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Numerical Modeling of Liquid Filtration Process

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Abstract. This paper deals with a flow modeling of liquid medium through a filter represented by a fiber structure. The CAD geometry of a microfibrous filter is based on structure and morphology observations using the microtomography and electron microscopy. The CAD model is created as two-dimensional. In the numerical model that uses real fluids, flow velocities in the pores of the filter are monitored. In conclusion, the possibilities and limitations of the model, incl. suggestions to optimize the simulation of the fiber filtration process are discussed.

Introduction

The choice of an individual filter depends on the specification of the required separation, so the specific filters differ not only in the separation properties, but also in the structure. Therefore, it is important to find the relationship among structural parameters such as size and distributions of pores, porosity, filter media thickness and separation properties. Filter manufacturers usually do not have clear information about which parameter is best suited for the performance and efficiency of the filter for a specific application. Therefore, filter performance characterization requires modeling of the morphological and structural properties of the filter unit.

Theory

For a model establishing of the liquid media flow through pores in porous system different relationships can be used. For example, the equation (1) according to the Kozeny-Carman relationship can be used. The relation is used in the field of fluid dynamics to calculate the pressure loss of fluid flowing through a filter medium that the pores are replaced with slits.

$$\frac{\Delta p}{\Delta L} = \frac{150 \cdot \mu}{{\varphi_p}^2 {d_p}^2} \frac{(1-\varepsilon)^2}{\varepsilon^3} \cdot v \tag{1}$$

Where Δp is pressure drop, ΔL is filter thickness, φ_p a weight mean of flowing particles, d_p, v is superficial velocity, where from the continuity equation follows the relation for the mean particle velocity in the model capillary $v_p = v/\varepsilon$. In the curved model capillary apply $v_p = (v/\varepsilon) \cdot q$, where q the pore curvature factor that has a value for spherical particles $q = \sqrt{2}$. It is therefore apparent that the transport of substances (liquid and particles) in filter media depends on the properties of the flowing medium and the particular type of material, morphology and structure of the filter medium. For modelling it is important to be able to design and create geometry of the structural unit of the filter.

Experiment

A validation measurement was performed to determine the pressure drop and flow rate of the filter. A sleeve filter made of polypropylene with a declared pore size of 5 microns was used (Figure 1). The measurements were carried out on a filter line designed for this purpose (Figure 2). Measurement was carried out for different values of the flow and pressure drop was measured. The results are shown in the graph Fig. 3.

Fig. 1 and 2 Sleeve filter (left), filtration line (right)

