PleatLab:

a pleat scale filtration simulation environment

Liping Cheng[1,2]*, Ralf Kirsch[2], and Andreas Wiegmann[1], Pierre-Colin Gervais[3,4], Nathalie Bardin-Monnier[3,4], Dominique Thomas[3,4]

1) Math2Markt GmbH, Trippstadter Str. 110, 67663 Kaiserslautern, Germany

2) Fraunhofer Institute for Industrial Mathematics, 67663, Kaiserslautern, Germany

3) Université de Lorraine, LRGP, UMR 7274, Nancy, F-54000, France

4) CNRS, LRGP, UMR 7274, Nancy, F-54000, France

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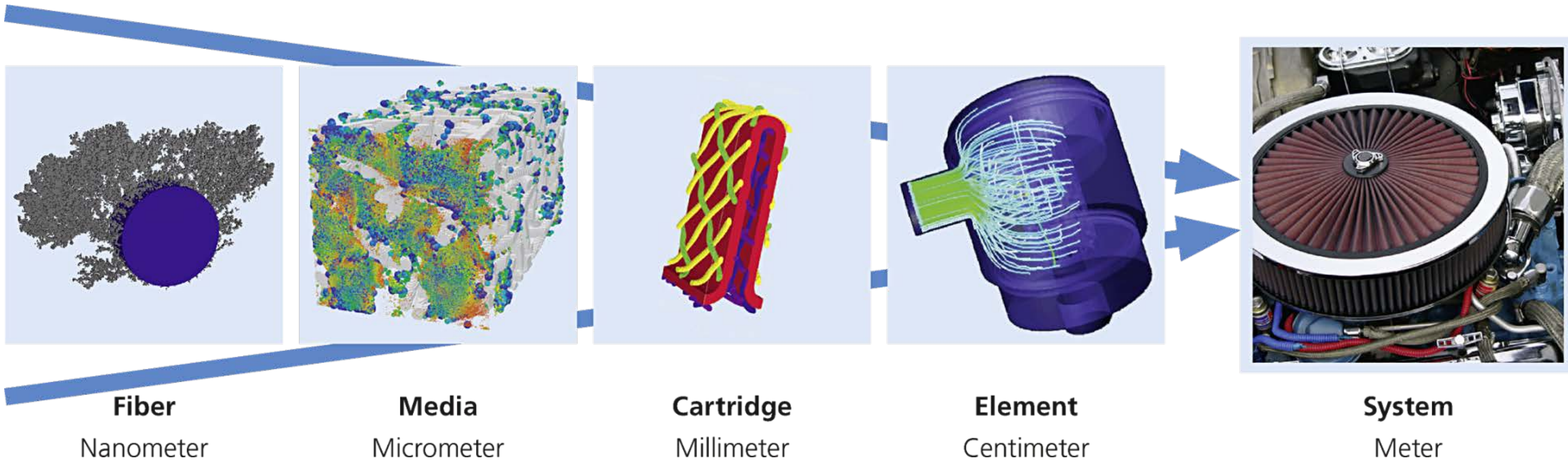
Filtration process simulation

- The precise geometry of the filter media/element
- The fluid flow in this geometry
- The transport and deposition of particles
- The changes of the geometry after particles have deposited

The scales of simulation:



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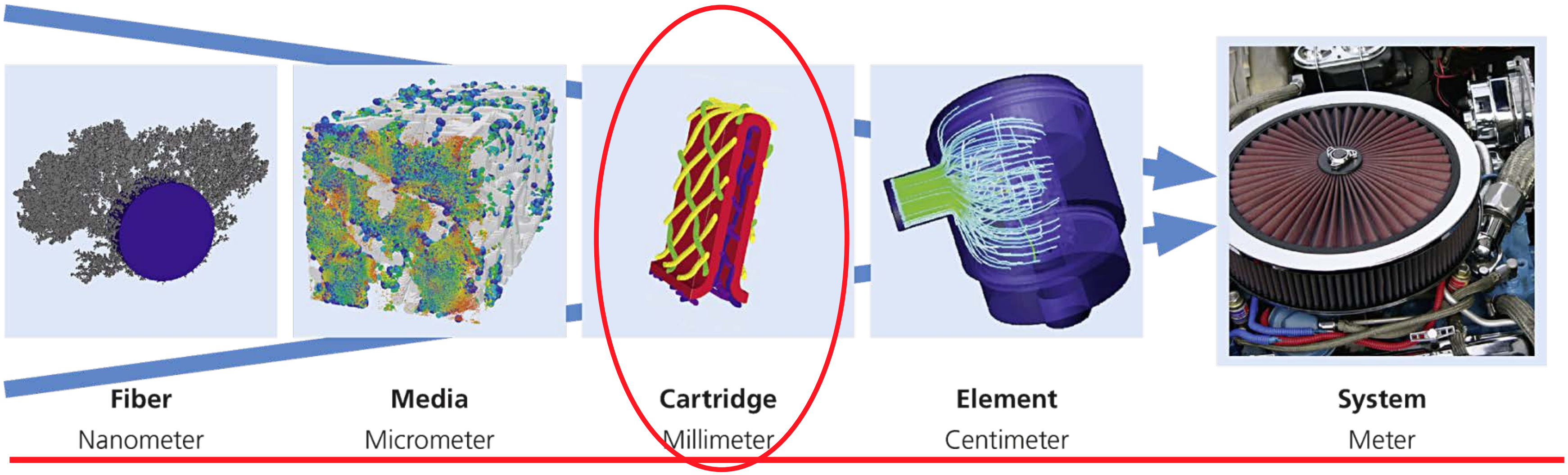

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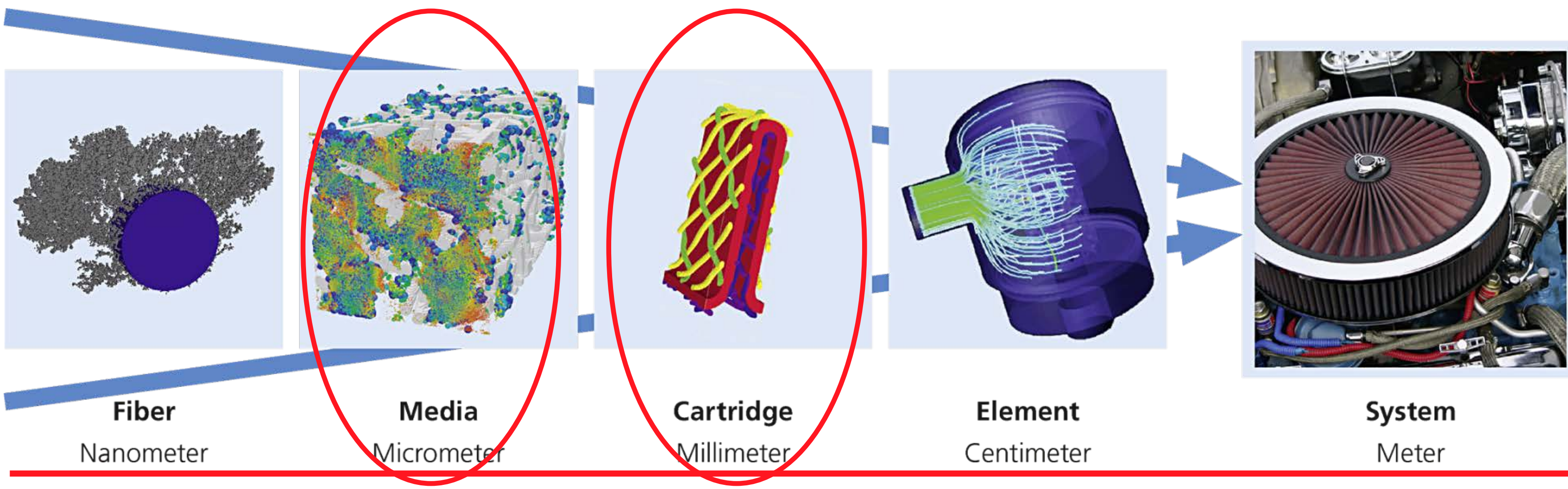
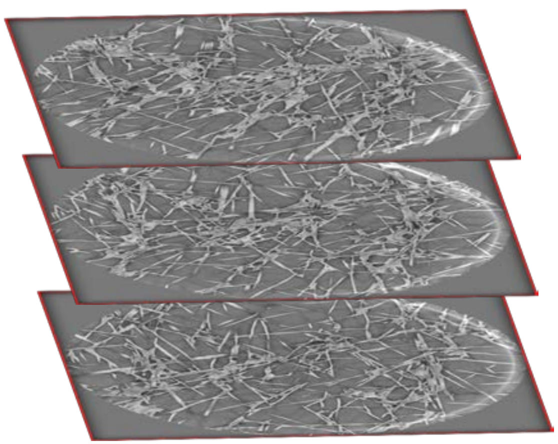


Microscopic simulation

- µCT: the detailed three-dimensional structure of filter media can be obtained. The 3D model of the filter media is partitioned into small cells, the computational grid, to perform the simulation.



