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Vorwort

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Darüber hinaus bietet die Reihe ein Forum für die Berichterstattung über die zahlreichen Kooperationsprojekte des Instituts mit Partnern aus Industrie und Wirtschaft.

Berichterstattung heißt hier Dokumentation des Transfers aktueller Ergebnisse aus mathematischer Forschungs- und Entwicklungsarbeit in industrielle Anwendungen und Softwareprodukte – und umgekehrt, denn Probleme der Praxis generieren neue interessante mathematische Fragestellungen.

Prof. Dr. Dieter Prätzel-Wolters
Institutsleiter

Kaiserslautern, im Juni 2001

STRUCTURE AND PRESSURE DROP OF REAL AND VIRTUAL METAL WIRE MESHES

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Abstract. An efficient mathematical model to virtually generate woven metal wire meshes is presented. The accuracy of this model is verified by the comparison of virtual structures with three-dimensional images of real meshes, which are produced via computer tomography. Virtual structures are generated for three types of metal wire meshes using only easy to measure parameters. For these geometries the velocity-dependent pressure drop is simulated and compared with measurements performed by the GKD - Gebr. Kufferath AG. The simulation results lie within the tolerances of the measurements. The generation of the structures and the numerical simulations were done at GKD using the Fraunhofer GeoDict software.

Keywords: metal wire mesh, structure simulation, model calibration, CFD simulation, pressure loss

1. Introduction

Woven metal wire meshes 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 metal wire meshes to meet customer demand. Using computer modeling for the simulation of the porosity, flow and filtration processes can shorten the optimization process and reduce its cost. However, one first has to assure that the simulations agree with reality. We will establish such an agreement for a mathematical model for the virtual generation of metal wire meshes.

The structure of a weave can be calculated using the mechanical properties of the wire material [1]. The force-equilibrium modeling [2] and the energy-based approach [3] are common techniques. A different approach is the direct modeling 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 present a simple model for the direct generation of the weave geometry. 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 are included. These variations emerge during the weaving process and have a strong influence on the weave geometry. The accuracy of the model is checked using images of real metal wire meshes produced via computer tomography.

Important parameters for the characterization of filter media are the pressure drop (during the perfusion with air, water or oil), the bubble point and the pore size distribution [6]. The purpose of the mathematical modeling of a weave geometry is to predict these parameters as accurately as possible [7, 8, 9, 10] via numerical simulations. For the presented model such simulations of the velocity-dependent pressure drop are compared with corresponding measurements performed by the GKD - Gebr. Kufferath AG. Simulations and measurements agree to within the measurement tolerances, which are less than 3%.

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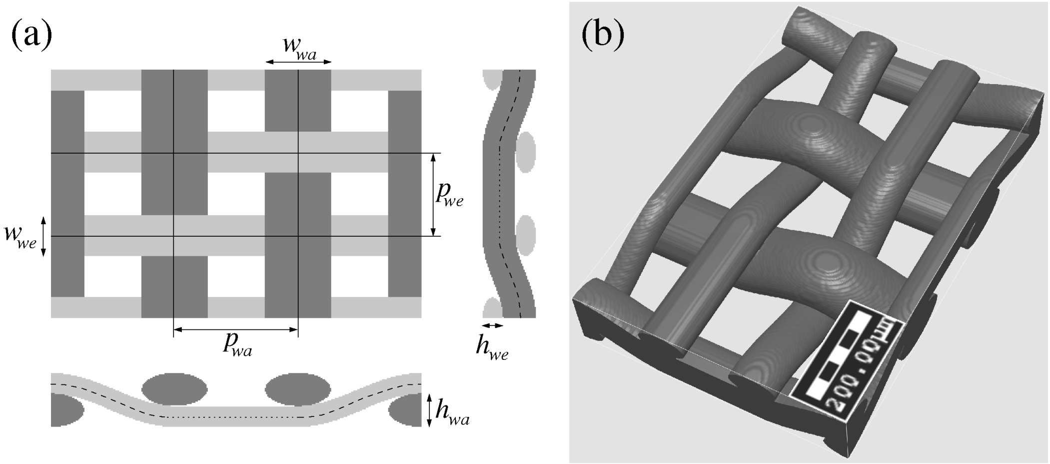

FIGURE 1. *The model of a twill* $2/1$ *weave, with* $h_{wa} = 80\ \mu m$, $h_{we} = 50\ \mu m$, $w_{wa} = 160\ \mu m$, $w_{we} = 100\ \mu m$, $p_{wa} = 300\ \mu m$ *and* $p_{we} = 200\ \mu m$. *(a):* 2D *views from the top and the sides explaining the model parameters, (- -) sine function and (· ·)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

2. VIRTUAL METAL WIRE MESHES

The metal wires of a weave are compact objects without an inner structure. For simplicity we assume at first that the profile of such a wire 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 centers 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.

