FILTRATION PERFORMANCE SIMULATIONS BASED ON 3D STRUCTURAL DATA OF REAL FILTER MEDIA

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Abstract

The performance of a particle filter is primarily determined by its media. Today's filter media is a composition of different layers known as MULTIGRADE or MICROGRADE media. Selecting the right combination of layers requires a lot of experience. Recent progress now enables the simulation of complex structures to support the development by adding information about the media utilization. However, published results point out that the local inhomogeneity of the fiber structure plays an important role. Thus computer models have been developed to reproduce 3D fiber structures. But these 3D fiber structures are still simplified models, as they have just a few input parameters and do not account for the production process. But state-of-the-art simulation software, such as GeoDict, provides the opportunity to import 3D images of real fiber structures as initial geometry. Micro-tomography now promises to deliver this quantitative data about the real 3D fibrous structure. In this paper first results are presented, indicating that we extracted the true fibrous structure of a synthetic media by segmentation of the raw XCT data with the software MAVI. In contrast to other publications, the packing density of the media was not used as fitting factor, but obtained without a priori knowledge. The results discussed show a reasonably good agreement with measured data for packing density, fiber diameter distribution, initial pressure drop and initial efficiency. However, it is crucial to select a region of interest large enough to be representative.

Keywords: *filtration, filter media, XCT, simulation, fibrous structure*

1. Introduction

Today's request for lower CO_2 engine emissions demands for more advanced filters, particularly optimized for a given engine design. A key factor to meet the requested filtration efficiency and dust holding capacity is the filter media. Thereby the filter media is optimized by combining layers of different filtration properties to an advanced media, well known for example as MULTIGRADE or MICROGRADE media.

Traditionally cellulose based papers are used as fibrous filters. Thereby different woods offer various fiber sizes and shapes. Thus layers of different fiber diameters are combined into a gradient filter media offering better performance. Cellulose paper, however, is a natural product, with all its inherent fluctuation of properties and its limit of minimum fiber diameter. But synthetic media is a highly technical product, offering a lot of parameters to control product quality and properties, e.g. smaller fibers. Consequently, a trend is developing to add synthetic media to or on top of cellulose or even shifting to fully synthetic media.

Simulation now promises to be the enabling step for optimizing synthetic media. Testing a media sample just reports the macroscopic performance. Simulations based on 3D fiber structures, however, provide data of local media performance. Thus an optimization within one layer itself is possible. Consequently, there is often no noticeable change from one layer to another as properties slightly shift. This makes it difficult to generate a virtual structure similar to the real media as a baseline for optimization. More over it is questionable to apply classical filtration theory to such a gradient media, as it is based on a simplified porous model with average properties. A common approach is the Kuwabara cell for pressure drop calculation and 2D models of parallel single fibers for prediction efficiency. However, published results point out that the local inhomogeneity of the fiber structure plays an important role [1, 2]. Thus computer models have been developed to rebuild 3D fiber structures, such as GeoDict [3] and algorithms therein [4]. But these 3D fiber structures are still simplified models, as they just have a few input parameters and do not account for the production process. However, state-of-the-art simulation software, such as GeoDict [3], provides the opportunity to import 3D images of real fiber structures as initial geometry. Simulations of these 3D images then set the baseline for further improvements of performance. As the local 3D fibrous structure is known, a virtual media can be easily generated to locally optimize the filter media.

Recent progress in applying medical tomographic methods to technical products makes it now possible to investigate the 3D fibrous structure of filter media [5 - 7]. The detailed information about the 3D fibrous structure is then used as input for mesoscopic models [8] or for simulations based on spatial geometry of the fibers [9]. These research groups have also shown that the calculated values of initial pressure drop are in good agreement with experimental measurements [8, 9]. But initial pressure drop is only one performance parameter of a filter media. As it has to clean particles from fluids, the filtration performance is quite important as well. A comparison with measured data is still missing, partly because research groups at universities are more focused on loading kinetics than on initial efficiency.

