CFD modelling tool for multiple filter systems on the macro level

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In many systems, multiple filter elements are used to increase the filter area. Typical examples are dust filter plants with hundreds of single filter bags or cartridge filter plants with several filter elements. The crucial factor for an efficient use of the installed filter area is a uniform loading of the filter area. However, this cannot always be achieved on the upstream side, especially if the filter system has to be individually adapted to the constructional conditions. If the filters are not loaded evenly, this can easily lead to increased operating costs due to high pressure loss, frequent cleaning, damage to the filters and thus shorter service lifetimes of the filter system.

The contribution presents a simulation tool based on flow simulations (CFD) for filtration plants. The simulation tool is based on the open-source CFD toolbox OpenFOAM. In the modelling approach an Euler-Lagrangian formulation for particle transport and a porous media representation for the filters are used. The interactions of local loading on the filter segment, the local resistance increase due to particle deposition and the resulting shift of the continuous flow are considered in an iterative approach.

This modelling approach has been extensively extended with regard to multiple filter systems in order to represent these systems efficiently. The first step is the conversion of the real geometry into a numerical mesh: In order to mesh multiple filter systems efficiently, a combination of block-structured background meshing with contour-adapted polyhedral meshing is used. On the one hand, this allows the porous resistance zones of the individual filter elements to be resolved geometrically precisely and numerically with high quality; on the other hand, complex housing contours or filter chambers can also be reproduced, which would be very costly with pure block-structured meshing. Within the scope of the simulation tool extension, these pre-processing steps of the mesh generation were extended and automated.

One focus of the extensions on the solver side for multiple filter systems is a more efficient particle transport: The impacting particle mass and particle size determines the increase in resistance during loading on the filter. In order to hit the many filter elements of the numerical grid with a sufficiently high number of particles of different sizes, high quantities of particles or parcels are required, typically several million parcels for one loading step. Here, the particle transport was extensively optimised to transport large particle quantities sufficiently fast in each loading cycle.

Another focus of the modelling tool enhancements is damage modelling. In large dust filter systems, it is often only possible to guess which mechanism has led to damage of the filters. Damaged filters often show cracks in the filter fabric, the cause of which usually cannot be clearly determined. One possible source of damage can be, for example, a large amount of mass being applied to individual filters, so that the filter gradually becomes too heavy and is torn out of the mouthpieces. On the other hand, a large momentum input such as local hits of big particles with high velocity can also damage the filter. The simulation tools make it possible to pursue different damage hypotheses and to evaluate and assess the particle input on the filter both locally and integrally for a filter as a whole.

The simulations then allow filters with multiple elements to be optimised in terms of flow mechanics. For this purpose, e.g. internals can be integrated into the model and these geometry variants can be evaluated in relation to the filter inflow. This leads to improved utilisation of the installed filter area, uniform filter loading and thus lower operating costs due to reduced pressure loss and, in the case of damage prevention, to longer service lives.

KEYWORDS

Filtration simulation, CFD, OpenFOAM, Macro-scale modelling

1 Modelling Approach

The solver for simulating the filter loading with particles, taking into account the interactions with the continuous flow, is developed by DHCAE on the basis of the open-source toolbox OpenFOAM [1] [2]. The solution of choice for this investigation is a macro-scale approach considering single filters or systems with multiple filter elements together with their upstream and downstream sections. The macro-scale approach is characterised by the fact that it does not resolve interactions of particles with microscopic filter elements such as fibre-particle interactions but describes the filter medium as a porous resistance zone [3] [4]. The modelling approach is based on an Eulerian-Lagrangian consideration. Here, the continuous phase (the gas flow) is modelled in a stationary Eulerian system with RANS turbulence modelling.

The particle transport in the fluid domain is realized based on a Lagrangian approach which can consider additional forces and effects on the particles e.g., gravity, drag and inertia or individual and local particle-wall interactions such as sticking or rebounds. Effects of the turbulence of the continuous flow on the trajectories of the particles are taken into account by a dispersion model. The Lagrangian particle transport in OpenFOAM has been adapted to specific needs of filter modelling. This includes improvements of performance, accuracy (e.g., adaptive local Courant numbers for local time stepping procedures) and stability.

