

Article

Modeling of Filtration Phenomenon in Hydrostatic Drives

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Abstract: Some users consider modern hydrostatic drives and controls to be unreliable and difficult to maintain. This view is often due to operational problems caused by issues with obtaining and then maintaining the appropriate cleanliness class of the working fluid. Recommendations on the selection of appropriate filtration system elements can be found in the literature, but there is no numerical model that could be helpful in a detailed analysis of the phenomenon. In the article, the authors tried to fill the research gap regarding the lack of a filtration model based on the filtration efficiency coefficient of filter elements used in hydraulic drives and controls. The developed model allows users to determine the influence of selected filtration system parameters on the separation of contaminants by filter elements. The model is intended to help designers and users of hydraulic drives and controls in optimizing the filtration system in order to obtain and then maintain the required cleanliness class of the hydraulic fluid. This paper also includes the results of the sensitivity analysis of selected filtration-system operating parameters in terms of the highest efficiency. In order to verify the developed model, experimental tests were also carried out, with the results presented in this paper. Based on the numerical analyses and experimental studies, recommendations that may be helpful in the selection or development of filtration systems used in hydrostatic drives and controls were developed.

Keywords: hydrostatic drives; filtration; filter beta ratio; numerical model; filtration efficiency



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1. Introduction

Despite great progress in the technology of drives, users of hydrostatic drives and controls still report many failures caused by contamination of the working fluid [1–9]. Problems with obtaining and maintaining the appropriate cleanliness class during drive operation are among the most common causes of reduced durability and operational reliability of hydraulic systems [4,10–13]. Machine downtime caused by drive failures often results in the need to conduct complex and time-consuming diagnostic actions, aimed at identifying a faulty element that should then be replaced, leading to an increase in production costs and delays.

Designers and users of hydrostatic systems, wanting to increase the durability and operational reliability of these drives, should carefully analyze the factors influencing the level of working fluid contamination and the possibility of separating contaminants. The professional literature contains information on how to arrange filtration systems in hydrostatic systems, required cleanliness classes for individual drive components, the method of selecting filter elements [14–20], as well as methods of monitoring working fluid parameters [21–24]. However, this information often does not take into account the environmental conditions of the machine's operation, the possibility of external contamination entering the drive system, changes in the parameters of filter elements during their exploitation, as well as the generation of contaminants by worn drive components. Failure to take into account the above-mentioned variable parameters results in problems with

obtaining, and then maintaining, the required cleanliness class of the working fluid, which may consequently lead to failure. There is currently no quantitative analysis regarding the influence of filtration system parameters on the quality of contaminant separation in the literature. There is information that increasing the efficiency of contaminant separation can be achieved by increasing the fluid flow through the filter element [25,26]. However, there is no information on how much the flow through the filter should be increased in order to, for example, halve the number of contaminants.

Bearing in mind the operational problems of users of hydrostatic drives and controls, related to keeping the working fluid appropriately clean, and noting a gap in the literature, the article's authors decided to develop their own filtration model, and then conduct experimental research aimed at validating the developed model. Based on the obtained results of theoretical considerations and experimental research, conclusions were drawn up aimed at helping designers and users of hydrostatic drive systems in the selection or modification of filtration systems to improve the separation of contaminants.

It is generally accepted that, when selecting a filter element, the most important factor is the beta filtration coefficient, β_x [15,16,19]. The results presented in this paper, analyses of the developed mathematical model of the filtration process, and experimental tests suggest that, besides the coefficient β_x , additional factors influence the achievement and maintenance of the appropriate cleanliness class of hydraulic fluids, including parameters of filtration systems that are perhaps even equally important.

2. Developed Filtration Model

To determine the impact of selected filtration system parameters on the separation of contaminants in hydrostatic drives, experimental or model studies can be carried out [27–33]. Experimental analyses involve the verification in various arrangements of filters with different parameters in the tested drive systems with different compositions, to which contaminants are introduced. This solution is expensive, time-consuming, and has numerous functional limitations. In computer-aided model tests, it is possible to analyze the impact of changes in selected parameters of the filtration system, whose composition can be changed, with the possibility of reducing particles in the working fluid. Such analyses have a much wider range of possibilities, are much cheaper to implement, and are also faster. The problem, however, lies in the mathematical model of the filtration process. Due to the lack of appropriate models for the described process on the market, it was decided to develop our own [34,35].

One of the important parameters of filter elements is the beta filtration coefficient, β_x . This parameter is determined on the basis of a multi-pass test (in accordance with ISO 16889 [19]), which determines the ability of the filter element to separate particles of given sizes. The higher the value, the more thoroughly the filter removes particles. The filtration coefficient is defined by Equation (1):

$$\beta_x = \frac{N_u}{N_d} \quad (1)$$

where

- N_u —The number of solid particles in the fluid at the filter entrance;
- N_d —The number of solid particles in the fluid at the filter outlet;
- x —Minimum size of counted particles [μm].

A parameter directly related to the coefficient β_x is filtration efficiency, n_f , which can be viewed as the probability of capturing particles flowing through the filter (Figure 1). The relationship between β_x and n_f is expressed by the following formula:

$$n_f = \left(1 - \frac{1}{\beta_x}\right) \cdot 100\% \quad (2)$$

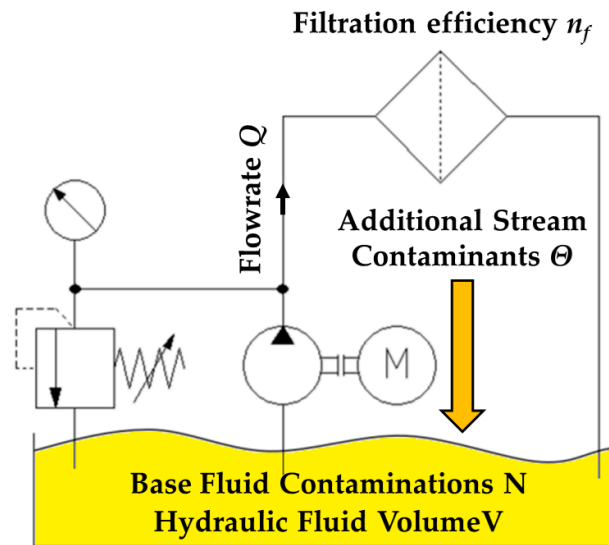


Figure 1. Simplified hydraulic diagram of the analyzed hydraulic system.

The developed filtration model is based on the following assumptions:

- The effectiveness of a filter is equal to the probability of capturing particles of size x or larger;
- The particles are evenly distributed in the fluid (complete homogenization);
- Internal and external particles with a total stream Θ enter into the hydraulic fluid, with the particle stream assumed to be constant;
- Particles appear evenly throughout the entire hydraulic fluid volume;
- The entire fluid volume from the tank passes through the filter.

The probability of capturing a particle per unit of time λ can be taken as [3]

$$\lambda = \frac{n_f}{100\%} \cdot \frac{Q}{V} \quad (3)$$

where

- Q —Flow rate through the filter [dm^3/min];
- V —Total hydraulic fluid volume [dm^3].

Assuming a low value of λ , the formula for the number of contaminants N in hydraulic fluid can be defined as follows:

$$\frac{dN}{dt} = -\lambda N + \Theta \quad (4)$$

where

- Θ —Stream contaminants [particles/s].

