Solid-liquid separation in filter presses: A sustainable design and optimization of multi-scale processes through digitalization

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Abstract

Process engineering faces a transformation toward resource-efficient production. In addition to the development of new processes and plants, this also includes the optimal operation of existing production plants to ensure efficient use of energy and materials and to guarantee consistently high product quality, even if the process behavior changes. For this challenge, the use of resolved simulation and real-time models is essential. The focus of this presentation is on filter presses. Their design is based on analytical models and the experience of the manufacturer. Dynamic processes are not considered, which enforces expensive pilot-scale experiments for scale-up. The presented method fully considers the multi-scale nature of separation processes. Simple laboratory experiments form the basis and provide appropriate material functions. CFD simulations allow to investigate the hydrodynamic interaction of solid and liquid phase during a separation process. Digital twins support the design of filter presses and the scale-up to industrial scale.

Keywords: Filter presses, solid-liquid-separation, resolved simulation, CFD

1. Introduction

Filtration is a fundamental mechanical process for the separation of solids from liquids, and is therefore widely used in water treatment and mining as well as in the chemical industry. Cake filtration enables a low residual moisture content. Here, a porous filter medium allows the liquid phase to pass through while retaining the particles. Because of their simple design and reliable performance, chamber filter presses are widely used. Figure 1 shows the working principle of a chamber filter press. First, the chamber filter press is filled centrally. Each chamber is lined with filter cloth. The liquid passes through the filter cloth and is discharged via the filtrate drain, while the particles remain on the inside and form the filter cake. When the cake formation is complete, the feed stops and the filter plates are pulled apart to open the chambers. The filter cake falls down and is discharged. Afterwards, the filtration cycle is repeated. However, design and operation are usually based on the experience of manufacturers, while effects such as sedimentation as well as flow conditions in the apparatus are neglected. [2]

Numerical methods help to improve the process understanding in solid-liquid separation in separation devices. However, the process takes place on different time and length scales: For example, sedimentation is influenced by the properties of the disperse phase on the microscale, but at the same time, the separation process is superimposed by the flow in the apparatus on the macroscale. For this reason, there is a relatively large number of modeling and simulation approaches that fully or only partially take into account the interactions between particles and the fluid. For example, CFD simulations enable flow resolution and particle tracking, while reduced-order models model fluid-particle interactions but track the process in real time. Thus, it is possible to model entire process chains with reduced-order models [3]. The interactions between disperse and continuous phases are modeled. In comparison, computational fluid dynamics (CFD) provides the resolution of the flow in the apparatus [4]. Here, the disperse phase is modeled either by porous structure models or two-phase models (Euler-Euler), or tracked as lagrangian particles (Euler-Lagrange).

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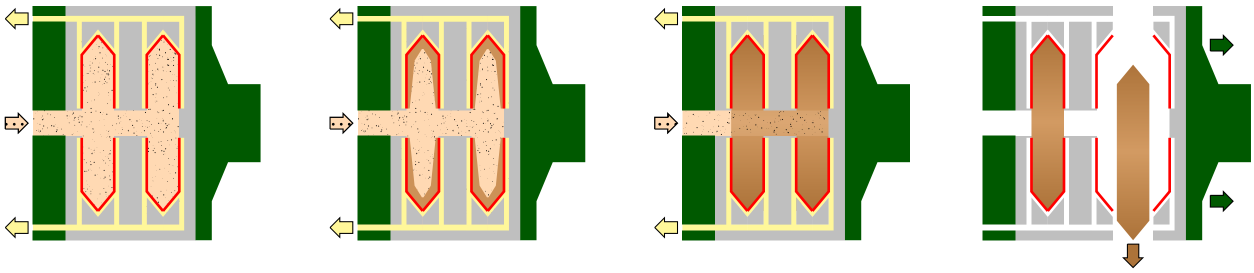


(a) Start of feeding   **(b)** Cake built-up   **(c)** Filter cake compression   **(d)** Filter cake discharge

Figure 1: Working principle of a chamber filter pressaccording to [1]: start of feeding (a), filtration and cake formation (b), compression (c) and filter cake discharge by opening the filter press (d).

By coupling CFD and the discrete element method (DEM) it is also possible to investigate the processes on the micro scale, e.g. the interactions between the particles due to the acting forces [6] and the filter medium [5]. One difficulty of resolved simulations is the computation time, which leads to resolving only the filter itself, or the deposition on the filter, but not the entire apparatus.
The present work provides a method for deriving material functions from laboratory experiments. By implementing these functions in CFD, it is possible to simulate and investigate the cake build-up, dewatering process due to filter cake expression and its structure within the whole filter press. The basis is a simulation model developed by Baust et al. [7] for the investigation of the separation process in centrifuges. The flow is simulated by means of the Navier-Stokes equations. The dispersed phase is calculated using an additional transport equation based on the work of Kynch [8] and Garrido et al. [9], which allows the material behavior to be considered in terms of material functions.

