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EXPERIMENTAL STUDIES OF THE SUPERPOSED FILTRATION MECHANISMS IN A CANDLE FILTER

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ABSTRACT

Coolants and lubricants are necessary in the hard metal industry for the cutting, grinding and polishing processes. These fluids are contaminated during the process with impurities. Therefore, a cost-effective and regenerative recycling system is needed. An adequate filter for this aim is a candle filter consisting of a paper stack held together by a spring. Filtration experiments with a suitable particle-oil suspension were done in such a candle filter at laboratory scale in order to investigate the mechanisms taking place in the process. The results show that blocking and cake filtration occur, to some extent, simultaneously, but the cake filtration is the mechanism relevant for the modeling and scale-up of the filtration process.

KEYWORDS

Candle filter, blocking filtration, cake filtration, clogging.

1. Introduction

Solid-liquid separation is an important operation, especially in the industrial post-processing for the recycling of fluids or recovery of solids. Coolants and lubricants are used in the hard metal (carbide) industry for the cutting, grinding and polishing to avoid the overheating caused by mechanical stress. These fluids are contaminated during the process with impurities and must be recycled. This recycling system demands to be cost-effective and regenerative to maintain low investment and operational costs. The candle filter from the company Transor Filter GmbH fulfils these requirements, being able to remove small particles from the grinding oil down to 5 µm. Its accomplished regeneration capacity leads to low maintenance cost and long service life. Nevertheless, this filter system can be improved regarding the separation efficiency and the specific throughput. The knowledge of the internal flow phenomena and the involved filter mechanism is decisive to improve the filtration process.

The aim of this study is to find out an analytical treatment of the filtration mechanisms taking place in this specific candle filter. This mathematical modeling can be applied to predict the local filter resistance and the volume of the filtrate as a function of the time, particle concentration and operation conditions. Furthermore, it allows a reliable scale-up of the filter device.

First, the structure and characteristics of the candle filter consisting in a paper stack held together by a spring was analyzed. Then, filtration experiments with a suitable particle-oil suspension were done in a laboratory filter in order to investigate the clogging mechanisms taking place in the process. Moreover, the flow in a single candle and in the whole vessel was simulated to investigate the velocity patterns and the pressure lost during the filtration process.

2. Theory of the filtration mechanisms

The filter resistance increases due to the accumulation of the particles over and inside the filter medium in a different manner for different filters and particulate systems. Thus, diverse particle deposition or clogging mechanisms must occur. The different filtration mechanisms were first mathematically modeled in 1935 by Hermans and Bredée [1].

$$\frac{dR}{dV} = \frac{d^2t}{dV^2} = K\left(\frac{dt}{dV}\right)^q \qquad (1)$$

This equation, valid for filtration under constant pressure difference, describes the dependence of the resistance R with the time t, the filtrate volume V, a constant K and an exponent q, which takes different values for the different mechanisms. After some experiments, it was found that for $q = 0$ the cake filtration occurs, that means that particles deposit on the filter medium and over other particles forming a cake layer which prolongs the pores existing on the filter medium. Intermediate blocking corresponds to $q = 1$ and it takes place if some of the particles go throw the filter medium being the others retained to block partially the pores and to form a cake. Standard blocking or depth filtration, with $q = 1{,}5$, happens if the particles deposit on the internal walls of the filter medium pores, reducing its cross section area. Complete blocking filtration, $q = 2$, arises if the particles obstruct the filter medium pores. With this filtration mechanism, the resistance increases in the most rapid way compared to the other mechanisms.

Each of these models is represented by a different equation. These equations depend on operation conditions, such as pressure drop and concentration, on physical parameters, such as viscosity, and on the variables filtrate volume and time in a different manner. All of them can be converted to linear functions including just the variables filtrate volume and time. Thus, in order to determine which is the filtration mechanism relevant for the mathematical modeling of the process, experiments to obtain the filtrate volume data in the time are needed.