Microscopic simulation

- Stationary slow flows in the no-slip regime may be described by the Stokes equations

$$-\mu\Delta \vec{u} + \nabla p = 0 \qquad \text{(Momentum balance)}$$

$$\nabla\cdot \vec{u} = 0 \qquad \text{(Mass conservation)}$$

$$\vec{u} = 0 \text{ on } \Gamma \qquad \text{(No-slip on fiber surface)}$$

Microscopic simulation

- Description of particle motion

Friction with fluid — Electric attraction — Diffusive motion

$$
\begin{aligned}
d\vec{x} &= \vec{v}\,dt, \\
d\vec{v} &= -\gamma \times (\vec{v}(\vec{x}) - \vec{v}_\circ(\vec{x}))\,dt + \frac{Q\vec{E}_\circ(\vec{x})}{m}dt + \sigma \times d\vec{W}(t), \\
C_c &= 1 + \frac{\lambda}{R}\left(1.17 + 0.525e^{-0.78R/\lambda}\right), \\
\gamma &= 6\pi\rho\mu\frac{R}{C_c m}, \\
\sigma^2 &= \frac{2k_B T\gamma}{m}, \\
\left\langle dW_i(t), dW_j(t)\right\rangle &= \delta_{ij}dt
\end{aligned}
$$

γ:	friction coefficient
k_B:	Boltzmann constant
$\vec{E}_\circ$:	electric field
$\vec{v}_\circ$:	fluid velocity
ρ:	fluid density
μ:	fluid viscosity
t:	time
$\vec{x}$:	particle position
$\vec{v}$:	particle velocity
R:	particle radius
m:	particle mass
Q:	particle charge
T:	ambient temperature
λ.	mean free path
$d\vec{W}(t)$:	3d probability (Wiener) measure

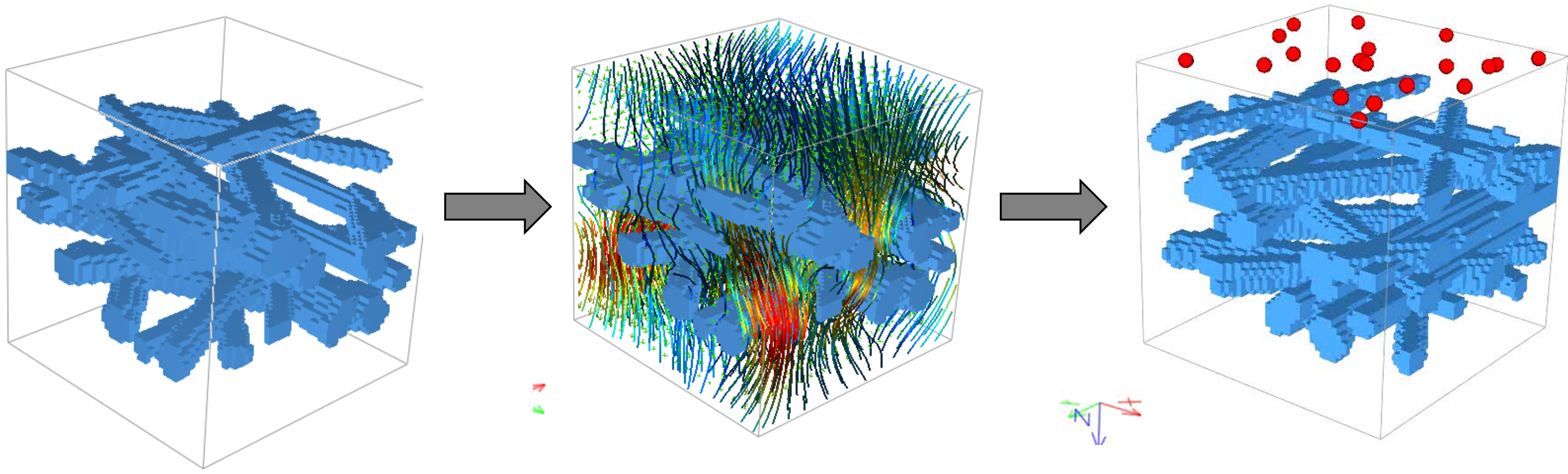
Microscopic simulation

- Filter efficiency

Basic idea:

1. Filter model
2. Determine flow field
3. Track particles (filtered or not?)

- Modeled effects:
  - Interception
  - Inertia impation
  - Brownian motion
  - Electrostatic attraction or repulsion

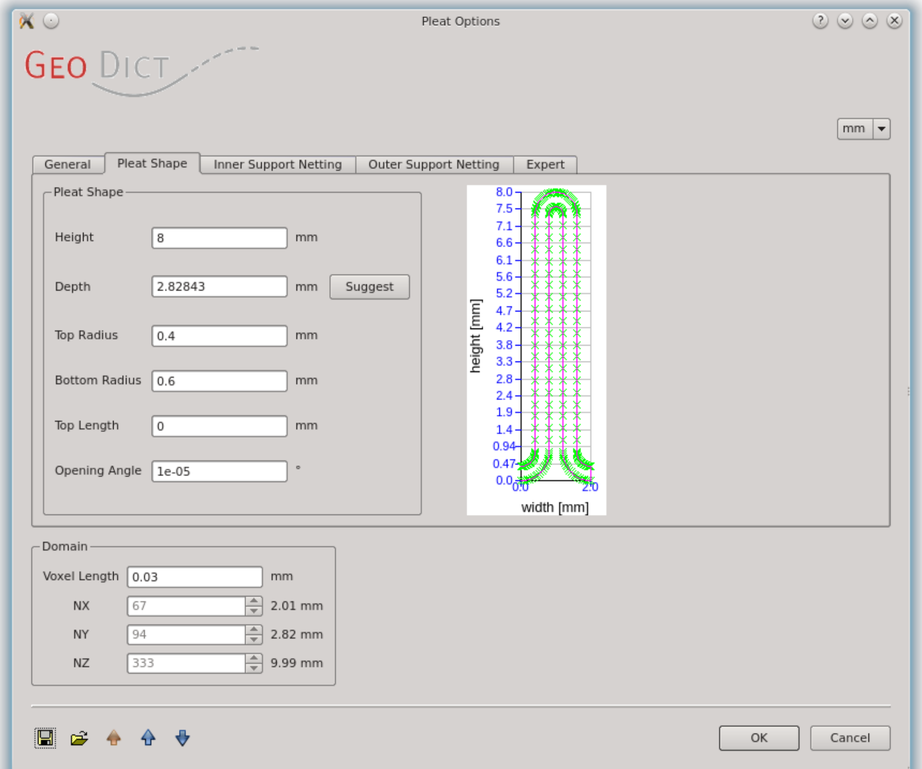


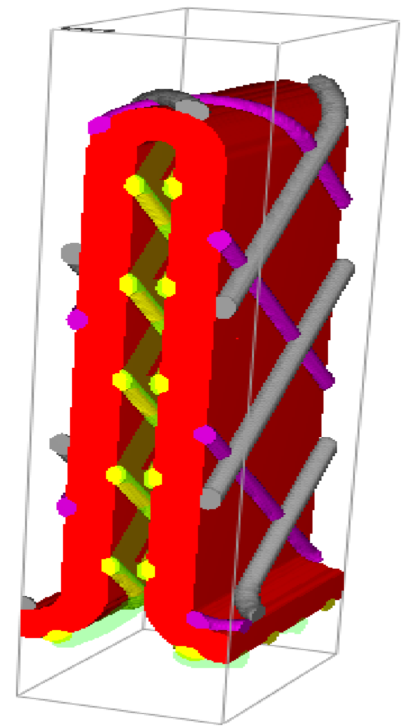
Pleat scale simulation

- The micro scale of filter media may not be enough to investigate the performance of the filter.
- The effects of the pleat shape, height and width must be considered.
- A huge domain if the micro resolution for the media scale is used.
- The detailed structure inside a medium has to be discarded and the medium is considered as a continuum with specific properties.
- The properties, such as permeability and filter efficiency, of the medium can be obtained from micro scale simulation as described previously.

