CFD modelling of a bag filter plant for flue gas cleaning under consideration of flow shift and particle deposition relocations

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Abstract

Bag filter systems for exhaust gas purification are characterized by a large number of bag filters (usually over 1000), which are loaded with dust particles and cleaned at regular intervals with a pressurized medium. In plant operation, malfunctions often occur due to uneven loading of the filters, which leads to reduced service life with typically high repair costs and plant downtime. In the problem at hand, a bag filter system for flue gas cleaning in a power plant operation showed several failures within one year, in which cracks occurred in the filter fabric of individual bags. As a result, the specifications for air pollution control could no longer be met. The plant had to be shut down frequently and defective filters had to be replaced.

The size of the bag filtration plant with its high number of filters to be considered, the complex dynamic interactions between the continuous particle deposition on filters, the local increase in flow resistance at the filter and the associated flow and deposition relocation make it difficult to optimize the plants with typical flow simulation tools. Since common CFD tools cannot take these interactions between deposition, resistance increase and flow shift into account, adapted calculation tools are required especially for these problems.

In the case study presented here, the CFD modelling was done using the filter modelling tool from DHCAE Tools based on the CFD toolbox OpenFOAM. The modelling extension uses an Eulerian-Lagrangian approach whereby the interactions between filter loading, shift of the continuous flow due to the increase in resistance and subsequent particle deposition are considered in an iterative process.

The meshing of the geometry is of particular importance in the implementation of the simulation model: to be able to resolve the large number of bag filters in the iterative loading process, a particularly efficient meshing technique is required to ensure high mesh quality with lowest number of elements possible. This was achieved by a combination of a structured basic background grid with special matching to the overall housing geometry of the filter system. The determination of the input data in the filter modelling, especially the resistance increase with the particle loading, is also of great importance in the simulation. Here, a resistance characteristic could be derived from experiments on loaded filters.

The filters with permanently high particle load in the plant could be identified with the application-adapted CFD analysis. In the simulation, these filters showed a high proportion of deposited mass due to particle transport. In the real plant the filter bags with long excessive loads were torn out of the mouthpiece due to their high weight. The critical filters identified in the simulation coincided with the filter elements where damage occurred more frequently. From observation of the real plant the reason for the severe overloading was not obvious and could not be explained without the flow and particle deposition visualization from CFD. With the CFD case study, various means for eliminating the unequal load distribution could be examined numerically in advance to ensure that no disadvantageous secondary effects occur.

Finally, the measures derived from the simulation were implemented in the plant and no new failures are known so far.

KEYWORDS: Bag filter plant, filter simulation, CFD, OpenFOAM

Background

In a bag filter system for cleaning exhaust gases from power generation, frequent damage occurs on certain filters at no suspicious locations and for no obvious reason. The downstream filter unit is a flue gas desulphurisation unit using hydrated lime. The assumption is that individual filters are permanently loaded more heavily, thereby increasing the mass of the filters, causing cracks in the filter bag and finally tearing the filters out of the mouthpiece. This leads to the fact that the limit values for particle loading on the clean gas side are no longer complied, the plant must be shut down and the filters must be replaced. The plant downtime is associated with considerable costs.

In a CFD analysis the process of the filter loading is investigated. The cause of the uneven filter clogging is identified and appropriate means to avoid the problems are reviewed.

A major difficulty in the investigation of operating problems in complex plants for industrial use cases is the uncertainty about the process details within the plant. In a CFD analysis, it is possible to simulate different scenarios in the form of simulation variants. A variety of initial filter loadings and various particle feed sources can be simulated. Together with the plant operator and his experience with the plant the results are evaluated regarding the probability and potential of causing damage.

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 a 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.

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.