In this paper, we present the first results from comparing initial pressure drop and initial efficiency predicted by simulations based on CT structures with measurement. The following chapters will describe the methodology of obtaining the 3D fibrous structures, present the simulation tools and boundary conditions, and finally discuss the results.

2. Methodology of obtaining 3D fibrous structures

This chapter will briefly describe the general procedure of obtaining information about the 3D fibrous structure of a real filter media by XCT. The results are 3D images consisting of voxels being either marked as containing fiber material or as being void. These images are the key input geometry for our simulations described in the next chapter.

The 3D XCT images of the fiber structure of a flat sheet were obtained by measurement with a SkyScan MicroCT 1172. The sample size was around 3 mm and the resolution was around 0.9 µm/pixel. For extracting the real 3D structure from the raw data, the commercial image processing software MAVI from the Fraunhofer Institute ITWM, Kaiserslautern, was used [10]. We first cropped the 3D data set to an image size later used for simulation. Then image segmentation steps were applied such as mean filter, binarization with Otsu's method, ultimate erosion and self-dual reconstruction. The great advantage of MAVI is that these steps do not require user input or a fitting factor. No prior media data is needed. The structure is recovered solely based on intrinsic information of the raw XCT image.

The question if these structures represent the real one will be discussed in the results chapter. One key comparison will be the fiber diameter distribution. It was derived from counting single fiber diameters based on SEM images of real filter media or based on cross sections of the reconstructed fiber structures. Before presentation of the results, we will briefly describe the tools used for flow simulation and particle filtration.

3. Simulation tools

This chapter will briefly describe how we obtained the initial pressure drop and the initial fractional efficiency. The key input is the 3D image of the structure with voxels marked as fibers or void space, enlarged by an inlet and outlet zone.

The FlowDict module of the commercial software suite GeoDict [11] is used to calculate an air permeability of the 3D fibrous structure. The software GeoDict is developed by another research group at the Fraunhofer ITWM, Kaiserslautern. As in our standard paper test, the permeability is determined at a given pressure drop of 200 Pa. At this pressure level, we can assume laminar and Stokes flow within the media. Consequently, the EJ Stokes Solver [12] was selected. The boundaries of the domain are periodic. Alternatively, a more accurate Lattice-Boltzmann solver [13] could be selected. But due to the huge penalty for memory and calculation time, we just kept this as an option. Domain size was selected in such a way that even a Lattice-Boltzmann simulation would fit into the memory of a typical Computer Aided Engineering (CAE) computer.

The particle filtration is simulated by FilterDict, another module of the commercial GeoDict suite. Based on a given flow field, it calculates particle tracks. Thereby 55 particles per surfel were injected at once, assuming that they do not affect each other. The particle capture at the fiber surface was modeled by our own proprietary User Defined Function (UDF), taking into account advanced physics of particle bounce and adhesion based on [14]. Good correlation to measurements has been demonstrated through the combination of GeoDict/FilterDict and our UDF results for oil filters [15]. Due to this correlation, we focused on particle filtration from oil at conditions replicating a Multi-Pass Efficiency test. Initial Efficiency during a Multi-Pass test of a flat sheet sample is derived from test data during minutes four through ten. The results of the simulation are presented and discussed in the next chapter.

4. Results and discussion

This chapter will briefly present and discuss the results of our investigation. A description of the selected filter media will be discussed first. Then a discussion of the fibrous structures extracted from the XCT-raw data follows. Third is a comparison of the packing density to measure data of flat sheet media. Next, fiber diameter analysis shows the similarity of real and extracted fibers. Then air permeabilities are compared to experimental data. Finally, the initial efficiency is illustrated and compared with data from the Multi-Pass test.

The filter media selected for this paper consists of synthetic fibers and has a gradient fibrous structure but the “two layers” cannot easily be separated. It is commonly used for liquid filters. However, this does not limit the results to liquid filtration, as the methods and simulation tools used are of general purpose and can be applied to other filter media as well.