3. Filter structure and characteristics

The filter system consists of a pressure vessel containing the filter candles. Each of them is formed from a stack of paper rings held together by a spring. The grinding oil is pumped into the vessel and the particles deposit over the candles while the clear oil leaves the system. When the pressure loss reaches an upper limit, the system is regenerated by back-flushing. Further explanation of how this filter works can be found in [2].

The paper rings are made of common non-coated 80 g paper with a porous cellulose structure containing fillers such as limestone (Fig.1). The paper rings are approximately 95 µm thick but the size of the gaps between them depend on the load of the spring that held together the paper stack. The pore size distribution was analysed with a porometer for different loads of the spring giving the diagram shown in Fig. 2. An increase of the spring load has a strong influence on the largest pore size and just a small influence on the mean pore size. That means that there is a homogenization of the pore size distribution by elimination of only the largest pores.
For example, for a spring load of 100N the gaps represent just 5% of the filter area compared to the surface of the paper. Nevertheless, the flow resistance of the pores

is much smaller than trough the paper and after some measurements it was shown that 90,5% of the flow goes through the gaps and only 9,5% through the paper structure.

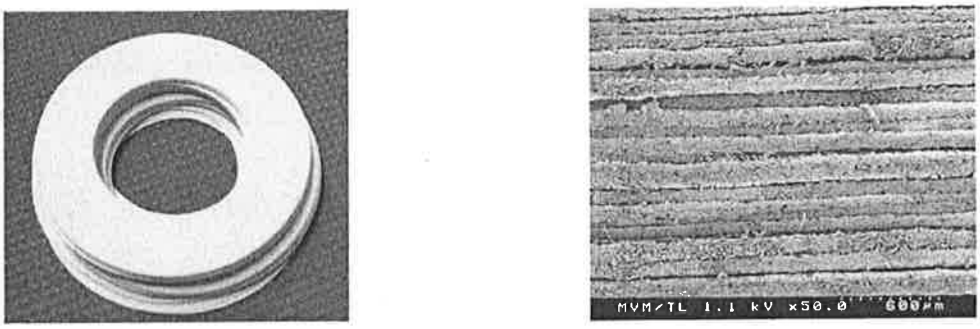

Fig.1. On the left: filter paper rings. On the right: REM of a fragment of the paper stack candle filter.

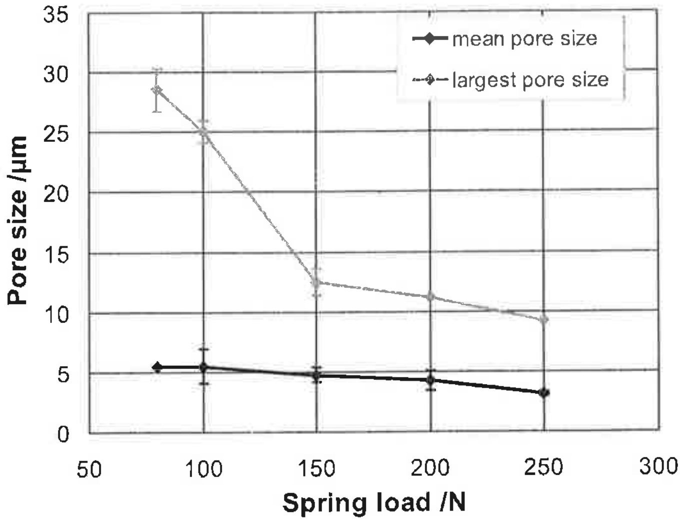

Fig. 2. Mean and biggest pore size of the paper stack as a function of the spring load.

4. Flow simulation

In these filters a uniform suspension flow of sufficient velocity through the vessel and through the filter medium is desired. In order to carry out an investigation and optimization of this candle filter system, a study of the internal flow phenomena is demanded. Computational Fluid Dynamics (CFD) is an outstanding tool to simulate the flow pattern in a single filter candle and even in a filter vessel. Furthermore, the simulation allows a prediction of flow phenomena for desired quantities with high resolution in space and time, for any operating conditions of the industrial filtration.

