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PLEATLAB: A PLEAT SCALE SIMULATION ENVIRONMENT FOR FILTRATION SIMULATION

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ABSTRACT

On the micro-scale, the detailed geometry of filter media can be considered. With such high resolution, filtration simulations can directly model all different effects that contribute to the filter efficiency, such as interception, inertial impaction and diffusion. However, on the pleat scale, the filter media is not resolved and must be modeled as homogenized cells with defined permeability. Explicit modeling of the interaction between the particles and the media is not possible. We develop an environment for numerical experimentation combining 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 by statistical methods. The combination of GeoDict® and MATLAB® is called PleatLab.

The flow field is computed by solving the Stokes-Brinkman equations. In these, the additional term models the permeability of the filter media that cannot be resolved on the scale of a complete pleat; the permeability of the porous media formed by the sub-grid sized deposited particles, and the combination of the two. The filter efficiency of flat sheet media can be obtained from micro-scale simulations or experimental measurements. By analyzing particle paths, the probability of a particle being captured is modeled. In turn, captured particles lead to lower permeability of the pleat and increased capturing probability for later batches of particles over time.

With PleatLab, all three phases of pleat clogging, namely in-depth filtration, cake filtration, and surface reduction, can be modeled. Also, the modified SIMPLE-FFT algorithm accelerates the flow simulation greatly and allows simulations to be performed in a timely manner. Besides, task automation, automatic result extraction and improved pre- and post-processing make PleatLab a user-friendly environment for performing research employing pleat scale filtration simulations.

The comparison is made between results simulated with PleatLab and experimental data for a pleated filter. A good agreement is found for the evolution of the overall pressure drop across the filter element during clogging for a given flow rate.

KEYWORDS

Pleated filter, simulation, filtration, GeoDict®, PleatLab

1. Introduction

Compared to traditional bag filters, pleated filters greatly increase filter surface area so that lower air to cloth ratios are allowed in the same space and higher dust retention rates can be obtained. Therefore the number of filter cleaning cycles is reduced and the overall performance of the dust collector system is improved.

For numerical simulations of filtration processes the scale of the simulation plays an important role. For the purpose of designing the fibrous material of a pleated filter, the following considerations have to be taken into account:

1. The precise geometry of the filter media
2. The fluid flow in this geometry
3. The transport and deposition of particles
4. The changes of the geometry after particles have deposited

Due to the availability of 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. Stationary slow flows in the no-slip regime may be described by the Stokes equations with periodic boundary conditions:

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

$$\nabla \cdot \vec{u} = 0 \quad \text{(Mass conservation)}, \qquad (2)$$

$$\vec{u} = 0 \ on \ \Gamma \quad \text{(No-slip on fiber surface)}, \qquad (3)$$

$$P_{in} = P_{out} + c \quad \text{(Pressure drop is given)}. \qquad (4)$$

Here µ is the fluid viscosity, $\vec{u}$ is the (periodic) velocity, and *p* is pressure (periodic up to the pressure drop in the flow direction). We use the finite difference approach on staggered grids [1] to solve the Stokes equations to get the flow field that is needed for particle tracking.

To compute the filter efficiency, particles are placed at random positions at the beginning of the inflow regime. These particles are then tracked according to increasingly complex laws of motion that are always based on the air flow. If during the tracking procedure a particle touches a fiber surface, then in the *caught on first touch* model it is captured and accounted for as filtered. Three distinct effects contribute the filtration efficiency [2]. Firstly, simply by following a stream line of the flow, a particle may get so close to a fiber that it touches. This effect is called *interception*. Secondly, based on its mass a particle may leave a curving stream line and travel straight due to its inertia. This effect is called *inertial impaction*. Finally, very small particles may leave the trajectory based on the flow and inertia due to random hits by air molecules. This effect is called *Brownian diffusion*. All these effects can be described by a stochastic differential equation for the position $\vec{r}(t)$ and the velocity $\vec{u}(t)$ of the particles [3]

