Computer Aided Engineering of hydraulic filter elements
From theory to patent and products

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Abstract. A highly improved next generation filter element was developed based on computer simulations with experimental validation. The new filter element exhibits a significantly lower pressure drop than the previous generation while achieving the same filter efficiency and same filter capacity.

Very high oil pressures are intrinsic to mobile hydraulic applications. Under such high pressures, the individual pleats of a pleated filter tend to collapse and thus, significantly diminish the accessible filter media surface. In order to prevent such collapse, supporting meshes can be used both on the outside and inside of the filter media. Computer simulations allowed to study a new design, in which the weave type in the outflow channel of the pleat was changed from plain weave to 2/2 twill. The simulations suggested that the new design results in a 30 % lower the pressure drop of the filter element while maintaining the good performance with regard to filter efficiency and filter capacity. The predictions were found to be correct by ensuing measurements on prototypes. One main benefit of the computer simulations was the establishment of this improvement. Few prototypes needed to be built. Also, the simulations identified a set of optimal yet stable parameters. Thus, small variations in the production process do not disturb the performance of the filter element.

The joint work led to a patent and a new product by Argo-Hytos. The hydraulic filter element EXAPOR®MAX 2 features a 30 to 50 % lower pressure drop than the previous filter element generation. The work also laid the foundations for new computer software. The modules PleatGeo and PleatDict for ITWM's GeoDict Software are tailor-made and easy-to-use for the simulation and design of pleated filters.

1 Introduction

The initial pressure drop ΔP_o of any hydraulic filter element should be low because ΔPo is directly proportional to power consumption by the filter. The higher ΔP_o, the more engine power does not do “useful” work. Secondly, during the operation of the filter, ΔP will increase as the filter clogs. So, ΔP_o is the base line for the whole life time of the filter.

Several aspects contribute to the pressure drop of a filter. Here, we neither consider the shape of the pipes leading to the filter, nor the design of the filter housing. The focus is strictly on how the design of a single pleat influences the pressure drop. Besides the obvious influence of the filter media, there exists also a contribution from the inlet and outlet channels or "geometry" of the pleat [1, 2]. Manufacturers of hydraulic filter elements are aware of this fact and build pleats in layered fashion, with nettings or wire meshes that protect the filter media on the inlet side and nettings or wire meshes that keep the outflow channel open against the high oil pressure that tends to collapse the pleat.

Computer models for the pleat geometry and computation of the resulting pressure drop where developed with the original goal of lowering the overall pressure drop of the filter element by about 10%. The models were first validated against measurements to correctly predict the pressure drop of an existing filter element. With this agreement established, the parameters of the pleat geometry were varied, most notably the weave type of the support structure in the outflow region. In several dozen computer experiments, a design was found that lowered the pressure drop by about 30%. The design was stable to small variations that can always occur in the production process and the design retained the size of the filter element and the open area of the filter media. Thus, the pressure drop was improved while retaining the filter efficiency and filter capacity of the original design.

The achieved improvement of 30 % lower pressure drop was much more than the 10% improvement hoped for at the onset of the project.

A prototype of the new hydraulic filter element was built and proved this improvement to be achievable also in reality. Argo-Hytos has since patented the design [3] and markets it since April 2009. The validated simulation technology, consisting of the pleat shape design module PleatGeo and pressure drop computation module PleatDict are available from Fraunhofer ITWM since November 2008. The development of the simulation tools continues.

The following sections give the details of the experimental, modeling and simulation work that lead to this success.

2 Pressure drop simulation

We consider purely viscous, incompressible fluids and stationary flows, i.e. the flow does not vary with time. Conservation of momentum and conservation of mass can be written as stationary Navier-Stokes equations in the pressure – velocity formulation:

$$-\mu\Delta\vec{u} + (\rho\vec{u}\cdot\nabla)\,\vec{u} + \nabla p = \vec{f} \text{ (NS conservation of momentum)} \qquad (1)$$

