MODELING AND CFD-SIMULATION OF WOVEN TEXTILES TO DETERMINE PERMEABILITY AND RETENTION PROPERTIES

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Abstract:

The previous paper (No. 2, Vol. 12-2011) [1] were analyzed the weave and construction parameters of high density woven fabric and their influence on the pore morphology, which directly effects the functional properties such as permeability and retention. The analysis encompassed physical and optical methods of testing. In this paper, newly developed methods, tools and programs will be presented for virtual imaging of the multi-filament woven fabric geometry with pore structure used to determine permeability and retention properties. Two methods are applied for the generation of virtual fabric. One method involves developing software that is able to model woven fabric in new condition from a series of realistic input parameters. In this step, deterministic and stochastic methods are combined to create the fabric's geometry. The other method involves reconstruction/generation the 3D woven geometry from sequences of 2D cross section images. The results prove that the 3D pore morphology of high density multi-filament fabric can be illustrated in correlation of the woven construction parameters. The developed methods for modeling and the CFD simulation of woven fabric build an important basis for determining the mechanical flow properties such as permeability and retention characteristics of filters and barrier textiles. Additionally, the effects of mechanical loads on the fabric morphology and on the permeability values will be analyzed by applying uniaxial and biaxial tensile loads to the fabric. The tests provide the basis for a realistic prediction to the effects of the machine and construction parameters on the fabric properties and the resulting permeability and retention. These predictions can aid in analyzing the suitability of a fabric for a specific application.

Key words:

Filtration, micro modeling, high density weaving, CFD simulation, permeability, retention.

Introduction

The pore morphology of textile structures determines numerous functional properties in the end product. Barrier characteristics (impermeability and particle retention) and quality of comfort (air and water vapor permeability) are two such properties.

To date, basic research has not been successful, either theoretically or experimentally, in describing the complex correlation between the 3D pore structure of woven fabric and their permeability and barrier properties. This can be accounted for by the fact that until now, the influence of construction and weaving parameters on the 3D pore structure of the woven fabric has not been researched. Furthermore, to date, there is no knowledge of the effects of mechanical loading on the pore morphology and consequently the permeability and retention properties of high density woven fabric. To understand this correlation, it is not only necessary to record the micro and meso pore structure, but also to characterize the yarn deformation in the cross section beyond the pattern repeat. A characterization of the microstructure of multi-filament fabric and the rough model mesh in a single simulation is limited so far, since at this time no software with sufficient functionality and efficiency is available to generate a fabric model for the CFD simulation to determine the fluid flow properties of the textile. Because of this, the design and development of many technical products (e.g. surgical protective textiles, textile filters) are still required an intensive experimental effort to adjust the permeability and barrier properties by trial and error method. There are unresolved scientific issues that need to be explored with respect to the predictability of the 3D pore structure of the woven fabric dependent on construction and process parameters, which subsequently result in permeability and retention properties. A listing of these issues is shown in Figure 1.

high density woven fabric with defined adjustable permeability and retentoin			
construction/ use	structure	modeling	simulation
influence of process parameter and realistic work load on the pore structure in woven fabric	measuring method for pore determination on the micro, meso and makro layers	realistic simulation of woven fabric geometry on the micro, meso and macro layer	properties of permaebilty and retention of gases, fluid and particles
	preparation of microtome	changeable yarn cross section beyond the pattern repeat	comprehensive evaluation

Figure 1. Scientific inadequacy in the modeling and simulation of high density woven fabric.

In various studies [2-8], fabric models were compiled considering warp and weft yarn crimping and yarn compressibility and displacement, which directly result from the warp and weft yarn strain during the weaving process. Currently, the fabric production process can be modeled in which textile's construction parameters and the machine's mechanical parameters are considerated. Traditionally, macroscopic effective models were implemented to simulate permeability and retention of particle in fluids and gases through porous media [9-14]. Mathematically, effective flow equations were formulated based on the Navier-Stokes Equation using suitable averaging methods such as volume averaging and homogenization [15]. These methods show the importance and value of CFD simulation as a tool to analyze the permeability and particle retention. Modeling the correlation between the textile machine parameters and the resulting woven fabric's properties, especially the permeability and the retention, i.e. filtration, has not been conducted up to now.