$$d\vec{v} = -\gamma \times \left(\vec{v}\big(\vec{x}(t)\big) - \vec{u}\big(\vec{x}(t)\big)\right) dt + \sigma \times d\overrightarrow{W}(t), \tag{5}$$

$$d\vec{x} = \vec{v}\big(\vec{x}(t)\big)dt, \tag{6}$$

$$\sigma^2 = \frac{2k_B T\gamma}{m}, \tag{7}$$

$$\langle dW_i(t)dW_j(t)\rangle = \delta_{ij}dt. \tag{8}$$

Here T is the ambient temperature, k_B is the Boltzmann constant and $dW(t)$ is a 3d probability (Wiener) measure. γ is the friction efficiency and the friction model is based on Stokian friction of spherical particles, supplemented by the Cunningham Slip Correction factor $C_c(Kn)$ as introduced in [4] for solid particles at NTP conditions.

$$\gamma = 6\pi\rho\mu\frac{R}{C_c m}, \tag{9}$$

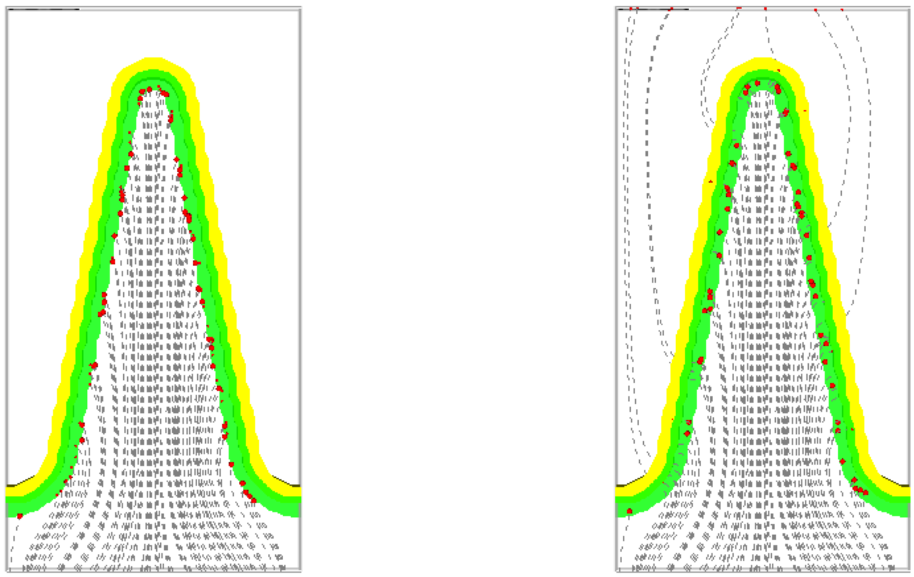
$$C_c = 1 + \mathrm{Kn}\left[1.142 + 0.558e^{-\frac{0.999}{Kn}}\right]. \tag{10}$$

However, the study on the micro scale of filter media may not be enough to investigate the performance of the filter on the pressure drop, filter efficiency, and filter life time. The effects of the pleat shape, height and width must be considered. It will produce a huge domain if the micro resolution for the media scale is used. Therefore the detailed structure inside a medium has to be discarded and the medium is considered as a continuum with specific properties. In other words, another scale comes into play, the pleat scale. The properties, such as permeability and filter efficiency, of the medium can be obtained from micro scale simulation as described previously.

To numerically simulate filtration effects on the pleat scale, we firstly also need to obtain or create realistic three dimensional geometric models. CAD data are commonly available for the filter and the PleatGeo module of GeoDict® automatically generates three-dimensional computer model from analytic or statistical descriptions.

To compute the flow field the stationary Stokes-Brinkman equations with periodic boundary conditions are solved. The flow solver provided in the FlowDict module of GeoDict® recognizes the void, solid, or porous voxels by permeability tensor.

