

MODELING NON-UNIFORMITIES IN PLATE-AND-FRAME FILTER PRESS OPERATIONS

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Frame-and-plate filter presses are widely employed in industrial solid–liquid separation due to their high efficiency and modular design. Conventional sizing and design methodologies, however, typically assume uniform suspension distribution across all filter chambers. In industrial operation, this assumption is rarely satisfied, leading to non-uniform filling, heterogeneous cake formation, and an increased risk of overfilling and clogging. To compensate for these effects, conservative safety margins are commonly applied, resulting in suboptimal operation and process efficiency.

This contribution investigates the mechanisms governing non-uniform flow distribution and cake buildup in an industrial-scale filter press, with the aim of developing a deeper understanding of the optimal parameters for filter press operations, and formulating a predictive modeling framework suitable for Digital Twin applications. Quantitative descriptions of compartment-level non-uniformities are lacking in the literature, as direct experimental measurements are invasive and often impractical, while CFD simulations of complete filter presses have traditionally been considered computationally prohibitive.

Building on compartment-scale CFD modeling that allow for a reduced complexity of the internals of each plate, a numerical framework is presented that enables the simultaneous simulation of multiple filter chambers with sufficient local resolution to capture relevant flow phenomena. The approach provides detailed spatial information on pressure losses, flow maldistribution, and chamber-to-chamber interactions under realistic operating conditions, allowing for a systematic analysis of the origins of uneven cake formation.

Finally, a mechanistic model for flow division within the filter press is formulated and validated against the CFD results. The model successfully reproduces the compartment-level flow distribution observed in the CFD simulations over a range of operating conditions, including varying Reynolds numbers, numbers of compartments, and suspension properties. This validation enables the identification and physical interpretation of the key model parameters governing flow maldistribution, providing a rational basis for improved filter press sizing and operation.

KEYWORDS:

Filtration Modelling, Filter Press, Plate-and-frame Element, Industrial Process
Filtration, Computational Fluid Dynamics (CFD)

1. INTRODUCTION

Frame-and-plate filter presses are widely used for industrial solid-liquid separation due to their robustness and high separation efficiency. Conventional design and sizing approaches typically assume uniform suspension distribution across all filter chambers, but in many industrial applications uneven chamber filling can be observed, increasing the risk of overfilling and clogging, and ultimately reducing process efficiency, or even leading to mechanical failure.

A detailed understanding of the mechanisms driving non-uniform flow distribution and cake buildup is therefore essential for improved design and operation. However, compartment-level characterization remains challenging, as experimental measurements are often invasive and full-scale CFD simulations are computationally demanding. This work addresses these limitations by developing a mechanistic model for flow distribution with the support of multi-chamber CFD simulation, enabling systematic analysis and prediction of flow distribution effects at different scales and for a wide range of operating conditions.

2. CAKE FILTRATION MODELING

The standard approach to model filtration involves using Darcy's law for low-Reynolds flow through a porous body [1]:

$$\vec{q} = -\frac{K}{\mu} \vec{\nabla} p \quad (1)$$

where $\vec{q}$ is the local flux vector, K is the permeability tensor for that specific porous body, μ is the fluid's viscosity, and p is the local fluid pressure. For filtration, a simpler, integral form of the equation is used:

$$\frac{Q}{A} = -\frac{1}{\mu d h} \Delta p \quad (2)$$

where Q is the volumetric flow (often expressed as $\dot{V}$), A is the filtration area, d is the Darcy resistance of the filter, h is the height of the filter in the flow direction, and Δp is the pressure difference applied to the filter. This form is less general, as it assumes pseudo-1D flow, but this is often easy to motivate when the filter is thin, the filter's permeability in the normal direction is higher than in the tangential direction, and there are no meaningful additional pressure gradients for the flow. Some studies have challenged the pseudo-1D assumption for filter press chambers specifically [2], or have performed 3D-CFD studies of liquid-solid separation [3], but those go to further prove that, in most cake filtration applications of industrial interest, the assumption of pseudo-1D flow is valid.

For cake filtration specifically, it's helpful to express the permeability as a resistance instead, and consider the resistance of the cake as an additive term:

$$\Delta p = \mu (R_m + R_c) \frac{\dot{V}}{A} \quad (3)$$

Where R_m is the filter medium resistance ($R_m = 1/k$) and R_c is the filter cake resistance, which increases throughout the experiment. It's typically assumed that the filter cake resistance is proportional to the cake height, which can be expressed in terms of the filtrate volume. If the cake is also considered incompressible, this leads to writing the equation as:

$$\Delta p = \mu \left(R_m + \frac{\alpha_H \bar{C}}{A} V \right) \frac{\dot{V}}{A} \quad (4)$$

Where α_H is the specific cake resistance in terms of the cake height, and $\bar{C}$ is the concentration parameter which relates the cake volume to the separated liquid volume [1]. This equation is an ordinary differential equation (ODE) in the filtrate volume and time. Thus, the system can be understood either as volume-controlled, in which the feed flow rate is controlled (e.g., using a peristaltic pump) and the pressure is a result, or as pressure-controlled, in which the pressure differential is controlled (e.g., the inlet pressure is adjusted with a feedback system to achieve the differential pressure required) and the flow rate is a result.

A volume-controlled system is very easy to study in terms of throughput, but often the pressure is a mechanical limit that must be enforced as a constraint, as it may cause damage to the equipment if values exceeding technical specification are reached. On the other hand, a pressure-controlled system does not have this issue, as the differential pressure is controlled directly. In this case, it's very important to understand the relationship between the applied pressure and the throughput to plan an efficient filtration process.