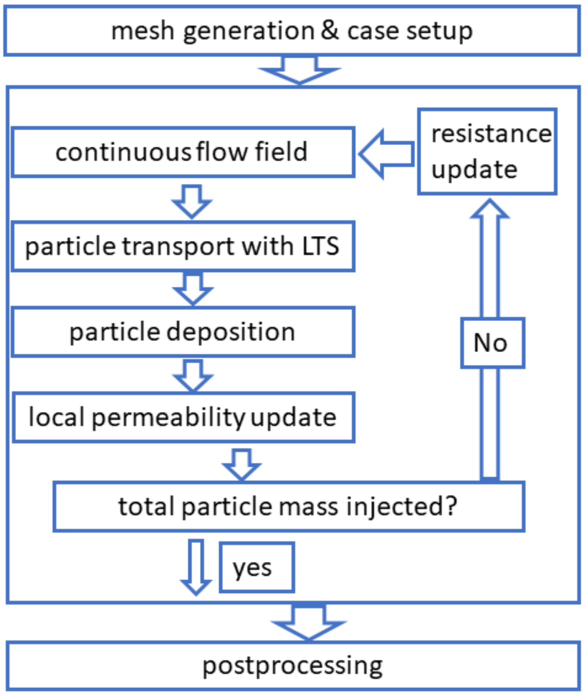

Figure 1: Iterative Solution procedure

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].

Geometry setup and meshing

The system consists of two filter houses, each with 4 filter blocks. The simulation model consists of a single house, where all filters of the 4 blocks are geometrically resolved. There are 288 filters in blocks 2,3,4 and 253 filters in block 1, a total of 1117 individual filters.

This high number of filters is a special challenge for the creation of the model and the meshing. Since the entire simulation process is an iterative approach with approx. 100 load cycles at several million parcels per cycle, the optimisation of the grid is crucial for an efficient calculation time. The filters are modularly constructed from block-structured elements, see Figure 2. The filter media are represented here as porous resistance zones. After an optimisation of the porous media representation in OpenFOAM, grid studies have shown that 4 cells across the thickness are sufficient to describe the basic resistance. Particle deposition occurs on the central surface of each filter.

The basic filter elements are created with the help of a Python script that feeds the basic meshing utility of OpenFOAM based on an input matrix containing the geometric description. Selected filters can be omitted in the meshing process, so that the entrance region of the real plant, which contains additional installations for flow redirection, can be considered appropriately.

The hexahedral grid of the filter elements forms the background mesh for the further meshing process with polyhedron cells, in which the grid is extended and adapted to the outer contour of the filter unit and the further installations within the filter house.

Other elements such as a protective wall (red line in Figure 2) on the inflow side, which changes into a perforated wall (green line in Figure 2), were realised by means of thin shell baffles and anisotropic resistance zones.

With this implementation of the meshing process, it is possible to realise a numerically efficient hexahedral grid in the filter bag region and a contour-adapted polyhedral grid on the outer walls of the filter house at the same time.

