Modeling the separation performance of depth filter considering tomographic data

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Abstract
Fibrous depth filters are frequently used for the purification of gas streams with low dust loadings, as well as processes where a high initial filtration efficiency is required (e.g., clean rooms for aseptic production). One tool suitable for supporting the development of optimized filter media is the use of numerical simulations. The drawback of this technique is the high computational resources required. In this work, a new and fast approach based on a one-dimensional model was applied. Structural characteristics (e.g., porosity distribution and fiber diameter) of two different filter media were successfully determined using a novel X-ray microscope. These characteristics were incorporated in the filtration model, and their influence on the calculations was evaluated. It was found that the porosity distribution does have an impact on local (microscopic) deposition rates, but only a minor influence on the macroscopic filtration efficiency (around 3%). Benefits of the model are the application of measured structural data and the low computational expense. Compared to experimental data (VDI 3926 / ISO 11057), the prediction of the filtration efficiency can be improved by incorporating the structural data in the model.

1 | INTRODUCTION

Due to the expected adverse health effects of particulate materials, the demand for effective and resource-saving separation systems for removing particles from fluids is rising sharply.1-3 Filtration systems are used in several areas such as wastewater treatment or gas purification.4-7 Due to their flexible handling and low investment costs, fibrous filters may be applied in various civil and industrial applications. For the purification of gas streams with low to medium dust loadings, or for applications where a high initial filtration efficiency is required (e.g., clean rooms in aseptic production), fibrous depth filters are the means of choice. In the context of filtration, a high filtration efficiency with a low pressure-drop is required. The optimization of the structural properties of the filter media (e.g., porosity and fiber diameter) with respect to the separation task at hand is vital.8-12 In this field, simulations and predictive tools are an excellent tool for realizing this task.11

Accounting for the large variation and complex geometry of the filter media in simulations is still challenging. Although the main physical processes involved in the particle separation process (diffusional deposition, interception, and impaction) have been described mathematically by numerous researchers since 1960,13-20 predicting the influence of the filter media is challenging. The heterogeneous nature of filter media (e.g., large variation in porosity) is a particular challenge, and most of the models are unable to account for this.9,21,22 In fact, most of the developed models were derived based on Kuwabara’s flow field,23 which makes assumptions such as parallel flow through a structured cylindrical array. Equations based on Kuwabara’s flow are inadequate to predict filtration behavior24 due to their over-simplification of the process.

Schweers et al.21 developed one of the first numerical approaches that included structural heterogeneity of the filter media by dividing the filter into several sub-filter layers. Along with other parameters, variation in fiber diameter and porosity were considered as important

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parameters for predicting the filtration efficiency. Due to the improvement in computer performance in recent decades, computational fluid dynamics (CFD) simulations are commonly used to predict filtration efficiency and are described in various publications.\textsuperscript{9,24–34} In these simulations, the incompressible Navier–Stokes equations are typically solved numerically for the flow-field through an array of virtual cylinders. The particle deposition is then simulated by tracking individual particles in the flow field.

Commonly, the influence of structural parameters (e.g., fiber diameter or porosity) or fiber particle interaction is studied. In some CFD simulations, a study of the influence of electrostatic effects can also be found.\textsuperscript{35} The high computational expense and the representation of the filter media using simplified virtual filter structures with averaged porosity or fiber diameter limit the accuracy of these simulations.

Current research focuses on the influence of microscopic effects (e.g., local structural parameters, local deposition rates, etc.) on macroscopic parameters such as filtration efficiency and pressure.\textsuperscript{10,11,36}

However, the description of the macroscopic filtration efficiency of the filter media is still a challenge, and evaluations of the interaction between microscopic and macroscopic parameters are still sparse in literature. Possible reasons are the mentioned limitations in computational resources and also the frequent lack of access to high-resolution, structural parameters.

