

TOWARDS 3D CFD-DEM SIMULATION OF SOLID-LIQUID MULTI-PASS FILTER TESTING

Kilian Schmidt¹, G M Burhan²

¹ IT for Engineering (it4e) GmbH, Morlauterer Straße 21, 67657 Kaiserslautern

² BinNova Microfiltration GmbH, Dr.-Hermann-Ludewig-Ring 5, 07407 Rudolstadt
Germany

Abstract

Solid-liquid Multi-Pass filter tests are applied in particular to nonwoven filter media for filtration of transmission oils, hydraulic oils and fuels. The simulation of such filter processes on the pore-scale of the filter medium enables characterization and optimization of the nonwoven material for industrial applications.

Because of high drag forces, particles in solid-liquid filtration tend to have an adhesion probability < 1 , so that the simulation of such filter processes on the pore-scale of the filter medium involves more detailed contact models and the necessity to determine particle-particle and particle-structure adhesion forces. Correspondingly, in preceding work with DNSlab[®], a suitable 1½-way CFD-DEM coupling approach was developed.

This contribution shows an application of the developed simulation method to model standardized Multi-Pass testing of BinNova nonwoven flat sheets.

For the calibration of simulation parameters, in particular adhesion forces, the parameters are fitted to experimental results of simple filtration efficiency measurements with a clean filter medium. With the simulation parameters found in this manner, the continuous Multi-Pass filtration process is simulated and the simulation results are validated by comparing them to the Multi-Pass measurements. The simulations are automatically conducted for numerous different cutouts of the tomography and averaged, so that the simulation results are more representative for the whole material.

Keywords

Nonwoven, Solid-Liquid, Filter Testing, Simulation, CFD, DEM

Background

The long-term goal is to enable efficient simulation of pore scale solid-liquid separation with DNSlab to match experimental data in particular for standardized continuous Multi-Pass tests.

Modeling approaches with simplified contact models [Petersen2016] and no modeling of detachment or re-ordering of deposited particles [Hund2018] were lacking the modeling of effects which have a significant influence on the development of pressure drop and filtration efficiency during continuous solid-liquid filtration processes.

Subsequently, DEM contact models were introduced in DNSlab which allow more detailed contact models including friction, adhesion and detachment of previously deposited particles.

Regarding the coupling of CFD and DEM methods, it was found that fully resolved CFD-DEM coupling with the Lattice-Boltzmann Method [Puderbach2021] needs too much computational resources for industrial applications with wide particle size distributions and tens of thousands of particles. To improve the computational efficiency, 1½-way CFD-DEM coupling was introduced by [Schmidt2022] and the further development of the method was shown by [Puderbach2024].

The matching of simulation results with the CFD-DEM 1½-way coupled approach and experimental data of Multi-Pass tests was not shown up to now.

Objectives

In this work, the objectives are, firstly, a proof of concept of the CFD-DEM 1½-way coupled approach for an industrial application by comparing Multi-Pass simulation results and experimental data for a reference material, and secondly the calibration of friction and adhesion simulation parameters for subsequent design of optimized fiber structures for specific requirements by simulation.

Experimental Setup

Flat sheets of BinNova's AH0022 nonwoven material are used as reference material, see Fig. 1.

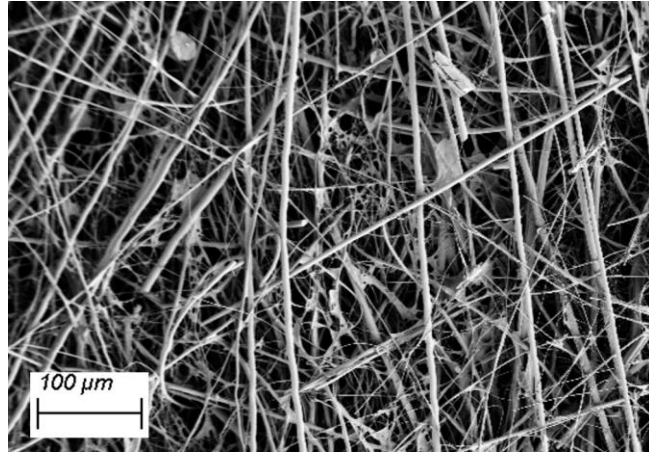


Fig. 1: SEM image of a flat sheet of the AH0022 material.

