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HYDRAULIC FILTERS AND THEIR EFFECT ON THE HYDRAULIC SYSTEM

Bachelor’s Thesis
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ABSTRACT

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It is important to keep the hydraulic system clean to avoid any unwanted failures, which in the worst case can cause severe damage to infrastructure or even workers. Often contamination in the hydraulic system is treated using filters. There are many types of contamination as well as many types of filters to deal with them. Contaminant particles are taken care of by filters where the flow is forced through a mesh inside the filter. Other types of contamination are water and gases. Both can be harmful to the system and there are special ways to remove them from the system. Other types of filters used in hydraulic systems are power filters and hydrodynamic filters.

Hydraulic systems have different requirements for clean fluid. Therefore, in addition to the filter size, the location of the filter can differ depending on the needs. The filter can be positioned almost everywhere in the system. An external filter circuit is also possible where fluid is pulled from the tank with a pump, and it goes through the filter and comes back to the tank. Even when the rest of the system is not functioning.

Measurements in this thesis were made using a crane test rig. That crane has a motor that powers two pumps that supply flow to the cylinder. That is a DDH (Direct Driven Hydraulics) system which means that there are no valves to control it. The system is controlled using the motor driving the pumps. The main parts of the system for this thesis were the filters. There were three different kinds of filters present in this measurement. The first set of filters was clean and new. The second and third sets were pre contaminated so that they had pressure drops of 2,5bar and 5bar. Those pressure drops were measured using a flow of 38l/min.

The main part of the measurements made was pressure drop over the filter. Unfortunately, the flow that the test rig was able to produce was not sufficient for any pressure drop to exist. The measurement figures from the test rig only show the noise from the sensors. The reason why the pressure differences did not show was that the flow of the test rig should have been over 17l/min for the most clogged filters. 25l/min would have been needed for the filters that had the 2,5bar measured pressure drop. To solve this issue the system would need some changes that would make the filters less adequate for the system. Those ways might be either downsizing the filters or changing the whole test rig to something that can produce significantly higher flows.

Keywords: Contamination, hydraulic filter, pressure drop

TIIVISTELMÄ

Jussi Välimaa: Hydraulisuodattimet ja niiden vaikutus hydraulijärjestelmään
Kandidaatin työ
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Hydraulijärjestelmissä on tärkeää, että järjestelmä pidetään puhtaana, jotta pystytään välttämään rikkoutumiset, joista voi huonoimmassa tilanteessa aiheutua suurta vahinkoa järjestelmille tai jopa ihmisille. Monia hydraulijärjestelmän epäpuhtauksia voidaan ehkäistä käyttämällä suodattimia. Hydraulijärjestelmissä on monenlaisia epäpuhtauksia ja näistä eroon pääsemiseksi on monenlaisia suodattimia. Muita mahdollisia epäpuhtauksia hydraulijärjestelmässä ovat vesi ja kaasut. Molemmat voivat olla haitallisia järjestelmälle ja niistä eroon pääsemiselle on omat menetelmänsä. Erilaisia hydraulijärjestelmissä käytettäviä suodatintyyppejä ovat tehosuodattimet ja hydrodynaamiset suodattimet.

Hydraulijärjestelmissä on erilaisia vaatimuksia puhtaalle hydrauliöljylle. Tästä johtuen suodattimen suodatuskoon lisäksi myös suodattimen sijoittamisella on väliä. Suodatin voidaan sijoittaa järjestelmässä käytännössä mihin tahansa vaatimuksista riippuen. On myös mahdollista käyttää ulkoista järjestelmää vain suodattamiseen. Tässä piirissä pumppu pumppaa hydrauliöljyä tankista suodattimelle ja suodattimen jälkeen öljy ohjautuu suoraan takaisin tankkiin.

Tässä kandityössä suoritetut mittaukset tehtiin nosturiin liitetyillä suodattimilla. Nosturissa on moottori, jolla ajetaan kahta pumppua, joiden tilavuusvirtaa käytetään sylinterin ohjaukseen. Järjestelmä on suoraan ohjattu, eli siinä ei ole venttiiliä, vaan ohjaaminen tapahtuu pumppua säätämällä. Kandityö keskittyy erityisesti järjestelmässä oleviin suodattimiin. Käytettävissä oli kolme erilaista suodatinsettiä. Näistä ensimmäinen setti oli uusi, kaksi muuta settiä taas sisälsivät jo epäpuhtauksia. Näille suodattimille oli mitattu painehäviöiksi arvot 2,5bar ja 5,0bar 38l/min suuruisella virtauksella.

Mittauksissa keskityttiin suodattimen yli tapahtuvaan painehäviöön. Järjestelmällä ei kuitenkaan saatu tuotettua näkyvää mittausdataa, vaan ainoa mittaussuureissa näkyvä asia on sensorien mittauskohina. Syy sille, että paine-eroa ei nähty on järjestelmän liian pieni tilavuusvirta. Minimi tilavuusvirta, joka olisi riittänyt riittävän mitattavan paine-eron syntymiseen, on 17l/min eniten tukkeutuneilla suodattimilla. 2,5bar painehäviöiset suodattimet taas olisivat tarvinneet 25l/min. Tämä ongelma voidaan ratkaista joko pienentämällä suodattimia, jolloin paine-ero tietyllä tilavuusvirralla kasvaa. Toinen vaihtoehto on tehdä uusi testausjärjestelmä, joka on mitoitettu juuri saatavilla oleville suodattimille. Tällöin olisi hyödyllistä kytkeä suodattimet kiinni johonkin yksinkertaiseen järjestelmään, jossa mukana on esimerkiksi pumppu ja moottori, jolloin tilavuusvirta saataisiin suuremmaksi.

Avainsanat: Epäpuhtaudet, hydrauli suodatin, painehäviö

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NOMENCLATURE

ΔP	Pressure drop over the filter (bar)
ε	Porosity
μ	Dynamic viscosity of the hydraulic fluid $\left({kg \cdot s}/{m}\right)$
A_{filter}	Filtering area of a filter (m^2)
DDH	Direct Driven Hydraulics
DS	Downstream
EHA	ElectroHydraulic Actuator
ESC	ElectroStatic Charge
k	Permeability constant of the filter media
Q	Fluid flow (l/min)
t_{filter}	Filter material thickness (m^2)
UP	Upstream

1. INTRODUCTION

Hydraulic systems are often used in our everyday life. They are used as a way to transport energy. Energy is transferred into the system using a pump that accumulates pressure and fluid flow to the system. That flow and pressure are used to drive actuators that often are cylinders or motors. Hydraulic systems are used due to their ease of construction, flexibility, and great power-to-weight ratio. (Kauranne et al 1999)

The hydraulic system needs to be maintained for them to function properly. One way to maintain those systems is to filter the fluid that flows inside them. The filtration decreases the amount of contamination in the fluid. According to Phillips et. all. 55-75% of failures of hydraulic systems happen because there is contamination in the system (Phillips et al. 2015).

Particle contamination can be generated in many ways. It can enter the system from the environment, or it can be originally from the system. The contamination can enter the system from the environment by the breather of the tank or by sticking to the cylinder rod. (Kauranne et al. 1999) The contamination that originates from inside the system can be a result of wear or corrosion of the hydraulic components (Burenin 2011). There are also other kinds of contamination such as water, and gases (Zhang et al. 2017).

This thesis is about filters and their effects on the system. Especially the pressure drop over the filter. At first, information has been collected about the filters and contamination. Then tests are conducted on a crane test rig using different kinds of filters and system options. The rig uses LabView for data collection and crane control.

2. THEORY

Every hydraulic system is unique and therefore different kinds of filters are needed to match the system requirements. These requirements are the guidelines about what the system must do and how. Even in the same field or the application, the requirements can vary. For example, most aircraft use 210bar systems but Airbus A320 uses a 350bar system. This can also require the filter to be different to achieve the best possible results. Aircraft are also a good example of such applications where accidental failures cannot happen. (Brazhenko 2019) Brazhenko writes that analysis conducted by The West-Siberian and National bureau indicates that many accidents were connected to the pump of the hydraulic system. In these cases, the pump malfunctioned because of mechanical particles in the working fluid. (Brazhenko 2019)

Good filtration is one of the major requirements for hydraulic systems. One of the primary causes of severe accidents and failures is contamination within the hydraulic oil. For example in aviation contamination in the oil causes 20% of aviation accidents. (Zhang 2017) Those failures are often caused by mechanical impurities in the oil (Brazhenko 2019).

System failures that are due to contamination are divided into three different classes. The first one of those classes is catastrophic. It can occur if a component breaks down because of contamination. If the component does not break but it stops working for a small while, the failure is part of the second class and it is called intermittent. The third type of failure is degradation that can be caused by wear. It can cause more internal leakages inside the system. (Downs 1997)

The cost of a system failure can be high because if a hydraulic system needs maintenance, it cannot be used, and therefore the process it was doing is not moving forward. Dealing with that kind of situation is hard for the engineers and can be costly for the company. (Downs 1997) The following chapter introduces the types and sources for the contamination that causes failures.

2.1 Contamination sources and types

Contamination in the hydraulic fluid can be formed in multiple ways. Some of the contamination particles come from outside the system such as dust, metal particles, and fibers. These can appear during the system assembly or maintenance or they can mix into the oil in the tank through the breather on the tank. (Burenin 2011) For example, when adding oil to the system the oil is usually many times dirtier than the system requirements need it to be (Downs 1997). Some parts of the contamination on the other hand are from inside the system such as particles broken off from the components. (Burenin 2011) The third way for particle generation is the oxidation of the working fluid (Burenin 2008). Damage caused by these kinds of particles is presented in Figure 1.

