A flexible approach for meso-scale filtration modelling based on Open-Source CFD

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Abstract

Modelling of filter applications becomes more and more important for many industries such as chemical, automotive or domestic appliances. DHCAE Tools presents a framework for the simulation of filtration processes based on the open source CFD library OpenFOAM®.

The numeric models describe the interactions of discrete particles in a continuous flow with porous media on a meso-scopic scale. An iterative algorithm was implemented to simulate the interactions of the continuous flow with the filter media loading or cake growth.

A steady state particle tracking in combination with the SIMPLE algorithm for the flow field calculation results in an efficient solution process for a wide range of industrial scale problem sizes.

Particles are injected as Lagrangian particles and tracked with a local time stepping (LTS) approach. A wide number of deposition models for the cake and filter media are available. Furthermore, experimental data or relationships from a micro scale approach can be used as input for the meso-scale model. Based on the local deposition, the local porosity is calculated, and the resulting permeability is estimated. Also for the porosity and permeability computation, different models for the cake and filter media are available. With the updated resistance in each cell of the filter media and cake, the continuous flow is recalculated.

The target of the framework is to shift the geometric scale from the micro modelling with particle-particle in the cake or particle-fiber interactions in the filter media to a larger scale by using a porous media formulation. The larger scale model with porous media formulation allows finally to simulate the flow and particle transport from the entry into the filter housing, across the filter media to the exit. To establish a consistent transition from the micro modelling to the meso-scale modelling, the modelling approach was verified by rebuilding typical filtration configuration with transitions from depth to cake filtration based on micro model tools.

KEYWORDS

Filter simulation, CFD, OpenFOAM

Microscopic, Macroscopic, Meso-scale modelling

Introduction

Modelling of flow problems by computational fluid dynamics became more and more state of the art in many applications. Starting with automotive and aerospace applications in the early 80s, CFD prove itself meanwhile as an indispensable tool in nearly every sector with typical fluid flow challenges such as plant engineering, medical product development, environment analysis or HVAC.

The general advantage of CFD is that the base solution methods are general and can be applied to a wide range of flow problems. However, in certain applications additional closure assumptions based on experimental data need to be integrated into the code to cover specific effects. These effects very often happen at smaller time or geometry scales, which cannot be resolved in all details and within the same model. Filtration applications represent a typical multi-scale problem: the geometric dimensions of the filters are in the range of millimetres to metres, while the relevant physical effects considering the particle and fibre interactions take place in the micrometre length scale. The multi scale problem in filtration simulation requires a consistent transfer of physical effects to the higher scales: E.g. if within a micro-scale analysis the effects of cake build up or fibre structure has been analysed and models have been found by particle-particle or particle-fibre interactions, it is important to transfer these models to higher scales without resolving each individual interaction phenomena. On the higher scale, additional effects such as particle separation or settling in the filter housing including turbulent effects can be analysed.

Furthermore, the requirements of a filter modelling can be widely spread: In some situations, it might be sufficient to estimate an initial loading or initial deposition profile of particles in the filter media without considering the increasing resistance. In other cases, it might be important to consider the filter cake build up and local resistance increment during the filtration process.

The Open-Source CFD toolbox OpenFOAM has been designed to extend the common CFD models for specific needs. DHCAE Tools develops a flexible filter-modelling framework to cover a wide range of filter applications on a meso- and macro-scale perspective [1]. The target is to investigate flow behaviour ahead of the filter media in combination with local effects at the filter, e.g. increasing local resistance and cake generation effects.

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 or drag and inertia or individual and local particle-wall interactions such as sticking or rebounds. The Lagrangian particle transport in OpenFOAM has been adapted to specific needs for filter modelling. This includes improvements for performance, accuracy (e.g. adaptive local Courant numbers for local time stepping procedures) and stability.