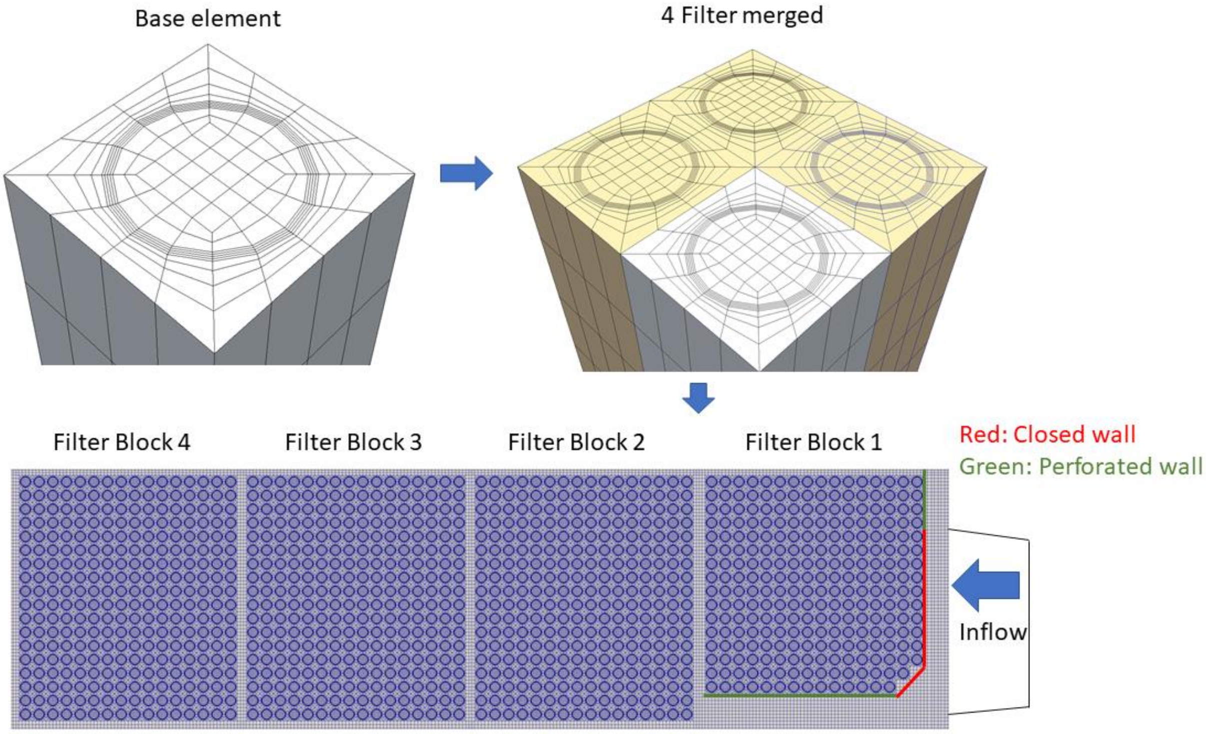

Figure 2: Grid structure for the filter system

Determination of the parameters for the filter resistance

In the operating plant the bag filters are cleaned row by row with the help of a reverse pulse jet. With this approach one row in each filter block is completely cleaned, while the other rows are clogged in an ascending order, with the mostly clogged row being the next one to be cleaned.

To obtain representative conclusions about the influence of these differing local initial resistances in the CFD analysis, different simulations were carried out in which different rows were assumed to be just cleaned at the beginning of the simulation. The loading with particles was thus calculated starting from a purified state for a particular row, while high initial resistances are assigned to all clogged filter rows.

The initial resistances before cleaning and after cleaning in a row are assumed to be isotropic. A spatial dependency of the resistances across the individual filters only occurs after the iterative particle transport, whereby the resistances are increased locally depending on the impinging mass.

The load dependent filter characteristic is based on resistance values from the experiments of used filters. Filter bags are replaced as part of the regular maintenance. Elements from different areas of the plant were examined and characteristic sample sizes from the filter bags were analysed in a test rig. Samples from the used filters were weighed in a laboratory and then evaluated in a test rig with regard to resistance/flow characteristics. Subsequently, the samples were cleaned, weighed and again determined with regard to resistance. The resistance increase of the filter media caused by particle loading was determined as input for the simulation from information from the stored particle mass and pressure loss values at different flow rates.

In the simulation, the experimentally determined resistance before cleaning is used as the basic resistance. Starting from this value, individual rows are reset to the resistance after cleaning. Building on this base resistance, the local filter resistance increases according to the mass deposited by particles based on the resistance characteristics from the test rig.

Boundary conditions

A volume flow of 86.3 m^3/s at a temperature of 110°C is used for the continuous flow. The particle size distribution corresponds according to the measurement of the hydrated lime provided by the plant operator. The size of particles is between 1 and 125 µm.

