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Ville Raunio

CONTAMINATION IN HYDRAULIC SYSTEMS AND ITS SOLUTIONS

Bachelor's Thesis
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ABSTRACT

Ville Raunio: Contamination in hydraulic systems and its solutions
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Hydraulic systems are widely used in the industry. Most common reason for failures is contamination in fluid. The amount of contamination increases over time and thus accelerates the damage on components and systems. However, it is possible to limit and reduce the amount of contamination efficiently. This thesis introduces how contamination damages the hydraulic system and how it is possible to limit the amount of contamination.

First part of this thesis shows that the most common types of contamination are solid, gaseous, and liquid. Depending on the type of contamination, it reduces the efficiency of the system and damages the components increasing the expenses. If contamination is not reduced in the system, the amount of it will keep increasing and damages happen faster than before. Damage in components may lead to failures in the end.

The second part in turn focuses on the reduction of contamination with hydraulic filters. With choosing the location and the number of filters carefully it is possible to affect the outcome significantly. Sizing of the filter depends on system it is intended for. It must withstand the maximum operating conditions.

The second part also introduces simulations as a tool to estimate the characteristics of the filters. Even though existing handbooks give a good guideline for locating and sizing of the filter, simulations can also be used. With simulations it is possible to estimate the pressure drop across the filter and the lifetime of it. It is also possible to simulate the flow phenomenon inside the filter to figure out how the design could be improved to make it more efficient.

Keywords: Contamination, hydraulics, hydraulic filters, simulation

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TIIVISTELMÄ

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Hydraulijärjestelmiä käytetään laajasti eri teollisuuden aloilla. Yleisin syy hydraulijärjestelmän vikaantumiselle ovat öljyn epäpuhtaudet. Epäpuhtauksien määrä kasvaa ajan myötä, jolloin myös niiden aikaan saamien vaurioiden määrä kiihtyy. Epäpuhtauksien määrää on kuitenkin mahdollista rajoittaa ja jopa vähentää tehokkaasti. Tässä työssä selvitetään, miten epäpuhtaudet vahingoittavat hydraulijärjestelmiä ja miten epäpuhtauksien määrää on mahdollista rajoittaa.

Tutkielma ensimmäinen osa tuo ilmi, että yleisimmät epäpuhtaustyypit ovat kiinteä, kaasumainen ja nestemäinen. Epäpuhtaustyypistä riippuen järjestelmän teho voi alentua ja komponentit vaurioitua, mikä puolestaan lisää yllättäviä kustannuksia. Mikäli epäpuhtauksia ei poisteta, niiden määrä jatkaa kasvuaan ja vauriot tapahtuvat entistä nopeammin. Vauriot voivat ajan myötä johtaa komponenttien ja jopa koko järjestelmän vikaantumiseen.

Toisessa osassa puolestaan keskitytään epäpuhtauksien vähentämiseen suodattimilla. Suodattimien sijoittamisella hydraulijärjestelmään on mahdollista vaikuttaa epäpuhtauksien vähentämiseen. Suodattimen mitoittaminen riippuu puolestaan täysin kohdejärjestelmästä. Huomioon tulee ottaa kovimmat mahdolliset olosuhteet, joista suodattimen tulee selviytyä.

Toinen esittelee myös simulaation yhtenä aputyökaluna suodattimen ominaisuuksien arvioinnissa. Vaikka olemassa olevat käsikirjat antavatkin hyvän ohjenuoran suodattimen sijainnin valitsemiselle sekä mitoittamiselle, myös simulaatiota voidaan hyödyntää. Niiden avulla on mahdollista selvittää suodattimen yli tapahtuva painehäviö niin kuin myös arvioida suodattimen elinikää. Myös suodattimen sisäisiä virtauksia on mahdollista simuloida suodattimen tehokkuuden selvittämiseksi ja parantamiseksi.

Avainsanat: Epäpuhtaudet, hydrauliikka, hydrauliikkasuodattimet, simulaatio

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NOMENCLATURE

β	Ratio of the number of given size particles upstream of the filter to the number of same size particles downstream.
ΔP	Pressure drop
ε	Porosity
μ	Dynamic viscosity of the fluid
A	Filtration area
C	Contamination level
k	Permeability of filter media
Q, q	Fluid flow rate
T	Temperature
t	Thickness of the filter material

.

1. INTRODUCTION

Hydraulic systems are used to perform different kinds of tasks by utilizing pressurized fluid. The pressurized fluid is used to drive various actuators like motors or cylinders. Hydraulic systems are used widely in various applications due to their simple structure and high power-to-weight ratio. These applications can be, for instance, off-road machines e.g. tractors or industrial applications e.g. paper machines.

Failures of hydraulic systems in these applications produce economic losses, but they may also be dangerous for the operators. Depending on the severity of the failure in a component, other components may suffer damage as well and, therefore, incur even more expenses. The components are expensive, but also the downtime incurs costs as the hydraulic system cannot be operated and the work of it cannot be done. For that reason, it would be crucial to maintain the components and systems undamaged.

Hydraulic contamination is a significant concern for hydraulic systems. According to the several sources, contamination in hydraulic systems is causing an estimated 75 – 80% of all failures. [1, pp. 325] [2, pp. 58] Contamination occurs in various types, for instance, solid or gaseous. It may enter the system through multiple sources, depending on the type. For example, liquid contamination or dust could get into the system through imperfect seals, or solid contamination could be left inside from the manufacturing [1, pp. 325] [2, pp. 56]. Contamination may also cause changes in viscosity [1, pp. 311-312].

Even though contamination causes several concerns, it can be treated quite simply. A wide range of filters is available to reduce the contamination of the system and make them contaminant-free. Filters are several kinds, e.g. suction and pressure filters. Depending on the location of the filter, various effects can be obtained. [3, pp. 47] [4, pp. 234-239] Choosing the correct size of filter and its location in the system may be difficult from time to time. It may also be hard to estimate the change interval for the filter. However, simulations are useful tool for that. By simulating it may be possible to estimate the pressure drop and lifetime of the filter.

This thesis is a review of choosing the location and sizing of the filter for oil hydraulic systems. Simulation is introduced as a tool to help with previously mentioned tasks in order to reduce contamination efficiently. The structure for the rest of the thesis is the following: In the second chapter, the background theory of contamination is explained.

After that, in the third chapter, filters, sizing and common filter locations are introduced and explained. Finally, the fourth chapter presents the summary of the main findings.

2. CONTAMINATION IN HYDRAULIC SYSTEMS

Contamination can refer to multiple things regarding hydraulic systems, although it almost always causes challenges in hydraulic systems over time. Contamination can be of various types, and it can form through many sources. It will affect components in different ways. Fortunately, there are ways to reduce the contamination from the hydraulic fluid. It is also possible to prevent it from forming in the first place. Section 2.1 provides review of common types of contamination meanwhile section 2.2 focuses on the sources of contamination. Section 2.3 covers the consequences caused by contamination on component and system level. Finally, section 2.4 summarizes this chapter.