The microstructure simulation presented and described in this paper cannot be performed by any commercial software currently available. Microstructure simulation means that in the first step, the material to be analyzed, here high density multi-filament fabric, is created virtually resolving the smallest scale of the material. The second step entails determining the simulative fabric properties. These properties include the geometrical characterization using pore size distribution and the characterization of the flow dynamics through permeability and particle retention properties. This purely computer-aided virtual method used to analyze the woven fabric is advantageous in many respects. Not only does it offer cost savings and shortened development times by reducing the number of necessary experiments, but it also allows for a very localized analysis of fabric behavior, which is difficult to achieve on an experimental basis. By implementing the newly developed methods and simulation programs, the barrier and permeability properties can be accurately predicted and extrapolated to include other fabric constructions.

However, the complex stresses (mechanical, thermal and chemical) that occur in reality can influence the pore morphology to varying degrees. Generally, mechanical stress presents itself in every filtration application as well as in use and reprocessing (washing) of surgical textiles. The effect of the mechanical stresses on a change of pore morphology was investigated by implementing mechanical uniaxial and biaxial cyclical stress and then evaluated microscopically and with air permeability measurements.

Methodology

Material

In order to research the impact of the construction and weaving parameters on the complex 3D pore structure in the fabric, 41 model woven fabrics were produced using the Dornier rapier weaving machine. These model fabrics were used to compile data on the effects of mechanical strain on the pore morphology and consequently how the permeability and retention properties were affected. The fabrics were produced with two different warp yarn systems composed of multi-filament yarn with a normal titer (2.5 dtex) and with a microfilament yarn (0.8 dtex). During production, weaving process parameters, such as the warp yarn tension, were varied as well as the construction parameters, such as the warp yarn fineness, density and binding pattern. A listing of the parameters is shown in [1]. For this article, a plain weave (model weave No. 24) and a twill weave 2/2Z (model weave No. 36) were selected from the 41 model weaves for the modeling and CFD simulation [1, see Table 3]. Both models weaves exhibit the same warp yarn system with a yarn fineness of 100 dtexf40 and a weft yarn fineness of 150 dtexf48. The difference in the two yarns is the number of weft yarns in each. The plain weave possesses a weft yarn number of 36 yarns/cm and the twill weave has a weft yarn number of 48 yarns/cm (Table 1).

Table 1. Process and construction parameters of selected fabric.

Model waeve No.	24	36
Warp yarn count [dtex]	100	100
Weft yarn count [dtex]	150	150
Number warp yarns [cm-1]	68	68
Number weft yarns [cm-1]	36	48
Binding	L 1/1	K 2/2 Z
Index	0.90	0.67
Machine speed r [rpm]	380	380
Shed closing t [°]	0	0

Virtual morphology of the weave - 3D-weave generator

The pore structure of the fabric was prepared using a novel method of microtome sectioning. With the aid of microtome section images, the distribution of the single filaments, perpendicular to the plane of the fabric, were optically recorded with their exact layer position in the warp as well as in the weft directions. 2D images of the fabric's cross section were taken at defined intervals. To ensure an accurate representation of the weave's morphology over the complete repeating pattern, more than 100 2D microtome images were generated.