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 (state of the wire). The three basic weaves are the plain, the twill and the satin weave, whereas only plain and twill weaves are discussed in this work. However, satin weaves can be dealt with in the same way.

2.1. **Creating the wire skeleton.**

The virtual creation of the weave requires the parameterization of the position of the center of the wire profiles in the lateral direction (in the weave plane) and the vertical direction (perpendicular to the weave plane). This parameterization defines the skeleton of the weave. The warp and weft wires are approximately perpendicular to each other and hence it is easy to calculate their lateral position, if one knows the warp and the weft pitch [see Figure 1(a)].

The vertical wire position can be computed using the weave diagram. A wire takes its highest position if it is on top of another, and its lowest position, if it is below another wire. Moving along a wire, starting from one intersection point, two behaviors are possible. In the first case, the state of the wire does not change (float interval) and the height of the wire stays constant. In the second case, a transition between the two states of the wire occurs. This transition is modeled by a sine function. Therefore the vertical position of a wire is approximated by a composition of straight segments (float intervals) and sine functions (transitions) [side views in Figure 1(a)]. This approximation seems rather arbitrary, but we will see that its results are in good agreement with real weaves in many cases. However the choice of other functions may provide better results depending on the weave under consideration. We present such a different choice in section 3.

FIGURE 2. *Virtually generated twill* $2/2$ *weave with* $h_{wa} = h_{we} = 50$ μm, $w_{wa} = w_{we} = 100$ μm *and* $p_{wa} = p_{we} = 150$ μm. *(a): Weave without shape variations. (b): Weave with broadening and lateral deformation,* $b_{wa} = b_{we} = 0.2$ *and* $d_{wa} = d_{we} = 15$ μm. *(c): Weave with stiffness and crank,* $s = 0.5$ *and* $c = 1$.

To calculate the vertical wire position one needs the information about the height of the wires. To achieve the thinnest possible wire mesh, the maximum amplitude of the weft wire is assumed to be half the height of the warp wire and vice versa. If the weft and warp wires are under different tension, this description is not correct. Different tension in warp and weft direction may result from different materials, different profiles or simply from production parameters. We present more details regarding this phenomenon in section 3.

2.2. **Discretization of the wires from the skeleton.** With the information about the position of the center of the wire profiles one can model the geometry of a weave. Therefore, the skeleton of each wire is divided into straight line segments, where each segment is the central axis of a cylinder with ellipsoidal profile. The height and width of the cylinders are given by the parameters h and w of the corresponding wire. At both ends of each cylinder a matching semi-ellipsoid is added. It provides a smooth wire shape at the joints where adjacent segments have different directions. The overlap of the cylinders and the ellipsoids model the structure of the weave.

In a next step such an analytic geometry model is used to construct a discrete model of a weave. A cuboidal volume, which contains a repetitive unit of the weave, is divided into small cubes, so-called voxels (for volume cells). A voxel is part of a wire if and only if its center lies inside one of the cylinders or ellipsoids that make up that wire. 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.

3. SHAPE VARIATIONS

Real weaves exhibit a wide range of shape variations. These variations can be seen for example in tomographic images. They are included in the weave models to get a better approximation of the real structures.

Many real weaves do not have an approximately constant wire width, such as the one shown in Figure 3(a). Instead, one often identifies a regular broadening of the wires at the float intervals. The parameter b characterizes this broadening relative to the standard thickness. Furthermore, a regular lateral deformation of the wires is often observed. This lateral deformation is directly connected with the weave diagram. This effect can be approximated by an additional lateral sine oscillation of the wires. The amplitude of this oscillation is given by the parameter d. The broadening and the lateral deformation are displayed in Figure 2(b) using the example of a virtually generated twill $2/2$ weave, which is plotted without shape variations in Figure 2(a).