Results

Initial State

Figure 3 shows the flow conditions in the form of velocity contours at the centre plane of the plant in the initial state. In this case, it is assumed that the first row of each filter block has just been cleaned. Starting from the inflow side (right part), the flow meets the baffle plate, from which the volume flow is partly transported along the filters sideways along the 4 filter blocks. However, another part of the volume flow is directed by the baffle wall into the collection hull for block 1/2. In the real system, the lime dust is collected in the collection hopper and returned to the system loop. Due to the cleaning of the first row of each block and the lower resistance of these filters, a higher amount of gas reaches the outflow channel from these filters.

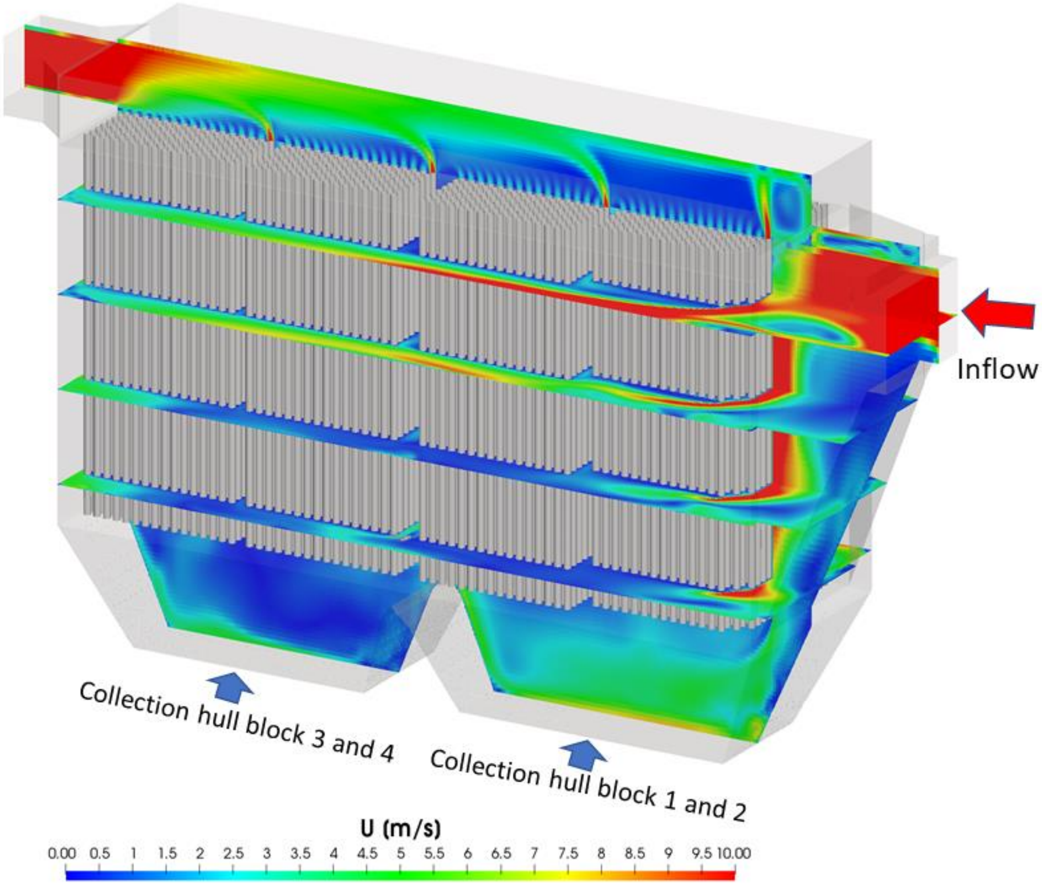

Figure 3: Velocity plot at the centre plane of the plant. Row 1 cleaned is just cleaned.