4.1. Simulation models and set-up

CFD solves the governing equations of fluid flow, continuity and momentum equations, using numerical methods and applying the adequate boundary conditions. A porous media model is incorporated to take the pressure drop through the filter medium into account. This model adds a sink term in the momentum equations which includes a viscous loss term (represented by Darcy's law) and an inertial loss term. For a homogeneous porous media the sink term S in the direction i is represented by Eq. 2.

$$S_i = -\frac{\mu}{\alpha} u_i + C_2 \frac{1}{2} \rho \, |u| \, u_i \, , \tag{2}$$

where $1/\alpha$ ($1/m^2$) is the viscous resistance coefficient, C_2 (1/m) is the inertial resistance factor, u the velocity through the filter medium and μ and ρ, the liquid viscosity and density respectively.

The viscous resistance and inertial resistance are experimentally determined in the following manner. According to the momentum equation for porous media there is a quadratic relationship between the pressure drop Δp through a filter medium of length L and the velocity u of the filtrating fluid (Eq. 3). In order to obtain a curve between the pressure drop and the velocity, through flow experiments in a candle filter, varying the volumetric flow, were performed. There, the variation of pressure drop is registered by a pressure sensor. Then, the data of ΔP and u can be plotted and fitted to Eq. 3 to obtain the resistance coefficients $1/\alpha$ and C_2.

$$\frac{\Delta p}{L} = -\frac{\mu}{\alpha} u_i + C_2 \frac{1}{2} \rho u_i^2 \, . \tag{3}$$

A three dimensional grid of the single candle (Fig. 3) was created in order to simulate the flow. As boundary condition a certain velocity at the inlet and a pressure of 1 bar at the outlet were specified. The density ($\rho_{20°C}$ = 810 kg/m^3) and the viscosity ($\mu_{20°C}$ = 0,0054 kg/ms) of an industrial grinding oil, used also in the experiments, were defined for the fluid.

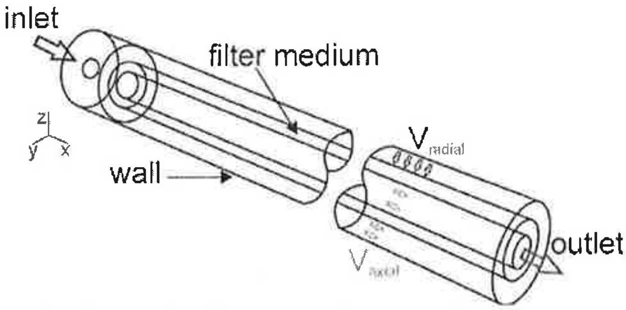

Fig. 3. Geometry of the single candle filter and relevant velocity components.

4.2. Simulation results

The highest velocity is reached at the entrance in front of the candle filter. Before the fluid goes through the ring channel between the candle and the casing, two eddies are formed beside the candle. Fig. 4 describes the radial velocity across the filter media, which is the filtration velocity, along the candle length (x axis). At the entrance there is a higher velocity due to the existence of eddies, but then it is almost constant along the candle length.

The axial velocity in the ring space around the candle and in the channel inside the candle is represented over the radius in Fig. 5. This diagram shows that the velocity in the channel around the candle decreases along the candle length and the velocity inside the candle, with a parabolic profile, increases along the candle length. This confirms that the fluid travels through the filter medium slowly until it passes completely to leave the filter through the outlet.

To check the validity of the model, the pressure drop obtained in the simulation is compared with the pressure drop measured in the filter. The results for different initial flow rates, given in Table 1, agree with each other. Therefore, the simulation model is valid for the study of the internal flow phenomena occurring in the filter.

