A study into representative domain size for microstructure simulations of oil filter media and the modelling of non-spherical particles

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The microstructure simulation of filter media is becoming an increasingly important tool in virtual media development. Faster computers and larger memories now make it possible to simulate fiber geometry beyond the recommended domain sizes. The question as to whether or not it is at all possible to perform a simulation is therefore no longer a common one. More current questions include: (1) Is the domain size you are using representative? (2) How can modeling the particles as spheres make a difference? Since both questions are closely related, we will first illustrate why the shape of the particles needs to be considered. Then we will ascertain the representative domain size for a filter medium using the improved method. The results will demonstrate that the new method of deriving the domain size from the largest pore measurement will yield a sufficiently large domain size.

Introduction

Although one may not immediately associate filtration with motor vehicles, the process is essential for their performance. Vehicles are fitted with various filter elements and stringent requirements are placed on filter technology and, in particular, filter media (3). Over the last few years, virtual media development software has gone from being a mere academic tool (4)(5) to becoming an increasingly industrialized application, e.g. (6). What has not changed is that the continuous filtration process is generally split into two alternating phases for the purposes of simulation. These are the flow field calculation and particle tracking. The flow field calculation takes separated particles into account; however particles which have not been separated do not affect the flow field. This simplified Euler-Lagrange approach usually considers the particles as spheres and tracks them by their center of mass.

It is known, however, that particles of the ISO medium test dust used for oil filtration testing should ideally not be considered as spherical. Some studies have defined a shape factor for these particles (7). However, a projected surface area is still used in simulations to model the particles as spheres with equal surface areas and it is evident that liquid filtration results are affected by particles with non-spherical shapes. Since in liquid filtration adhesive force is less than in air filtration, the particles do not remain in the same position once they come into contact with the filter medium fibers. The particles continue to move and may change their alignment. It is thus possible for seemingly large particles to pass through the filter medium (Fig. 1). It is therefore necessary to model this effect if a good correlation with the measured data is to be attained.

The accuracy of the simulation is also determined by the selected resolution or domain size. A high resolution is required to illustrate the physical geometry. A large

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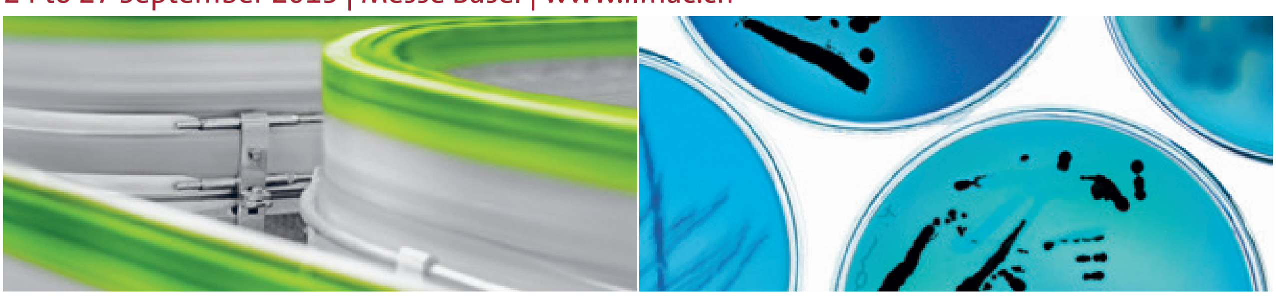

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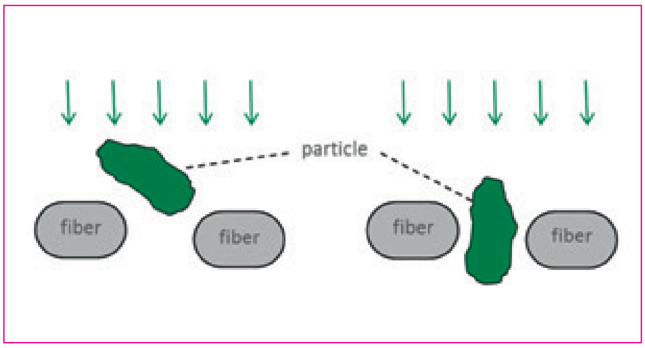

Fig. 1: Diagram showing the passage of non-spherical particles through a fiber structure