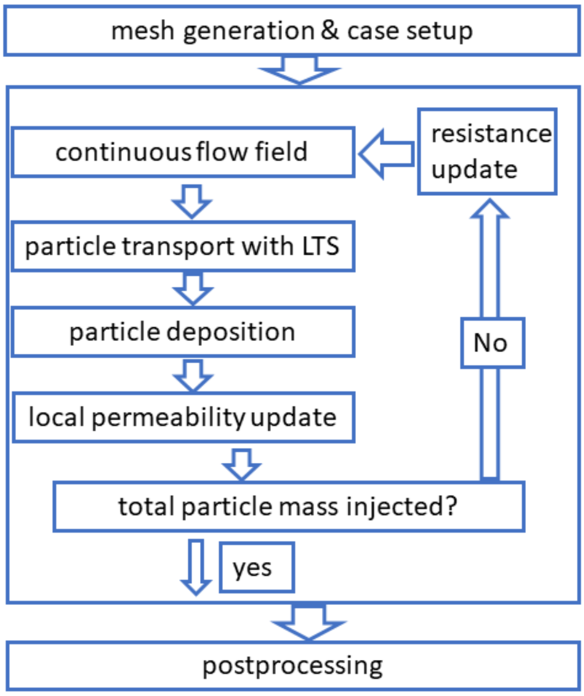
The filter modelling is based on a meso scale approach, which considers the filter media and the filter cake as porous zones. The approach combines relationships derived from a micro model, from literature or from test rig measurements to a cell-based filter model for the filter cake and the filter media. The models are organized in different groups:

- Resistance models: Here a number of resistance models such as the Ergun equation, Jackson-James relation or Darcy's law are available. Typical input parameters are the porosity, characteristic diameters or sub models to calculate the latter.
- Porosity models: Constant or locally predefined porosity models are available, as well as sub models to develop the porosity within the iterative particle depositions.
- Efficiency and deposition models: Various deposition models are available for the filter media and the filter cake, e.g. lookup tables for deposition probabilities as a function of particle diameter and particle velocity.

These models can be combined to specific application areas according the available input: E.g. if filter efficiency relations for flat filter media are available from an experimental setup, these input data can be used to model the local deposition at pleated filters. Here an Ergun equation for the local permeability of the developing cake and a Jackson-James relation can be used for the permeability in the media. If no appropriate data to a specific model are available assumptions can be made e.g. to consider the filter loading with specific permeability models at 100 % efficiency. Furthermore, already integrated models can be extended to match the available input of experimental data at the user's side.

The models for the filter media and filter cake are locally and cell based. For instance, each computational cell in the domain can have an individual resistance, filling level and porosity. Already deposited particles contribute to the local characteristic particle diameter representative for the cell, hereby affecting the resistance, porosity and efficiency models.

Modelling approach



An iterative algorithm is implemented to simulate the filter loading, shown in Figure 1. In the first step the steady state flow field is calculated.

In this flow field a certain particle 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.

In the Lagrangian framework of the particle transport effects like drag and lift forces, gravity etc. can be considered.

Figure 1 - Algorithm.

Depending on the different particle sizes, the additional forces may result in particle path lines differing from the idealized streamline of the continuous flow: Particles may hit walls or settle due to gravity. These effects are typically rather important in configurations where a higher difference in the density between the particles and the continuous flow occurs, e.g. solid particles in air.

The particle tracking itself uses a Local Time Step (LTS) approach. Local time stepping overcomes the typical small time step size estimated by the highest velocity with smallest cell combination in the overall domain. In local time stepping, each cell receives an individual time step, resulting from local velocity, local cell size and global maximum Courant number. By this local time stepping provides a very fast steady state particle transport mechanism.

Those particles, which reach the filter, can depending or their local state and the local state of the filter either pass the filter, deposit in the media or build a cake.

For the media, different deposition models are available. E.g. a cell can be considered to be filled, if a predefined minimum porosity is reached. On the other side experimental deposition curves, representing a deposition probability can be used if these data are available. These relationships can be either estimated in experiments or from data derived from a micro model. For the penetration depths of individual particle sizes and particle velocities, the model of Iwasaki is used [2].

Based on the mass transported with the particle, the local porosity can be updated. Typically, for a filter media the porosity decreases based on the deposited mass and limiting porosities can be defined. Finally, a resistance model for the media can be applied, here for example the Kozeny-Carman model is integrated. Also, a combined permeability model suggested by Osterroth [3] based on the Jackson-James model can be used: In case of the Jackson-James correlation the user defines the initial fibre radius (rf) and the initial porosity e_0.

$$k(\varepsilon) = \left(\frac{1}{k_{load(\varepsilon)}} + \frac{1}{k_{clean(\varepsilon_0)}}\right)^{-1}$$

$$k_{clean}(\varepsilon_0) = -r_f^2 \cdot \frac{3}{20} \frac{\ln(1-\varepsilon_0) + 0.931}{1-\varepsilon_0}$$

$$k_{load}(\varepsilon, \varepsilon_0) = \frac{1}{180} \cdot \frac{\varepsilon^3}{(\varepsilon_0 - \varepsilon)^2} \cdot d_{32}^2$$

The load depended permeability results from the local porosity in the media, which is estimated by the deposition model and the mean diameter d_{32} by the accumulated particle transport into the cell.

If the build up of the cake is considered, the deposition can be modelled by a constant cake porosity and filling level of the cells. The permeability of the cake is estimated for example based on an Ergun-equation.

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

Here the slope of pressure curve $k_1(e)$ can be estimated by an experimental study or may be derived from a micro-model tool.

The non-uniform resistance of the filter media and cake are recalculated in each load cycle. Each cell on the filter media and the filter cake represents an individual resistance to the flow, calculated with one of the common laws like Ergun, Darcy Kozeny-Carman or Jackson-James, and respecting the impact velocity, local particle size, local porosity etc. The shift of the continuous flow field by the local resistance changes in the filter media and cake is considered in an iterative approach then: in the next continuous fluid flow update the new local resistance is applied in the solver.

Model Verification

The target of the model approach is to transfer the micro effects at a filter during the depth and cake filtration to a higher level to use a porous media formulation instead of a detailed resolution of particles and fibres. To establish a consistent upscaling of the relevant effects, a filtration case based on a micro model is implemented to prove the suitability of the porous media setup.

A fibrous structure with cake build-up has been analysed with DNSlab [4]. For a short period of pure depth filtration, the resulting porosity and deposition probabilities were identified. The transition point from depth filtration to cake build was determined.

Finally, the resulting cake characteristics, in particular the cake porosity and permeability has been estimated.

With the collected data the appropriate models for the meso-scale investigation where identified and the necessary input parameters were derived. For the depth filtrations resistance, the Jackson-James model together with the Kozeny-Carman model for the clogging process are suitable. The deposition regime follows the approach from Iwasaki. The transition point from depth to cake filtration can be handled by the minimum porosity model. The cake build-up happens linear with a constant average porosity on the cell level. For the cake resistance the Ergun model is appropriate.

Figure 2 shows the simulation results of both DNSLab and OpenFOAM in the moment of transition from depth to cake filtration. A number of particles have entered the fibrous structure, mostly depositing near the filter medias front (top). The meso-scale approach (bottom) reproduces this effect with a lower porosity near the filter front as well. Orange cells indicate the cells of the evolving filter cake.

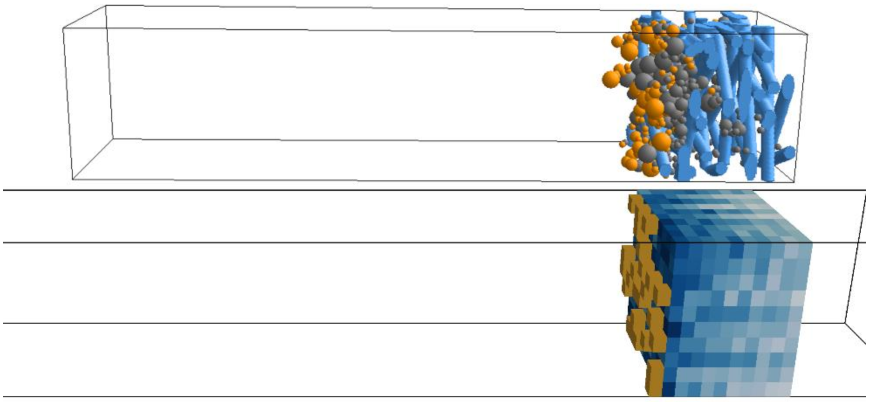


Figure 2 – DNSlab (top) vs OpenFOAM simulation (bottom), transition from depth filtration to cake filtration.

