



This is an electronic reprint of the original article. This reprint may differ from the original in pagination and typographic detail.

Calonius, Olof; Jokinen, Anton; Pietola, Matti; Gorle, Jagan

# Effects of oil contamination level, flow rate and viscosity on pressure drop development and dirt holding capacity of hydraulic filter

Published in: ASME/BATH 2019 Symposium on Fluid Power and Motion Control, FPMC 2019

DOI: 10.1115/FPMC2019-1631

Published: 07/10/2019

Document Version Peer-reviewed accepted author manuscript, also known as Final accepted manuscript or Post-print

Please cite the original version:

Calonius, O., Jokinen, A., Pietola, M., & Gorle, J. (2019). Effects of oil contamination level, flow rate and viscosity on pressure drop development and dirt holding capacity of hydraulic filter. In *ASME/BATH* 2019 *Symposium on Fluid Power and Motion Control, FPMC* 2019 American Society of Mechanical Engineers. https://doi.org/10.1115/FPMC2019-1631

This material is protected by copyright and other intellectual property rights, and duplication or sale of all or part of any of the repository collections is not permitted, except that material may be duplicated by you for your research use or educational purposes in electronic or print form. You must obtain permission for any other use. Electronic or print copies may not be offered, whether for sale or otherwise to anyone who is not an authorised user.

© 2019 American Society of Mechanical Engineers

## EFFECTS OF OIL CONTAMINATION LEVEL, FLOW RATE AND VISCOSITY ON PRESSURE DROP DEVELOPMENT AND DIRT HOLDING CAPACITY OF HYDRAULIC FILTER

Anton Jokinen<sup>1</sup>, Olof Calonius, Matti Pietola Aalto University,

Department of Mechanical Engineering Espoo, Finland Jagan Gorle Parker Hannifin, Hydraulic and Industrial Process Filtration EMEA Urjala, Finland

#### ABSTRACT

In hydraulic systems, the presence of foreign material in the system oil accounts for the majority of system troubles due to mechanical wear of components, sticking of different parts etc. Therefore, it is essential to maintain an adequate cleanliness level of the fluid at all times through filtration. Mechanical filters are used for this purpose, to separate solid particles from the system oil. As a hydraulic filter gets accumulated with dirt throughout its service life, the pressure drop over the filter element increases. This pressure drop is typically used for determining the lifetime of a filter element: once a predetermined pressure drop at certain flow conditions has been reached, the filter has accumulated enough dirt to require servicing or replacement.

In this paper, a correlation model has been developed to describe the effects of flow and fluid properties on the dirt holding capacity and the service life duration of a hydraulic filter. For this purpose, extensive laboratory tests have been carried out in order to measure the pressure drop development of a filter unit at different oil flow rates, viscosities and gravimetric contamination levels.

The work in this paper has been done as part of the initial research for investigating the effects of different flow and fluid parameters on hydraulic filtration. The aim of the overall research project is to develop an IoT-enabled smart filter unit that could predict its remaining lifetime, and estimate the condition of the system oil as well.

Keywords: hydraulic filtration, pressure drop, correlation model, predictive maintenance

#### NOMENCLATURE

ν	kinematic viscosity	$[mm^2/s]$
ρ	gravimetric contamination level	[mg/l]
a,c	coefficients for pressure drop	[bar]
b,d	coefficients for pressure drop	[1/mg]
f	coefficient for pressure drop	$[bar/(mg)^2]$
g	coefficient for pressure drop	[bar/mg]
M	presented mass	[mg]
$M_{ m p}$	packed mass	[mg]
$\Delta p$	pressure drop	[bar]
$\Delta p_0$	initial pressure drop	[bar]
$q_{ m V}$	volumetric flow rate	[l/min]
Т	temperature	[°C]
V	filtrate volume per filter area	[m]
$x_1 - x_{22}$	constants for pressure drop	[-]

## INTRODUCTION

In hydraulic systems, maintaining an adequate cleanliness level of the system oil is one of the most important factors for ensuring the functionality of the entire system. Many equipment manufacturers specify a cleanliness level for the oil according to ISO 4406, and even require sampling of the oil as part of the condition monitoring procedures.

