Microstructure Simulation of Virtual Woven Filter Media

Stefan Rief, Erik Glatt and Andreas Wiegmann
Fraunhofer-Institut Techno- und Wirtschaftsmathematik,
Fraunhofer-Platz 1, 67663 Kaiserslautern

ABSTRACT

In contrast to their random nonwoven counterparts, woven filter media possess much higher regularity and precision. However, they are more expensive and their application is in general only justified where high-tech requirements have to be met. As a matter of course, the woven manufacturer is very much interested in understanding the complex interplay of geometrical, flow and filtration properties, being the prerequisite for further optimization of his products.

The Fraunhofer ITWM software GeoDict is especially tailored to virtually generate and characterize filter media and, therefore, reveal the aforementioned interplay by means of computer simulation. During the last two years, substantial progress and extensions have been made to the software to satisfy industrial demands concerning technical woven.

This paper gives an overview on the latest developments in the generation of woven structures with WeaveGeo, a tool of the GeoDict Software. It is organized by application covering metal wire meshes and filter media for protective clothings.

KEYWORDS

Virtual Structure Generation, Woven Filter Media, Numerical Simulation

1. Introduction

Woven structures are an important class of filter media. For the manufacturer it is essential to understand the complex influence of the weave geometry on the flow and filtration properties. Such an understanding is the prerequisite for further optimization of woven filters to meet customer demand. Using computer modelling for the simulation of the porosity, flow and filtration processes can shorten the optimization process and reduce its cost. However, one first needs a reliable mathematical model for the virtual generation of woven structures.

The structure of a weave can be calculated using the mechanical properties of the wire material [1]. The force-equilibrium modelling [2] and the energy-based approach [3] are common techniques. A different approach is the direct modelling of the geometry of a weave. Examples are the idealized Peirce-Model [4] and the approximation of the wire profiles using splines [5]. Here we use a simple model for the direct generation of the weave geometry [6, 7], which is included in the GeoDict software. This model allows for the generation of a corresponding virtual geometry knowing only a few easy to measure parameters of a real weave. The advantage of the presented model is that shape variations of the wires, which emerge during the weaving process, are included.

Important parameters for the characterization of filter media are the pressure drop (during the perfusion with air, water or oil), the largest penetrating particle, the bubble point and the pore size distribution [8]. The purpose of the mathematical modelling of a weave geometry is to predict these parameters as accurately as possible [9, 10, 11, 12] via numerical simulations.

In this article the mathematical model for the generation of weaves, used by the WeaveGeo module of the GeoDict software, is shortly introduced. This model provides geometrical approximations of mono- and multifilament weaves. Using the generated structures the parameters for the characterization of filter media can be calculated with the Dict-tools of GeoDict.

To demonstrate the accuracy of the model and the numerical simulations two examples are studied. The first example is a monofilament metal wire mesh. The geometry model is directly compared with a tomography of a real mesh. Afterwards exemplary numerical simulations of the velocity dependent pressure drop and the largest penetrating particle are performed for the model and for the tomography.

A dense multifilament plain weave, which may be used for protective clothings, is the second example. Three geometrical models are generated and compared to a tomography of the weave. Calculating the velocity dependent pressure drop for the tomography and the models the agreement between the models and the tomography is studied.