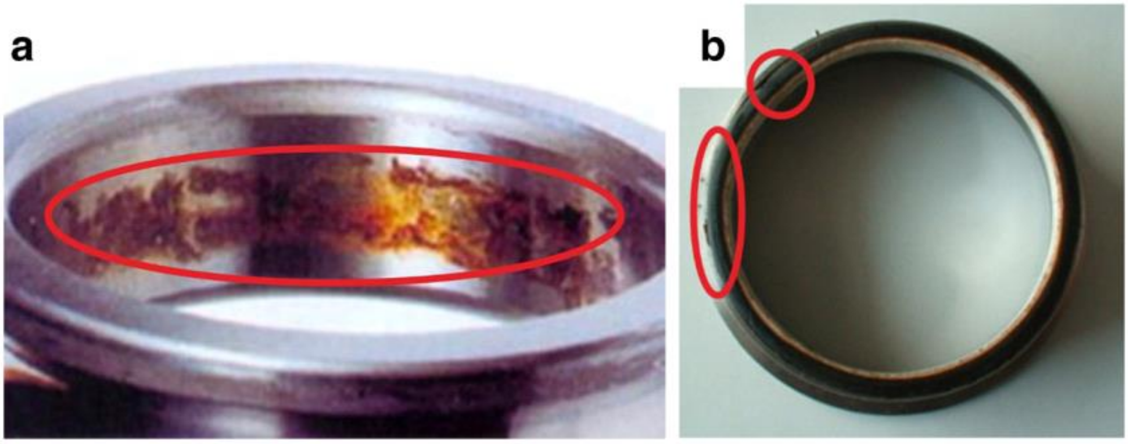

Figure 1: Damage on bearing (a) and seals (b) caused by the contamination particles (Zhang et al. 2017)

The particles inside the system can vary in size. Smaller mechanical particles have not always been regarded as dangerous to the system. It was thought that they are too small to cause damage (Figure 1) in the system. They are also quite often soft particles that do not cause wear. When entering the tank, the hydraulic fluid can be in a turbulent motion. This motion can cause these small, not so dangerous, particles to stick together and form larger particles that then can damage the system. Also, a static charge within these smaller particles can cause them to unite. These particles can be removed with conventional filters that have very fine filtering media. A centrifugal filter can be used as well. (Phillips et al. 2015)

In addition to the particles, there are also other forms of contamination. One of them is water. The water inside the hydraulic system can cause mechanical failures by way of rust or causing mechanical wear by reducing the viscosity of oil and therefore the oil film between components can vanish. Disappearing oil film means that parts that should not touch each other start touching and therefore they start to wear. (Zhang et al. 2017) That causes particle contamination to be generated (Burenin 2011). Other destruction causing situation comes when the water freezes inside the system. Water also increases the acidity of the hydraulic oil and therefore speeds up the corrosion. An example of corrosion damage is shown in Figure 2. The water inside the oil significantly decreases the bearing life when the water level rises at low levels (up to 250ppm), but the effect is not that significant when the water level is already high (>1000ppm). (Zhang et al. 2017)

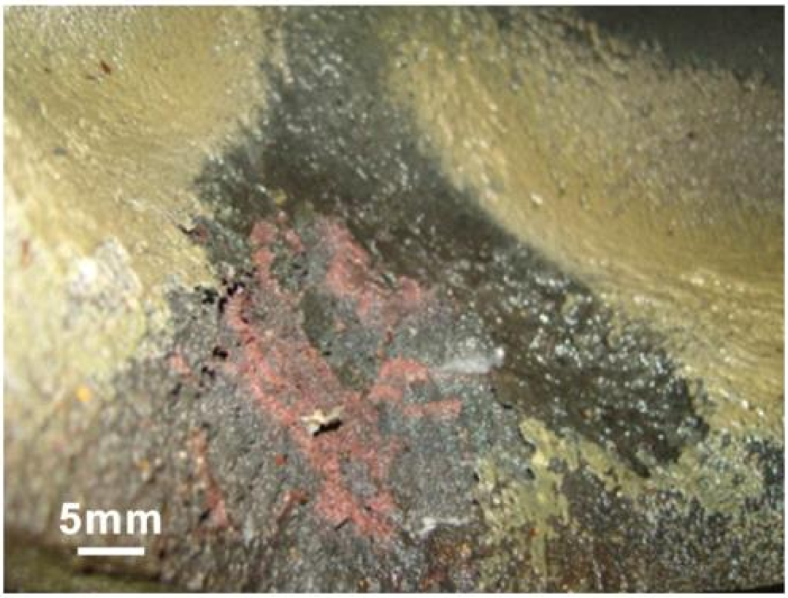

Figure 2: Corrosion caused by water on the pump casing (Zhang et al. 2017)

Another kind of contamination is gas. They are also rarely investigated. Flowing around the system in a dissolved form gas is not that dangerous but when it causes bubbles it can be very dangerous. (Zhang et al. 2017) Bubbles can be generated from the dissolved gas when the pressure in the hydraulic system drops below the gas separation pressure. When those bubbles collapse due to rising pressure, they can cause erosion and structural damages (known as cavitation, Figure 3) to the components. (Zhou et al. 2015)

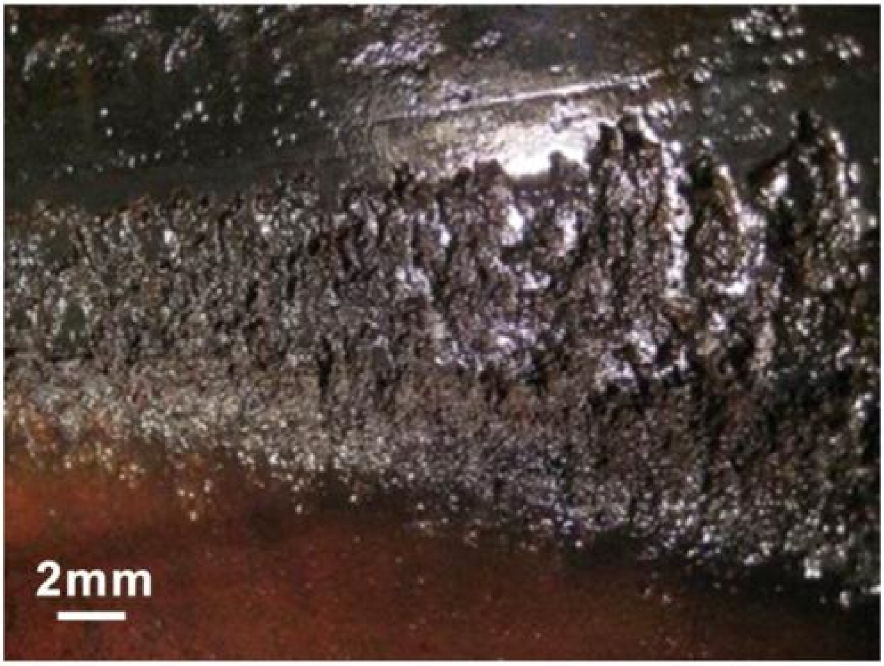

Figure 3: Cavitation damage on valve surface (Zhang et al. 2017)

In addition to the physical contaminations, there is also a fourth kind of contamination that is mostly caused by the filter itself. It is an electrostatic charge (ESC). ESC is generated when hydraulic fluid rubs the filter media. More electrostatic charge is generated if the system requirements are higher (equivalent to more stress on the filter) and if the used oil has low conductivity. Electrostatic charge can cause damage to the system components, especially to sensors and transducers. Damage to the filter is also possible because electrostatic charge can burn holes into the filter media. Even arching can be spotted inside the oil tank due to ESC. (Staudt et al. 2020) Contamination in the systems can be handled using filter types that are represented in the next chapter.

2.2 Filter types

Although in many situations the filter is an essential part of the system, sometimes it is beneficial to be able to complete the system without the filter. One of the reasons can be lack of space. An example of this kind of system is an electrohydraulic actuator (EHA). It has a closed circuit with a pump and an actuator, all powered by an electric motor. Having a filter would require a lot more room and costs would rise. (Michel et al. 2017)

In addition to installing a filter, it is good to think of ways to prevent contamination from entering the system in the first place. It is a lot more cost-effective to prevent the contamination from coming than to get rid of the contamination. (Downs 1997)

Figure 4 shows the structure of a filter. It consists of the housing and the filter element itself. The housing is usually made of metal such as aluminum alloy. The housing has two parts in it. The filter head (top of Figure 4) has the fluid ports and the clogging indicator. The bowl on the other hand is the part that surrounds the filter element. (Aruljothi et al. 2010)

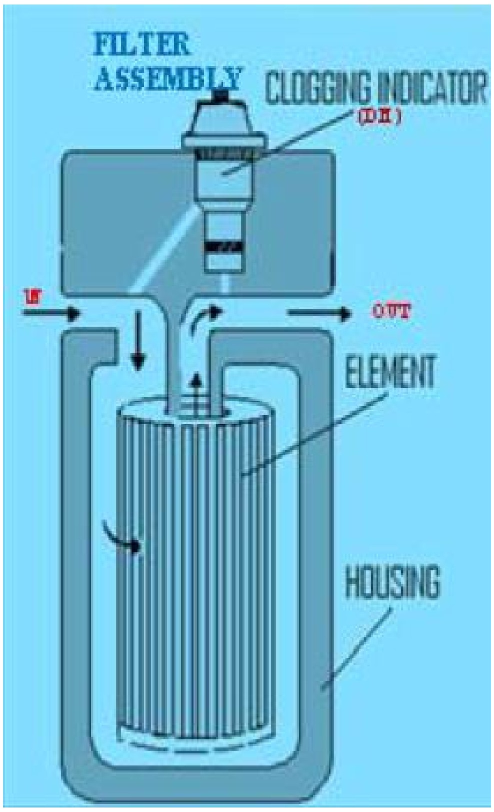

Figure 4: The structure of a filter

The most common materials for filter meshes are glass fiber and stainless steel. From those two the glass fiber mesh has a lot better fluid compatibility when in contact with hydraulic fluid. The filtration efficiency of a glass fiber mesh is also a lot better. On the other hand, stainless steel meshes resist higher pressures. (Aruljothi et al. 2010, Aruljothi et al. 2014) Meshes can also be made out of other materials. Those materials are fabric, activated charcoal, and mineral wools but they are not used in hydraulics (Sutherland 2007). The structure of the mesh is pleated because that way it is possible to fit more surface area to the smaller case (Aruljothi et al. 2010).

Another filter group is called power filters. They use force fields to filter contamination out of the fluid. Fields such as magnetic, inertial, gravitational, and electrical can be used depending on the application. (Burenin 2011)

One application of the power filter category is a magnetic filter. It can be used to filter out the ferromagnetic particles that react to magnets. These kinds of particles are a result of wear within the system and sometimes cannot even be filtered with mechanical filters due to their small size. Analysis shows that some nonmagnetic particles are bound to ferromagnetic particles which means that a magnetic filter removes some nonmagnetic particles as well. (Burenin 2008)

Centrifugal filters are also part of the power filter category. They are not used that often because they are not continuous filters. Meaning that they need to filter the fluid in patches. They can remove as small as 0.1 µm particles. They are usually not used for the full flow of the system (only 2-10% of the flow) due to the non-continuous filtering. Lower the viscosity of the fluid the better is the filtration. Viscosity lowers as the temperature rises so centrifugal filters are good for high-temperature applications. A continuous centrifugal filter exists and it is called a cyclone, but it does not get rid of the smaller particles. (Phillips et al. 2015)

Another group of filters is a hydrodynamic filter. That filter includes a velocity that is a tangent to the filter surface. That velocity component is used to continuously keep the filter open and remove the filtered particles from the filter. A force in the way of centrifugal or vibrational can be added to prevent the settlement of contamination on the surface of the filter. (Devisilov et al. 2019)

The filter types presented in this chapter are collected in Figure 5. It also contains a couple of power filter types that were not introduced in this thesis. They are named after the used force field.