2. Method

The formation of the filter cake depends on the filter medium and the properties of the dispersed phase. The interactions between the particles themselves and between the disperse and continuous phases are summarized in material functions for sedimentation, cake permeability and consolidation. It is assumed, that all of these functions depend only on solids volume fraction. The implementation of these functions in CFD allows the resolved simulation of the separation process in the whole apparatus.

2.1. Numerical setup

To simulate filtration processes, the solver of Baust et al. [7] was extended. Analogous to Bürger and Concha [10], the sedimentation and consolidation behavior was described via the flux density function. The coupling with CFD allows the simulation of the flow behavior in the apparatus during the separation process. Therefore, the disperse and continuous phases were considered as a single mixed phase. The flow of this mixed phase was simulated using the Navier-Stokes equations.

$$\frac{\partial \boldsymbol{u}_{\text{mix}}}{\partial t} + (\boldsymbol{u}_{\text{mix}} \cdot \nabla)\, \boldsymbol{u}_{\text{mix}} = -\nabla p + \nu_{\text{mix}}\,(\phi) \cdot \nabla^2 \boldsymbol{u}_{\text{mix}} + \boldsymbol{f}_{\text{c}} + \boldsymbol{f}_{\text{fm}} \tag{1}$$

Here, $\boldsymbol{u}_{\text{mix}}$ describes the velocity of the mixing phase, p is the kinematic pressure and ν is the kinematic viscosity, which depends on the solids volume fraction ϕ. Additionally, the equations were extended by the filter cake resistance $\boldsymbol{f}_{\text{c}}$ and the filter medium resistance $\boldsymbol{f}_{\text{fm}}$. The implementation of a transport equation for the solids volume fraction allows the consideration of the material functions.

$$\frac{\partial \phi}{\partial t} + \nabla \left(\phi \boldsymbol{u}_{\text{mix}} \;+\; f_{bk}(\phi)\right) = \nabla \left(D \nabla \phi\right) \tag{2}$$

The flux density function f_{bk} is defined as the product of solids volume fraction and the settling velocity u_{p} and thus includes the sedimentation hindrance. The compression of the sediment is taken into account via a kind of diffusion coefficient D, which depends on the compressive resistance p_{c} [11]. The settling velocities the and cake resistance may be determined by means of simple laboratory experiments.

2.2. Experimental setup

Sedimentation describes the settling of specifically heavier particles in a fluid due to the acting mass forces. A first approach to calculate the settling velocity neglects particle interference and is limited only for small Reynolds numbers. According to Stokes [12], the settling velocity of a single, round particle in a stationary, Newtonian fluid can be calculated as follows:

$$u_{\mathrm{p,St}} = \frac{\rho_{\mathrm{p}} - \rho_{\mathrm{l}}}{18\,\eta_{\mathrm{l}}} \cdot g \cdot x^2 \tag{3}$$

The settling velocity $u_{\mathrm{p,St}}$ depends on the density of the particles ρ_{p} and the liquid ρ_{l}, as well as the dynamic viscosity η of the liquid and is proportional to the square of the particle size x. The variable g stands for the acceleration due to gravity. In reality, single grain sedimentation is often not present and the particles influence each other. The higher the solids volume fraction, the more the particles hinder each other and the slower they sediment. Richardson and Zaki [13] adapted Stokes' approach to consider increasing particle interactions as a function of the solids volume fraction.

$$u_{\mathrm{p}} = u_{\mathrm{p,St}} \cdot (1 - \phi)^{4.65} \tag{4}$$

The LUMiReader (LUM GmbH, Berlin) enables the measurement of the settling velocity of particle systems [14]. Thereby, slurries with different solid volume fractions were investigated. Plotting the settling velocity u_{p} related to the Stokes settling velocity $u_{\mathrm{p,St}}$ as a function of the solids volume fraction leads to the hindrance settling function (Figure 2 (a)). This function is implemented in OpenFOAM and allows the calculation of the settling velocity in each volume element according to the present solids volume fraction. These hindrance settling functions may be modeled by an extension of the approach of Richardson and Zaki [13], as for example proposed by Michaels and Bolger [15].

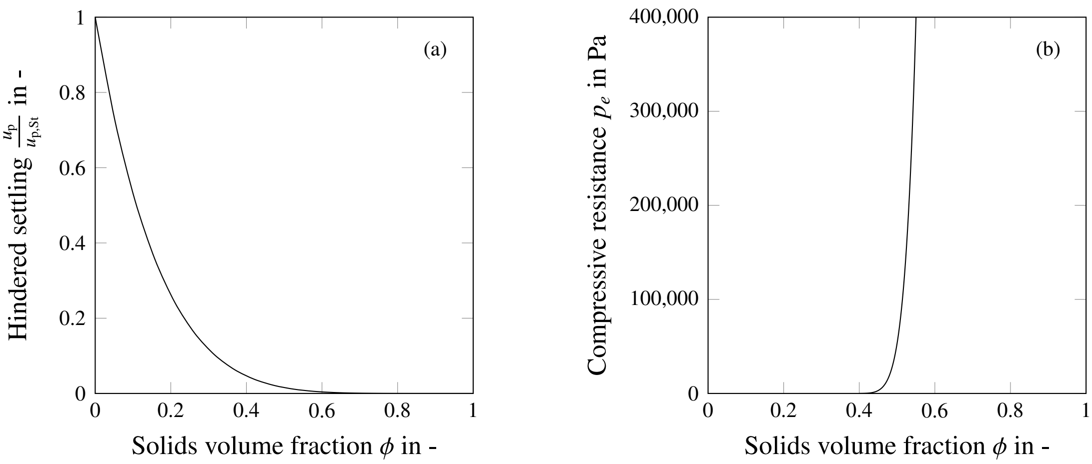


Figure 2: Material functions: Hindered settling function (a) and consolidation function (b).

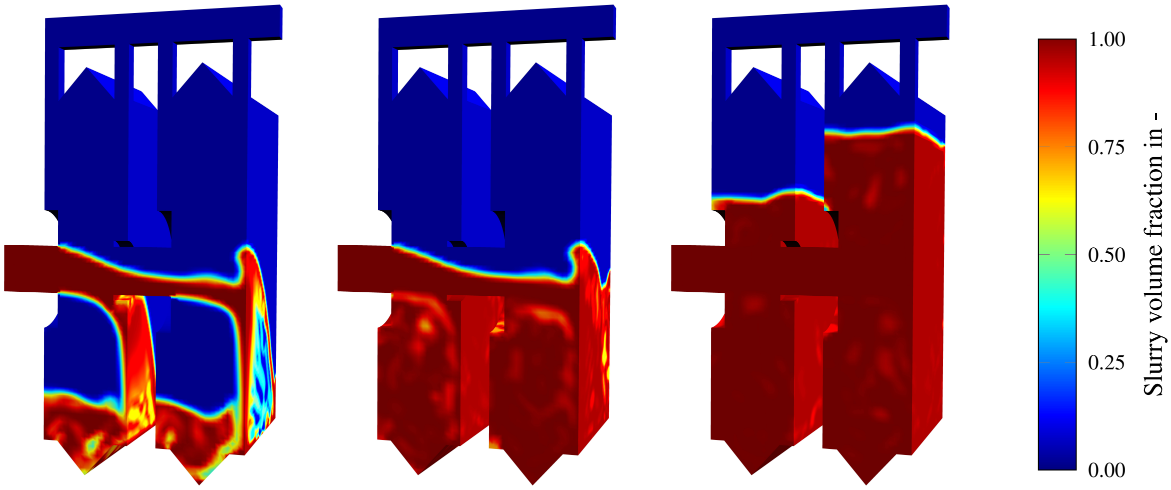
Another material function is the consolidation of the filter cake. The filter cloth retains the particles, which leads to the formation of the filter cake. The sediment consists of permanent particle-particle contacts. To describe the transition between slurry and sediment, a critical solids volume fraction, the gel point ϕ_{gel} is defined. Within the filter cake, the particles of the upper layers press on the layers below. Compressible networks show a dependence of the porosity in filtration direction on the applied stress. This effect represents the second important material function in the separation process and may be quantified by the compressive resistance. C-P cells (compression permeability cells) enable the measurement of the compressible behavior of cakes [16]. Figure 2 (b) shows a characteristic graph of the compressive resistance as a function of the solids volume fraction. Above a critical solids volume fraction of $\phi_{\mathrm{gel}} = 0.4$, sediment is present. At solids volume fractions below $\phi < 0.5$, the sediment is highly compressible. In contrast, at higher concentrations the sediment becomes quasi incompressible. Landman et al. [17] describe the consolidation behavior by a power approach and links the compression resistance

$$\sigma_e(\phi) = c_1 \left(\frac{\phi}{\phi_{\mathrm{gel}}} - 1 \right)^{c_2} \tag{5}$$

with the solids volume fraction. The parameters c_1 and c_2 are empirical values.