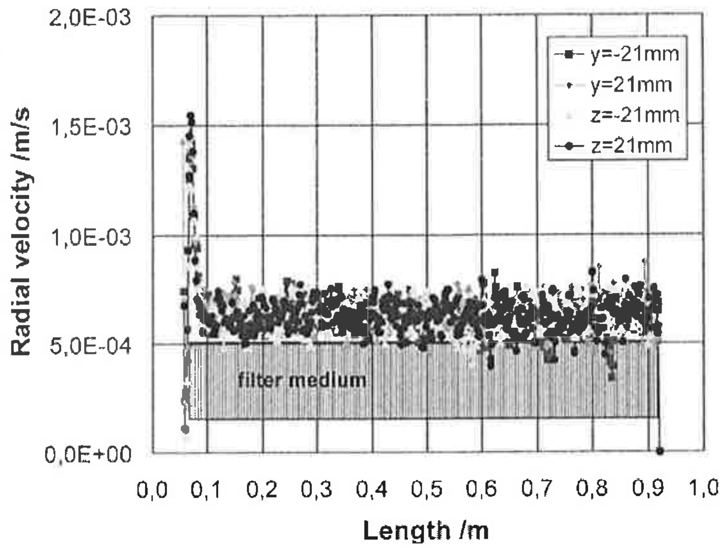

Fig. 4. Radial velocity across the filter media along the candle length.

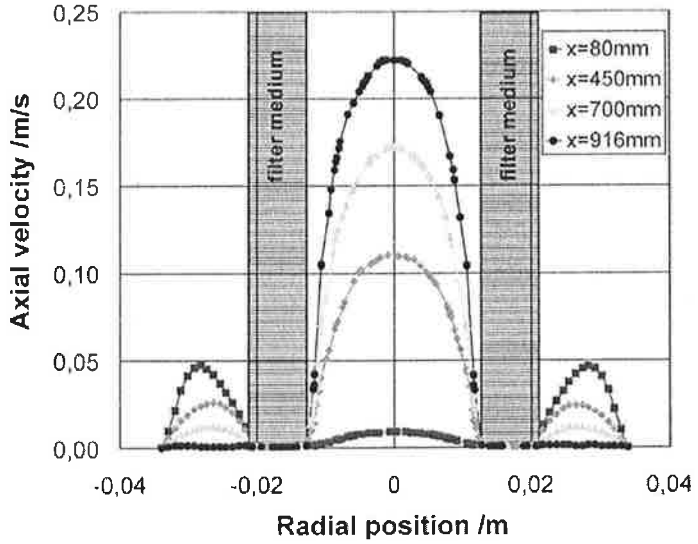

Fig. 5. Axial velocity in the ring space around the candle and in the channel inside the candle over the radial position.

Flow rate (l/min)	Experimental Δp (bar)	Simulation Δp (bar)
2	0,83	0,88
4	1,85	1,88
6	2,42	2,58

Table 1. Experimental and simulated pressure drop through a single paper stack candle filter.

5. Experiments

5.1. Experimental set-up

Experiments with an adequate oil-particle system (grinding oil and limestone particles with a particle diameter $x_{3,50}$ = 5,5 µm) were carried out; first in a pilot filter containing a single industrial candle filter and afterwards in a small candle filter to study in detail the deposition mechanisms of the particles during the filtration. The advantage of the laboratory filter is that the industrial conditions of particle concentration and filtration time can be reproduced. Other important parameters like pressure difference and flow rate were varied too.

In both experimental set-ups, it was possible to investigate the evolution of the filtrate and the permeability in time. These experimental values were fitted to the various mathematical models for the different filtration mechanisms found in the literature [1]. The flow resistance was also experimentally measured and compared with the results of the filtration model.

5.2. Experimental results

After the filtration process, a thin layer of particles was seen at the surface of the candle. Therefore, although the concentrations here used are clearly lower than the typical ones for the cake filtration, this was the first mechanism tested. The cake filtration model predicts a variation of the filtrate volume in the time inversely proportional to the filtrate volume described in Eq. 4.

$$\frac{dV}{dt} = \frac{A\,\Delta p}{\mu\,(R_m + \frac{w\,r_c}{A} \cdot V)}, \qquad (4)$$

where A represents the filter area, Δp the pressure difference, R_m the filter medium resistance, r_c the specific particle deposition resistance for the cake filtration, w the concentration of the suspension to be filtered and V the filtrate volume. After integrating Eq. 4, it can be expressed in a linear form (t/V versus V) as in Eq. 5:

$$\frac{t}{V} = \frac{w\,\mu\,r_c}{2A^2\,\Delta p} V + \frac{\mu R_m}{A\,\Delta p}. \qquad (5)$$

The values of the filtrate volume and the time were represented as shown in Fig. 6. The experimental values do not have a linear form during the whole process. Only two thirds of the experiment upwards, the represented values behave in a linear way. This indicates that, although cake filtration happens, there is another mechanism at the beginning.