2.1 Contamination types

Contamination in hydraulic systems is often considered as solid particles. According to [3], that is the most common type of contamination, and it affects all the components of the system [3, pp. 42]. Solid particles are often very small. Even though particles are small they are capable of causing very severe damage on the hydraulic system. This kind of contamination causes wear, and it may block gaps in the orifices which could lead to an insufficient lubrication due to low amount of fluid flowing through the orifice [5, pp. 209]. In other words, it will cause degradation or failures on components of the system. However, it should be noted that contamination can also be liquid or gas.

Liquid contamination generally means presence of other, unwanted, fluids in the system. Such fluids can have various effects on the performance of the system. Some fluids could cause corrosion on the components [3, pp. 42]. The most common liquid contaminant is water, which would create several issues in the system. According to [3], water reduces the lubrication effect of the oil. Water may also cause rusting in hydraulic components which can furthermore create solid contamination [6, pp. 44]. Moreover, high vapor pressure of water is not a desired attribute in hydraulic system, as it can lead to vapor cavitation which could possibly cause instabilities or damages on the mechanical components. [3, pp. 42] According to [5], water will noticeably change the fluid characteristics only if the concentration in fluid reaches at least 1% [5, pp. 209]. Water will also create issues if the operating temperatures are below freezing point of water. In this case *ice crystals* would form in the fluid, which would act in the system just like solid contaminants causing unnecessary wear and failures. [5, pp. 209] However, this is mostly only a concern for systems which have to operate outside in cold conditions, for instance mobile machinery in Northern countries. Some alcohols, acids, or sludges may form due to unwanted reactions between the hydraulic fluid and water [3, pp. 42]. That would lead to furthermore lowered oil characteristics or even corrosion on components.

Gas contamination is one of the three major contamination types for hydraulics systems. It typically refers to undissolved or entrained gas within the hydraulic oil [3, pp. 42]. According to [5], undissolved gases will most likely be trapped in high points of the system lines or in hydraulic pumps or actuators. In such places gas will cause the most damage as it can cause cavitation in pumps and motors or prevent components from being lubricated. [5, pp. 209] Cavitation happens when the pressure is too low and the dissolved air in the fluid starts to undissolved and form bubbles. When the pressure increases back to normal level again the bubbles rapidly dissolve. This furthermore causes huge changes in pressure and may damage the material. [7, pp. 106] Lack of lubrication will increase friction and, therefore, create higher temperatures, and material fatigue [1, pp. 327]. It will also expose components to unnecessary wear. Production of material fatigue is presented in figure 1. First, stresses will develop at the surface leading to deformation

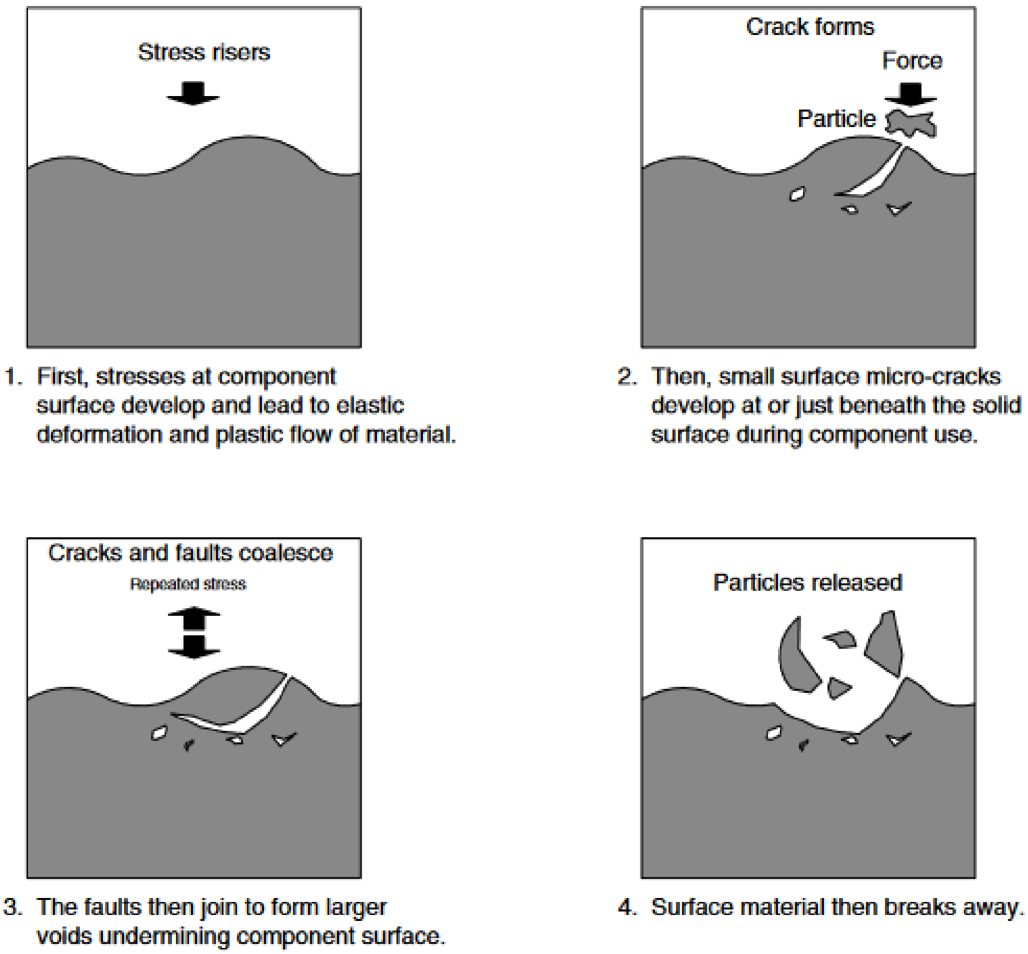

Figure 1: Production of fatigue wear damage [1]

of the material. Next microscopic cracks start to develop. These cracks start to join each other forming larger cracks. Finally, the cracks become so large that they break away from the surface.

Authors in [5] mention heat and microbial contamination. They would both generally accelerate the degradation of the hydraulic fluid properties. [5, pp. 209-210] Worse fluid properties could cause for instance, increase of friction related losses.

2.2 Contamination sources

Contamination in the system can appear in multiple ways, and it will affect the whole system. Some contamination sources may be more severe for different components than others. In this section ways how system and its oil become contaminated are introduced.

One of them occurs during the manufacturing process of components, when small metal particles, debris, or dirt can be left inside the components [2, pp. 56]. If the components are not cleaned well enough, contamination will stay inside through the assembling process and get inside the system right from the beginning and, therefore, contaminate the fresh oil. [5, pp. 208] Despite even the components are cleaned before assembling, small pieces of fabric may separate from the cloth used for cleaning. Due to this, it is recommended to use only *lint free* clothes for cleaning [2, pp. 56]. It is also important to use only clean and correct tools for assembling. Dirty or wrong tools could break or foul otherwise clean components [8, pp. 212].