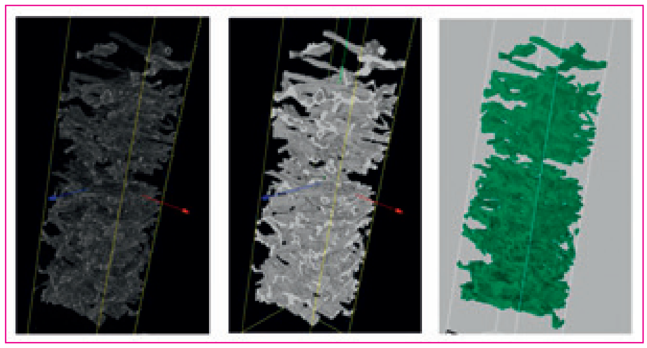
Fig. 2: Example of a 3D fiber structure (from left to right) Raw data from the XCT image, segmented fiber structure in MAVI, fibers imported as voxels in GeoDict.

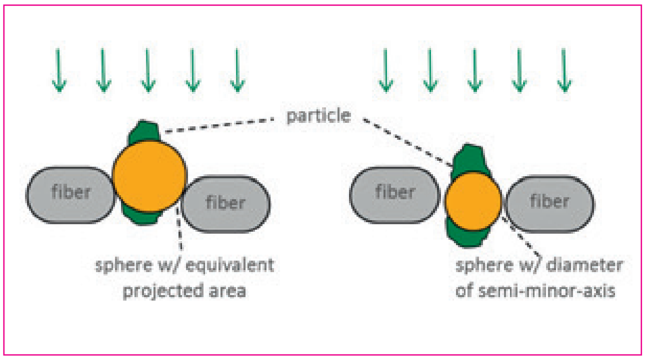

Fig. 3: How the choice of characteristic diameter determines filtration

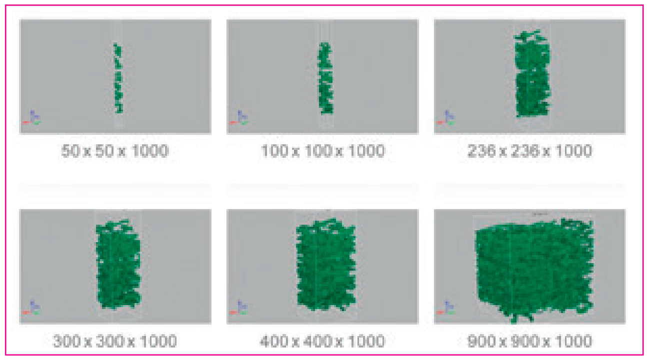

Fig. 4: Fiber structure image for different domain sizes (Resolution: 1 voxel = 1 µm)

domain size offers more representative results. In the early stages of virtual media development, the choice of domain size was limited solely by the amount of available memory, e.g. 16 GB in 2006. However, current work stations often have a memory exceeding 96 GB, thus enabling us to conduct further studies into the domain size of fiber structures.

When selecting the resolution, one may refer to the recommendations made by the software manufacturer (8) or to publications which detail the minimum resolution required to calculate pressure drop or separation efficiency (9). The domain size, however, often used to be set in accordance with the amount of available memory. A larger domain usually means longer runtimes. In order to reduce development time and development costs, it is therefore desirable to perform calculations based on the smallest possible domain sizes. It is therefore necessary to find a calculation model for deriving a representative domain size for filter media.

The domain size set out in publications is usually an assumed value. If discussed at all, it is assumed that the domain size should be set at 14 times the Brinkman screening length (9), (10). The referenced source (11) states that the Brinkman screening length is a measure for the decay of disturbance behind a single fiber and therefore values of 6 to 20 times the Brinkman screening length should be selected for the calculation cells. However, we could not find any specific recommendation regarding domain size.

Some time ago, we therefore started our own study into domain size. We took different sized extracts from XCT images of a real fiber structure and calculated both pressure drop and separation. To do this, we used the commercial software GeoDict. The preliminary research (12) (13) revealed that a domain size set at 14 times the Brinkman screening length was too small for the filter media we were using.