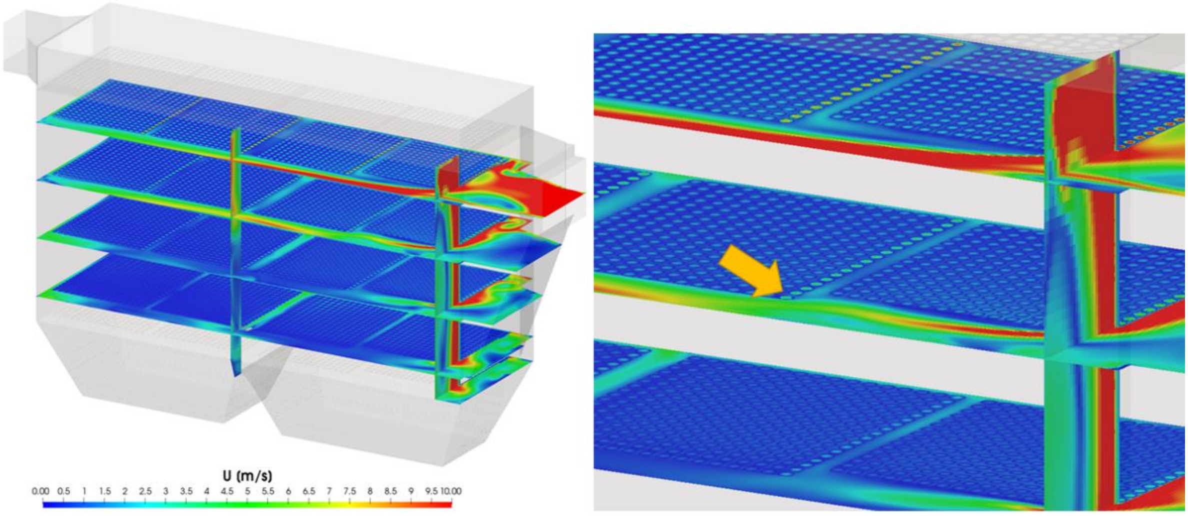

Figure 4: Velocity contours

Figure 4 shows the contours of the velocity without the bag filter elements. The velocity is decreasing from the inlet side, because along the filters a part of the volume flow is absorbed by the filters and reaches the clean gas side. Between block

1 and block 2, where some filters in the block 1 have been left out, there is a region that is strongly affected by frontal inflow (see detail Figure 4). A particularly critical zone is visible in the section where the gas hits the filter head-on (see arrow marking): While the flow is still gliding along the wall in the upper area of the filter system as shown in the first horizontal section, the free-standing filter is hit frontally by the flow in the central height. At this point, for example, a relatively high particle loading must be expected.