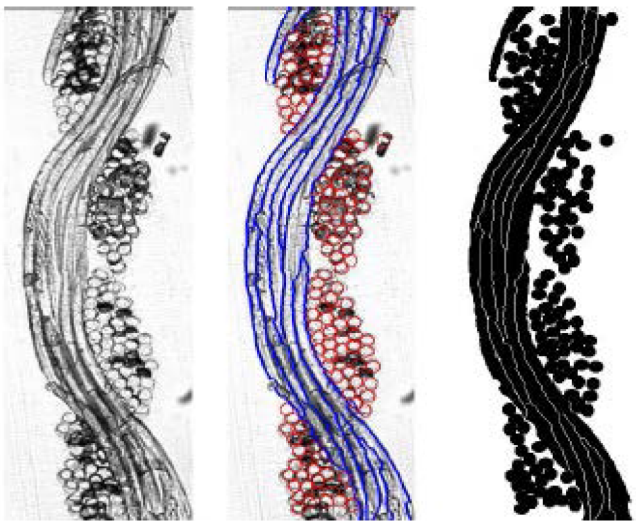

Figure 2. Microtome section (left),microtome section after contour detection (middle) und segmentation (right).

After image processing the microtome sections, the 3D weave structure was digitally constructed. Figure 2 shows the original section image, contour detection and segmentation. The warp and weft sections were analyzed separately, where only the circular fiber sections from at least one pattern repeat were used for the 3D reconstruction and as the foundation for the CFD simulation.

The second method for creating a woven structure is purely virtual. By using a series of so-called structure generating parameters, such as binding type, geometrical dimensions of the pattern repeat, filament diameter and several other partially stochastic parameters, it is possible to create a woven fabric with high geometrical accuracy (Figure 3 & 4) using the software program GeoDict® [16].

Furthermore, methods for geometrical characterizing e.g., using for determination of pore size distribution or the maximum size of trough path were developed and validated.

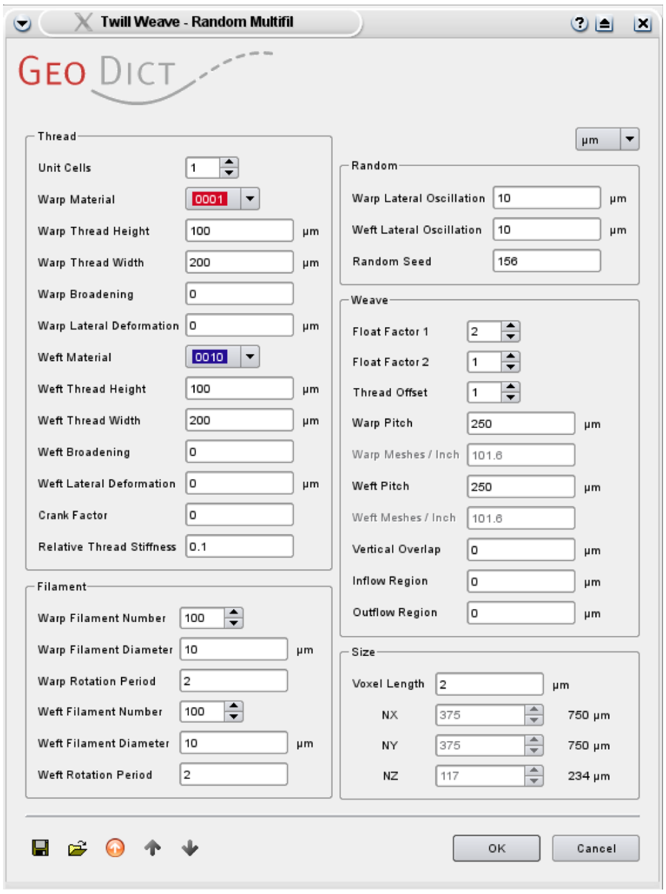

Figure 3. Digital generation parameters.