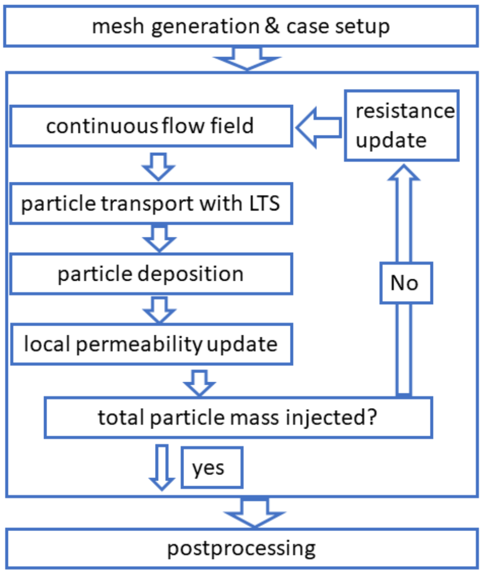

Figure 1 - iterative solution procedure

An iterative algorithm was implemented to simulate the filter loading (Figure 1). The initial situation is given by a stationary flow field with a uniform basic resistance. During the subsequent filter loading process, a fraction of the mass to be considered in a load cycle is injected as Lagrangian particles and tracked with a local time stepping (LTS) approach. The local particle deposition is stored on each single face of the filter baffle mesh. With the local particle concentration, the non-uniform resistance of the filter is recalculated.

While the particles are collected on the 2D face representation, the according resistance is either assigned to the 2D face elements directly or to a layer of several volume cells in front and behind the filter face.

After each resistance update, the new steady state flow field is calculated considering the new filter loading, and the iteration starts again. The solution methodology was verified by means of recalculated laboratory experiments for the filter loading from the literature and experiments on real dust filter systems [5].

2 Modelling Requirements and Challenges

When simulating filter systems on a macroscopic scale with porous media, particularly high demands are placed on the grid quality in the region of the filter elements. As shown in Figure 2, a high pressure drop occurs here over a very short distance orthogonally through the filters. In addition, very strong changes in the direction of flow are present here: the filters are subjected to tangential cross-flow on the raw-gas side and an orthogonal flow throughout the filter. Inside the filter cartridge, another drastic change of direction of the flow occurs, this time in the longitudinal direction of the filter cartridge. Figure 5 and Figure 6 give further impressions of the complexity of the flow field developing in the filter bag proximity.