Pleat scale simulation

- Pleat Generator: **GeoDict -PleatGeo**





MATH 2 MARKET

Fraunhofer ITWM

Pleat scale simulation

- The flow in a mixed free-flow and porous medium is described with the stationary Stokes-Brinkman equations

$$-\mu\Delta\vec{u} + \nabla p + \kappa^{-1}\vec{u} = 0 \qquad \text{(Momentum balance)}$$

$$\nabla\cdot\vec{u} = 0 \qquad \text{(Mass conservation)}$$

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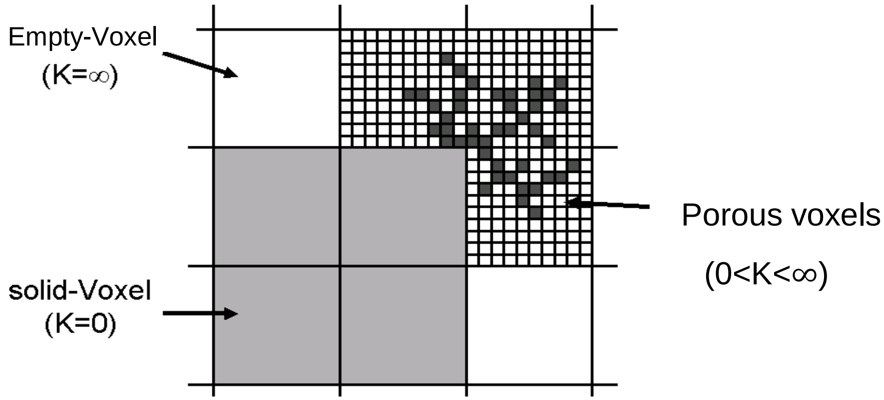


- as part of the porous media
- as part of the cake forming on the media surface
- as porous media containing additional sub-grid sized deposited particles

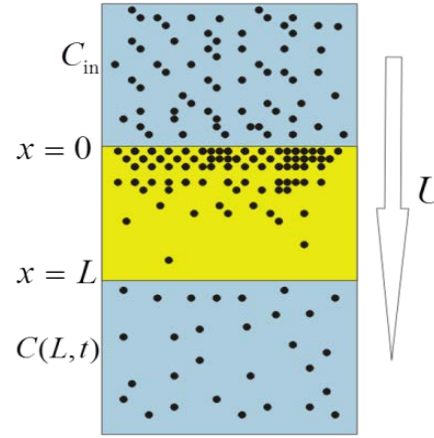
Pleat scale simulation

- Particle tracking

A macroscopic equation for the concentration of particles, the Convection Diffusion-Reaction equation, can be adopted for particle transport [1, 2]:

$$\frac{\partial C}{\partial t} + \vec{u}\nabla C - D\Delta C = \frac{\partial M}{\partial t}$$

where *C* is the concentration of particles, $\vec{u}$ is the velocity, *D* is the diffusivity coefficient; M is the mass of the captured particles in the filter medium, and $\frac{\partial M}{\partial t}$ means the rate of deposition.



When diffusion is negligible, the time variation of the concentration is solely governed by the deposition rate, and the 1D case is considered, then

$$u\frac{\partial C}{\partial x} = -\frac{\partial M}{\partial t}$$

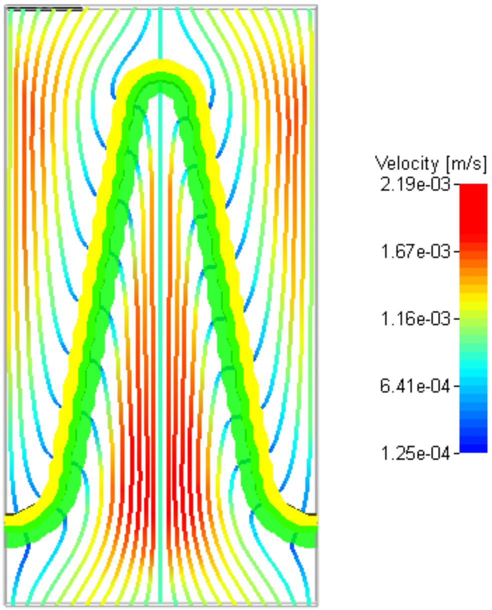
When assuming deposition rate is proportional to concentration of dissolved particles, a constant absorption rate model is used:

$$\frac{\partial M}{\partial t} = \alpha C$$

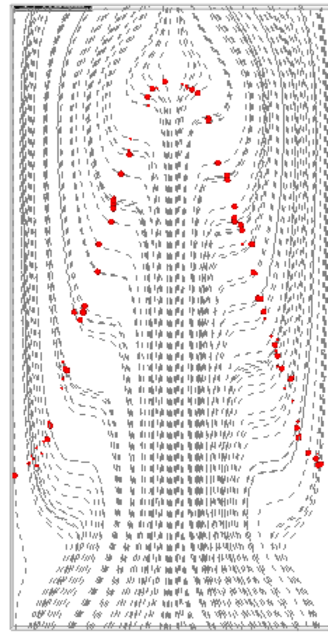
[1] O. Iliev, V. Laptev, D. Vasileva, Algorithms and software for flow through oil filters. *Filtech Europa*, Volume I, pp. I-327-I334, October 2003.

[2] M. Dedering, W. Stausberg, O. Iliev, Z. Lakdawala, R. Ciegis, V. Starikovicius, On new challenges for CFD simulation in filtration. *World Filtration Congress*, Leipzig, 2008.

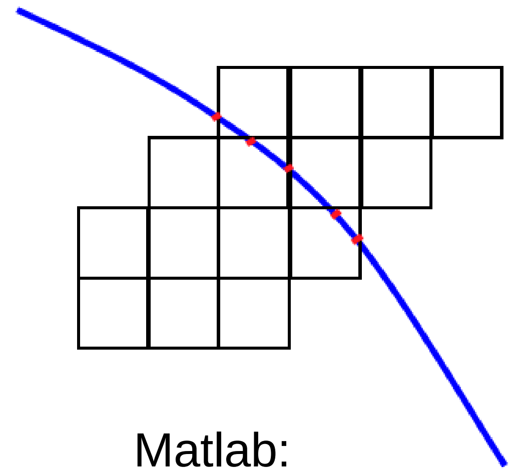
Pleat scale simulation



GeoDict -**Flow**Dict : computes the fluid flow in pleated filter.



GeoDict -**Filter**Dict : tracks the particle and find the trajectories following the flow field without obstacles.



Matlab:
The crossing of the trajectories and grids is found and the probability of a particle being captured in a voxel is determined.

Pleat scale simulation

- Resistivity model

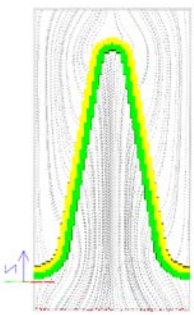
After distributing the captured particles,

- updates the local solid volume fraction ρ,
- updates the local resistivity σ,
- passes this data on to the flow solver.
- After recomputation of the flow field, the next batch is processed.

$$\sigma(\rho) = \begin{cases} 0 & , \ \rho \le \rho_{\text{min}} \\ \dfrac{\rho - \rho_{\text{min}}}{\rho_{\text{max}} - \rho_{\text{min}}} \sigma_{\text{max}} & , \ \rho_{\text{min}} < \rho < \rho_{\text{max}} \\ \sigma_{\text{max}} & , \ \rho \ge \rho_{\text{max}} \end{cases}$$

PleatLab – How it works

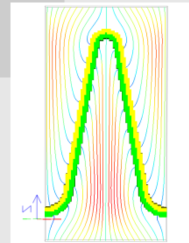
GEO DICT



MATLAB

PleatGeo
Geometry/Material colors
(only initial stage)

FlowSimulation
- Velocity field
- Pressure distribution



Particle trajectories
(without porous obstacle)

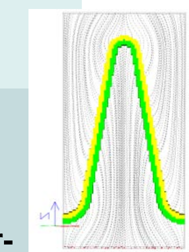
Read and analyze

while batch(es) left:
setup / control
(via macros)

Input data
- Fluid and flow
- Media properties
- Particle and batch data
- Models/solvers and their parameters

Update/summarize
- Update local solid volume fraction and resistivity
- Evaluate efficiency
- Write results to GDR

Simulate filtration process
- Compute captured mass/multiplicity passing through for each type (user-defined code)
- Distribute captured mass