The AH0022 material has a thickness of 0.575 mm (mechanic measurement) respectively 0.474 mm (determined by SEM image) and a measured air permeability of 300 L/m²s.

For the 3D microtomography with about 0.25 μm resolution, a cutout of a flat sheet of about 1 x 1 mm size was prepared. The raw tomography imported in DNSlab has 0.25 μm resolution (in other words, a voxel edge length of 0.25 μm), 4048 x 3788 voxels face area and 3788 voxels height. The grayscale values of the 3D model were appropriately adjusted during the import of the image slices in order to minimize noise and ensure the optimal reconstruction of fiber density and accurate representation of the physical fibers. Further artifacts like noisy dots and rounded model boundaries (which arise from the rotation of the material sample in the tomograph; see Fig. 2) remained to be removed before simulation of fluid flow, particle transport and deposition.

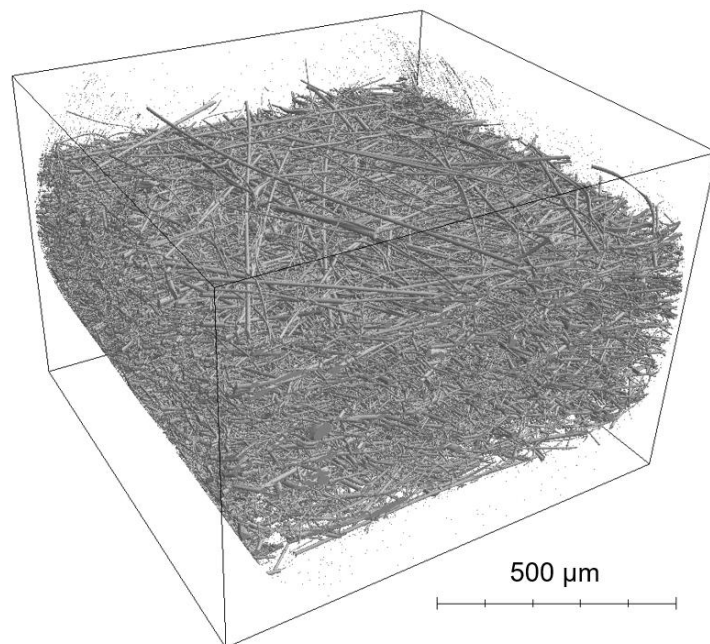


Fig. 2: Raw tomography with artifacts which arise from the measuring method.

For the flat sheets of the AH0022 filter medium, ISO 16889 Multi-Pass testing (see Fig. 3) is conducted with ISO 12103-1 A3 Medium Dust particles and UNIVIS HVI 13 oil with 13.5 mm²/s viscosity at 40°C. A constant volume flow of 6 L/min is applied, the filter area is 200 cm² and consequently the average face flow velocity at the filter medium sample is 0.005 m/s.