Therefore, there is a need for a simulation method that is not computationally intensive and is based on actual structural data of the filter media and particle size distributions. The desired approach must also be able to account for the interaction between microscopic and macroscopic parameters. As an alternative to CFD simulations, one-dimensional models are used, which discretize the filter along its depth.\textsuperscript{12} These have the advantage of being less computationally intensive, which makes an investigation in a wide range of applications possible. However, there are also limits due to the use of average structural values. An improvement in understanding of filtration within fibrous depth filters might be attainable by combining the advantages of one-dimensional models with the use of high-resolution structural data. In this study, a one-dimensional model was developed that accounts for the actual structure of depth filters.

Structural data of the filter media were determined by imaging tomographic methods. In this study, tomographic data were obtained using an X-ray microscope (XRM). Compared to conventional computed tomography (CT), this system obtains higher resolution images by converting the X-ray radiation into visible light and then magnifying the image optically. New measurement and evaluation methods also increase the contrast between different materials.

Two different depth filter media were measured using XRM to obtain the porosity distribution of the material. These data were implemented in the model, and their influence on the calculation of the filtration is discussed. To evaluate the validity, the filtration efficiency was measured using a certified setup for the measurement of filter media according to the standard test procedure described in the VDI 3926/ISO 11057.\textsuperscript{37} Experimental data were then compared to the calculated filtration efficiencies.

## MATERIALS AND METHODS

### Materials

#### Filter media

The following filters were used as received: a gradient filter comprised polyester fibers (TH 300-T20; T15/500, batch no.: 3200560/6, Afprofilter, Bönen, Germany), and a fine filter made of glass fibers donated by Trox GmbH (F7, batch no.: 1800655, Trox GmbH, Neunkirchen-Vluyn, Germany). Characteristic data of both filter media are summarized in Table 1. The median fiber diameter, \(d_{50,0}\), was measured by digital image analysis using the open source software Fiji (64-bit, Laboratory for Optical and Computational Instrumentation, University of Wisconsin-Madison, Madison, WI) and its plug-in for diameter analysis, Diameter\textsuperscript{38} For this purpose, 24 SEM images of each filter material on the raw and clean gas side were evaluated. In each image, around 20,000 diameters were counted and evaluated. Filter samples for analysis were prepared from randomly chosen positions on the filter media.

#### Test dust

For the measurement of loading characteristics, the test dust Pural NF© (Pural NF®, Sasol, Brunsbüttel, Germany) was chosen. The test dust mainly consisted of aluminum oxide (\(\rho_m = 3,950 \text{ kg/m}^3\)). The particle size distribution was measured using laser diffraction (Mastersizer 3000, Malvern Panalytical, Worcestershire, UK) with deionized water as the dispersant. Particle size distribution statistics are summarized in Table 2.

### Methods

#### Modeling

All modeling work within this article was carried out using MATLAB (MATLAB 2016a, MathWorks Inc., Natick, MA). The model is discussed in detail in the discussion section.

#### Tomographic data

Tomographic data were obtained using an XRM (Xradia520, Versa, Zeiss, Jena, Germany). Attenuated X-rays were converted to visible light by converting the X-ray radiation into visible light and then magnifying the image optically. New measurement and evaluation methods also increase the contrast between different materials.

### Table 1 Filter media data (av ± s, n = 24)

| Material      | \(\rho_{\text{material}}\) (kg/m\(^3\)) | \(d_{50,0}\) (μm) |
|---------------|----------------------------------------|-------------------|
| Glass filter  | 2.515                                  | 4.32 ± 0.23       |
| Polyester filter | 1.500                                | 24.81 ± 3.85     |
light by a scintillation crystal. The generated visible light was then focused by an optical system (Figure 1).

Scans were carried out using an X-ray energy of 30 keV. The spatial resolution can be increased to 700 nm for an area less than 1 mm². In the following examination, the region of interest is about 10 mm², which limits the resolution to 30 μm.