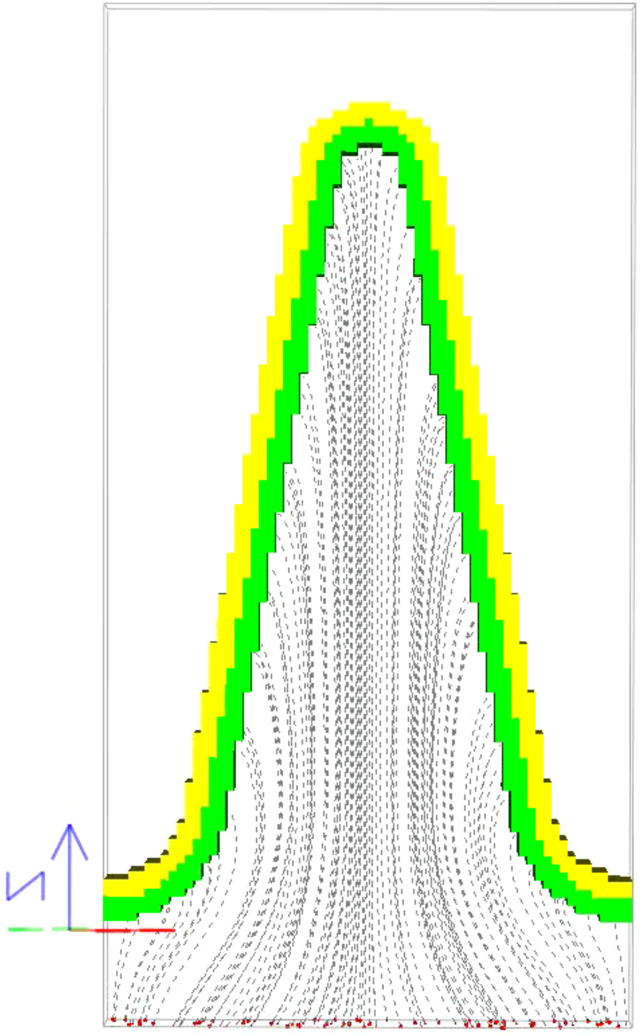


PleatLab – What it is (for)

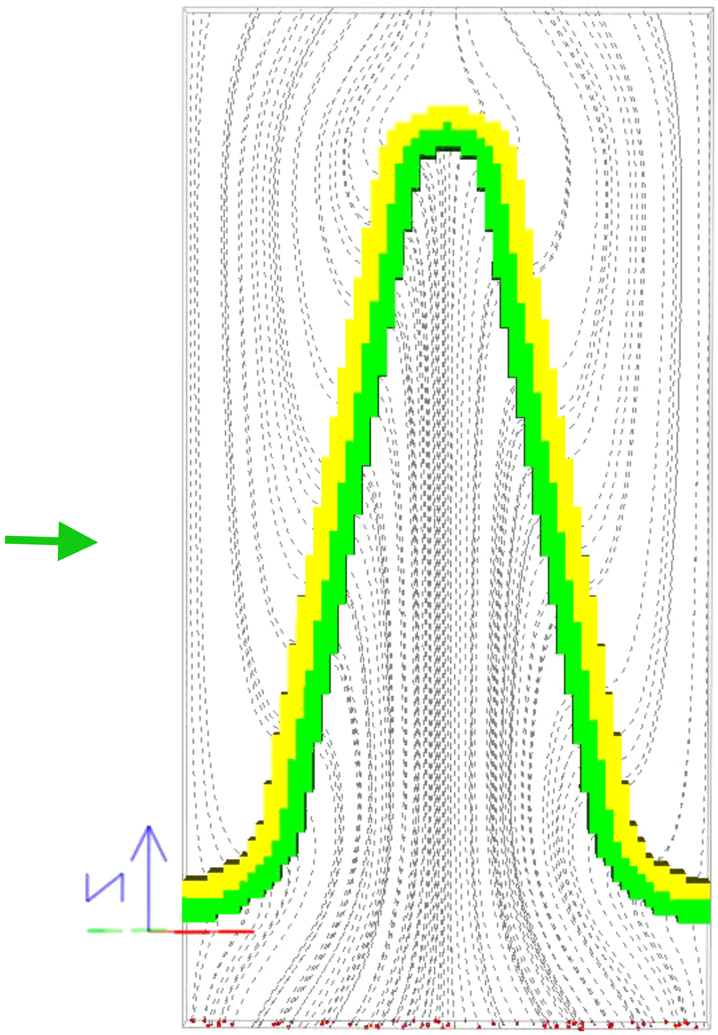
PleatLab is a flexible GeoDict® – MATLAB® interface that enables users to run customized flow and filtration simulations on the pleat scale in a quite easy way. Main features are:

- Input data and control of the simulation is done via MATLAB® modules and GeoDict® macros.
- Users can introduce/modify their own filtration models (MATLAB® code) for the simulation.
- NEW: Particle types in the batches can be assigned a multiplicity, i.e. each particle in the batch represents a group („swarm“, „packet“) of identical particles.