XCT raw data of the synthetic media was obtained for a field of view of 3.4 x 1.6 x 1.7 mm^3. The resolution was 0.9 µm/voxel. In this paper, we confined ourselves to investigations of regions of interest as shown in fig. 1. Samples B1 and B4 were obtained by cropping the original 3D image to a size of 94 x 94 x 1375 µm^3 whereas B5 was cropped out of a structure B=B1+B2+B3+B4 after the segmentation. Furthermore, the size of the maximal samples B1 to B5 was limited by the memory consumption of the Lattice-Boltzmann solver to save the option of more accurate flow calculation.

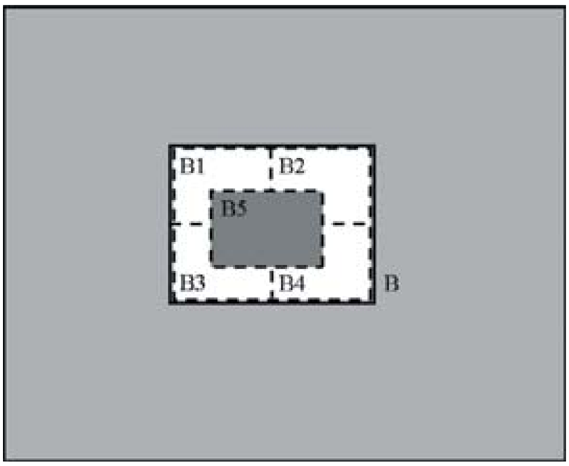

Fig. 1. Schematic illustration of the samples selected from the XCT raw data for further analysis

The fibrous structure of the samples B1 - B4 and B was extracted from the raw data by segmentation with the software MAVI; after segmentation of B image size was cropped to B5. Therefore no fitting factor or a priori knowledge about properties of the flat sheet media was necessary. As a typical example, the raw data and the processed image of B are shown in Fig. 2. The structure looks realistic and the fiber diameters change gradually, as expected. The other extracted structures are shown in Fig. 3. Obviously all structures belong to the same filter media.

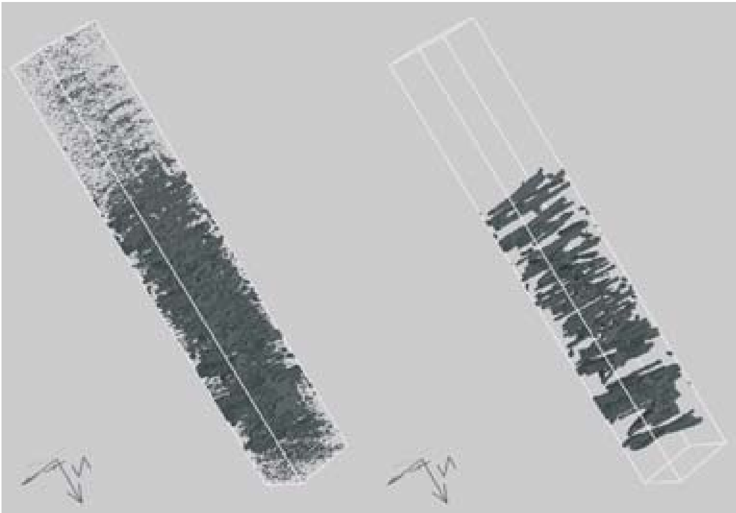

Fig. 2. 3.D image of sample B: the raw data (left) and fibrous structure after segmentation (right)

Calculation of the packing density of each sample (Tab. 1) and determination of the fiber diameter of Sample B was performed to determine whether fibrous structures B1 to B5 resembled the real flat sheet media. Considering that the local packing density within a media can vary by a factor of five, a relative error of less than 20% is quite good. Derivation of the packing density was solely from the intrinsic data of the XCT raw image. Thus, the segmentation worked well. Probability plots of the fiber diameters display the same slope as a bimodal distribution with good correlation between the values. A few missing small fibers of the B sample are cut off due to the resolution of 0.9 µm/voxel. Consequently, the samples B1 to B5, as a smaller part of B, are a true representation of the original flat sheet with regard to packing density and fiber diameter.