Obtained images were evaluated using the open source software Fiji. Images were binarised by applying Fiji’s maximum entropy threshold algorithm to the images. The porosity was then obtained by computing the ratio of white pixels (material) to black pixels (no material) in each image, which corresponds to the packing density, α, of the material. From the packing density, the porosity was calculated as

\[ \epsilon = 1 - \alpha. \]  

(1)

Since the choice of correct threshold is a crucial step in image analysis,\(^{39}\) obtained porosity data by XRM were averaged and compared to the average porosity determined by gravimetric analysis (\( \epsilon_{\text{grav}} \)). To determine the average porosity, a filter sample with a known volume was weighed using a scale (Sartorius, Analytic AC 210S, Göttingen, Germany), and the porosity of the material was calculated as

\[ \epsilon_{\text{grav}} = 1 - \frac{V_{\text{material}}}{V_{\text{sample}}}. \]  

(2)

where \( V_{\text{material}} \) is the volume of the fibers in the filter, and \( V_{\text{sample}} \) is the bulk volume of the filter. \( V_{\text{sample}} \) was calculated based on the cylindrical geometry of the filter samples (24 mm diameter for the glass filter and 26 mm for the polyester filter). The depth of the filter media was obtained from the XRM data. \( V_{\text{material}} \) was calculated from the mass of the sample (\( m_{\text{sample}} \)) and the density of the material (\( \rho_{\text{material}} \)) as follows:

\[ V_{\text{material}} = \frac{m_{\text{sample}}}{\rho_{\text{material}}}. \]  

(3)

2.2.3 | Deposition efficiency

The measurement of the deposition efficiency was carried out according to the VDI 3926 using a certified setup (MMTC 2000, Palas, Karlsruhe, Germany). A schematic drawing of the setup is shown in Figure 2. The test dust was dispersed using pressurized air, and the pressure drop across the filter media was measured. The filtration performance was determined gravimetrically by weighing the dust that penetrated to the absolute filter. For both filter media, a face velocity of 0.03 m/s was chosen with a dust concentration of 2.5 g/m³ and a volume flow rate of 20 L/min. The size of the circular test filter was approximately 14 cm in diameter. The glass filter was loaded for a time interval of 5 min, and the polyester media for 30 s. The different time intervals were based on the gravimetical measurement of the efficiency, which required a minimum dust loading of the absolute filter for an accurate analysis. All measurements were carried out three times.

3 | RESULTS AND DISCUSSION

3.1 | Filtration model

To describe the filtration efficiency of the filter media, the filter was divided into several filter layers, called sub-filters (Figure 3). Each sub-filter had a defined depth and defined structural data such as porosity and fiber diameter.

The filtration efficiency of a sub-filter (\( T_i \)) was calculated as the ratio of the separated number of dust particles (\( n_i - n_{i-1} \)) to the ingoing number of dust particles (\( n_{i-1} \)), and the total filtration efficiency (\( T \)) of whole filter media was calculated analogously to \( T_i \):

\[ T_i = \frac{n_i - n_{i-1}}{n_{i-1}} \]  

(4)

| TABLE 2 | Mass based particle size distribution statistics of the test dust Pural NF (av ± s, \( n = 5 \)) |
|---------|---------------------------------|
| \( d_{p,10,3} \) (μm) | \( d_{p,50,3} \) (μm) | \( d_{p,90,3} \) (μm) |
| 2.1 ± 0.002 | 9.93 ± 0.006 | 33.35 ± 0.065 |

FIGURE 1  Scheme of measurement procedure of the X-ray microscope [Color figure can be viewed at wileyonlinelibrary.com]
The filtration efficiency depends on the fiber diameter ($d_{f,i}$), the porosity of the sub-filter ($\varepsilon_i$), the depth of the sub-filter ($L_{f,i}$), and the total deposition efficiency ($\phi_i$) on a single fiber inside each sub-filter. These parameters were used to predict the filtration efficiency as follows:

$$T_i = 1 - \exp \left( -\frac{4}{\pi} \frac{1 - \varepsilon_i}{\varepsilon_i} \cdot \frac{L_{ij}}{d_{ij}} \cdot \phi_i \right)$$

The deposition efficiency on a single fiber ($\phi_i$) was calculated based on individual separation efficiencies for diffusional deposition ($\eta_{D,i}$), interception ($\eta_{I,i}$), and inertial impaction ($\eta_{J,i}$), assuming interaction between interception and diffusion only ($\eta_{D+R,I}$). Therefore, $\phi_i$ was calculated as the sum of the individual mechanisms as follows:

$$\phi_i = \eta_{D+R,I} + \eta_{I,i} + \eta_{J,i}$$

Due to the low gas velocity and the small particle size, it can be assumed that adhesion forces are predominant in this case. Therefore, particle bounce was not considered in the calculations.