$$\nabla\cdot\vec{u} = 0 \text{ (conservation of mass)} \qquad (2)$$

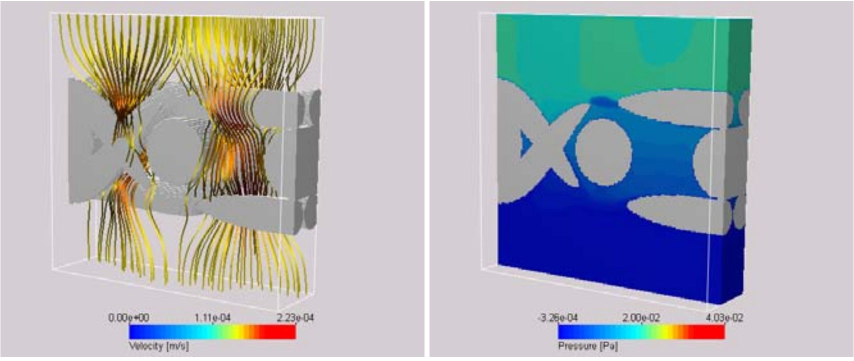
In equations (1) and (2), $\vec{u}$ is the fluid velocity, p is the pressure, μ is the fluid viscosity and $\vec{f}$ is a force density. The simulations compute the velocity-field for a given pressure drop by converting the pressure drop into a force density and using periodic boundary conditions on the computational box (c.f. white edges in Fig. 10). On the surfaces of solids, i.e. the netting or wire mesh, the no-slip boundary condition is used:

$$\vec{u} = 0 \text{ (no slip boundary condition)} \qquad (3)$$

Since in most filtration settings the mass flow is prescribed, multiple Navier-Stokes simulations are run. One adjusts the pressure drop until the computed mass flow matches the prescribed one. This inconvenience is due to the fact that our Navier-Stokes solver [4] can only handle periodic boundary conditions.

The flow rates in most filtration processes are so low that one may drop the inertia term from the conservation of momentum in the Navier-Stokes equations due to its negligible influence. This simplification yields the Stokes equations.

$$-\mu\Delta\vec{u} + \nabla p = \vec{f} \text{ (Stokes conservation of momentum)} \qquad (4)$$



a) b)

Figure 1: Stream lines (a) and pressure (b) for flow through a Dutch weave wire mesh computed via the Stokes equations. Computational box illustrated by its white edges.

The main benefits of using equations (2), (3) and (4) are a shorter time to individual solution and that the flow field needs not be computed more than once. Due to the linearity of the Stokes equations, the velocity field and pressure can be simply scaled to match the prescribed mass flow.

For pleat design simulations, a third set of equations must be considered: the Navier-Stokes-Brinkman equations [5]. The additional term accounts for the fibrous filter media that cannot be resolved on the scale of a complete pleat. The equations couple the free flow in the pores with the so-called Darcy flow in porous media.

$$-\mu\Delta\vec{u} + (\rho\vec{u}\cdot\nabla)\vec{u} + \mu K^{-1}\vec{u} + \nabla p = \vec{f} \text{ (NS-Brinkman conservation of mom.)} \qquad (5)$$

K^{-1} is the inverse of the permeability tensor and μK^{-1} is the flow resistivity. In the free flow regime in the empty cells, K^{-1} vanishes so that equation (5) becomes equation (1). In the porous cells, K^{-1} becomes large, and the velocity $\vec{u}$ small. In that regime, the velocity terms on the left of equation (5) are neglected to find Darcy's law

$$\vec{u} = -\frac{K}{\mu}(\nabla p - \vec{f}) \text{ (Darcy's law).} \tag{6}$$

By combining the equations for the unconstrained flow and flow in porous media, the pressure drop of cartridge filters (see section 3) can be computed.

For the varying requirements of the equation sets, different solution methods are available. The ParPac Lattice-Boltzmann code [4] for all three sets of equations is very well parallelized and works on very large structures in resolved filter media on distributed memory machines. A finite volume code SuFiS® (see [5]) also for all three sets of equations is designed for computations of complete filters, including the housing. Another finite volume code, EFV-Stokes [6] was conceived to combine the features available for [4] with the lower memory requirements and solution times of [7].