Tab. 1 Packing density of samples B1 - B5, and error compared to value of standard paper test of the flat sheet media

Sample	B1	B2	B3	B4	B5
packing density of sample in %	9.98	9.59	10.68	10.91	10.90
relative error in %	-15.8	-19.1	-9.9	-7.9	-8.0

The initial pressure drop of the sample B1 to B5 was calculated with FlowDict as part of the GeoDict software suite. The results are illustrated in Fig. 4. Despite the fact that the packing density is lower compared to the average of the real flat sheet media, the air permeability of all samples is below the range of measured values. The relative error ranges from about 20% to almost 50%. The approximate 10% error of the Stokes solver can not be the only reason. The artifacts by the periodic boundary conditions might cause the lower permeability, as fibers virtually move closer together at the fringes. This might not be negligible because of the very small domain size. Other simulations based on XCT data showed good correlation of pressure drop with measurements for larger inlet sizes of around 300 x 300 µm² [9] or even larger [8]. A low prediction of air permeability is not necessarily proof that the wrong structure was extracted but could indicate the need to analyze a larger domain size. Therefore, we added a simulation of the entire sample B. This simulation of predicted air permeability yielded a value that was lower than the measured average air permeability by less than 8%. This is another indicator that we have extracted the true fibrous structure of the filter media.

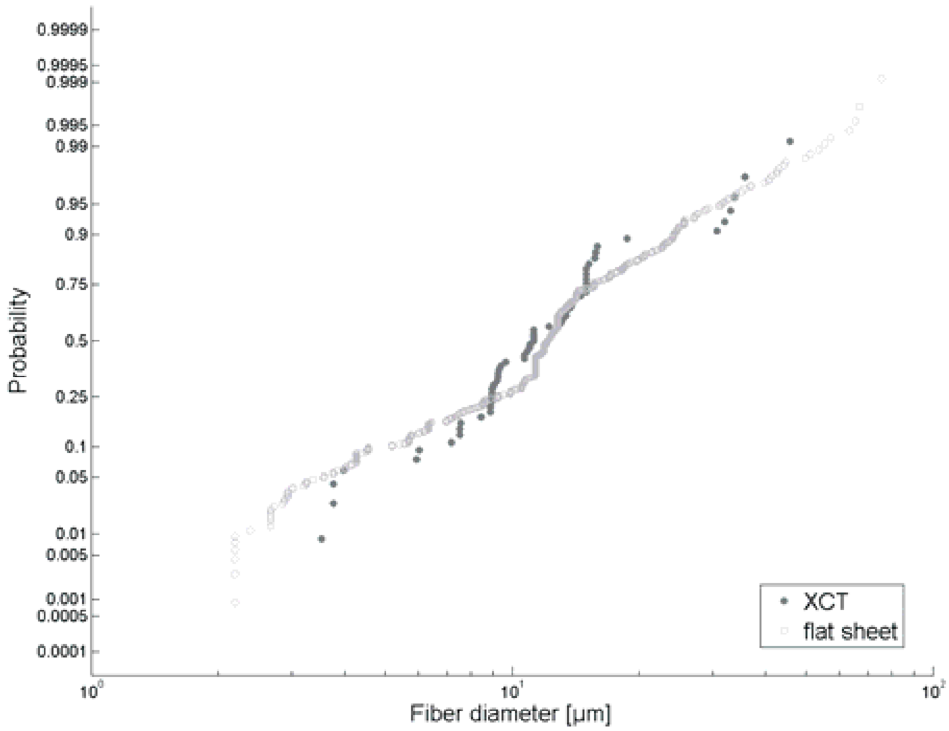

Fig. 3. Probability plot of fiber diameter distribution of flat sheet media and sample B