The further progress of the simulation is given in Figure 3. Pure cake filtration is active and both simulations show equivalent growth of the cake. Comparing the pressure loss against the deposited mass show excellent agreement in Figure 4 and again an excellent agreement for the exact cake height in Figure 5.

This demonstrates that the model implementation is suited to transfer the local effects within and near the filter media to higher scales, and that a porous media formulation can be applied in the meso-scale modelling approach giving coinciding results.

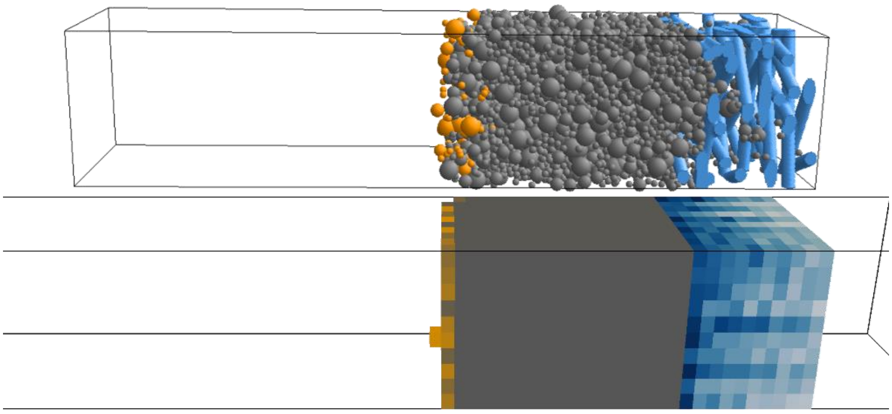


Figure 3 – DNSlab (top) vs OpenFOAM simulation (bottom), showing pure cake filtration.

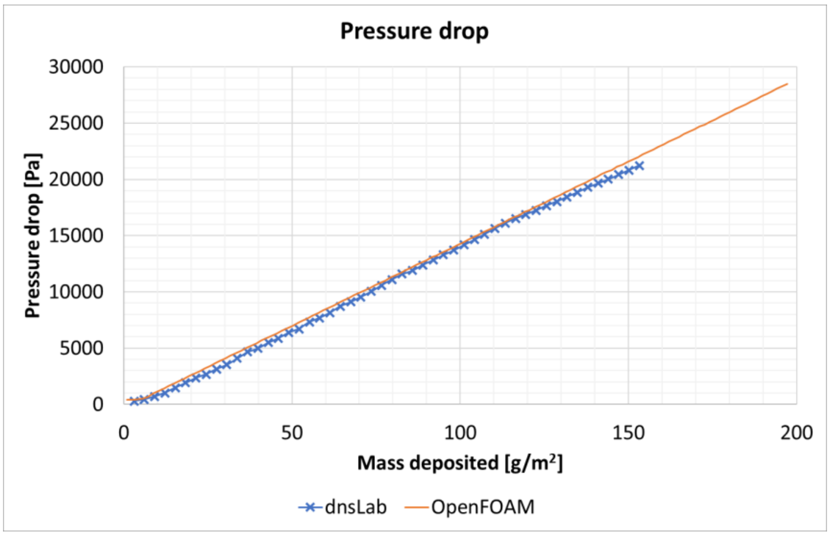


Figure 4 – Pressure loss comparison.