Particles which have worn off from the inside of components will keep circulating inside the system unless they are filtered off or the oil has been changed. Such particles will keep causing more wear and damage to other components and, thus, increase the amount of contaminants in the system. This kind of contamination is called *wear regeneration cycle* [1, pp. 326].

Contamination can enter the system also during normal operation even though all the components would be working properly and with no faults occurring earlier. For instance, mobile machinery often has a hydraulic fluid reservoir and while the machine is moving, also the fluid inside the reservoir moves. If there are sudden and rapid changes in the moving speed or direction the liquid will start sloshing. Heavy sloshing can lead to fluid being ejected through filler or breather caps. If there is no fluid at the outlet port of the reservoir, it would lead to air entering the system. [5, pp. 205] According to [5] this kind sloshing could be prevented or at least reduced by dividing the reservoir into smaller sections by proper use of baffles [5, pp. 205]. However, that will make the reservoir heavier. According to [4], the breather cap concern regarding the oil reservoirs could be fixed at certain level by using filter breathers, to filter the air [4, pp. 233]. Any contamination that can be prevented to enter the system is important as the prevention will be cheaper option than filtering the oil. However, breather caps are not the only source for contamination during normal operation. Dirt or especially very fine dust could get inside the system through seals [5, pp. 208]. Rod seals are also imperfect, and they cannot totally prevent the ingression of contamination [1, pp. 325]. Increasing the tightness and therefore reducing the possibility of contaminants entering through seals would significantly increase the friction and therefore add huge losses and decrease the efficiency of the system [5, pp. 219]. It is also possible that dirt particles or humidity will enter the reservoir with the airflow to compensate the fluid level changes during normal operation [6, pp. 43].

Humidity entering the system was discussed earlier, but very often it is not the main cause for liquid contamination. According to [3] water can be dissolved into the hydraulic fluid without changing the main properties of the fluid, just like air. Instead of humidity, the main reason for water level rising above the saturation levels is that liquid, like dirt and other solid contamination, can enter the system through cylinder seals during cylinder retraction. [3, pp. 42]

2.3 Consequences of contamination

Contamination is almost always causing challenges in hydraulic systems over time. According to [1], fluid power systems have three types of failures: 1. *Degradation*, performance gets weaker, but system still work. 2. *Intermittent,* Components are not working perfectly anymore, and the operation becomes intermittent. 3. *Catastrophic,* Major components break down. Also, debris from the first component may cause failures or breakdowns in other components. Therefore, in a worst-case scenario a total replacement of the system would be required. [1, pp. 325] The following sections introduce the effects of contamination on common components and system level.

2.3.1 Pumps

Pumps are crucial components for fluid power systems and without pumps the systems are unable to perform. According to [1], gear pumps can handle contamination better due to larger clearances and lower pressures [1, pp. 330]. Contamination also shortens the life of bearings. It may cause vane slots to wear out or vanes to get stuck inside them which would lead to erratic action and premature change of cam ring. In general, contamination causes wear or other kinds of alterations which further increases the internal leakage of the pump and therefore decreases the efficiency of the pump. [2, pp. 60] Once the internal leakage is higher, the flow rates start to decrease. This does not only affect the pump but also the whole system and the actuator because less flow will reach it. At some point the internal leakage will be so high that the pump cannot build up any pressure and that will lead to sudden failure of the pump. [5, pp. 209] That would be an example of catastrophic failure as the system would be unusable without the pump. Therefore, it is important to keep it undamaged and avoid untimely replacements.

Gas contamination is one of the major contamination forms as mentioned. All liquids have dissolved air, but the real problem is undissolved gases. If the gas is trapped in pumps or motors, it will cause severe cavitation. Cavitation furthermore damages interior surfaces.

2.3.2 Cylinders

Common reason for cylinder failures is failure of seals. The purpose of seal is to prevent leakage, but it also protects the hydraulic system from ingression of contamination. Contamination in the system will cause abnormal wear on seals and degrade them [2, pp. 58-59]. This would lead to internal and external leakage in the cylinder. If the fluid is able to get through the seal, then also the contaminants outside the system are able to get through the seal and get inside the system. This would lead to even more contaminants getting inside the system and, therefore, speeding up the degradation and shortening the lifetime of the whole system. In addition, leakages would cause pressure losses and lead to decreased efficiency. [5, pp. 218-219] Leakages in cylinder would count as degradation at first. However, once the leakages become high enough and the pressure is not high enough to operate the cylinder, the stage of failure changes to catastrophic.

2.3.3 Valves

Depending on the application, hydraulic system will use variety of valves. Valves generally have small clearances and that makes them very sensitive to contamination. Most of the valves are affected in the same way by contamination [2, pp. 59-60]. However, some minor differences occur.

Certain types of directional valves have very small clearances between the bore and spool. The clearance is typically in range of 4 to 13 µm. It is difficult to manufacture perfect products with these tolerances, so the spool is never precisely in the center of the bore. [1, pp. 331-332] This allows solid contaminants to get into the clearance and bridge it and cause the valve to stick. According to [1], directional valves also suffer from *silting.* This happens when pressure forces small particles into clearances and the valve is not used frequently. If the valve is not used for a long time, there would be even more particles in the clearance and the valve would be stuck. That would be an example of intermittent failure. [1, pp. 331-332] According to [1] it is hard to prevent silting because particles that cause it are so small that filters could not remove them. However, using the valve frequently could help. Author in [1] also suggest that if an application has history of silting, spool valves could be replaced with poppet valves as they are less subject to silting. [1, pp. 331-332]

Flow control valves often suffer of orifices eroding [2, pp. 59]. Though it depends on the orifice configuration. Sometimes different configurations have the same area even though the shape is distinct. That will define the minimum size of particle which would damage the valve. [1, pp. 332] Eroding would cause the valve to have new flow characteristics and lower ability of regulating the flow [2, pp. 59].

Pressure relief valves are important for the hydraulic system because they will prevent pressure from getting too high. According to [1], when the relief valve opens and oil flows through the opening with a high velocity, possible contaminants would erode the spool and opening [1, pp. 332].

2.3.4 Fluid

As earlier mentioned, the fluid properties are very essential when observing a hydraulic system and its performance. These properties often decrease by time, but they may decrease also because of contamination or inappropriate use of the system.

The fluid suffers of contamination just as other components. For hydraulic fluid liquid contaminants are probably the most dangerous as earlier stated they may react together. Water may cause reactions which will produce new solutions that furthermore degrade the oil. These contaminants together cause oxidation and generally degrade the oil. Lubrication effect may suffer due to changes in viscosity, and friction can increase. Therefore, also the temperature of the fluid will increase. That is not dangerous unless the temperature is high constantly. According to [1], operating consistently above 70 degrees of Celsius is harmful for the fluid. That would furthermore lead into oxidation of the oil, loss of lubricity and changes in viscosity. [1, pp. 311-312]

The worst-case scenario is that the fluid characteristics have changed so much that the fluid must be replaced [2, pp. 60]. This could be due to high level of oxidation or changes in viscosity. Oil replacement under such conditions would count as catastrophic failure. According to [2], replacing the oil would lead to unnecessary maintenances and increased production costs as also the oil disposal like the new oil is not free [2, pp. 60].

