Computational Study of Pressure Drop Dependence on Pleat Shape and Filter Media

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ABSTRACT

It is demonstrated how the influence of pleat shape and filter media on pressure drop can be easily studied by computer simulation, without any knowledge of computational fluid dynamics. This is made possible by thorough interaction of the software tools **PleatDict** (virtual design of pleats) and **ParPac** (computational fluid dynamics). Furthermore, it is shown how the capabilities of those codes can be extended by coupling them with the software tools **GeoDict, FilterDict**, and **SuFiS**.

Keywords

Solid-Liquid Separation, Pleated Filters, Computational Fluid Dynamics, Computer Simulation

Introduction

One of the most important parameters governing performance and quality of a filter is pressure drop, which strongly depends on the properties of the actual filter media. In case the filter is pleated, also the shape of the pleat strongly influences the pressure drop.

The purpose of this paper is to demonstrate how the dependence of pressure drop on pleat shape and filter media can be easily studied by computer simulation using the software tool **PleatDict** developed at Fraunhofer ITWM. **PleatDict** allows for easily designing pleats with different shapes, and for running flow simulations in the created geometry.

The shape of the pleat is parameterized to make the design procedure fast, robust and simple. In order to provide detailed information on local flow velocities and local pressures that explain the contributions to the overall measurable pressure drop, the Navier-Stokes-Brinkmann system of equations is solved in the created geometry. The lattice Boltzmann code **ParPac** [1, 2] is used for discretizing and solving this system of partial differential equations. However, all the details of the numerical procedure, as well as most of the details of the flow equations, are hidden from the user. The aim is to make the code easily accessible to people with no experience in computational fluid dynamics. To achieve this, we set by default most of the parameters of the algorithm, based on many years of experience in the field and on the limited information specified by the user.

The developed software is used in a computational study of the influence of the pleat length and the filter media on the performance of the filter. In particular, valuable information about the flow details assist engineers in deciding on what changes to the pleat shape and filter media might lower the overall pressure drop. We also present the perspectives of extending the developed tool by coupling it to micro scale simulations in **GeoDict** and **FilterDict**. The meso-scale simulations can also be used for particle tracking, allowing for simulating and monitoring the local loading of the pleat with dirt particles, as well as coupling with our macro-scale simulation tool **SuFiS** [7], where information about the calculated pressure drop through a pleat can be used in an iterative procedure for simulating the flow in a complete filter element.

Pleat Grid Generation

The three-dimensional representation of the pleat is generated by **PleatDict** in three steps. First, a two-dimensional shape of the pleat is defined by a sequence of points (x_i, y_i). In the simple cases used here, these points are taken to lie on two semi-circles that are connected by straight lines, as illustrated in Figure 1 on the left. Through these points, a periodic cubic spline is fitted on which all further operations are based. By periodicity we ensure that the pleat can be considered a *representative* part of a real filter media. The right image in Figure 1 illustrates this effect as well as the possibility of generating more complex shapes by combining, for example, shorter and longer pleats in a single simulation run. The spline is then extruded to a pleat central surface into the third dimension. Finally, the filter media can be described as being within a certain distance from this surface. The computational domain is a rectangular parallelepiped or box geometry that is divided into n_x by n_y by n_z cubic cells called voxels. In our examples, each cell is 50 µm long / wide / high and n_x=56, n_y =64 and, in case of the long pleat, n_z = 360, i.e. the box is 2.8 mm by 3.2 mm by 18 mm. These cells are marked as either fluid or porous media, depending on their location with respect to the pleat central surface.