2. Virtual Generation of Woven Filter Media

The threads of a weave can often be modelled as compact objects without an inner structure. Such weaves are called monofilament weaves. For simplicity we assume at first that the profile of a monofilament thread has a constant ellipsoidal form. By profile we mean the shape of the cross-section of the wire. Two parameters, the height h and width w identify the ellipsoidal form of the profile. Parameters for warp and weft wires are distinguished by subscript $_{wa}$ for the warp and $_{we}$ for the weft wires. The parameter p indicates the pitch, or distance of the wire profile centres in the plane. Figure 1(a) shows these weave parameters and their connection to the geometry using the example of a twill 2/1 weave.
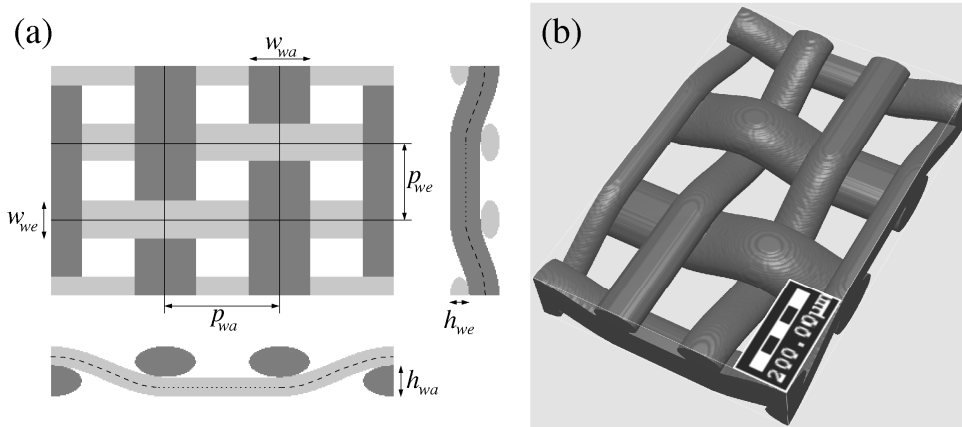

Figure 1: The model of a twill 2/1 weave, with $h_{wa} = 80\mu m$, $h_{we} = 50\mu m$, $w_{wa} = 160\mu m$, $w_{we} = 100\mu m$, $p_{wa} = 300\mu m$ and $p_{we} = 200\mu m$. (a): 2D views from the top and the sides explaining the model parameters, (- -) sine function and (· ·) straight segment. (b): Virtually generated 3D model.

The structure of a weave is furthermore determined by the interlace of the warp and weft wires, which is usually given by the weave diagram. This diagram may be represented by a binary matrix, where one entry of the matrix characterizes one point of intersection of the wires. The value of the matrix element determines, which wire is on top of the other. The three basic weaves are the plain, the twill and the satin weave.

The virtual generation of the weave requires the parameterization of the position of the centre of the wire profiles in the lateral direction (in the weave plane) and the vertical direction (perpendicular to the weave plane). This is done using the mathematical model described in [6, 7], which is implemented in the GeoDict Software. With this model one can generate an analytic description of a weave.

In a next step such an analytic geometry model is used to construct a discrete model. A cuboidal volume, which contains a repetitive unit of the weave, is divided into voxels (volume elements). A voxel is part of the weave if and only if its centre lies inside one of the threads. This method was applied to the twill 2/1 weave from Figure 1(a). The surface of the resulting discretized 3D geometry is presented in Figure 1(b). For weaves with other weave diagrams one gets corresponding results.
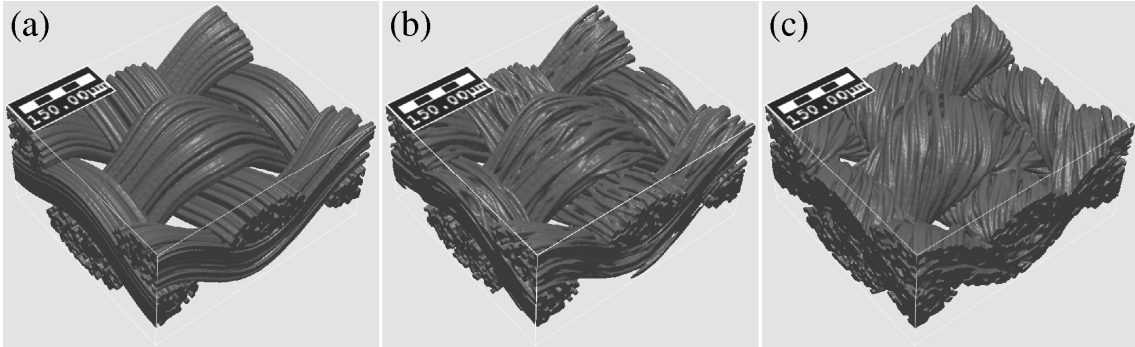