The presence of foreign material in the system oil is considered to account for the majority of all system troubles [1]. Typical causes of failure due to solid particles in the oil include jamming or silting of control valves, and particle induced wear between contacting surfaces e.g. in pistons or pumps. These

<sup>&</sup>lt;sup>1</sup> Contact author: anton.jokinen@aalto.fi

issues stress the importance of continuous filtration of the system oil for separating the solid particles from the fluid.

As hydraulic filters accumulate dirt during their service life, their resistance to flow increases, thus increasing the pressure drop over the filter unit. This pressure drop is commonly used for determining the level of clogging of the filter. Were the clogging allowed to continue without maintenance, the filter might eventually become entirely blocked by the particles. The maintenance of filters is typically carried out as time-interval replacements or inspections. However, this sort of preventative maintenance is ineffective, as it does not take the actual timehistory of the filter unit and its operating conditions into account, which could lead to premature replacement of a properly functioning filter, or to downtime due to unexpected filter blocking. Filter maintenance may also be performed as reactive maintenance, where the filter is deemed to require servicing once a measured pressure drop over the filter at certain flow conditions has reached some predetermined level. However, reactive maintenance of filters also does not consider the timehistory, and could lead to filter blocking if the clogging were to occur rapidly. To enable a predictive maintenance strategy for hydraulic filters where the remaining lifetime could be estimated, it is important to understand the consequences of different flow and fluid conditions on the evolution of the pressure drop, and how they affect the dirt holding capacity of the filter.

Over the years, many research teams have worked on developing equations describing the pressure drop associated with fluid flow through fibrous or porous media. The interrelation between influencing variables and the associated pressure drop over a porous material bed has been reviewed by Lage [2]. Examples of influencing variables in flow through porous media are, for example, average fluid velocity, specific permeability, dynamic viscosity, and thickness (in flow direction) of the bed of porous material. In a study involving flow of air through a porous aluminum layer. Lage et al. [3] showed that pressure drop over the porous layer (the pressure gradient) is proportional to a cubic function of fluid speed (seepage velocity). The cubic equation was in much better agreement with experimental pressure gradient values than the earlier (Forchheimer -extended Darcy) quadratic equation. In addition, the cubic equation was accurate up to a fluid velocity of 19.26 m/s. In another study by Dukhan et al. [4], involving compressed and uncompressed open-cell aluminum foam samples tested in a wind-tunnel setting, it was found that the pressure drop followed a quadratic equation with respect to the seepage velocity. In that study, however, the highest seepage velocity in the experiments was 2.73 m/s, implying that the quadratic correlation equation could be adequate at low seepage velocities.

Studies involving model equation building for fibrous cartridge oil filters appear to be infrequent compared to studies involving air filters. In a paper by Jaisinghani and Sprenger [5], an equation was developed for the pressure drop (and the friction factor) for fluid flow through fibrous material beds. However, this equation was developed for clean filters, which restricts its usage in filter condition monitoring. An example of a diagnostic

system for hydraulic filters in industrial use (in connection with a system of servo hydraulic actuators) is described in [6]. The software developed in the study was used for predicting the service life of the hydraulic filter based on the evolution of the pressure difference over the filter. A cost-effective way of estimating the flow rate (using down-stream pressure measurement instead of flow meters) was presented and thus the effect of flow rate on the pressure difference was taken into account. However, the work did not take the effect of changing viscosity (temperature) on the pressure difference over the filter into account.

This paper has been made as part of the initial research in a project that is aiming to develop a smart oil filter that could estimate its remaining lifetime. For this study, extensive laboratory experiments have been conducted for observing how the pressure drop over a hydraulic depth filter develops as the filter is being subjected to a stream of particle-contaminated ISO VG 32 oil at different flow and fluid conditions. The different conditions included the oil gravimetric contamination level, the oil flow rate, and the oil viscosity, which was varied by varying the oil temperature. From these experiments, a mathematical correlation model has been derived in this paper for describing the evolution of the pressure drop based on the aforementioned flow and fluid conditions. The modelling process also included an investigation on how the apparent dirt holding capacity of the filter seems to vary at the different flow and fluid conditions.

## **METHODS**

In this section, the laboratory experiments for observing the pressure drop development at different conditions is explained in Section 2.1. The resulting correlation model and how it was derived is described in Section 2.2.