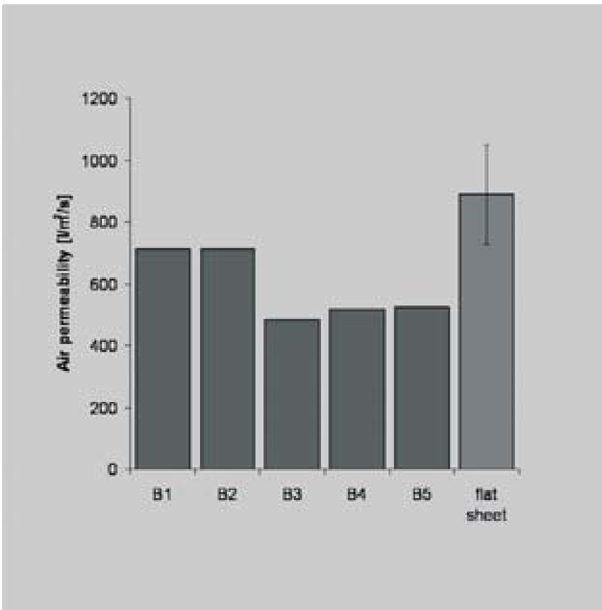

Fig. 4. Air permeability of samples B1 to B5 compared to test data of real flat sheet sample

Particle collection efficiency is another key performance factor of filter media. The initial efficiency of samples B1 to B5 and a larger sample B5* were calculated with FilterDict, which is another module of the GeoDict software suite. B5* is as sample B5 cut out of the sample B, located in the center of B but with longer edges. Fig. 5 illustrates the fractional efficiency of each sample compared to an initial efficiency derived from the Multi-Pass test of the flat sheet media (minutes 4 to 10).

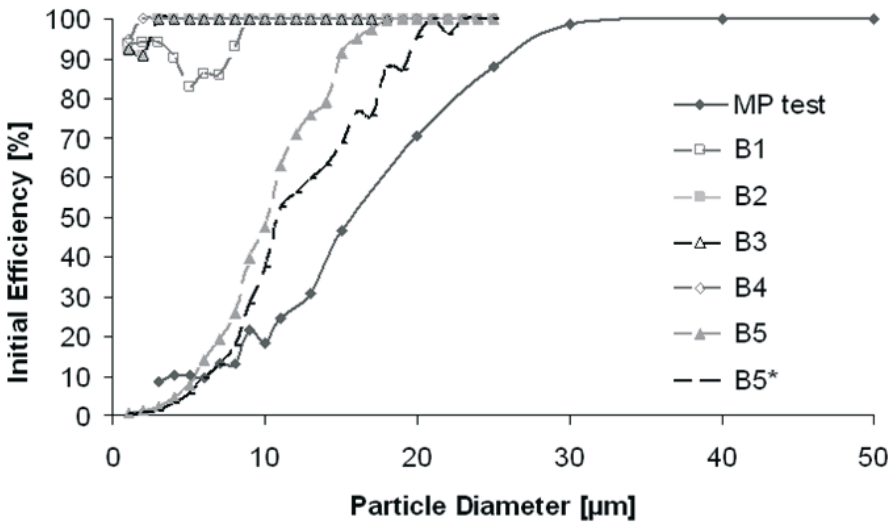

Fig. 5. Air permeability of samples B1 to B5 and a larger sample B5 compared to test data of real flat sheet sample*

Only the initial efficiency of samples B5 and B5* are close to the measured data. However, the efficiency is still too high. Initial efficiency for Samples B1 to B4 is too high due to some blockage of fibers at the top. This is not uncommon for fibrous media where fibers are locally closer together and where fibers are locally more wide spread. This inhomogeneity is a topic of ongoing research for years. In our case, it also explains the too high efficiency of sample B5. For the real media, the flow is forced to pass through regions with more open fiber structures, such as sample B5, because regions such as samples B1 to B4 are soon blocked by collecting particles. Thus, the flow velocity of sample B5 is in reality higher. This would shift the fractional efficiency slope closer to the measurements. Therefore, we calculated the initial efficiency of a larger centered sample B5*. As expected the result shows a better agreement with the Multi-Pass test data. This further supports that the extracted fibrous structures resemble the true structure of the original filter media.