Figure 2: The virtually generated multifilament structure of a plain weave with $n_{wa} = n_{we} = 200$, $w_{wa} = w_{we} = 180 \mu m$, $h_{wa} = 80 \mu m$, $h_{we} = 100 \mu m$, $p_{wa} = 250 \mu m$, $p_{we} = 220 \mu m$, $f_{wa} = f_{we} = 10 \mu m$, wire broadening $b_{we} = 0.3$ and crank $c = -0.25$. (a): Without random deformation and without twist. (b): With random deformation $a_{wa} = a_{we} = 10 \mu m$ and without twist. (c): With random deformation $a_{wa} = a_{we} = 10 \mu m$ and with twist $t_{wa} = p^{-1}_{wa}$, $t_{we} = p^{-1}_{we}$.

A weave with threads composed of many filaments can often not be modelled as a monofilament structure. For such multifilament weaves one additionally has to model the position of the centre of the filament profiles in the threads and the geometry of the filaments. This is demonstrated here for filaments with a fixed circular diameter, where the diameter of the filaments is given by the parameter f and the number of filaments per thread by n.

The vertical and lateral position of the centre of a filament profile is calculated relative to the position of the thread, to which it belongs. Assuming that the filaments are randomly (random multifilament) distributed over the wire cross-section one gets a simple approximation of this relative filament position. A second possibility is to pack the filaments in a thread as dense as possible without overlap (regular multifilament). Other, more complex approximations, may lead to better results according to the weave under consideration.

The shape of a filament is modelled analogue to the shape of a thread of a monofilament weave [6, 7]. The resulting geometry of a multifilament plain weave with randomly over the wire profiles distributed filaments is presented in Figure 2(a). One discerns that the relative position of the filaments with respect to the centre of the associated thread profile does not change. This behaviour is not realistic for many woven structures, where one finds a more or less pronounced random change of the relative filament positions. To model this random movement a lateral sine oscillation with a small random frequency is added to each wire. The mean of the

randomly distributed amplitude of these oscillations is given by the parameter a. A multifilament plain weave with such a random filament movement is shown in Figure 2(b).

The wires of multifilament weaves may be twisted. This leads, additional to the random changes, to systematic changes of the relative filament position. This filament movement along the thread profiles can be modelled by adding a lateral and vertical sine oscillation to each filament, where the amplitude of these oscillations is proportional to the distance of the filament from the centre of the wire profile. The spatial frequency of the twist is given by the parameter t. The geometry of a multifilament plain weave with twisted wires is shown in Figure 2(c).

Real weaves exhibit a wide range of shape variations. These variations can be seen for example in a tomography. They have to be included in the weave model to get a better approximation of real structures. The shape variations included in the GeoDict Software, which are explained in detail in [6, 7], are:

- the broadening of the threads at the float intervals (the relative broadening b)
- the lateral deformation of the threads (deformation parameter d)
- the different bending behaviour of warp and weft threads (crank factor c)
- the stiffness of the threads (stiffness parameter s)
- the reduction of the amplitude of the vertical thread oscillation (parameter o)

For the modelling of special weaves it may be necessary to include additional shape variations, however the model with the discussed variations leads to a close correlation between virtual and real woven filter media in many cases.

3. Metal Wire Meshes

In this section a tomography of a metal wire mesh is examined. It was provided by the GKD - Gebr. Kufferath AG. The 3D geometry of the weave can be studied using the GeoDict software by importing the image with an appropriate threshold value. In this way the geometrical properties of the mesh are determined and a virtual model of the structure is validated.