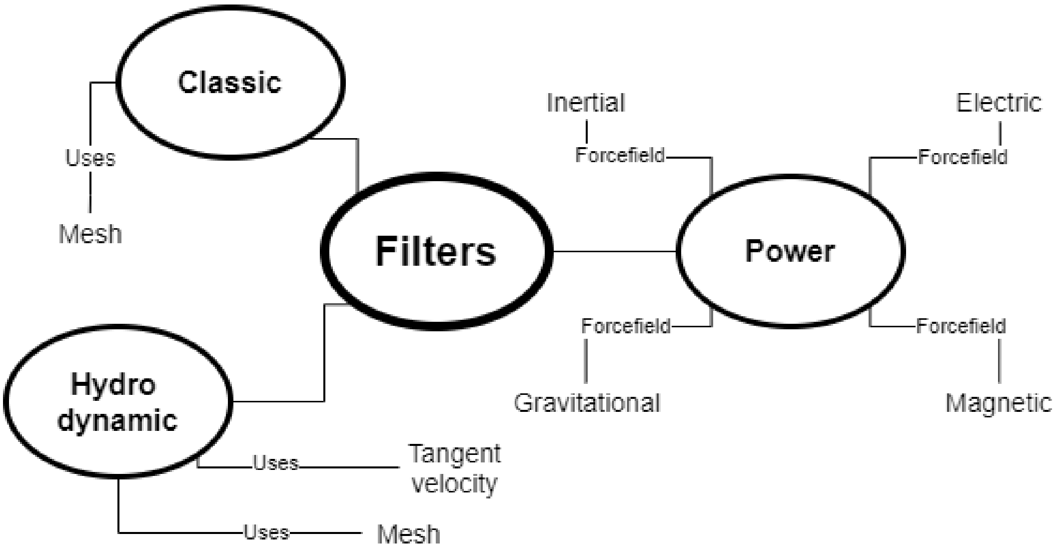

Figure 5: Chart of the filter types

The filter type has to be chosen, but also the size of the filter must be decided according to the needs of the system. The next chapter is about choosing the size of the filter.

2.3 Sizing the filter

When sizing the filter, it is needed to know what kind of clearances are in the system. Typically, those clearances are between 0.5 µm and 250 µm. For example, gear pump has a clearance of 0.5 µm - 5 µm and piston pump has a clearance of 0.5 µm - 40 µm. To avoid component wear, the size of the filter should be approximately the same as the size of the smallest clearance between components. (Phillips et al. 2015)

The size of the filter can be described as a cleanliness rating. That rating represents the number of particles allowed inside the system. Examples of cleanliness ratings are shown in Table 1. The rating starts at one and goes up in steps of one. A smaller rating means more tight requirements and therefore fewer particles in the fluid.

Table 1: Filtration rating of filters (partial). Information from standard ISO 4406. Table based on a similar table from (Kauranne et al. 1999)

Cleanliness rating	Particles allowed (pcs/100ml)	
	Minimum	Maximum
1	1	2
2	2	4
5	16	32
10	500	1000
15	$1.6 \cdot 10^4$	$3.2 \cdot 10^4$
20	$5.0 \cdot 10^5$	$1.0 \cdot 10^6$
25	$1.6 \cdot 10^7$	$3.2 \cdot 10^7$

Components in hydraulic systems have different requirements for fluid cleanliness. Those requirements are considered when designing the filter for the system. The requirements can differ depending on the component, manufacturer, and pressure level inside the system. (Kauranne et al. 1999)

Another way to characterize filters is to use the ß ratio. It is defined by the number of particles above a specific size. The ratio is taken between the number of particles upstream and downstream. (Aruljothi et al. 2010) The particle numbers can be obtained from samples taken from the fluid. Companies also offer testing as a service. They have fast and accurate automated test rigs for finding out the ß ratio of the filter. (Sutherland 2007)

Measuring the ß ratio can be done using the multi-pass test or the single-pass test. The difference in them is based on the way the fluid is handled within the system. The circuits for these tests are shown in Figure 6. Downstream is marked with DS and upstream with US. Contamination amounts calculated from those measurement points are used when calculating the ß-ratio.

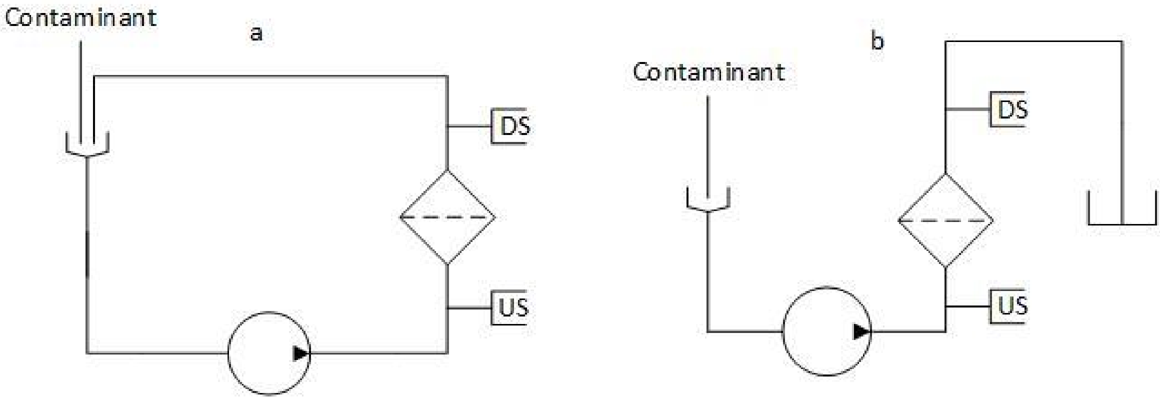

Figure 6: Multi-pass (a) and single-pass (b) test circuits.
Schematics adapted from (Sutherland 2007 p. 32-33)

In a multi-pass test, the fluid is circulating the system. A predefined amount of contamination (dust or particles) is added to the fluid and then that fluid is directed to the filter. (Aruljothi et al. 2014) The contamination must be added continuously because it gets stuck to the filter and some of it goes out of the system with the samples. The goal is to keep the flow of contamination constant. After a while, two oil samples can be taken from the system. One of the samples is taken from downstream of the filter where the oil has not gone through the filter. The second sample is taken from the upstream where the oil is not yet purified. Also, a predefined pressure drop across the filter must be maintained for this test to be reliable. (Sutherland 2007 p. 32-33)

The single-pass test does not circulate the oil. It takes oil from a source where contamination will be added to the fluid and then deposits the oil to a second container. The accumulation of contamination on the filter surface can happen and therefore the pressure drop across the filter rises. The samples are obtained in the same way as in the multi-pass test, from upstream and downstream. This test can easily show how the filter gets affected by the contamination on its surface. In other words when the filter becomes too clogged to work or when the pressure drop becomes too high. (Sutherland 2007)

According to Aruljothi et al., the ß ratio is found to be better when using glass fiber filter media over stainless-steel filter media in hydraulic systems. Glass fiber filter is more efficient, has a longer service life, and a higher dust holding capacity. (Aruljothi et al. 2014) The ß ratio can vary also when the upstream contamination sizes or the distribution levels differ from the ones used in testing. In many cases, the ß ratio also decreases when the pressure drop over the filter increases. This can happen when the filter gets clogged due to the contamination in the filter media. (Sutherland 2007)

2.4 Location of the filter

Filters can be positioned in different ways to a system. There can also be multiple filters in one system. Possible filter locations are showcased in Figure 7. Locations are specified with numbers 1 to 6. Note that the figure does not depict a fully functional hydraulic system, but it shows everything needed for understanding filter positioning basics.

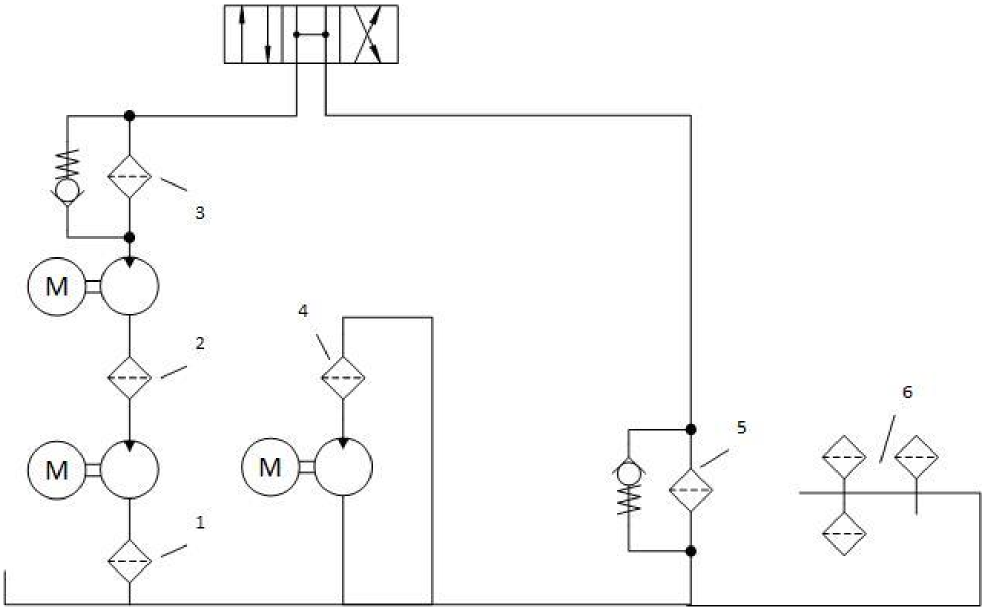

Figure 7: Different positions of filters (adapted from reference (Kauranne et al. 1999))