  → significant reduction of computational cost

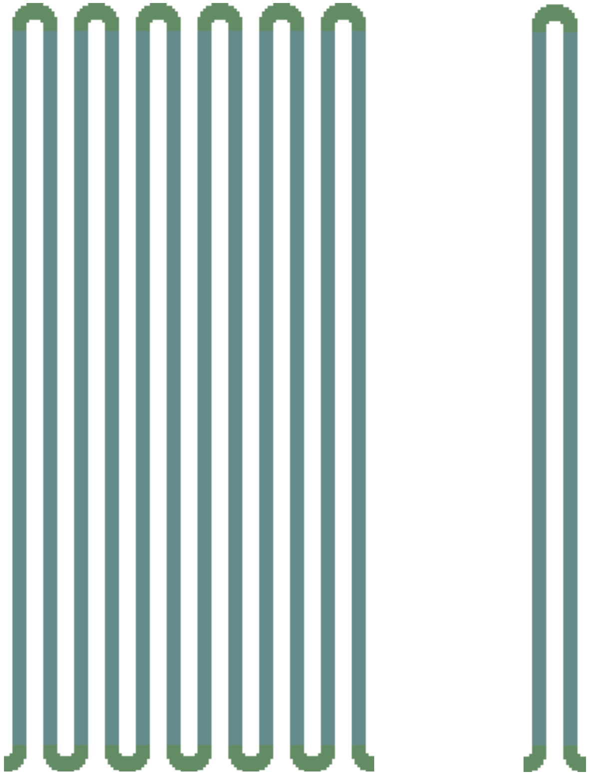


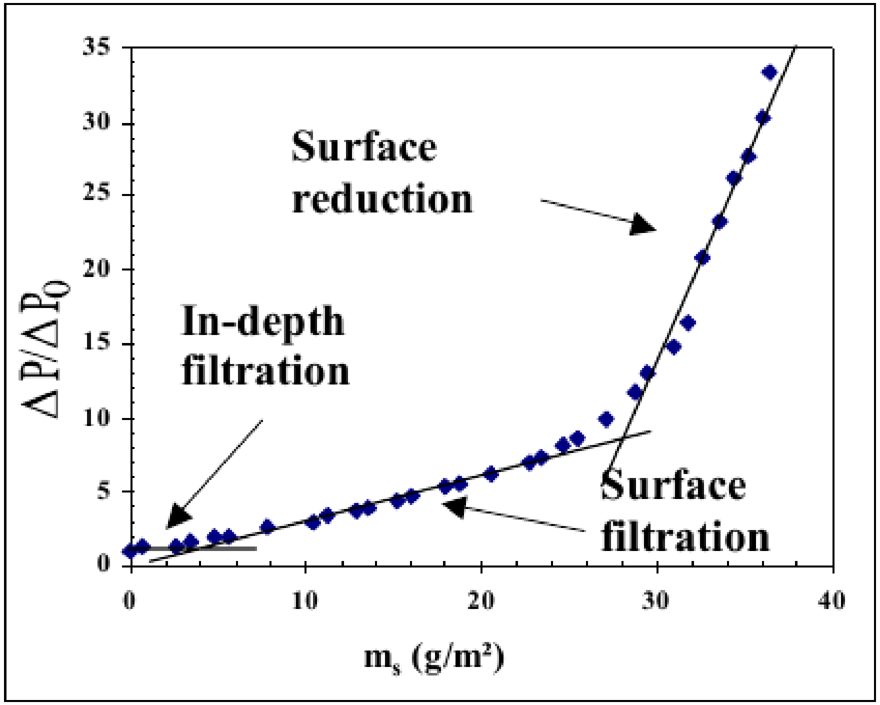
Cake filtration



In-depth filtration

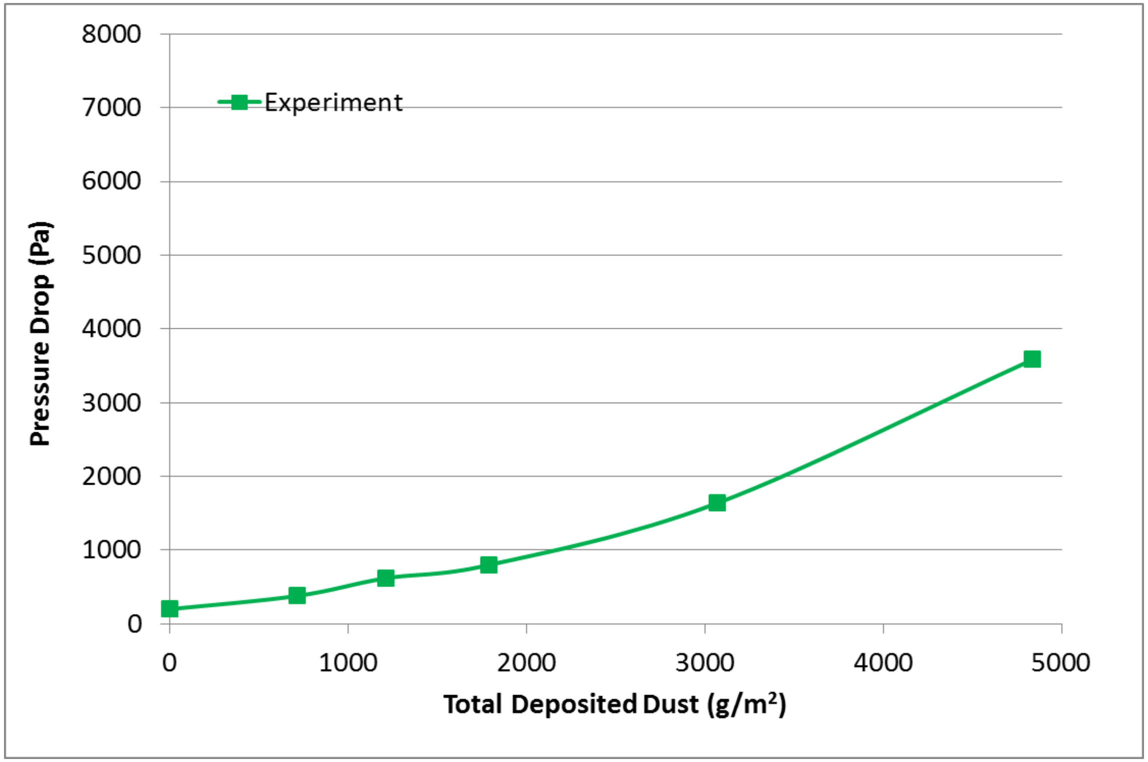
PleatLab – Comparison with experimental data





Experimental data*

- Pressure drop vs. load of a pleated filter



*Pierre-Colin Gervais, Experimental and numerical study of clogging of pleated filters. PhD thesis, CNRS, LRGP, UMR 7274, Nancy, F-54000, France, 2013.

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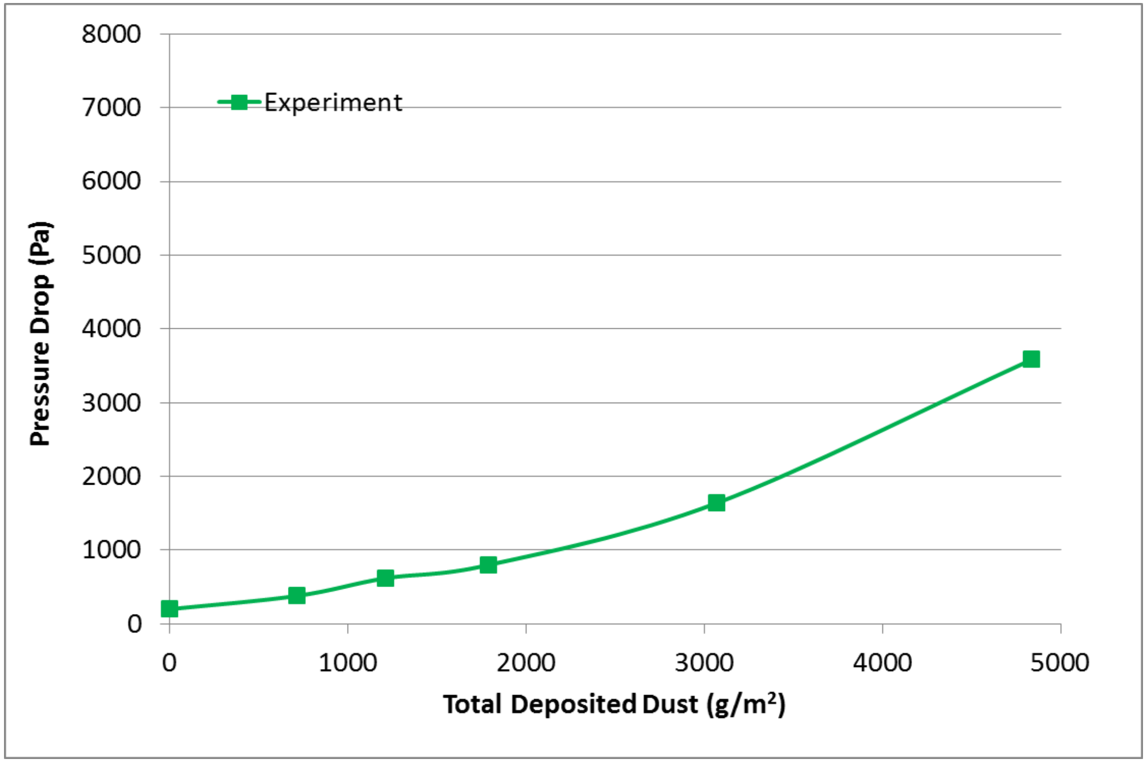

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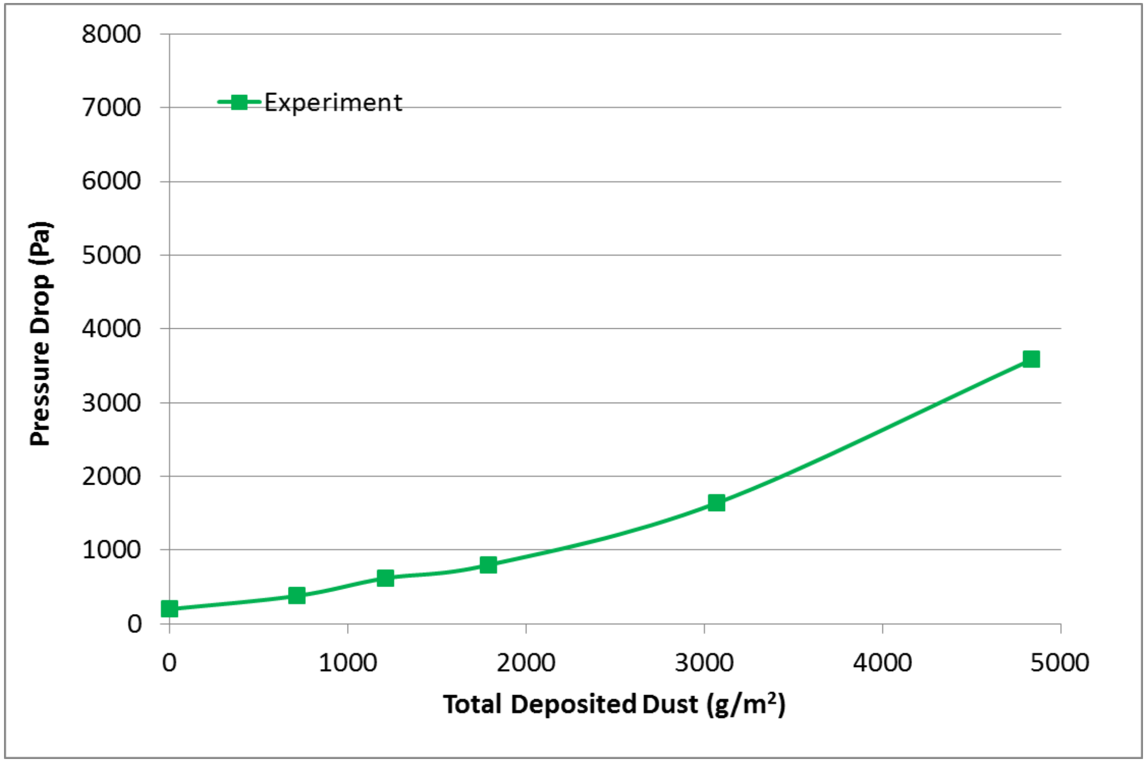