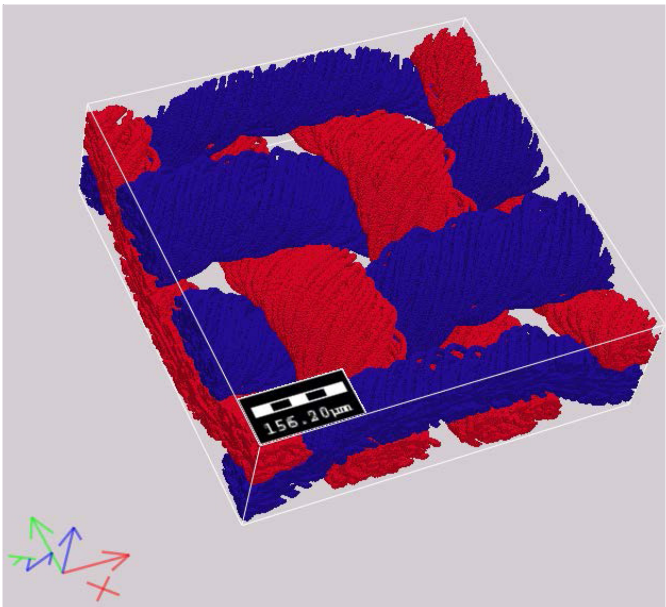

Figure 4. Resulting multi-filament structure.

Simulation of realistic working loads

The mechanical stresses occurring in the fabric during use and their effect on the change in pore morphology were tested and evaluated in the laboratory using a Zwick brand tensile testing machine. The weaves were tested using uniaxial and biaxial, cyclical mechanical stress loads (Figure 4). An optical evaluation of the changes that occurred was conducted with an Axiotech 510 reflecting light microscope manufactured by Zeiss. The dynamic stresses were limited to 30% of the maximum breaking strength of the sample and the rate of strain (elongation) was set at 5 mm/min and 50 mm/min respectively. Stress was applied to the samples simultaneously in both directions. The condition of the woven structure during stress application and immediately after in relaxed condition was fixed using a light hardening epoxy resin. This allowed the changes to be recorded microscopically.

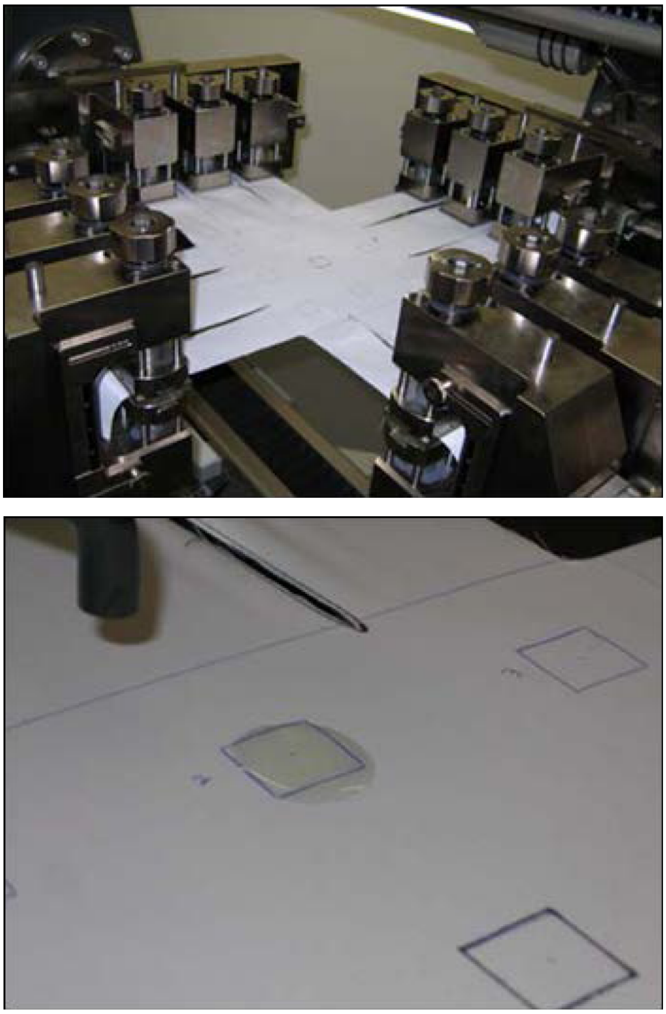

Figure 4. Experimental testing with biaxial tensile stress applied to the specimen (top) and fixation of fabric structure's condition (bottom).