Number 1 points to a suction filter and it is located between the tank and the pump. The pump pulls fluid from the tank through the filter. Numbers 2 and 3 represent pressure filters. They are located between the pressure generation and the actuation part of the system. The difference between these two is that the number 3 also has a pressure relief valve that can relieve the pressure by letting the fluid go past the filter if the filter is not allowing enough flow through it. A situation like that can happen if contamination is clogging the filter. Number 4 is part of a separate circuit, and it will be introduced later. Number 5 points to a filter that is commonly used in hydraulic systems, and it is called a return line filter. It cleans the fluid before it comes back to the tank after being in the actuators. Filters pointed by group 6 are air filters. Two different types are a breather filter or both fill and breather filter. (Kauranne et al. 1999) Breather filters can lower the amounts of particles and moisture that enter the system (Downs 1997). They are used to filter the air coming from the environment to the tank and the other way around when the volume of the oil inside the tank changes. That is to avoid contamination such as dust coming to the system from the air around the system because the industrial environment of the system is not usually clean. (Kauranne et al. 1999)

In Figure 7 the filter number 4 is also called an auxiliary or offline filter. When using auxiliary filtering the fluid is pulled from the tank to the filtering system and immediately back to the tank. The filtration process is made with a series of filters with all the time decreasing filter sizes. The series structure is used to avoid clogging. This kind of filtration can be useful if the system is not running continuously. Without filtration, the oil would stay still and collect contamination, but an auxiliary filtration system keeps the oil clean whether the system is running or not. (Singh et al. 2012)

A second way to categorize filters is to divide them into protective and work filters. In Figure 7 the filters 2, 3, 4, and 5 are work filters, whereas 1 and 6 are protective filters. Work filters take care of the filtration requirements given to the system by component restrictions. (Kauranne et al. 1999)

2.5 Estimating the pressure drop over the filter

Pressure drop over the filter is good to know when sizing a hydraulic system. A situation where the system is sized so that pump produces exactly enough for the actuator but then filter pressure drop is unaccounted for, can lead to the system not being able to do the cycle it was designed for. The pressure drop is caused by the resistance to the fluid flow. The pressure drop of the filter can be counted using Darcy's equation (1). (Momin et al. 2017)

$$\Delta P = \frac{Q \cdot \mu \cdot t_{filter}}{A_{filter} \cdot k \cdot \varepsilon} \tag{1}$$

In equation (1) ΔP is the pressure drop when fluid goes past the filter. Fluid is handled using two variables. Q is the flow going through the filter and μ is the dynamic viscosity. The rest of the parameters are filter-related. A_{filter} is the filtering area, t_{filter} is the thickness of the filter material, k is the permeability constant for the filter material and ε is the porosity. (Momin et al. 2017) This equation shows that pressure drop gets higher if the fluid flow rate increases.

A second way to find out the pressure drop is to use the filter datasheet if that is available. That is a better way when compared with Darcy's equation. Those datasheets often contain pressure drop charts that are made based on that specific filter. Therefore, the datasheet is more accurate than the data counted using Darcy's equation. The theoretical pressure drop of the filters used in the measurements will be counted later in this thesis.

3. EXECUTION OF THE MEASUREMENTS

This chapter is the practical part of the thesis. First, the test rig and its components, like filters, are introduced. After that, the same is done to the measurement cycles and measurements in general. Three filter sets are included in the tests. They are referred to as clean filters (new filters), 2,5bar filters (filters that are clogged and are measured to have 2,5bar pressure drop), and 5,0bar filters (filters that have 5,0bar pressure drop). Those pressure drops were measured at 38l/min flow through the filter. The test rig is a DDH crane. DDH comes from Direct Driven Hydraulics which means that the system is controlled with a motor that drives the pump(s) and not by valve. The next chapter showcases the test rig in a more detailed way.

3.1 Test rig

Experimental investigation for this research was made using the test rig presented in Figure 8 and Figure 9. That test rig has two different hydraulic systems that can be switched using two sets of shutoff valves. Now, DDH1 (black markers) that is visible on the bottom of the system next to filters (yellow markers) was used while DDH2 (visible behind the cylinder with red outline) was blocked out and not used in this experiment.

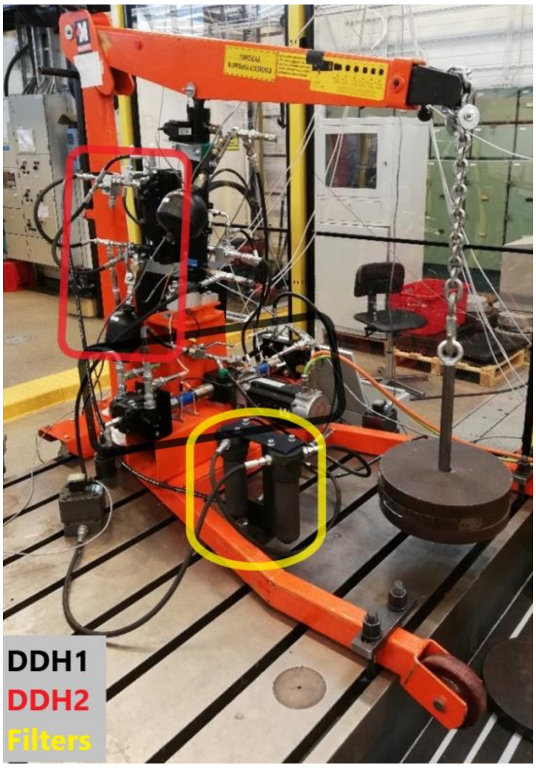

Figure 8: Picture of the test rig used in measurements

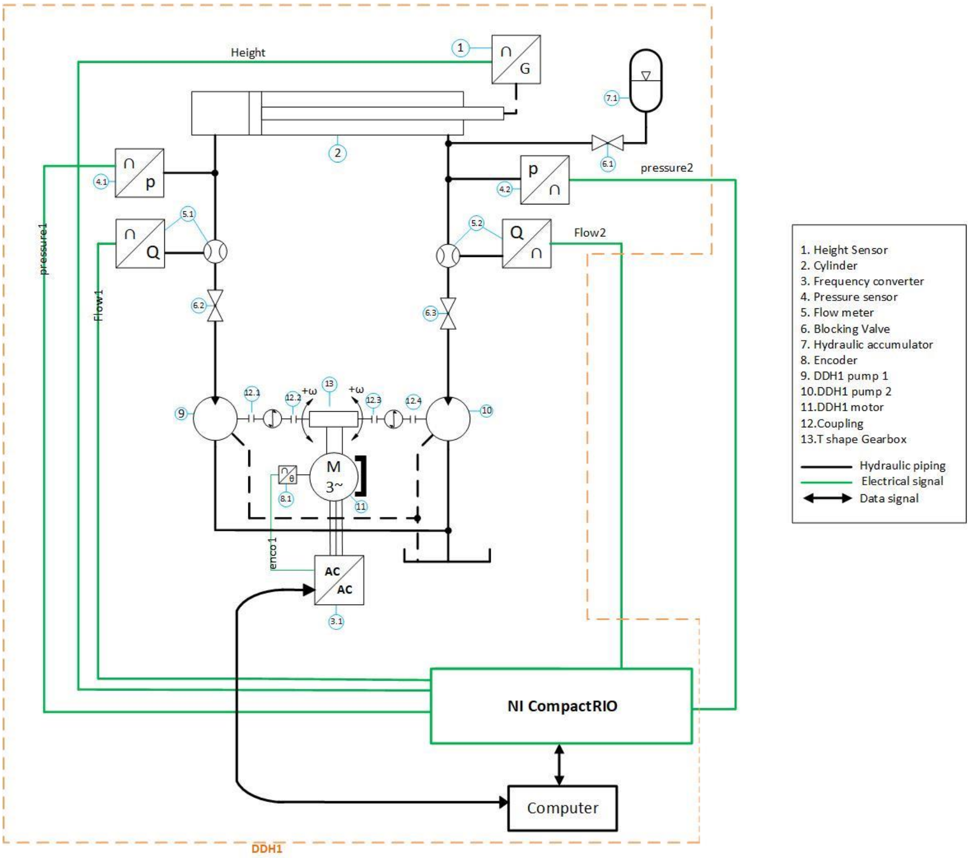

Figure 9: Crane schematics

Photograph of the system is in Figure 8 and schematics for the test rig can be found in Figure 9. As the name DDH describes, the system is direct driven. That means that there are no valves taking care of the controls. Instead, the control is realized using the rotation of the pump. This system has two pumps and one motor that is driving both pumps. The two pumps must spin in opposite directions for the system to function. When one pump is pushing fluid to the cylinder, the other must be emptying the cylinder. The T-gearbox between these is used to divide the rotational movement into two directions and the directions are correct.

Pumps in the system are gear motors, but they can be used as pumps due to their structure and therefore they are referred to as pumps. The pumps are not similarly sized because the flow needed is different depending on the side of the cylinder, because the other side has the piston rod. Their sizes are 22.80${}^{cm^2}/_{rev}$ and 14.40${}^{cm^2}/_{rev}$. The ratio between the pump sizes is ${}^{14.40\ cm^2/rev}\Big/_{22.80\ cm^2/rev} = {}^{12}/_{19} = 0.631578 \ldots.$

The cylinder used in this test rig has a 60mm shaft diameter and a 30mm rod diameter. The ratio between the areas where the pressure effect during operation is

$\pi \cdot (60mm)^2 - \pi \cdot (30mm)^2 \big/ \pi \cdot (60mm)^2 = 3/4 = 0.75$. The ratio between the pump sizes and cylinder areas is unequal. This causes problems due to uneven flow during the operation. In this experiment that effect is not that big due to the small size of the system. The accumulator next to the cylinder is balancing the flow in the system by absorbing or supplying flow.

The maximum rotational speed of the driving motor in DDH1 is 4800rpm, but in this test rig, 1000rpm was used as the maximum at the time. The rotational energy is transferred to the system using a T-Gearbox that splits the rotation to both motors. The gearbox has a ratio of 1.5:1 which means that the rotational speed from the motor must be 1.5 times the speed that is wanted from the pumps. In this thesis, the rotational speeds are referred to as the motor speeds, and therefore pumps speeds are lower than the given rotational speed. Table 2 shows the components used in this test rig.