Combining Equations (3) and (4), we obtain the following:

$$\frac{dN}{dt} = \frac{-n_f}{100\%} \cdot \frac{Q}{V} N + \Theta \quad (5)$$

In general, the factors determining the number of contaminants in accordance with (5) are not constant. For example, filtration efficiency may depend on the degree of wear of the filter element. The volume of filtered fluid or the fluid flow rate through the filter may also change. Determining the number of contaminants by taking into account the variability of coefficients n_f , Q , V , and Θ would require the use of advanced numerical methods to solve Equation (5). Therefore, in a further analysis, a simplified filtration model was adopted, in which the above-mentioned parameters have constant values. In accordance

with the adopted simplification, the solution of Equation (5) is a special integral over the time interval from 0 to t , defined as

$$N = N_0 e^{\frac{-n_f}{100\%} \cdot \frac{Q}{V} t} + \Theta \frac{V \cdot 100\%}{n_f \cdot Q} \left(1 - e^{\frac{-n_f}{100\%} \cdot \frac{Q}{V} t} \right) \quad (6)$$

where

- N_0 —Initial number of contaminants in the analyzed fluid.

Determining the total number of contaminants N is not easy. It is more preferable to transform Formula (6) into a form from which the particle concentration, ρ_c , is determined in the assumed volume unit. Any volume value can be set as the volume unit, e.g., 100 cm³. As a result of this, the user can directly link the obtained result of the analyses carried out in accordance with generally accepted cleanliness classes, e.g., ISO 4406:1999 or NAS 1638 [19]. After transformation, the equation takes the following form:

$$\rho_c = \rho_{c0} e^{\frac{-n_f}{100\%} \cdot \frac{Q}{V} t} + \frac{\Theta \cdot 100\%}{n_f \cdot Q} \left(1 - e^{\frac{-n_f}{100\%} \cdot \frac{Q}{V} t} \right) \quad (7)$$

where

- ρ_{c0} —Initial particle concentration.

For Equations (6) and (7), it is possible to enter a filtration time constant, T_f , as

$$T_f = \frac{V \cdot 100\%}{n_f \cdot Q} \quad (8)$$

It should be noted that for filtration times $t \gg T_f$, the particle concentration is simplified to the following value:

$$\rho_c = \frac{\Theta \cdot 100\%}{n_f \cdot Q} \quad (9)$$

From (9), it follows that for a given particle stream Θ , the particle concentration can be reduced by increasing the filter efficiency, n_f , or by increasing the flow rate through the filter Q .

3. Analysis of the Mathematical Model of Filtration

The filtration model presented in Equation (7) should not be identified with a first-order inertial object, although one of the adopted model's elements is the filtration time constant, T_f . Treating the model described by Equation (7) as if it were similar to a first-order inertial object could lead to the conclusion that, after a filtration time greater than three to five time constants, the highest possible purity of the filtered fluid will be achieved, regardless of its initial contamination and environmental conditions.

To verify the above, it was decided to perform a simple calculation experiment, namely, determine the time histories of particle concentration for four cases selected so that the constant according to Equation (8) is the same for all of them. In short, these would be four filtration cases in the same hydraulic system with a filter element of the same efficiency.

For the accepted assumptions, filtration time constant T_f equals 240.8 [s]. The obtained results are presented in Figure 2.

As can be seen in Figure 2, reaching a set particle concentration requires a filtration time that is dependent, apart from the filtration constant according to Equation (8), on the initial particle concentration as well as the stream of contaminants entering the fluid during filtration.

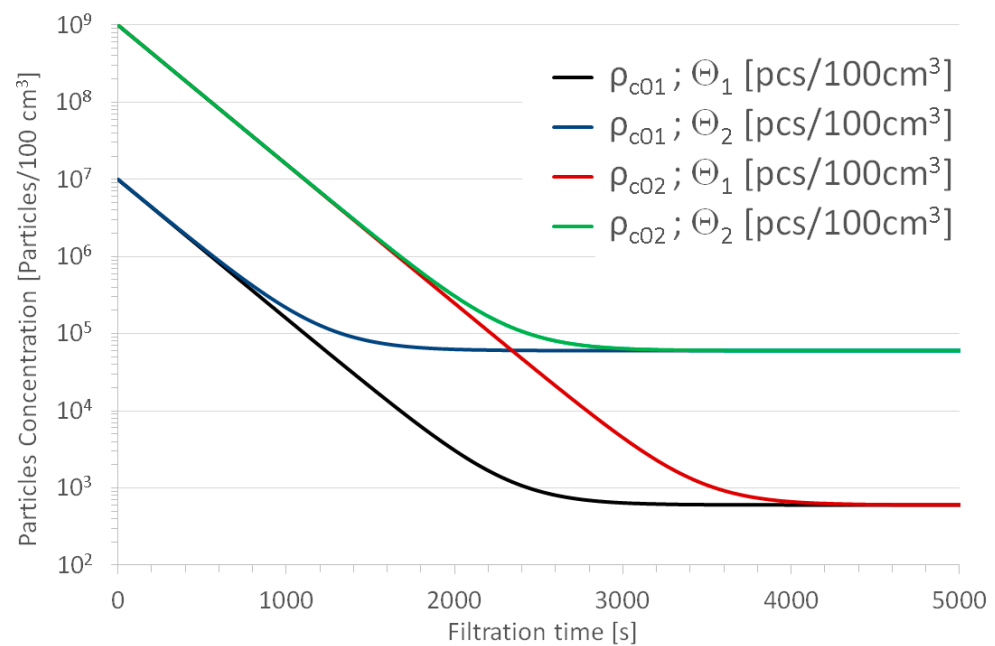


Figure 2. Calculation experiment results for the assumed filtration process conditions (Table 1).

Table 1. The assumed values in the calculation experiment.

Parameter	Value
Flow rate through filter	$Q = 10 \text{ [dm}^3/\text{min}]$
Fluid volume in the tank	$V = 40 \text{ [dm}^3]$
Filtration efficiency factor	$n_f = 0.9967^*$
Initial particle concentration (min)	$\rho_{c01} = 10^7 \text{ [particles/100 cm}^3]$
Initial particle concentration (max)	$\rho_{c02} = 10^{12} \text{ billion [particles/100 cm}^3]$
Stream of contaminants (min)	$\Theta_1 = 10^3 \text{ [particles/s]}$
Stream of contaminants (max)	$\Theta_2 = 10^5 \text{ [particles/s]}$

* The value corresponding to the coefficient β of filter 300.

According to the results shown in Figure 2, the following practical tips can be derived:

- Cleaner hydraulic fluid requires less filtration time in the same hydraulic system and the same operating environment.
- Long-term filtration of fluid in a hydraulic system operating in a difficult environment, that is, in a system exposed to a strong stream of contaminants entering the hydraulic fluid, is not justified. Such a system will reach the set particle concentration faster than a twin system operating in a more favorable environment. Of course, the values of particle concentration (i.e., numbers of contaminant classes) will vary for such systems.
- It is advantageous if, during filtration, the hydraulic fluid condition is continuously monitored with a device for monitoring the cleanliness and condition of the hydraulic fluid. In such a case, the operator should observe whether the number describing the contaminant class in the selected size group decreases by 1 at regular intervals. This means that the filtration process is in the descending part, as in Figure 2, and filtration should be continued, because even better fluid purity can be achieved.