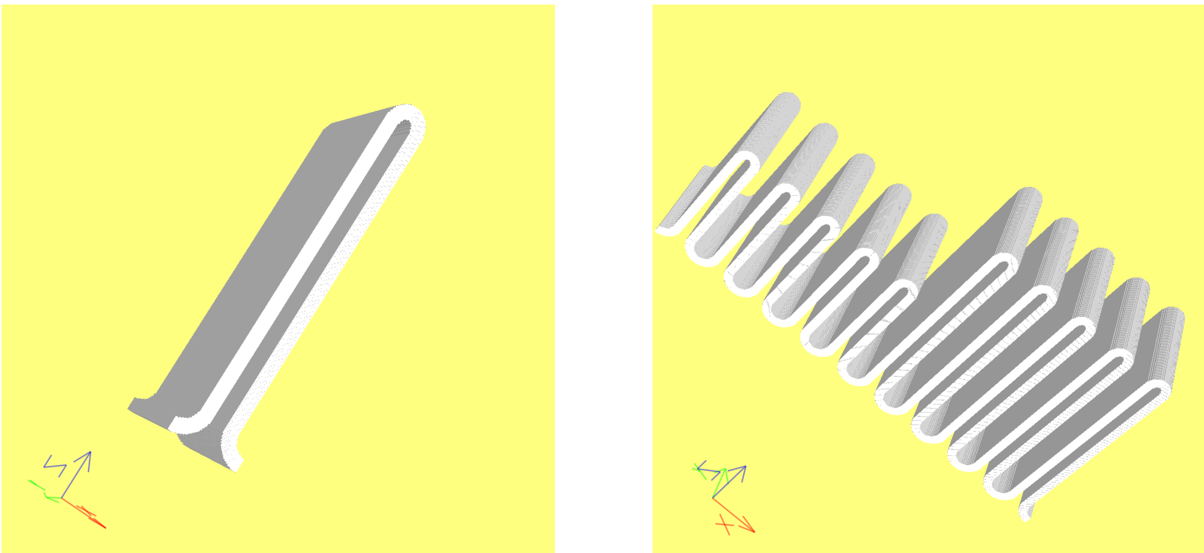

Figure 1: Left: Single pleat used in the three-dimensional simulations. Right: two pleat lengths are considered: ca. 8 mm and ca. 14 mm. The pleats are not symmetric; the inflow region is narrower than the outflow region.

Pressure Drop Simulation

Slow liquid flows or gas flows through pleats may be described by the Stokes -Brinkmann equations with periodic boundary conditions [3]:

$$
\begin{aligned}
-\mu\Delta\vec{u} + \nabla p + \kappa^{-1}\vec{u} &= \vec{\mathbf{f}} \text{ (momentum balance)} \\
\nabla \cdot \vec{u} &= 0 \text{ (mass conservation)} \\
\vec{\mathbf{f}} = (0,0,f) &: \text{ force in flow(z)-direction,} \\
\kappa = \kappa(x,y,z) &: \text{ porous voxel permeability,} \\
\vec{u} &: \text{ velocity,} \\
\mu &: \text{ fluid viscosity and} \\
p &: \text{ pressure.}
\end{aligned}
$$

Here the shape of the pleat determines where κ is not infinite. By different values of κ on various regions, different permeabilities may be assigned in different locations. In the two tangential directions, periodic boundary conditions mean that the pleat extends “similarly” in those directions. In the direction of the flow, we have to add a large enough inflow and outflow region so that periodicity does not create artefacts in the computed flows. The computations were performed with ITWM’s lattice Boltzmann Code **ParPac** [1, 2]. Figures 2 and 3 illustrate computed pressures and velocities in a cross section parallel to the flow. In Figure 2, the longer pleat shape is considered while in Figure 3, the shorter pleat shape is considered. In both Figures, on the left the filter media is assigned a homogeneous permeability κ = 1.1e-10 m², while on the right a lower permeability κ = 2.5e-11 m² is assigned in the folds as compared to the straight parts, where the permeability is also κ = 1.1e-10 m². The thickness of the media is 0.5 mm in all cases, and the pleat heights are 14.07 mm and 8.07 mm, respectively. In all four views, the flow rate is identical, and the viscosity is 0.088 Pas (SAE 10 oil). In Figure 2 left, the pressure drop is 71.2 kPa, on the right 82.0 kPa. In Figure 3 left, it is 52.2 kPa and on the right 64.4 kPa. That is, a longer pleat leads to a higher pressure drop, and also a lower permeability in the folds leads to a higher pressure drop. There is a noticeable asymmetry between the inflow and outflow side of the pleat. This is due to the fact that the pleat shape is not perfectly symmetric. The radii of the two semi-circles are different, the larger one occurs near the inlet, at the bottom of the Figures.
The larger pressure drop for the longer pleat is due to the narrowness of the inflow region. Compared to the short pleat, more liquid “wants” to pass through the neck of the inflow region, and the narrowness causes a large pressure differential in the area marked by the red circle. The purpose of **PleatDict** is precisely to study such questions of pleat shape design.