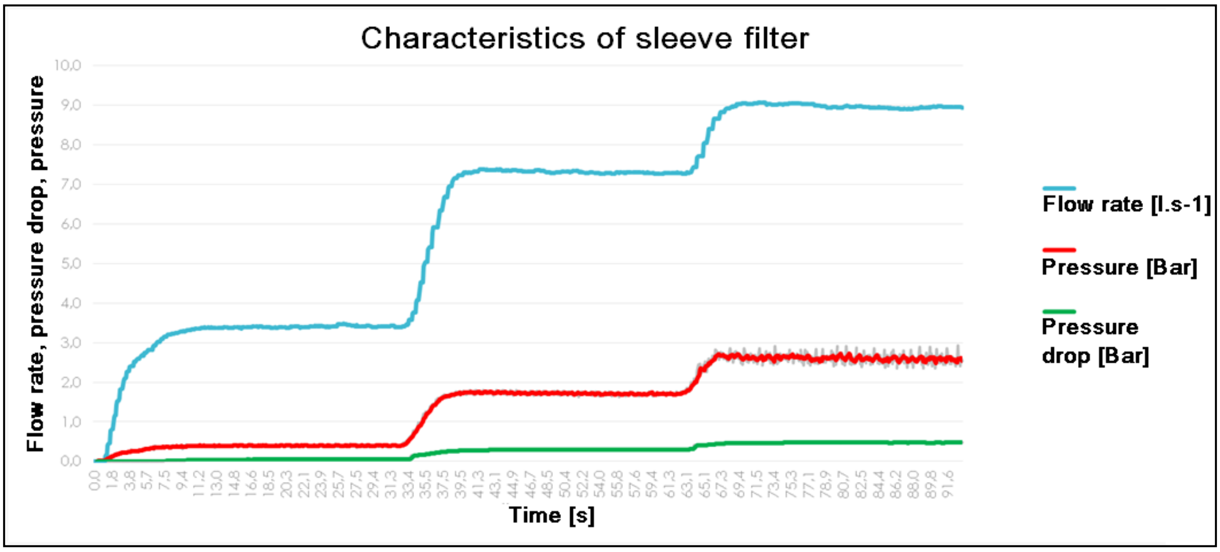


Fig. 3 Graph of filtration characteristics of the sleeve filter

From the pressure drop of the filter it is necessary to subtract the value of 0.02 MPa, which represents the pressure resistance of the filtering line. For the simulation were chosen values of the pressure gradient at a flow rate of 7.3 $l.s^{-1}$. The values applied in numerical model are put in tab. 1.

Tab. 1 Values applied in the model

Flow rate [$l.s^{-1}$]	Pressure drop [MPa]	Input pressure [MPa]
7,3	0,2 – 0,06	1,8

Establishing of the model

The design and creation of model geometry of the filter structural unit, which appropriately represents the layout of the given material structure, should be based on detailed visualization. For this purpose, a micro-computed tomography SKYSCAN 1272, using the X-ray principle, was used to capture the entire structure of the test sample. The picture of the filter structure from this device is put in Fig. 4.

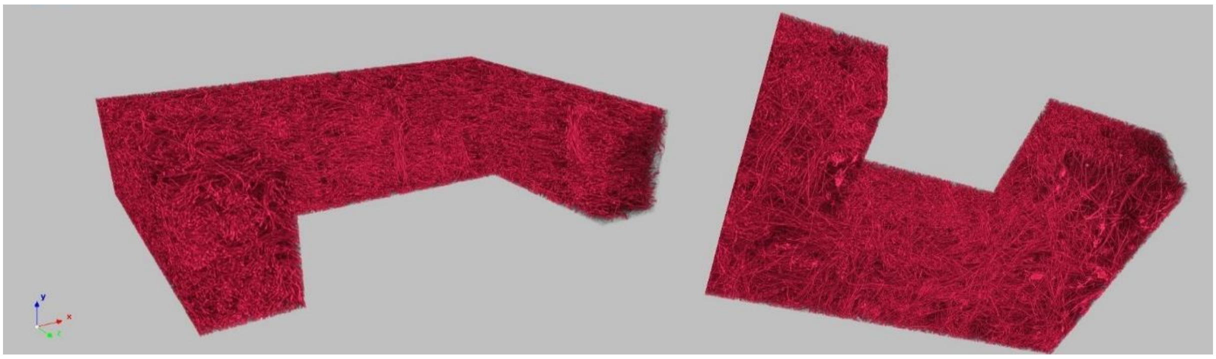
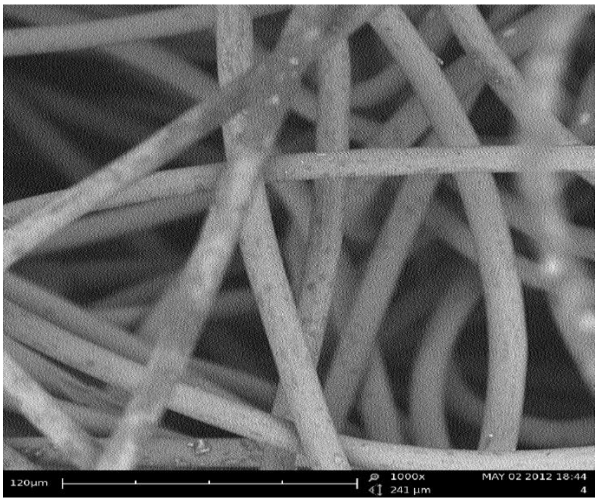


Fig. 4 The picture of fibrous filter taken by the microtomography

Electron microscopy was used to determine the morphology (Fig. 5). From these images, a 2D substrate in binary form (Fig. 6) can be obtained by image processing and used as a background for a CAD model of a structural unit of the filter media.