2.3.5 System level

Contamination will do harm on the component level, but it is also harmful on the system level. The efficiency of the system is based on all the components so if singular components are degrading and their efficiency decreases, it will affect the whole system.

Hydraulic systems are divided into open (figure 2a) and closed systems (figure 2b). These systems are affected differently by contamination due to their differences in the design. For open systems it is typical to have large reservoir and a pump which pumps the fluid only in one direction. The direction of flow would be therefore controlled with valves. Closed systems on the other hand do not have large reservoir but the fluid from return line is led back to the pump. Often closed systems do not use directional valves as they are controlled by the pump which is able to work in two directions. [7, pp. 5]. Open system can handle contamination better as it has huge volume of fluid, and the solid particles may stay in the reservoir once they enter it. However, in the closed system the fluid never goes into a reservoir and, therefore, also the contamination keeps circulating in the system damaging other components and producing even more contamination.

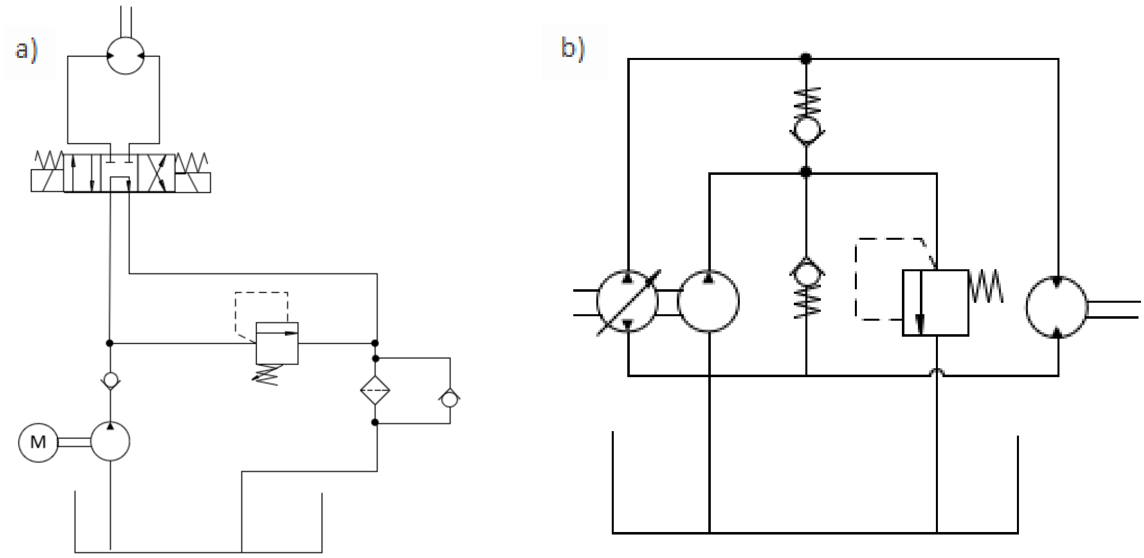

Figure 2: a) Open system, b) closed system

As previously said contamination will cause failures for components and it will increase form of new contamination due to *wear regeneration cycle.* Catastrophic failure of one component could add the contamination so much that it would cause even more failures in other components [2, pp. 60-61]. This kind chain of failures would be extremely expensive due to the broken components but also due to the long downtime. First, the new components and oil are needed. As there would be new components a system flushing could be required and that would cause more costs [1, pp. 341-342]. At last, the downtime of the system is also expensive as there would be no production with the broken hydraulic system.

2.4 Summary

The main contamination types are solid, liquid and gas contamination. They cause wear, cavitation, corrosion, and degradation of the whole system. Often the degradation causes more contaminants which furthermore speeds up the degradation. It is almost impossible to prevent any contaminants from entering the system. Solid contaminants may be left inside the components from the manufacturing process, but any type of contamination may enter even under normal operating conditions.

Components often suffer of degradation in the first place as it can be seen in table 1, but if the contamination issue is not handled, some intermittent failures like valves getting stuck may occur. However, if the contamination is not reduced the damage will be more and degradation be more severe. Valves usually start having intermittent failures before totally breaking down meanwhile other components usually suffer of lowering efficiency until totally breaking down. For this reason, the system often has filters to reduce contamination.

Table 1: Stages of failures for common components

Component	Degradation	Intermittent failures	Catastrophic failures
Pump	x	→	x
Cylinder	x	→	x
Valves	x	x	x
Fluid	x	→	x

3. SOLUTIONS TO REDUCE CONTAMINATION

Contamination is a major concern in hydraulic systems. This concern can be treated in various ways depending on the application. Downtime of hydraulic systems are wanted to be as small as possible. Because of this a target cleanliness levels are set on hydraulic systems. Choosing the right cleanliness level depends on the components [1, pp. 333-343]. Other components do not suffer from contamination as much as others so the cleanliness level should be chosen regarding the most sensitive component. Also factors such as fluid, temperature, duty cycle, system design life, cost of production interruption and safety should be considered [1, pp. 333-343]. In section 3.1 different filters and their sizing are introduced as a solution in order to create contaminant-free system. Section 3.2 introduces simulation as a tool to estimate the attributes of the filter. Finally in section 3.3 there is a summary of this chapter.

3.1 Creating contaminant-free system

According to [3] solid contamination cannot be avoided in hydraulic systems and due to this, filters are needed. Filters are used to reduce the amount of existing contamination and prevent it entering the most vulnerable parts of the hydraulic systems by trapping the solid contaminants in the filter. Filters are multiple types, and they can be located and sized depending on the needs. [3, pp. 43-47] Before making any final decisions about the filter type, location or size, simulations can be run in order to confirm the right decision.

Creating a contaminant-free system takes a lot more than just one filter in the system. Every hydraulic system may have highly varying parameters. One system may be operating in a very low-pressure areas such as 1 to 3 megapascals meanwhile other application may use constant pressure of 30 megapascals. These systems may need totally different types or sizes of filters. It is also possible to not use a filter at all or use more than one filter. However, not using a hydraulic filter would let the amount of contamination grow all the time.

3.1.1 Sizing of filter

Sizing of the filter depends on the cleanliness level and the location of the filter. Different filter locations are introduced in the next section. Correct size can be chosen by evaluating the maximum flow rates and pressures which the filter must withstand. Using a simulation to estimate the lifetime can be useful because that way designers can choose a larger filter if a longer change interval is wanted. Depending on the location of the filter, the filtration rate should always be connected to the most sensitive component of the hydraulic system as otherwise larger particles could block smaller clearances.