3. FILTER PRESS MODELING

While cake filtration is generally well-modeled by Darcy's law, with correction terms where required to account for a non-linear growth of the cake resistance [1], the efficiency of filter presses comes from the ability to have a much larger effective filtration area by parallelizing several chambers. In sizing, perfect parallelization is usually assumed, using a safety factor to account for non-idealities. Interestingly, informal observations from industry indicate two contrasting behaviors in such systems: some report greater cake accumulation in the "first" chamber (closest to the feed port), while others report greater accumulation in the "last" chamber (farthest from the feed).

The main cause for the non-ideal parallelization is that each chamber acts as an independent dynamical system, but the control each receives is different, and affected by every other chamber. Ensuring unbiased division of a feed flow across multiple branches within a distribution system is a classical problem in hydraulics, as flow-splitting manifolds is a common type of equipment.

LOW-REYNOLDS ELECTRICAL ANALOGY

At low Reynolds numbers, hydraulic network models are usually formulated with the electrical analogy: each source of pressure drop is modeled as a resistance, and then

the problem is solved as an electrical circuit in which pressure is represented by voltage and flow rate is represented by current. To account for cake filtration, the chambers are not static linear resistors but are rather charge-controlled memristive resistances: resistances whose value depend on their history due to the gradual increase of the filter cake resistance. In electrical analogy terms, this is represented as:

$$R_i(t) = R_m + \alpha_Q \int_0^t I_i(t) dt \quad (5)$$

Where $R_i(t)$ is the resistance of the i -th compartment at time t , α_Q is a scalar parameter that dictates the rate of growth of the memristor, and $I_i(t)$ is the current through the i -th chamber. As such, the integral represents the cumulative charge, or, in terms of filtration, the cumulative volume of the filtrate.

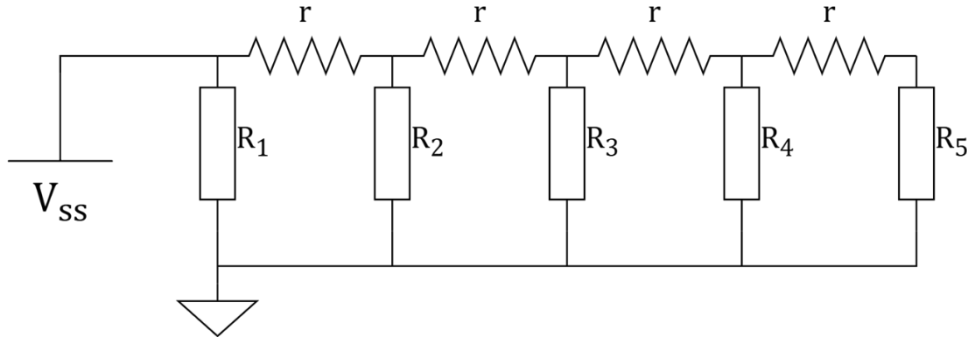


Figure 1: Electrical analogy for a filter press.

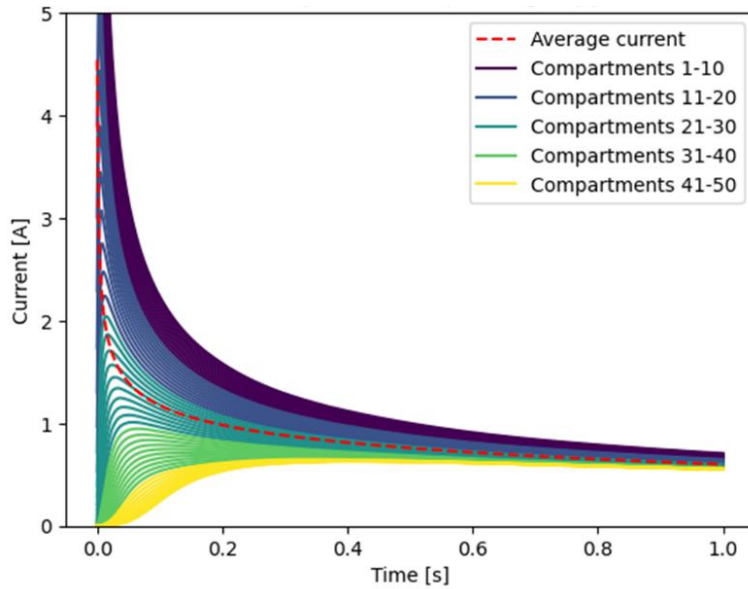


Figure 2: Flow rate ("Current") distribution in time according to electrical analogy.

The network model for this problem, as represented in Figure 1, can be solved through a time-marching explicit Euler approach: the instantaneous resistance of each memristor is evaluated at time t , then the current is calculated through a linear

electrical circuit solver (e.g., employing the Modified Nodal Analysis method [4]), which is used to compute the new resistance at $t + dt$.

As shown in Figure 2, this model predicts a higher flow rate in the chamber closest to the inlet due to the lower cumulative resistance in the duct, which is in accordance with some industrial observations. However, the assumption of low-Reynolds flow in the ducting is limiting, adding more chambers is typical to increase the throughput, but as the ducting size does not change this necessarily increases the Reynolds number. As such, a generalization that accounts for high-Reynolds effects is required to generalize the results to high-throughput equipment.