Comparing the weft and the warp direction of a weave one often finds a different bending behavior of the wires [see Figure 4(a)], because the wires are under different tension. This behavior is modeled using the crank factor c. It parameterizes the continuous transition from straight warp ($c = -1$) to straight weft wires ($c = 1$). Furthermore, for very stiff wires the description of the vertical wire position using straight line segments and sine functions is not a good approximation. For such

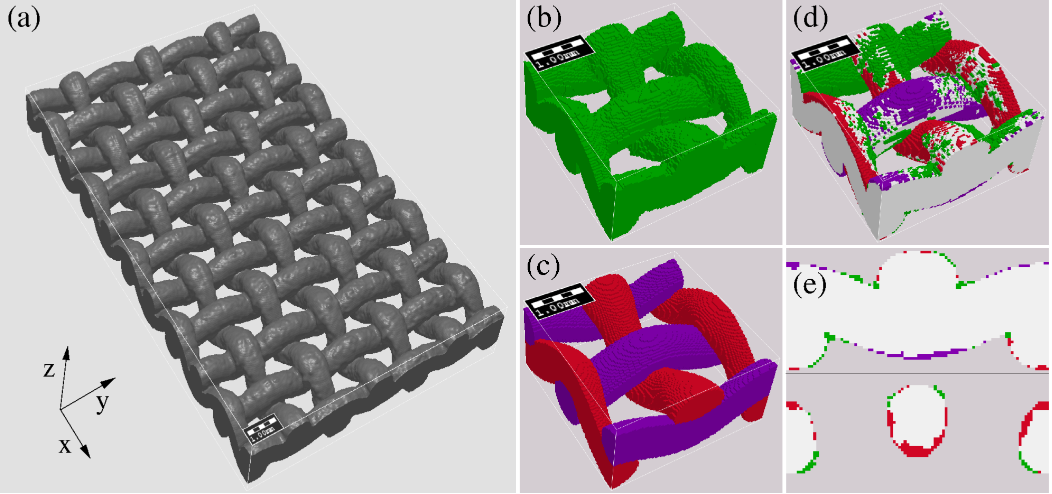

FIGURE 3. *Tomography of a metal wire plain weave and its comparison with a virtually generated structure. (a), (b): Tomography, where (b) shows one repetitive unit. (c): Virtually generated structure of a repetitive unit with* $w_{wa} = 745\ \mu m$, $w_{we} = 888\ \mu m$, $h_{wa} = h_{we} = 780\ \mu m$, $p_{wa} = p_{we} = 1703\ \mu m$, $c = 0.25$, $b_{wa} = 0.4$ *and* $o = 142\ \mu m$. *(d), (e): Comparison between the tomography and the generated structure, where (d) shows a* $3D$ *image and (e)* $2D$ *cross sections for* $x = 0\ \mu m$ *(front side) and a parallel cut for* $x = -710\ \mu m$.

weaves it is more realistic to describe the vertical wire position using quadratic functions. This is realized introducing the stiffness parameter s in the model. This parameter characterizes a continuous transition from the approximation of the wire position with straight line segments and sine functions ($s = 0$) to one with quadratic functions ($s = 1$). The twill 2/2 weave in Figure 2(c) illustrates the effects of the stiffness parameter and the crank factor.

Furthermore, a reduction of the maximal amplitude of the vertical wire oscillation is often observed. This phenomenon arises from a deformation of the weft and warp wires at their intersection points (see Figure 3). It is covered by the parameter o in the model. For the modeling 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 metal wire meshes in many cases.

4. GEOMETRIC VALIDATION

In this section tomographic images of metal wire meshes are studied. They were provided by the GKD - Gebr. Kufferath AG. The $3D$ geometries of the weaves can be studied using the GeoDict Software by importing the image with an appropriate threshold value. In this way the geometrical properties of the meshes are determined and virtual models of the structures are validated.