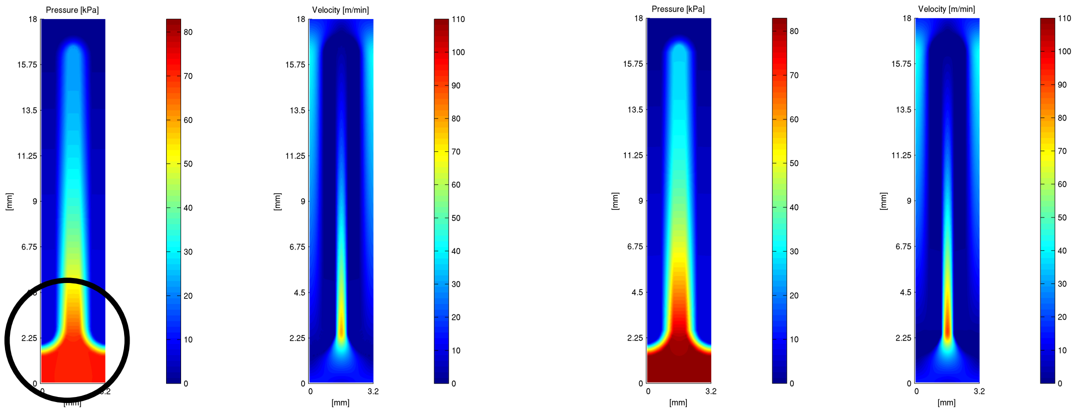

Figure 2: Pressure and velocity for the long pleat. Left: porous media with uniform permeability. The circle marks the relatively high pressure drop in the neck of the inflow region. Right: porous media with lower permeability in the folds.

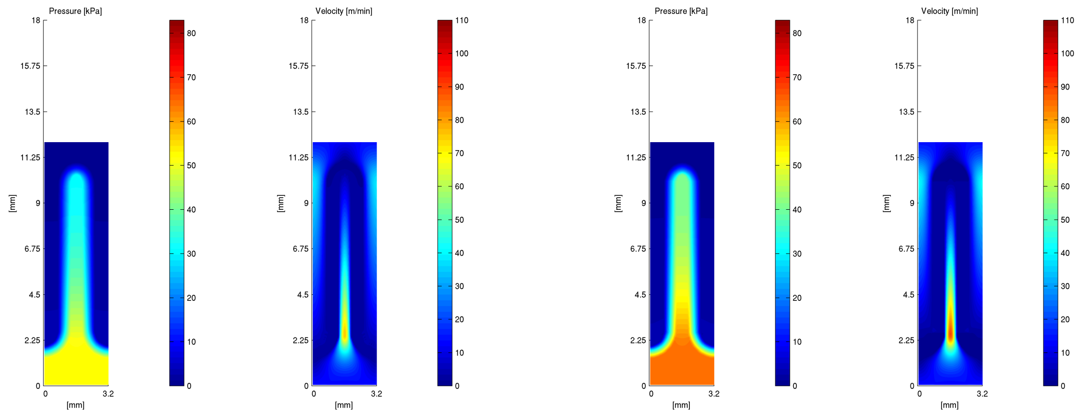

Figure 3: Pressure and velocity for the short pleat. Left: porous media with uniform permeability. Right: porous media with lower permeability in the folds.