Once the flow field is solved, as shown in Figure 1, the particles need to be tracked to simulate the filter efficiency. With the current FilterDict® module of GeoDict®, the particle tracker does not handle particles traveling through a porous voxel. It considers all colored voxels as solid, so when a particle encounters such voxels, in the *caught on first touch* model it is filtered. As shown in Figure 1(a), a pleated filter structure is closed to the particles, all of which deposit on the filter surface. And no trajectories are possible behind the filter. This is not true, even though it is possible that 100% of the particles are captured with some type of filters, not all the particles stay on the top of the filter, but enter the filter and travel a certain distance inside. In other words, in-depth filtration as shown in Figure 1(b) is not realized. In [5], [6] and [7], only the cake filtration is modeled for pleated filter media during dust loading. In [8], only the in-depth filtration is simulated. None of them has implemented all stages of pleat-scale filtration in a single simulation.



(a) (b)

Figure 1: particle trajectories and final deposition position for cake filtration(b) and in-depth filtration(c).

The aim of the work presented in this paper is to overcome the difficulty that the particle tracker cannot recognize porous obstacles and provide a simulation environment via external tool, MATLAB® in our case, for numerical experimentation on pleat scale filtration simulation by separating the direct interaction from the simulation, but accounting for the micro-scale filter efficiency and pleat scale flow simulation, so as to provide users an easy-to-use environment to simulate the whole process of pleat filtration, including in-depth filtration, cake (surface) filtration, and surface reduction filtration.

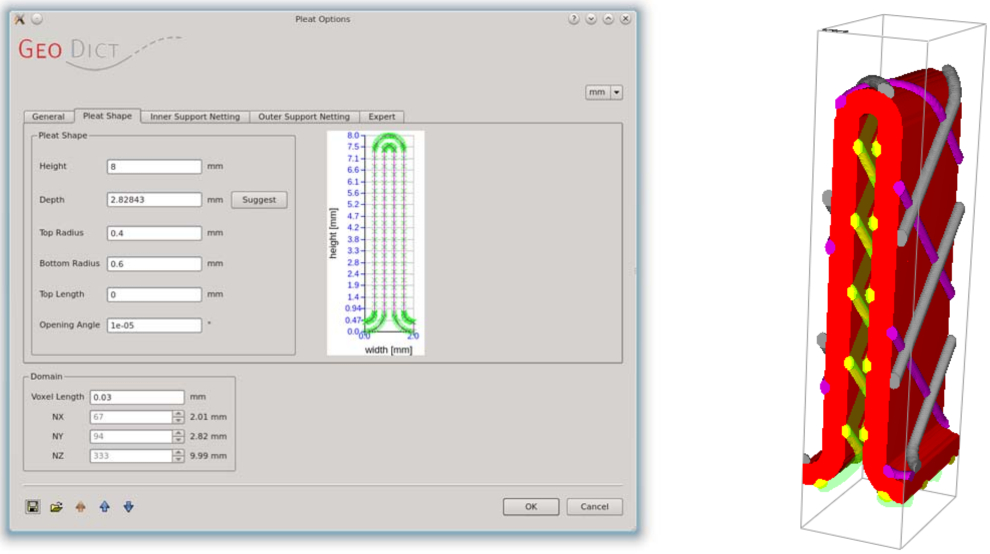
2. Method

2.1 Pleat Generator

The PleatGeo module [9] automatically generates a virtual structure given the following parameters:

- Inlet length (inflow region)
- Outlet length (outflow region)
- Up to 5 layers and thickness for each

- Pleat depth (a single voxel for 2d simulations)
- Pleat height
- Layer material types
- Pleat opening angle
- Pleat radius at inlet (pleat radius top)
- Pleat radius at outlet (pleat radius bottom)
- Voxel length (the resolution for the simulations)



(a) (b)

Figure 2: (a) Input dialog of PleatGeo, (b) generated pleat with inner and outer support.

Figure 2 illustrates the conversion from the geometrical parameters of a pleat filter and mesh description to a three-dimensional virtual structure of a pleat that has a single-layer media and inner and outer supports.