Filter loading

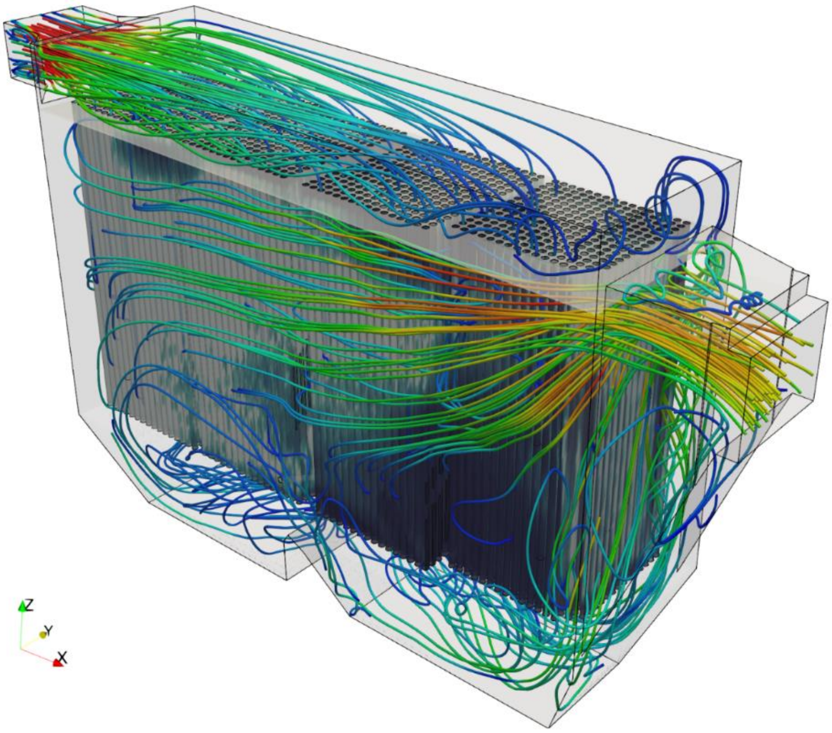

Figure 5: Path lines of the flow and filter load

Figure 5 shows the path lines of the flow (coloured with the respective velocity). It can also be seen in the path lines that the flow portion is directed from the protection wall at the first block into the collection hull. Here it sweeps over the wall with a relatively high velocity, which can potentially cause the re-entrainment of already deposited particles from the ground of the collection hopper. The filter elements are shaded by amount of particle mass deposited on the filters.

The iterative particle loading cycles are calculated on the basis of various initial resistances due to cleaning and the resulting flow conditions. The deposited masses on the filter at the end of the loading cycle are displayed both locally along a filter as a contour plot and integrally for each individual filter in Figure 6.

