Determination of Pressure Drop and Filtration Efficiency of Filled Nanofiber Based Filters by using 3D Filtration Model

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Abstract: In this work, two different boundary conditions dealing with the filter cake formation due to particle-particle interaction (fully sticking and slip conditions) has been tested in a theoretical study. Filtration efficiency and pressure drop are evaluated utilizing realistic SEM image based 3D structure model, transition/free molecular flow regime, Brownian diffusion, particle-fiber interactions, aerodynamic slip and sieve. It has been found that the filtration efficiency of the fully sticking condition is higher than when particle slip was allowed. The pressure drop shows the opposite trends. Additionally, visualisations of the cake formation were created and has revealed that the cake is double in size and less dense in case of full sticking conditions.

Key-Words: Cake formation, Nanofiber Based Filter, 3D Filtration Modeling

1 Introduction
Nanofibers based nonwovens are widely applied in different areas such as filter media, tissue engineering, personal protective clothing, cosmetic skin care, life science, nanosensors and other medical and industrial applications [1-6]. Filter media is one of the largest application group of nanofiber nonwovens due to their small fibers (having fiber diameter typically in order of tens and hundreds of nanometers), high surface area (which significantly increases their filtration efficiency), and low filtration pressure drop (due to aerodynamic slip occurrence at the nanofiber surfaces). Until now, numerous studies were done to get a better understanding in the filtration mechanism. Therefore experimental studies [7-8] as well as theoretical studies [9-14] on clean and filled filters have been done. This work will focus on cake formation due to particle-particle interactions during the filtration process. In several studies dealing with cake formation the fully sticking boundary condition has been used which has been experimentally proved for certain test conditions for particle sizes between 10 nm and 5 µm [15-16]. This assumption has been used in other cake forming investigation studies. On the other hand there are also more advanced theories were particle chains are dynamic and are able to bend or break [19]. Therefore, in this work a theoretical comparison between two different boundary conditions for particle-particle interactions applied on nanofiber based filters penetrated by ultra-fine particles will be examined. To full fill this aim, a 3D filter media model has been created and the filtration efficiency and pressure drop methodology has been suggested and used to simulate air filtration considering both suggested boundary conditions.

2 Filter Media Model Creation
In this work the methodology proposed in our previous work [20] has been applied to create a 3D filter media model. This methodology utilizes a SEM top view image of the nanofiber based filter to build up the model. Here, the nanofiber based filter prepared by electrospinning is used, see Fig. 1. This grayscale SEM image has been transformed to a black/white image by applying a proper threshold level. In the following step the centerlines have been calculated from this binary image and a single three dimensional layer has been created by fitting spheres in the fiber area with as centerpoint a point
of the centreline. In the final step these single layers have been combined to reach the complete 3D model according the experimentally defined mass area of the filter. A perspective view of the used filtration media model in this work is depicted in Fig. 2.

![SEM image of a nanofibers nonwoven based filter prepared by electrospinning process.](image1)

![Utilized 3D model of the filtration media.](image2)

3 Filtration Process Simulation

3.1 Flow Field Calculation

In this work, the filtration efficiency is predicted by tracing each individual particle inside the nanofiber structure considering small fiber diameters/particles and low pressure drops. In such case, the gas flow field can be assumed to be uniform due to significant slip flow occurrence at the fiber surface as suggested by Maze et al. [13]. In the utilized filtration model, the Brownian motion is the driven force of the particle movement and has been calculated with the equations defined by Maze et al. [13].

3.2 Fiber-Particle Interaction

When a fiber-particle interaction occurs during the flow, the stick or slip at the fiber surface is defined by the force balance developed in our previous work [11] based on the force balance suggested by J. Altmann and S. Ripperger [22]. This force balance takes the drag force, lift force, van der Waals force and friction force between fiber and particle into account. It is assumed here that the flow through the particular pore between the fibers can be viewed as the Poiseuille flow in a 2D duct, which is characterized by its gap distance and height. Due to the aero-dynamic slip created by the thin fibers the gas viscosity has been corrected at high Knudsen numbers ($Kn>0.01$). In order to calculate this corrected viscosity the viscosity definition proposed by M.J. McNenly et al. [23] has been used in our filtration model.

3.3 Particle-Particle Interaction

In order to investigate the possible differences in cake formation due to particle-particle interaction in static and dynamic conditions, two different boundary conditions has been proposed and tested. The first assumption, which is generally used [15-18], takes no particle-particle slip into account. This means that fully sticking conditions between particles will be applied as illustrated in Fig 3a. In this case the buildup chains will be seen as static, which means that they cannot bend or break down during the filtration process.