Figure 3(a) shows the tomography of a metal wire plain Dutch weave. The geometry was oriented so that the warp wires run in y-direction, the weft wires run in x-direction and the z-axis is perpendicular to the plane of the mesh. The smallest part of a periodic mesh, containing all the information about the geometry, is called repetitive unit. A repetitive unit from a tomography is the most accurate possibility to get all the information one needs to generate a model of a weave. For the plain weave under consideration a repetitive unit is displayed in Figure 3(b) and the model geometry based on this structure is presented in Figure 3(c).

A difference image of the structures shows the correlation between the model and the real weave. Figure 3(d) shows 2D cuts from the 3D difference image. White indicates the part of the mesh that is present in both the tomography and the model. Light grey is assigned to empty voxels. The dark grey parts belong to voxels, which appear only in the model or only in the tomography. 15% of the voxels of the mesh are not white and not light grey, so the difference between the structures is approximately 15%.

A tomography makes the difference between the virtual and the real weave visible and quantifiable. The shape variations discussed in Section 3 are based on detailed looks at such images. With the shape variations the mathematical model leads to structures which are in very close correlation to real metal wire meshes. This finding is not limited to the example presented in this section and was checked using tomographies of many more metal wire meshes.
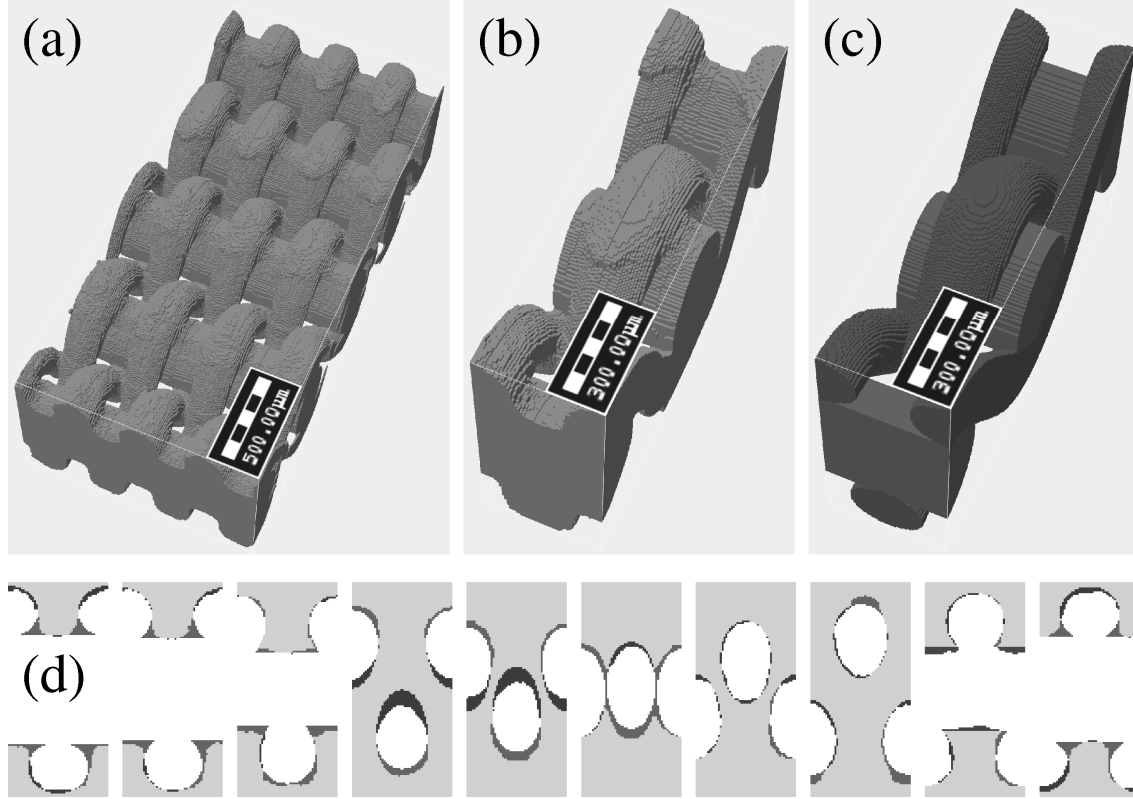
Figure 3: Tomography of a metal Dutch plain weave and its comparison with a virtually generated structure. (a), (b): Tomography, where (b) shows one repetitive unit. (c): Virtually generated structure of a repetitive unit with $w_{wa} = 391\mu m$, $w_{we} = 195\mu m$, $h_{wa} = 451\mu m$, $h_{we} = 195\mu m$, $p_{wa} = 721\mu m$, $p_{we} = 203\mu m$, $c = 1$, $b_{we} = 0.25$ and $o = 8\mu m$. (d): 2D cross sections from the difference image of (b) and (c) for $x = 0\mu m$ (front side) and parallel cuts at $x = -75, -150, .., -675\mu m$.