Results and discussion

Virtual morphology of the woven fabric

With the aid of the software tool GeoDict®, specially developed at the Fraunhofer ITWM, it is possible to create a virtual 3D woven fabric using 2D microtome sections, provided the individual microtome images are digitally reconstructed in their accurate positions. The fabric generator is a dependable software building block to virtualize various weave types and patterns. In Figure 5, such modeled 3D fabric reconstructions are illustrated.

Tomography

In addition to the microtome based and purely virtual fabric modeling, µCT images of the woven fabrics were taken. Figure 6 exhibits such an image with a 3 µm resolution. Because the same data format is used, they are analogous to the virtual woven fabrics and can be compared with respect to geometry, fluid dynamics and retention properties to the simulated fabrics.

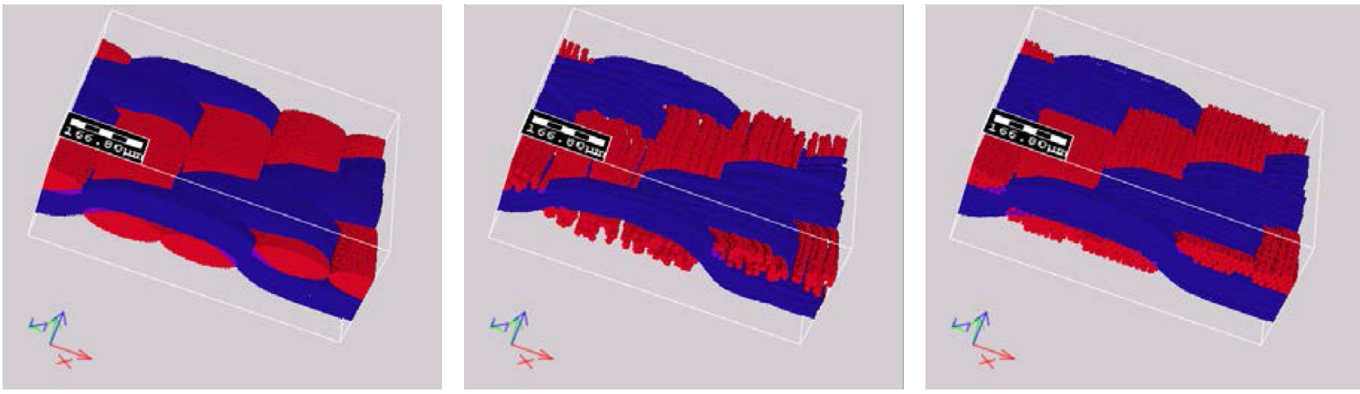

Figure 5. 3D-woven structure models with a monofilament yarn structure – as a simple analogous model (left), a densely woven multi-filament yarn structure with less (middle) and more filament alignment (right).