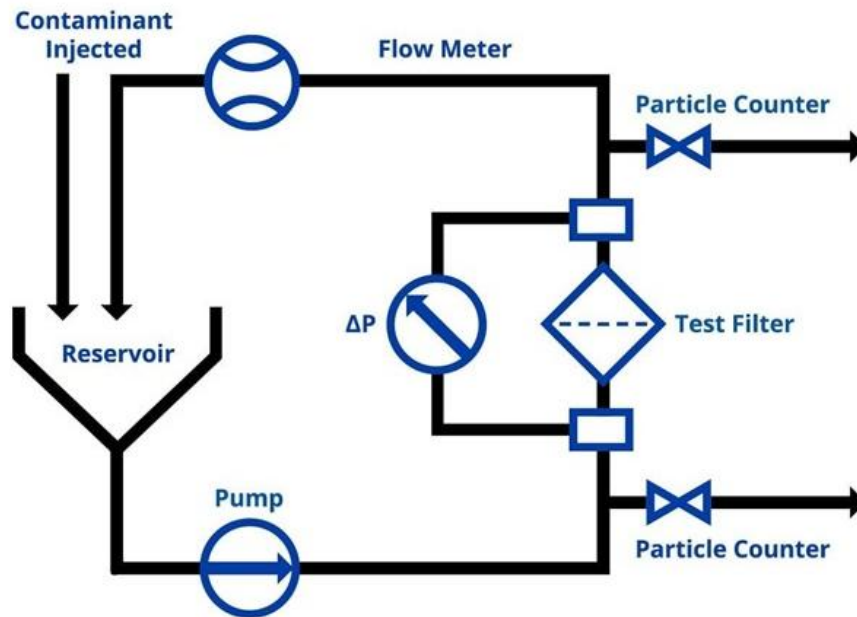


Fig. 3: Scheme of the test rig used for the Multi-Pass tests.

Modeling Method

For the simulation of the Multi-Pass filtration process, the tomography is reprocessed by cropping defective model boundaries, coarsening with a factor of 2 (meaning that 2 x 2 x 2 voxels of the raw tomography are combined to 1 voxel of the reprocessed tomography to reduce the 3D model size and save computing power) and removing noise. The height respectively thickness of the material is read off the tomography to reconcile the measured height.

The reprocessed tomography is subdivided into 5 x 5 sections with 300 x 300 voxels face area. DNSlab's Python interface is used to pre- and postprocess the simulations for the 25 sections by a Python script. For each section, simulations of fluid flow, particle transport and deposition are conducted.

The averaged results of the flow computations are compared with measured air permeabilities and pressure differences for oil permeation.

At first, particle deposition at the clean filter medium is simulated for particle sizes 5, 7 and 9 μm and for each model section without particle-particle interactions, with adhesion force proportional to the particle size, sliding friction constant 0.5 and static friction constant 0.9. The resulting averaged fraction deposition rates are compared

and matched with the initial fraction deposition rates measured at the Multi-Pass test rig by adjusting the particle-fiber adhesion force.

Then, the Multi-Pass test is simulated with a 300 x 300 voxel and a 200 x 200 voxel model section, to assess the deviation of the results when using a smaller section and to save computing power. For the Multi-Pass simulation, particle-particle interaction is taken into account, where at first the adhesion parameters are taken over from the particle-fiber contact. The resulting development of the pressure difference is compared to the measurement.

The computations of the flow fields and particle trajectories for the 25 sections are conducted on a Windows gaming PC with Intel i7-14700K processor and 96 GB DDR5 RAM.

The Multi-Pass simulations are also run on a Windows PC but with AMD Ryzen Threadripper PRO 5965WX processor and 256 GB DDR4 RAM.

Later, in future work, if the match of simulation and measurement results should not be sufficient, the particle-particle adhesion parameters can be adjusted to improve the match of the simulated temporal development of the pressure difference and the particle deposition rates with the results from the Multi-Pass test rig.

Results

Evaluation of the Tomography

A height of 0.5 mm was determined by marking the bordering planes of the fiber structure in the raw tomography as shown in Fig. 4 (left). The determined height is precisely between 0.552 mm (mechanic measurement) respectively 0.474 mm (determined by SEM image).

For the simulation of fluid flow permeation, particle transport and deposition, the reprocessed tomography with face area 1594 x 1774 voxels and 0.5 μm resolution is subdivided into 5 x 5 sections with 300 x 300 voxels face area each, see Fig. 4 (right).