Having an accurate discrete model of the weave one can use it for numerical simulations with the GeoDict software. Two important parameters for the characterization of filter media, namely the pressure drop during the perfusion with air and the largest penetrating particle, are calculated exemplarily. The results for the tomography and the model are shown in Table 1. The difference between the results for the tomography and the model is thereby 10% for the largest particle and 15% for the flow velocity.

	tomography	model
mean velocity	$2.49 m/s$	$2.11 m/s$
largest particle	$90\mu m$	$80\mu m$

Table 1: Results of the numerical simulations using the GeoDict software. First row: The mean velocity for the perfusion with air at a pressure drop of $200 Pa$. Second row: The diameter of the largest penetrating particle.

A tomography is not necessary to adjust the model to a real weave. This can often be done with just a few easy to measure parameters. Comparing numerical simulations of the pressure drop on resulting geometry models with corresponding measurements one finds that they are in very good agreement with each other [6, 7].

4. Protective Clothing

Woven multifilament structures are of great importance for many applications, where the example of a protective clothing is presented in this section. Using the GeoDict software for geometric modelling of weaves and for numerical simulations on the resulting structures one tries to understand the filtration properties of the protective clothing.
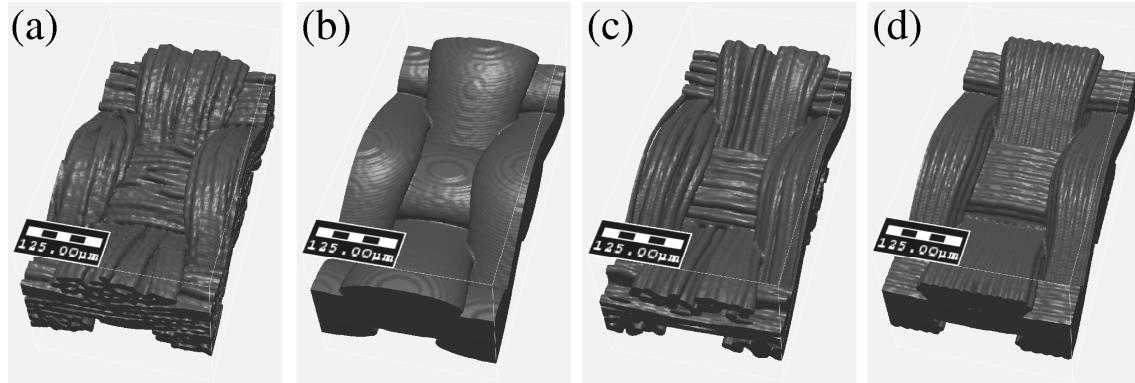