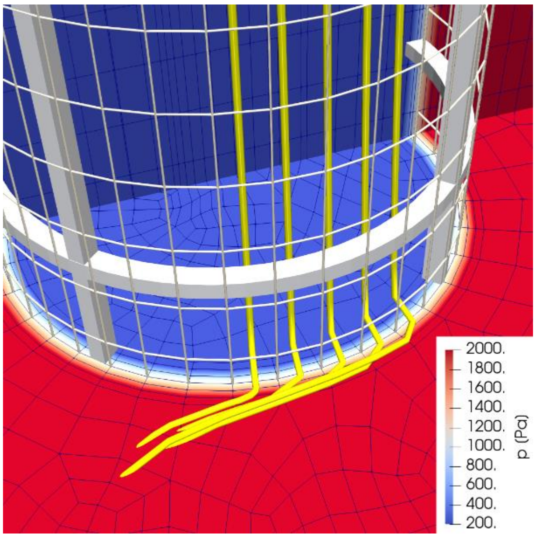

Figure 2 - streamlines and pressure drop in the filter proximity

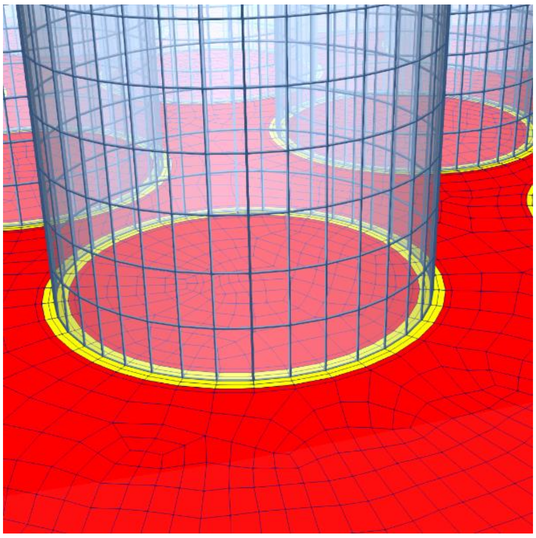

Figure 3 - cell zone (yellow) and grid elements

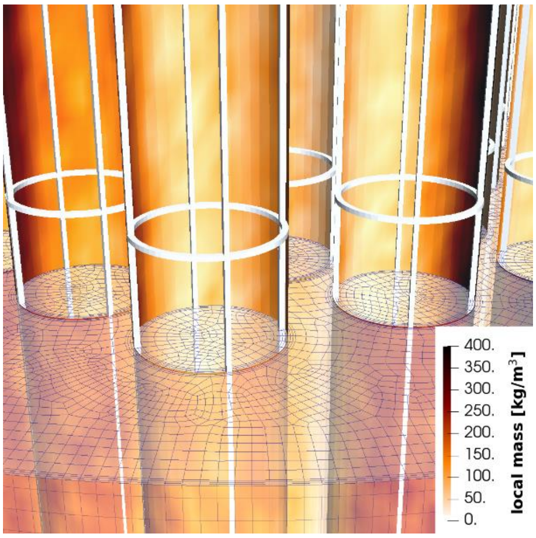

Figure 4 - filter elements with heavily clogged and almost clean parts

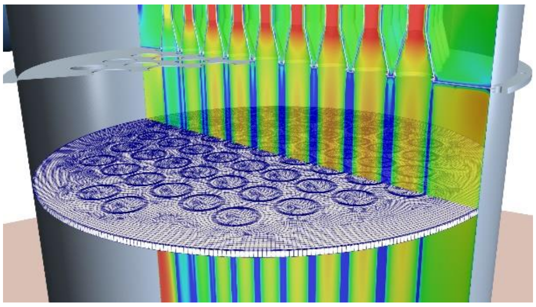

Figure 5 - velocity field in the filter bags

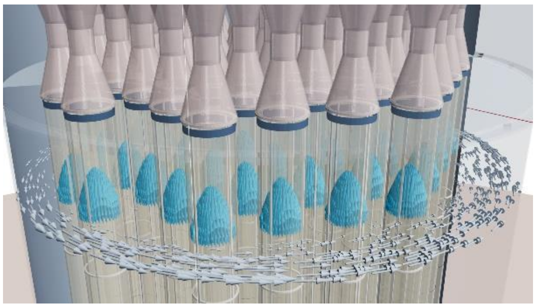

Figure 6 - flow direction and near the top of the vessel

The pressure jump of the unloaded filter fabric is realised by a porous cell zone. Figure 3 shows the cells of the porous zone in yellow, while the grid of the free flow is coloured red. By combining this with a permeable 2D surface (also shown in Figure 3), the modelling of particle deposition is realised. The cell surfaces in the centre of the porous zone accumulate the incoming particles and, depending on the model chosen, calculate the additional pressure jump due to the dynamically increasing loading of the filter. Figure 4 shows clogged filter bags with very different local mass accumulations.

3 Meshing Approach

For an accurate modelling of the dynamically changing flow resistance of the filters a 3D tensor approach is necessary. One requirement of this approach is the use of hexahedral grid elements with an excellent cell quality and a very accurate shape. These hex cells must both resolve the filter geometry and guarantee a very uniform boundary layer thickness around the filters.