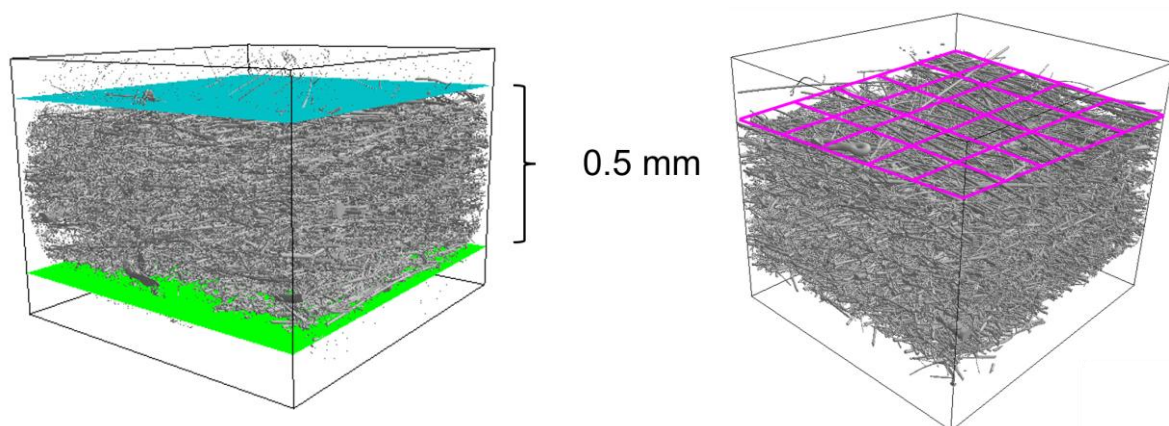
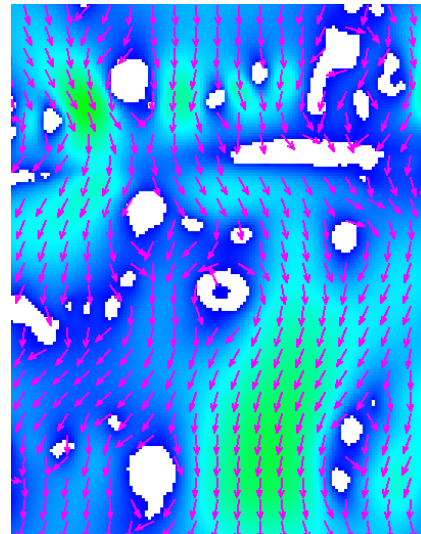
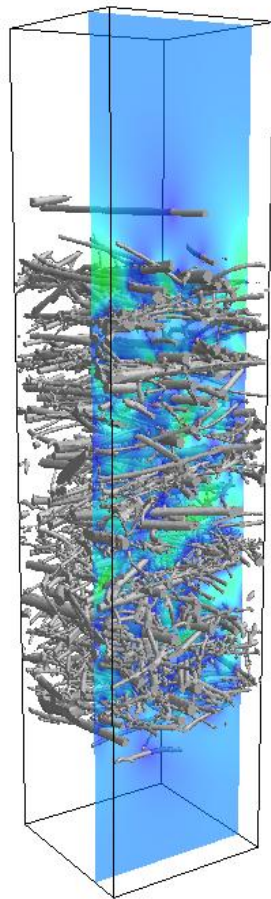


Fig. 4: Determination of the nonwoven height by the tomography (left); 5 x 5 sections of the reprocessed tomography (right).

Simulation of Fluid Flow Permeation

The flow velocity field (see Fig. 5) as dimensionless solution of the Stokes equations is only computed once for each model section to obtain the air permeability as well as the initial oil flow field for the Multi-Pass process.



Flow Velocity
low  high

Fig. 5: 2D slice of the computed dimensionless 3D flow velocity field (left), detail with arrows showing the local flow directions (top).

Air Permeability

The pressure differences obtained from the flow computations for the 25 model sections are translated to air permeabilities, see Fig. 6.