Figure 4: Tomography and models of a repetitive unit of a plain weave protective clothing. The model parameter are $w_{wa} = 167\,\mu m$, $w_{we} = 176\,\mu m$, $h_{wa} = 64\,\mu m$, $h_{we} = 76\,\mu m$, $p_{wa} = 152\,\mu m$, $p_{we} = 302\,\mu m$, $c = 0.8$, $b_{we} = 0.2$ and $o = 6\,\mu m$. (a): Tomography. (b): Monofilament model (model 1). (c): Random multifilament model (model 2) with $n_{wa} = n_{we} = 40$, $f_{wa} = f_{we} = 15\,\mu m$ and $a_{wa} = a_{we} = 3\,\mu m$. (d): Regular multifilament model (model 3) with $n_{wa} = n_{we} = 40$ and $f_{wa} = f_{we} = 15\,\mu m$.

The clothing under consideration is a very dense plain weave provided by the "Institut für Textil- und Bekleidungstechnik" of the TU Dresden. A tomography of a repetitive unit of this weave is shown in Figure 4(a). As a first approximation one can determine the form of the threads to generate a monofilament model (model 1). The resulting geometry is visualised in Figure 4(b). Comparing now the mean velocity of air at a pressure drop of $200\,Pa$ for the tomography and model 1 (Figure 5) one finds that the velocity for the model is 17% less than for the tomography. The clothing is so dense that only a small part of the flow goes through the threads and therefore model 1 is a relatively good approximation. One way to improve the model is to calculate the permeability of the threads and to assign the resulting value to the monofilament model.

A second way to get a better approximation is to generate a more accurate multifilament geometry model. At first a random multifilament weave (model 2), which is shown in Figure 4(c), is generated. At a first view the direct comparison of the structures looks promising. However, comparing the mean velocity of model 2 and of the tomography, one finds an error of 60%. The filaments in the threads of the model are not dense enough and a lot of air can flow through the threads. For a very dense protective clothing the random multifilament weave is hence not a good model.
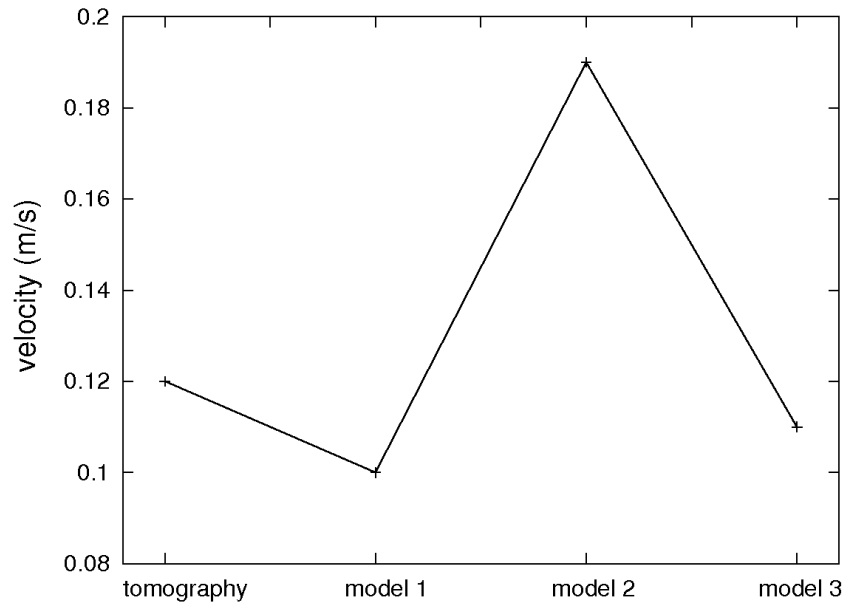
Figure 5: Comparison of the mean velocity for the perfusion with air at a pressure drop of $200Pa$ for the tomography and the models.

The filaments in the threads are packed very dense and thus one can model the weave as a regular multifilament weave (model 3), where the resulting structure is shown in Figure 4(d). For this model one finds a difference of 8% of the mean velocity compared to the result for the tomography. The regular multifilament weave is hence a very good approximation of the real weave geometry.