Particle Deposition Simulation

The motion and deposition of particles may be described by a stochastic ordinary differential equation [4, 5]:

$$
\begin{aligned}
d\vec{v} &= -\gamma \times (\vec{v}(\vec{x}) - \vec{v}_\circ(\vec{x}))\, dt + \sigma \times d\vec{W}(t) \\
\frac{d\vec{x}}{dt} &= \vec{v} \\
\gamma &= 6\pi\rho\mu\frac{R}{m} \\
\sigma^2 &= \frac{2k_B T\gamma}{m} \\
\left\langle dW_i(t), dW_j(t) \right\rangle &= \delta_{ij} dt
\end{aligned}
$$

Here the variables mean

t:	time
$\vec{x}$:	particle position
$\vec{v}$:	particle velocity
R:	particle radius
m:	particle mass
T:	ambient temperature
k_B:	Boltzmann constant
$d\vec{W}(t)$:	3d probability (Wiener) measure
$\vec{v}_\circ$:	fluid velocity
ρ:	fluid density
μ:	fluid viscosity

The initial positions of 20000 spherical particles drawn from the SAE fine particle size / particle mass distribution are shown in Figure 4 on the left, together with the filter media and stream lines based on the Stokes-Brinkmann equations. The right picture in Figure 4 and the left picture in Figure 5 show later stages of the particle motion. The particles are visualized as if travelling at the same time, but the computation really tracks one particle at a time, without influencing each other or influencing the flow field. They are shown as pixels, which makes them look larger than they actually are, in order to see them at all. The right picture in Figure 5 shows the final positions of the particles where they enter the filter media.

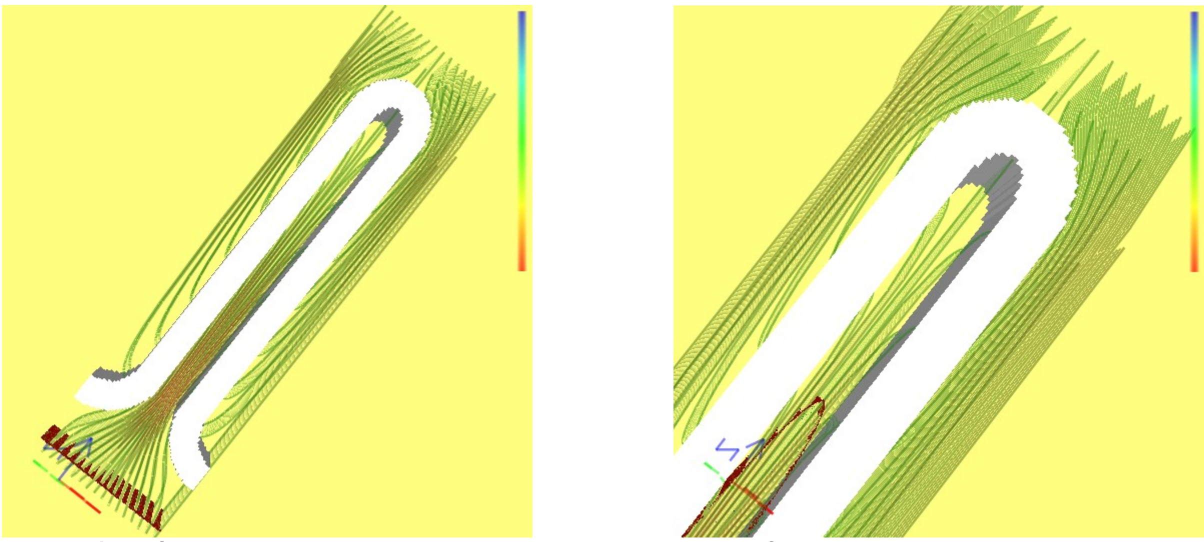

Figure 4: Left: Pleat, stream lines and initial particle positions for the particle deposition simulation. Right: Detail near the end of the pleat, with particles advancing in the inflow region. Particles are visualized as single pixels and larger than they actually are, in order to see them at all.