#### 2.1 Experimental

The experimental part for this study consisted of measuring the pressure drop evolution of a depth filter at different flow and fluid conditions. The multi-pass test methodology was used (ISO 16889), and indicators and sensors were calibrated before going into the tests. In test cases where the pressure drop did not follow regular trends, the tests were repeated in order to increase confidence. However, comprehensive uncertainty analysis deserves a separate investigation, which was out of the scope of the present research.

The filter type used in the experiments was a 5  $\mu$ m rated commercial filter with a glass fiber medium, which has an effective surface area of 0.154 m<sup>2</sup> through 57 pleats. The beta ratios were:  $\beta_{10} = 90\%$ ,  $\beta_{100} = 99\%$ ,  $\beta_{200} = 99.5\%$ ,  $\beta_{1000} = 99.9\%$ . The oil used in the experiments was the standard ISO VG 32 hydraulic oil. The different conditions that were considered in the experiments were the oil flow rate, temperature and gravimetric contamination level.

The gravimetric contamination level was adjusted by mixing the oil with ISO Medium test dust (ISO12103-1-A3) at different rates. The level of contamination was maintained during the test by connecting a stream of contaminated oil from the separate injection circuit to the test filter circuit. As a result

of this, four different oil contamination levels -2 mg/l, 5 mg/l, 8 mg/l and 10 mg/l - could be precisely achieved for the oil entering the test filters.

The temperature of the oil was adjusted to 30 °C, 40 °C, 50 °C, or 60 °C at the different experiments. The oil flow rate was varied between 40 l/min, 80 l/min and 120 l/min. The different conditions were kept constant at each experiment, and each experiment was started with a clean filter. Before beginning a new experiment, the circuits were rinsed with fresh oil and filter housings were cleaned, using 4/6/14 as cleanliness class criterion (ISO 4406).

As a summary, the experiments consisted of measuring the pressure drop evolution at four different oil contamination levels, four different oil temperatures, and three different oil flow rates. This resulted in 48 experiments in total. The experimental results, including the test bench description, was described in more detail in [7].

Figure 1 illustrates examples of the different experiments. The experiments were terminated once the pressure drop had reached 5 bar. This terminal pressure drop value was selected because it has been defined as the limit for laboratory tests of this 'medium pressure filter' by the manufacturer.

Measurements during experiments were taken with a 2second sampling period. In the upmost graph in Figure 1, the effect of contamination level on the pressure drop development is demonstrated by showcasing different cases where the flow rate and temperature were kept at 80 l/min and 50 °C, respectively. The middle graph illustrates the effect of temperature which affects the oil viscosity, and the lower graph demonstrates the effect of flow rate.



**FIGURE 1:** EXAMPLES OF HOW THE PRESSURE DROP DEVELOPMENT CHANGED WITH DIFFERENT OPERATING CONDITIONS

## 2.2 Data analysis for modelling

The main objective in the modelling process was to create an equation for the pressure drop  $\Delta p$  with the help of the different physical variables that were varied between experiments. The equation for  $\Delta p$  will be of the form:

$$\Delta p = f(\rho_c, q_V, \nu, M) \tag{1}$$

where  $\rho_c$  is the oil gravimetric contamination level,  $q_v$  is the oil volumetric flow rate, v is the oil kinematic viscosity which is calculated from the oil temperature, and M is the amount of filtered mass.

The kinematic viscosity of the ISO VG 32 oil can be derived from the following equation, which was determined in [7]:

$$\nu = 300.98T^{-0.585} \tag{2}$$

where T is the oil temperature in degree Celsius. General equations for the viscosity-temperature relationship can be found in [8] or in ASTM D341-17 (Standard Practice for Viscosity-Temperature Charts for Liquid Petroleum Products, ASTM International).

Another approach in the modelling procedure was to investigate how the clogging of the filter would affect the pressure drop. In other words, the pressure drop due to filter clogging would be separated from the initial pressure drop. Therefore, in the final model, the pressure drop will be expressed as the sum of two separate terms:

$$\Delta p = \Delta p_0 + \Delta p_M \tag{3}$$

where  $\Delta p_0$  is the initial pressure drop of a clean filter, and  $\Delta p_M$  is the pressure drop due to filtered mass. The initial pressure drop is affected by the physical characteristics of the filter element, the oil flow rate, and the oil viscosity. Darcy's law (1856) also gives this relation for a pressure drop due to a flow through a packed bed.