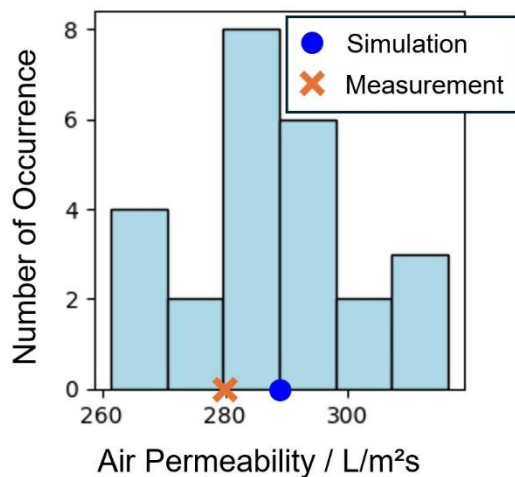


Fig. 6: Occurrences of the simulated air permeabilities for the 25 model sections, average: 288 L/m²s; average of measurements: 280 L/m²s.

Initial Particle Deposition Rates

The results of the particle deposition simulation at the beginning of the Multi-Pass test, so at the clean filter medium, are shown in Fig. 7. The best agreement of simulation and measurement was achieved by using adhesion forces $5\text{e-}10$ / $7\text{e-}10$ / $9\text{e-}10$ N for the 5 / 7 / 9 μm particles.