Another probable mechanism taking place in the paper stack candle filter is the blocking filtration. The equation for this model is given by Eq. 6:

$$\frac{dV}{dt} = \frac{A\,\Delta p}{\mu}\left(\frac{1}{R_m} - \frac{r_b\,w}{A} \cdot V\right). \qquad (6)$$

Here represents r_b the specific particle deposition resistance for the blocking filtration model. Eq. 6 can also be integrated and linearized leading to Eq. 7:

$$\ln\left(\frac{dV}{dt}\right) = \ln\left(\frac{A\,\Delta p}{\mu\,R_m}\right) - \frac{\Delta p\,w\,r_b}{\mu} \cdot t. \qquad (7)$$

The representation of the values according to the blocking filtration is shown in Fig. 7. Only at the beginning of the filtration there is a linear correlation. Indeed, both mechanisms occur simultaneously in the first phase of the filtration. While some of the particles deposit on the outer surface of the filter rings making a cake, other particles deposit in the gap between the paper rings blocking them partially. Once all the gaps are blocked, just the cake filtration mechanism is relevant for the particle deposition.

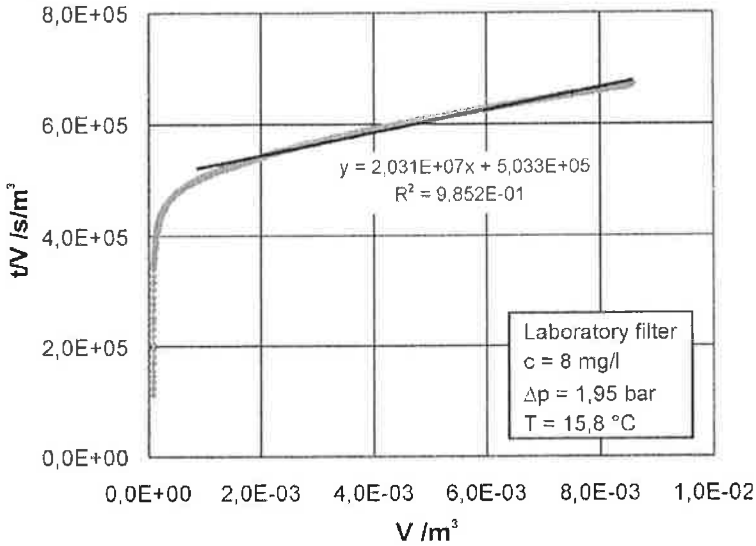

Fig. 6. Experimental data represented in the linear form of the cake filtration model.

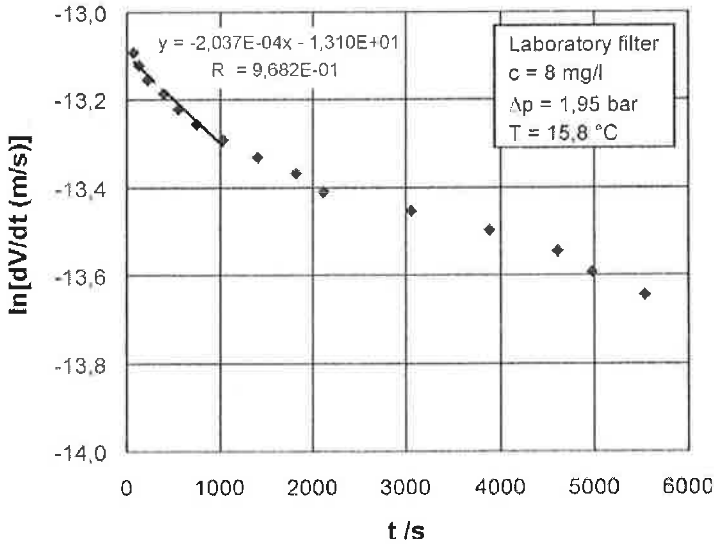

Fig. 7. Experimental data represented in the linear form of the blocking filtration model.