The efficiency of the filter can be described by using β ratio which is determined by going through standardized Multipass Filter Performance Beta Test or simply Beta or Multipass test. This test reports its results as ratio of number of above given size particles upstream compared to the same size particles downstream. [1, pp. 335] In other words it describes the ability to trap contaminants above certain size. Table 2 adopted from [1, pp. 336] shows the connection between β ratio and the efficiency of the filter. Particle size may often be shown as a subindex in the β rating, for example $\beta_{15} = 5$ would mean that 80% of particles larger than 15μm were trapped in the filter [10, pp. 67].

Table 2: Filter efficiencies for given β ratios determined with beta test [1].

β ratio	Efficiency (%)
1	0
2	50
5	80
10	90
100	99
200	99.5
1000	99.9
5000	99.98

Another critical thing to pay attention on choosing a filter is the pressure drop it causes. To estimate the pressure drop, Darcy’s equation is commonly used as given in equation 1

$$\Delta P = \frac{Q \cdot \mu \cdot t}{A \cdot k \cdot \varepsilon}\ , \qquad \textbf{\textit{(1)}}$$

where *ΔP* is pressure drop, *Q* is fluid flow rate, *μ* is dynamic viscosity of the fluid, *t* is thickness of the filter material, *A* is filtering area, *k* is permeability constant for the filter material and *ε* is porosity. [11] However, if the pressure drop caused by the filter is not significant in the scale of whole hydraulic system, it can be ignored in dynamic modelling. On the other hand, if the filter has to be considered in simulations, its resistance values can be estimated from the data sheet from the manufacturer or from the filter characterization experiments. [12, pp. 39] It is also suggested that filter media is chosen carefully as different medias have varying capture efficiencies and dirt-holding capacities. [13]

Sometimes it might be feasible to also look at the economic side. According to [4], using oversized filtration area may give better filtration efficiency. In certain cases, doubling the filtration area would triple the dirt-holding capacity. Larger filter area would also allow more flow rate and thus decrease the resistance and therefore reduce the energy consumption. Another way to cut the expenses is using series of filters. First one would trap the largest contaminants meanwhile the last one would be catching the finest and smallest particles. [4, pp. 235-236]

3.1.2 Filter location

Filters are divided into types depending on their location in the system. Filters are used to reduce contamination and prevent it entering the most vulnerable parts of the system. Choosing the correct location of filter may be challenging. For instance [8] suggests that filters could be placed in inlet, pressure or return line. All these three solutions would give different results [8, pp. 47-48]. Authors in [4] also suggests off-line filtration as one option [4, pp. 238]. These most common filter locations are illustrated in figure 3.

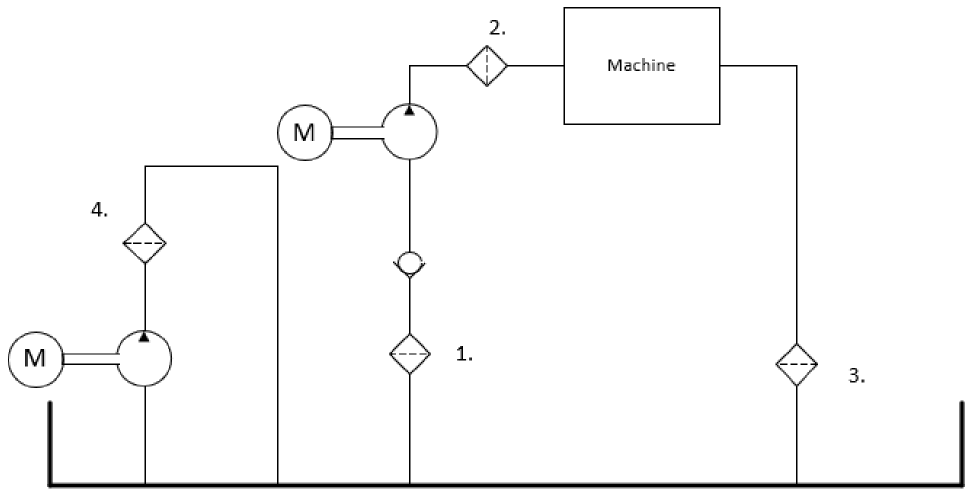

Figure 3: Common filter locations: 1. Inlet line 2. Pressure line 3. Return line 4. Off-line

Inlet line filters (number 1. in figure 3) are located right before the pump [2, pp. 81]. Their main object is to prevent particles from entering the pump from the reservoir and, therefore, prevent particles from damaging the pump. [8, pp. 48] A pump is crucial component, and it is critical to keep it undamaged. As inlet line filters are placed before pump, it is essential that they cause as low pressure drop as possible. Otherwise, the fluid would not be able to raise from the tank. Due to this challenge, the inlet line filter can only provide filtration of larger particles [8, pp. 47-48].

Pressure line filters (number 2. in figure 3) are located right after the pump. Their main purpose is to protect components like actuators and valves. [4, pp. 238] According to [4,7], conditions after the pump are more extreme than in other locations as the filters must withstand full system flow and operating pressure. [4, pp. 238] [8, pp. 48] The filter should be located before pressure relief valve in order to filter maximum amount of flow. Therefore, it needs to sustain great pressures [7, pp. 392]. Pressure line filters are often more expensive than other filters and, therefore, the cost for each gram of contamination removed with pressure line filters will be higher than for the other filters. Due to this, designers often design the pressure line filters only to protect other components in case of pump breakdown and use other filters for contamination removing. [4, pp. 238]

Return line filters (number 3. in figure 3) are filters which are located after all the other components where the oil is flowing back to the tank. Their main purpose is to reduce the amount of contamination reaching back to the tank. [9, pp. 140] Return line filters are very efficient as all the fluid running in system flows through them [8, pp. 48]. Therefore, a notable amount of particles will be trapped inside. However, this increases the pressure drop across the filter once the filter starts to become clogged [8, pp. 48]. Return line filters use a relief valve which would open once the filter is too blocked and pressure has risen high [8, pp. 48]. However, in this situation the filter becomes useless as all the contaminants can pass it freely. In this kind of event, as [8] also says, the filter should have been already replaced with a new one. [8, pp. 48] Authors in [4] also say that return line filters may be affected by severe conditions. According to them, these filters do not suffer from extreme pressure but from highly varying flow rates. Flow rate for return line is highly affected by the load conditions from the actuators and, therefore, the flow may be three times the flow from pump. However, it is said that this challenge can be simply solved by using oversized filters [4, pp. 238-239]. Also, according to [7], return line filters should be designed according to the maximum possible return flow [7, pp. 392-393].