Figure 3(a) shows an example of a geometry that was obtained from a tomography of a metal wire plain 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 the $3D$ difference image and Figure 3 (e) shows $2D$ cuts from this $3D$ image. White indicates the part of the mesh that is present in both the tomography and the model. The other colors belong to voxels, which appear only in the model (red, violet) or only in the tomography

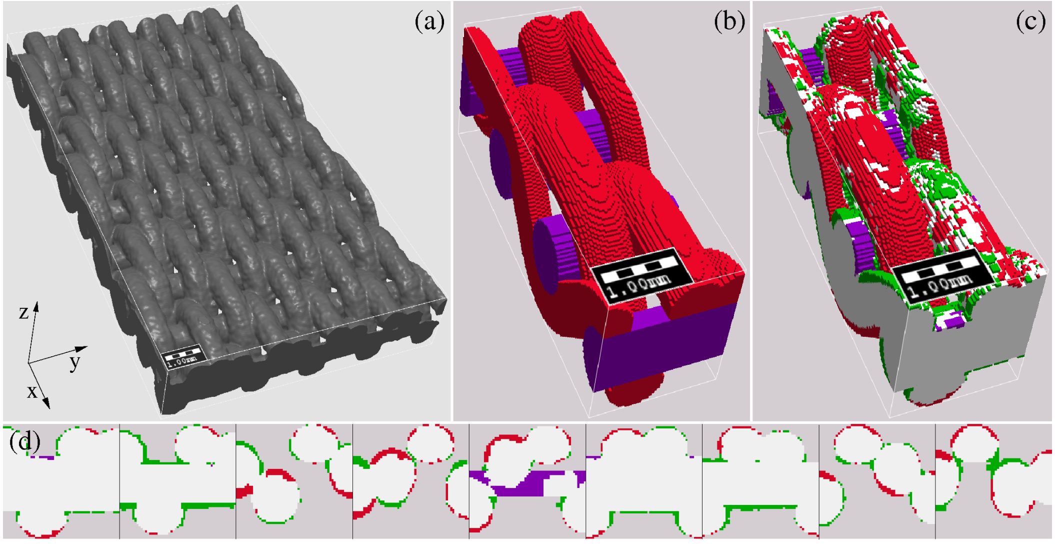

Figure 4. *Tomography of a metal Dutch twill* 2/1 *weave and its comparison with a virtually generated structure. (a): Tomography. (b): Virtually generated structure of a repetitive unit with* $w_{wa} = 798$ *µm*, $w_{we} = 922$ *µm*, $h_{wa} = 656$ *µm*, $h_{we} = 922$ *µm*, $p_{wa} = 656$ *µm*, $p_{we} = 1809$ *µm*, $c = 1$, $s = 0.1$ *and* $o = 195$ *µm. (c), (d): Comparison between the tomography and the generated structure, where (c) shows a* 3*D image and (d)* 2*D cross sections,* $x = 0$ *µm (front side) and parallel cuts at* $x = -354.7, -709.4, .., -2837.6$ *µm.*

(green). 15% of the voxels of the mesh are not white and not transparent, so the difference between the structures is approximately 15%.

In Figure 4 one sees the more complex Dutch twill 2/1 weave. The tomography is shown in Figure 4(a). Again we generated a virtual model of the structure from a repetitive unit of the geometry. It is plotted in Figure 4(b). Matching the structures as shown in Figure 4(c) and (d), one finds that the difference between them is approximately 10%.

The tomographic images make the difference between the virtual and the real weaves visible and quantifiable. The shape variations discussed in section 3 are based on detailed looks at these 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 two examples presented in this section and was checked using tomographic images of many more metal wire meshes.

5. Pressure drop

The following tools were used to compare GKD's laboratory measurements of real woven meshes with simulation results of the GeoDict software

- WeaveGeo for the generation of the mesh structures
- ProcessGeo to define inflow and outflow regions for the simulations
- FlowDict (LB [10]) for the calculation of the velocity-dependent pressure drop

The chosen meshes were manufactured by GKD and measured in GKD's laboratory. The required parameters are the pitch in warp and weft direction, the wire diameters (tolerances in accordance with DIN ISO 4782), the wire roundness and the ovalness, the crimping behavior and the stiffness of the wires. The measurements of the geometric parameters required for the modeling of the geometries with WeaveGeo were done with the precision of one micron. A computer tomography is not necessary to get these parameters.