Table 2: Component list of the test rig

Component	Manufacturer	Model	Information
Motor	Emerson industrial automation	Unimotor 115U2C300VACAA115190	n_{max} = 4800rpm P_{max} = 2,54kW
T-Gearbox	Nidec Graessner GMBH	PowerGear P90FL	Gear ratio 1.5:1
Pumps	Vivoil	X2M4901EPPE	V_k = 14,40 cm^3/rev
		X2M5501EPPE	V_k = 22,80 cm^3/rev
Cylinder	MIRO	C-10-60/30x400 A-SS	L_{stroke} = 40cm d_{shaft} = 60mm d_{rod} = 30mm
Filter mesh	MP Filtri	HP0504A16ARP01	Inorganic 16µm microfiber
Filter casing	MP Filtri	FMM0504ZACA16RP03	With reverse flow. bypass valve and sensor connection

The main parts of this experiment were the filters. The mesh of the filter is made of inorganic microfiber and the size of the filter is 16µm. The filter casing has a 6bar bypass valve and it can also receive reverse flow without contamination being released to the system. There were three different sets of filter meshes available for this research. The filter sets were introduced at beginning of chapter 3.

It is also possible to alter the load hanging from the tip of the boom. The load can be changed in increments of 25kg. The boom can also be extended but it was not used in the experiments for this thesis because it was stuck.

Data acquisition of this system is done using LabView and National Instruments data acquisition system. Temperatures were measured using RedLab and recorded using

LabView. The sensors are connected to the crane and the NI board. A LabView program records the measurement data and writes it to an excel file. That Excel file is later visualized using MatLab. The LabView program is also responsible for controlling the motor that is driving the crane.

Also, software called CTScope is used to get information from the motor itself. That information is not connected to LabView, so it must be synchronized using MatLab. The point used for synchronizing was the first change in motor speed and as CTScope was started first, the extra measurement data, in the beginning, was taken out so that the start time in CTScope was the same as in LabView. The data from the LabView was not edited during this synchronization.

3.2 Test procedure

The main measurement from the test rig was the pressure drop over the filter. That was measured using differential pressure sensors connected to both filters. Other factors were also measured. These include flow, piston side pressure, cylinder position, and temperatures. In this research, the changing values within the system were the hanging load, motor speed, and filter cleanliness.

The tests were performed by completing every given combination of the changing elements. Filters that were used are the new set as well as the 2.5bar and the 5.0bar set. Motor speeds on the other hand were 200rpm, 500rpm, and 800rpm. In these measurements, the used loads were 0kg, 50kg, and 100kg. For the 0kg load, the weight rack was still attached to make the weight difference between loads constant 25kg. These motor speed and load values were chosen to achieve as wide coverage as possible of possible working conditions.

Automatic control of the crane allowed usage of a predefined cycle. The cycle was decided to be first up then down, and this was repeated three times to get some idea of what happens in the long run. The form of the cycle was decided because the crane is meant for lifting car engines and other similar tasks where an up-and-down cycle is used often with some amount of waiting on the top position. The repeating of the cycle is done to have more than one cycle to compare in case some errors would happen in the system. The cycle is visualized in Figure 10.

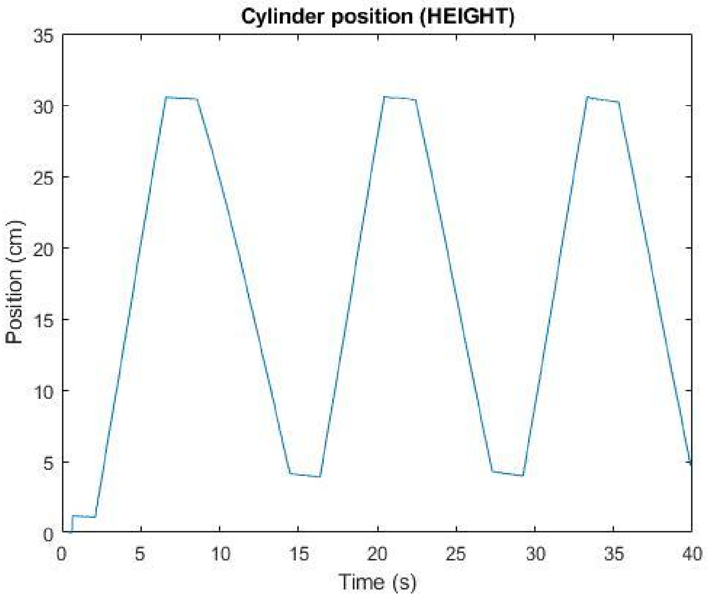

Figure 10: Cylinder position as cycle example (800rpm, 0kg, 0bar)

The data for this is from the clean filter test with a motor speed of 800rpm with no load. The start of the cycle is at a height of 0cm. The top value of the height during the cycle is 30cm and the lowest value is at 5cm. Those values were defined in the LabView program to be good values for the thesis because they were close to the maximum values for the cylinder and also possibly realistic values for the duty cycle.

4. RESULTS

Measurements in this thesis did not go as planned due to the differential pressure of the filters being too small for the sensors. The presentation of the results is divided into three chapters divided by the used filters. One example measurement is provided in every chapter.

4.1 Set 1 – Clean filters

As an example of the results from this cycle the cycle with 50kg of weight and 500rpm of motor speed is shown in Figure 11 and Figure 12. All of the results can be found in attachments.

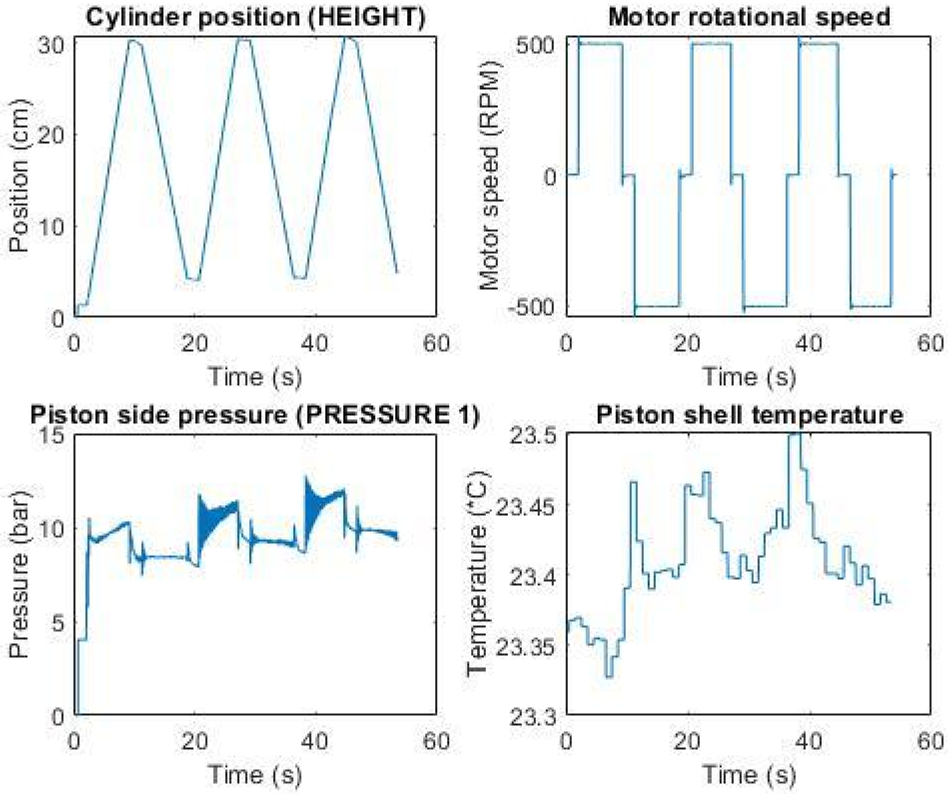

Figure 11: Cylinder position, pressure, piston shell temperature, and motor rotational speed from the measurements (500rpm, 50kg, and 0bar filters)

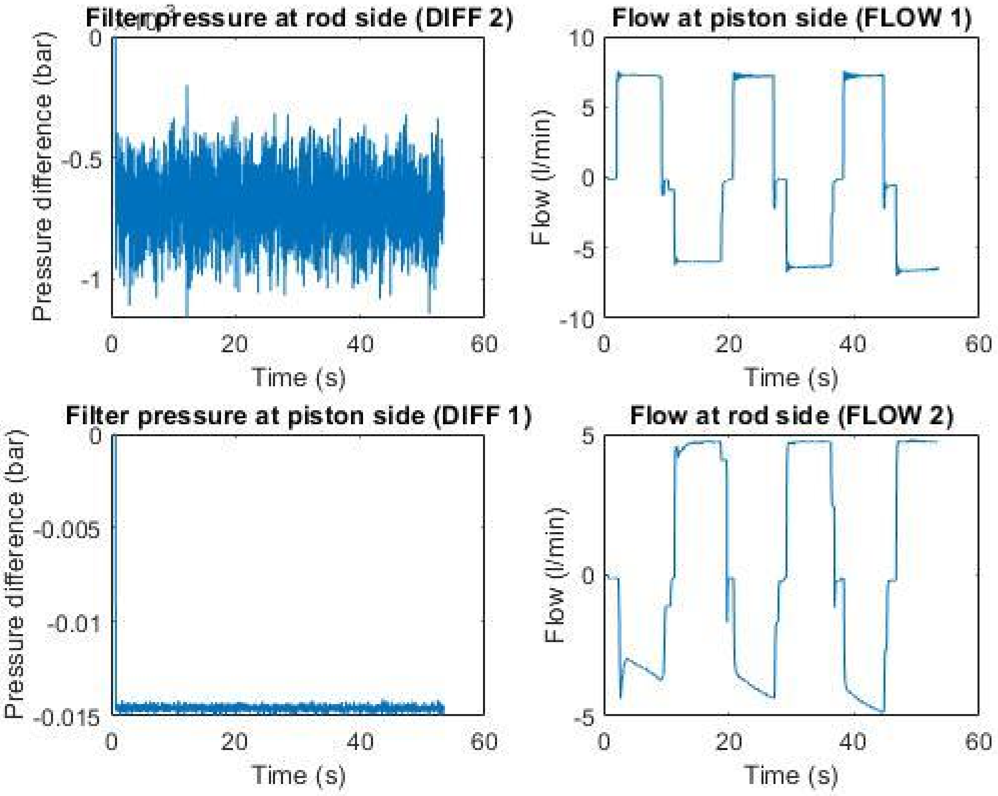

Figure 12: Filter pressures and flows from the measurements (500rpm, 50kg, and 0bar filters)

Figure 11 shows the piston temperature to vary occasionally in a very small scope. That is noise from the sensor that is most likely due to the interference caused by a massive number of electrical wires and changing voltages close to the crane and the thermocouple. Also, the amount of variation is small because the minimum and maximum temperatures are inside 0.2°C. The motor rotational speed is a measured value like is the height. Piston side pressure looks to be sensible and has a maximum value of a bit over 10bar which is low but sensible for a small system like the one used in these measurements.