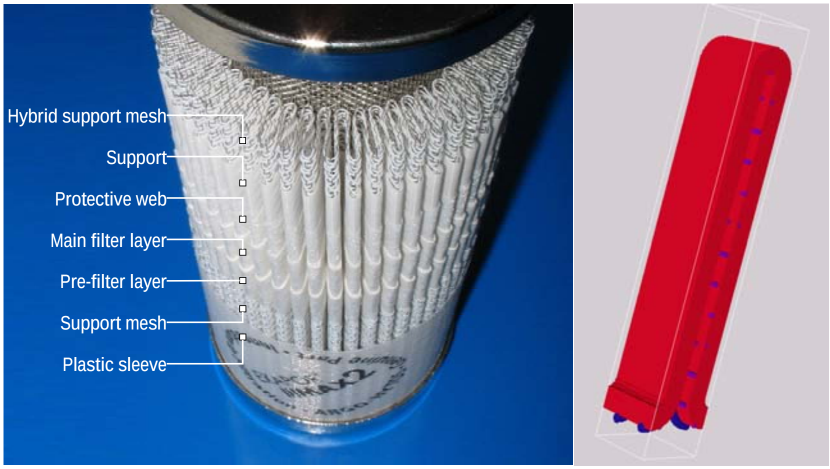
Several challenges exist for the computation of flow fields for pleat-scale filtration simulations. The first is the need for an accurate geometric representation of the pleat and its translation into a computational grid. This challenge is met by the pleat generator PleatGeo, as seen in section 3. The computational grid is simply identical a 3 dimensional image. This is different from the usual approach of creating a separate, usually unstructured tetrahedral mesh that allows use of a standard flow solver such as Fluent®, CFX® or Star-CD®. Because the computational domains can become very large and in design projects many computations are necessary, highly efficient codes in terms of memory and run-time are needed. The regular grid given by the 3d image helps saving memory for coordinates, sophisticated new algorithms are used and the power of modern computers is utilized by parallel implementations. While the current state of the art for about 1,000 x 1,000 x 1,000 cell structures is sufficient for the prediction of the pressure drop and deposition of large particles, nano particles and nano fibers require even better resolved obstacle surfaces [8].

3 Simulation-based design of a new hydraulic filter element

A highly improved next generation filter element was developed based on pleat geometry and flow simulations with experimental validation. The new filter element exhibits a significantly lower pressure drop while achieving the same filter efficiency and same filter capacity as the previous generation.

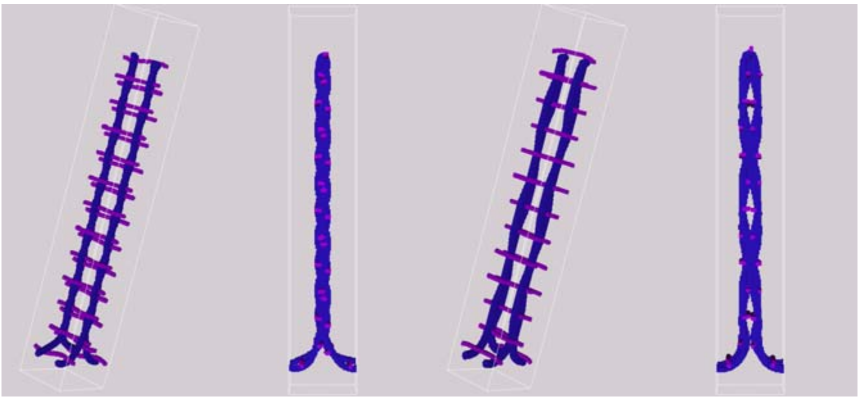
Very high oil pressures are intrinsic to mobile hydraulic applications. Under such high pressures, the individual pleats of a pleated filter tend to collapse and thus, significantly diminish the accessible filter media surface. In order to prevent such collapse, supporting meshes can be used both on the outside and inside of the filter media. Computer simulations predicted that a new design, in which the weave type in the outflow channel of the pleat is changed from plain weave to 2/2 twill, would lower the pressure drop of the filter element by 30 % while maintaining the good performance with respect to filter efficiency and filter capacity. One main benefit of the computer simulations was the establishment of this improvement. Very few prototypes needed to be built, and they simply verified these predictions. The second benefit was that the simulations identified a set of optimal yet stable parameters. Thus, small variations in the production process do not disturb the performance of the filter element.

To establish the methodology, the existing filter element including the plain weave support structure was modeled. Figure 2 a) shows a cut up filter element that shows the filter media and twill inner support mesh. For simplicity the multi-layered filter media was modeled as a single layer, shown in red in Fig. 2 b).



a) b)

Fig. 2: Detail of the new hydraulic filter element (a) and computer model of a single pleat of the filter element with filter media in red and supporting mesh in the outflow channel (b).



a) b) c) d)

Fig. 3: The main difference between the original and the new design. The plain weave a), b) allows the blue wires to slide next to each other b) and creates a rather narrow outflow channel.