2.2 Flow Simulation

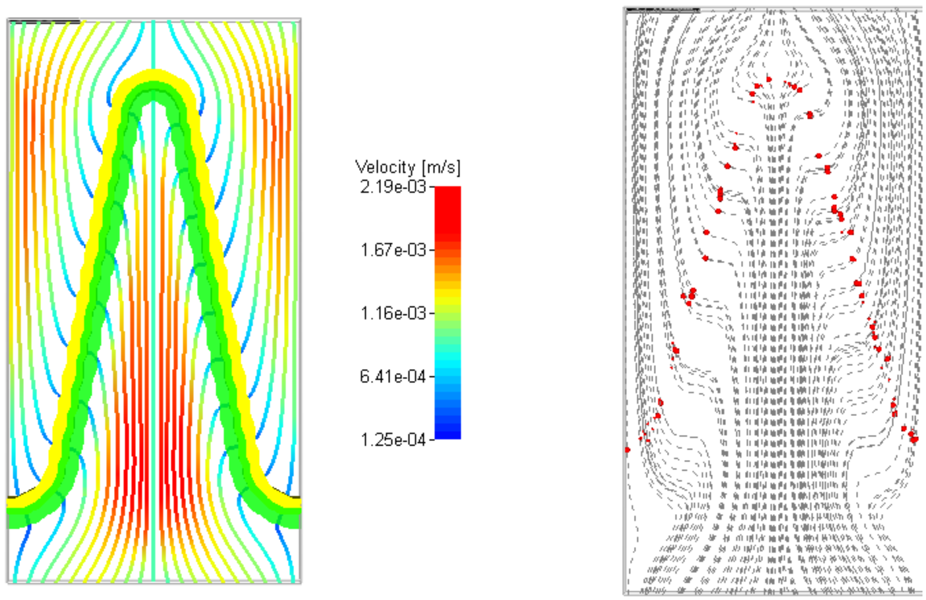
The flow in a mixed free-flow and porous medium is described with the stationary Stokes-Brinkman equations introduced for numerics by Iliev and Laptev [10] with periodic boundary conditions. Different from (1), the momentum balance equation becomes

$$-\mu\Delta\vec{u} + \nabla p + \kappa^{-1}\vec{u} = 0 \qquad \text{(Momentum balance).} \qquad (11)$$

The computational grid images contain different colors, which represent different materials and their properties. The voxel cell can be void, solid, or porous. Voxels may be porous as part of the porous media, as part of the cake forming on the media surface, or as porous media containing additional sub-grid sized deposited particles.

For example, the empty space in Figure 2(b) has color 0 and has free flow. The voxels in the red domain are porous so the inverse of the permeability tensor κ^{-1}

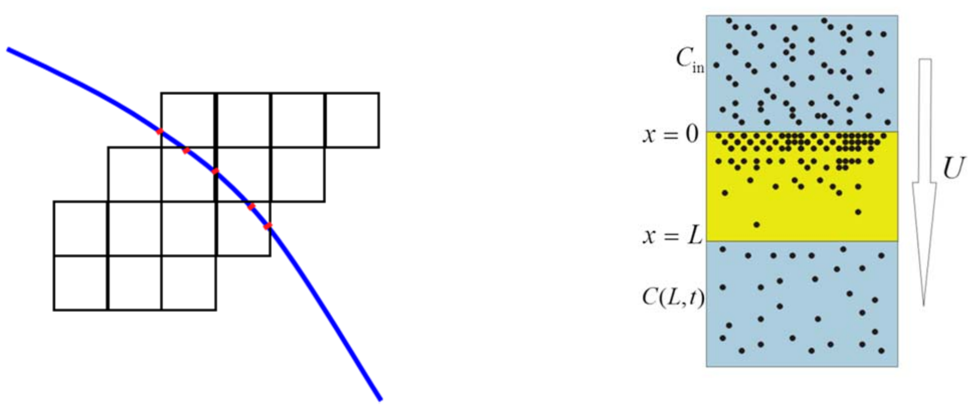
has to be taken into account. Or, for example in Figure 1, when the size of a particle is much smaller than a voxel and after it deposits in an empty voxel neighbor to a pleat surface, the influence of the particle on the flow is described with κ^{-1}, too. The other colors model the support of the pleat. They are all solid; no-slip boundary conditions hold on the surface and there is no flow inside.