As visible in Figure 12 measurements on clean filters did not produce any data on filters. The differential pressure sensors have a dead zone of 1.25bar in them. With the clean filters that dead zone was not exceeded and therefore the only thing that was visible in the data was the measurement noise of the sensor. The differential pressure sensor 2 also has a multiplier of 10^{-3} that is not visible due to the chart title. They are negative values, which is not realistic, but the values are so small that they are most likely caused by bias in the sensor.

In addition to the piston shell temperature also other temperatures were recorded from the system. All of the temperatures were measured outside the system components, and they are collected in Figure 13.

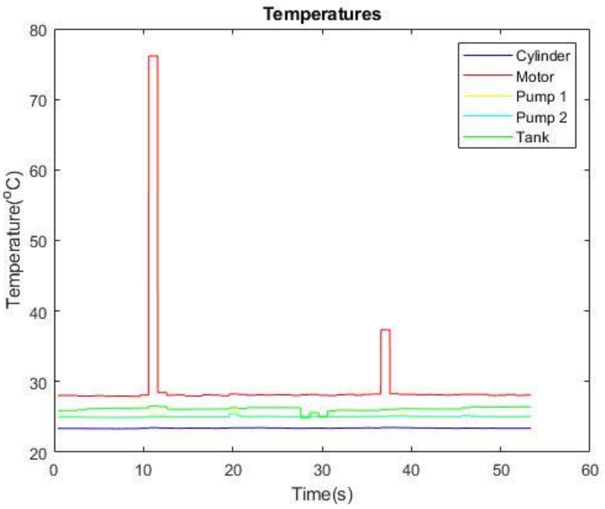

Figure 13: System temperatures (500rpm, 50kg, 0bar)

The motor temperature has a couple of spikes which can be considered as measurement error. Otherwise, nothing stands out on the chart. The motor is the warmest component and it is not surprising because it is not insulated, and it is an electric machine.

After the measurements, new filters were changed to the second set of filters. These filters have already some contamination in them and should therefore cause a reaction in differential pressure sensors.

4.2 Set 2 – 2,5bar pressure drop filters

According to the company that provided these filters the contamination inside these filters should cause around 2.5bar pressure drop. Test measurement was made using the highest speed for maximum pressure drop. This was decided using Darcy's equation (equation 1) which shows that maximum flow gives out maximum pressure drop. Although these filters had some contamination, the sensors still did not produce any detectable pressure drop and the filters were immediately changed to the 5.0bar filters without conducting measurements using these filters.

4.3 Set 3 – 5,0bar pressure drop filters

Set 3 had filters where the pressure drop was described to be 5.0bar. That pressure drop was measured using 38l/min flow. As an example, charts are presented from the maximum motor rotational speed case with no load. The rotational speed should make this to be the best configuration to get some pressure drop data from the filters. That data is presented in Figure 14 and Figure 15.

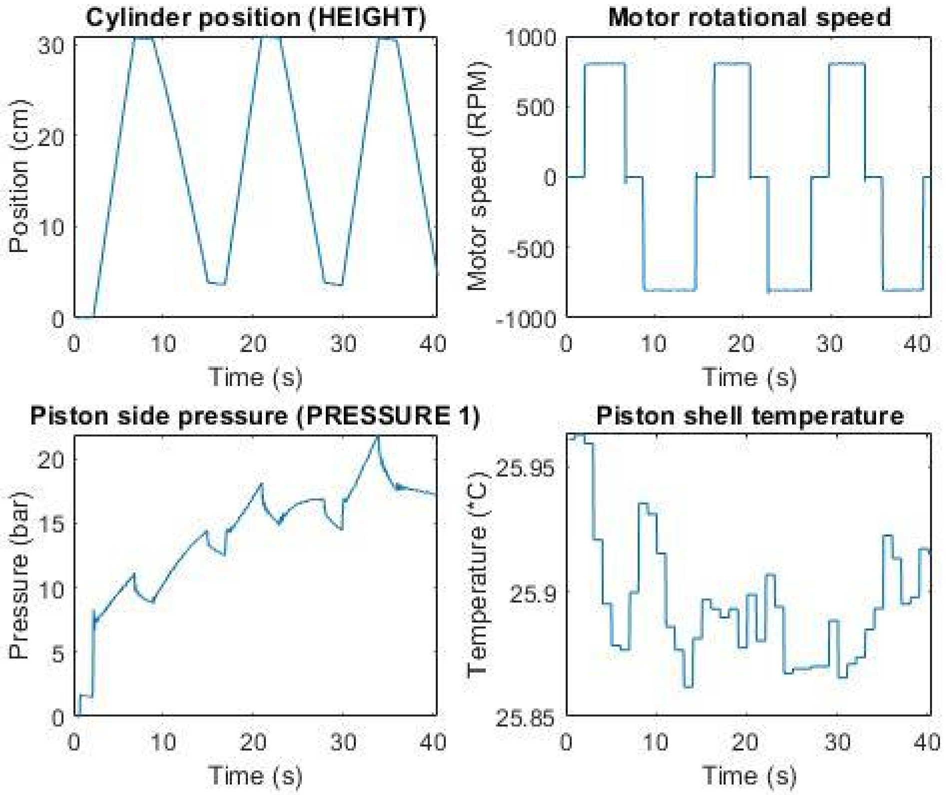

Figure 14: First four charts from the measurements (800rpm, 0kg, and 5.0bar filters)

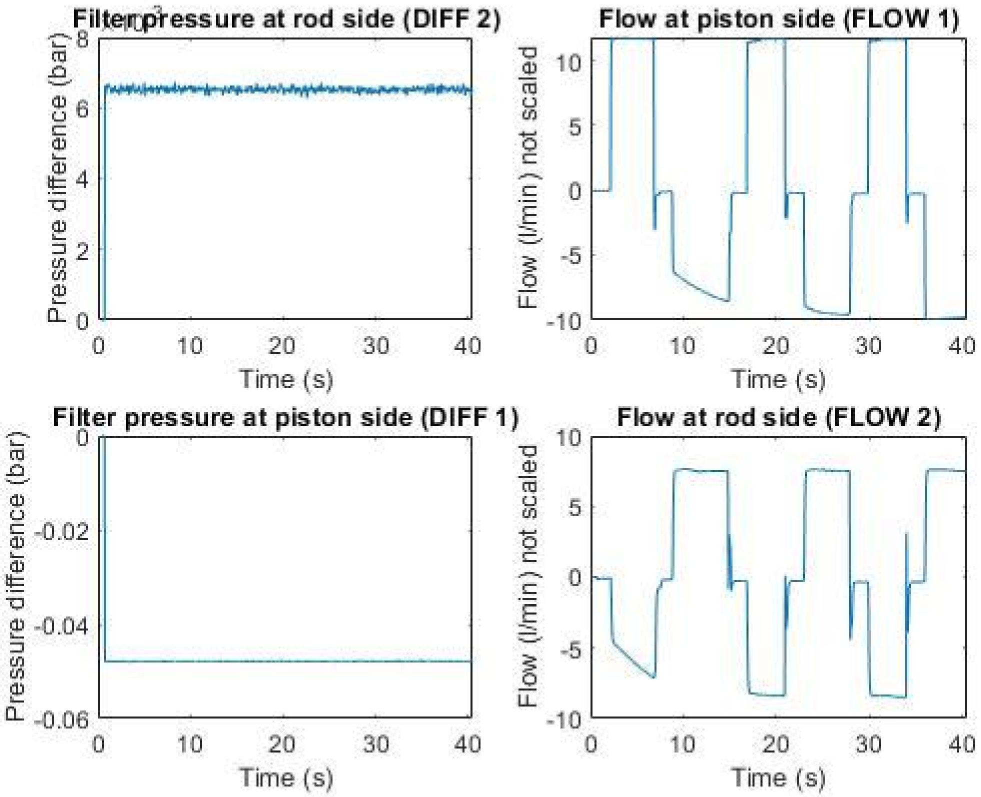

Figure 15: Second four charts from the measurements (800rpm, 0kg, and 5.0bar filters)

As visible in Figure 15 there is still no visible signal from the differential pressure sensors. Now the system reaches approximately 12l/min flows but still, it is not enough to cause a high enough pressure difference for the sensors to measure. Temperatures were also measured, and they are presented in Figure 16.

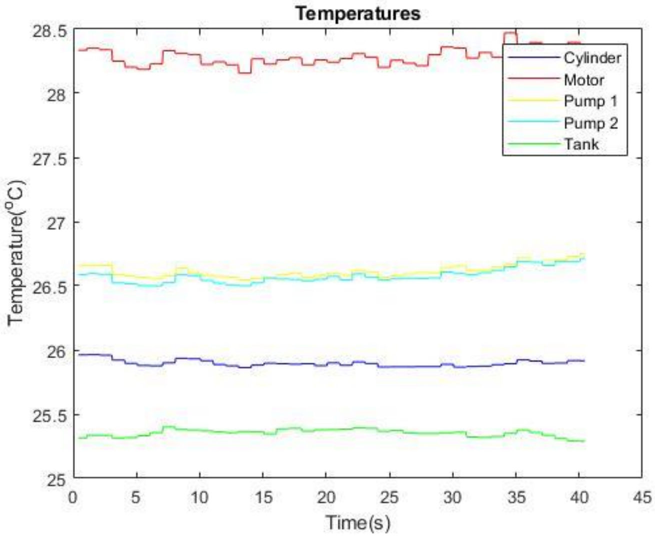

Figure 16: Temperature data from 800rpm, 0kg, and 5.0bar measurement

As expected, 45 seconds of measurements do not cause any big differences in the temperature. Especially with these sensors that are outside the components and not in the oil. Also, the same thing that happened in previous measurements is that the motor is the warmest component. This time there were no spikes in the measurement graphs.

4.4 Data comparison

The differential pressure sensors did not show anything in the charts, but it does not mean that there is nothing to be noticed. Now flow 1 and pressure 1 are taken into a more accurate investigation. Figure 9 can be checked for more accurate sensor locations. First, the 200rpm rotational speeds with both filters and all three loads are in Figure 17 and Figure 18.

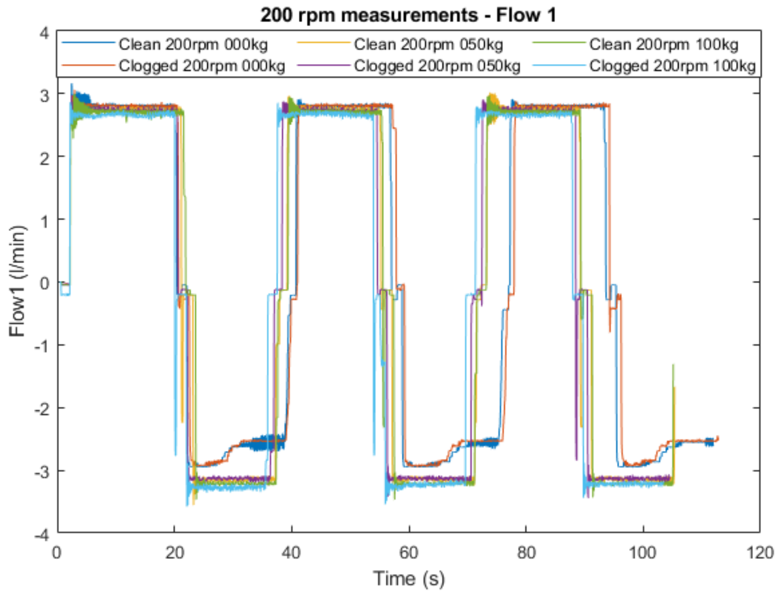

Figure 17: Flow charts with 200rpm and different loads

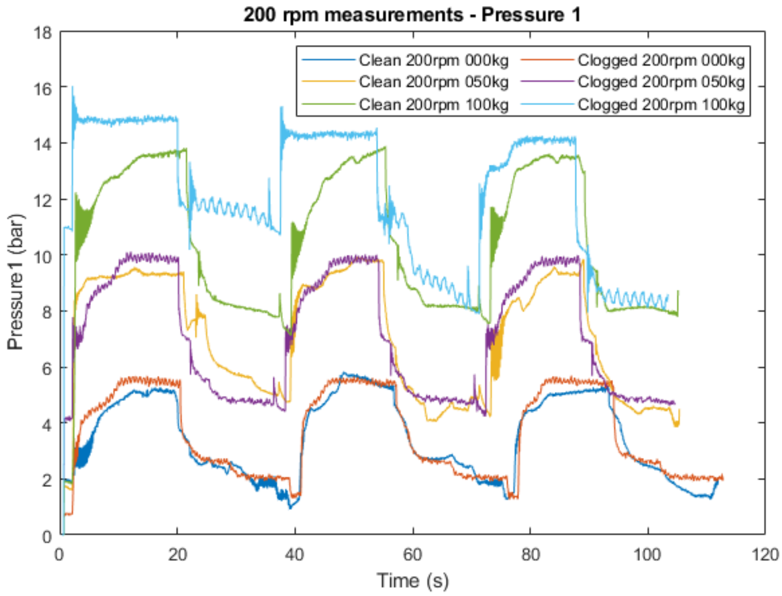

Figure 18: Pressure charts with 200rpm and different loads

In Figure 17 the flow charts look quite similar. Small differences are present, but it is good to remember that measurement error can cause variation. The maximum values from the no-load case are a bit different from other measurement runs. That varying can be caused by the change in system dynamics because there is no weight trying to pull the crane downwards.

Pressure-wise (Figure 18) there are more differences. This time the differences are caused by the increased load. The increased load needs more force to lift, and more force needed means more pressure is needed. In a no-load case, there is almost no difference between the charts. The biggest difference can be seen in the 100kg-load case where clean filters reach the maximum pressure almost instantly, but the clogged filter seems to restrict the rise of the pressure and the cycle took a couple of seconds longer.

Next, the same kind of analysis is conducted on the 500rpm cycles. The data about the flow can be found in Figure 19.

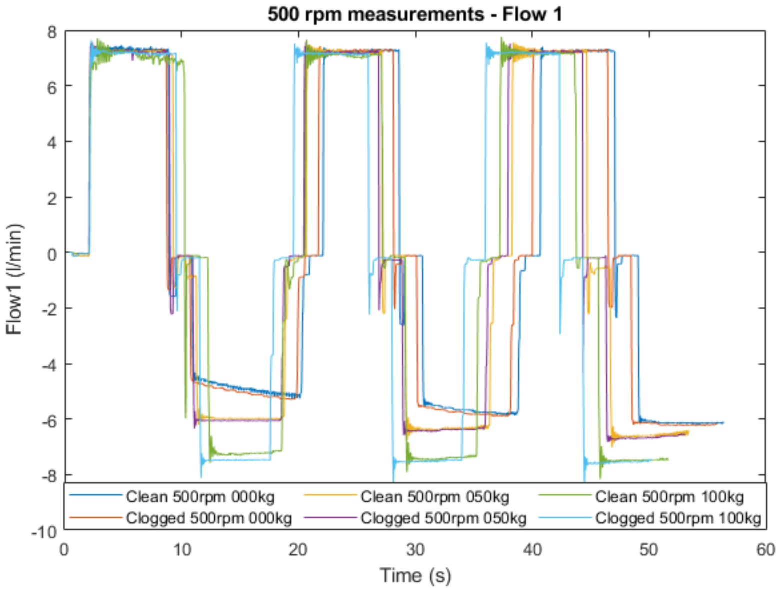

Figure 19: Flow 1 charts with 500rpm and different loads

Figure 19 shows that now some differences are starting to form. These are there because of the weight and not that much because of the filters. On these measurements, the clogged filter with 100kg weight was the fastest to reach the end of the cycle. Now lower loads meant longer cycle times and those longer cycles came because the flow was lower when the cylinder was coming back down. This is most likely due to the weight pulling the crane down with higher loads. Pressures on the other hand did not show that much diversity in Figure 20.

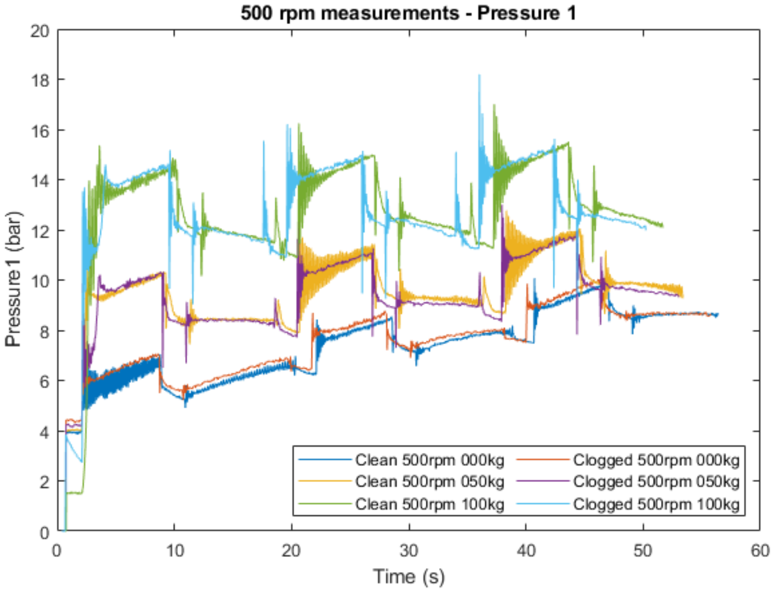

Figure 20: Pressure 1 charts with 500rpm and different loads

Like in the 200rpm cases, the higher loads cause higher pressures but nothing else significant is visible. A couple of measurements show that filter choice causes a difference in the pressure chart. On the 0-load case, the clean filter has constantly lower pressures when compared to the clogged filter. On the other hand, the 50kg-load case shows the pressures the other way. The difference is so small that it is most likely caused by the measurement error and inaccuracy in the sensor.

Lastly, the 800rpm cases are left. Flows for that case are plotted in Figure 21

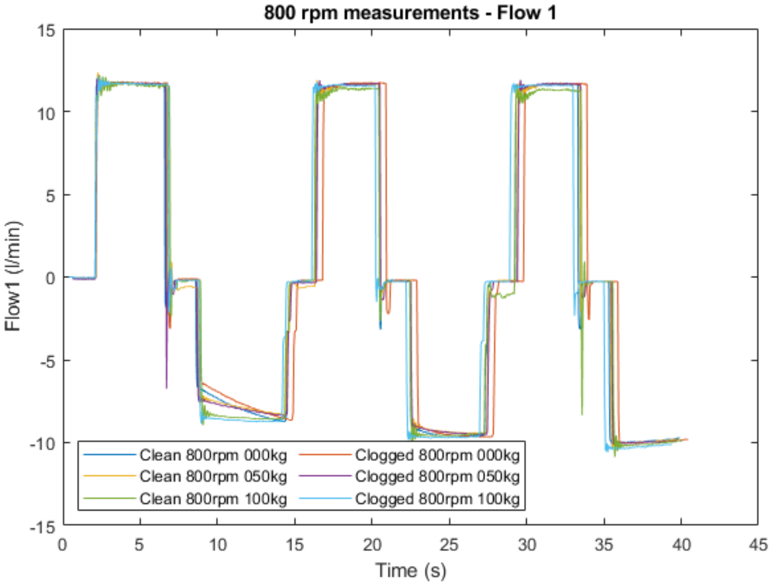

Figure 21: Flow 1 charts with 800rpm and different loads

Now the charts are almost on top of each other and therefore no visible data is available. In the end, the no-load case with a clogged filter (orange line) is taking a little bit longer to complete the cycle. Even that variation is only around a second so any significant conclusions cannot be drawn from that. Another small difference is visible in the first down motion of the cylinder. Now four of the charts gradually reach the minimum flow but two of the charts go down to it immediately. The two that do not have a soft landing are the 100kg-load cases. Like in the 500rpm case the weight most likely pulls the boom down faster than in lower weight cases. Pressures from the 800rpm cases in Figure 22 on the other hand look different compared to previous cases.