As part of the numerical experiment, it was decided to determine which of two filtration strategies in the hydraulic system would lead to better results:

- Filtration using a fine filter element (e.g., absolute filter of $6 \mu\text{m}$ with the coefficient $\beta_{6\mu\text{m}} = 1000$) at a lower flow rate through the filter;
- Filtration using a less precise filter element (e.g., absolute filter of $10 \mu\text{m}$ with the coefficient $\beta_{10\mu\text{m}} = 1000$) at a higher flow rate through the filter.

The particle concentration for particles from 4 μm is analyzed, for which the efficiency of the 6 μm filter can be assumed as 98%, while the efficiency of the 10 μm filter can be assumed as 75%. The assumed values in the calculation experiment are presented in Table 2.

Table 2. The assumed values in the calculation experiment.

Parameter	Value
Flow rate through the 6 μm filter	$Q_{6\mu\text{m}} = 5 \text{ [dm}^3/\text{min}]$
Flow rate through the 10 μm filter	$Q_{10\mu\text{m}} = 10 \text{ [dm}^3/\text{min}]$
Fluid volume in the tank	$V = 40 \text{ [dm}^3]$
Filtration efficiency factor	$n_f = 0.9967^*$
Initial particle concentration	$\rho_{c0} = 10^7 \text{ [particles/100 cm}^3]$
Stream of contaminants (min)	$\Theta_1 = 10^3 \text{ [particles/s]}$

* The value corresponding to the coefficient β of filter 300.

The calculation results are shown in Figure 3. In the obtained waveforms, a logarithmic scale with a base of 2 was adopted for the particle concentration axis. Thanks to this, a change in the particle concentration value by one division corresponds to a change in the number of contaminants by one class.

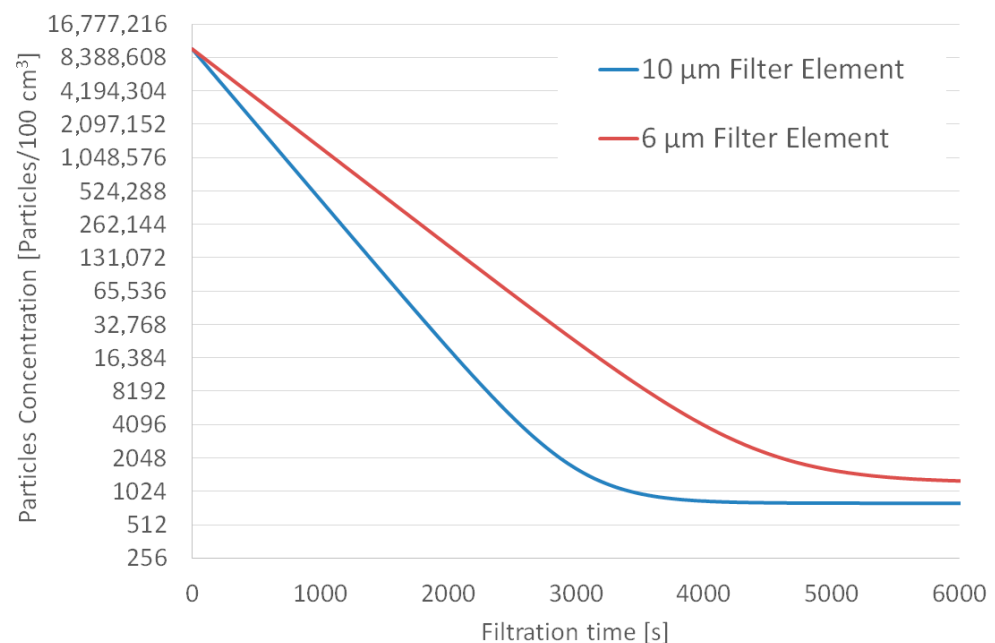


Figure 3. Results of calculations of the particle concentration in the fluid carried out for two filtration process solutions: a 10 μm filter element with greater flow rate; a 6 μm filter element with half the flow rate.

The obtained results, as shown in Figure 3, suggest that a better solution is to use a less precise filter, through which a large stream of fluid will be directed, than adopting a fine filter element with reduced flow (e.g., due to the greater hydraulic resistance of such a filter). In the discussed case, the application of a 10 μm filter element with a flow rate of 10 dm^3/min would allow hydraulic fluid up to one class cleaner to be obtained in a time 33% shorter than a 6 μm filter element with a flow rate of 5 dm^3/min .

4. Sensitivity Analysis for the Adopted Filtration Model

Equation (7) answers the question: what can be done to reduce the number of contaminants contained in the hydraulic fluid? However, it does not specify the parameter change that brings the best result in contaminant separation. To determine which filtration system

parameter should be changed first, a relative sensitivity function was determined for the adopted filtration model.

The relative sensitivity function indicates how strongly changes in individual parameters affect the system properties or the values of quantities describing the phenomena. The relative sensitivity function of the phenomenon described by function F to changes in parameter “ y ” is defined by

$$S_y^F = \frac{\partial \ln F(y)}{\partial \ln y} = \frac{y}{F(y)} \cdot \frac{\partial F(y)}{\partial y} \quad (10)$$

The form of the relative sensitivity function was determined for two cases:

- An unsteady state of the particle concentration number ($t < 3T_f$);
- A set state of the particle concentration number ($t \gg 3T_f$).

It was assumed that the sensitivity of the particle number to the following changes would be examined:

- Filter filtration efficiency (i.e., changing the filter);
- Flow rate of the hydraulic medium through the filter (for a set state);
- The ratio of the hydraulic medium flow rate through the filter to the hydraulic fluid volume in the system (for an unsteady state);
- Contaminant stream.

It seems that analyzing the sensitivity of the hydraulic medium purity to changes in the stream of contaminant particles is a purely theoretical issue for the user of a specific system. Most frequently, it has no influence on this parameter. However, this statement is not entirely true. For example, in conditions of severe environmental pollution, special design solutions can be adopted, e.g., actuators, increasing the efficiency of removing contaminants stuck to piston rod surfaces. Moreover, the presented sensitivity analysis can illustrate the impact of changing the drive operating conditions on the cleanliness of the hydraulic medium.

Relative sensitivity functions for the filtration process in a transient state, described by Equation (10), take the following forms:

- For the influence of filtration efficiency:

$$S_p^{\rho_c} = \frac{-p \left[\frac{\Theta}{p^2 Q} + e^{-\frac{pQ}{V}t} \left(\rho_{c0} \frac{Q}{V} + \frac{\Theta}{p^2 Q} + \frac{\Theta t}{pV} \right) \right]}{\rho_{c0} e^{-\frac{pQ}{V}t} + \frac{\Theta}{pQ} \left(1 - e^{-\frac{pQ}{V}t} \right)} \quad (11)$$

- For the influence of the flow rate of the fluid contained in the system through the Q/V filter:

$$S_{Q/V}^{\rho_c} = \frac{-Q p t e^{-\frac{pQ}{V}t} \cdot \left(\rho_{c0} - \frac{\Theta}{pQ} \right)}{V \left(\rho_{c0} e^{-\frac{pQ}{V}t} + \frac{\Theta}{pQ} \left(1 - e^{-\frac{pQ}{V}t} \right) \right)} \quad (12)$$

- For the influence of a stream of contaminants Θ :

$$S_{\Theta}^{\rho_c} = \frac{\Theta \left(1 - e^{-\frac{pQ}{V}t} \right)}{pQ \left(\rho_{c0} e^{-\frac{pQ}{V}t} + \frac{\Theta}{pQ} \left(1 - e^{-\frac{pQ}{V}t} \right) \right)} \quad (13)$$

As can easily be seen, the values of the relative sensitivity function for the first two parameters will be negative (the value of the relative sensitivity function for Q/V may be positive under certain conditions), which means that increasing the filter efficiency and the Q/V ratio will result in a reduction in the number of contaminants in the hydraulic fluid.