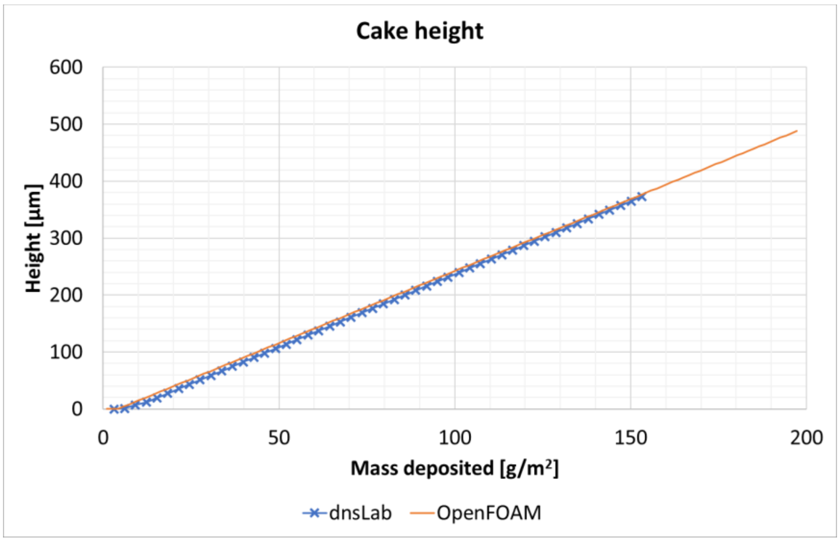


Figure 5 – Cake height comparison

In the next step, the model approach has been extended to a pleated filter as shown in Figure 6. Streamlines coloured by the flow velocity traverse the filter media almost surface normal. Pressure loss is given for the clean filter media. The simulation setup makes use of symmetry boundary conditions, so the results can be extended to a complete filter element.

For this pleated filter element different stages of the filtration cycle can be analysed, e.g. the pure depth filtration based on the deposition model of Iwaski. Depending on the particle velocity and particle size the penetration depth and the deposition probability of the particle is estimated, resulting in a declining particle deposition in the filter media in flow direction.

When the outer cells in the media are filled the transition to cake generation takes place. After a short transition period, a constant slope of the pressure increase can be observed (Figure 10). The cake porosity remains constant, while the thickness of the cake increases according the deposited mass.

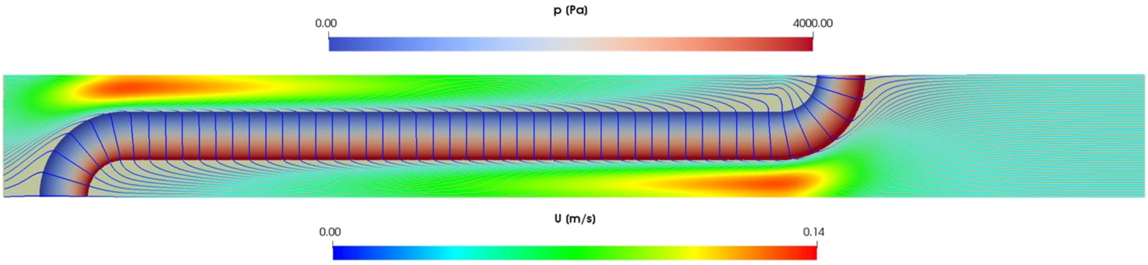


Figure 6 - Part of a pleated filter element.

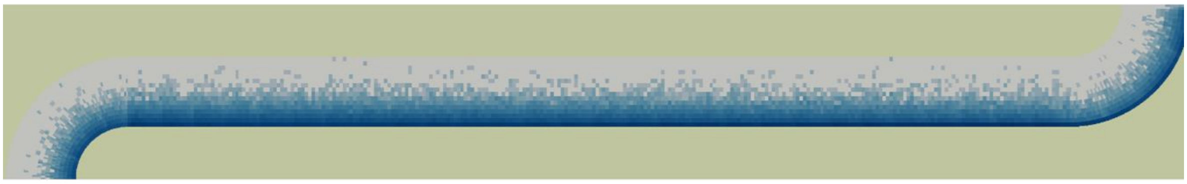


Figure 7 - Particle deposition, pure depth filtration.

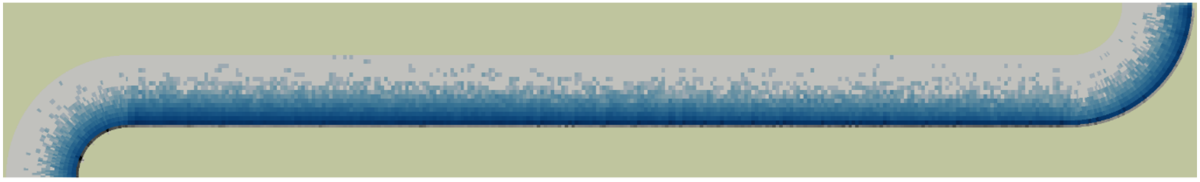


Figure 8 - Particle deposition, transition from depth to cake filtration.

