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SIMULATION AND MEASUREMENT OF DUST LOADING OF PLEATED AIR FILTERS

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ABSTRACT

In order to increase the filtration surface per volume, air filters are frequently implemented in a pleated geometry. In the case of surface filtration, particles deposited in the pleat form a dust cake. The location of the dust deposition depends on the air volume flow distribution in the pleat and the density and size of the particles.

In this work, the dust deposition in a model pleat was simulated using the discrete phase model of FLUENT. Additionally the dust distribution in a pleated filter sample was determined experimentally and compared to the simulation results for validation.

KEYWORDS

Pleated Filter, CFD- simulation, Dust Cake, Dust Filtration, Surface Filtration, X-Ray Tomography

1. Introduction

If a pleated air filter is challenged with dust, the deposition location of the dust particles will depend on the flow field and the particle size and density. Particles at high Stokes numbers tend to impact on the pleat tips or to be collected at the pleat bottom. Particles at low Stokes numbers tend to follow the streamlines and are distributed along the filter surface more homogeneously. Therefore the dust distribution in a filter pleat differs for different test aerosols, filter geometries and filtration velocities (see fig. 1). Along with cake permeability, the dust distribution determines the total air flow resistance the filter poses. The growing dust cake starts to block the filter pleat, thus reducing the effective surface available for filtration. Consequently the increase of pressure drop per unit mass grows steeper until maximum dust capacity is reached (see fig. 2). While there are numerous publications to be found on air volume flow distribution and pressure drop of pleated filter elements [1], [2], [3], only few publications attempt to numerically simulate or analytically calculate the loading kinetics of a pleated filter medium [4], [5]. In these works either the effect of surface reduction (to determine pressure drop) or particle inertia (to determine dust deposition location) have been neglected. In this work CFD-simulations were utilized to predict the evolution of pressure drop with increasing dust load of the filter. Only surface filtration was considered. For validation, the dust distribution in real loaded filter samples was determined by analyzing sectional images of loaded filters recorded via computer tomography (CT).

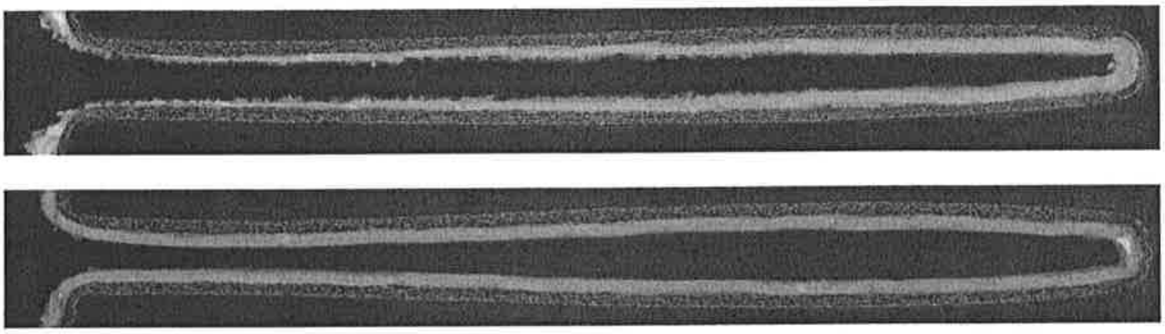

Figure 1: Sectional CT-images of dust-loaded filter pleats. The upper pleat was loaded with a limestone dust at particle stokes numbers of St = 0.014 ... 0.328 (range for 80% of total particle mass). The lower pleat was loaded with a fine cut of a standard test dust at particle Stokes numbers of St = 0.002 ... 0.022 (range for 80% of total particle mass). The Stokes numbers were calculated using the velocity of the gas in front of the filter sample and the width of the pleat inlet.

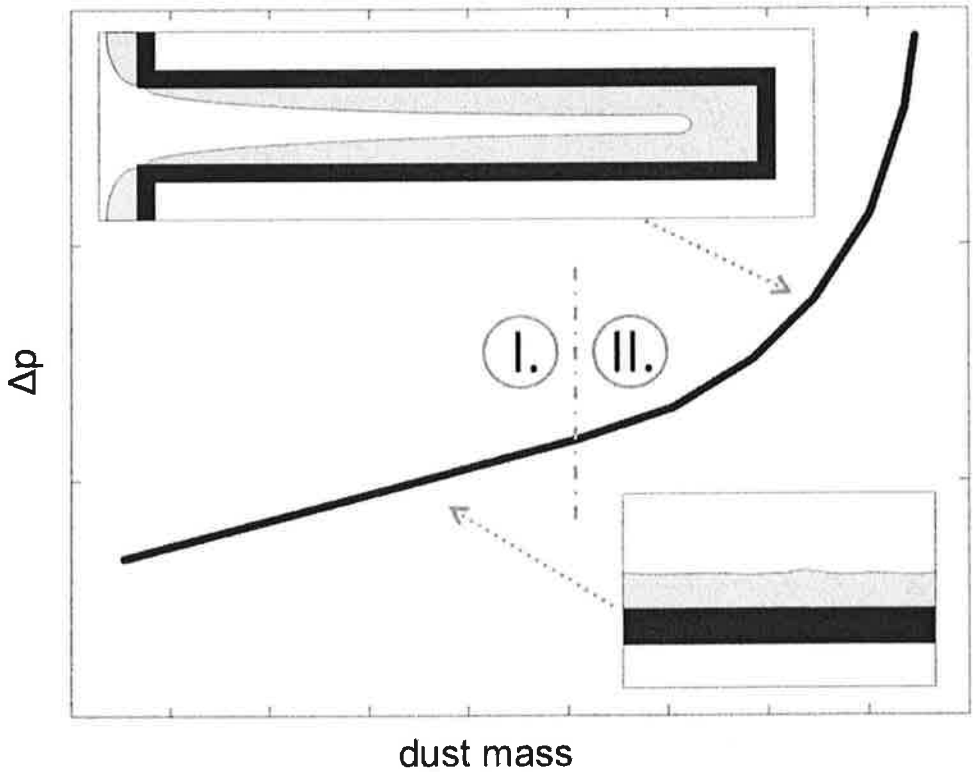

Figure 2: Typical loading curve of a pleated air filter. In stage I. of the filtration the pressure drop rises linearly with deposited dust mass (cake filtration). In stage II. the dust cakes growing from either side of the pleat begin to touch and the filter area available for dust deposition is reduced (surface reduction). The specific shape of the loading curve is dependent on filter geometry, dust type and filtration velocity (taking into account surface filtration only).

2. CFD-Simulation

In order to model the dust accumulation in a pleated filter ANSYS 12.1 / FLUENT was used. The simulations were made in several recurring steps:

I. Set up the simulation domain.
II. Calculate the flow field.
III. Determine particle trajectories using FLUENT's discrete phase model (dpm). Based on this, determine the dust accumulation in the filter, using user defined functions (UDF).
IV. Assign reduced permeability to grid cells that contain dust particles.
V. Return to step II.

The simulation domain is divided into three parts. The cake domain upstream of the media, the downstream domain and the filter medium domain itself. For symmetry reasons it is sufficient to simulate the flow through a two-dimensional half-pleat with symmetry boundary conditions for a model pleat. However, for validation and comparison with experimental results, a 2D-section of a filter sample consisting of several pleats, as well as a complete 3D model was used for simulation. Thus it was possible to account for geometric imperfections of a real filter sample.

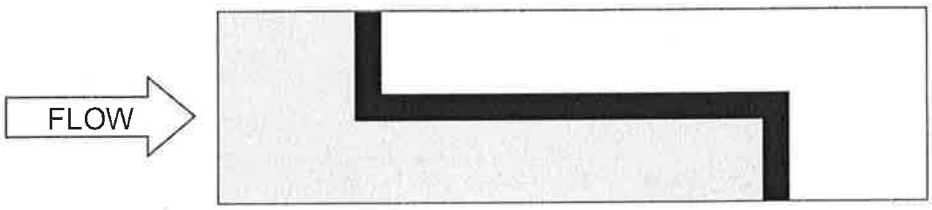

Figure 3 Schematic illustrating the simulation domains: upstream or cake domain (grey), filter medium domain (black), downstream domain (white).

Permeability and porosity are assigned to the filter medium domain during setup. The flow distribution through the pleat and initial pressure drop is then calculated. FLUENTs built-in discrete phase model is used to determine particle tracks. Each track has an assigned total mass, particle diameter and particle density. The particles are injected randomly distributed on the inlet face. A polydisperse aerosol is approximated by randomizing the particle sizes based on their relative frequency in the dust. Since only surface filtration is to be simulated, the filter is assumed to be 100% efficient, consequently all particle tracks are stopped on the filter or cake surface respectively.

For the cake domain a homogeneous maximum packing density and minimum permeability is assumed. These values are determined experimentally with flat sheet filter samples. The permeability of a cake cell is lowered linearly with the dust packing density, until both values reach their limit. After recalculating the permeability in the cells of the simulation domain, airflow and particle injections are simulated anew. By writing the pressure drop and total dust load to file at every iterative step, a loading curve can be derived from the simulation.

3. Experimental setup

Pleated filter samples were loaded with different test dusts. The dust particles were dispersed with a brush feeder and a dispersing nozzle. The air volume flow was controlled by a thermal mass flow controller. (See figure 4 for a schematic of the experimental setup.)

The samples used were rectangular and had inner dimensions of 20 x 20 mm², with pleat depths of 25 mm. The number of pleats, general pleat shape (parallel and v-shaped pleats), mean filtration velocity v_f and the dust type are parameters that were varied in the experiments. In this work, one set of data is presented exemplarily. To determine the evolution of the dust distribution in this sample, CT-images were recorded of the unloaded sample, and several times of the same sample with increasing dust loads. The progression of the dust cake height could then be directly determined from sectional CT-images.

4. Comparison

In order to validate the results of the simulation, both the dust distribution in the filter samples and the pressure loss as a function of total dust mass were compared with measurements (see figures 5, 6, 7) The experiment presented here was made with a mean filtration velocity of v_f = 7 cm/s, pleat count of 3.25 cm^{-1}, and parallel pleat geometry. The dust used was limestone with median particle size of $x_{50,3}$ = 4.3 µm and standard deviation σ = 2.3 µm. The dust cake packing density was estimated to be α = 0.27, its permeability k = 2.1e-13 m^{-1}. The presented simulation was made with a 2D domain consisting of a total of about 50.000 cells. The pleat geometry used as a base for the simulation domain was directly taken from a sectional CT-image of the unloaded filter sample.

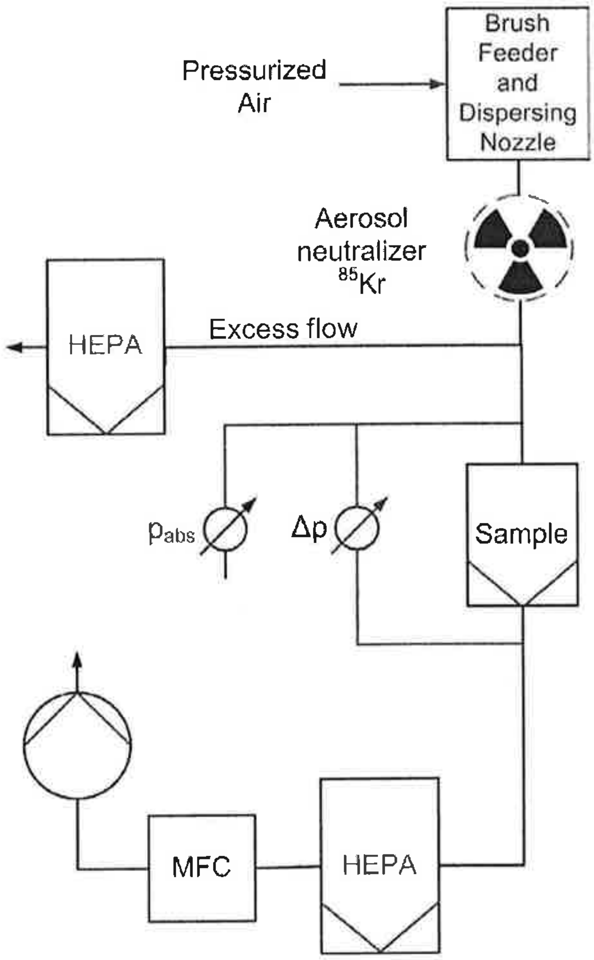

Figure 4: Schematic of the experimental setup used for dust loading of the filter samples.

As can be seen from figures 5 and 6, the predicted dust distribution at an intermediate loading stage is in good agreement with the experimental findings. In the last third of the pleat length, the simulated cake height is slightly lower than the measured cake height however. The pressure drop (fig. 7) shows some deviation in the surface reduction stage, where the simulated development is steeper than the measured one. Apart from this, it also is in good agreement with the simulation.

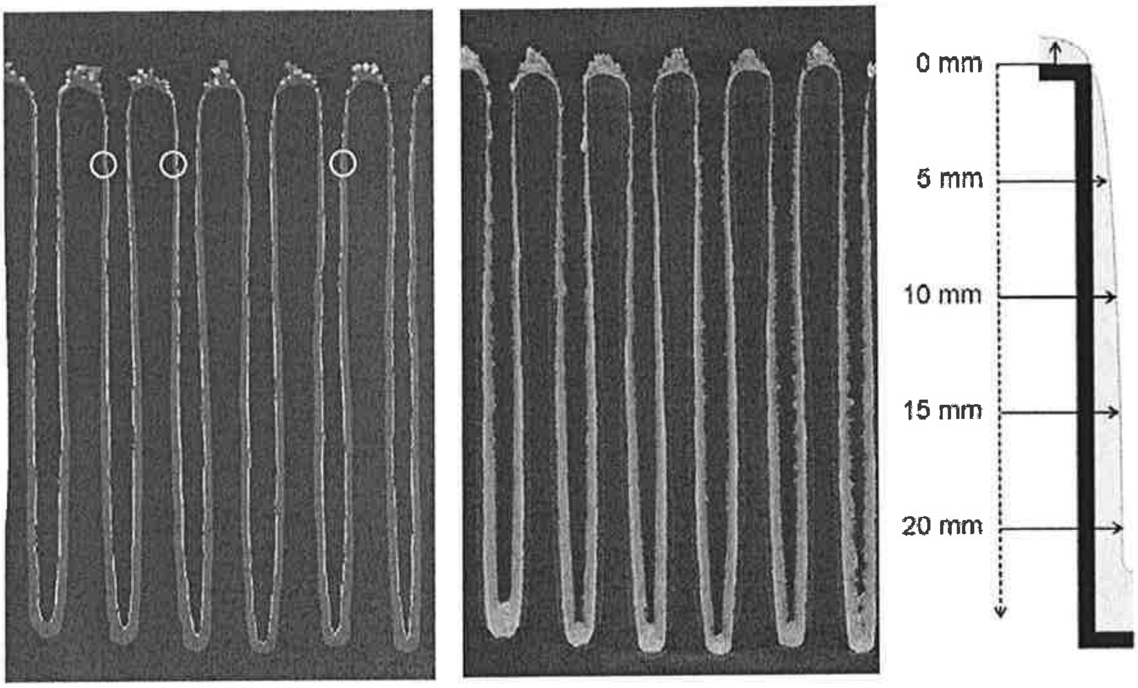

Figure 5: Sectional images of the dust distribution in a filter sample at an intermediate loading stage. Left: simulation (grey scale corresponds to fill level of the cake domain cells); middle: experiment. The CT-image shows the middle section of the filter sample. The simulation was made with a 2D domain based on that same section. The pleat sides for which the dust distributions are shown in fig. 6 are marked with circles. The schematic on the right illustrates the direction of measurement of the cake height distribution.

The mentioned deviations can be attributed to several factors:

- The particle size distribution of the test dust was determined with an optical particle sizer. Particle tracks in the simulation were calculated for perfect spheres with the unconverted optical diameters. The unknown difference between optical and real particle sizes and the unknown aerodynamic form factor can lead to slightly different particle deposition locations.
- The abrupt increase in pressure drop visible in the later stage of the simulated loading curve occurs when a single pleat closes down completely. The resolution of the surface reduction stage (i. e. the process of the cakes growing from either side of the pleat touching and thus making sections of the filter unavailable for filtration) in the simulation is limited by the mesh cell size. Very narrow channels open to airflow remain open longer in the experimental measurements than in the simulation. Since the mesh can't be made infinitely fine, this effect can't be eliminated completely.
- Both cake solidity and cake permeability are functions of the particle size distribution of a dust. Since the particle deposition locations in the filter pleat are size dependent, this parameters will vary locally. This was not accounted for in the simulation. A model or lookup-table linking packing density and permeability to the local particle size distribution would be needed to take this effect into account.

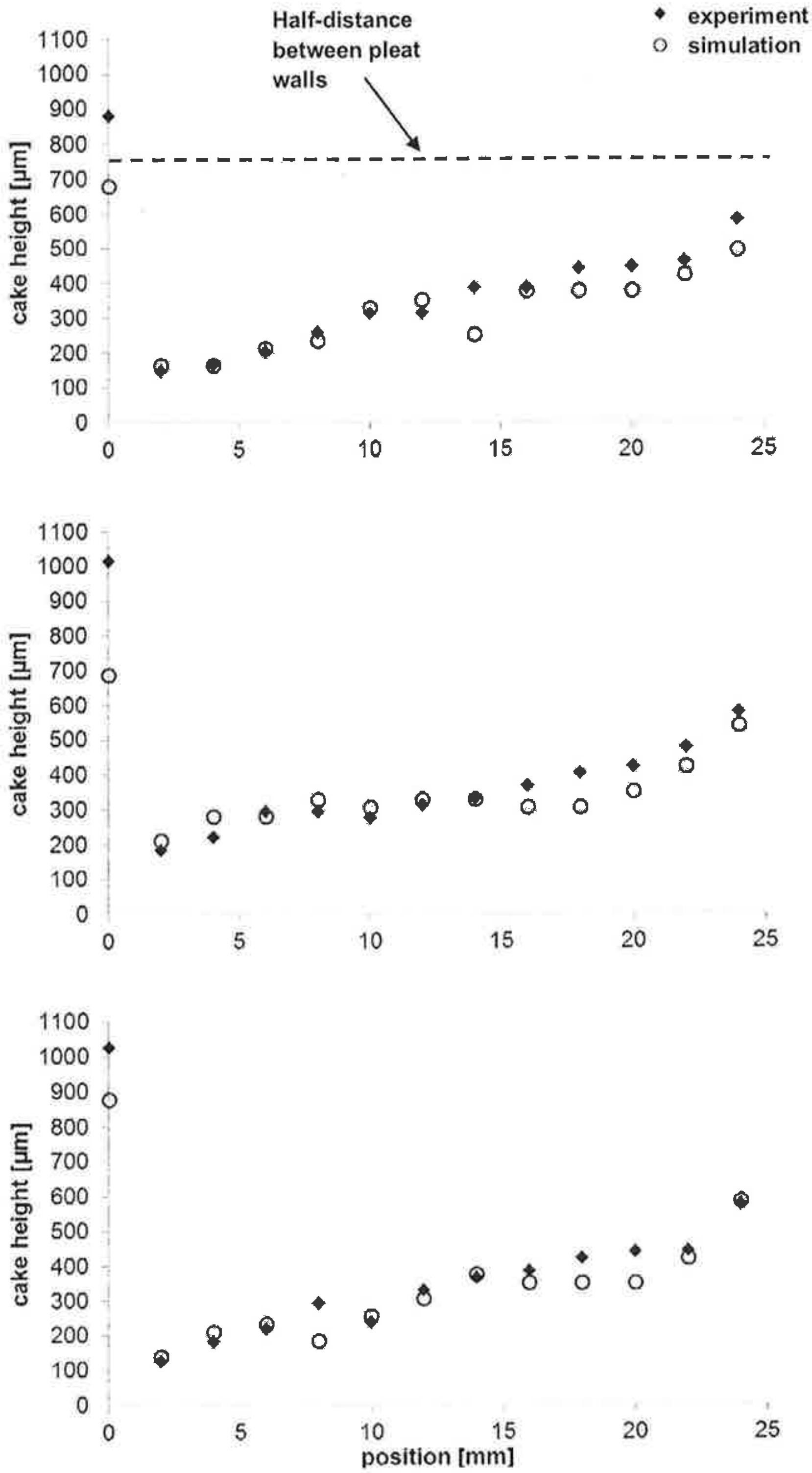

Figure 6: Dust cake height as a function of pleat depth at an intermediate loading stage. Experiment: black diamonds; simulation: white circles. The x-axis runs from pleat inlet (0 mm) to pleat bottom (25 mm). The half-distance between pleat walls averages at 750 µm. The three pleat sides shown here are marked in fig. 5.

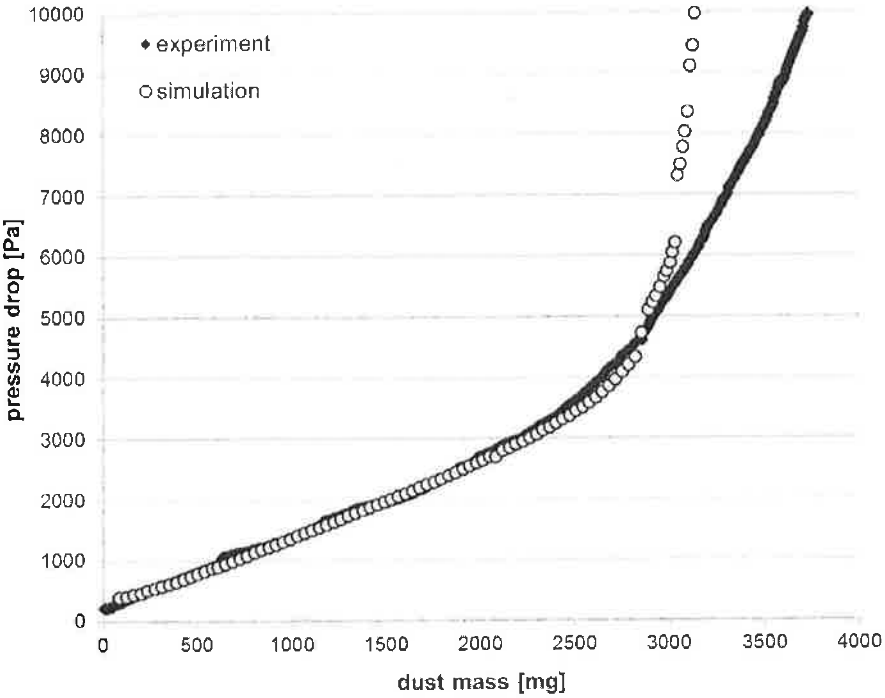

Figure 7: Pressure drop as a function of total mass in the filter sample. Experiment: black diamonds; simulation: white circles. Total filter area was 68 cm^2. Total volume flow was 25.2 lpm.

5. Conclusion

A CFD-simulation method to determine dust distribution in pleated filters as well as pressure drop evolution was developed. To validate the method, loading experiments and CT images of loaded filter samples were utilized. First comparisons yielded promising results, although a systematic variation of parameters remains to be carried out. In places the simulation method is open to improvements, especially concerning the variation of dust cake parameters based upon the local particle size distribution. The spatial resolution of the surface reduction process, and thus the agreement between measured and simulated pressure drop curve in the advanced loading stage could potentially be improved by optimizing the mesh geometry.

6. Acknowledgements

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7. References

[1] Chen, D., Pui, D., Liu, B.: *Optimization of pleated filter designs using a finite-element numerical model,* Aerosol Science and Technology 23:579-590 (1995)

[2] Nassehi, V., Hanspal, N.: Waghode, A., Ruziwa, W., Wakeman, R., *Finite-element modelling of combined free/porous flow regimes: simulation of flow through pleated cartridge filters*, Chemical Engineering Science 60:995-1006 (2005)

[3] Del Fabbro, L., Laborde, J., Merlin, P., Ricciardi, L.: *Air flows and pressure drop modelling for different pleated industrial filters*, Filtration and Separation 39.1:34-40 (2002)

[4] Rebai, M., Prat, M., Meireles, M., Schmitz, P., Baclet, R.: *Clogging modeling in pleated filters for gas filtration*, Chemical Engineering Research and Design (2009)

[5] Huurdeman, B. Banzhaf, H., *CFD simulation of flows in air cleaners with transient dust loading of the filter element*, SAE Technical Paper Series 2006-01-1316 (2006)