In the second assumption, slip around the particle is allowed to simulate the dynamic like character of the particle-particle interaction. Therefore it is assumed that a particle can slip over another particle until two connection points (between particle-particle or particle-fiber) has been reached. In Fig 3b, the situation is shown where a first particle is touched to the fiber surface and a second particle slips over it until an extra touching point with the fiber is obtained. The next particle slips over the previous until the condition of two touching points, in this case a particle, is fulfilled. It has to be mentioned that the particles are slipping over each other in a plane defined by the touching point and the vertically aligned centerline though the particle.
In order to evaluate the pressure drop during the filtration process over a filled filter a novel technique has been proposed in this work. This methodology utilizing the generated 3D model for pressure drop calculation, which is depicted in Fig. 2. To define the overall pressure drop through the structure the model has been divided in numerous thin layers with equal thickness as illustrated in Fig. 4a. From all this thin layers the pressure drop has been calculated with the main assumption that the air flow is based on the pore size normalization with respect to the largest in this single layer. In order to evaluate the biggest pore the Euclidian distance map of a single binary layer (see Fig. 4b.) has been used. In a distance map, all black pixels (representing a pore) are labelled with a number (visualized by a grayscale value) which gives the shortest distance to a white pixel (representing a fiber) as illustrated in Fig. 4c. The maximum found value in the obtained distance map has been used as maximum pore radius used in the basic equation to calculate the pressure drop over a circular capillary, expressed as:

$$\Delta p = \frac{Q \cdot 2 \eta' L}{\pi \cdot 0.25 R^4}$$  

Eq. 1

where $Q$ is the volume flow rate of the air through the filter, $L$ is the height of a single slice, $R$ is the radius of the representative pore and $\eta'$ is the Knudsen number dependent gas viscosity defined by McNenly et al. [23] as

$$\eta' = \eta \left[ a_0 + a_1 \arctan(a_2 K_p^2) \right]$$  

Eq. 2

where $\eta$ is the gas viscosity at given pressure and temperature, $a_0 = 1.066$, $a_1 = 0.679$, $a_2 = -2.082$, $a_3 = 0.866$. $K_p$ is particle based Knudsen number defined as $2\lambda/d_p$, where $\lambda$ is the mean free path of molecules and $d_p$ is particle diameter. The sum of all pressure drops calculated according the previous described calculation for every slice of the model will result in the overall pressure drop over the filter model.

This methodology has been verified for four different nanofiber based filters produced from a polyurethane solution by electrospinning and it has been found that the suggested methodology is able to capture the trends in a good way with a certain over-prediction as shown in the bar plot in Fig. 5.

In this work this suggested technique will be used to calculate the pressure drop over filled filter structures for one filter type during the filtration process.

**Fig. 3: Two boundary conditions descriptions; a. Single touching point, b. Double touching points**

**Fig. 4: Pressure drop calculation based on slices of the fiber media model and creation of the distance map**
5 Theoretical Study and Discussion

In this part of the work, two above-described possible particle-particle boundary definitions will be evaluated and tested with respect to the filtration efficiency and pressure drop predictions during the cake formation on top of the nanofiber based filter. Therefore, a filter model has been built up based on the SEM image depicted in Fig. 1 as described before (see Fig. 2). In the next step an experimentally determined particle distribution given in Table 1 of 50000 particles has been randomly penetrated through the model considering both types of boundary conditions. Hereby the filtration efficiency and the pressure drop during the simulation for both considered boundary conditions have been visualized in Fig 6.

Table 1: Experimentally defined particle distribution.

<table>
<thead>
<tr>
<th>Particle Size [nm]</th>
<th>Fraction [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.35%</td>
</tr>
<tr>
<td>35</td>
<td>10.08%</td>
</tr>
<tr>
<td>50</td>
<td>24.83%</td>
</tr>
<tr>
<td>70</td>
<td>31.25%</td>
</tr>
<tr>
<td>100</td>
<td>20.27%</td>
</tr>
<tr>
<td>140</td>
<td>9.69%</td>
</tr>
<tr>
<td>200</td>
<td>2.90%</td>
</tr>
<tr>
<td>280</td>
<td>0.59%</td>
</tr>
<tr>
<td>400</td>
<td>0.06%</td>
</tr>
</tbody>
</table>

From this graph it can be seen that the filtration efficiency in the case of the full stick between the particles will increase faster than in case of the slip over the particles is allowed. This can be explained by the fact that the cake growing rate will be more pronounced in the first case. Moreover it has been found that the pressure drop is higher in the case of two touching points has been required. Due to this allowed slip the particle will penetrate deeper in the structure and the pore size will decrease, which will result in a higher pressure drop. The steeper increase located at a higher mass area, shows that at this load level the structure get satisfied with particles which lead to a pressure increase. This is not the case when single stick has been used. In this case a linear increase in the pressure drop is obtained.

Fig. 6: Filtration efficiency and pressure drop as a function of mass area for both boundary conditions.

In order to visualize the differences in the cake formation, the simulated structures with the build up cakes is shown in Fig.7, in perspective, side and cut top view. In these visual represented simulation results, it can clearly be seen that the cake height is approximately double in high for the single contact point condition. Moreover it can be seen that less particles can penetrate deep in the structure when fully stick condition is applied which explains the better filtration efficiency. From the cut view, which has been made just above the upper fiber, can be seen that the cake is much denser in the case of two touching points which obviously leads to higher pressure drops as shown before.
6 Conclusion

In this work a three dimensional nanofiber nonwoven filter media model has been created based on a SEM image. A theoretical study of the cake formation due to particle-particle interactions has been done for two different boundary conditions (no slip and slip). In this study it has been found that in case of full particle-particle interaction (no slip) the efficiency is higher while the pressure drop is lower in comparison with the case when particle slip is allowed. Additionally, a visual representation of the cake formations for both cases has revealed that the cake height is double for no slip condition in comparison with the particle-particle slip condition.

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References:


