IMPROVED MODELING OF FILTER EFFICIENCY IN LIFE-TIME SIMULATIONS ON FIBROUS FILTER MEDIA

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ABSTRACT

A general recent trend in determining the quality of filter media and filters lies in counting particles rather than weighing the media or filter. By using counters before and after the filtration – as in the standardized multi pass test - the filter efficiency can be determined in a detailed way by listing the quotient of captured over total particles as a function of particle diameters. This measure can also be simulated on detailed models of fibrous filter media with GeoDict.

In this work, we report on multi pass test results for an oil filter media exhibiting a non-intuitive filtration behavior. After an initial rise, the fractional filtration efficiencies decrease again, until the filter material is clogged. To understand the cause for these experimental findings, fractional efficiencies are determined numerically taking into account a possible re-entrainment of particles.

To achieve statistically reliable efficiency results, a large number of particles must be considered. Filter loading experiments are carried out on at least a few square centimeters of media. Even for those, the statistics of particle counting for large particles usually rely on very few particles. Media scale simulations, on the other hand, consider even smaller surfaces of about a square millimeter. For these smaller surface areas, arrivals of large particles are even less probable than in experiments and the predicted filter efficiency curves would have low statistical relevance. By interspersing filter efficiency simulations with many more particles than would actually arrive at the media during life time simulations, the quality of the filtration statistics of media scale simulations can be improved such that a quantitative comparison with experimental data becomes possible.

KEYWORDS

Media Scale Simulations, Filter Efficiency, Life Time, GeoDict, Filtration Modeling
A. INTRODUCTION

The multi-pass test bench (ISO 4548) is a standardized test for the filtration of hydraulic fluids and engine filters for oil and fuels. By using particle counters upstream and downstream of the filter, the filter efficiency can be determined in a detailed way. The quotient of captured over total particles is listed as a function of the particle diameter. During the test, the changes of the fractional efficiency over the life time can be observed.

It is usually assumed that fractional efficiencies increase over time: particles deposited in the filter block the pores progressively which results in a decrease in permeability. Thus one tends to conclude that fewer particles will be able to pass through the filter and the efficiency rises over time.

However, measurements performed on filter media sometimes contradict this assumption, as can be seen in Fig. 1. Here, we observe decreasing efficiencies over a long period of time. In fact, it decreases until the filter becomes complete clogged, at which point the efficiency sharply rises to 100%.

![Figure 1: Results of a multi-pass experiment showing decreasing filter efficiencies.](image)

Three completely different explanations are possible for this behavior:

1. **Re-entrainment**: particles deposited at an earlier time step break free again at a later time step. Thus, more particles appear at the outlet at a later time step leading to a lower efficiency number. The break free might be caused by locally higher flow velocities due to the higher pressure drop.
2. **Lingering**: particles may take a long time passing through the filter. Thus, they are counted in the outflow at a later time step which leads to higher efficiency numbers at earlier times.
3. *Changed flow paths*: particles may prefer different (and more open) routes through the filter at later time steps. This would be caused by changes in the flow field due to clogging.

In this paper we investigate which of these explanations holds true for a particular filter media showing decreasing efficiency in the multi-pass test.

**B. GENERAL APPROACH TO FILTER LIFE TIME SIMULATIONS**

To understand the observed effect, simulations on the filter media scale are indispensable. Models which describe the filter media as homogenized porous layer cannot contribute to this goal, as the reason must lie in the pore structure or local changes of the flow field.

The FilterDict [1, 2] module of the GeoDict [3] software simulates particle filtration on the filter media scale. Filter efficiency simulations are done by

1. Computing the fluid flow inside the filter media.
2. Tracking the movement of dust particles inside the fluid and finding collisions with the filter media.
3. The ratio of particles captured in the filter to the overall number of particles is the efficiency.

In oil filtration, we generally assume that particles do not stick to the fibers due to adhesive forces when they collide. Sieving is considered the dominant capture mechanism, i.e. particles rebound and move until they are eventually caught in a small pore.

To model the evolution of the fractional efficiencies over time in a multi-pass test, the above approach is iterated over time [4,5]. In each time step the fluid flow is determined and a *batch* of particles is tracked. For a single batch, we assume that particles do not interact with each other as dust concentrations are comparatively low. At the end of the time step, the filtered particles are deposited, i.e. they are added to the filter structure and are then impenetrable to flow and particles in the following batches.

To enable a study regarding the hypothesis of re-entrainment, lingering and flow path changes, two features had to be added to FilterDict:

a. To enable lingering, particles can now carry over from one batch to the next. A batch corresponds to a certain time interval. If, at the end of this time interval, the particle is neither filtered nor has reached the filter outlet, it continues to move in the next batch.

b. Deposited particles can (optionally) re-entrain into the flow. At the beginning of each batch a new flow field and the forces the flow exerts on each particle
are determined. If these forces allow for re-entrainment, i.e. if they exceed the adhesive forces and point into an open direction, the particle is re-entrained.

C. SIMPLIFIED FILTER STRUCTURE MODEL

To demonstrate that changed flow paths can be a reason for decreasing filtration efficiencies, a simple model is sufficient. As example, we consider a 2D mesh with hexagonal structure, uniform fiber diameters, and arbitrary fiber. Fig. 2 and 3 show the results of a particle loading simulation done with FilterDict where all particle diameters are smaller than the largest pore size. We observe that with increasing particle loading, the smaller gaps between fibers and particles already separated are clogged progressively. Therefore, path lines shift to the larger pores possessing the least flow resistance, which decreases the probability for additional particles to be separated. As the large pores remain open for all times, the filtration efficiency decays to an asymptotic lower limit.

Figure 2: Particle loading on a single layer simulated with FilterDict.

Figure 3: Fractional filtration efficiencies determined during the particle loading simulation shown in Fig 2. Initially, only the large particles are captured. Smaller particles are captured between the large particles.
The single 2D layer cannot yield an explanation for the final increase of filtration efficiency observed in experiments. This can be modeled using a stacked structure. As particle structures deposited on one fiber layer grow higher, open pores in the above lattice eventually get clogged from underneath. With decreasing number of open passages in all layers, the probability of particle separation rises again (Fig. 5) until the entire fiber layer stack is filled which corresponds to filter clogging.

Thus we concede that changed flow paths are a possible explanation to sinking filter efficiencies as they are observed in the multi-pass tests.

Figure 4: Particle loading of a stack.

Figure 5: Fractional filtration efficiencies determined during the particle loading simulation shown in Fig 4.
Having seen in the previous section that simulations can explain the observed phenomenon in principle, we now simulate the performed experiment to see if we capture this behavior also numerically.

For this, we use a 3D tomography image of the filter media as input for the simulation. The image consists of 400x400x1200 grid points with a voxel length of 1 µm. Particle size distribution, pump flow rates, reservoir volume and dust concentration was chosen as in the multi-pass test. Fig. 6 and 7 show results of the simulation.

Figure 6: Particle loading simulation on 3D tomography image. The first image shows the particles deposited in the first batch, the second and third image show all particles deposited by the end of the simulation. Blue particles are deposited in the current batch, grey particles have been deposited in previous batches.
For this structure, re-entrainment or lingering does not contribute significantly to the results. The particles are captured due to sieving, thus they cannot simply break free with increasing pressure drop. Breaking free would require the local flow field to flip flow directions and this does not seem to happen. Also, the vast majority of particles pass the filter in a very short time. Only at later stages of the simulation, small particles do linger in the very small pores between larger, previously deposited particles.

**E. ENHANCED EFFICIENCY RESULTS**

The efficiency results from the simulation as presented in Fig. 7 are not very meaningful for larger particle diameters, e.g. it is not possible to tell from the data if the filtration efficiency of 15 µm particles is decreasing or not. This is due to the small number of large particles simulated in each batch. The test dust used in experiment and simulation counts 75.06% of the smallest particles (1 µm diameter) and only 0.001115% of the largest particles (50 µm diameter), which means that there are 67318 particles of 1 µm diameter for one particle of 50 µm diameter. To get statistically meaningful results also for the large particles one would need to simulate much larger filter areas (higher numerical costs) or use larger time steps (lower accuracy), which is in general not desirable.

To overcome this dilemma, we introduce *ghost particles* into the simulation. A ghost particle is tracked as a regular particle and the outcome (filtered/not filtered) is noted.
The difference between ghost particles and regular particles is that a filtered ghost particle is not deposited at the end of the batch time but removed. As the particles inside a batch do not interfere with each other, adding ghost particles does not change the behavior of the common particles. But the enlarged number of tracked particles enables to get statistically meaningful results for all particle diameters. Figure 8 compares fractional efficiency results for some particle diameters with and without the use of ghost particles. The decrease in efficiency is now clearly discernible. Figure 9 shows the enhanced fractional efficiency results. A decrease in efficiency is visible for particle diameters from 7 µm to 20 µm. For smaller particles, the efficiency is continuously increasing. These particles are caught in the pores between previously deposited larger particles. Particles above 30 µm cannot pass the filter; all pores in the imaged area were too small.

Figure 8: Enhancement of efficiency results. The grey lines show the computed fractional efficiency without ghost particles, the red lines with ghost particles. This simulation used smaller time steps than the one presented in Figure 7.
F. SUMMARY AND OUTLOOK

With the presented enhancements, FilterDict proves as a tool capable to help developing an understanding of the observed experimental results. For the presented example, the decreasing fractional filter efficiencies were caused by changed flow paths. By the introduction of ghost particles, statistically meaningful results could also be obtained for rare particle sizes. With this, the evolution of the fractional filter efficiency can be determined for all particle sizes.

With this work, a quantitative comparison of fractional filtration efficiencies measured in multi pass tests with simulations becomes possible. Currently observable differences may be caused by the limited size of the tomography data. As we have seen in Section C, a single huge pore has a drastic effect on the overall efficiency, as it will collect all the flow once the smaller pores are clogged. Thus, it is of utmost important that the pore size distribution of the imaged sample is representative for the whole filter media.
REFERENCES