In the case of a contaminant stream, a positive value will be obtained, meaning that a larger contaminant flow will result in a greater number of solid particles in the hydraulic fluid.

To facilitate the interpretation of dependencies 11 ÷ 13, it is possible to use examples. It was assumed that the filtration process is carried out in a system with the parameters presented in Table 3.

Table 3. The assumed values in the calculation experiment.

Parameter	Value
The probability of capturing a particle by the filter	$p = 0.8$
Flow rate through the filter	$Q_{10\mu m} = 3 \text{ [dm}^3/\text{min]}$
Fluid volume in the tank	$V = 10 \text{ [dm}^3]$
Filtration efficiency factor	$n_f = 0.9967^*$
Initial particle concentration	$\rho_{c0} = 10^5 \text{ [particles/100 cm}^3]$
Stream of contaminants	$\Theta_1 = 10^4 \text{ [particles/s]}$

* The value corresponding to the filter efficiency $\beta_x = 5$.

An analysis of the relative sensitivity function of the particle concentration on the probability of particle capture by the filter was performed for four values of parameter p : 0.8; 0.6; 0.4; and 0.2, which correspond to the coefficient β_x equal to 5; 2.5; 1.667; and 1.25. This is illustrated in Figure 4.

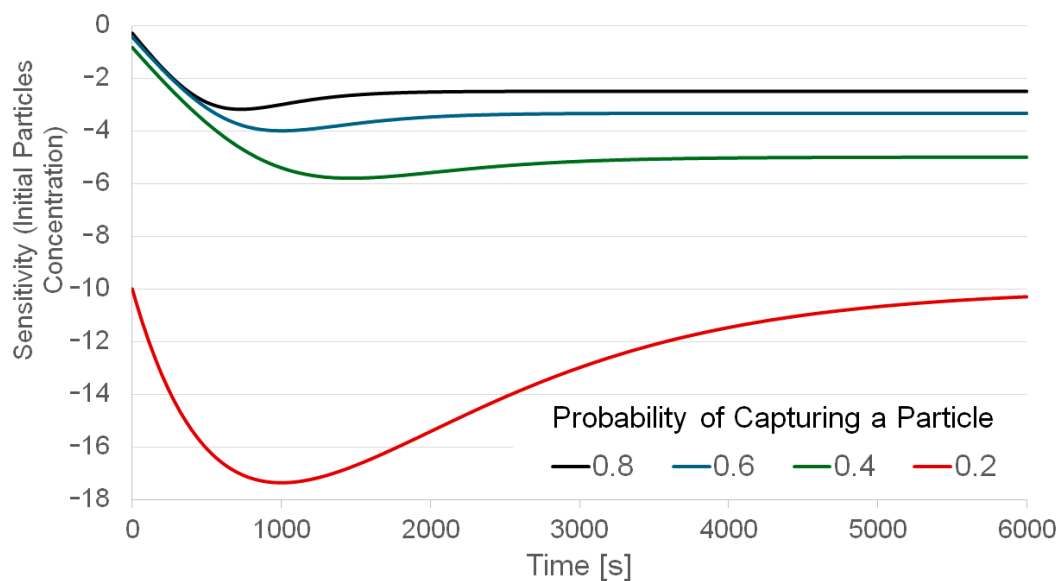


Figure 4. The course of the relative sensitivity function of the particle concentration on the probability of capturing particles by the filter.

The results presented in Figure 4 should be interpreted accordingly. It is obvious that a negative value of the relative sensitivity function indicates that the particle concentration in the filtered fluid will decrease during filtration.

What is important is how to interpret a large absolute value of the sensitivity function for a low probability of particle capture by the filter. This should be understood to mean that greater changes in the particle concentration in the filtered fluid will be noticed when changing filters with very low efficiency, for example, when replacing a filter with efficiency $\beta_x = 1.25$ to a filter with a higher β_x coefficient.

Of course, practitioners may note that no manufacturer on the filter market offers products with such poor efficiency. This is true in the context of filter efficiency related to a dedicated particle size. However, filters also capture particles smaller than those

declared by the manufacturer, but they perform this with less efficiency as these particles become smaller.

Next, the relative sensitivity function of the particle concentration on the ratio of the flow rate through the filter and the fluid volume in the system was examined. The analysis was performed for four Q/V parameter values, namely 0.005 [1/s], 0.015 [1/s], 0.045 [1/s], and 0.135 [1/s]. The Q/V parameter should be understood as the flow rate of the fluid contained in the system through the filter. This is illustrated in Figure 5.

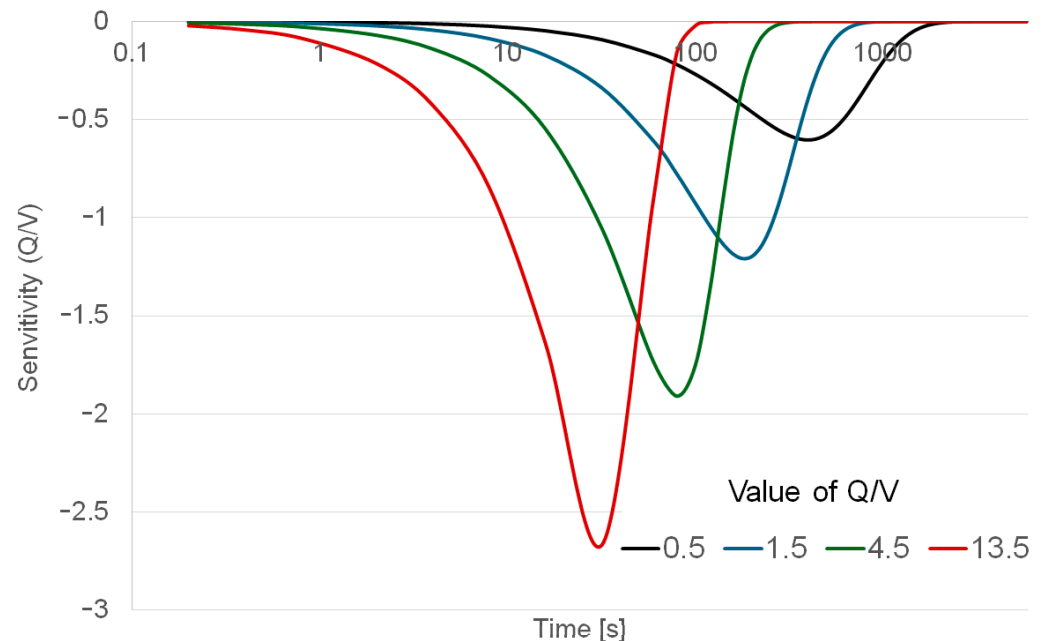


Figure 5. The course of the relative sensitivity function of the particle concentration to the Q/V parameter (fluid flow rate through the filter).

The negative value of the relative sensitivity function of the particle concentration to the Q/V parameter observed in Figure 5 indicates a decrease in the number of impurities in the filtered fluid, while the increase in absolute value with the increase in the Q/V parameter proves that the velocity of fluid purification during filtration is also related to this parameter.

