Multi-scale filtration process modelling based on Euler-Lagrange approaches including fluid-structure interactions

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Summary:

Filter applications are important for the chemical, automotive and domestic appliances industries. DHCAE Tools developed a solver for the simulation of filters based on the open source CFD library OpenFOAM®. In this presentation DHCAE Tools presents two major approaches for filtration process modelling, a meso scale and a macro scale model. Furthermore, the deformation of filter media can be considered by iterative Fluid-structure interaction coupling (FSI) with the open-source structural solver CalculiX.

The numeric models describe the interactions of discrete particles in a continuous flow with thin-walled, porous media on a macroscopic scale. An iterative algorithm was implemented to simulate the filter loading. Particles are injected as Lagrangian particles and tracked with a local time stepping (LTS) approach. With the local particle concentration, the non-uniform resistance of the filter is calculated. The pressure drop caused by the filters is calculated with the Darcy-Forchheimer law.

New flow conditions have been implemented, for example to deal with the damping of the turbulence across the filter baffle, the orientation of the velocity field and the correct calculation of the pressure drop.

The macro scale modelling approach allows the simulation of depth filter applications as well as surface filters with a filter cake up-building. A meso-scale model allows geometrically growing filter cakes with complex porous structures.

A steady state particle tracking in combination with the SIMPLE algorithm for the flow field calculation result in a very efficient solver for a wide range of industrial scale problem sizes. The macro scale modelling was validated based on literature data and in filter plants.

A coupling between OpenFOAM and the open source finite element solver CalculiX has been integrated to model the deformation of the filter caused by pressure and dynamic particle loading. To handle high structural deformations an automatic local remeshing functionality has been integrated. The FSI coupling has been validated in a number of cases.

Keywords:

Filter, CFD, FSI coupling, OpenFOAM, CalculiX, Microscopic, Macroscopic, Meso-scale modelling

1 Modelling approaches

A multi-stage, continuous numerical method, covering different geometry scales, is implemented. The complete flow modelling is based on open-source solver technology. The entire CFD modelling including the continuous phase and particle modelling is conducted in OpenFOAM, while the structural analysis (deformation of the filters) is done with CalculiX, an open-source non-linear finite element code or with Abaqus respectively. Two based modelling approach for filtration processes are available:

Macroscopic model approach

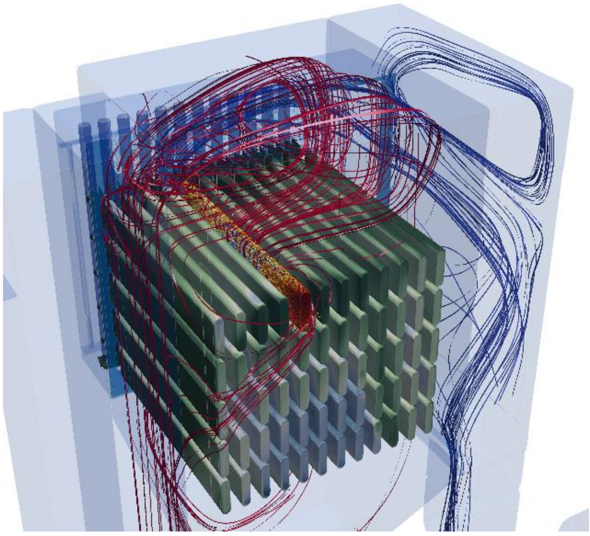

Fig. 1: Filter plant with 60 filters

The macroscopic modelling uses resistance functions depending on the flow velocity and particle load. After estimating these relationships in a filter test stand for single filter, these functions can be applied to multiple filter arrangements e.g. in a filter plant for an iterative particle load simulation.

Meso-scopic model approach

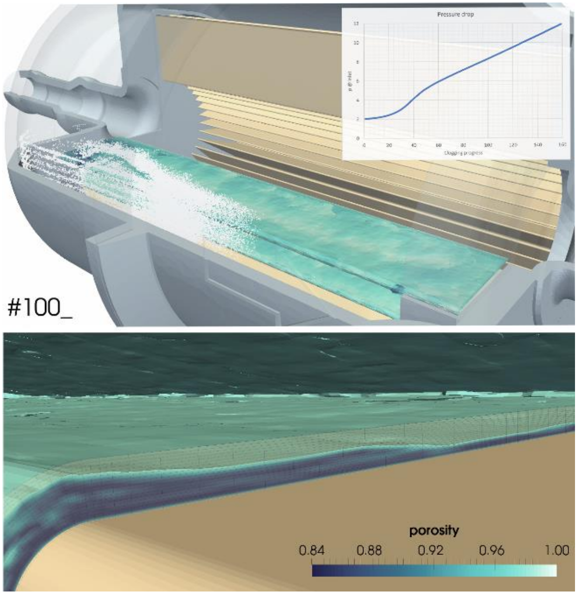

Fig. 2: Fuel filter

The meso-scale modelling considers a geometrical cake generation and estimates the pressure loss in the filter cake based on the Ergun equation according the local particle sizes and porosities in each cell. Due to the geometrical resolution of the filter cake by a layered mesh typically single or few filter faces should be considered.