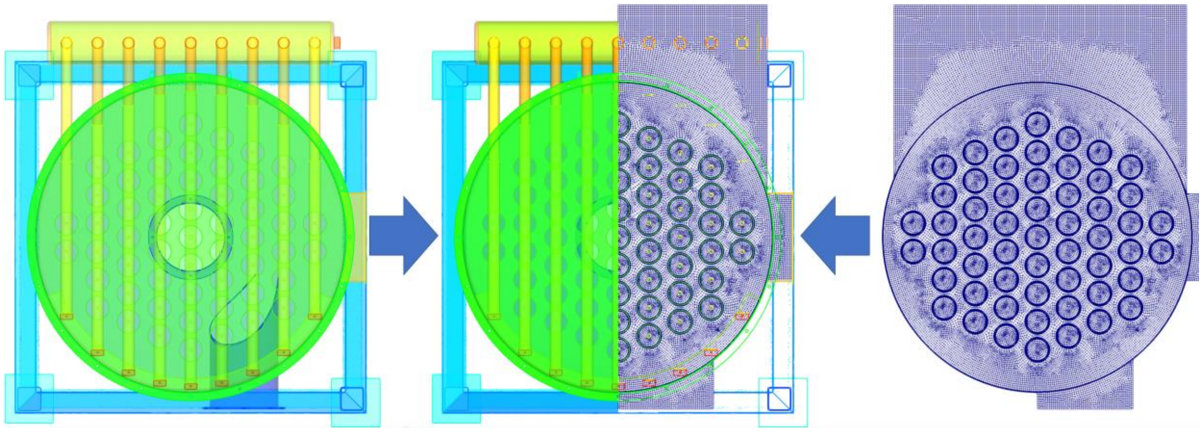

Figure 7 - combination of background grid with exact CAD geometry

In addition to the filter modelling, the pressure vessel must be meshed with all flow-relevant internal components, such as the backwash device, perforated plates, filter suspension, etc. For this purpose, a background grid was created with the dimensions of the plant, in which the filter cartridges were already perfectly fitted. The outer contours of the filter system were then already roughly prepared in the background grid. Compared to the use of a fully structured background grid, which due to the grid topology can lead to excessively high cell numbers in regions that do not require high local resolution, the unstructured hex background grid method offers significantly more freedom in taking component shapes into account beforehand (like the cylindrical pressure vessel wall) and delivers significantly fewer grid cells with higher grid quality in the finished mesh.

During the final grid creation, cells outside the geometry are removed from the grid and the cells near the wall are projected onto it.

A setup in a CAD model based graphical user interface is realized in particular for the generation of the background mesh. The final mesh generation can be automated based on this setup to a large extent: By using naming conventions when naming the background grid, the other areas of the grid, such as the filter bags, are automatically identified and numbered consecutively, so that the subsequent evaluation of individual filter bags is facilitated. Other components of particular interest in the evaluation are recognised with the help of STL files during the final mesh creation and named for further processing.

The workflow scales very well, and filter houses with several thousand pocket filters in complex arrangements can be calculated with short preparation times and on modern standard CFD workstations [6].

4 Particle Separation by Cyclone Effect

The general design of the cartridge filter leads to a pronounced cyclone effect. The inflow is eccentric and located at the bottom of the housing, and thus does not directly hit the filter bags. Figure 8 shows the streamlines running along the outside of the wall and only gradually shifting towards the filter bags in the centre.

Large and heavy particles thus hit the wall early and are separated there without reaching the filter bags. Only the smaller particles follow the streamlines and reach the filter fabric, where they are finally retained. For filtration applications with a strong density difference, such as in the air cleaning of solid particles, the advantage of Lagrangian particle modelling is particularly evident here, as the individual forces on the respective particle size are taken into account. This has a significant effect on the particle size and mass deposited on the filters.