For describing diffusional deposition and interception, the model obtained by Payet et al. was chosen, where

$$\eta_{D+R,I} = \frac{1}{6} \cdot \frac{1}{\varepsilon_i} \cdot \frac{L_{ij}}{d_{ij}} \cdot \phi_i$$

Here, $K_u$ is the Kuwabara factor, $Pe_i$ is the Pedet number (defined as the ratio of convective transport to diffusive transport), $C_{D,i}$ is the slip correction factor, and $C_{D,i}^0$ accounts for the interaction between the interception and diffusion mechanisms. The Kuwabara factor is given by

$$K_u = -0.5 \cdot \ln(\alpha_i) - 0.75 + \alpha_i - 0.25 \cdot \alpha_i^2$$

and the Peclet number is calculated as

$$Pe_i = \frac{u_0 \cdot d_{ij}}{D_i}.$$  

The diffusivity ($D$) of each particle size was calculated from the Einstein–Stokes relation:

$$D = \frac{k_B \cdot \theta}{3 \cdot \pi \cdot \mu \cdot d_p}$$

Here, $k_B$ is the Boltzmann constant, $\theta$ ($25^\circ C$) is the temperature, $\mu$ ($1.824 \times 10^{-5}$ Pa s) is the dynamic viscosity of air at ambient pressure at the chosen temperature, and $d_p$ is the particle diameter.
The velocity \( u_{0,i} \) for estimating \( Pe_i \) was calculated by multiplying the velocity in the previous sub-filter \( u_{0,i-1} \) by the ratio of the porosity in the current sub-filter to the porosity in the previous sub-filter \( \varepsilon_{i-1} \):

\[
u_{0,i} = u_{0,i-1} \cdot \frac{\varepsilon_i}{\varepsilon_{i-1}} \tag{12}\]

The two correction parameters, \( C_{D,i} \) and \( C_{D,j} \), are given by

\[
C_{D,j} = 1 + 0.388 \cdot Kn_{D,j} \cdot \left( \frac{1 - \alpha_j}{Kn_j} \right)^{1/3} \tag{13}
\]

\[
C_{D,j} = \frac{1}{1 + \eta_{D,j}} \tag{14}
\]

Particle separation by interception was taken into account and calculated as follows:
Here, $C_{R,i}$ is a correction parameter for slip flow analogous to Equation (13), and $R$ is the interception parameter defined as the ratio between fiber and particle diameters given by

$$R_i = \frac{d_p}{d_f}$$  \hspace{1cm} (16)

Separation based on inertial impaction was accounted for using the model proposed by Zhu et al.\textsuperscript{40} Zhu developed an analytical model of the filtration of particles on cylindrical fibers based on Kuwabara's flow field:

$$\eta_{R,i} = 0.6 \frac{1 - \alpha}{K_u} \frac{R_i^2}{1 + R_i} \cdot C_{R,i}$$  \hspace{1cm} (15)

The inertial deposition depends on the Stokes number ($St_k$), which was calculated as

$$St_k = \frac{\rho_p \cdot d_p^2 \cdot u_0}{18 \cdot d_f \cdot \mu}$$  \hspace{1cm} (19)

Both filter media were successfully measured by XRM, and their 3D-structures were visualized (Figure 4). From these images, an overview of the structure can be observed. The spatial resolution of the tomosgrams in Figure 4 left is 3 μm, and right is 15 μm.