Off-line filters (number 4. in figure 3) are filtering the fluid in the tank. Normally these filters have their own circuit with only pump and the filter. [7, pp. 393-394] They are used only to circulate the fluid in tank and remove the possible contamination from the fluid [3, pp. 47]. As off-line filtration is an independent unit in the hydraulic system, it can run alone without rest of the system [4, pp. 239]. It is efficient way to remove contamination meanwhile rest of the system is not creating new contamination. According to [4], off-line filtration has few additional benefits when compared to other filter locations. Such benefits are easy service, possibility to build heat exchange in the loop and constant flow which optimizes the capacity for dirt-holding and the efficiency of the filter. On the other hand, it is stated that off-line filtration has higher initial cost as it requires another pump. [4, pp. 238]. As the pressure drop of this filter does not affect the rest of the system, the filtration level is possible to be set even higher than the system would need, in order to maximize the reduction of contamination. [7, pp. 393-394]

Each of these options have their own advantages. More complex applications may use more than one filter and in such application a mix of different filter locations can be applied. However, [10, pp. 109] recommends that filters should not be located in areas which suffer of vibration or where the flow is not constant. Both recommendations are related to the event of trapped contamination in filter could possibly pass the filter. Unfortunately, that is not always possible and then the designer has to evaluate various options. If it is hard to decide between different filter locations, simulations can be performed and the effect of filter can be studied that way.

3.2 Filter simulations

Simulating and modelling are flexible ways of studying the best ways to achieve a wanted result. Engineers have done the designing work without simulations for centuries. However, sometimes the experiments may be dangerous, or the outcome is unpredictable. In some cases, experiments may also be too expensive to execute. Due to these reasons, simulations are performed.

In this paper, contamination has been discussed so now the focus is on creating a contamination free system. Simulations and modelling can give a great help in order to achieve that. Different studies have been using modelling as a tool to estimate the pressure drop, lifetime, and flow of the filter. Using that kind of models and simulations, the designers could get an idea of where to put filters, what size they should be and when a new filter would be approximately needed. Simulations may also be helpful when design of components are being improved. However, very often simulations require powerful computer and expensive software, so it is necessary to evaluate whether doing the simulation work is beneficial enough.

3.2.1 Pressure drop and lifetime

Simulations can be used to estimate pressure drop of the filter. Pressure drop of the filter can be furthermore used to estimate the lifetime of the filter. Modelling the pressure drop is combination of parameters and factors and therefore it might become very complex. Simulation studies have been carried out to find what factors affect the lifetime of the filter.

Flow rate have been found to affect the lifetime [14]. The lifetime is estimated by simulating the value of pressure drop. Real parameters of existing filter provided by manufacturer are used in the simulation. The simulated system in [14] is shown in figure 4.

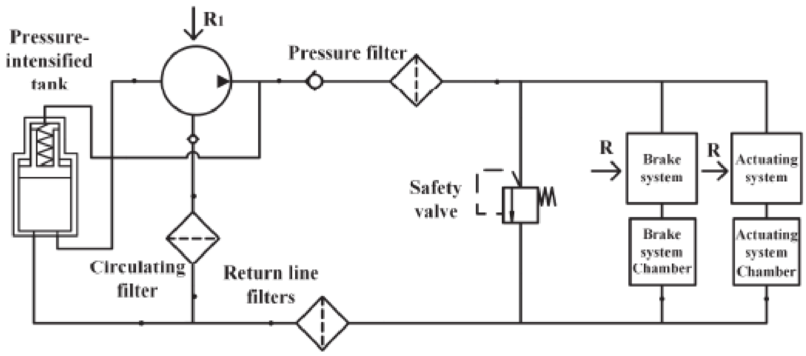

Figure 4: Simulated system [14]

“Significant increase point” refers to point where maximum allowed pressure drop is achieved and that is marked as A point in figure 5. It describes when the filter is becoming too clogged, and it should be changed. That is also close to a value provided by the filter manufacturer [14]. Pressure drop was then simulated with three different flow rates. Results of simulations are compared in figure 6. According to the simulations it looks like increasing the flow rate will slow down the development of the pressure drop and, therefore, increase the lifetime [14]. The lifetime of the filter in these simulations were estimated according to the A point [14]. However, it does not seem logical that when the flow rate is higher the filter lasts longer. With higher flow rate, there should also be more

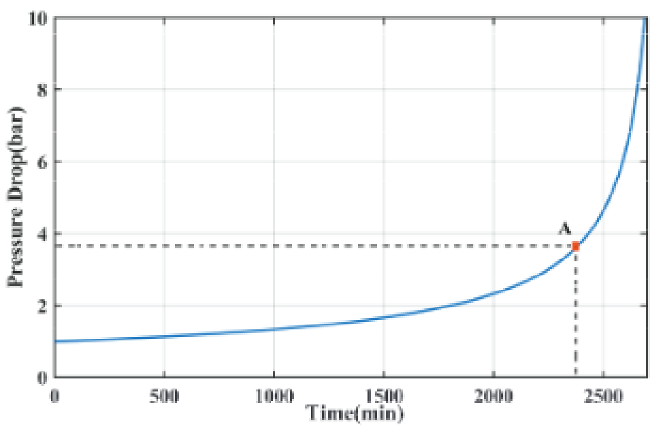

Figure 5: Simulation of pressure drop [14]

contaminants and, therefore, the filter would get clogged faster which would lead to a decreased lifetime. Also, experimental studies show that increasing the flow rate decreases the lifetime of the filter [15]. Figure 7 shows the experimental results in [15].

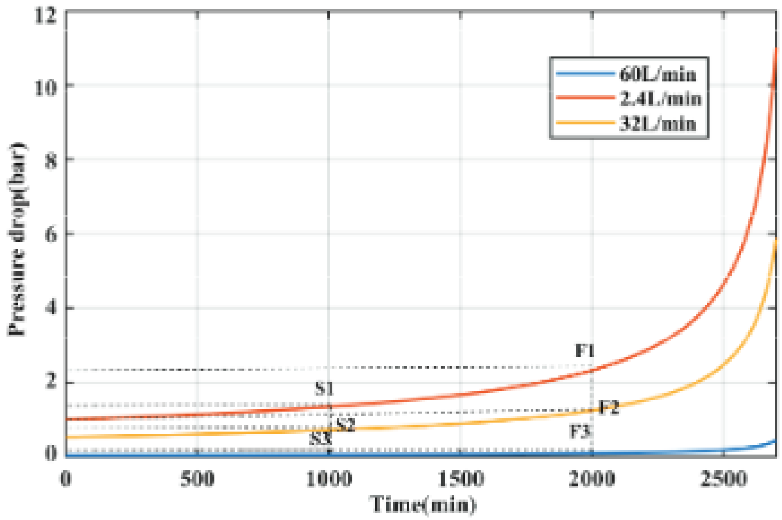

Figure 6: Simulated results of different flow rates [14]

Study in [16] presented a simulation model to predict the lifetime of the filter. Results were similar as the experimental results in [15]. Both of these studies were performed for same system which schematics are shown in figure 8. Increased flow rate and decreased temperature reduced the lifetime of the filter. Also, as in table 3, where *q* is flowrate (l/min), *T* is temperature (Celsius) and *C* is level of contamination, can be seen, their model was compared with real data and the ability to predict the lifetime of the filter was great [16]. The model was tested with several combinations of flow rates, temperatures, and contamination levels and in all tested cases it succeeded relatively well. As