3. Results

Starting from the meshing of a laboratory chamber filter press, the simulations were performed with the OpenFOAM software. First, the filling process of the filter press was simulated (Figure 3) with the standard solver *interFoam* of OpenFOAM, which represents a phase fraction based approach for the interface capturing (volume of fluid). The color bar shows the volume fraction of the inflowing slurry. At 0 there is no slurry and only air (blue), at 1 there is exclusively slurry but no air (red). The slurry flows with $500\,\mathrm{L\,h^{-1}}$ into the press. It can be seen that both chambers are filled and the flow fans out at the respective back wall (a). This could also be observed in experiments. The liquid level initially rises evenly in both chambers (b). Only when both chambers are filled to the inlet level, the liquid volume increases first in the rear chamber (c). This observation is also consistent with experimental findings.



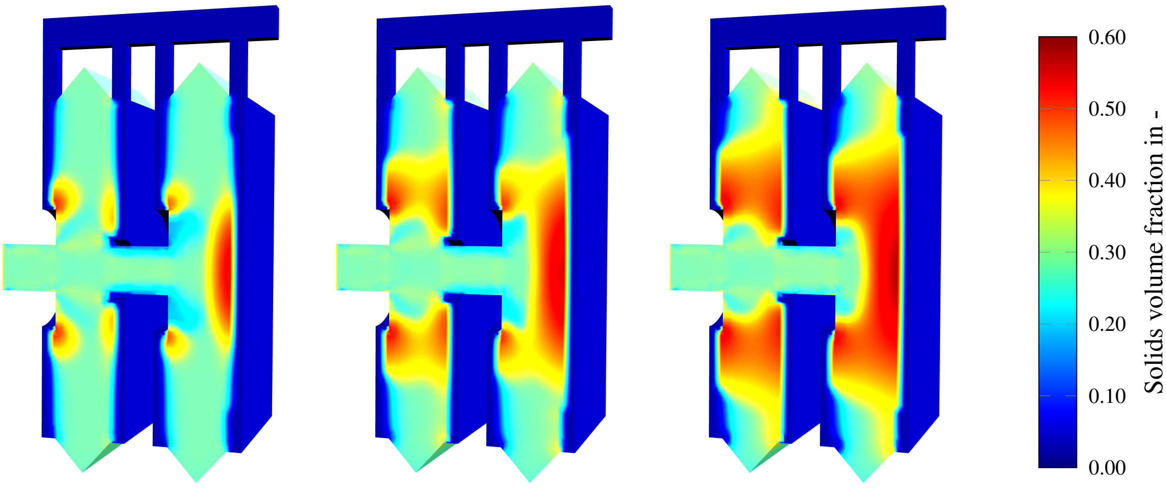
(a) 1 s **(b)** 3 s **(c)** 5 s

Figure 3: Filling the chamber filter press with slurry.

The consolidation was simulated with the solver presented in this paper. For this purpose, it was assumed that the chambers of the filter press are evenly filled with slurry. Figure 4 shows the cake formation in the chamber filter press. In this case, the colorbar visualizes the solids volume fraction in the slurry. If no particles are present, the solids volume fraction is 0 (blue), while a solids volume fraction of 0.6 (red) corresponds to the maximum solids volume fraction determined with the consolidation function (Figure 2). The solids volume fraction of the inflowing slurry was $\phi = 0.27$. As in the experiment, the inflow velocity was controlled by a predefined pressure difference of 4 bar. The filter medium was modeled by a cell layer. The simulation can be used to investigate how the cake formation in the two chambers proceeds over time. Initially (a), the filter cake forms at the back walls of the chambers and at the transitions at the chamber inlet. As time passes, the cakes of the two opposing chamber walls grow together (b). As the solids volume fraction rises, the flow resistance increases. For this reason, the time until the cake grows together could be regarded as a critical point in time, since the filtration process may come to a standstill earlier than expected at a defined pressure difference. In the present case, the chambers are not yet completely filled and the corners of the chamber filter press show less high solids volume fractions (c).

4. Conclusion

The separation process in a filter press is complex. Although the geometry of a filter press is relatively simple, the flow and characteristic separation functions of the slurry overlap. The presentation shows an approach to characterize and simulate the solid-liquid separation in filters in the future. For this purpose, first the material characterization is



(a) 30 s **(b)** 90 s **(c)** 150 s

Figure 4: Consolidation of the filter cake in the filter press.

performed by means of simple experiments on laboratory scale, which allow the derivation of material functions for sedimentation and consolidation. Implemented in OpenFOAM, it is now possible to investigate the separation process in a digital twin of the laboratory filter. The medium-term goal is a more efficient and sustainable filtration process with the help of such digital twins. Thereby, the approach is applicable for the design of new filters as well as for the verification of existing plants.

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