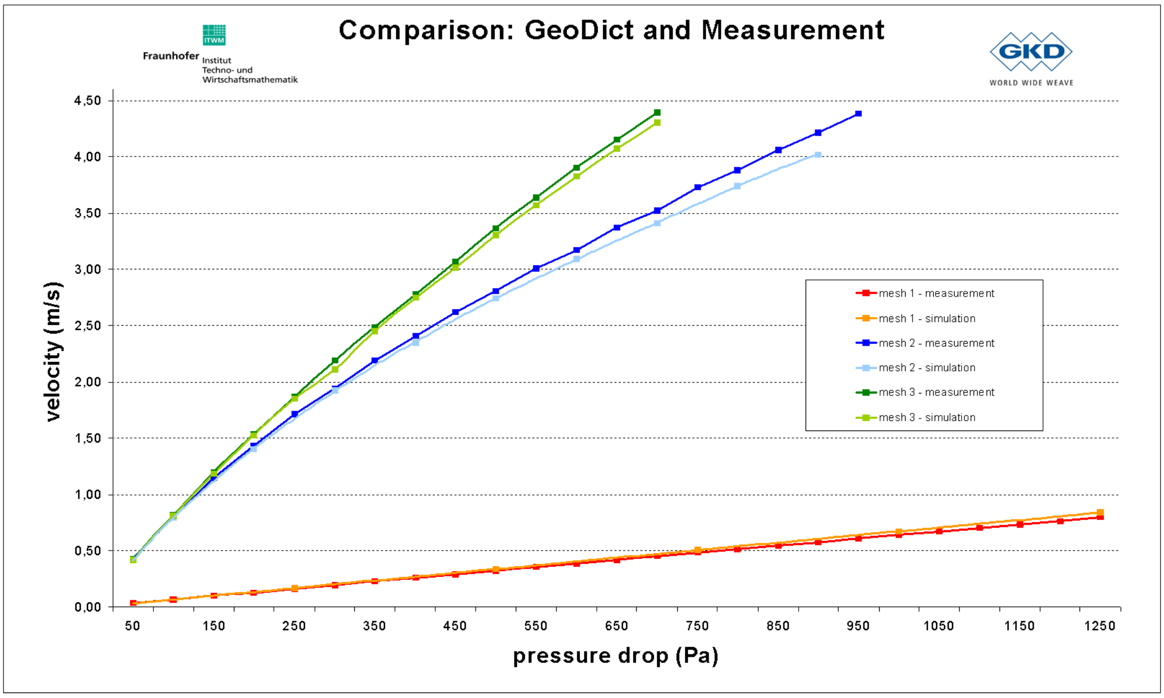

Figure 5. *Velocity-dependent pressure drop for three weave types. x-axis: The pressure difference in Pa. y-axis: The flow velocity in m/s.*

The measurement of the fluid velocity at a given pressure drop is performed with an air permeability tester (Textest FX 3300) according to EN ISO 9237. The pressure drop starts at 50 Pa and is increased in 50 Pa steps until the measurement range is achieved.

The measurement is compared with numerical simulations for three exemplary weaves. These are GKD's plain Dutch weave (mesh 1), PZ-microdur (mesh 2) and an optimized plain Dutch weave (mesh 3). The velocity-dependent pressure drop is displayed in Figure 5. The calculated values of the velocity for different pressure drops closely matches the measurements from GKD's laboratory. The discrepancy between the calculations with GeoDict and GKD's laboratory measurements is shown in table 1.

	Mesh 1	Mesh 2	Mesh 3
Average deviation	4.70%	-2.20%	-1.60%
Standard deviation	0.70%	0.81%	0.46%

Table 1. Deviation of the GeoDict simulations from the measurements.

The calculations with GeoDict provide reliable values. Similar calculations can be provided for mesh parameters like the maximum glass bead, the bubble point and the porosity.

The accuracy of the simulation results depends on the accuracy of the parameter measurements and the parameter tolerances, respectively. On the side of the software it is limited by the experience based parameter input of the geometry model. The GKD mesh production tolerances and wire tolerances are usually known so that the simulation of minimum and maximum values is possible.

6. Conclusions

The presented mathematical model provides virtual 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 measurements of corresponding real meshes. Both the structure generation and pressure drop simulation are implemented in the GeoDict software and thus accessible to all industrial and academic users.

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. It took GKD only 5 to 15 hours per mesh to calculate the series shown in Figure 5. GKD - Gebr. Kufferath AG uses the GeoDict software to develop and optimize customer designed woven meshes.

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