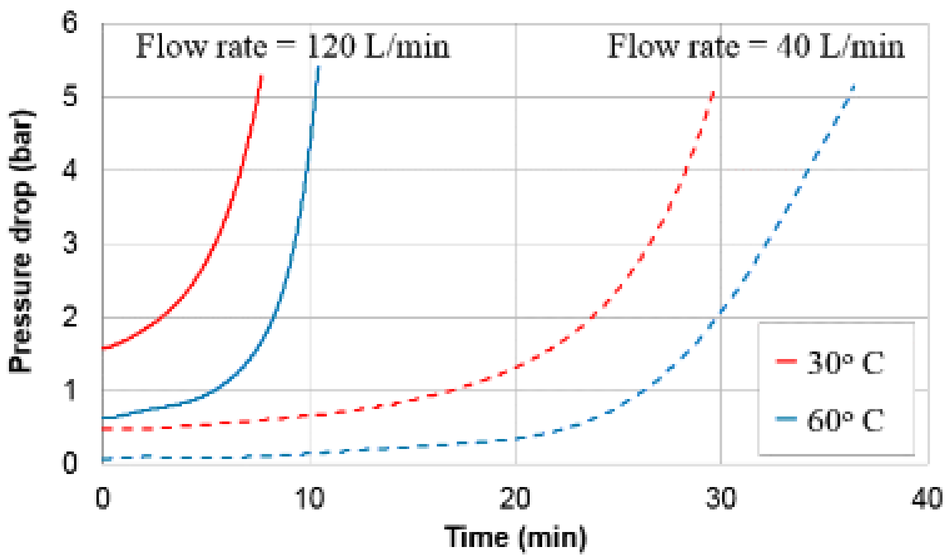

Figure 7: Experimental results of two flow rates and temperatures [15]

the same model can handle different parameters and the accuracy of the model is still great, it may save time and money compared to performing the same experiments with real devices. Simulation can be performed as many times as needed meanwhile a new filter is needed if old one is already clogged.

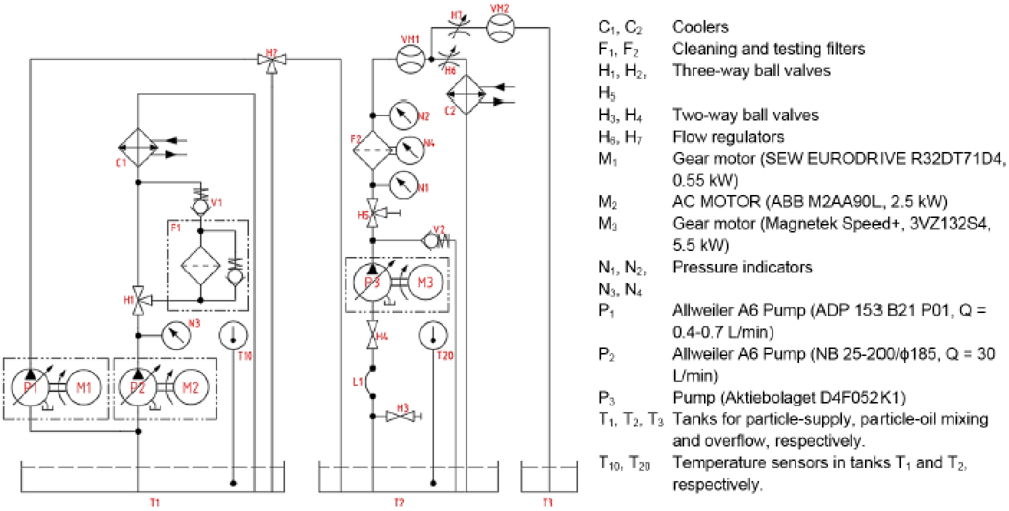

Figure 8: System used in [15] and [16]

One factor to affect the lifetime of filter is obviously the size of filtration area [14]. Increasing the filtration area means adding more dirt holding capacity so the result is obvious. Though the simulation can be used to estimate the lifetime once all the operating parameters are known. This way it is possible to provide the operators some idea of the change interval in normal use. Once the model is set up and proven to work, it is easy to change other filter parameters and compare the results and proceed with more suitable option.

Table 3: Correlation model results [16]

Flow configuration (q-T-C)	Actual lifetime (min)	Predicted lifetime (min)	Error (%)
40-30-2	136.33	138.31	1.45
40-40-10	31.71	33.77	6.10
80-50-5	30.54	31.65	3.51
80-60-10	16.31	16.53	1.33
120-50-5	19.43	18.87	2.98
120-30-8	8.98	9.17	2.05

Temperature is another factor which affects the pressure drop development and lifetime. In figure 7 can be seen that experimental studies provide information that filtration is more efficient in temperature of 30 Celsius degrees than in 60 degrees of Celsius [15]. Therefore, filter lifetime would be decreased in 30 Celsius degrees compared to 60 Celsius degrees. This kind of result is due to changes in viscosity [15]. Another study has got similar results with simulations but for more than two different values of temperature [17]. Temperatures of 30, 40, 50 and 60 degrees of Celsius are compared with different fluid contamination levels in a flow rate of 80 l/min. Based on the results in the paper, it was said that temperature or viscosity has great effect on the pressure drop development and therefore on the ability of trapping contaminants [17].

According to the studies [14,15,16,17], it is possible to deduce that the main factors affecting the pressure drop and lifetime of the filter are temperature, flow rate and the contamination level of the oil. The effect of flow rate has had conflicting results. However, the results in [16], where increased flow rate decreased the lifetime of the filter, were validated with experimental data. Therefore, it is possible to note that increased flow rate is decreasing the lifetime. Increased temperature on other hand is extending the lifetime. That is due to changes in the viscosity of the oil. However, as it was concluded in the chapter 2, constant high temperature may affect the characteristics of the oil in a negative way even though here it appears in a positive light. Contamination level of the fluid obviously affects the filter lifetime as it describes the amount of contamination in the system.

3.2.2 Contaminated flow

Pressure drop and lifetime predictions are important when choosing the correct filter for the hydraulic system. However, it is also important to know how the flow acts inside the filter in order to know whether the filter is efficient or not [18].