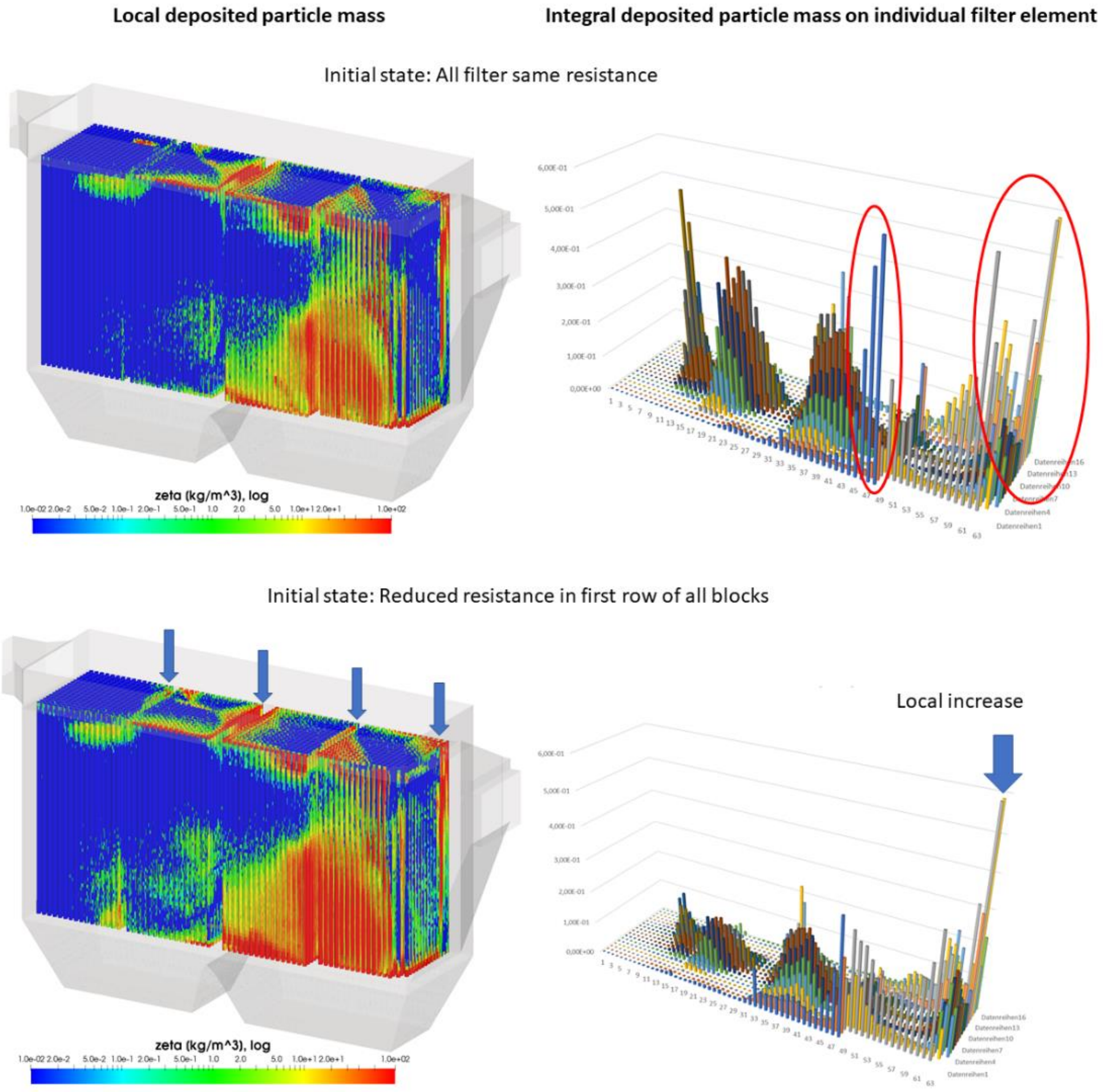

Figure 6: Deposit particle load along the filters and integrated filter mass. Particles from inflow, different initial filter resistance

Figure 6 also shows the mass of the deposited particles at the end of the iteration process on the left and the evaluated total deposited integral mass on the individual filters on the right. The inflow side into block 1 is on the right in each case.

The upper part of figure 6 shows the loading at the end of a cycle when assuming a uniform initial resistance of all filters. Here, the flow rate is approximately the same in all filters. The analysis was carried out for comparison purposes in order to be able to evaluate the effects of cleaning on the individual filter series.

In the case of uniform initial resistance there are two characteristic high deposition areas of the particles: The first zone with higher particle deposition is located directly at the flow inlet, namely at the transition of the guiding and the perforated plate, see figure 2. The second significantly increased particle deposition area occurs at the transition from block 1 to 2 at the corner of the set-back filters. As already expected by the flow description above, this area is permanently over proportionally hit by particles. The permanent loading also continues, when the flow velocity through the filters in this area is reduced due to the increased particle deposits. In fact, in this area the deposition of particles is also greater in the middle and lower area of the filters (red zones), since in the upper area (blue zone) the flow tends to sweep along the wall and the filters are not so strongly exposed to the particle-transporting flow. In this transition area between blocks 1 and 2, increased damage is to be expected.

The lower part of the picture shows the case of particle loading, when the first row of each filter block has been cleaned. These filters have a lower initial resistance. Consequently, a shift of the flowrate to higher volume flow through these filters has been observed according Figure 3 and Figure 4. A comparison particle deposition with the scenario in which the first row of filters is considered to be cleaned (Figure 6 below) shows in principle the same areas of particle mass overshoots. However, there is a significant increase in particle loading directly on the first row in the area where the particles are no longer completely protected by the guiding plate: Here, the stronger flow through the cleaned filters of the 1st row results in a higher mass input on certain filters.

As explained above, different scenarios with different initial and input conditions are considered in the simulation, which resulted from imprecise knowledge and uncertainties of the actual processes in the cleaning plant. Different initial conditions for the initial resistance distribution result from the row-by-row cleaning of the blocks.

However, one variant turned out to be particularly interesting, in which the particles were not applied from the inlet area on the raw gas side, but directly from the bottom area of the collection hopper. In the plant, the particles typically settle here after the cleaning process and are then removed from the system. The flow pattern of the single-phase flow suggests that a considerable proportion of the gas volume flow dives into this collection hopper and re-entrains particles from there.

Compared to the other considerations, in this case the filters near the inlet or the transition region between units 1 and 2 are of course no longer heavily loaded as before, since no more particles are transported with the inflowing gas. This scenario does, however, make it possible to assess where particles are deposited that are re-entrained from the collection hopper.