The simplest method for calculating the filtered mass is to take the time integral of the oil contamination level multiplied by the flow rate:

$$M = \int_0^t q_V \cdot \rho_c \, dt \tag{4}$$

However, it should be noted that in Equation (4), the "filtered" mass is merely the mass that has been presented to the filter, and not necessarily the mass that is being held by the filter. Some smaller particles may get through the filter, and in addition the filtration efficiency is affected by the flow properties.

To investigate how the filter clogging would affect the pressure drop development, the pressure drops were plotted against the filtered mass calculated with (4), Figures 2-4. The initial pressure drops were subtracted to have the pressure drop due to filter clogging start from zero.



**FIGURE 2:** PRESSURE DROPS PLOTTED AGAINST PRESENTED MASS. EXAMPLES ILLUSTRATING THE EFFECTS OF DIFFERENT FLOW RATES ON THE PRESSURE DROP DEVELOPMENT

Figure 2 showcases the effect of flow rate on the filter clogging. Again, the other variables (contamination level and temperature) are kept at constant to illustrate only the effect of flow rate. The pressure drop data has been smoothened to demonstrate the effects more clearly.



**FIGURE 3**: EXAMPLES SHOWCASING THE EFFECT OF DIFFERENT TEMPERATURES ON THE PRESSURE DROP DEVELOPMENT

Figure 2 illustrates a clear correlation between the flow rate and the filter clogging speed. The type of filter used in the experiments is more efficient at filtration at higher flow rates; therefore, the filter clogs faster with presented mass. In the examples shown in Figure 2, all the experiments at 30 °C and different contamination levels are presented, however similar trends were observed at the other temperatures as well. The type of effect that the oil viscosity has on the pressure drop development is illustrated in Figure 3.



**FIGURE 4:** EXAMPLES SHOWCASING THE EFFECTS OF DIFFERENT CONTAMINATION LEVELS ON THE PRESSURE DROP DEVELOPMENT

Based on the results shown in Figure 3, the fluid temperature or viscosity has a notable effect on filter clogging as well: at lower temperatures, i.e. higher viscosities, the pressure drop increases faster with presented mass. While a low viscosity fluid is typically considered ideal for many applications, based on these results the filtration efficiency could be better at higher viscosities. However, in contrast the filter has more longevity at lower viscosities. Lastly, Figure 4 illustrates the effect of gravimetric contamination level on filter clogging. While the deviation between the curves with respect to contamination level in each graph is not as noticeable as with the case of flow rate or viscosity, a clear trend does seem to exist where the filter seems to be able to filter out more mass at higher contamination levels before the terminal pressure drop of 5 bar is reached. This effect is illustrated more clearly in Figure 5, which presents the cases of 40 l/min and 40  $^{\circ}$ C.



The phenomenon illustrated in Figures 4 and 5 is somewhat surprising, as the particle size distributions are identical at the different contamination levels. Nevertheless, the filtration capacity with respect to presented mass seems to be increased at higher contamination levels. Similar trends were observed at other flow rates and temperatures as well. These findings will be taken into account when developing the correlation model for the pressure drop.

## 2.3 Modelling

The correlation model for this paper was constructed with the help of regression analysis in the MATLAB/Simulink environment. The initial approach was to apply curve fitting for the experimental data of  $\Delta p$  and the presented mass. Different form of fittings were experimented with, though the best fitting was found to be with an exponential function that has two exponential terms. However, the exponential fitting did not always fit the very beginning (when  $\Delta p \approx 0$ ) of different  $\Delta p$ curves accurately, as exponential functions cannot get to zero. The beginning of the  $\Delta p$  curve is almost linear, and it can be accurately expressed as an almost linear function with a small quadratic term. The exponential fitting was found to be accurate for all different 48 cases from 3000 mg onwards of presented mass. Therefore, the general form for the function for the pressure drop due to accumulated mass in Equation (3) will be of the form:

$$\Delta p_{M} = \begin{cases} fM^{2} + gM, & M \le 3000 \ mg \\ ae^{bM} + ce^{dM}, & M > 3000 \ mg \end{cases}$$
(5)