(a) (c)

Figure 3: (a) Streamline of the flow field for a pleated filter, (b) particle trajectories when no obstacles exist.

The Semi-Implicit Method for Pressure-Linked Equation (SIMPLE) algorithm by Pantakar and Spalding [11] is available in GeoDict®. The recently improved version, SIMPLE-FFT [12], for the Stokes equations provides a good initial guess for Stokes-Brinkman equations, and to greatly speed up the convergence.



(a) (b)

Figure 4: (a) travel path of a particle inside the filter media and the crossing with the grid cells, (b) schematic plot of capture filtration model.

2.3 Particle Tracking

When injecting the particles in the flow calculated previously (Figure 3(a)) but firstly assuming no obstacles/pleat structure in the field, the trajectories of the particles can be computed with the FilterDict® module, as shown in Figure 3(b). Then we can get the travel path inside the media by taking the geometrical information of the medium structure and the trajectories with MATLAB®.

The capture probability model of the particles can be introduced. Users are allowed to implement their own model in the MATLAB® code. Some examples of such models follow.

On the macro scale, a macroscopic equation for the concentration of particles, the Convection Diffusion-Reaction equation, can be adopted for particle transport [13, 14].

$$\frac{\partial C}{\partial t} + \vec{u}\nabla C - D\Delta C = \frac{\partial M}{\partial t}, \quad (12)$$

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 as shown in Figure 4(b). Then Equation (12) can be simplified to

$$u\frac{\partial C}{\partial x} = -\frac{\partial M}{\partial t}. \quad (13)$$

Under the assumption that the amount of the deposited particles is small compared to the pore space of the filter medium, the mass of the deposited particles is considered to be proportional to the concentration of particles [15]

$$\frac{\partial M}{\partial t} = \alpha C, \quad (14)$$

where α is the constant deposition rate. The analytic solution can then be derived for Equation (13) and (14):

$$C(x,t) = C_{in}e^{-\frac{\alpha}{U}x}, \quad (15)$$

$$M(x,t) = \alpha t C_{in}e^{-\frac{\alpha}{U}x}. \quad (16)$$

The value of α can be obtained from analyzing the experimental measurement or from micro scale simulations. And *x* is the travel length and is obtained from analyzing the crossing of the particle trajectories and voxels, as in Figure 4(a). Then the Beta ratio and the corresponding efficiency can be computed:

$$\beta(t) = \frac{C_{in}}{C(L,t)} \tag{17}$$

$$E(t) = 1 - \frac{1}{\beta(t)} = \frac{C_{in - C(L,t)}}{C_{in}} \tag{18}$$

The simulation in this step has not been implemented in the FilterDict® module, but is done by coding in MATLAB®.

2.4 Resistivity model

The possibility of a particle being captured during travelling in a voxel can then be determined from Equation (17) and (18). If it is captured, the particle resides in the voxel and produces resistance to the flow. The resistivity σ within the voxel is calculated as:

$$\sigma = \begin{cases} 0 & , \quad f < f_{min} \\ \frac{f - f_{min}}{f_{max} - f_{min}} & , \quad f_{min} < f < f_{max} \\ \sigma_{max} & , \quad f > f_{max} \end{cases} \tag{19}$$

where *f* is the volume fraction of a voxel taken by particles. When *f* is smaller than f_{min}, the influence of the particles is neglected. When *f* is greater than f_{max}, the resistivity is σ_{max}. The geometric model, updated with deposited particles and changed properties, is then sent to FlowDict to compute the gas flow again, and the simulation loop is repeated with the next batch of particles.

