickly find customer tailored product solutions. In order to achieve virtual filter testing methods with high predictive quality, great care has to be taken to accurately capture the essence of the structure (geometry) and the physical processes. Consequently, we develop models, algorithms and software implementations related to virtual structure generation, geometric structure analysis, fluid dynamics and solid mechanics. To avoid parameter uncertainties, all methods operate on the microstructure of the filter media.
In the present paper, we perform a basic study of weave patterns subject to deformation using our software suite GeoDict and the new elasticity module FeelMath. More precisely, we consider basic weave patterns like plain and twill weave and compute their structural behavior under tension, compression, shear and bending forces. Having undeformed and deformed weaves as computer models, pore morphology changes, permeability and filter performance are computed and analyzed. The results provide fundamental insights into the governing mechanisms on the micro scale and their influence to the filter media scale.

KEYWORDS

Filtration, Woven, Filter Media, CFD, Deformation, Simulation

1 Introduction

Woven structures constitute an important class of filter media. The complex interplay of media geometry, flow and particle transport provides huge challenges to the manufacturer wanting to optimize his products. In this paper, we present a computational approach aiming to provide decision support to the media producer.

The starting point of our approach is the virtual structure generation. Fully resolving the microstructure of the filter media we end up with geometries as illustrated in Figure 1. From a manufactures point of view, a set of readily available parameters like warp and weft thread diameters, weave patterns etc. allow for a precise definition of the woven. At first, the computer representation of the woven structure is analytically exact. For the elasticity and flow simulations we discretize the analytical geometry into beam elements and regular cubical meshes, respectively. The subsequent virtual deformation provides detailed information on local stress and strain distributions in the woven and, finally, allows for the reconstruction of the deformed weave structure.

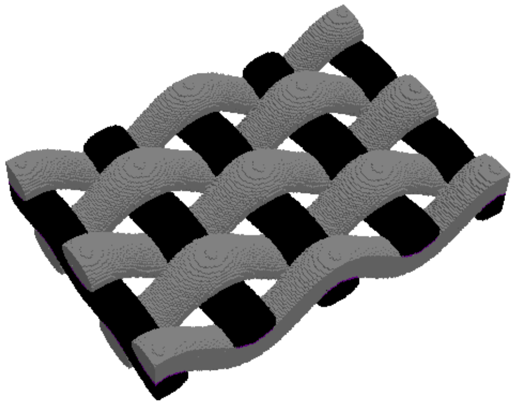

Figure 1: A virtual plain weave filter medium.

Both, undeformed and deformed woven are then fluid dynamically characterized yielding velocity - pressure drop relations which are a measure for *openness* of structures. The next simulation step consists of a filtration simulation which computes initial filter efficiencies for a pre-defined set of particles. The simulation chain is realized within the software suite GeoDict [1].
The paper is organized as follows. In Section 2 we provide further details on the simulation approach. First numerical results are given in Section 3. The paper closes with conclusions and an outlook on future developments.

2 Simulation Approach

To establish the intended simulation chain we use the modules WeaveGeo, FlowDict, FilterDict and the quite recent elasticity solver FeelMath of the Fraunhofer software GeoDict [1]. The package allows for virtual woven generation and fluid dynamical characterizing including deformation and particle filtration.

2.1 Virtual Woven - WeaveGeo

The module WeaveGeo allows for the precise microstructural definition of virtual woven by a set of readily-available input parameters. Besides the basic weave pattern, e.g. plain or twill weave, warp and weft thread cross-sections must be specified. Pitch parameters control the repetition length of each thread defining the pattern repeat, i.e. the dimensions of the periodicity cell of the woven. In Figure 2, the graphical user interface shows additional parameters defining inflow and outflow regions and various other fine-tuning adjustments.
The structure generation process provides both, an analytical description and discretized cubical (voxelized) geometry of the virtual woven. Generally speaking, the analytical data format has the advantage of being exact and compact with respect to storage consumption. Moreover, it can be discretized to any needs of subsequent numerical solvers like FeelMath for instance. The voxel geometry is the native input format used by FlowDict and FilterDict.