The structures were represented by a stack of cross-sectional images, which were evaluated to determine the porosity distribution along the depth of the material (see Section 2.2.2). For this investigation, the whole sample was analyzed. In this case, the resolution of the tomographic system was optimized based on the size and depth of the samples. Therefore, the glass filter was represented by 374 images (constant depth of 2.1 μm for a cross-sectional image), and the polyester filter was represented by 1,444 images (constant depth of 14.35 μm for a cross sectional image). In Figure 5 (left), a representative cross-sectional image obtained by XRM is shown. Additionally, a representative, binarised image is shown (Figure 5, right). Images were binarised by applying a threshold in order to quantify the location of solid material so the porosity distribution inside the filter could be calculated. Similar results were obtained for the glass filter.

The porosity distributions in both filter media (Figure 6) were estimated using the binarised image data. In addition, the exact depth of both filter media (approx. 0.78 μm in case of the glass filter and 20.72 μm in case of the polyester filter) for the two filter samples used were obtained. In the case of the glass filter, porosity was relatively

![FIGURE 6](image-url)  

**TABLE 3** Averaged porosity data of filter media measured by XRM ($n = 1$) and gravimetric analysis ($av \pm s, n = 3$)

| $l_f$ (mm) | $\varepsilon_{XRM}$ (-) | $\varepsilon_{grav}$ (-) |
|-----------|--------------------------|--------------------------|
| Glass filter | 0.79 | 0.967 | 0.966 ± 0.001 |
| Polyester filter | 20.72 | 0.981 | 0.988 ± 0.0006 |

3.2 | Tomographic data

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constant inside the filter but increased sharply at the raw and the clean gas sides. This phenomenon was due to fibers protruding out of the bulk material, which were detected by XRM, giving the appearance of high porosity at the surface layers on the raw and clean gas sides of the filter media. This result agreed with observations made by Roscoat et al.41 where the microstructural properties such as the porosity distribution of four paper materials were investigated by micro-CT. In the case of the investigated polyester media, a progressive manufactured filter media was observed having two areas of porosity. On the raw gas side, a high porosity around 98–99% was observed, followed by a decreasing porosity at the lower layer of the material to 96%. Due to fibers protruding from the bulk material at the surface, the same artifacts observed for the glass filter were present. Higher average porosity and depth of the material, as well as the gradient in porosity, made those artifacts at the surface layers less pronounced in the polyester-filter porosity-curves than in the case of the glass filter. The image data also enabled the depth of the two filter samples to be obtained to a high degree of accuracy.

The gravimetrical average porosity was calculated according to Equations (2) and (3). Average porosity obtained by XRM and gravimetric analysis data are summarized in Table 3. The gravimetric porosity agreed well with the average porosity obtained by XRM. The good agreement between the two methods supports the validity of the image analysis of the cross-sectional images of the two considered filter media.

### 3.3 Calculation of filtration efficiency

In the previous section, XRM was used to obtain tomographic data such as the porosity distribution along the depth of the two filters. These data were used in the filter model presented in Section 3.1.1. Each sectional image obtained by XRM represented a sub-filter of the model with the porosity extracted from the digital image analysis. The mass of the particles captured by the glass filter was calculated based on 374 sub-filters with a depth of 2.1 μm. In the case of the polyester filter, 1,444 sub-filters with a depth of 14.3 μm were applied for calculations. Here, the discretization of each sub-filter image was chosen based on the optimized resolution of the tomographic system. Therefore, the highest resolution calculation possible of the particle deposition inside the filter media was ensured. Spherical particles having the density of aluminum oxide (see Section 2.1.2) were assumed. For both filter media, a face velocity of 0.03 m/s was used. Calculations were carried out using average porosity and porosity distribution data from XRM. In this work, the medium fiber diameter (given in Table 1) was assumed to be constant in each sub-filter, and the mean value was used for both filter media. Results of the calculation are shown in Figure 7 (left). The graph of filtration efficiency as a function of particle diameter exhibited a minimum in filtration efficiency for particle sizes around 1 μm, as expected. Taking into account, the obtained microstructural porosity distribution inside of the investigated filter media led to an increase of predicted filtration efficiency for both media. In particular, inertial impaction and interception were observed to have a more significant impact on efficiency than diffusional deposition. Similar tendencies were observed for both filter media when accounting for porosity distribution data. In order to study the plausibility of the method, the face velocity was increased to 0.1 m/s (Figure 7, right). Expected results were obtained. Increasing the gas velocity led to an increase of inertial dominated filtration and to a decrease of diffusional deposition. Based on the particle size of the test dust in these calculations, it was concluded that the dust particles were separated mainly by inertial forces (gray marked regions in Figure 7). Here, it also became evident that both filter media were
effective at separating the majority of the dust particles (more than 50% of the mass of particles in the dust, see Table 2).