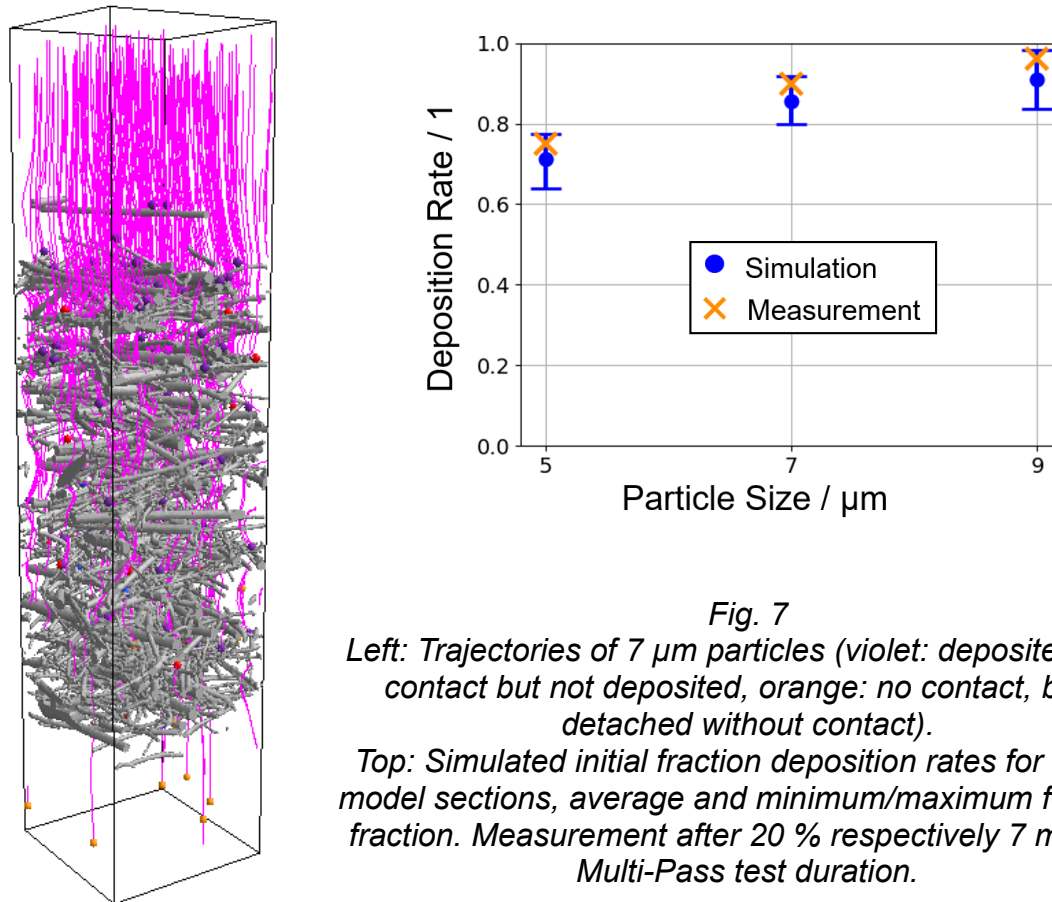


Fig. 7

Left: Trajectories of $7\text{ }\mu\text{m}$ particles (violet: deposited, red: contact but not deposited, orange: no contact, blue: detached without contact).

Top: Simulated initial fraction deposition rates for the 25 model sections, average and minimum/maximum for each fraction. Measurement after 20 % respectively 7 minutes Multi-Pass test duration.

The simulations for the air permeability and the initial particle deposition rates of the Multi-Pass process for the 25 model sections altogether took about 3 days on the Intel PC.

Results for the continuous Multi-Pass Process

Because at first, see below, just the initial phase of the Multi-Pass process was simulated, only the resulting pressure differences are compared to the measurement. The particle fraction deposition rates during the first 5 minutes of the test should not differ much from the initial rates shown in Fig. 7.

Fig. 10 shows the measured pressure differences for the AH0022 material during the Multi-Pass test.

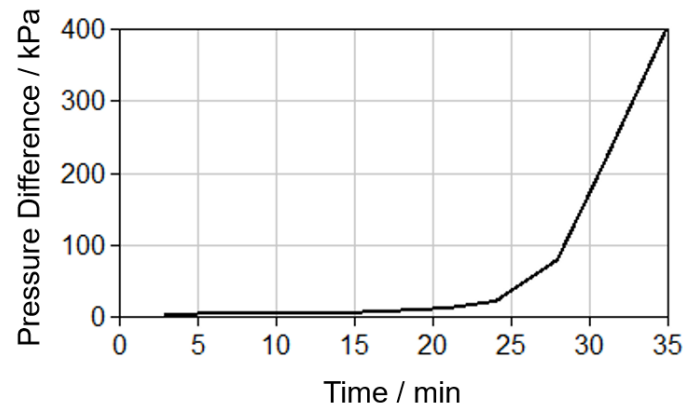


*Fig. 10: Measured pressure difference curve for the complete Multi-Pass test.
At $t = 3$ min the pressure difference is 3.2 kPa.*

The Multi-Pass simulation with the 300 x 300 model was stopped after 3 min simulated time, with the 200 x 200 model after 5 min. Fig. 11 shows the 200 x 200 simulation in the final state.