5. Conclusions
The presented mathematical model provides virtual monofilament structures in very good agreement with real metal wire meshes. Using further tomographic images from the GKD - Gebr. Kufferath AG it was assured that this statement holds for a large range of metal wire meshes with different structures. Pressure drop simulations on the basis of the geometry models are in good agreement with simulations on tomographies of corresponding real meshes. The same is true for the simulation of the largest penetrating particle. One finds furthermore that the simulations on basis of the geometry models are in very good agreement with corresponding measurements [6, 7]. Both the structure generation and simulation tools are implemented in the GeoDict software and thus accessible to all industrial and academic users.

For the optimization of products, based on multifilament weaves, numerical simulations, for which one needs discretized models of the weave geometries, are needed. Thereby a virtual model for the generation of these multifilament weave structures has the advantage to be very cost efficient. Though one has a high reliability on the geometry generation and a good agreement with the real structures, what was shown for a protective clothing (multifilament plain weave). Numerical simulations of the velocity dependent pressure drop on the regular multifilament model are in good agreement with corresponding simulations on the tomography of the clothing. One finds similar results for multifilament twill weaves.

The advantages of the use of GeoDict for the generation of woven meshes and the simulation of filtration processes are the precise and accurate prediction of mesh parameters, the visualization of complex meshes, the easy operation of the software, the acceptable cost and the reduction of engineering costs and engineering time.

References

[1] I.Verpoest and S.V.Lomov. Virtual textile composites software Wisetex: integration with micro-mechanical, permeability and structural analysis. Composites Science and Technology, 65(15-16): 2563-2574 (2005)

[2] S. Kawabata, M. Niwa and H. Kawai. The finite-deformation theory of plain weave fabrics, J. Text. Inst. 64: 21-61 (1973)

[3] J. W. S. Hearle, P. Potluri and V. S. Thammandra. Modelling fabric mechanics, J. Text. Inst. 92(3): 53-69 (2001)

[4] F. T. Peirce. The geometry of cloth structure, J. Text. Inst. 28: 45-96 (1973)

[5] M. A. Smith and X. Chen. CAD and constraint-based geometric modelling algorithms for 2D and 3D woven textile structures, J. of Information and Computing Science 3(3): 199-214 (2008)

[6] E. Glatt, S. Rief, A. Wiegmann, M. Knefel and E. Wegenke. Struktur und Druckverlust realer und virtueller Drahtgewebe, F&S 23(2): 61-65 (2009)

[7] E. Glatt, S. Rief, A. Wiegmann, M. Knefel and E. Wegenke. Structure and pressure drop of real and virtual metal wire meshes, Fraunhofer ITWM 157 (2009), ISSN: 1434-9973

[8] G. R. Rideal, E. Mayer and R. Lydon. Comparative Methods for the Pore Size Calibration of Filter Media. Filtech 2003 International Conference for Filtration and Separation Technology, 1: 280-287 (2003)

[9] S. Schütz, P. Kopf and M. Piesche. Prediction of Pore Size and Pressure Drop of Porous Woven Wire Cloth Filter Media on the Basis of Calculation Models. Filtration, 4(8): 335-344 (2008)

[10] M. A. Nazarboland, X. Chen, J. W. S.Hearle, R. Lydon and M. Moss. Modelling Filtration through Woven Fabrics. Filtech 2007 International Conference for Filtration and Separation Technology, 1: 45-52 (2007)

[11] R. J. Wakeman, K. C. Ting and V. Nassehi. Finite Element Modelling of Flow Through Plain Twill and Satin Weave Monofilament Cloths. Filtech 2005 International Conference for Filtration and Separation Technology, 1: 108-115 (2005)

[12] D. Kehrwald. Parallel lattice Boltzmann simulation of complex flows. Simulation of Complex Flows (CFD) - Application and Trends (2004)