Experiment Settings	aerosol collected mass (g)	DP0 (Pa)	DP end of manip.(Pa)	Q_initial (m^3/h)	Q_final(m^3/h)	Rescaled DP (Pa)
	0	200	200			200
2DP0	16.05	195	380	40	40.6	374
3DP0	27.23	203	620	40.6	39.4	639
4DP0	40.18	200	798	40.1	38.8	825
8DP0	69.07	200	1640	40.5	37.6	1766
18DP0	108.81	200	3585	40.7	30.7	4753

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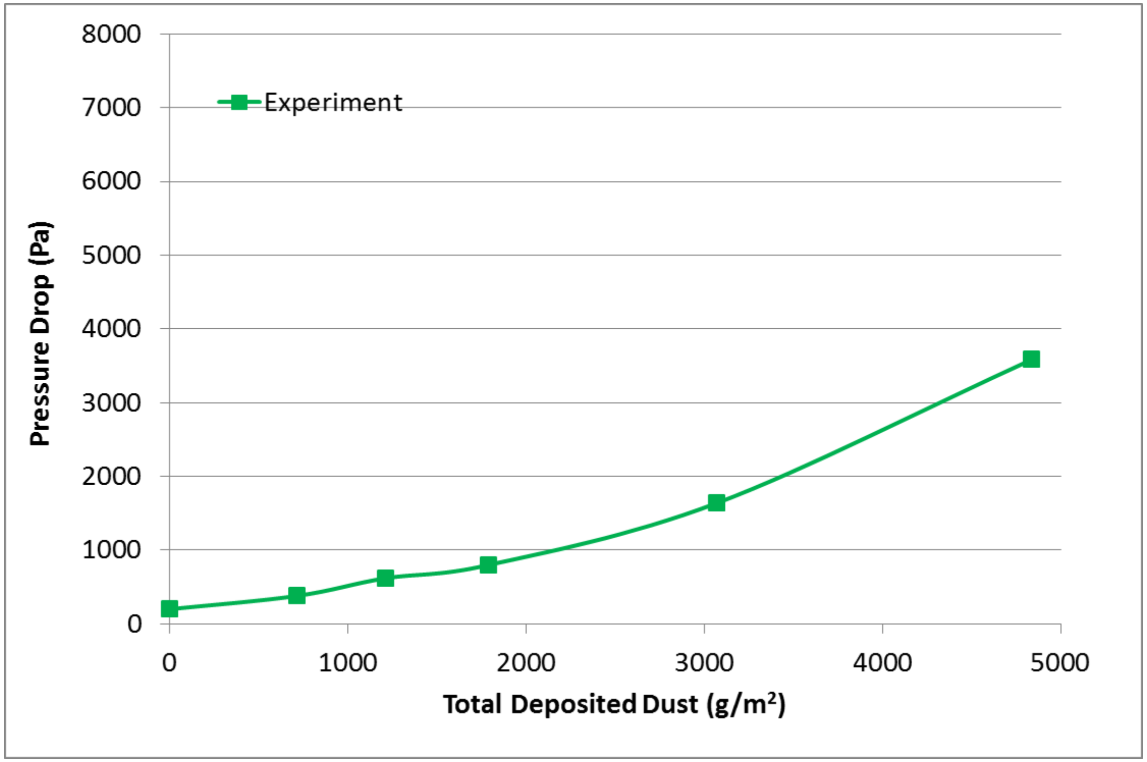

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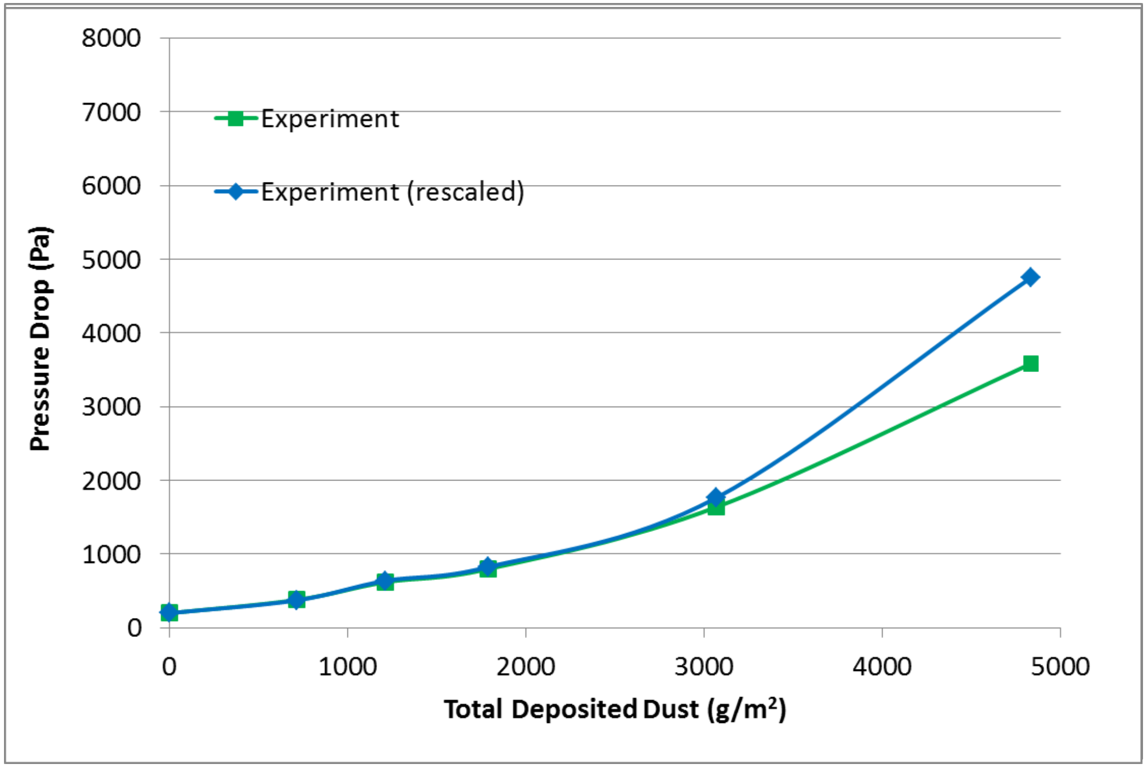
Experimental data*

- Pressure drop vs. load of a pleated filter
- Rescale to constant flow rate, what the pump was asked to do but did not do



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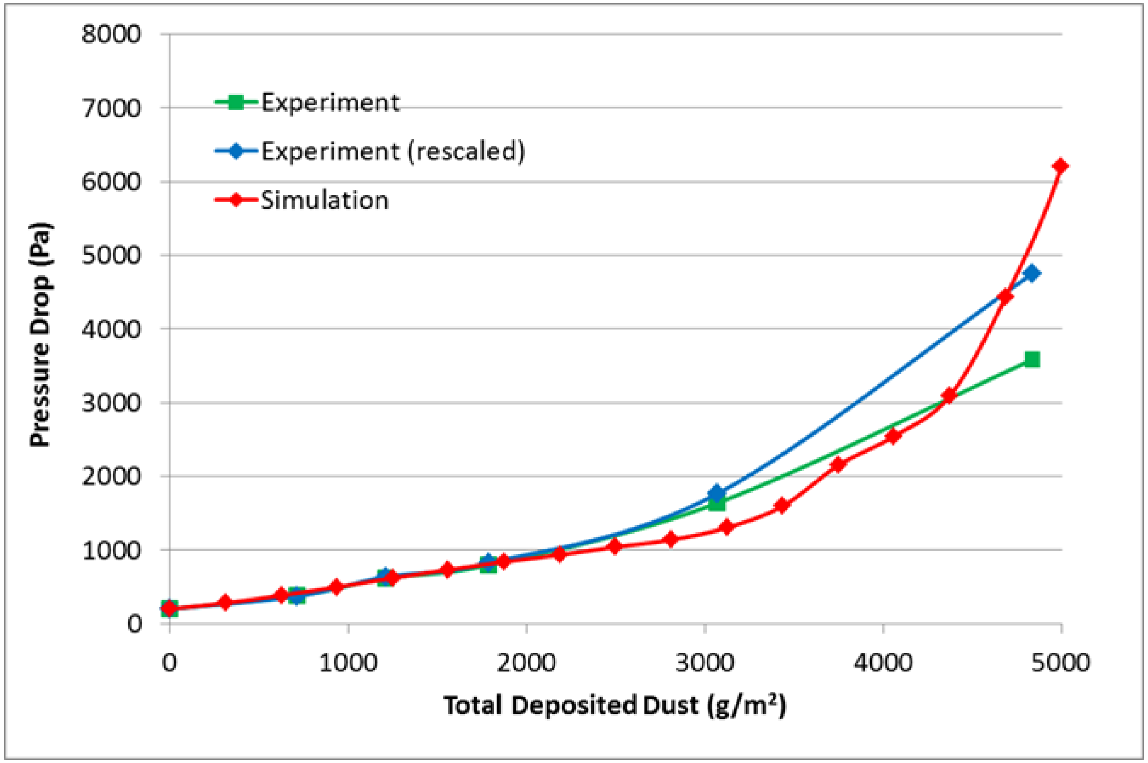
PleatLab – Comparison with experimental data