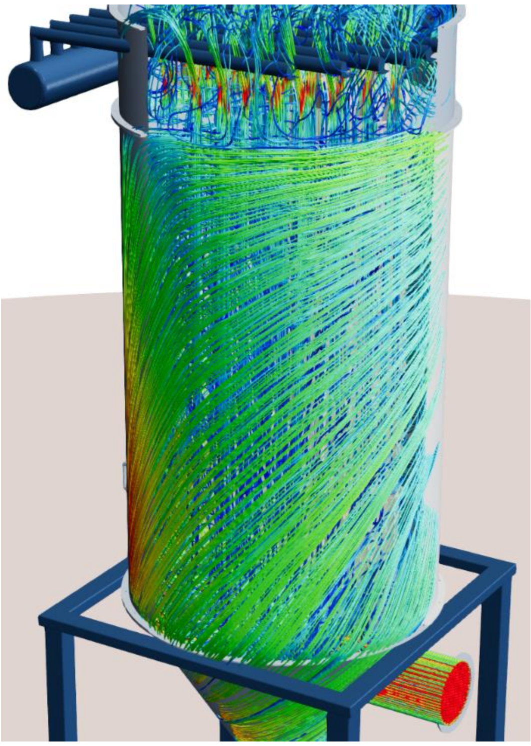

Figure 8 - streamlines showing the cyclone effect

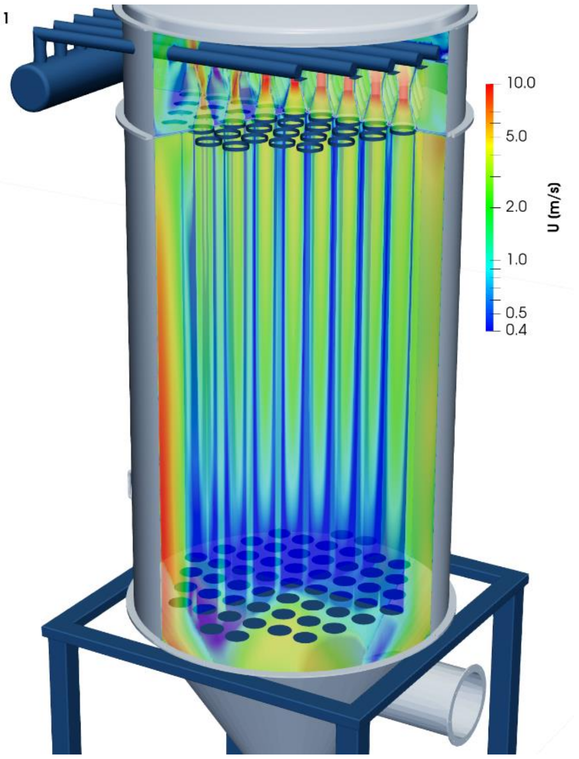

Figure 9 - velocity field in filter bags and upstream region

In the simulation, this behaviour is shown by a clear separation of the particle sizes: Figure 10 shows a particle size distribution of all injected particles (blue), as well as the size distributions of the particles finally deposited on the wall (green) and on the filter bags (red).

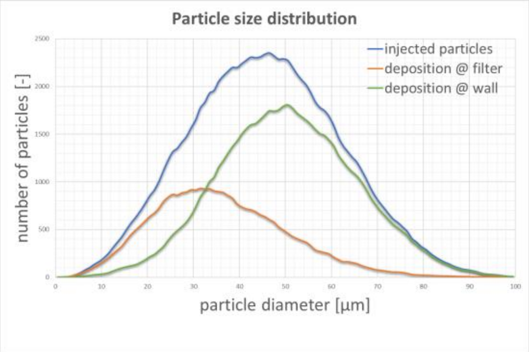

Figure 10 - deposition of particles at filter and walls

This design approach offers several advantages. On the one hand, the cartridge filters are not loaded so quickly, as a lot of particle mass is separated prematurely. Cleaning can therefore take place later and less frequently.
Secondly, especially heavy and fast particles that hit the filter bags with high momentum and that can potentially cause greater damage to the filter fleece are separated in advance on the outer walls of the system.

5 Erosion Models for Potential Damage Analysis

The loading of the cleaned filter bags is not uniform. The simulation shows that the filters on the opposite side of the inflow are initially hit much more often by particles. As the loading increases, the local flow resistance across the filter fabric increases and the flow shifts. The particle paths also shift, but not to the same extent as the gas flow due to mass inertia. Nevertheless, in the further course of the process, the particles are increasingly deposited on previously unloaded cartridge filters. The focus of deposition shifts from the "back" to the "front" and from top to bottom.