The analysis shows that in this case (see Figure 7), especially the filters between blocks 2 and 3 are loaded with particles very heavily. Beside the already described critical regions in the first two blocks, this area has been identified as a region where indeed increased filter failures occur in the real plant. Thus, it can be assumed that the plant-specific flow routing, in which a high proportion of the flow dives into the collection hopper, leads to the increased loading of filters in the central area of the plant.

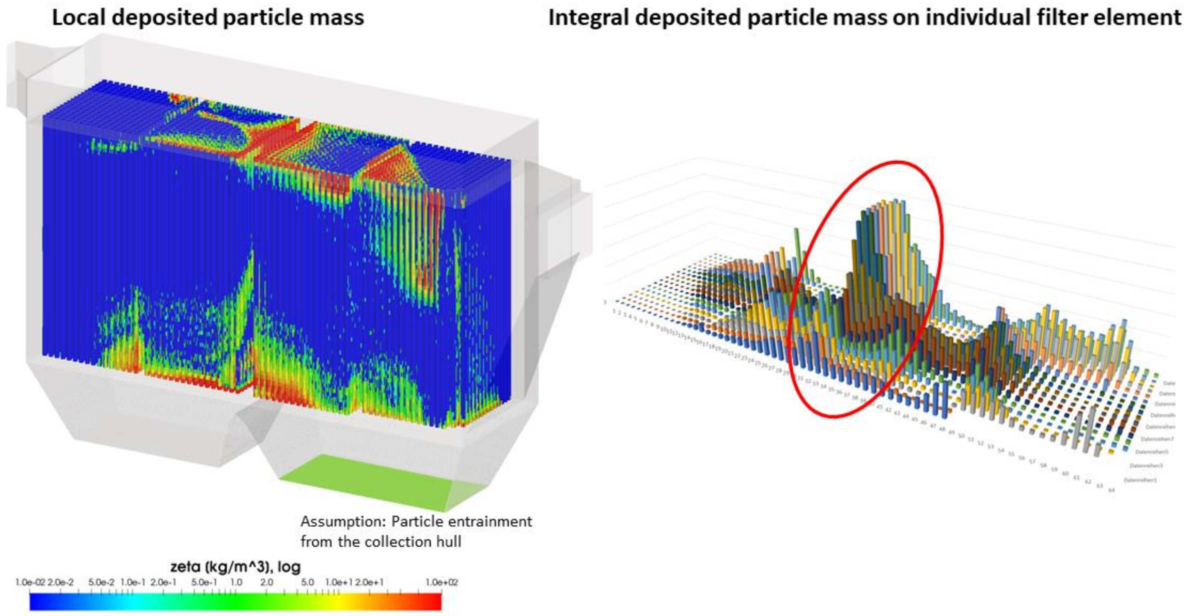

Figure 7: Deposit particle load along the filters and integrated filter mass. Particle entrainment from collection hopper.

Conclusion

Within the scope of the project, a filter system in which system failures frequently occur due to defective filters was investigated in a CFD analysis. An iterative simulation approach was used, which considers the interactions between particle deposition on individual filters and the shift of the continuous flow due to the local increase in resistance. Because of the increased simulation effort due to the iterative approach, an efficient meshing approach was required, especially for an installation with more than 1000 individual filters, in order to be able to calculate the problem on a typical workstation architecture.

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. This makes it possible to identify areas of permanent high filter loading due to high particle input. In these regions, there is no equalisation of the flow or reduction of particle loads even if the local resistance is already significantly increased. This leads to damage to the filters with subsequent system failures and resulting high costs.

CFD makes it possible to isolate and investigate unclear conditions and processes in complex plants by means of simulation variants and to work out the relevance of a particular effects. Together with the experience of the plant owner, the significance of the effect can then be evaluated, and appropriate measures can be derived. These measures can then be examined and evaluated in advance in the CFD analysis before they are implemented into the plant.

In the present case, it was thus possible to reproduce the positions of the filter bag damage in good agreement with the actual problem areas and to clarify their cause. Measures were analysed and implemented in the plant and so far, no further failures are known.

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