The Brinkman screening length (or the square root of permeability) is the term generally used to describe a length scale that is representative of the effective pore diameter (14). It was therefore logical to compare the effective pore diameter of a homogeneous porous medium with the pore size distribution of a filter medium. The pore size distribution is derived from the bubble test. The largest pore is significantly larger than the Brinkman screening length. Hiel (13) therefore suggests that the size of the largest pore should also be taken into account when calculating the domain size. During his research, he came to the conclusion that a representative domain size can be derived from the greater of the Brinkman screening length and 55% of the largest pore radius. We have slightly corrected his formula and rearranged it as follows:

$$B = f_{Br} {*} \left(\max\left(\sqrt{k}; 0{,}55 * \frac{d_{Pore,\,max}}{2} \right) \right) \quad \text{where } f_{Br} = 14 \tag{1}$$

Where B is the edge length of the domain with a known media thickness, f_{BR} is the commonly used factor 14, k is the permeability in m^2 and $d_{Pore,\,max}$ is the diameter of the largest pore in m.

This study demonstrates how to model particles with a non-spherical shape. It also illustrates the effect the domain size has on pressure drop as well as the separation calculated using the improved method. Furthermore, the study tests the new method used for calculating a representative domain size. The fiber structure of a real filter medium is used in order to evaluate the simulation results.

Determining the fiber structure

A key objective of virtual media development is to replace existing media with enhanced media, which are optimized to suit the relevant application. The first step is to acquire a real filter medium. The fiber structure is usually determined by taking XCT images which are then processed. When investigating domain size, it is also beneficial to use the fiber structure of a typical filter medium which has actually been produced. Since production effects are inherent in the fiber structure, this method can determine a domain size which not only satisfies the theoretical composition of an ideal fiber structure, but can also be applied to filter media in practical use.

We initially took a XCT image of a filter medium which was made of cellulose fibers and used in lubrication oil filtration. The resolution was selected in such a way that the smallest fiber is represented by at least five voxels over its diameter. This is the same as the recommended resolution for subsequent pressure drop simulations (8). The MAVI software was then used to segment the fiber structure (15) and import it into GeoDict (Fig. 2).

We then checked whether the fiber structure characteristics matched the measured data for the filter medium. Both the packing density and the fiber diameter distribution showed a good correlation (15). This confirms that the structure of the actual fiber has been ascertained.

Modelling non-spherical particles

Particles are often considered spherical for the purposes of particle measurement and simulation. If the particle diameter is determined based on the projected surface (i.e. using the same method as for particle measurement), the separation efficiency is overestimated (Fig. 3). When simulating particles, they must be modeled as smaller spheres in order to obtain the actual separation efficiency. This smaller diameter is calculated based on the shape factor associated with the dust. This new way of modeling particle shapes was applied to perform the following particle separation calculations. The adhesive forces which are present in oil filtration were also implemented using a User Defined Function (UDF) in GeoDict (6).

Study into domain size

To investigate the domain size, different sized extracts were cut from the actual fiber structure (Fig. 4). The common calculation model, based on the Brinkman screening length, was applied to determine the smallest size. The maximum size was limited by the 96 GB memory. The media thickness had to be the same in all cases because we wanted to compare the simulation results against the measured data for pressure drop and separation efficiency. The only variation was the edge length of the quadratic cross-section.

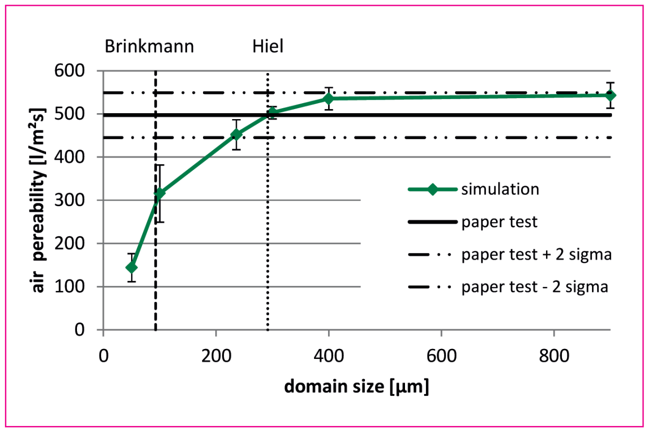

Fig. 5 – Initial pressure drop – simulations for various domain sizes compared to the target range of twice the standard deviation from the measurement results (DIN EN ISO 9237) (••• new formula)