2 Macroscopic modelling

In the macroscopic perspective, the particle transport in complete filter plants is considered.

In general, the distribution of the particles is inhomogeneous, not only between different filters, but even within a single filter element. This results in a continuously changing flow field during the operation, e.g. of the filter house in chemical engineering.

The numeric models describe the interactions of discrete particles in a continuous flow with thin-walled, porous and non-porous media on a macroscopic scale. Due to the complex geometries of bag filter houses, the filter elements are defined as 2D porous baffles.

An iterative algorithm is implemented to simulate the filter loading. In the first step the steady state flow field is calculated.

On this flow field a certain mass is injected and transported with a Lagrangian method. Hereby parcels, each representing a large number of physical particles with properties like mass, density, diameter etc. are tracked. For the particle transport effects like drag and lift forces, gravity etc. can be considered. The particle tracking itself uses a Local Time Step (LTS) approach, which provides a very fast steady state transport mechanism almost independently from the local mesh resolution. The final particle location on the filter surface is evaluated and the increasing particle concentration is stored on each single face on the filter baffle mesh.

The macro scale modelling was validated based on literature data for filter loading under laboratory conditions and in demonstration filter plants with 60 filter elements [1].

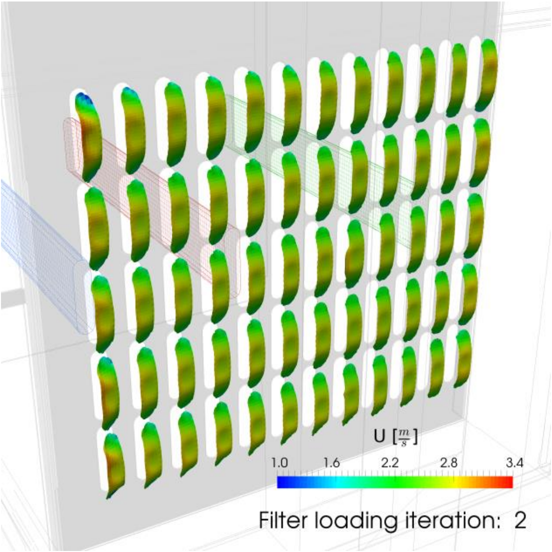

Fig. 3: Velocities at the filter outlets after two loadings

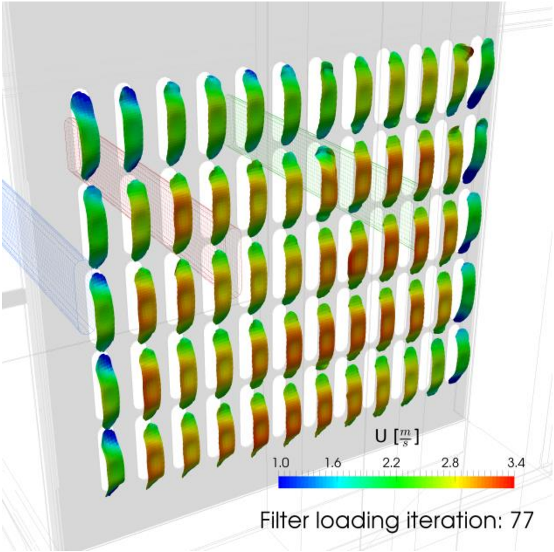

Fig. 4: Velocities at the filter outlets after 77 loadings

According to figure 1 a filter plant has been experimental investigated and numerically modelled. Due to the initial flow and subsequent particle transport, a higher number of particles settle at the outer filter elements at the beginning. This results in an increasing local resistance at the outer filters and decreasing mean velocity through theses filters during the loading. The continuous flow shifts to the inner filter elements and results in increasing mean velocity through the inner filters. The shift of the flow during the particle loading process, judged by increasing or decreasing mean velocity through the particular filter, shows a good agreement with experimental results: Here, the same slope of mean velocity during the loading has been observed [1].

Considering all 60 filter elements, the shift of the continuous flows shows a realistic and expected behaviour (Fig 3 and Fig 4): At the beginning, all filters are clean and provide the same resistance. Therefore, they show nearly the same mean velocity and flow pattern. At the end of the particle loading cycle, all outer filter rows show smaller mean velocities due to the preferred settling of particles at the outer filter bags and, by this, increasing resistance.

As a conclusion from the simulation results the outer filters will age much more quickly than the inner filters. An optimization goal for a revised plant can be the harmonisation of the filter lifetimes, for example by redirecting the inflow.

The steady state particle tracking in combination with the SIMPLE algorithm for the flow field calculation result in a very efficient solver for a wide range of industrial scale problem sizes.