where a, b, c, d, f and g are coefficients that vary at different flow rates and temperatures, and M is the filtered mass. In reality the contamination level affects the coefficients as well, as we learned previously in this section that the amount of mass that can be presented to the filter varies at different contamination levels, when the levels are kept constant throughout filtration. However, to have the equation work better with a contamination level that varies during filtration, the coefficients should not be affected by the contamination level of some particular moment, at least not in any significant way. Therefore, the equation for filtered mass was slightly adjusted, so that the coefficients a, b, c, d, f and g could be written without the contamination level:

$$M_p = \int_0^t q_V \cdot \rho_c^{x_1} dt \tag{6}$$

where  $x_1$  is a constant that is used for equalizing the differences between different contamination levels. From here on, the mass  $M_p$  will be referred as "packed" mass. However, Equation (6) might still not be used for revealing the actual mass that has been packed in the filter, as the oil flow rate and viscosity also have an effect on filter clogging, as we learned previously (Figures 3 and 4).

The next objective in the modelling process was to express the different coefficients in (5) with the help of flow rate and viscosity. Recall that curve fitting was performed for the different experiments. The authors inspected how the different coefficients in (5) varied between the different experiments. For example, it was discovered that flow rate has a linear effect on the coefficient c, which is illustrated in Figure 6.



Effect of flow rate on coefficient c for 40 °C and 5 mg/l

**FIGURE 6:** HOW THE COEFFICIENT c VARIED WITH THE FLOW RATE. CASES 40 °C AND 5 MG/L USED AS AN EXAMPLE.

After conducting a similar inspection for the different coefficients, the following equations for the coefficients were obtained:

$$a = (x_2 q_V + x_3 \nu) e^{x_7 q_V + x_8 \nu}$$
(7)

$$b = x_4 q_V^2 + x_5 q_V + x_6 \nu \tag{8}$$

$$c = x_9 q_V + x_{10} v (9)$$

$$d = x_{11}q_V^2 + x_{12}q_V + x_{13}\nu \tag{10}$$

$$f = x_{14}q_V^2 + x_{15}q_V + x_{16}\nu + x_{21}$$
(11)

$$g = x_{17}q_V^2 + x_{18}\nu^2 + x_{19}q_V + x_{20}\nu + x_{22}$$
(12)

In Equations (7) – (12), the terms  $x_2 - x_{22}$  are constants. The different constants were acquired by using parameter optimization in MATLAB. The object of the parameter optimization was to find the constant values that would give the most accurate results with (5) when compared against the measured  $\Delta p$  data. The packed mass calculated with function (6) was used in (5) as the filtered mass. The parameter optimization yielded the following value for the constant  $x_1$  in Equation (6):

$$x_1 = 0.957$$

The power  $x_1$  for the contamination level in (6) is less than one, which acts as a sort of penalty for smaller contamination levels. Due to this, the mass that has been packed in the filter at different contamination levels is approximately equal when the terminal pressure drop is reached. Figure 7 illustrates an example of this. The pressure drops at different contamination levels have been plotted against the packed mass. However, Equation (6) might not reveal the actual mass that has been packed in the filter as stated previously. In addition to fluid flow rate and viscosity having an effect on the filter clogging as well, no assumptions should be made that the 5 bar pressure drop is reached with the same amount of packed mass at different contaminant concentrations. The different contamination levels might affect the formation of the filter cake, and therefore have different effects on the flow and the pressure drop. The equation for packed mass is used for mainly practical purposes in this paper.



**FIGURE 7:** PRESSURE DROP VS. PACKED MASS. PACKED MASS CALCULATED WITH EQUATION (6). CASES 80 L/MIN, 60 °C SHOWN AS AN EXAMPLE

As a summary, the final function for the pressure drop, when the initial pressure drop is included, has the following form:

$$\Delta p = \begin{cases} \Delta p_0 + f M_p^2 + g M_p, & M_p \le 3000 \ mg\\ \Delta p_0 + a e^{b M_p} + c e^{d M_p}, & M_p > 3000 \ mg \end{cases}$$
(13)

The Equation (13) was experimented with a Simulink model. The model took only the physical variables as inputs: the oil flow rate, temperature and gravimetric contamination level. The simulation results will be demonstrated in the following section.

#### RESULTS

In this section, the simulation results are evaluated and compared with the experimental data. The different simulations were executed mimicking the different experiments. The simulation time each individual simulation had was the same that the corresponding experiment had had. Table 1 presents some comparisons between the end pressure drop of experiments and simulations. Figure 8 illustrates the simulation results corresponding to the cases listed in Table 1 plotted with the measurement data. The simulations used measured flow rate values from the experiments, thus the small vibrations in the simulation results. The oil temperature and gravimetric contamination level were set to be constants in the simulations.