Results

The permeability was calculated using the FlowDict module and the EJ flow solver from GeoDict version 2010R2. The permeability accuracy was set to 0.001. Based on the permeability derived from the paper test, the smallest domain size was determined to have an edge length of 93 µm. We simulated domain sizes ranging from 50 µm to 900 µm. To do this, we cut extracts of the appropri-

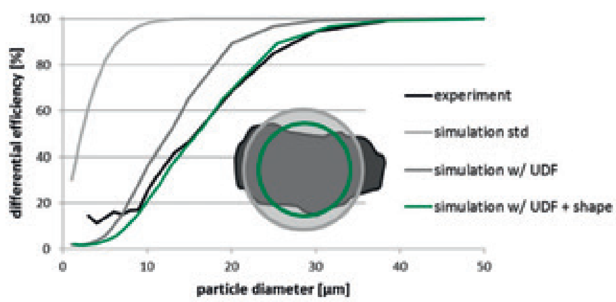

Fig. 6: Comparison of different separation efficiency calculations with measured data

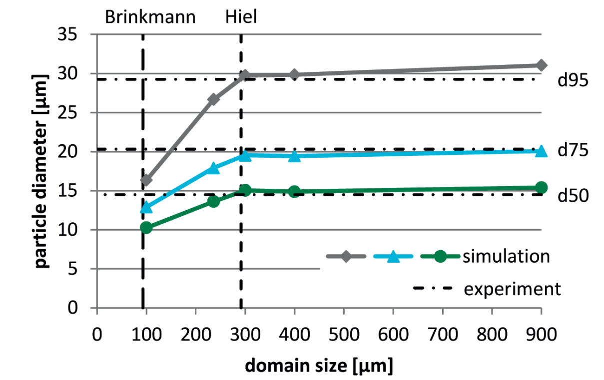

Fig. 7: Comparing measured data with simulation results for particle sizes, with the separation efficiency set in accordance with the domain size

ate size from various areas of the fiber structure. During this process we made sure that a smaller structure was always a subset of a larger one. The simulation results were compared with measurements in accordance with DIN EN ISO 9237 (Fig. 6). Since measured data also fluctuates during tests, we set a target range for representative domain sizes, allowing for twice the standard deviation from the measured permeability.

It is evident that the previously recommended domain size is too small for the filter medium studied in this case. The results only fall within the permitted target range when the edge length is at least 300 µm. This corresponds to the domain size calculated using the new formula (the dotted line in the diagram).

The initial separation efficiency was calculated using the FilterDict module from GeoDict version 2010R2. The input parameters were derived from the multi-pass test in accordance with ISO 4548-12; the volume flow was set at 2.3 l/min. To simplify the real measuring process, 500,000 particles were injected together in one batch. In addition to the UDF which had been used in previous simulations to enhance the modeling of particle adhesion, we also modeled spherical particles with a reduced diameter in order to compensate for their unideal shape. Fig. 6 shows the improvement this made. The mean value derived from the separation efficiency between the fourth and tenth minute of the multi-pass test was set as a benchmark.

The influence the domain size has on separation efficiency was examined using the same structures as those used when examining the initial pressure loss. To simplify the presentation of the results (Fig. 7), particle diameters are only shown if at least 50%, 75% or 95% of those particles are separated in the relevant structure. The particle sizes associated with the filtration medium and their respective separation efficiencies are indicated by a dotted line. It is once again evident that the previously recommended domain size is too small. The characteristic particle size barely changes when the edge length exceeds 300 µm. Unlike the initial pressure drop, smaller domain sizes may be sufficient for particle filtration. In each case, the new recommended formula is used to determine a domain size which achieves representative simulation results.

Summary

We have generally demonstrated that the modeling of non-spherical particle shapes has a significant bearing on particle separation. If the shape factor is applied to set a smaller diameter during the simulation, the simulation correlates very well with the measured data.

Our study into the domain size for a real oil filter medium has demonstrated that the previously used formula (14 x the square root of permeability) will yield a domain size which is far too small. At the same time we have demonstrated that very large domain sizes extend runtimes, yet yield results which are hardly any more positive. When we applied the new recommended formula and derived the domain size from the size of the largest pore, the simulation results for both initial pressure drop and initial separation efficiency did fall within the range which one would expect given the test readings. A representative domain size can therefore be derived from the new formula. This means future simulations for virtual media development can be performed faster since the domain size is no longer chiefly determined by the size of the memory and a smaller, more practical value can now be derived.

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