3. Lifetime clogging simulation of pleat filters

A high efficiency particulate air (HEPA) filter is a type of air filter that must remove 99.97% of particles that have a size of 0.3 µm. It is widely used in medical facilities, automobiles, aircraft, and homes. The aim of this work is to simulate the lifetime filtration of a HEPA filter and to predict the pressure drop and efficiency, and particle locations in or on the filter. The simulated results are validated by comparing them with experimental measurements [16].

It is found from visual observation of experiments that three phases exist in a clogging of pleated filters [17], shown in Figure 5. Firstly it is in-depth filtration that the particles are absorbed inside the filter and the increase of pressure drop is very limited. The second phase is surface filtration, or cake filtration, in which the particles are captured on the surface of the pleat or previously deposited particles and a filtration cake is formed. Finally, after a certain “critical” captured mass the surface reduction phase occurs. In this phase, the air inflow channel becomes narrower and narrower, even blocked by the particles. A significant increase of the pressure drop is observed.

To simulate the whole process of the filtration, a virtual filter structure is firstly generated. Figure 6 shows the structures of such a filter and due to periodicity, a computed domain shown on the right is used. The geometrical parameters of the pleat are: height 27.5mm, open angle 0, top and bottom radius 0.55mm, media thickness 0.55mm. And the size of particles ranges from 0.15µm to 6.8µm.

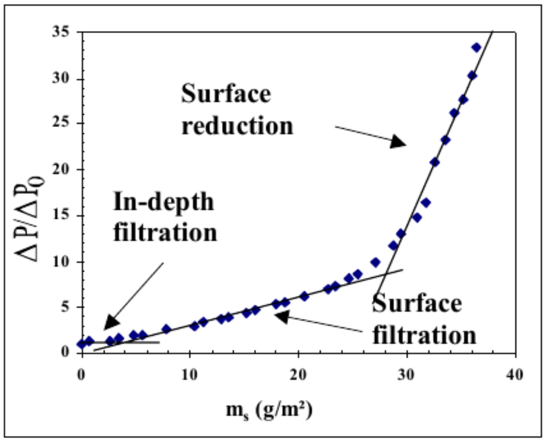


Figure 5: Clooging of pleated filters in three phases.

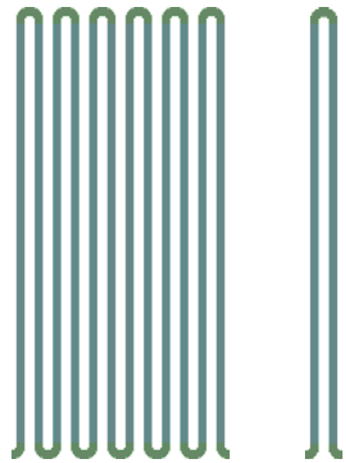


Figure 6: The structure of a HEPA filter generated by PleatGeo.

The simulation is then run with PleatLab on a one-voxel-thick pleat structure with constant absorption rate model, constant material permeability in the flat region and radius dependent values in the bent region, and different parameters for the resistivity model for particles depositing in-depth and as cake.

Figure 7 shows the evolution of the particle volume fraction during the lifetime filtration process. It illustrates the whole process of the filter from clean (Figure 7(1)) to being clogged. It shows clearly where the particles fall in different phases. In Figure 7(2), most of the particles enter the pleat and get captured. It is the in-depth filtration phase. The cake has begun to form in Figure 7(3), especially in the bottom and top of the filter. The surface filtration continues till the stage in Figure 7(5). In Figure 7(6) the cake on the two sides of the filter starts to connect with each other, and the surface reduction filtration begins.

Figure 8 shows the comparison between the numerical results and experimental data for the evolution of the pressure drop. The numerical results are averaged by three sets of simulation. The measurement data are rescaled because during the clogging experiments the air flow rate could not be kept constant, which become more and more visible for higher clogging levels. A correction then is made for the first approximation and the pressure drop is rescaled according to the initial and final mass flow rate. The good agreement of the numerical and experimental results is found in the in-depth and cake filtration. A bigger difference of the pressure drop is observed in the transitional period between the surface filtration phase and surface-reduction filtration phase. The reason is that the transitional period happens after some of the cake on the opposite sides of the pleat starts to connect and it occurs randomly for different numerical simulations or lab experiments. In the surface reduction phase, the agreement is also found with the measurements.