Figure 2: Weave parameters of the graphical user interface of WeaveGeo

2.2 Fiber Model Used for the Elasticity Simulation - FeelMath

Based on [2], [3] we use the Simo-beam approach to compute elastic deformations of the virtual weaves. Let $S \in [0, L]$ denote the coordinate along the center line of the undeformed beam. The deformation of the beam is described by the rotation of the cross-sections, i.e. by an orthogonal transformation $\Lambda(S)$, and by the position $\phi_0(S)$ of the centroids of the cross-sections. At an equilibrium configuration the spatial form of the local balance of momentum reduces to

$$\frac{\partial}{\partial S} n + \bar{n} = 0,$$

$$\frac{\partial}{\partial S} m + \frac{\partial \phi_0}{\partial S} \times n + \bar{m} = 0.$$

In the above equations n is the spatial stress resultant and m is the spatial couple stress over a cross-section.

Using the strain measures

$$\gamma = \frac{\partial \phi_0}{\partial S} - t_3,$$

$$\omega,$$

where the vector ω is defined by

$$\frac{\partial \Lambda}{\partial S} = \begin{pmatrix} 0 & -\omega_3 & \omega_2 \\ \omega_3 & 0 & -\omega_1 \\ -\omega_2 & \omega_1 & 0 \end{pmatrix} \Lambda,$$

the stress can be calculated by

$$\begin{pmatrix} n \\ m \end{pmatrix} = c \begin{pmatrix} \gamma \\ \omega \end{pmatrix},$$

with

$$c = \begin{pmatrix} \Lambda & 0 \\ 0 & \Lambda \end{pmatrix} C \begin{pmatrix} \Lambda^t & 0 \\ 0 & \Lambda^t \end{pmatrix}$$

being the spatial elasticity tensor.

The material elasticity tensor C of a homogeneous isotropic material is

$C = \mathrm{diag}\begin{pmatrix} GA & GA & EA & EI_x & EI_y & GI_p \end{pmatrix}.$

Here, GA denotes the shear stiffness, EA the axial stiffness, EI_x and EI_y the principal bending stiffness values and GI_p the torsional stiffness of the beam.

In FeelMath Dirichlet boundary conditions for the displacement can be applied in a flexible manner, e.g. to simulate bending stiffness and tensile strength experiments.

2.4 Computational Fluid Dynamics – FlowDict

To compute velocity – pressure drop relations of porous media, the module FlowDict provides the EFV solver. It solves the Navier-Stokes equations supplemented by velocity inflow and pressure outflow conditions. Laterally, periodic boundary conditions are prescribed. The discretization is done by means of a finite volume method. The solution algorithm of the discretized system is based on the well-known SIMPLE method proposed in [4]. The resulting velocity and pressure fields are *averaged* in a suitable way applying mathematical homogenization theory. Finally, we end-up with an effective velocity and effective pressure drop across the medium which can directly be compared to measurements [5].

2.5 Filtration Efficiency Simulation - FilterDict

In this paper we want to study how deformation changes filtration properties of woven structures. Therefore, FilterDict is used to compute initial filtration efficiencies of undeformed and deformed media.

The filtration simulation algorithm is based on flow fields computed by FlowDict CFD solvers and a Lagrangian particle transport model. The particles are modeled as spheres possessing distinct diameters and masses. Particles move according to Newton's second law subject to friction forces and Brownian motion. A collision detection method checks whether a particle collides with the filter medium or alternatively, with already deposited particles. Depending on the adhesion model, the particle gets stuck at the place where the collision happens or it reenters into the fluid and moves on. The adhesion models which we use in the next section are *sieving* and *caught on first touch*. When using the sieving model, particles deposit only if the filter medium or previously deposited particles geometrically obstruct a passage. *Caught on first touch* leads to immediate deposition when the particles collides. The two models are chosen because they are extreme in the sense that the *real* mechanism is typically found between the two bounds.

For further details on equations and on the general deposition model of FilterDict, we refer to [6].