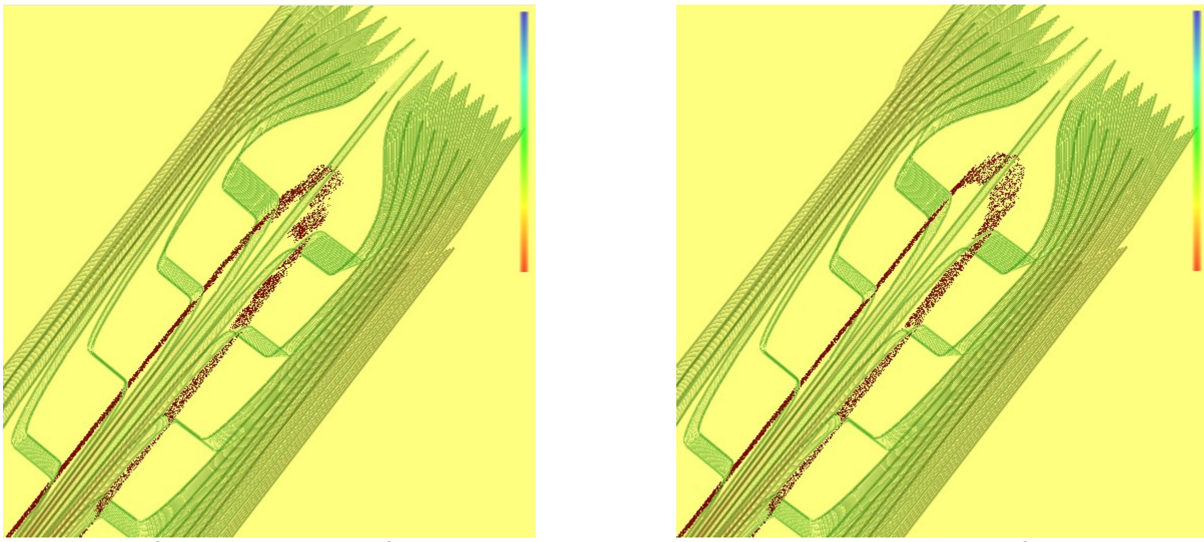

Figure 5: Left: detail near end of pleat, with particles advancing, and not showing the filter media. The streamlines tend to lie almost perpendicular to the media due to the lower permeability there. Right: final positions, where particles enter the porous media.

Figures 6 and 7 show the particle deposition patterns for the four cases illustrated in Figures 2 and 3. Figure 6 shows results for the long pleat, Figure 7 for the short pleat. On the left is the case of a homogeneous media, on the right the folds have a fourfold lower permeability than the straight parts. In each case, 20000 particles were tracked and the bars indicate percentages of these particles over distance from the inlet. The results are as expected from the pressure distributions: In the left figures, more particles / higher bars occur at the beginning and end of the pleat, because there exists more surface area per volume in these layers. On the right, the lower permeability of these regions leads to the opposite behaviour, namely fewer particles are deposited there. This illustrates the well-known balancing mechanism by which a filter regulates itself during operation. That mechanism tends to uniformly load the media. The other notable feature is a slight decrease of percentage of deposited particles over the depth of the pleat. Here, we only consider information on the overall ensemble of particles, but the simulations provide much more detail, for example information on particles of a given size.

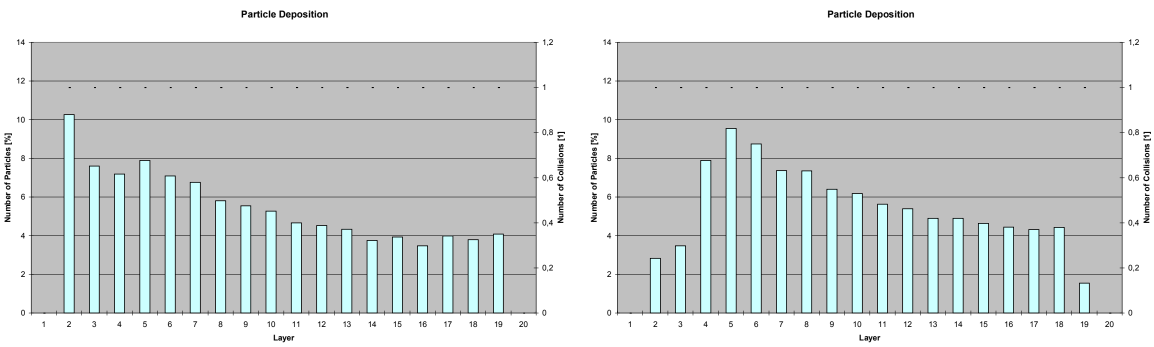

Figure 6: Left: percentages of 20000 particles deposited over the long pleat (Figure 2) with uniform permeability. Right: results for lower permeability in the folds.