In order to study the influence of local structural inhomogeneity and to gain a deeper understanding of mechanisms inside the material, the local filtration efficiencies of the particle sizes along the filter depth were calculated. It was possible to make this calculation for each observed particle size. Results are shown for three sample particle sizes, one in the diffusional dominated region, one in the filtration minimum, and one in the inertial dominated region (particle diameter of 0.01, 1.5 and 3 µm, Figure 8). It is shown, and was expected, that the calculated local efficiencies are highly linked to the porosity distribution. Nevertheless, a deeper insight into the physics of separation within these two materials has been gained. In the case of the glass filter, low efficiencies at the surface layer of the material were calculated, and a relatively constant efficiency inside the bulk of the material, corresponding to the porosity distribution, was found. Similarly, small filtration efficiencies at the surface layer were observed for the polyester filter.

Due to the different structure of the polyester filter media, the values and the distribution of local filtration efficiencies differ from the glass filter media. In general, the filtration efficiency of the polyester is about one order of magnitude smaller, which is compensated partially by the larger filter depth of the polyester filter. The filtration efficiency reaching higher values in the deeper layers of the media is a result of the composite structure of the media. This composite structure is usually manufactured to generate a more uniform loading of the material with particles.

In Figure 8, the local fractional separation efficiencies for chosen particle sizes along the filter depth were examined. It can be emphasized that the particle separation efficiency is inversely related to the porosity curve shown in Figure 6, which is due to the dependency of the separation on the porosity. An almost constant separation efficiency of the particles inside the glass filter and an increased particle separation in the second part of the polyester filter was observed. The order of the level of local separation efficiency as a function of particle diameter for the glass filter (T_{3µm} > T_{1.5µm} > T_{0.01µm}) and for the polyester filter (T_{0.01µm} > T_{3µm} > T_{1.5µm}) follows the calculated macroscopic filtration efficiencies shown in Figure 7. This order can be explained by the influence of the filter media structure and the operating conditions on the separation mechanisms. In general, the filtration efficiency increases for larger particle diameter due to higher inertial forces, and also for smaller particles where the deposition is mainly dominated by the diffusion. This behavior is shown in Figure 7. Due to the structural properties of the polyester filter media at the investigated operating conditions (gas velocity), particles of 1.5 µm size do not appear to be efficiently deposited either by diffusion or by inertia. It can explain that why this particle size causes the lowest separation efficiency. This is consistent with the results in Figure 7. In the case of the glass filter, separation by inertia appears to be the dominate separation mechanism, which means that the largest considered particle size is separated most efficiently. In contrast, the smallest particle diameter considered is the most efficiently separated particle size in the polyester filter. This can be explained by the differences in porosity. Due to the higher porosity of the polyester filter, the gas velocities in the filter are lower, which supports the separation by diffusion.