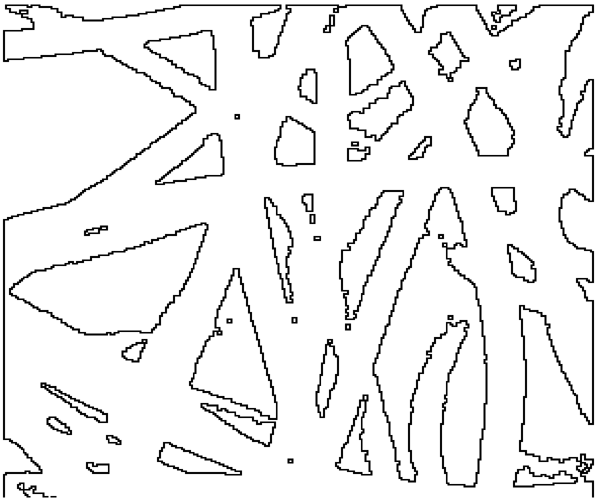


Fig. 5 and 6 SEM picture and its binary form

Based on the information about the geometry of the structure, morphology, configuration and type of fibers then can be modelled CAD model of structural units of the filter medium that can be consequently optimized. The CAD data prepared by this way can be already applied for complex model simulations of filtration media properties. The momentum equation of the fluid is described by the Navier-Stokes equation according to the relationship (2).

$$\rho(\boldsymbol{v} \cdot \nabla)\boldsymbol{v} = \nabla \cdot [-p\mathbf{I} + \mu(\boldsymbol{\nabla v} + \boldsymbol{\nabla v}^T)]. \tag{2}$$

Where **I** is identity matrix.

The geometry of a structural unit was based on CAD data. These data were based on image analysis. The material properties of the water and the fiber structure applied in numerical model were defined. To solve the equation (2) it is necessary to introduce initial and boundary conditions for space and time flow studies. The solution is to determine the boundary conditions from a known pressure distribution and velocities at different time levels. The initial conditions can be introduced in a stationary task as the initial temperature, T(x, 0) = T0 = 23 °C (initial ambient temperature) or in a non-stationary task as a function of temperature change over time. The boundary conditions enforcing a characteristic distribution of the flow through the filter media can be defined by input and output as shown in Fig. 7. The adaptive mesh refinement shows Fig. 8 and 9. The designed 2D mesh contained approximately 29077 elements.

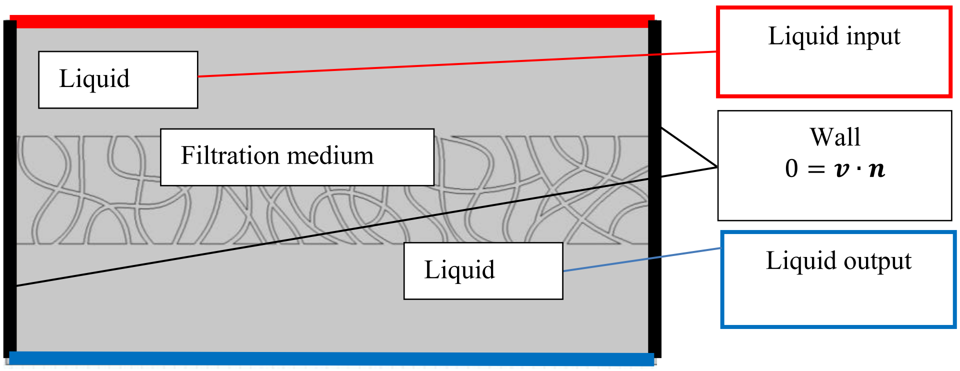


Fig. 7 Numerical model for analyzing the filter properties of the proposed media: defining of boundary conditions