HIGH-REYNOLDS MANIFOLD MODEL

At low Reynolds numbers, we assumed that the nodes of the circuit didn't affect the flow. However, those points are, geometrically, diverging tees, which at higher Reynolds numbers have meaningful inertial effects. Figure 3 shows the flow through a diverging tee in which both outlets have the same pressure, and thus the flow should split evenly. However, the main run receives the majority of the flow rate, with only a smaller fraction turning into the branch.

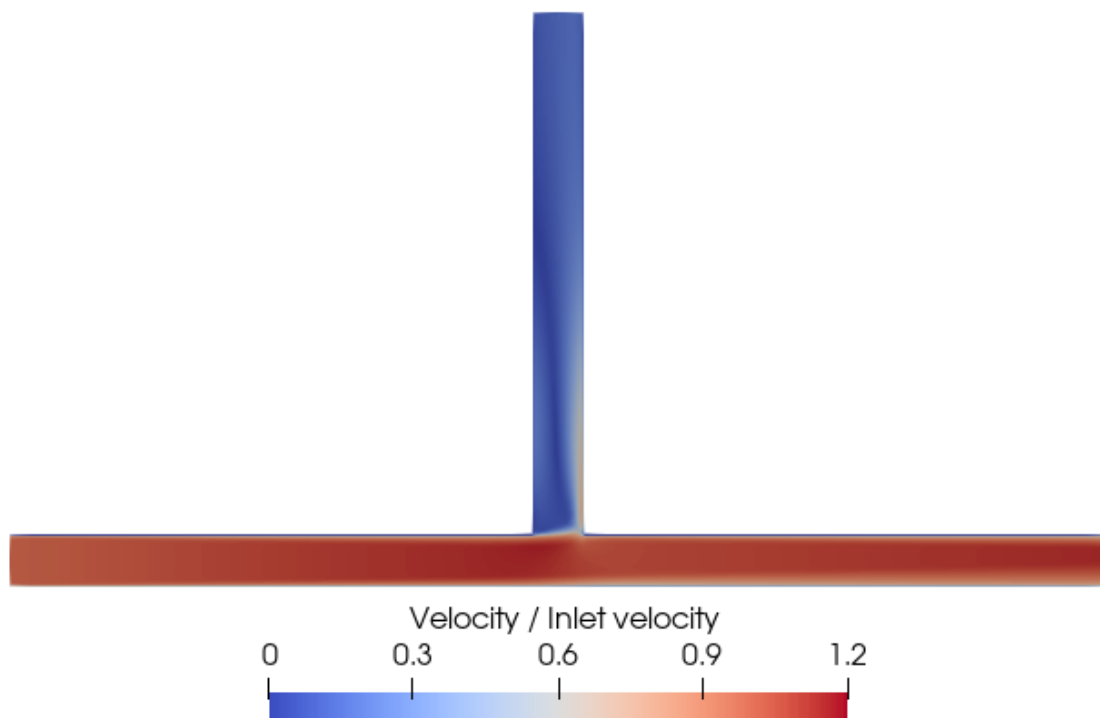


Figure 3: Flow in a diverging tee.

This issue is well-known in hydraulics, as flow-diverging manifolds are widely adopted to distribute a feed line into multiple branches, but the modeling of such a manifold is not straightforward. The general formulation of the pressure drops in such geometries uses the ζ factor, in which a concentrated pressure drop is considered, and it can be written as:

$$\Delta p = \zeta \cdot \frac{1}{2} \rho \frac{\dot{V}^2}{A^2} \quad (6)$$

For diverging tees, the value of ζ for the branch and for the run will be different, and in both cases, it depends on the flow ratio, defined as the ratio between the flow rate in the branch and the incoming flow rate. For standard geometries, [5] reports the value of ζ for different geometries and operating conditions, but even in that case, the problem is to be solved iteratively, as the flow ratio controls the pressure drop, but in turn the pressure drop controls the flow ratio.

This study implements the network model for manifold flow introduced in [6], hereafter referred to as the “Tomor manifold model”. While this model accommodates arbitrary geometries, provided its defining parameters are derived via the CFD procedure detailed in [7] or fitted to empirical data, our objective is to extend its application beyond its original formulation. Specifically, we extrapolate the model by investigating broader Reynolds number ranges, increasing the number of branches, and incorporating filtration effects.

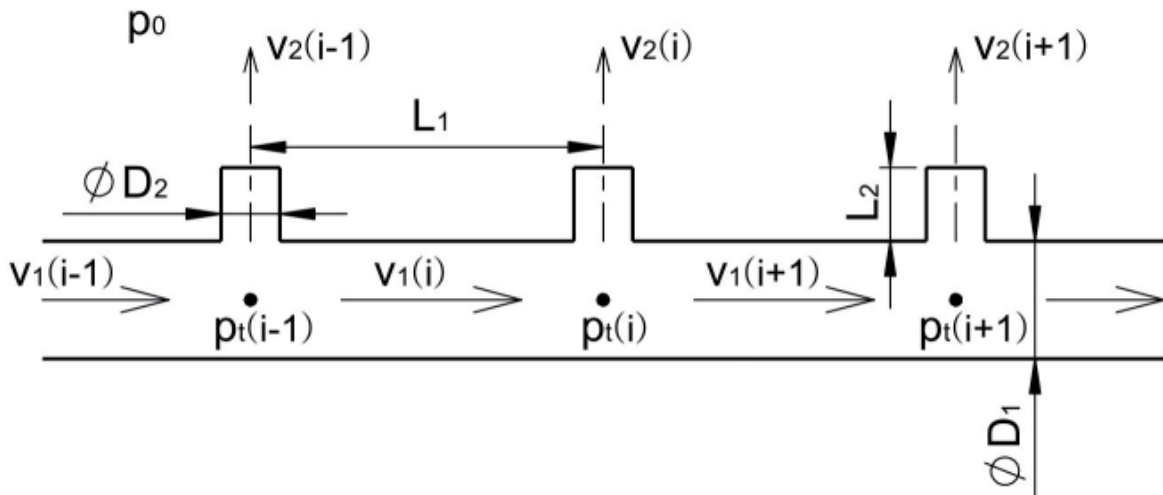


Figure 4: Nomenclature in Tomor manifold model (taken from [6]).