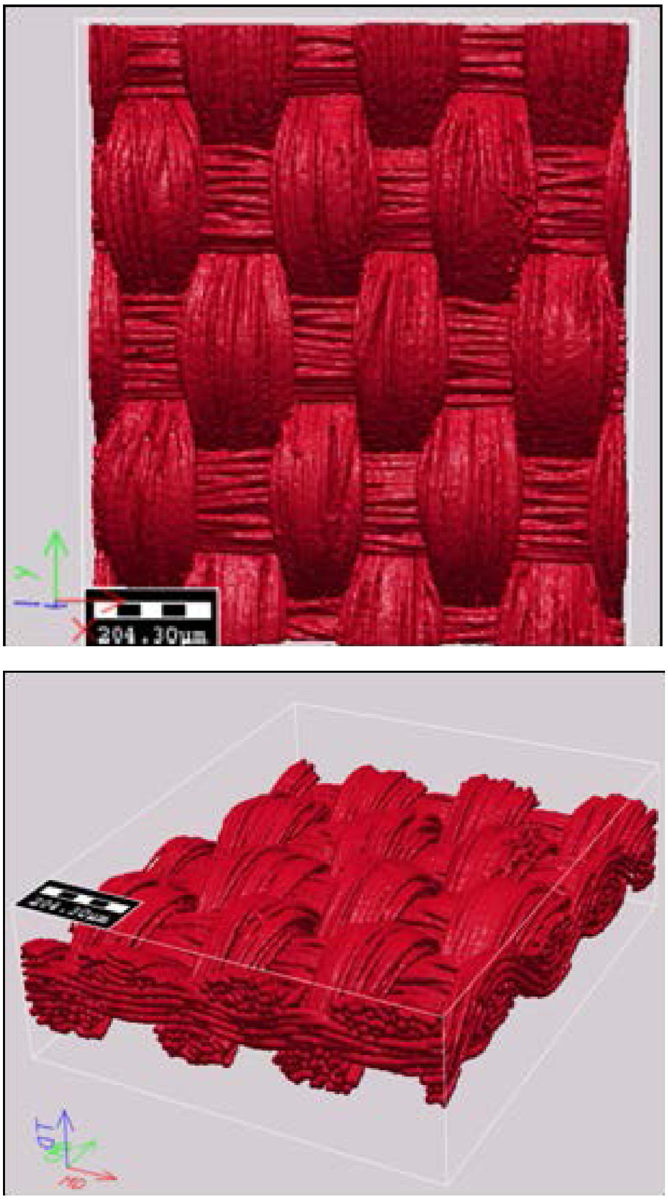

Figure 6. Tomography of a plain weave with a multi-filament yarn structure.

Semi-virtual 3D data series can be created from 2D microtome sections using a multiple step process. To do so, three tomography images need to be taken and reconstruct from the fabric and compared to the virtual fabrics for permeability and particle flow. Figure 7 shows a pattern repeat of a fabric tomography and three virtually constructed variations.

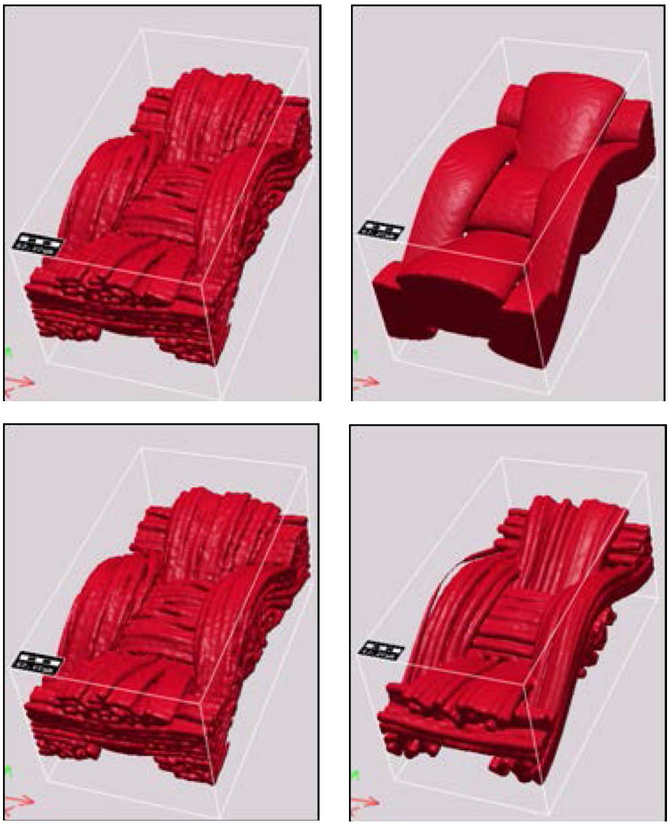

Figure 7. Tomography, virtual monofilament, virtual regular multi-filament and a virtual random multi-filament (from left to right).

CFD (Computational Fluid Dynamics)-simulation

Based on the virtualized geometries and the tomographies, a validation phase of the CFD simulation computations run was initialized. During the validation, the permeability and particle flow were used as reference values in the experiment for evaluation purposes (Figure 8).

It was found, that the flow measurements are particular relevance because they characterized the size of the pores at the yarns intersection. These pores generally determined the volumetric flow rate. The initial simulation tests showed that the micro pores between the single filaments in the multi-filament yarn firstly do not play a major role in the CFD simulation of high density fabrics in new condition.