Finally, the relative sensitivity function of the particle concentration to the stream of contaminants entering the filtered fluid was examined. The analysis was performed for four parameter values Θ , namely 1×10^3 [particles/s], 1×10^4 [particles/s], 1×10^5 [particles/s], and 1×10^6 [particles/s]. Parameter Θ depends, of course, on the environment in which the hydraulic system operates, but also on the technical condition of its components. Therefore, it is a highly individualized parameter. The sensitivity function curves presented in Figure 6 should be interpreted in such a way that the greatest changes in the particle concentration in the initial phase of the filtration process will be visible for a system exposed to extremely unfavorable conditions (a high value of the contaminant stream Θ).

It should be noted that dependencies (11 ÷ 13) may provide unexpected results if parameter values describing the filtration process that are unusual for most hydraulic systems are assumed.

Assuming a very low probability of capturing particles, which happens when low precision filters are used (e.g., 16 μm filters) to capture fine particles ranging in size from 4 μm to 6 μm , an unexpected course of the relative sensitivity function can be observed, as presented in Figure 7.

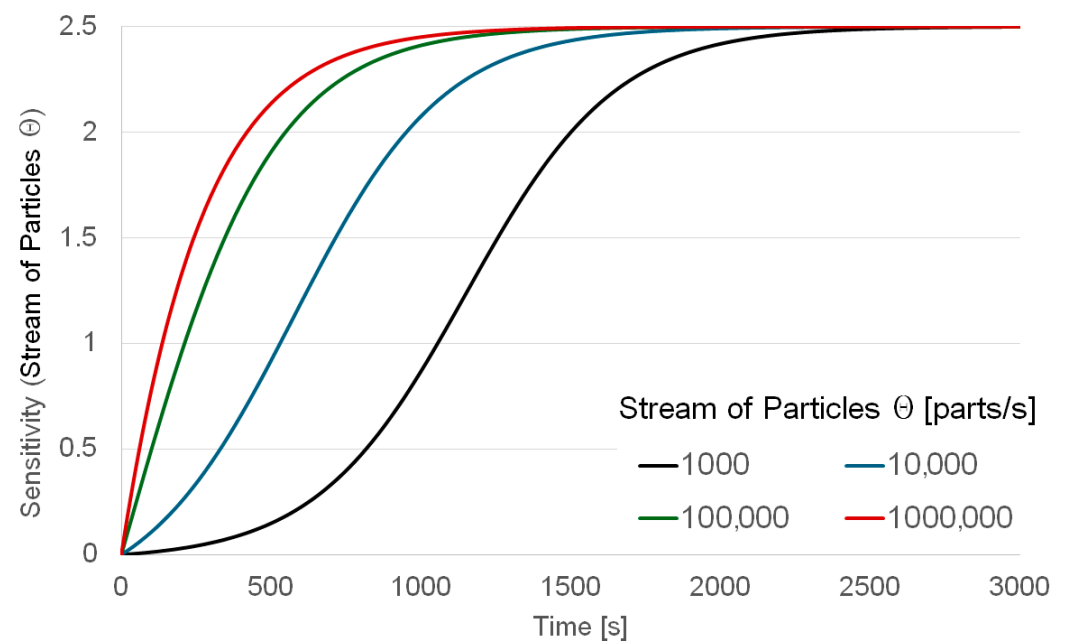


Figure 6. The course of the relative sensitivity function of the particle concentration to the contaminant stream Θ entering the filtered fluid.

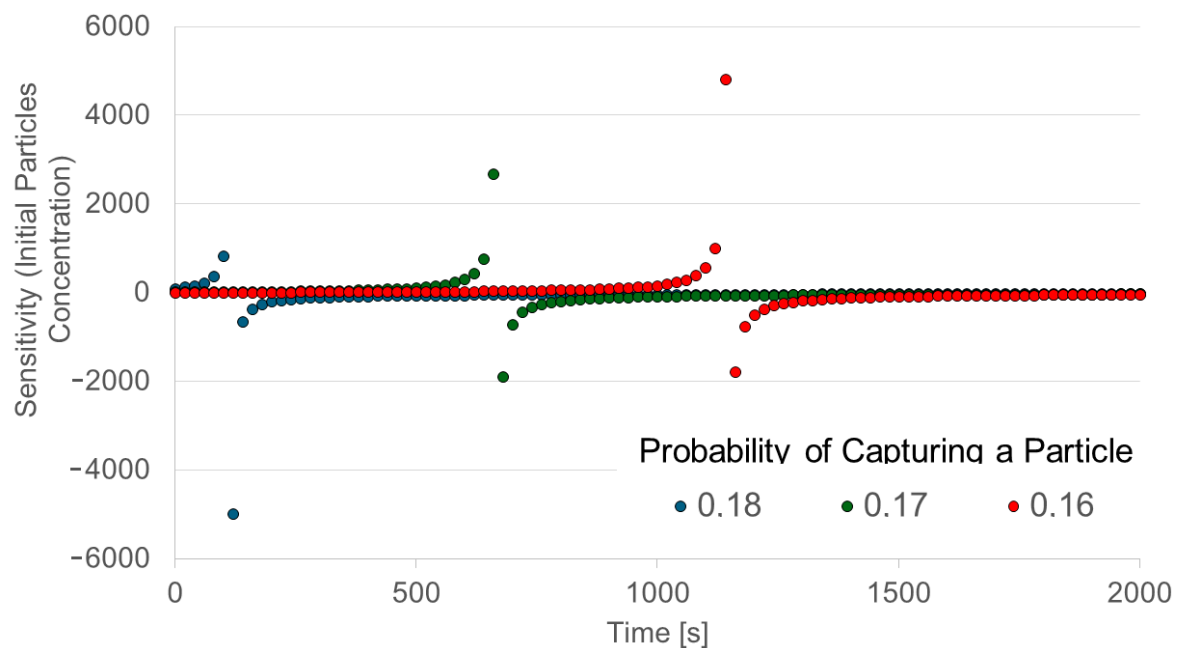


Figure 7. The relative sensitivity function course of the particle concentration on the probability of capturing particles by the filter at small values of this probability.

In Figure 7, the lines connecting the points for which the values of the sensitivity function were calculated were intentionally suppressed to indicate peculiarities in the course of the sensitivity function. Initially, the relative sensitivity values are positive and increase, but reach large negative values after passing the peculiarities and then asymptotically tend towards the established negative value.

These “strange” results should be interpreted in such a way that during filtration carried out with a low-precision filter, and therefore of low efficiency in capturing small particles, the concentration of fine particles will increase until saturation is reached. In

this state, particles of fine impurities entering the fluid in a high-intensity stream Θ will be captured on an ongoing basis.

In the case of filtration in a system characterized by a very low ratio of the flow rate through the filter Q to the fluid volume in the system V , the obtained results are shown in Figure 8.