The advantage of this mode is that it is mechanistic in its formulation, and it generalizes to our application without further modeling. The presence of cake filtration is then accounted for by adding a source term to the equation that calculates the total pressure as a function of the outlet pressure of each branch, which in the original model is formulated as:

$$p_t(i) - p_0 = \left(1 + C_{fe}(i)\right) \frac{\rho}{2} v_2^2(i) \quad (7)$$

Where $C_{fe}(i)$ is the extended turning loss coefficient [7], which accounts for the concentrated pressure drop into the i -th branch, $v_2(i)$ is the in-branch velocity for the i -th branch, and p_t is the total pressure at the i -th junction. The extended turning loss coefficient uses a total of 6 parameters (A_1 , B_1 , A_2 , B_2 , C , and D) that must be found for the current geometry and are semi-empirical in their definition.

As such, expanding this model to account for cake filtration requires adding one more pressure drop term to the right-hand side of the equation. The flow in a single chamber can be safely described assuming low Reynolds numbers, as the filtration area is typically quite large and the flow rate is just a fraction of the total feed. This means we can adopt the memristor formulation described in the electrical analogy to add a term which is now linear in $v_2(i)$, but accounts for the cumulative filtrate volume through that chamber:

$$\Delta p_{filter} = \mu (R_m + \alpha_v V(i, t)) v_2 \frac{A_b}{A} \quad (8)$$

Where A_b is the cross-section of the branch duct. This term can be added as is to the right-hand side of Eq. (7) and has no impact on the nature of the iterative solver implemented.

CFD SIMULATIONS

To generate data for fitting of the Tomor manifold model parameters and for validation of the network model, CFD simulations of a 2D manifold geometry were performed. OpenFOAM v2506 was used as the framework for the CFD simulations. Similar to [8], cake and filter resistances are modeled based on the porous zone approach.

Although [8] investigated a full single filter-press compartment, the present study reduces the geometry to a 2D representation to facilitate the modeling of multiple compartments. To simplify the analysis and isolate individual effects, the simulated 2D manifold geometry is utilized, as illustrated in Figure 5. In this geometry, the filter medium is placed at the outlet of each branch, which is equivalent to the full compartment simulation according to the results from [8] and [2]. This allows us to separate the manifold flow effects from the cake filtration phenomena and to study them independently.



Figure 5: 2D manifold geometry used in this study.

When the filter resistance is omitted, the simulation replicates the working conditions of the Tomor manifold model, providing reference data for the initial tuning of the model parameters. Conversely, when the filter is included, the model is used to compare the proposed additional term in the network model against the presented reduced-order CFD model.

4. RESULTS AND DISCUSSION

Using the network model, an analysis of the system's performance can be made. Therefore, two new main metrics are introduced:

- The coefficient of variation (CV) of the flow rate in each chamber, used to measure the uniformity of the flow distribution.
- The lumped resistance of the filter press (R_{FP}), which measures the pressure differential required to achieve a given flow rate.

The coefficient of variation is defined as:

$$CV = \frac{\sigma_Q}{\bar{Q}} \quad (9)$$

Where σ_Q is the standard deviation of the flow rate in each chamber, and $\bar{Q}$ is the average flow rate, which can also be expressed as $\bar{Q} = \dot{V}/n$, where $\dot{V}$ is the feed flow rate and n is the number of chambers. For a perfectly uniform flow distribution, $CV = 0$ because $\sigma_Q = 0$.

The lumped resistance is defined in analogy to the filter resistance as:

$$R_{FP} = \frac{\Delta p}{\mu \dot{V}} \quad (10)$$

To account for filtration an additional parameter needs to be introduced, representing the resistance of the filter and the cake. To express this resistance in terms of the branch velocity v_2 , which will be orders of magnitude higher than the filtration velocity, the reduced resistance applied directly in the branch defined as:

$$\hat{R}_m = R_m \frac{A_b}{A} \quad (11)$$

Which is the medium resistance scaled by the ratio of the branch's cross section and the filtration area. Although Eq. (3) includes cake resistance, the objective of this analysis is to characterize flow distributions for uniform resistance distributions. As such, the cake contribution is not taken into account.

Finally, the main parameters that are explored in this study are the number of compartments (or chambers), the resistance of the filter medium, and the Reynolds number at the feed duct.

MANIFOLD FLOW

Figure 6 shows the comparison between CFD simulation without medium resistance and the tuned Tomor manifold model. In all the plots, the flow rate in each chamber normalized with the mean flow rate is plotted. As can be seen, the agreement between CFD and the fitted model is very high overall. In total the coefficient of determination R^2 is equal to 0.97.

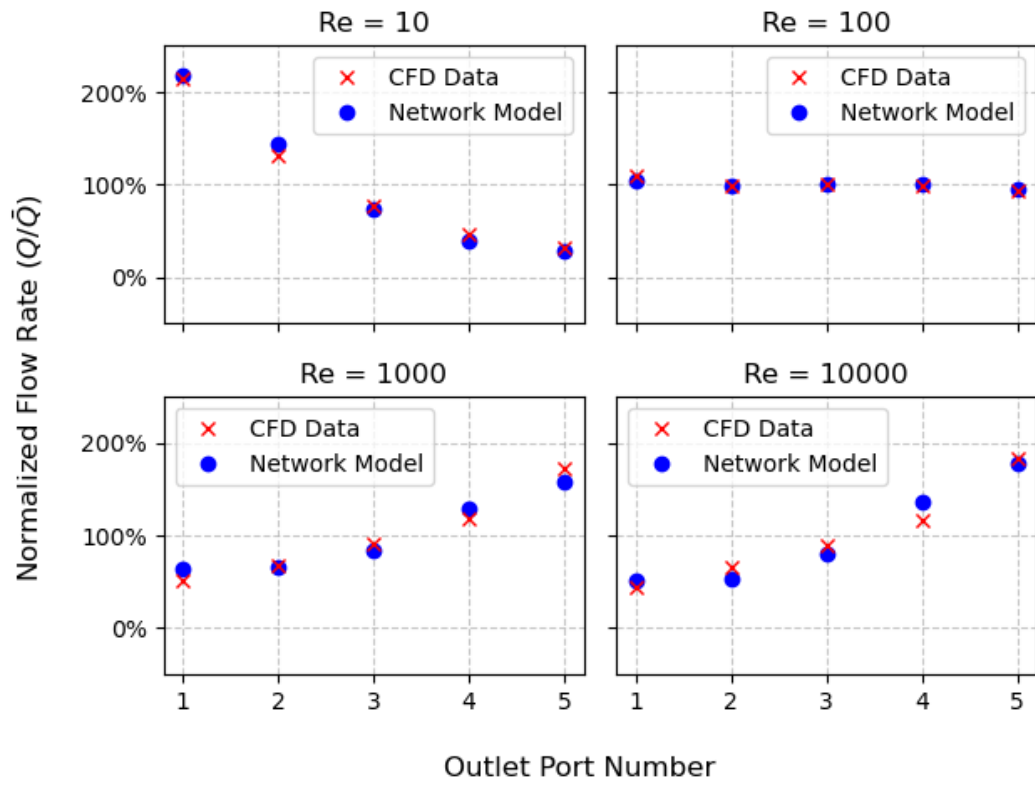


Figure 6: Manifold flow, comparison of fit of the network model to CFD.

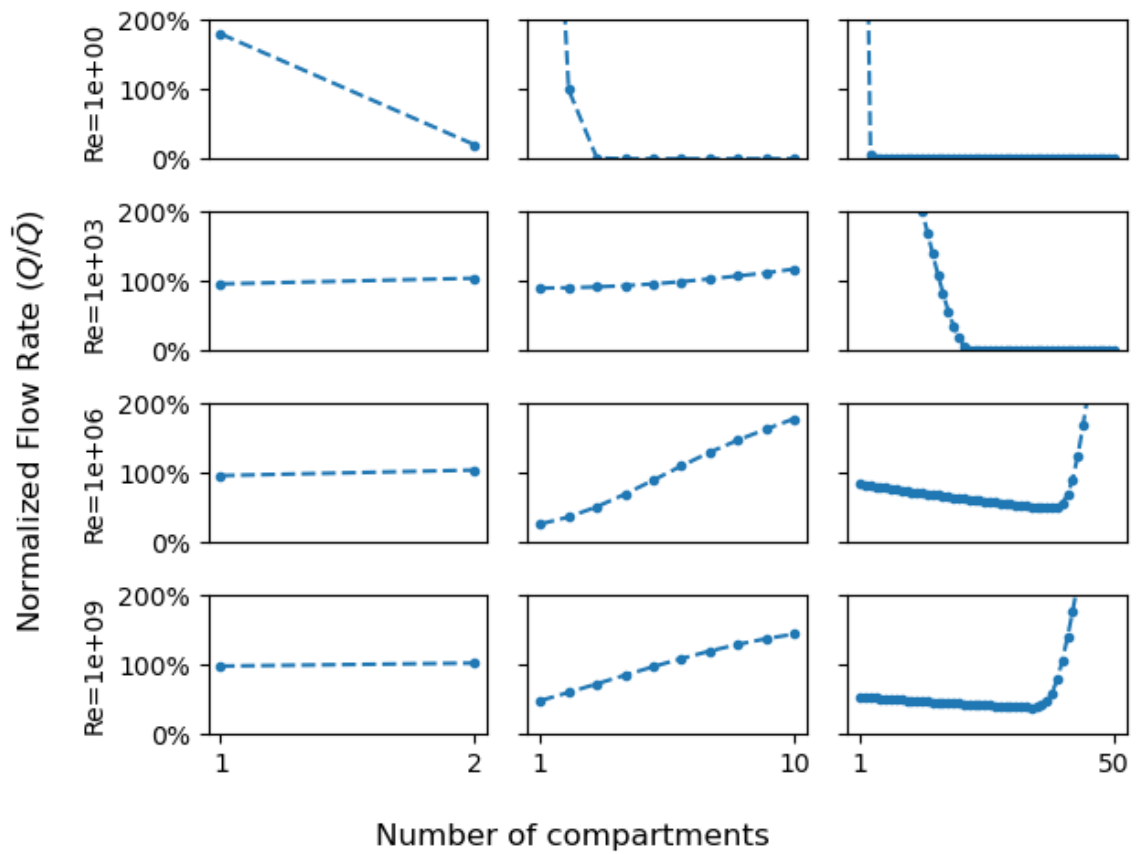


Figure 7: Manifold flow distribution grid sweep with network model.