For the same wire thicknesses, the 2/2 twill c), prevents the wires from sliding next to each other and creates a wider outflow channel d).

Comparison with measurements for the existing plain weave filter element allowed the determination of a few model parameters, such as the indentation of the wires into the filter media. Then, these parameters were preserved while design parameters, such as wire diameters and weave pattern, were varied. The geometric models confirmed what had been suspected by the designer: for the plain weave, there exist settings where the blue wires in figure 3 can lie in a plain (figure 3 b)). For the 2/2 twill this configuration cannot occur (figure 3 d)). The impact on the pressure drop is tremendous. Figure 4 a), b) show the pressure distribution for flow from left to right for the plain weave for two different cross sections while c), d) show the pressure distribution for the same mass flow and same wire diameters for the 2/2 twill. For the twill, a 35% decrease in the overall pressure drop occurs. The simulation results clearly illustrate the reason for this phenomenon. For the plain weave, there is a significant gradient in the pressure along the outflow channel, from left to right in figure 7 a), b). For the twill, the outflow channel shows pressure values very close to that of the outlet all through.

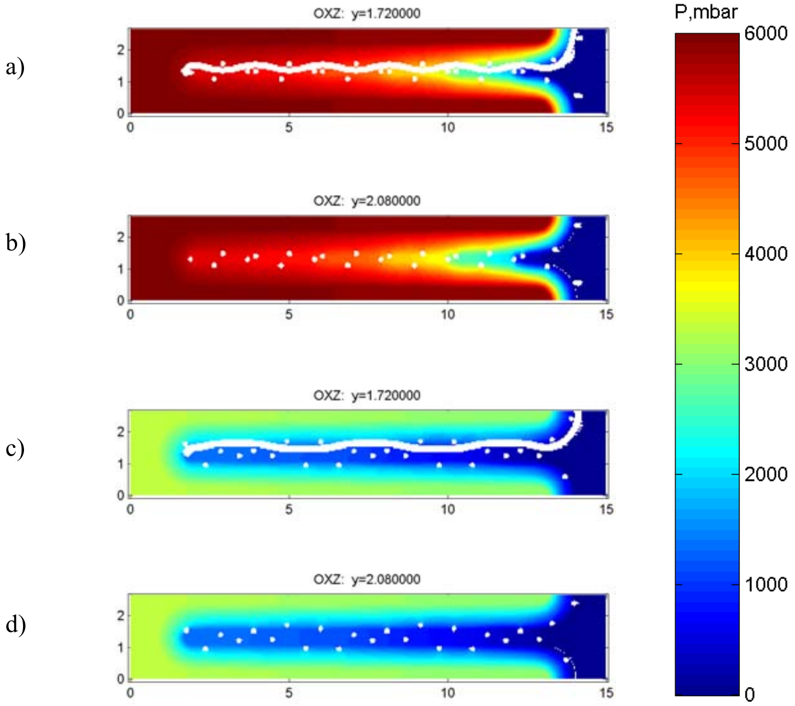


Fig. 4: a), b) show the pressure distribution ($p + \int f$ in the notation from equation (5)) for the plain weave for two different cross sections. c), d) show the pressure distribution for the 2/2 twill for the same areas. White areas mark the solid wires. The filter media is not shown but it can be envisioned from the strong gradients in the pressure fields.

Based on this strong evidence from the simulations, prototypes were built. For the configuration as shown, the same 30% pressure drop reduction as predicted by the simulations was found to occur in reality. For designs with longer pleats, the 2/2 twill weave improved the pressure drop up to 50%. Additional measurements showed that the filter efficiency and filter life time are not affected by the change in support mesh. The improvement is hence so significant that the design was patented [3] and is now on the market as Argo-Hytos' EXAPOR®MAX 2 hydraulic filter element.

4 Conclusions and outlook

Computational experiments provide a way of *rapid prototyping* filtration applications and can provide invaluable detailed insights into the behavior of pleated filter elements that help designing better filters for applications essential to the world's ecological balance. The project described in section 3 led to a patent by Argo-Hytos for the EXAPOR®MAX 2 hydraulic filter element. The pressure drop of EXAPOR®MAX 2 is between 30 and 50 % lower than that of the previous filter element generation. The work in section 3 also laid the foundations for new computer software. The modules PleatGeo and PleatDict for ITWM's GeoDict Software [9] are tailor-made and easy-to-use for the simulation and design of pleated filters.

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