The particle loading of the individual filter bags already gives indications of possible problems in long-term operation due to local maxima, which can be caused by increased clogging of individual areas. However, a direct transfer of this observation to the entire filter is only possible to a limited extent. Here, a damage prediction model is added, which provides a key figure for evaluating the damage potential depending on the particle impact. The key figure depends on the particle size or particle mass, the particle velocity, and the angle of impact on the filter fabric. Due to this consideration of the impact impulse, heavy and fast particles are weighted disproportionately more strongly with regard to possible damage than small and/or slow particles.

With the impact function given in Equation 1 the user can adjust the parameters a and b to individually weight the mass and velocity influence individually for his specific use case. The effect of the impact angle Θ can be modified with a function.

$$I_p = w(\theta_p) \cdot m_p^a \cdot u_p^b$$

w is a weighting factor as a function of impact angle θ_p

m_p is the particle mass flow in kg/s

u_p is the particle velocity in m/s

a and b are model constants

Equation 1 - impact equation

The damage index is applied to a local area segment of a few square centimetres and can be summed up for a single filter cartridge. On the one hand, this enables the evaluation of an entire cartridge filter with regard to its damage potential, and on the other hand, it provides a mean for comparisons of the different filter bags with each other.

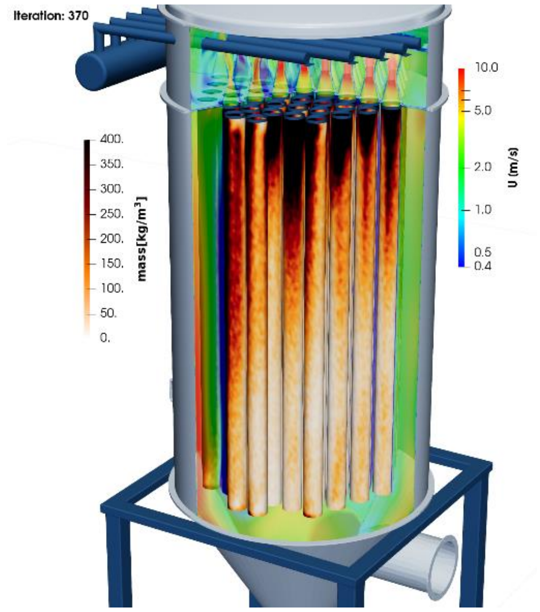

Figure 11 - clogged filter cartridges, "front"

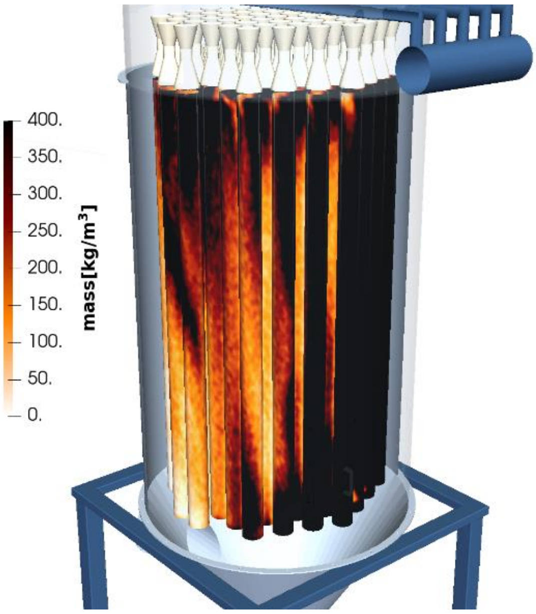

Figure 12 - clogged filter cartridges, "back"