3 Numerical Results

After having generated the undeformed plain weave shown in Figure 1, we apply a strain of 30 % in lateral direction. The local displacement information computed by FeelMath is used to construct the deformed structure which is illustrated in Figure 2. The elongation of the woven is clearly visible. The through pores cross-section initially being almost square have developed a rectangular shape. Thereby, the open area is only slightly reduced by 2 percent. The maximum through pore with circular cross-section has not changed at all. Its diameter stays at 10 µm. The final observation we make is that the medium is flattened.

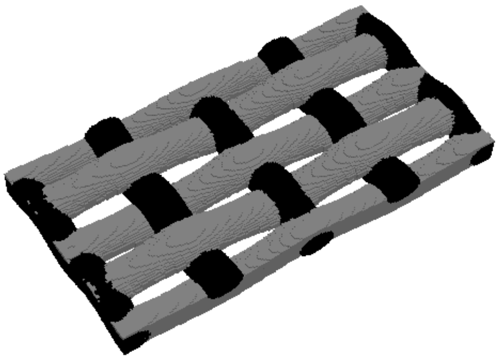

Figure 2: Deformed virtual plain weave.

The air flow simulation confirms these observations: Applying a pressure drop of 100 Pa across the media yields an effective velocity of 0.27 m/s in the undeformed case, and 0.34 m/s in the deformed case. The corresponding flow speeds are visualized in Figure 3.

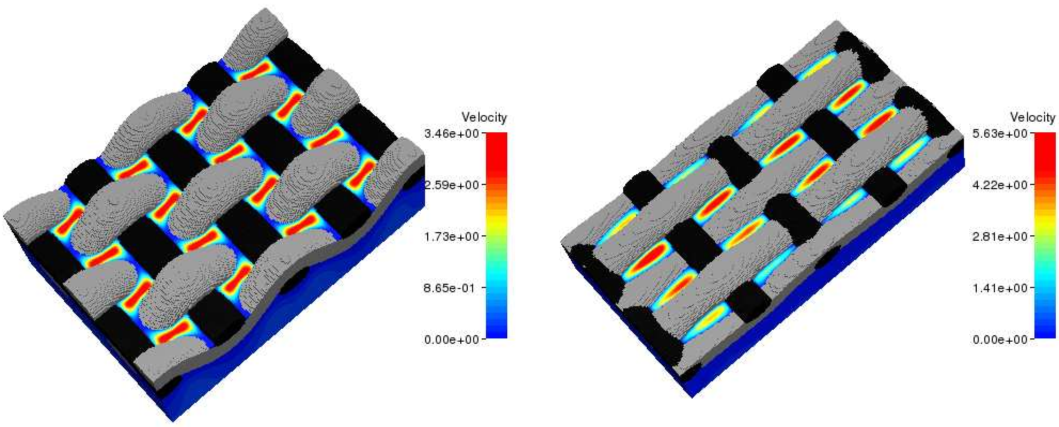

Figure 3: Flow speed in through direction (left – undeformed woven, right – deformed woven)

Due to the reduced thickness of the medium, the deformed medium provides less flow resistance. In contrast, the initial filtration efficiencies increase in the deformed case. In Figure 4 and 5, the underlying data is based on a simulation of initial filtration efficiencies using particle diameters between 1 and 10 µm. The average air flow is set to 0.1 m/s. Comparing Figure 4 and 5, the filtration efficiencies are, as expected, much larger in deposition mode *caught on first touch*. Due to the maximum through pore staying constant under deformation, all particles larger than 10 µm are captured. Since the pores are much larger than 1 µm the efficiencies are almost equal for the smallest particle class independently of any deformations and deposition mechanisms. Between particle sizes of 1 and 10 µm, we clearly observe differences showing an increase of efficiencies in the deformed case. When looking at the through pore cross-sections again, the area has not changed much, but they have become more narrow in the direction of the applied strain. Therefore, the spherical particles get stuck more easily due to higher collision probabilities.