In order to determine which model is the most suitable for the whole process, modeled and experimental values of the filtrate volume rate over the time were compared in Fig. 8. Although at the beginning the blocking model represents better the experimental values, the cake filtration is the one that better fits the experimental values during the whole filtration. Thus, it is the cake filtration the relevant mechanism to model the entire filtration process.

One advantage of modeling the filter mechanism in a filter system is to predict the evolution of the resistance with the time. Thus, it is possible to optimize the process regarding the operation conditions and the filtration and regeneration time. The values of the flow resistance according to both models are compared in Table 2 with the experimental one, measured at the end of the filtration. The blocking filtration model predicts a much higher value of the resistance as the one obtained experimentally. This is because this model expects a suddenly increase of the resistance after all the pores of the system are blocked. But in our system, instead, a continuously increase of the resistance occurs. In this aspect, also the cake filtration model fits the experimental flow resistance better.

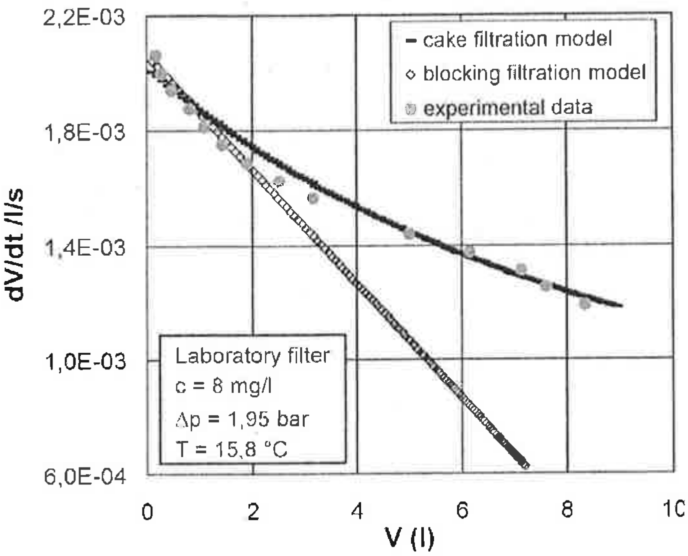

Fig. 8. Experimental data of the volume filtrate rate compared with the models.

$R_{experimental}$ (m^{-2})	R_{cake} (m^{-2})	$R_{blocking}$ (m^{-2})
$1{,}15\cdot10^{13}$	$1{,}80\cdot10^{13}$	$6{,}25\cdot10^{17}$

Table 2. Experimental and modeled resistances after 240 min filtration of a 8 mg/l suspension with a pressure difference of approximately 2 bar and a temperature of 18,7 °C.

6. Conclusions

The CFD simulation predicts a homogeneous radial flow through the filter medium along the whole candle length. The axial velocity in the ring space around the candle and in the channel inside the candle have a parabolic profile. The pressure drop obtained in the simulation agrees with the pressure drop with the pressure drop measured in the filter. Therefore, the simulation model is valid for the study of the internal flow phenomena occurring in the filter.

The experimental results show that more than one filtration mechanism takes place at the same time. At the beginning of the lifetime of a candle filter some particles penetrate the filter structure causing standard filtration, but after some cycles an equilibrium state is reached. Following particles obstruct the gaps and pores of the filtration medium and the blocking filtration mechanism predominates. After a gap or a pore is blocked, the particles are deposited following the cake filtration mechanism. Blocking and cake filtration occur, to some extent, simultaneously, but the cake filtration is the mechanism relevant for the modelling and scale-up of the filtration process.

7. References

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