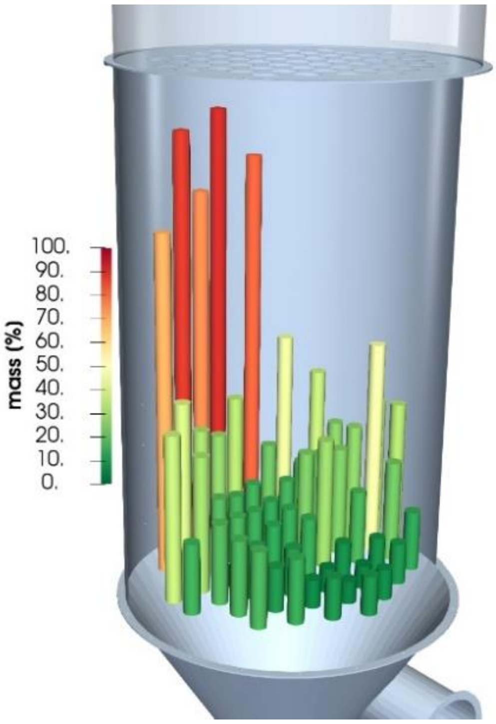

Figure 13 - mass deposited on filter bags

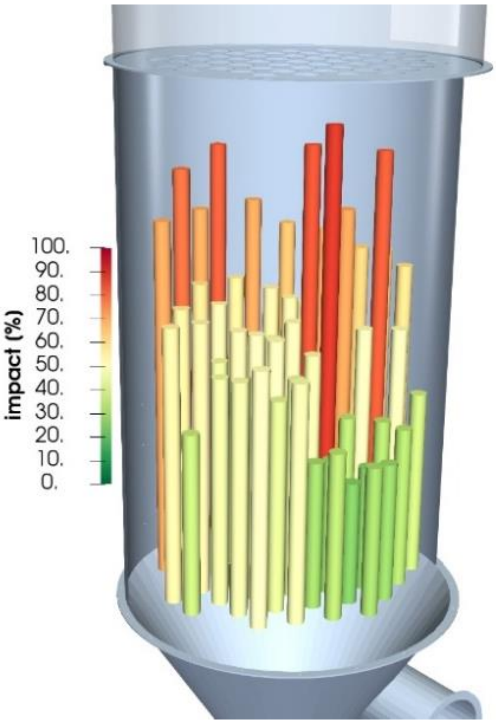

Figure 14 - impact key figure

Figure 13 - mass deposited on filter bags Figure 13 shows the degree of loading of the filters in the form of a column diagram, where the position of the column corresponds to the filter position in the system. The increased loading of the filters on the rear side opposite to the inflow is clearly visible. Filters in the direct vicinity of the inflow opening, on the other hand, are initially loaded significantly less. By considering the damage

index, which is shown in the same way as a column diagram in Figure 14, a deviation from the pure mass loading becomes visible: despite the lower loading density, the cartridge filters close to the inflow also show relatively high damage indexes. This originates in particular from the upper area of the filter bags near their suspension. Here, particles with high velocity hit areas where there is already a strong flow in the clean gas inside the filter cartridge. Only by weighting the damage index can these filter cartridges be evaluated appropriately.

It is also noticeable that the filter with the maximum damage potential is not the one with maximum mass loading. Although heavily loaded filters usually also have an increased damage index, much less loaded cartridge filters can also have high damage values as a result from the non-linearity and advanced weighting of the underlying damage model.

6 Conclusion

A macroscopic modelling of filter systems was presented, optimised for the application of multi-filter systems. The set-up, including high-quality meshing for complex systems, was largely automated and integrated into a graphical user interface.

The method of iterative loading, taking into account the interaction between continuous flow and deposited particles, allows the system to be analysed with a focus on the individual load cycles. Especially in inflow configurations, such as the swirl inflow or cyclone effect considered here, the Lagrangian particle transport, taking into account individual forces on the particles of different sizes, has decisive advantages in gas/solid systems: Here, a possible pre-separation of large particles in the housing is already taken into account, which leads to a more accurate representation of the actual mass input and the size-dependent load on the respective filter.

In combination with various damage models, critical filters can already be identified during the design of the plant and corresponding measures, such as a modified inflow or different filter material, can first be numerically examined and finally implemented. This leads to a better utilisation of the installed filter area, energetically optimised operation of the plants and reduces expensive downtimes of the plants.

7 References

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