The virtualized fabric geometries provide the basis for the CFD simulation of multi-filament weaves for the meso and macroscopic analysis of larger fabric specimens of up to 100 yarns in the warp and weft directions. The permeability of the virtual fabrics and the tomographies were determined based on a CFD simulation. After entering a pressure drop, the flow rate was computed locally and subsequently the effective speed was determined using integration.

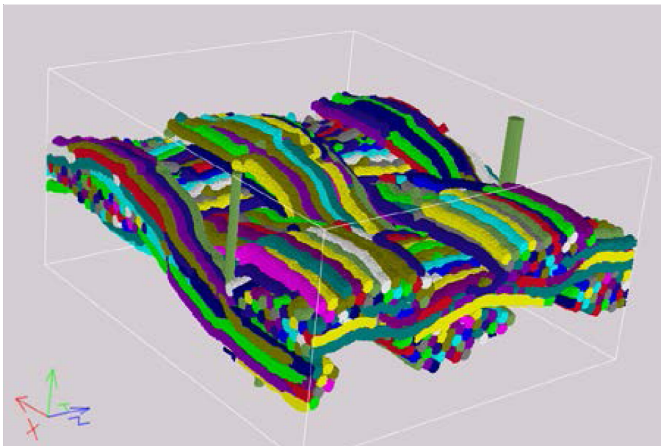

Figure 8. 3D-woven structure with the maximum particle flow at the intersection points (green cylinder).

The CFD simulations of the multi-filament fabrics shown in Figure 7 with a yarn thickness of 130 µm and 40 individual filaments produced an effective mean flow rate of approximately 0.1 m/s at a pressure drop of 200 Pa. The calculated size of particles able to pass through the fabric was approximately 18 µm. The most recent porometry measurements for the same fabrics gave a maximum particle size of approximately 10 µm. This difference can be explained by the rough resolution of the tomography.

A study in which the monofil yarn thickness was gradually increased by a few micrometers on a virtual basis, led to a monofilament weave that reached the experimentally determined maximum pore size. In the CFD simulation, this fabric (model variation 9) exhibited precisely the measured effective flow rate of 0.01 m/s (Figure 9). Consequently, we were able to successfully and accurately simulate the flow rate of monofilament fabrics.

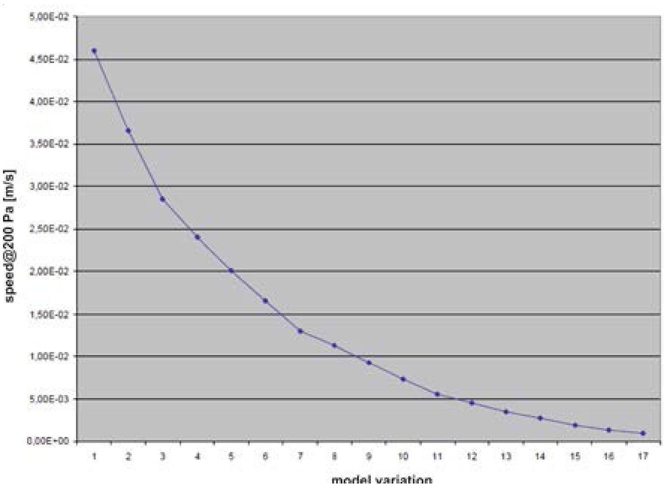

Figure 9. Correlation of average speed and yarn diameter.

<u>Effect of realistic working loads on the permeability and the macrostructure of woven fabric</u>

Results of initial positioned experiments conducted with uniaxial and biaxial tensile stresses to evaluate the effects of application loads on the model fabric's properties indicate that the mechanical stresses greatly influence the fabric morphology, and subsequently the permeability values. After loads were applied, air permeability declined by 25% at a loading rate of 5 mm/min as compared to fabrics in new condition (Figure 10). However, the sample tested with a higher loading frequency (50 mm/min) showed a reduction in air permeability of only 8%.