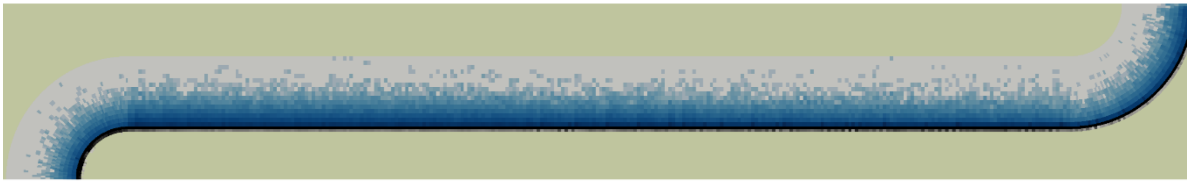


Figure 9 - Particle deposition, pure cake filtration.

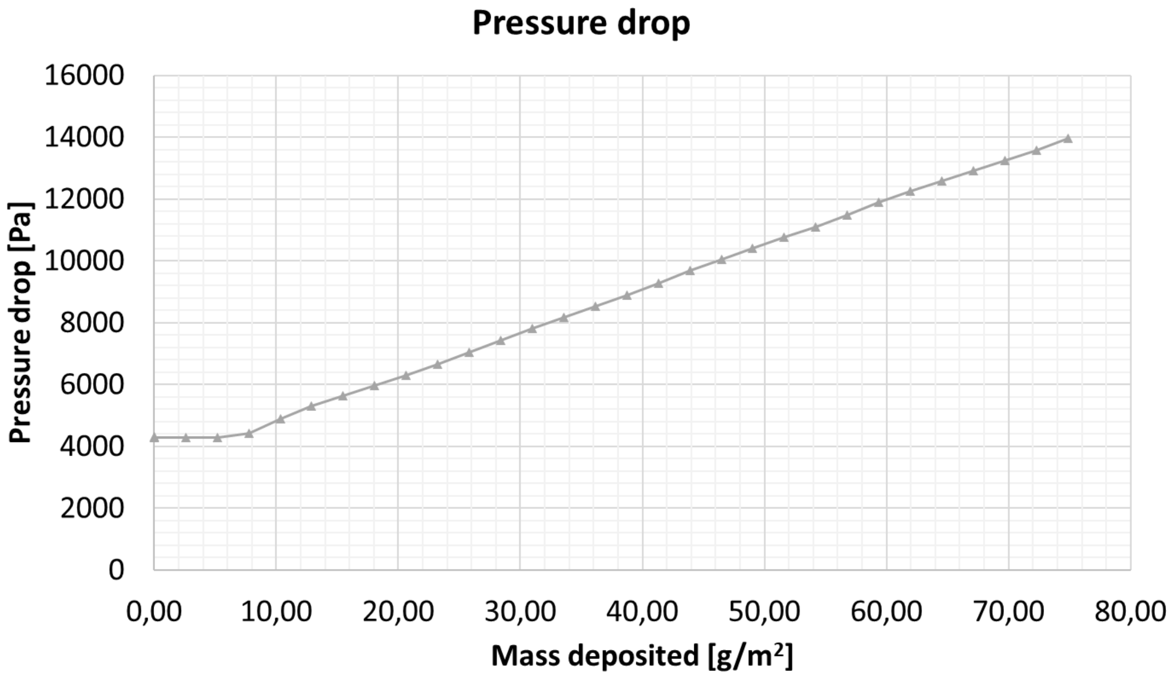


Figure 10 - Pressure drop across filter media and cake.

Summary

A new framework based on open-source CFD solver technology was introduced for filtration modelling to consider the depth filtration and the cake generation. The model is based on Lagrangian particle transport in combination with porous media formulation. Different models for permeability, deposition and porosity are already integrated. This allows using common relationships from literature, to integrate problem specific correlations based on micro-modelling tools or to set-up correlations based on experimental data.

References

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