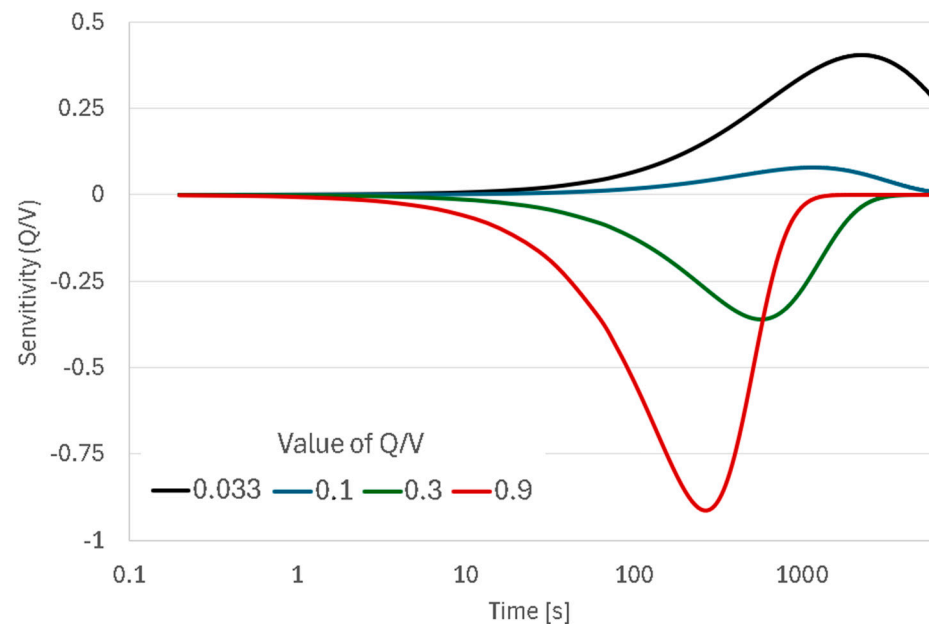


Figure 8. The course of the relative sensitivity function of particle concentration to the Q/V parameter (fluid flow rate through the filter) for small Q/V values.

As can easily be observed, adopting very small values of the Q/V parameter results in a positive value of the relative sensitivity function of the particle concentration to this parameter. The limit value of the Q/V parameter resulting in a positive value of the relative sensitivity function depends on the initial particle concentration ρ_{c0} in the filtered fluid. The higher the initial particle concentration, the lower the value of the Q/V parameter while maintaining a negative value of the sensitivity function.

It should be understood that, for the filtration process carried out in such conditions, an increase in the particle concentration will initially be observed until a steady state is reached. It is obvious that we should avoid such cases, which in practice may occur in hydraulic systems with bypass filtration, in which the flow rate in the filtration circuit is too low.

The filtration process, apart from filtration carried out as an intervention, is carried out for hydraulic systems throughout the operation of the drive system. Hence, in practice, the impact of the above-mentioned factors should be considered after a sufficiently long filtration period, for which it will be possible to recognize the achievement of a steady-state system.

The influence of filtration efficiency is presented in the equation:

$$S_p^{\rho_c} = \frac{p}{\frac{\Theta}{p^2 Q}} \left(\frac{-\Theta}{p^2 Q} \right) = -1 \quad (14)$$

where p is the probability of capturing a particle. For the influence of the Q/V parameter, the relative sensitivity function will contain the following expression:

$$\lim_{t \rightarrow \infty} (Q p t \cdot e^{-\frac{p Q}{V} t}) = \lim_{t \rightarrow \infty} (a t \cdot e^{-b t}) = 0 \quad (15)$$

Therefore,

$$\lim_{t \rightarrow \infty} (S_{Q/V}^{\rho_c}) = \lim_{t \rightarrow \infty} \left(\frac{-Qpte^{-\frac{pQ}{V}t} \cdot \left(\rho_{c0} - \frac{\Theta}{pQ} \right)}{V \left(\rho_{c0}e^{-\frac{pQ}{V}t} + \frac{\Theta}{pQ} \left(1 - e^{-\frac{pQ}{V}t} \right) \right)} \right) = 0 \quad (16)$$

For the influence of a stream of contaminants Θ is presented in the equation

$$S_{\Theta}^{\rho_c} = \frac{\Theta}{pQ \frac{\Theta}{pQ}} = 1 \quad (17)$$

The way of interpreting relationships (14) and (16) is obvious. The negative value of relationship (14) indicates that the better the filter (i.e., a filter with a greater probability of capturing particles), the lower the particle concentration in the filtered fluid after a sufficiently long filtration time.

A positive value of relationship (17) indicates that, in the steady state of the filtration process, the particle concentration in the fluid will be higher if the hydraulic system is exposed to a larger stream of contaminants.

A hasty interpretation of the results described by Equation (16) could lead to the conclusion that the value of the Q/V parameter is not important for the filtration process. However, a transient state analysis of the filtration processes, whose courses are illustrated in Figure 4, indicates that the Q/V parameter should be maximized. Increasing the fluid flow rate through the filter has the most beneficial effect on the contaminant separation process.

5. Experimental Studies of Filtration in Hydraulic Drives

In the next stage of the analyses, the focus was on bench tests of the influence of selected filtration system parameters on the removal of contaminants.

The set-up (Figure 9), where filtration was tested in an independent filtration system, consisted of the following:

- A universal hydraulic power supply with a special design dedicated to testing hydraulic elements, especially filters with a two-part tank containing 12 dm³ of contaminated mineral hydraulic oil in the part used;
- A KLEENOIL 1S filter unit with a single SDU-H8 filter with an SDFC element and pump with a capacity of 120 dm³/h [34];
- A CS1000 series contamination count sensor [35] together with a HYDAC HMG4000 recorder;
- An OPCom portable device for measuring contamination, manufactured by ARGO HYTOS [36].

The SDFC filter element is a cellulose insert, which, according to the manufacturer, can capture pollution particles of 1 µm with satisfactory effectiveness, although it achieves high filtration efficiency for contaminants of 4 µm, namely $\beta_{4\mu m} \geq 200$.

The CS1000 and OPCom devices can simultaneously record contaminant class values according to the ISO 4406 and SAE AS4059 standards [19]. Additionally, CS1000 instrument readings are accurate to a tenth of the contaminant class, and the OPCom device also records the absolute concentration of the number of contaminants in four size groups (4 µm; 6 µm; 14 µm; and 21 µm). The portable IcountOS device, shown in Figure 9 and manufactured by Parker Hannifin, enables measurement according to ISO 4406 and NAS 1638 [19] with a resolution of one class, which was considered insufficient and its recommendations were not used.

Figure 10 shows the particle concentrations recorded with the OPCom device in four size groups in accordance with ISO 4406 and SAE AS4059. The unit of time was one fluid

cycle, i.e., the time during which theoretically the entire fluid volume in the tank flows through the filter, which in the described case was

$$T_{ofc} = \frac{V_{fluid}}{Q_{pf}} = \frac{12 \text{ dm}^3}{2 \text{ dm}^3/\text{min}} = 6 \text{ min} \quad (18)$$

where

- T_{ofc} —One fluid cycle [min];
- V_{fluid} —Fluid volume in the tank [dm^3/min];
- Q_{pf} —Fluid flow rate through the filtration station [dm^3/min].



Figure 9. The test stand.