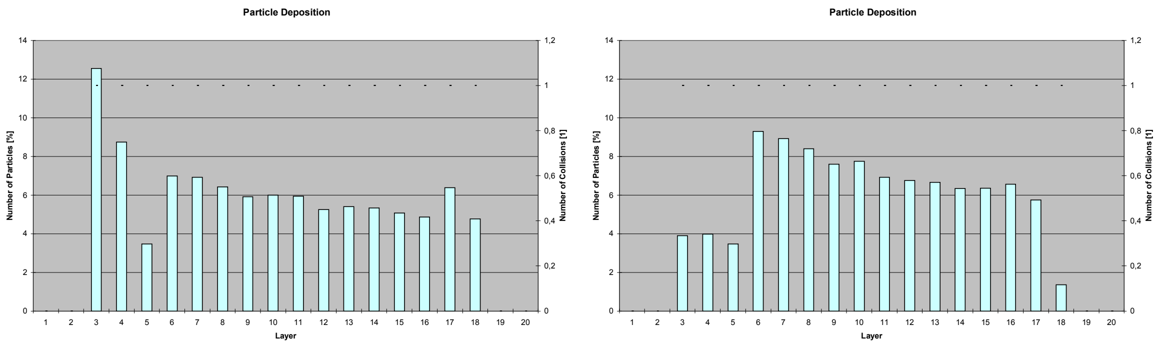

Figure 7: Left: percentages of 20000 particles deposited over the short pleat (Figure 3) with uniform permeability. Right: results for lower permeability in the folds.

Outlook on Coupled Micro-Scale / Meso-Scale / Macro-Scale Simulations

The ultimate goal of particle deposition simulation is the coupling of meso-scale simulations with microstructure simulations and macro-scale simulations. Regarding the micro-scale, the pleat is thought to consist of a finite number of regions. For each of these regions, the meso-scale simulation yields the number of particles and particle size distribution that enters the filter media there. This information will be used as input for micro-scale simulations in **GeoDict** / **FilterDict**, which resolve the fibres in the filter media. From the micro-scale simulations, the local filter efficiency, and via clogging simulations [4, 5] also new local permeabilities can be computed. Aggregating the efficiencies allows predicting particle numbers and particle size distributions at the pleat outflow. The new permeabilities can be used in the next flow simulation and particle deposition simulation on the meso-scale. The clogged micro-scale regions must be saved for the next micro-scale simulation, and must be used to produce new pressure and velocity-fields on that scale. So, iterating the meso-scale and micro-scale simulations will give insights into the time-dependent clogging of pleats.

Transition to the macro-scale has two components – upscaling for particles and upscaling for the pleated geometry. The amount of particles is usually too large to handle particles individually. Effective equations must be derived that use particle concentrations. These concentrations change due to diffusive and convective transport, i.e. due to Brownian motion and flow friction, respectively. Transport coefficients may be computed on the meso-scale quite analogously to the upscaling procedure described in the context of the micro-meso-coupling. As it was mentioned above, the meso-scale computations allow for upscaling the pleated geometry. In this case, the ring including the pleats can be considered as an effective porous media, with permeability being calculated by the above presented methodology for meso-scale computations. Extended macro-models and solution algorithms are planned as extensions to the simulation tool **SuFiS** [6, 7].

Conclusions

We presented results regarding the simulation of the dependence of pressure drop on pleat parameters such as length or permeability. The precise pressure distribution reveals details that allow engineers to redesign pleat shapes and filter media for better performance virtually, with great potential of reducing the need for prototypes. Particle deposition simulations can provide necessary data for micro-scale simulations that can in the future be used for clogging simulations across the scales, from the media scale through the pleat scale all the way up to the filter element scale.

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