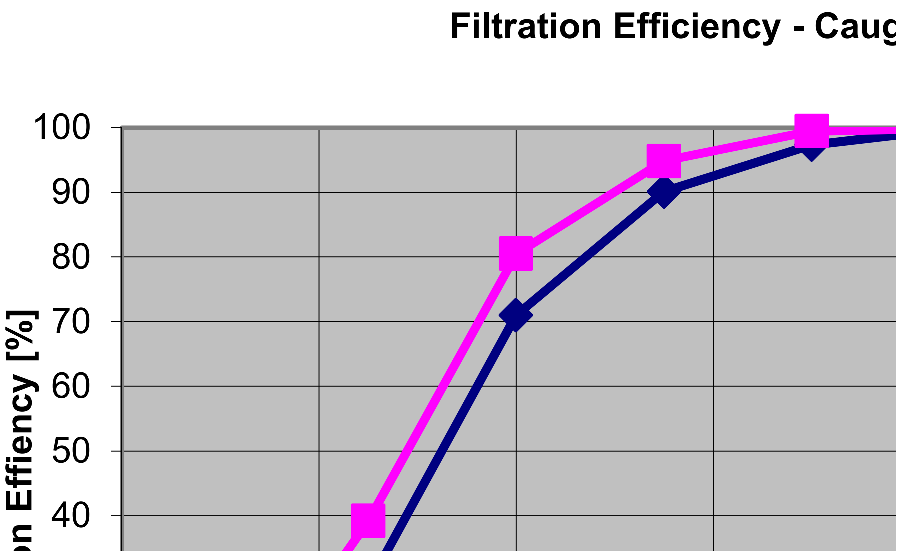

Figure 4: Filter efficiencies using the *Caught on first touch* deposition mechanism

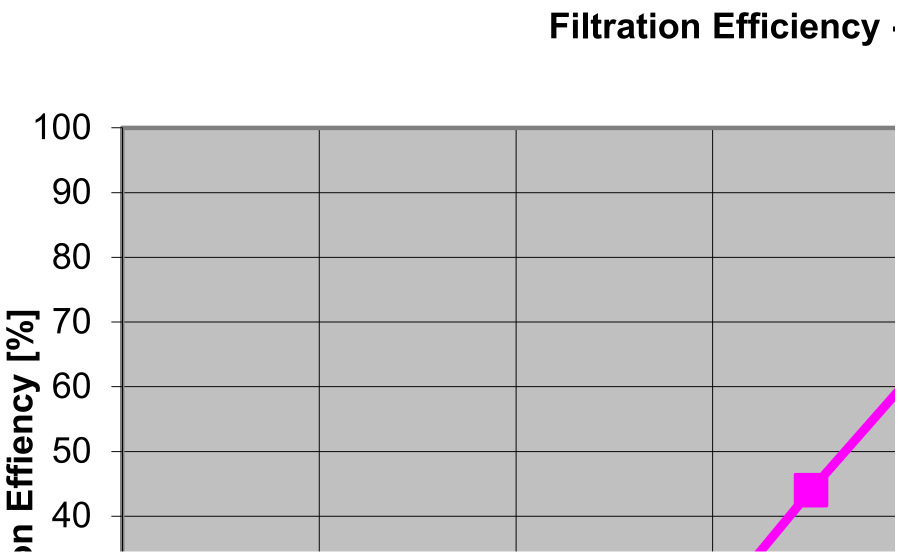

Figure 5: Filter efficiencies using the *sieving* deposition mechanism

4 Conclusions and Outlook

A simulation framework for the microstructure simulation of weaves is developed. The simulation chain starts from a fully resolved woven. Deformation under different load conditions, fluid flow and particle filtration can then be simulated. The single steps are performed using the Fraunhofer software GeoDict and the modules WeaveGeo, FeelMath, FlowDict and FilterDict. The innovation of this work consists in the presentation of the new elasticity solver and its application to woven filter media.

First studies show a qualitatively reasonable behavior of the computer models. We created a plain weave and applied a certain in-plane strain. Then we computed air flow and particle filtration through the undeformed and deformed structures. The results can be interpreted consistently within the models and confirm practical experience.

Our future work will focus on quantitative validation of the models and transfer the methods to other fields of applications.

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