3 Meso-scale modelling

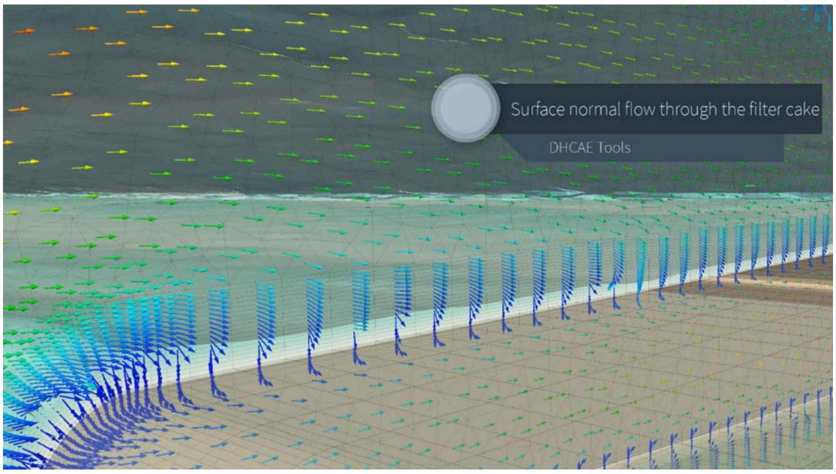

Fig. 5: Velocities at the flow through the filter cake

A meso-scale modelling approach is introduced to deal with the formation of a filter cake.

The meso-scale model is based on the modelling approach by Weber [2] and the implementation has been validated against the numerical and experimental data in his thesis [3].

Particles or parcels are tracked until they hit selected walls or permeable filter elements

The cells adjacent to these patches are filled with these particles, hereby reducing the porosity of the cell. After reaching a minimum porosity the cell is assumed to be filled completely and the next particles arriving settle in the preceding cell etc. The pressure loss Δp/l is estimated using the Ergun equation:

$$\frac{\Delta p}{l} = k_1(\varepsilon)\frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{\mu u}{d_{32}^2} + k_2(\varepsilon)\frac{1-\varepsilon}{\varepsilon^3}\frac{\rho u^2}{d_{32}}$$

$\mu = fluid\ viscosity$

$u = inflow\ velocity$

$d_{32}^2 = Sauter\ mean\ diameter$

$\rho = fluid\ density$

$k_{1/2}(\epsilon) = model\ parameter$

$\epsilon = local\ cell\ porosity$

In an iterative process the filter cake is building up. The continuous flow field is recalculated in each iteration step to consider the continuous flow shift according the local resistance changes by the particle settling. The particle tracking itself can be done either with a time efficient LTS algorithm for long-term view simulations or with PISO controlled transient simulations. The filter cake can develop complex porous structures.

4 FSI Coupling of OpenFOAM and CalculiX/Abaqus for filter applications

During the loading of the filter, typically large pressure gradients may occur across the filter media. Depending on the geometry, the fixation and the contact areas a deformation of the filter may take place. The deformation itself may again influence the available cross section for the continuous phase. Here a coupled fluid-structure interaction modelling is required to consider these effects.

The FSI coupling has been validated against typical benchmarks in literature [4].

In the filter test case a 3-dimensional swirling configuration is selected. The particles are collected by a 2D face located in the centre of the domain.

The structural component is modelled by shell elements. The increasing loading with particles and interaction with the continuous flow causes a pressure increase across the filter.

Due to the filter fixation lines a characteristic deformation occurs (Fig. 6). This deformation is considered in the continuous and in the particle flow of the next filter loading steps.

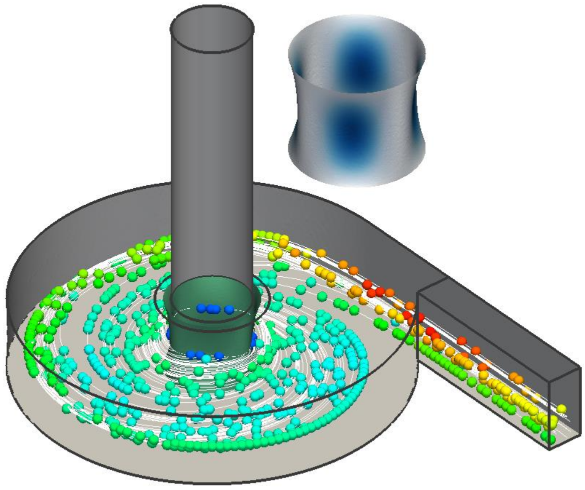

Fig. 6: FSI: Deforming filter

5 Summary

Based on open source solver technology, a multi-scale filter modelling is presented: The macro modelling can handle multiple filter arrangements in complex geometries such as filter plants efficiently. The meso modelling regards more detailed effects at the filter media such as cake building and geometrical blockage by the cake. Both approaches consider iterative filter loading cycles with resistance updates and associated flow shifts of continuous phase.

The macroscopic filter loading model has been integrated into an FSI-coupling between OpenFOAM and CalculiX to consider the deformation of the filter by pressure forces. The FSI modelling has been validated with several cases in literature.

6 Contact

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7 References

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