- Pressure drop vs. load of a pleated filter
- Rescale to constant flow rate, what the pump was asked to do but did not do
- Simulation results compared with experimental measurements (rescaling done w.r.t. fluctuations in the volumetric flow rate)



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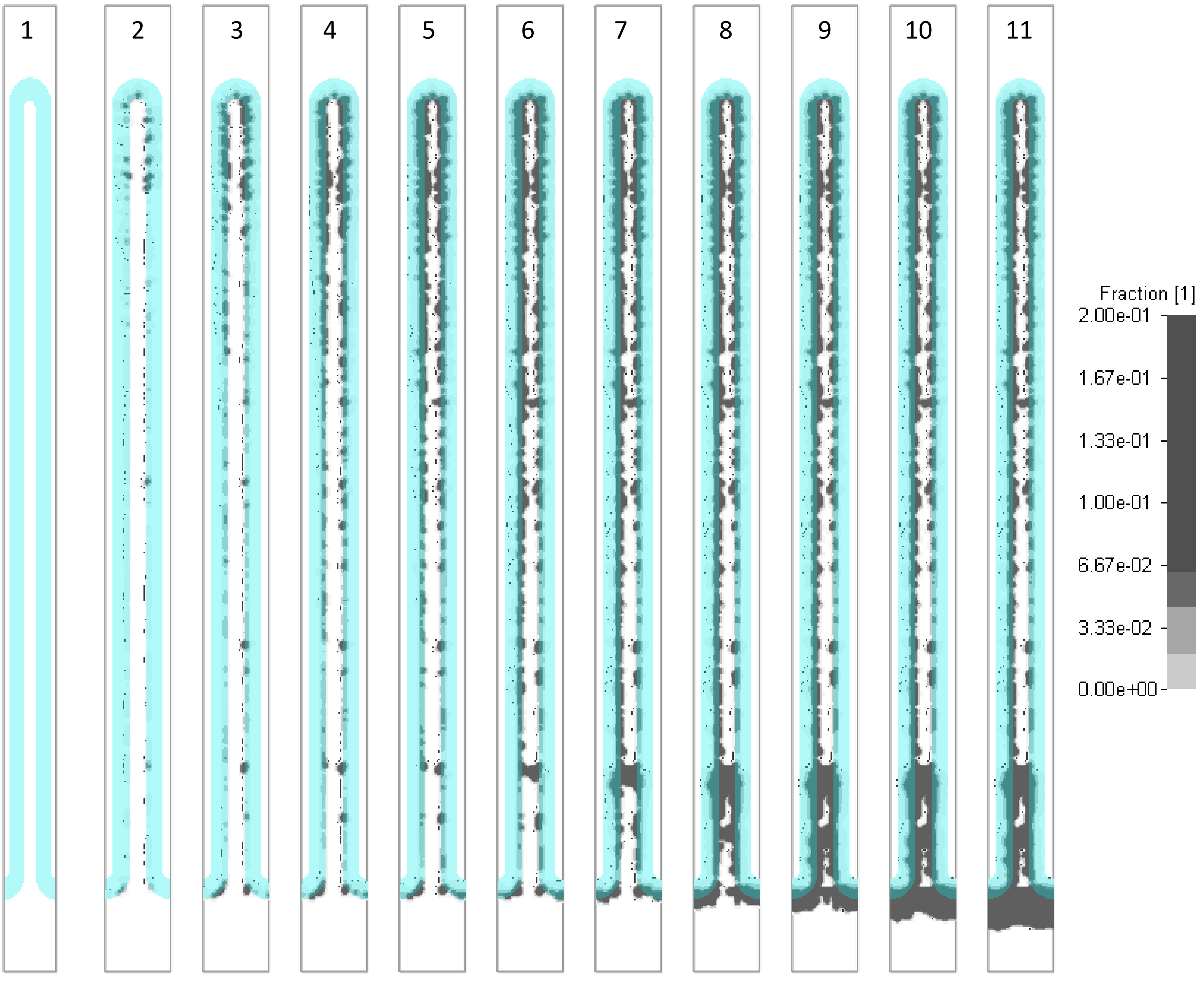
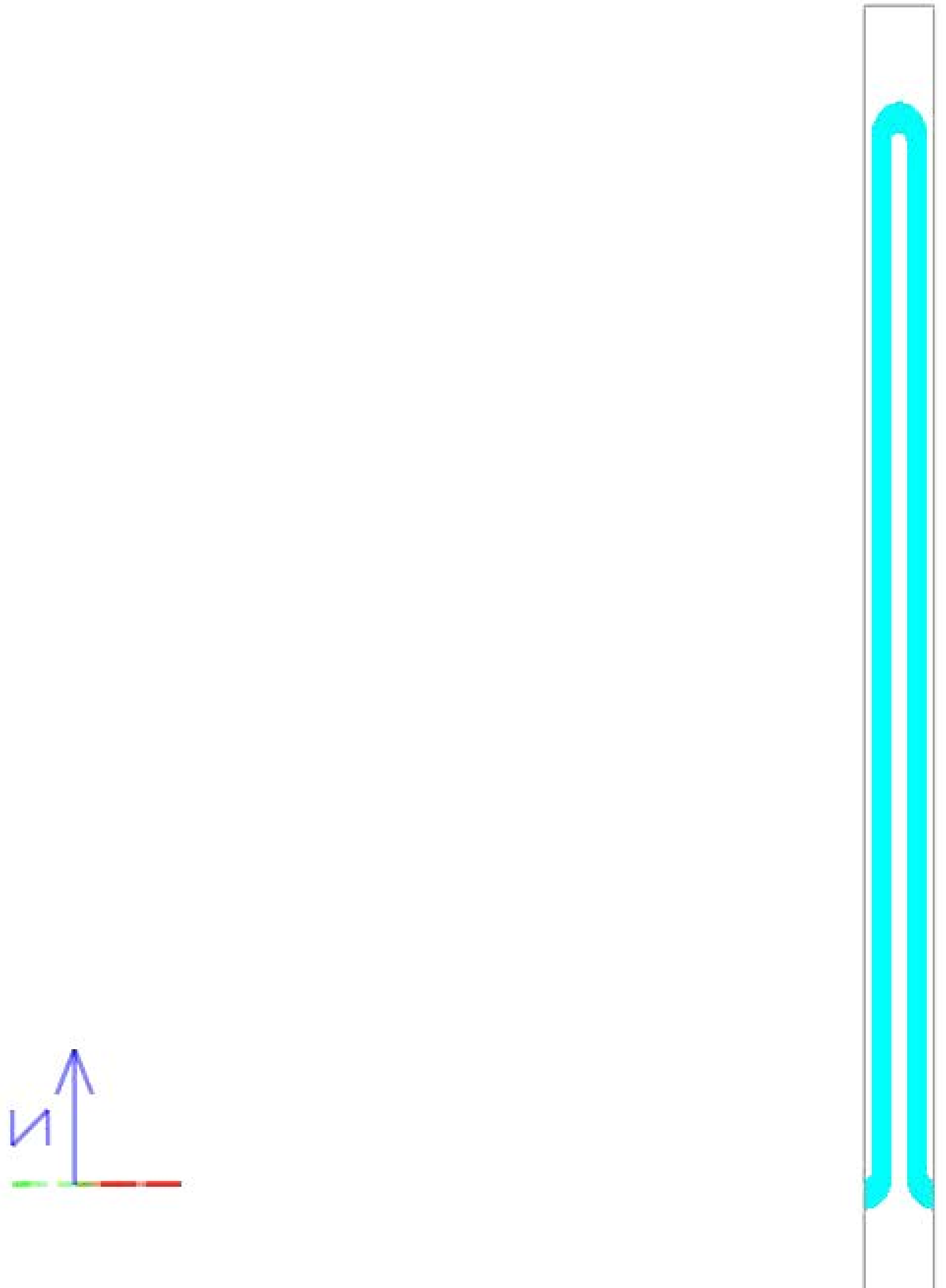
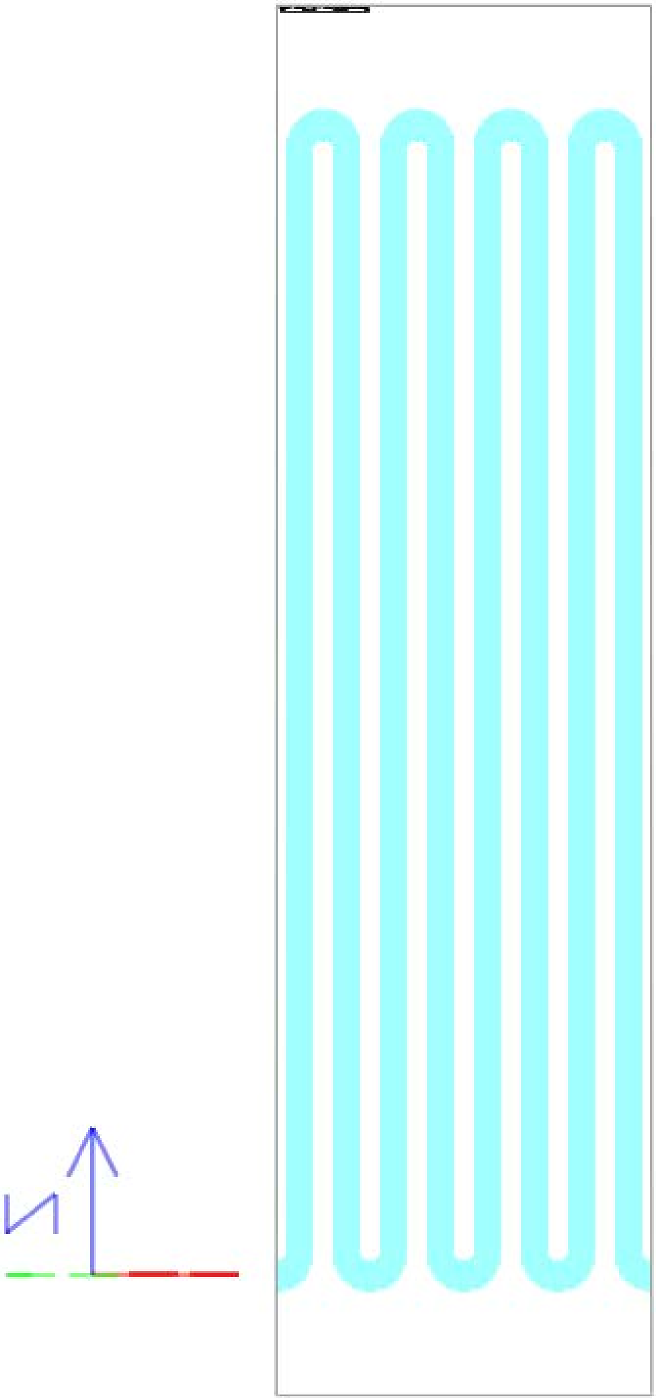