The flow phenomenon is extremely challenging to determine experimentally. That is why a simulation model is useful. A study performed experimental tests and after that, simulations regarding flow inside the filter. [18] First, experimental tests were done to get data for pressure drop with different Reynolds numbers. Temperature was kept constantly at 40 Celsius degrees and flow rate and pressure drop data was recorded. 3D model of the filter was created to be used in the simulation. A numerical simulation was done, and the simulation was validated with the experimental tests as results from both of them were in line. [18] After that the flow phenomenon was simulated. As figure 9 shows, the flow is not homogenous inside the filter. It actually shows that there is no flow at all in the upper parts of the filter on sides where inlet and outlet ports are located. If these idle areas could be employed, the filter would be more efficient. [18]

Figure 9: Velocity magnitude of streamlines around the perforated support tube [18]

Another study conducted experimental and simulation study regarding contaminated flow [19]. Real parameters of existing filter were used in the simulation. The model is validated against results from experimental study. Again, flow characteristics are in line with experiments. Results from the simulations are used for filter designing. However, as [18] focused on where the flow is going, [19] is focusing on the filtration rate. In [19] contaminated flow through the filter was performed in the simulation to determine filtration rate. Simulation and experimental results for the filtration are shown in figure 10. It can be seen that for particle diameters above 8 microns is great and yet between 5 and 8 microns it is still decent. According to them the result is significant as it proves their

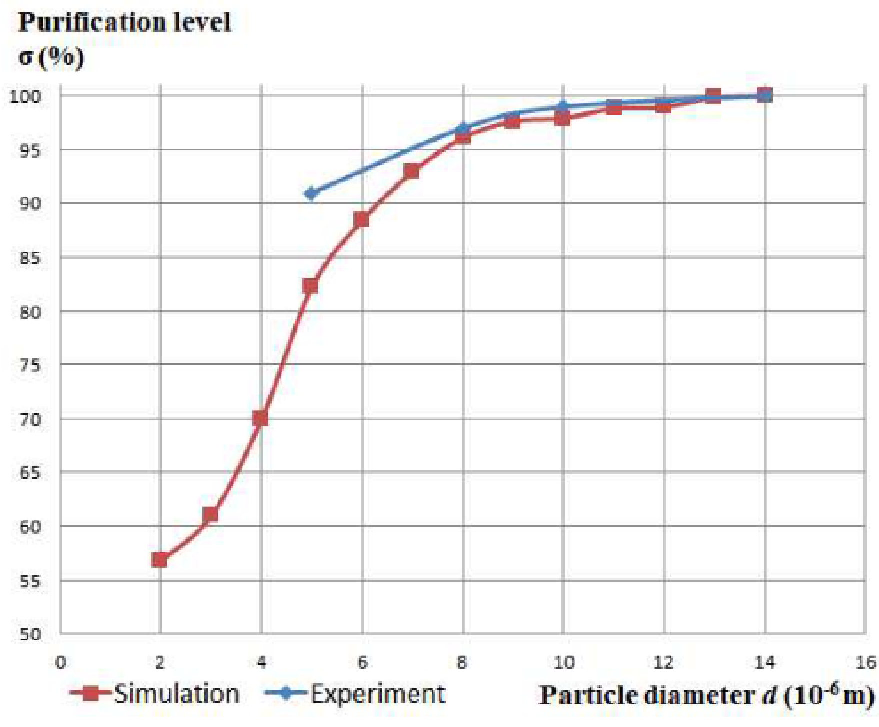

Figure 10: Dependence of purification level in the filter for different particle diameters [19]

methodology could be used to determine filtration rates during the design process of a filter. [19] Once the model is reliable enough it also saves time as experiments are not needed in the same amounts to figure the characteristics. However, the model is only accurate for certain size of particles so it would need improving if was to be used for all particle size simulation.

Linear electro-hydrostatic actuators are prone to failures caused by contamination. They suffer from high erosion and thus have a relatively poor reliability. Study in [20] was able to create a model to predict the location where erosion happens inside the valve of inear electro-hydrostatic actuators. Once the results from model was compared with erosion data from electro-hydraulic servo valve, the accuracy of model to calculate erosion rate and wear location was confirmed. [20] Such simulation gives essential information which can be used to improve design of the valve for the actuator and make it more reliable.

According to studies in [18,19,20] it is possible to simulate the contaminated flow inside the filters and other components. This gives valuable information of the ability of the filter to trap contaminants. As it was found, the flow does not distribute evenly for the whole filtration area. Actually, it is possible that in some points of the filter there is no flow at all. Therefore, the efficiency of the filter is not as high as it could be. The simulation could be used as a tool to assist in the efficiency improving. Other components may suffer from other contamination related challenges such as erosion. In that case simulation can provide information of how to improve the structure of such components.

3.3 Summary

Filters are the main component used to reduce contamination in the hydraulic systems. Sizing of this component is critical as it has impact on the whole system. Attributes that are looked into during the sizing are pressure drop and β ratio. Pressure drop is the most important as it has straight effect on the other components. β ratio on the other hand informs about the efficiency of the filter to trap certain size of particles. Also, the filtration area might be interesting as it defines the dirt holding capacity.

Filters are divided in different types according to their location in the system. Most common filter types are inlet, pressure, return and off-line filters. These filters have varying tasks as their operating conditions vary. Return and off-line filters are used to remove contamination meanwhile inlet and pressure line filters are more used to protect certain components. The pressure drop caused by these filter types affect the system in varying ways. For inlet line filter it is critical to not create too high pressure drop meanwhile for off-line filter it does not matter as it does not affect rest of the system.

Simulation may be useful tool in order to confirm the characteristics of the filter. It may save time and money if the actual experiments would be expensive. With simulation it is possible to estimate the development of the pressure drop and, therefore, the lifetime of the filter. In the studies [14,15,16,17], the main parameters affecting the pressure drop were studied. Once an accurate model is built, changing the parameters is easy, and another filter model can be simulated easily in different conditions. This kind of estimation may allow predictive maintenance and change of the filter before it is too clogged. Simulation may also be used to improve the efficiency of the filter and other components. In these cases, it has been possible to simulate how the flow acts inside the component. Therefore, the structure of the component could be improved according to the flow. Studies regarding simulations [14-20] are recent and it can be seen that the use of simulations is increasing.

4. CONCLUSIONS

This thesis is a review of hydraulic contamination and filters to reduce the contamination in oil hydraulic systems. Hydraulic contamination is a major problem for any hydraulic system, and it is capable to harm the whole system.

Contamination appears in forms of solid, gas and liquid. Solid contamination will cause wear on the components creating even more solid contamination. Small particles may also get stuck in small orifices blocking them. Gas contaminants can get stuck in pump causing severe cavitation and, therefore, wear in the pump creating solid particles. Liquid contamination on the other hand could cause degradation of the hydraulic fluid which could lead to improper lubrication furthermore causing higher stresses and again, more solid contamination. Damaged components may need to be changed causing unexpected expenses.

Filters are used to reduce contamination in hydraulic system, but they may also be used to protect components from it. Inlet line filters are used to protect the pump meanwhile pressure line filters are more about protecting other components from the contamination produced in the pump. Return and off-line filters in turn are used to reduce the contamination in the fluid. Depending on the application it may be feasible to use multiple filters in various locations. Sizing of the filter is done according to the maximum operating conditions. Pressure drop, β ratio and filtration area are the most useful characteristics of the filter and their adequacy to the system should be confirmed.

It was demonstrated that simulation is a great tool to confirm the fit of previously mentioned characteristics. As studies have shown, simulation can estimate the pressure drop development and lifetime of the filter according to the given parameters of flow rate, contamination level, temperature, and viscosity. Simulation studies have also managed to investigate the flow phenomenon which allows improving efficiency of filters and robustness of other components against contamination.

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