## DISCUSSION

Equation (13) that was derived in this study can predict the development of the pressure drop with good accuracy. However, in some cases deviation between the simulated and measured results was observed towards the end of the experiments, such as for the case of 40 l/min, 40 °C, and 10 mg/l, see the uppermost graph of Figure 8.

**TABLE 1:** COMPARING EXPERIMENTAL AND SIMULATEDEND PRESSURE DROPS

Flow	Experimental	Simulated	Error
configuration	end pressure	end pressure	[%]
$(q_{\rm V}-T-\rho_{\rm c})$	drop [bar]	drop [bar]	
40-40-10	5.13	6.17	20
40-30-2	5.11	4.91	-4.0
80-60-5	5.21	4.87	-6.5
80-50-8	5.24	5.49	4.7
120-30-2	5.21	5.24	0.5
120-60-10	5.295	5.293	-0.03



**FIGURE 8:** COMPARISONS OF SIMULATED AND EXPERIMENTAL RESULTS. CORRESPONDING END PRESSURES ARE SHOWN IN TABLE 1.

However, the end of the pressure drop curve has the highest area of uncertainty, and therefore is the hardest to predict. In addition, some of the experiments had inconsistencies between each other towards the end of measurements as illustrated in Figure 9.



**FIGURE 9:** EXAMPLE OF UNTYPICAL PRESSURE DROP DEVELOPMENT (50 °C CURVE CROSSES 40 °C CURVE).

That is, e.g. for the case of 40 l/min and 2 mg/l, at approximately 80% of the max. run time of the tests, the slope of the  $\Delta p$  curve for the 50 °C oil was steeper than that of the 40 °C oil, such that the 50 °C oil reached the terminal pressure drop value earlier than the 40 °C oil, Figure 9. The expected behavior, typical of most of the tests, was that at the end of the test the  $\Delta p$  curves were separated (cf. Figure 1, middle graph) and did not cross. In inconsistent cases, the test was either repeated or the untypical  $\Delta p$  curve was excluded from the overall data analysis.

Despite this, when the fitting of Equation (13) was compared with the experiments, the R<sup>2</sup> values were typically over 0.98, which is high enough to showcase a clear correlation. Though the equation can predict the development of  $\Delta p$  accurately, it should be noted that the equation is most likely media specific, as only one filter type was used in the experiments.

Overall, the pressure drop development was expected to follow a mode close to blocking filtration equations for constant rate filtration, cf., e.g., Iritani et al. [9]. This was because the Medium Test Dust (ISO 12103-1-A3) has a size distribution with an average size of approximately 10  $\mu$ m, whereas the tested filters had a filtration grade of 5  $\mu$ m. Correlation between the measurements and the blocking filtration equations is the topic of future studies, but the cases that have been analyzed so far have suggested complete blocking behavior ([9], Fig. 3a), see Figure 10 as an example.

The fluid flow rate and temperature have a clear effect on the capacity of the filter with respect to presented mass, as was illustrated in Figures 2 and 3. These findings are not surprising, as it is reasonable to expect that with higher kinetic energy acting on the particles, more of the particles would get attached to the pore walls of a depth filter. Interestingly, the gravimetric contamination level does seem to have an effect on the filtration capacity with respect to presented mass as well (Figures 4 and 5).



**FIGURE 10:** FILTER BLOCKING DEVELOPMENT SUGGESTING COMPLETE BLOCKING MECHANISM [9]. CASE FOR 80 L/MIN, 5 MG/L, AND 30 °C USED AS AN EXAMPLE.

This phenomenon might be caused by the differences in the filter cakes, as the formation of a filter cake has been found to be almost nonexistent at low contamination levels; when the solids account for less than 0.1 vol. % [10]. However, even a contamination level of 2 mg/l would typically be considered high for fluid power applications. These findings indicate that different particle sizes cannot be deemed as the sole factor when the filtration efficiency is concerned.