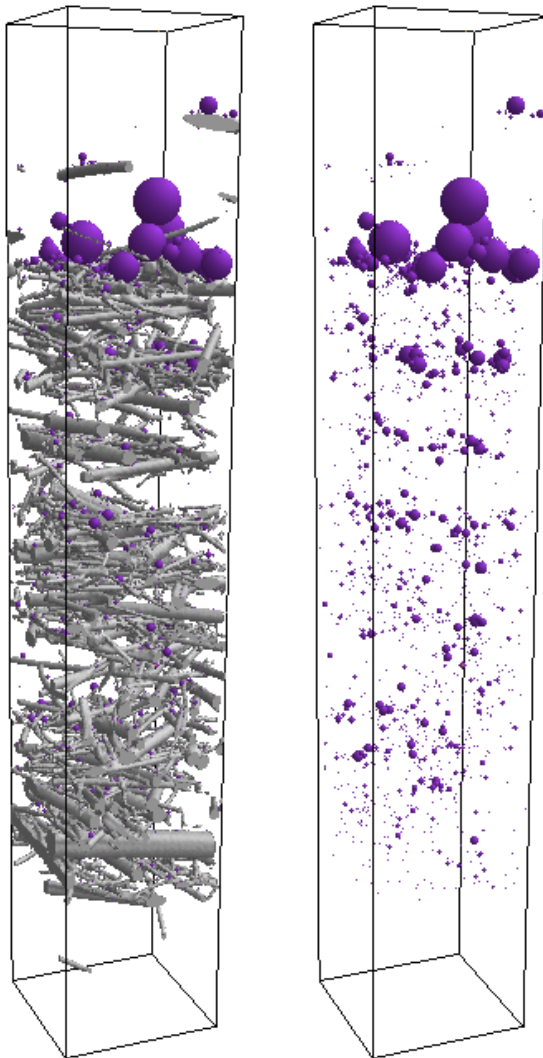


Fig. 11: Deposited particles with and without fibers after simulation of 5 min Multi-Pass test.

The pressure differences curve from the 200 x 200 simulation hardly deviates from the 300 x 300 simulation, see Fig. 12. The simulated and measured pressure difference curves have almost exactly the same slope, but the initial values differ by about 25 %.

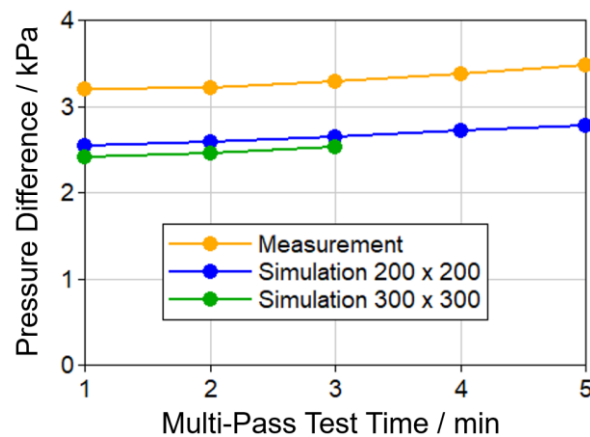


Fig. 12: Pressure difference curves simulated and measured for the Multi-Pass process.

The 300 x 300 and 200 x 200 simulations each took about 5 days on the AMD PC.

Conclusion

Regarding the results until now, the simulation method works well as it delivers a good agreement with experimental data. But it should still be clarified why the initial oil permeability of the reference material is measured lower than simulated, as shown in Fig. 12.

The computational efficiency must be further increased to enable simulation of about 30 minutes Multi-Pass testing with acceptable computing resources. As soon as the whole Multi-Pass test can be simulated within a couple of days, not only the particle-fiber but also the particle-particle adhesion parameters can be investigated respectively adjusted.

References

- [Puderbach2024] Puderbach, V.; Ataei, A.; Schmidt, K.: Numerical Modeling of Solid-Liquid Separation and Cake Formation Processes: Increasing the Computational Efficiency. FILTECH 2024 Proceedings
- [Schmidt2022] Schmidt, K.; Puderbach, V.; Antonyuk, S.: 1½-Way CFD-DEM Coupling with DNSlab: The optimal Compromise between Modeling Depth and Computer Resources Demand for the 3D Simulation of Microscale Fluid-Particle Processes. FILTECH 2022 Proceedings

- [Puderbach2021] Puderbach, V.; Schmidt, K.; Antonyuk, S.: A Coupled CFD-DEM Model for Resolved Simulation of Filter Cake Formation during Solid-Liquid Separation. Processes 2021, 9(5), 826
- [Hund2018] Hund, D.; Schmidt, K.; Ripperger, S.; Antonyuk, S.: Direct numerical simulation of cake formation during filtration with woven fabrics. Chemical Engineering Research and Design 139 (2018), p. 26-33
- [Petersen2016] Petersen, L.: Untersuchung der Tiefenfiltration wässriger Suspensionen mit Vliesen. PhD Thesis, TU Kaiserslautern (2016)