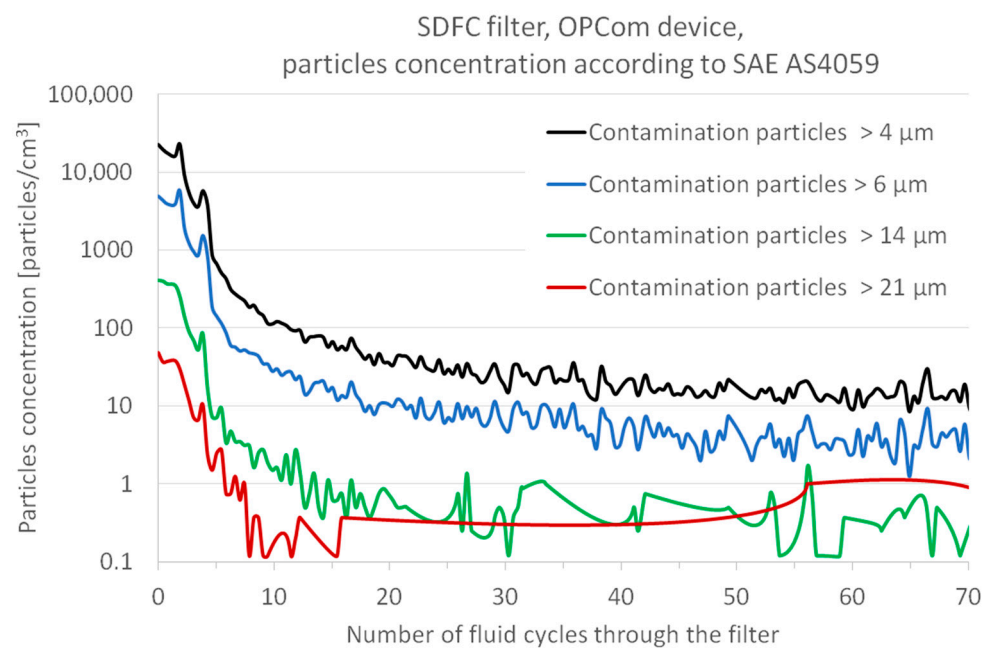


Figure 10. Changes in the particle concentration in particular size groups, measured using the OPCom device.

The waveforms presented in Figure 10 are consistent with the adopted filtration model. Analyzing them, a logarithmic decrease in the particle concentration for all groups of particle sizes can be observed. The initial plateau in the waveforms results from the time delay between starting the recorders and the filtration unit. The final peaks visible in the waveforms for the 4 μm and 6 μm size groups result from the reverse order of turning off the test stand elements.

The experimental results presented in Figures 10–12 are corresponding with model prediction results. The highest separation of contaminants in each size group is achieved in the first few cycles of the filtration process, i.e., the first 10 cycles of the liquid passing through the filter. Furthermore, the efficiency of removing contaminants from the liquid is lowered when approaching the asymptotic limit of filter capability to remove the contaminants for each size group. The specific maximal filtration limit of the filter cartridge is approached after approximately 20 cycles. To verify the measurement results obtained with the OPCom device, they were compared with the CS1000 device manufactured by HYDAC Germany (Sulzbach, Germany) results. Figure 11 shows the results of measurements of the number of contamination class according to SAE AS4059 obtained using the OPCom device, while Figure 12 presents those measured with the CS1000 device.

Comparing the waveforms presented in Figures 11 and 12, and especially the values of the numbers of contaminants in individual size groups in the steady state of the tested process, it can be seen that for the size groups 4 μm , 6 μm , and 14 μm , the contamination class numbers range from 0 to 2 according to the results from both measuring instruments. For the contaminant size range of 21 μm , the oscillations of the measurement results are greater, from 0 to 4, which was indicated by both the OPCom and CS1000 devices.

The greater amplitude of indications for the 21 μm contamination size range is due to the fact that, according to SAE AS4059 for particles from 21 μm in size, class 0 means a content of up to 10 particles in 100 cm^3 (compared to 54 particles for sizes from 14 μm , for example) and class 4 means a content of up to 152 particles in 100 cm^3 (compared to 864 particles for sizes from 14 μm). Therefore, it should not be surprising that the measurements are more sensitive in the largest contaminant size class.

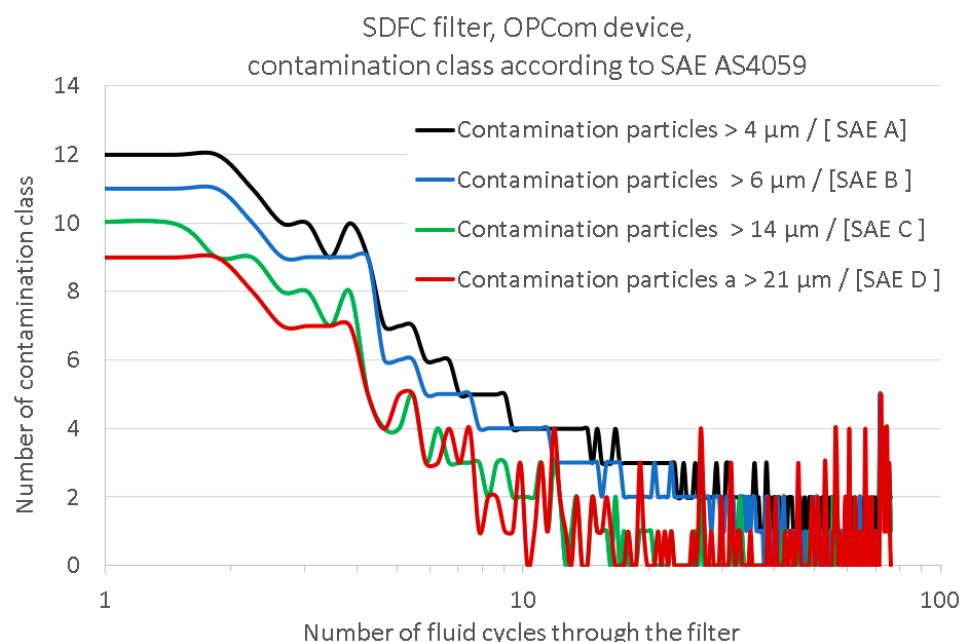


Figure 11. Contamination class number measurement results according to SAE AS4059 obtained using the OPCom device.

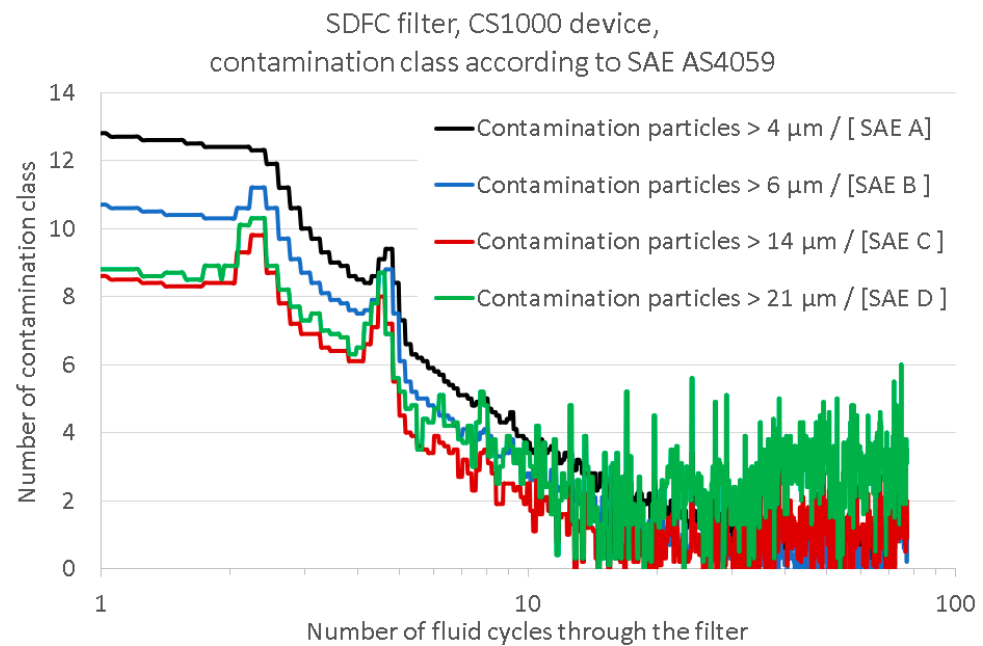


Figure 12. Contamination class number measurement results according to SAE AS4059 obtained using the CS1000 device.