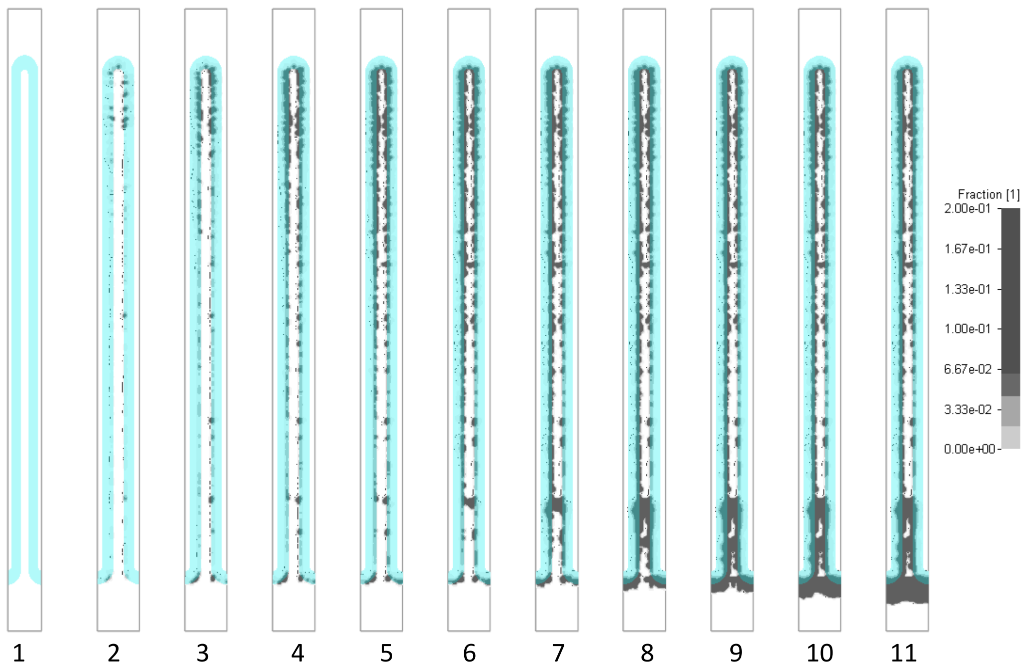


Figure 7: the lifetime filtration process of pleated filter: the evoluation of the particle volume fraction

Table 1 the experimental measurements

Experiment Settings	collected mass (g)	DP0 (Pa)	DP_end (Pa)	Q_initial (m^3/h)	Q_final (m^3/h)	Rescaled Q_final (m^3/h)	Rescaled DP_end (Pa)
2DP0	16.05	195	380	40	40.6	40.0	374
3DP0	27.23	203	620	40.6	39.4	40.0	639
4DP0	40.18	200	798	40.1	38.8	40.0	825
8DP0	69.07	200	1640	40.5	37.6	40.0	1766
18DP0	108.81	200	3585	40.7	30.7	40.0	4753

The particle mass is collected on different heights of the pleat in the lab. The ratio of the mass of particles deposited to the total deposited mass is plotted along the height of the pleat in Figure 9. Except the top and bottom of the pleat, the deposition distribution of particles from the simulation is in the reasonable range compared to the measured data. In the top and bottom region, however, the simulation has more particles deposited. This has to be further investigated in more detail in the future.