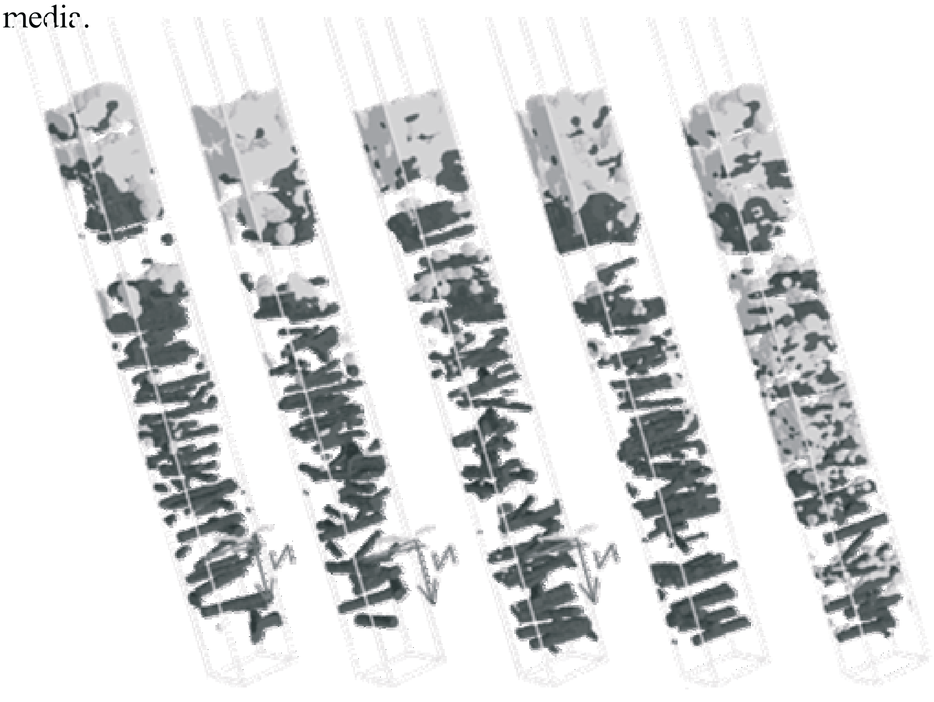

Fig. 6. Locations where particles are initially collected (light) within the fiber structure (dark) of B1 to B5, if 55 particles per surfel are injected at once without affecting each others track

5. Conclusion

Today's advanced filter media consists of multiple layers. The often gradient structure makes it a challenge to generate virtual structures just based on macroscopic test data of flat sheet samples. Micro-X-ray tomography now offers 3D images of the fibrous media. In this paper we have shown, that by selecting the right segmentation and domain size we obtain a fiber structure with similar properties and performance as the flat sheet sample. Not only packing density and initial pressure drop - as known before –, but also fiber diameter size distribution and initial efficiency display reasonable correlation to measured data. Consequently, the true fiber structure has been reconstructed without the need of a priori knowledge of the filter media or a fitting factor.

Revealing the true fiber structure from XCT raw images now enables us to simulate the local performance of gradient filter media as a baseline performance and to add or replace parts by virtual structures for further optimization. However, testing will stay important, as still only very small sample sizes can be modeled in the computer. Nevertheless, the starting point for virtually developing more advanced filter media that meets tomorrow's performance requests is now set.

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