The Equation (6) for the "packed" mass was used in Equation (13) so that the calculated pressure drop would rise relatively faster at lower contamination levels versus higher levels, based on the findings from Figures 4 and 5. This was done so that the different coefficients in Equation (13) could be written without the contamination level, so that the function could work with parameters that vary during filtration, and a contamination level of some particular moment should not have as major impact on the pressure drop at some particular moment as the fluid flow rate or viscosity. However, it should be noted that Equation (6) for the packed mass is used for mainly practical purposes in this paper. Confirmation of whether the filter's actual dirt holding capacity is affected by the oil contamination level would require a microscopic examination of the filter elements after each filtration process. In addition, as careful laboratory conditions were the basis of this study, further confirmation of Equation (13) would require additional field experiments.

Nevertheless, in real systems where the flow conditions are stable, the laboratory results should be quite relevant. For example, oil flow rate through filters in central lubrication of constant-speed machinery is likely to vary much less than that in hydraulic circuits involving big actuators and varying work cycles.

## CONCLUSIONS

This study has been done as part of the initial research in a project that is aiming to develop a smart oil filter that could predict its remaining lifetime. A smart filter could prevent unnecessary filter replacements, or downtime due to an unexpected filter failure. For this study, hydraulic glass fiber filters were subjected to a stream of contaminated hydraulic oil. Based on these experiments, Equation (13) was derived in this study to estimate the pressure drop development over a filter element from the fluid flow rate, temperature and gravimetric contamination level. The equation can predict the development of the pressure drop with a high degree of accuracy for the particular filter type that was used in this study. Clear correlations between the filter's longevity with respect to presented mass were observed as well. With presented mass, the pressure drop over the filter increased faster when the flow rate and viscosity were higher, and when the contamination level was lower.

Future prospects for the project include additional laboratory experiments with varying conditions, such as a flow rate that varies during experiments. Different size particle distributions will be experimented with as well.

#### ACKNOWLEDGEMENTS

This work was made as a part of a Finnish research consortium - INTENS, hosted by VTT Oy, and funded by Business Finland (project # 7733/31/2017).

#### REFERENCES

[1] Frith, R.H. and Scot, W. (1993). Control of solids contamination in hydraulic systems – An overview. Wear, Vol. 165, pp. 69–74.

[2] Lage, J.L. (1998). The fundamental theory of flow through permeable media from Darcy to turbulence. In: Ingham, D.B. and Pop, I. (Eds.). Transport phenomena in porous media. Elsevier Science Limited, Oxford, Pergamon, 1998, pp. 1–30.

[3] Lage, J.L., Antohe, B.V., and Nield, D.A. (1997). Two Types of Nonlinear Pressure-Drop Versus Flow-Rate Relation Observed for Saturated Porous Media. Journal of Fluids Engineering, Sep 1997, Vol. 119, pp. 700–706.

[4] Dukhan, N., Picón-Feliciano, R., and Álvarez-Hernández Á.R. (2006). Air Flow Through Compressed and Uncompressed Aluminium Foam: Measurements and Correlations. Journal of Fluids Engineering, Sep 2006, Vol. 128, pp. 1004–1012.

[5] Jaisinghani, R.A. and Sprenger, G.S. (1981). Resistance to Flow of Liquids in Fibrous Beds Applied to Cartridge Filtration. Filtration & Separation, March/April 1981, pp. 131– 134. [6] Rinkinen, J., Laukka, J., and Karinen, K. (1999). Online condition diagnosis of hydraulic filter in hot strip mill. The Sixth Scandinavian International Conference on Fluid Power, SICFP'99. Tampere, Finland. 26-28.5.1999, pp. 635–649.

[7] Gorle, J.M.R., Heiskanen, V-M., Nissi, S., and Majas, M. (2018). Effect of temperature, contamination and flow rate on hydraulic filtration. MM Science Journal 2018, pp. 2490–2493. <u>https://doi.org/10.17973/MMSJ.2018\_10\_201852</u>.

[8] Seeton, C.J. (2006). Viscosity-temperature correlation for liquids. Tribology Letters, Vol. 22, April 2006, pp. 67–78.

[9] Iritani, E. and Katagiri N. (2016). Developments of Blocking Filtration Model in Membrane Filtration. KONA Powder and Particle Journal No. 33, 2016, pp. 179–202.

[10] Shirato, M. Aragaki, T., and Iritani, E. (1979). Blocking filtration laws for filtration of power-law non-Newtonian fluids. Journal of Chemical Engineering of Japan, Vol. 12, pp. 162–164.