According to Figure 10, it can be assumed that the steady state of the filtration process, expressed in the number of cycles of the working medium according to Equation (10), was, respectively, as follows:

- Seven cycles for contamination from 21 μm ;
- Eighteen cycles for contamination from 14 μm ;
- Forty-seven cycles for contamination from 6 μm ;
- Fifty cycles for contamination from 4 μm .

At the same time, the particle concentration values averaged over the range of 58 to 68 fluid cycles were as follows:

- Particles/ cm^3 for contamination from 21 μm ;
- Particles/ cm^3 for contamination from 14 μm ;
- Four particles/ cm^3 for contamination from 6 μm ;
- Fourteen particles/ cm^3 for contamination from 4 μm .

Assuming that, according to relationship (8) and the results presented in Figure 2, the time of the filtration process necessary to reach a steady state depends on the following:

- The probability of capturing a particle by the filter;
- Fluid volume in the system (tank);
- Flow rate through the filter;
- Initial particle concentration;
- Stream of contaminants entering the fluid during filtration.

It can be noted that the obtained results of the experimental study seem to confirm the theoretical predictions. It should be assumed that the contaminant streams in the 4 μm and 6 μm size groups are many times higher than the corresponding ones in the 14 μm and 21 μm size groups—hence, the much longer filtration time necessary to remove smaller contaminants and higher values of their content in the steady state.

Using Equation (9), it is possible to determine the streams of contaminants entering the filtered fluid. Assuming for contaminants in the following size groups [19]:

- A total of 4 μm , the probability of capturing a particle $n_f = 0.995$;
- A total of 6 μm , the probability of capturing a particle $n_f = 0.996$;
- A total of 14 μm , the probability of capturing a particle $n_f = 0.999$;

- A total of 21 μm , the probability of capturing a particle $n_f = 0.9999$;
The following values of contaminant streams were obtained:
- For the size group from 4 $\mu\text{m} \rightarrow \Theta_{4\mu\text{m}} = 27820$ [particles/s];
- For the size group from 6 $\mu\text{m} \rightarrow \Theta_{6\mu\text{m}} = 7431$ [particles/s];
- For the size group from 14 $\mu\text{m} \rightarrow \Theta_{14\mu\text{m}} = 579$ [particles/s];
- For the size group from 21 $\mu\text{m} \rightarrow \Theta_{21\mu\text{m}} = 233$ [particles/s].

The fact that the initial concentrations of finer particles are also higher is a well-known fact to users of hydraulic systems.

The courses of particle concentrations obtained during the experimental study presented in Figure 10 do not contain a clearly straight (for the logarithmic scale of the particle concentration axis) initial part, as is the case in Figure 2. Without more detailed tests, it is difficult to interpret this discrepancy, but it should be borne in mind that the experimental tests were carried out for a hydraulic fluid in which most of the contaminants were water particles and not solid particles. The paper's authors do not know whether the cellulose SDFC filter element used is as effective at capturing water when it is heavily polluted as when it is new.

It can undoubtedly be said that the obtained results indicate the importance of drying, which should precede the fluid filtration, in the treatment of anhydrous hydraulic fluid.

6. Summary

It is generally accepted that the main cause of damage to hydraulic and hydrotronic systems is the presence of solid contaminant particles in the working fluid. To improve the reliability and durability of drive components, the degree of hydraulic fluid contamination should be controlled and maintained at the required level. The most important result of these studies is the ability to determine the value of the total stream Θ of solid particles. Measurements of Θ can be performed in both laboratory and industrial environments. Knowledge of the actual value of the total stream of solid particles is necessary for optimal design of the filtration system of hydraulic systems. At the same time, it was shown that the purity of the hydraulic fluid depends on the filtration efficiency of the filter element, although there is no significant difference between filter elements with similar filtration accuracy, e.g., between 3 μm and 5 μm filter elements. This is due to the fact that even if the β_x coefficient of a less-fine filter element (e.g., 5 μm) is much lower than the 3 μm element, the probability of capturing 3 μm particles will still be close to 1. As an example, let us compare two filter elements with the coefficients $\beta_{3\mu\text{m}} = 75$ and $\beta_{5\mu\text{m}} = 75$; it can be assumed that the filtration efficiency β_x of the 5 μm element for particles of 3 μm will be no worse than 10. That is, the probability n_f of capturing particles with a size of 3 μm by a 5 μm filter element will not be less than 0.9. In comparison with $n_f = 0.9867$ for a 3 μm filter element, this is not a difference that could significantly change the particle concentration in the steady state of the filtration process.

And, most importantly, if, for the correct operation of the hydraulic system, it is necessary to maintain the particle concentration value achieved in a steady state, maintaining this condition requires continued filtration. Breaks in filtering will result in a renewed increase in the number of contaminants.

It should also be noted that the need for an emergency filtration of the hydraulic fluid, using an additional filtration unit in order to reduce the number of contaminants in the fluid to the level required for a given hydraulic system undoubtedly proves that the filtration carried out in this system is insufficient. Such a case requires an in-depth analysis of the filtration design in the system to determine whether better purity of the hydraulic fluid can be achieved, e.g., replacing filter elements in filter systems with more precise ones or, perhaps, achieving better purity with filter systems requires design changes in the problematic system.

Important tips for practitioners also come from the sensitivity analysis for the filtration process conducted in the paper. The most important of them is to continuously record the particle concentration in particular size ranges when starting the hydraulic or hydrotronic

system in the target location. Thanks to this, it will be possible to refer to the results of theoretical considerations presented in the paper and determine whether the filtration parameters in the system being started (filter element efficiency and Q/V ratio) under given conditions, that is, for the contaminant stream Θ to which the system is exposed at a given location, are sufficient.

Information about the particle concentration in the working fluid after a long system operation period is not sufficient to reliably assess the correctness of the filtration solution in this system.

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Nomenclature

N_u	The number of solid particles in the fluid at the filter entrance [-];
N_d	The number of solid particles in the fluid at the filter outlet [-];
x	Minimum size of counted particles [μm];
Q	Flow rate through the filter [dm^3/min];
V	Total hydraulic fluid volume [dm^3];
ρ_c	Particle concentration [particles/ 100 cm^3];
ρ_{c0}	Initial particle concentration [particles/ 100 cm^3];
N_0	Initial number of contaminants in the analyzed fluid;
Θ	Stream of contaminants [particles/s];
β_x	Filtration coefficient ratio [-];
n_f	Filtration efficiency;
p	Probability of capturing a particle;
T_f	Filtration time constant [s];
T_{ofc}	One fluid cycle [min];
V_{fluid}	Fluid volume in the tank [dm^3/min];
Q_{pf}	Fluid flow rate through the filtration station [dm^3/min].

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