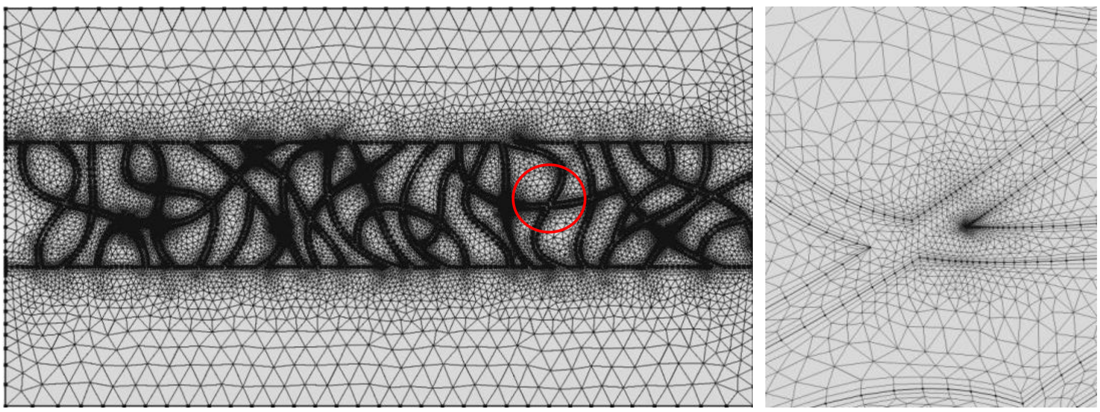


Fig. 8 and 9 Finite element mesh of the model geometry; a refiment of the mesh depends on dimension and a shape of locality

Results

From these results shown in Figures 10 and 11 it is clear that the flow of pure liquid is uneven in the individual pores of the designed filter media, because it is affected by the diameter and the curvature of the slits. It is evident that larger pore diameters and straighter slots will result in increased permeability. It is furthermore characteristic that some small pore diameters are poorly permeable compared to large pores, which is very well apparent on the model shown in Fig 10 and 11. This will at a minimum pressure$\mathbf{p_{min}} = \mathbf{2\gamma / r_{pmax}}$, where $\boldsymbol{\gamma}$ the surface tension is and $\mathbf{r_{pmax}}$ is the largest radius of the pores, that they will be impermeable. Therefore, for higher flow and small pore diameters, the operating pressure must be increased.

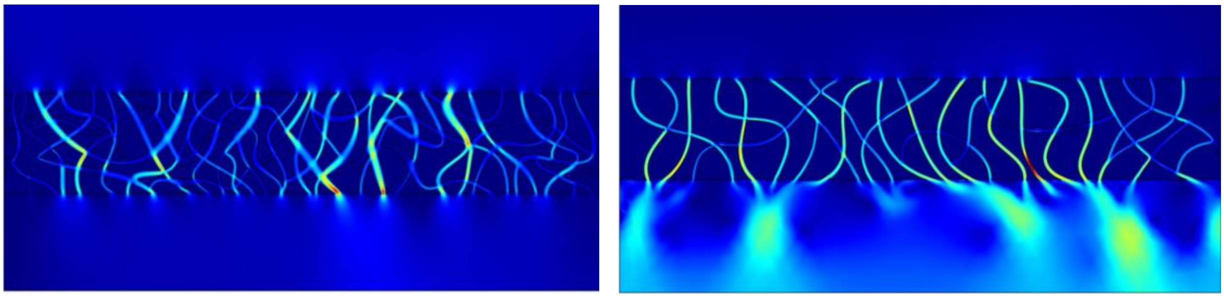


Fig. 10 and 11 The liquid flow under low and higher pressure

Conclusions

Fiber structures utilized for microfiltration do not contain pores of the same size, and therefore, the flow rate of the liquid through the filter media cannot be proportional to the increase of operating pressure. The total flow rate at a given pressure will be the sum of the contributions of all permeable pores. As mentioned above, this is a numerical model of the filter medium in two-dimensional form. This type of model can serve to better understand the processes that occur during filtration, and can also help to optimize the filter media as they allow determining the effect of the shape and the pore size of the filter media. In reality, however, these media are three-dimensional. As a result, it is impossible to obtain specific values of significant characteristics of filter media, including filtering efficiency and pressure drop. The reason is that the model does not respect the spatial shape of the pore, which in the 2D model represents only a planar projection. Information about the actual pore length, which has a significant effect on the filter characteristics due to the friction of the liquid on the pore walls, is lost. A partial solution could be a suitably introduced coefficient that would respect the length of the pores and the pressure loss and the filtering efficiency could then be determined with a certain degree of uncertainty. Thus a more appropriate model is three-dimensional. However, it is significantly more demanding on the number of elements, the quality of the mesh and the calculation time. However, it allows estimating of the pressure loss and filtering efficiency by introducing of filtered particles. Currently the authors develop such a type of the model.

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