The particle deposition with time

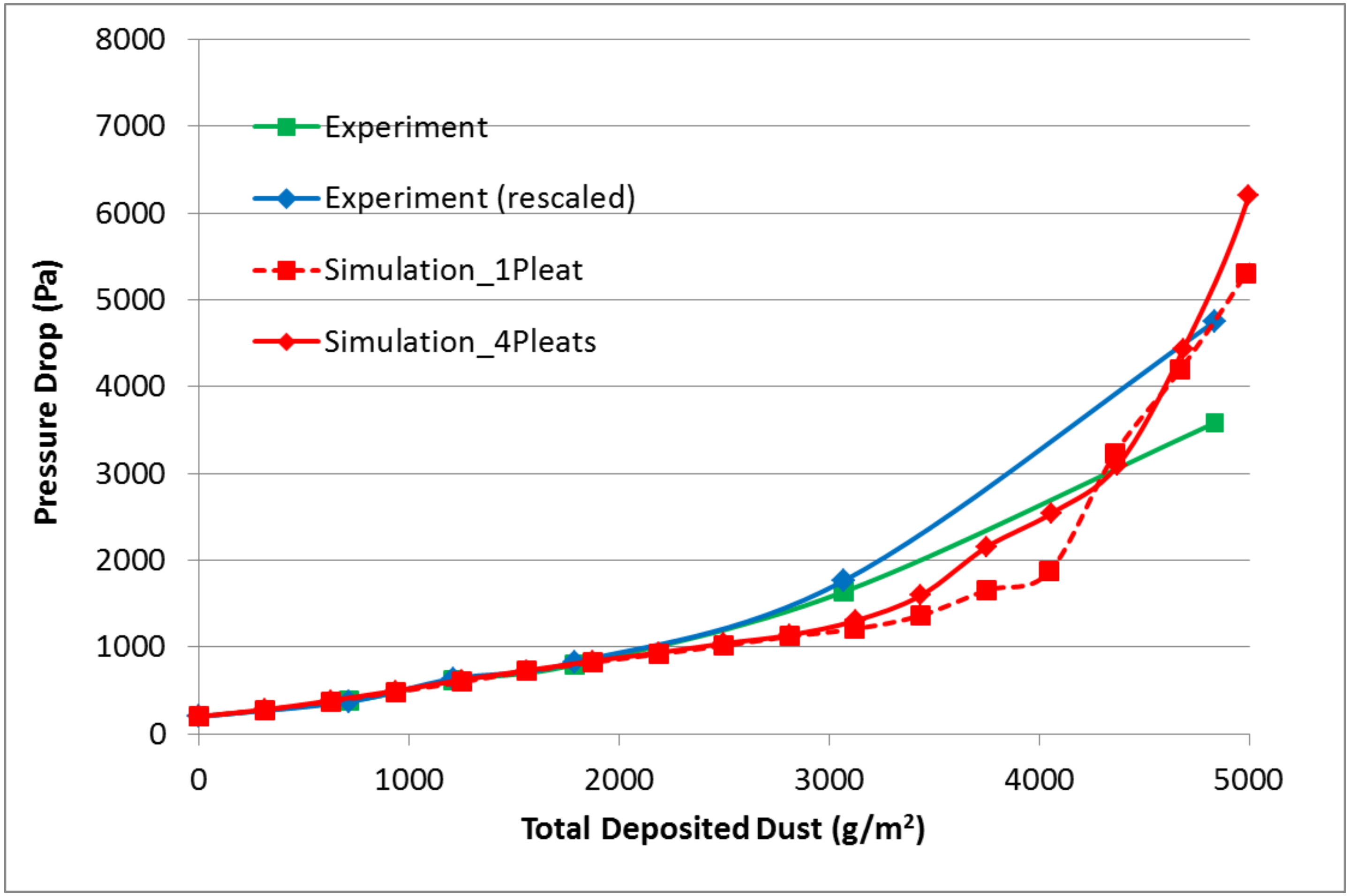


The simulation results with 1 pleat



The simulation results with 4 pleats

PleatLab – Comparison with experimental data



Conclusions

- With microscopic simulation for filter media, explicit modeling of the interatction between the particles and the media can be used for filtration simulation.
- But for pleat scale, due to the fact that the filter media are not resolved, the capture probability model of the particles are used.
- **PleatLab** combines GeoDict® and MATLAB® for pleat scale filtration simulations by separating the direct interaction from the simulation, yet accounting for the micro-scale filter efficiency and pleat scale flow simulation.
- Validation and first comparisons to experimental data are very promising and encouraging.
- It is shown that one pleat simulation is not enough to get smooth curve because the clogging on the pleat happens randomly.

Outlook

- Further comparison and validation with experimental data.
- Other capture probability models of the particles can be added.
- Further development will benefit from user experiences and feedback.
- Models will be integrated in **GeoDict**.

http://www.geodict.com
http://www.math2market.de

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