It is shown that the local filtration efficiency differs between the two filters by one order of magnitude (Figure 8). This is not reflected in the macroscopic filtration efficiency of both filters in Figure 7, as this is (partly) compensated by the higher depth of the polyester filter. The calculated local filtration efficiencies for all particle sizes of the considered test dust (data in Table 1) were then used to calculate the deposited mass in the initial (clean) state along the filter depth. This was done using the particle size distribution of test dust and the

![FIGURE 8](https://example.com/figure8.png)  
**Figure 8** Calculated local filtration efficiency of three representative particle diameters (0.01, 1.50, and 3.00 µm) in glass filter (left) and polyester filter (right) [Color figure can be viewed at wileyonlinelibrary.com]
operating parameter of the separation system such as the exposure time of both filter media (Figure 9). Here, the influence of the particular structure differences between filter media on a microscopic level was determined. It was determined that a higher mass of particles is separated in the glass filter than in the polyester filter. The higher mass of the separated particles in the glass filter cannot be explained by the higher filtration efficiency alone. The longer loading time compared to the polyester filter (see section Material and Methods) accounts for this result. It was shown that the majority of particles were separated in the first layers of both filter media. In the glass filter, the majority was separated within the first layer, within a depth of 0.1 mm of the media. In the case of the polyester filter, it was found that a significant amount of the material was separated within the first 200 μm in the first part of the filter. However, a more uniform loading was achieved with the polyester filter, which is explained by the structure of the filter and also by the coarse test dust used.

The influence of the particle size distribution on the deposition pattern was also determined. A finer test dust probably led to a different deposition profile, that is, a more uniform loading, since entrapment of a smaller amount in the first layer occurred leading to deeper penetration of the particles. In the glass filter, the low porosity and the comparably small fiber diameter are responsible for the high filtration efficiency.

For the first experimental validation of the applied method, the total separated mass was measured (Section 2.2.3). These data were also calculated with the developed model using data presented in Figure 9. The lower calculated filtration efficiency of the polyester filter in comparison to the glass filter was experimentally proved (Figure 10). Additionally, a nearly complete separation of the particles by the glass filter was observed. In comparison to calculated values, it was shown that the developed model underestimated the measured filtration efficiencies. However, accounting for the porosity distribution in the calculation of the filtration efficiency led to an improvement in the prediction of the filtration efficiency. In general, incorporation of the porosity distribution had a major impact on calculations at a microscopic/local level, but only a minor influence on the macroscopic level. Due to the coarse test dust and the comparably long exposure time, the filter materials clogged rapidly. This was noticed to a great extent for the glass filter. Clogging would normally lead to an increase of filtration efficiency, but this phenomenon is not taken into consideration by the applied model. However, the model is valid for predicting basic filtration efficiency and describes the influence of the structure of the filter media. It is especially useful as a tool for investigating phenomena inside the material utilizing tomographic
data, and seems robust enough to handle structural inhomogeneity of a specified filter sample. It can therefore be used as a tool to support the investigation of the influence of filter media characteristics on the separation performance of a filter media. It is especially useful to investigate local phenomena inside the filter media (Notations in Supplementary material).

4 | CONCLUSION

In this work, an approach for calculating the filtration efficiency of depth filter media was presented. The obtained model can be coupled with tomographic data sets of filter media. A novel tomographic method was applied, and high resolution structural data were obtained. This tomography method was successfully compared with a complementarily measured porosity and is suitable for further investigations where high resolutions are required. The model is useful to compute macroscopic filtration efficiencies, which are related to microscopic filtration efficiency. For example, it could be shown that the considered filter structure has a high influence on microscopic phenomena but a comparatively low influence on the initial macroscopic separation efficiency. According to the model, these effects could be partially compensated by the filter length. The local distribution of the particles, in the initial state, along the filter depth can be computed by considering experimental conditions such as the particle size distribution and the loading time of both filter media. The influence of the structure of the filter media was discussed. Experimentally obtained filtration efficiency deviations from the model indicate additional structural parameters are required. However, the model is valid for qualitative modeling and for determining the influence of the macrostructural parameters of the filter media on the filtration efficiency. It is also well-suited for explaining the mechanisms of particle separation within the media based on macroscopic and microscopic filtration phenomena. A benefit of the model is the use of experimentally measured structural filter data and low computation time of only a few minutes on a standard PC.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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