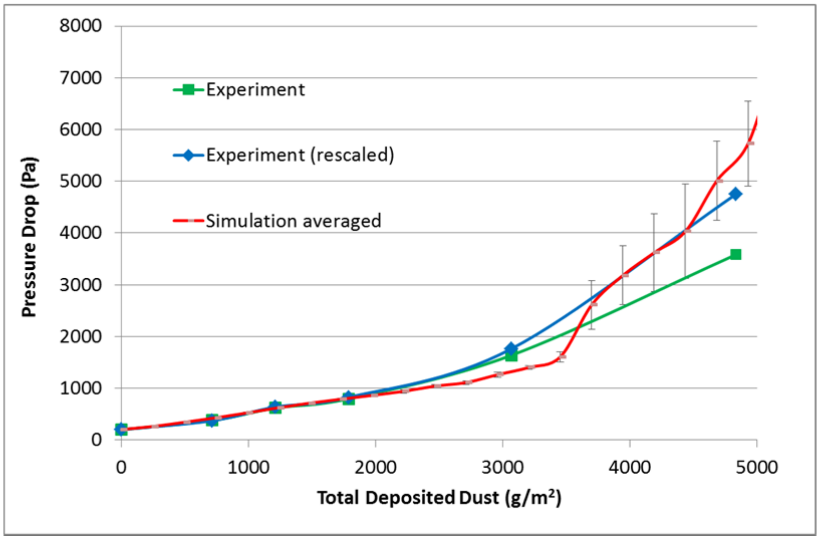


Figure 8: the pressured drop evolution during the lifetime filtration of pleated filter: the simulated results compared with experimental measurements

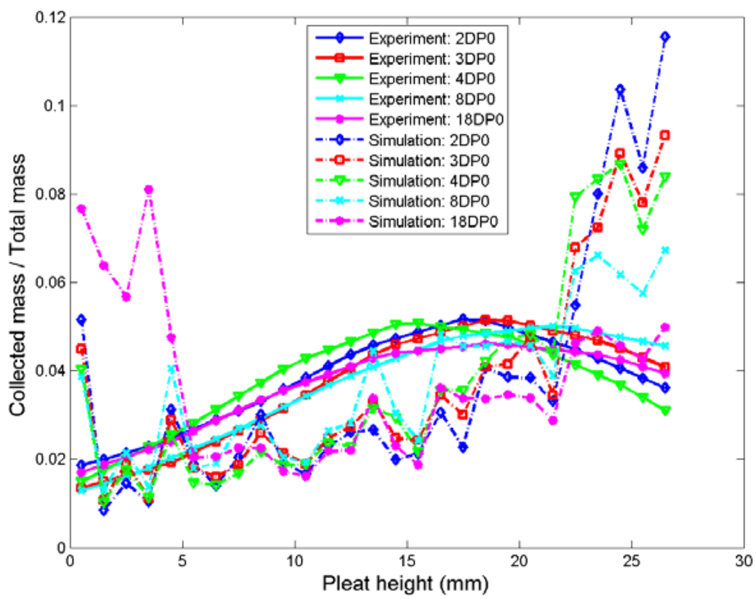


Figure 9: the particle deposition distribution on the pleat: the solid lines mean the experimental measurements and the dashed lines mean the simulated results.

4. Conclusions

To overcome the situation that explicit modeling of the interaction between the particles and the media is not possible for a pleat scale structure, the simulation tool PleatLab is developed, which calls GeoDict® to generate the pleat structure, run the flow simulation, and track particles in the flow field (neglecting the structure), then use preinstalled or user written Matlab codes to implement the probability-based filtration mode to make possible the lifetime clogging simulation of pleated filters.

The procedure of the numerical computation for the lifetime filtration simulation is described. A simple capture probability model for filtration and the resistivity model for updating the structure with particles are introduced.

With PleatLab, users are allowed to set up their own study cases easily to investigate the effects of pleat geometry, such as shape, width, angle, and particle size, or the influences of flow velocity, and so on. A study case of the lifetime clogging simulation is done for a HEPA filter and compared with experimental measurements. The three phases of the clogging, the in-depth filtration, surface filtration, and surface reduction filtration, are reproduced in the simulation. The good agreement of the pressure drop evolution is found. The deposition distribution of the particles along the filter height is compared.

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