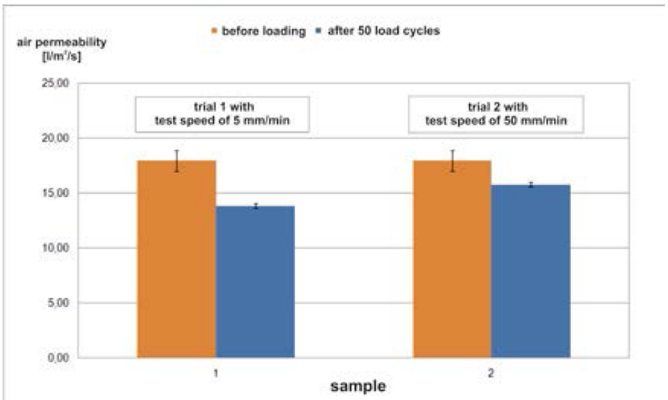

Figure 10. Air permeability of the fabric before and after biaxial loading.

The microscopic evaluations show just a minimal spread of the warp yarns and a marginal reduction in the meso pores (Figure 11). It can be assumed that due to the relatively low loads, approximately 30% of the fabric's breaking strength, a homogenization of the meso pores occurred and eventually a parallelization of the single filaments, which would result in reduced permeability.

It can be concluded from this experiment that the load profile, dynamically (load frequency, amplitude) and numerically differ greatly from the real loading conditions. The change in pore morphology resulting from application stresses will cause highly deviation of the retention properties in the fabric.

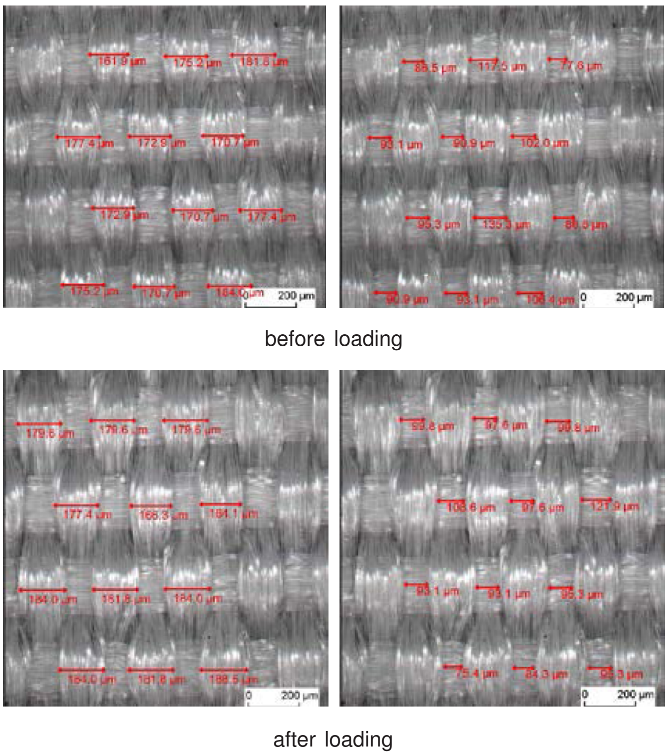

Figure 11. Macrostructure of the fabric before and after loading.

Initial measurements show that the manner in which the last is applied, as well as the actual load size can greatly influence the permeability of the fabric in diverse trends. Depending on the length of the dynamic loading, the expected results can even be reversed. To further explore this phenomenon, it is necessary to conduct more comprehensive research.

Conclusions

The developed methods exhibit that the 3D pore morphology of high density multi-filament fabrics can be characterized as a dependent of the weaving construction parameters.

Modeling and CFD simulations, with a definition of the macro, meso and micro structure and a determination of the associated model parameters for the permeability of the fabric when viewed macroscopically, provide a better understanding of the mechanisms at work in the blocking and loading of filters, as well as the change of pressure drop with increasing particle retention. However, the CFD simulation is to be improved under the aspect of mechanical load conditions, in due consideration of micro pores and their interaction.

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