Figure 7 shows the results of exploring the tuned Tomor manifold model with different number of compartments (increasing left to right) and Reynolds number (increasing top to bottom). Although some of the parameters considered here are outside the range of typical applications for filter presses, they are still represented to help visualize the main phenomena. Namely for all Reynolds numbers, moving to higher numbers of compartments causes the solution to generally become more skewed in either direction. On the other hand, while at low Reynolds numbers the same qualitative behavior is observed, increasing Reynolds numbers causes each example to form a different solution.

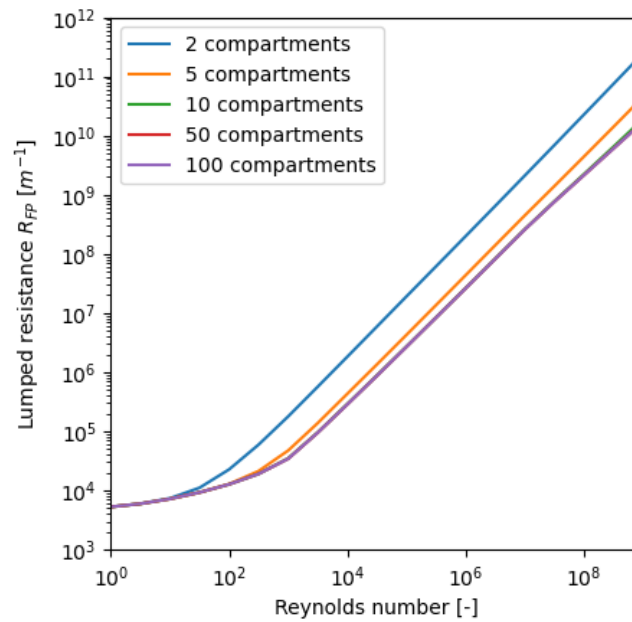


Figure 8: Lumped resistance for manifold flow.

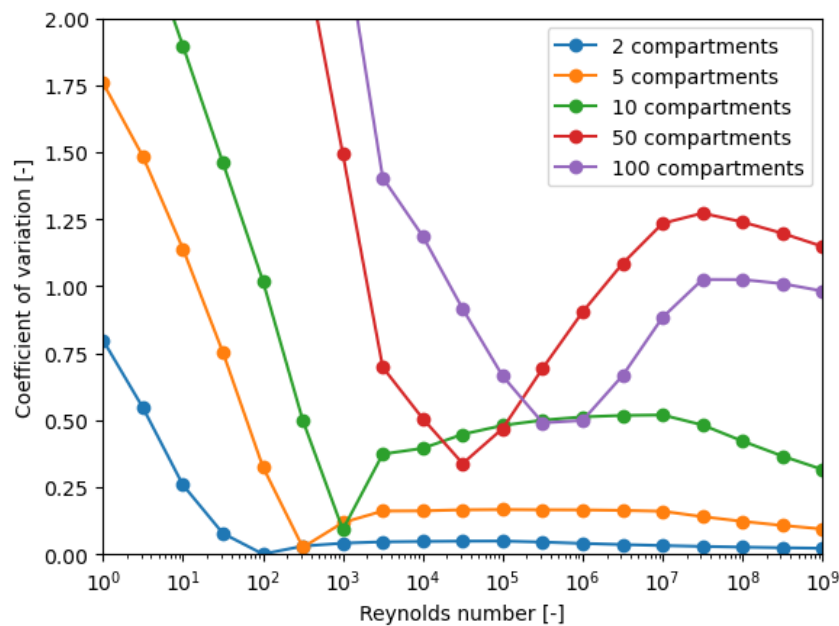


Figure 9: Coefficient of variation for manifold flow.

Comparing the topology of the flow distribution makes it hard to scale the analysis, so, instead, plots such as the one in Figure 8, showing the lumped resistance as a function of Reynolds number for different numbers of compartments, are preferred.

A low-Reynolds and a high-Reynolds regime can be identified: at low Reynolds numbers, the total lumped resistance is unaffected by the number of compartments, and the dependency on Reynolds itself is weak; at high Reynolds numbers there is a linear dependency between Reynolds number and the lumped resistance. At very high Reynolds, there seems to be no noticeable difference in increasing the number of compartments above 10 for this geometry.

The coefficient of variation shown in Figure 9 is, instead, strongly dependent on the number of compartments, and in general achieving low CVs (<0.3) seems to be impossible for manifolds with more than 10 compartments for the current geometry.

This also shows that there doesn't seem to be a direct effect of the CV on the lumped resistance, as all solutions have the same resistance, but a drastically different CV at low Reynolds numbers, and the 10, 20 and 50 compartments cases also show a different CV at higher Reynolds despite the similar resistance.

FILTRATION

Similar to the manifold flow analysis, we compared the CFD simulation incorporating filter resistance against the network model with the added filter term. Figure 10 illustrates the normalized flow rates across representative combinations of Reynolds numbers and Darcy resistances. The network model demonstrates strong overall agreement with the CFD data, yielding a coefficient of determination $R^2 = 0.95$.

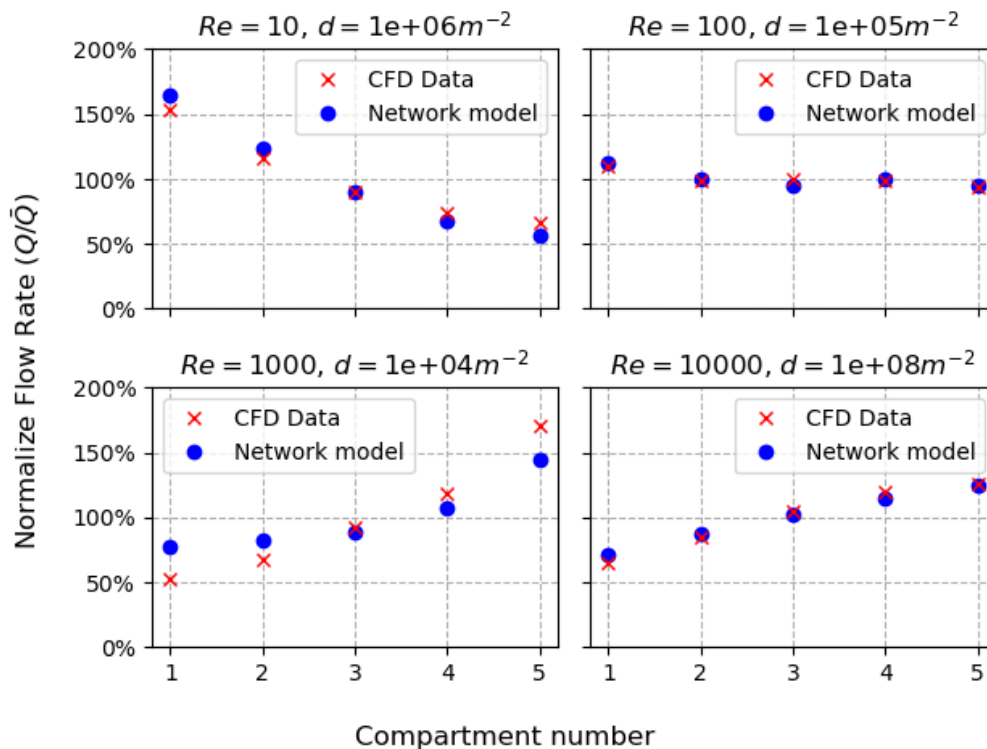


Figure 10: Examples of flow rate distributions for different Reynolds numbers and Darcy resistances.

To systematically evaluate the tuned model with filter resistance, we avoided simultaneously varying all three parameters. Instead, the number of compartments was fixed at 20 to isolate and analyze the effects of the Reynolds number and reduced resistance.

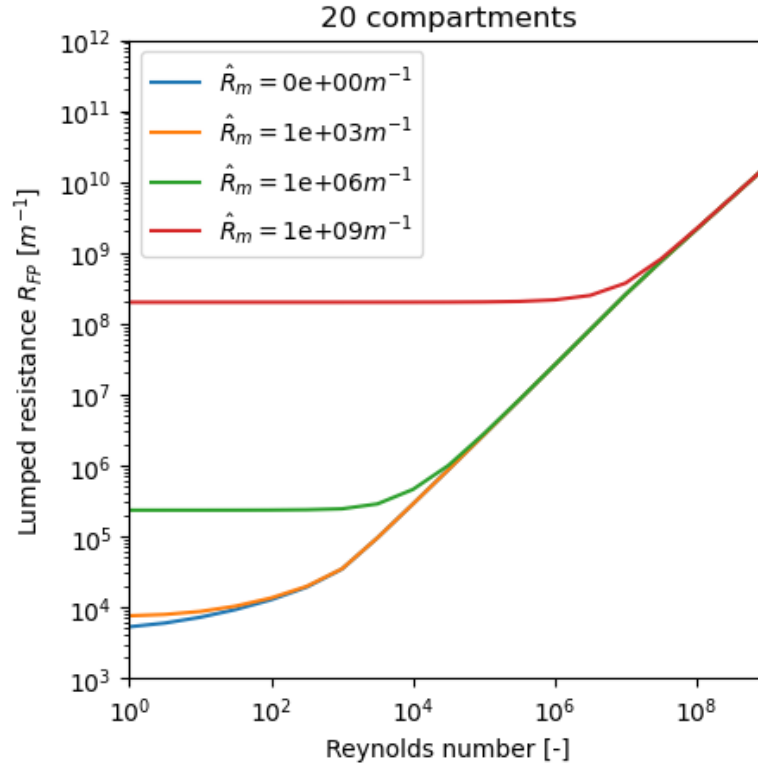


Figure 11: Filter medium effect on the lumped resistance.

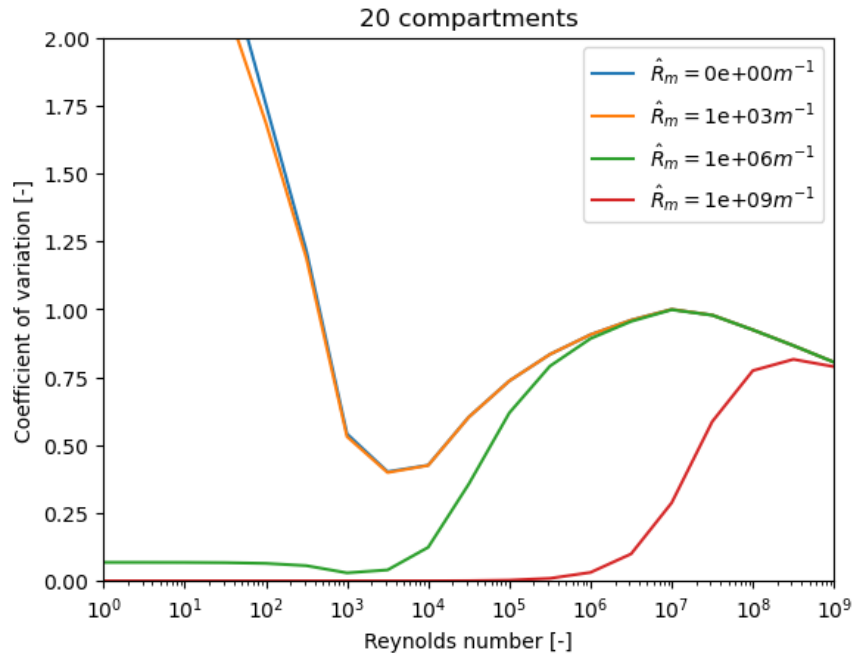


Figure 12: CV for different reduced resistances.

Figure 11 shows the lumped resistance of the system for different filter resistances. At low Reynolds number, when the lumped resistance of the pure manifold flow is sufficiently low (represented by the curve with $\hat{R}_m = 0 \text{ m}^{-1}$ in the plot), the filter resistance dominates, and a constant lumped resistance is measured for a range of Reynolds numbers.

Figure 12 shows that the addition of the filter allows for lower values of CV as the value of the reduced resistance $\hat{R}_m$ increases even for a larger number of compartments. While the behavior for high resistances is expected, in which the flow distribution is entirely uniform ($CV = 0$) until some critical Reynolds number, it's interesting to see how for $\hat{R}_m = 10^6 \text{ m}^{-1}$ the CV is approximately constant but not 0.

The same results for a wider range of resistances are shown in terms of the CV in Figure 13. For all Reynolds numbers the observed behavior is similar, which is well-described by a sigmoidal curve on the semi-log plot.

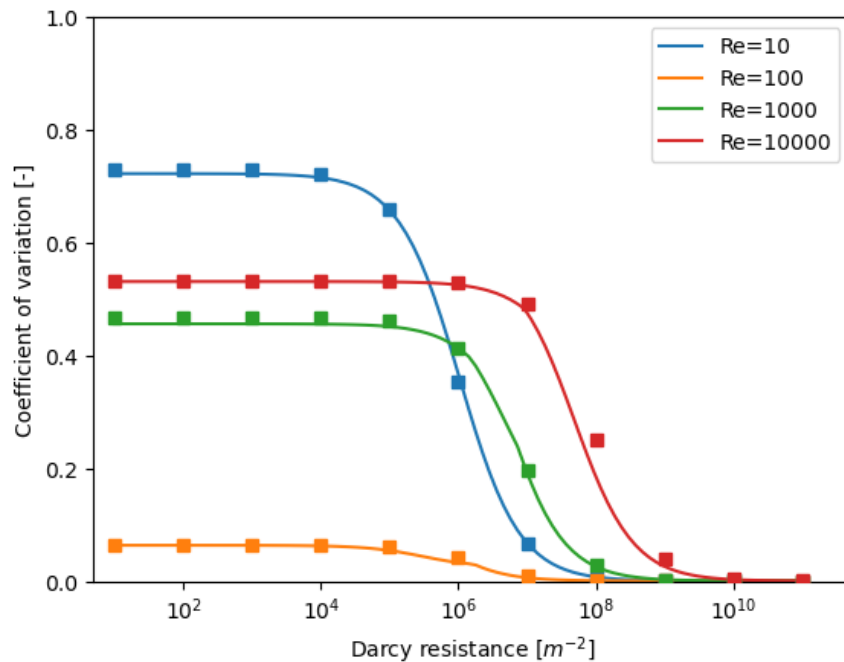


Figure 13: Comparison of CFD results (markers) with the model prediction (solid line).

5. CONCLUSIONS

A mechanistic network model for flow distribution in plate-and-frame filter presses was developed and validated against multi-compartment CFD simulations. The model, based on an extended manifold formulation, accurately reproduces the flow maldistribution observed in CFD across a range of Reynolds numbers, numbers of compartments, and filter resistances.

The results demonstrate that flow distribution is governed by a strong interplay between inertial effects in the manifold and the resistance of the individual chambers. In particular, increasing Reynolds number and the number of compartments leads to

pronounced flow maldistribution, while increasing filter resistance promotes a more uniform flow distribution. This effect is quantified through the coefficient of variation, which decreases systematically with increasing reduced resistance, following a sigmoidal trend.

Furthermore, the analysis shows that lumped system resistance and flow uniformity are not directly correlated: configurations with similar overall pressure losses can exhibit markedly different flow distributions. This highlights the importance of explicitly accounting for flow maldistribution in filter press design and operation.

While the proposed model provides a computationally efficient alternative to full CFD simulations, its applicability is currently limited by the need for geometry-specific parameterization, particularly for complex outlet configurations such as flow-joining manifolds. Extending the model to such geometries and validating it against experimental data remain key areas for future work.

Overall, the presented framework provides a foundation for predictive modeling of flow distribution in filter presses and represents a step toward the development of reduced-order Digital Twin models for industrial filtration systems.

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