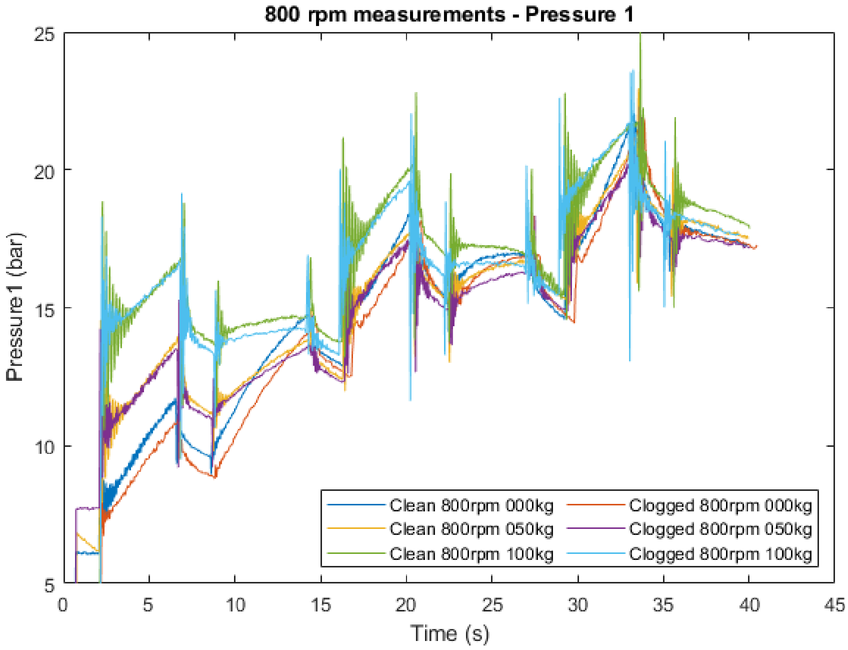

Figure 22: Pressure 1 charts with 800rpm and different loads

On the last two pressure charts (Figure 18 and Figure 20) the maximum pressure did not exceed 16bar. Now in the latest chart (Figure 22) the pressure is over 16 bar almost all the time. Before the pressure was more stable, and it did not rise all the time. Now the pressure does not drop while the cylinder is coming down or the system is stationary. The order of the pressures is still the same that 100kg-load cases have the highest pressure, and the lighter loads have lower pressure. In every pressure chart, there seems to be less damping with the not-clogged filters. To verify that it is happening because of the filters, more research is needed but it is a clear difference between charts where the load does not change.

Overall, not many varying aspects were visible in the charts. Even the few varying factors in the datasets were not caused by the change of the filters. The filters seemed to not affect the system performance.

4.5 Discussion

These measurements did not go as planned because the system was unable to produce a sufficient flow to cause measurable pressure drops over the filter. One way to find a number for the needed flow to get some measurement data is to expect them to work similarly to the clean counterparts. On the original chart (Figure 23) the pressure drop is slightly exponential. Used filters had ½" inlet and therefore the higher graph is the one that should be followed.

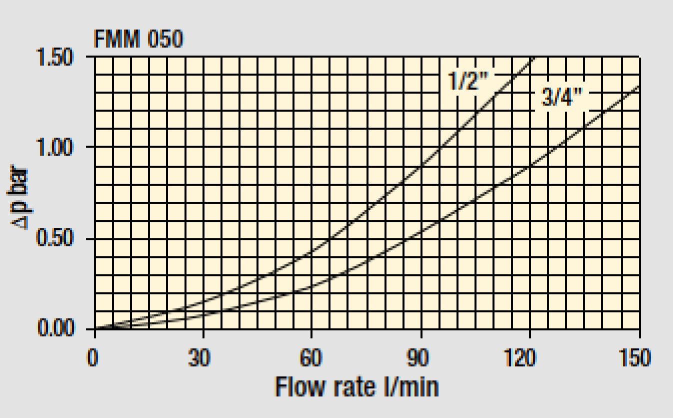

Figure 23: The dependency between pressure drop and flow rate through the filter (FMM-FHA series)

After using points from the original chart from Figure 23 and calculations in MatLab the chart can be generated for the situation where pressure drop at 38l/min is 2,5bar and 5bar. This was done by multiplying pressures with 2,5 and 5 respectively and then doing required scaling for the flow to make pressure drop values match at 38l/min mark.

Figure 24 contains the charts for the 2.5bar and 5.0bar filters. The clean filter graph is also present for reference. A blue horizontal line was also added to show the lower limit of the pressure sensor measurement range that is 1.25bar.

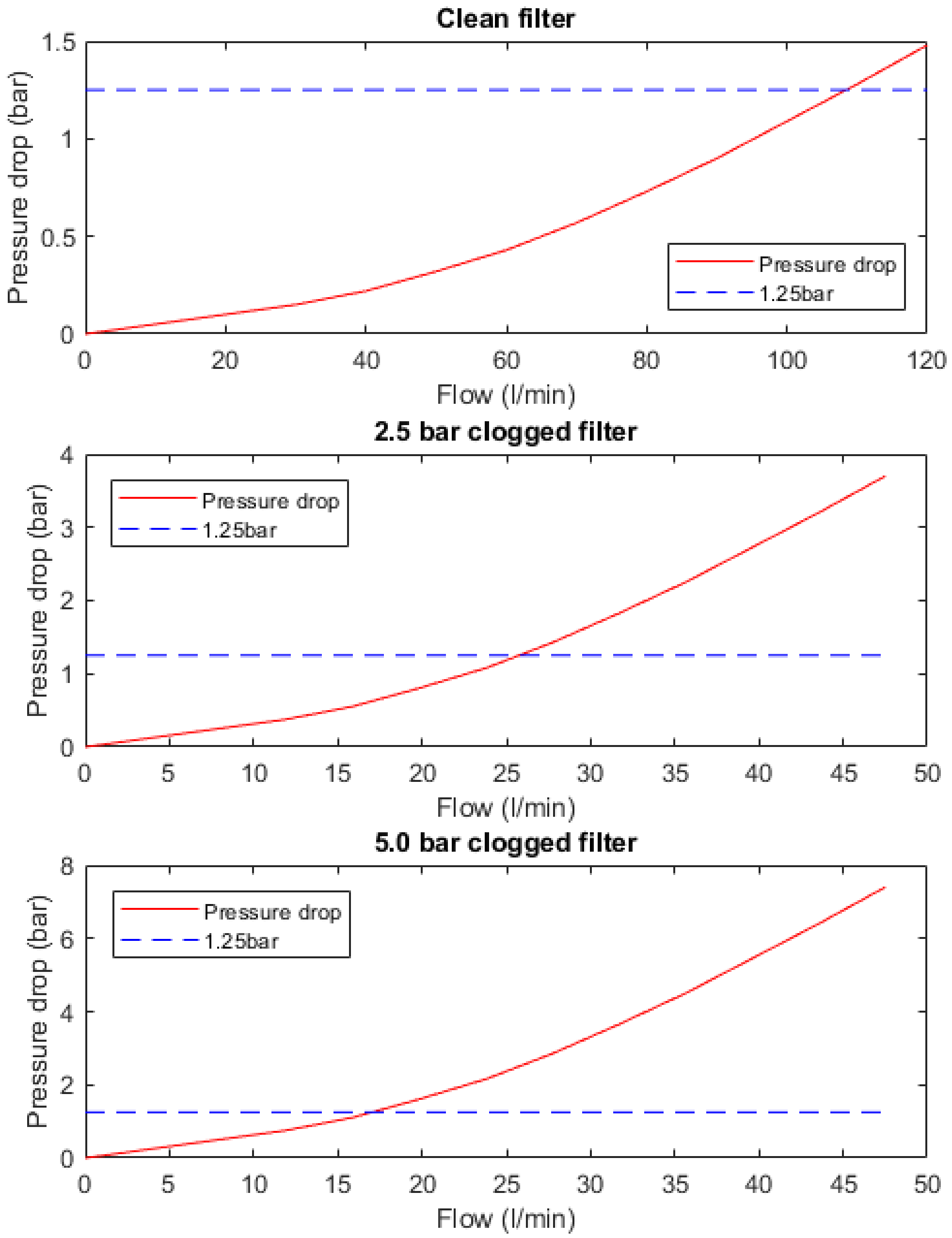

Figure 24: Pressure drops in different filters counted by the clean filter characteristics

This gives an idea about a reference value of what should the test rig be capable of producing for this research to have some actual results. Right now, the needed flow for the 2,5bar filter filters looks to be around 26l/min and for the 5.0bar filter, it looks to be around 17l/min. To achieve pressure data with 5,0bar filters the bigger pump on the piston side should produce 17l/min. For that pump to produce enough flow the following rotational speed is needed:

$$n = Q/_{V_k} = {}^{17\,l/min}/_{22.80\,cm^2/r} = 745.6140\ldots rpm. \tag{2}$$

Now a rotational speed of 746rpm must be transformed to the rotational speed of the motor that requires multiplying the rotational speed by 1.5 due to the T-gearbox. Therefore, the needed rotational speed from the motor is $745.6140\ldots rpm \cdot 1.5 = 1118.4210\ldots rpm$. The maximum value of the crane's control is currently 1000rpm. That can be changed but the needed value was counted without knowledge about the losses and possible restrictions in the system so the needed rotational speed might well be higher.

Tests without saved data were conducted on the motor speed of 1000rpm and still, no signal was received from the sensors as the theoretical calculations suggested. Higher speeds were temporarily tested as well but the system did not function smoothly at those speeds. These calculations apply to the bigger pump connected to the bottom of the cylinder. For the rod side pump and filter, the required flow is the same but the rotational speed needed from the motor is even larger due to the smaller rotational volume of the pump.

The system used in this research is not a good example of a hydraulic system due to the lack of any kind of backup system if something breaks. Usually, that is done using pressure relief valves. Right now, if for example the cylinder gets stuck or for some reason, it is driven against its maximum or minimum value, there is no place for the fluid to go but the pumps are pushing more fluid in all the time. That can cause a massive burst of oil from whatever place is most vulnerable for breaking. Another possibility is component breakage.

5. CONCLUSION

This thesis is about filters and more precisely about the pressure drop over them. The plan was to take measurements using the filters that were differently contaminated and see how their pressure drop behaviors change. The system that was used as a test rig was not capable of producing sufficient flow for something measurable to happen inside the filter.

Any results were not gotten because the sensors that were measuring the pressure drop over the filters had too high a dead zone before they started measuring. The dead zone of the differential pressure sensor was 1.25bar so the pressures from the filters even with contamination did not exceed that amount. That means that the data from the measurements was only noise from the sensors. All in all, the results from this thesis are good from the filter point of view because, in the end, the point of the filter is to filter the fluid with minimal pressure drop.

To counter this there are few things to do in the future. One option is to change the filter to something that does not fit the system as well. Options are to make it smaller when the filtering area shrinks. The second option is to change into finer filter media so that it intercepts more contamination. These are ways to produce higher pressure drop with lower flows. Another option is to increase the flow drastically. Pressure drops for the filters (2.5bar and 5bar) were measured at 38l/min and the minimum for the measurable pressure drop is 17l/min for 5bar filters and 25l/min for 2,5bar filters. For clean filters over 100l/min is needed. If the crane is left out, a dedicated system for filter testing with high flows would also solve the issues with the lack of flow. That system would need some kind of load. Maybe a hydraulic motor with a brake would be good so the cycle would be going in the same direction at all times.

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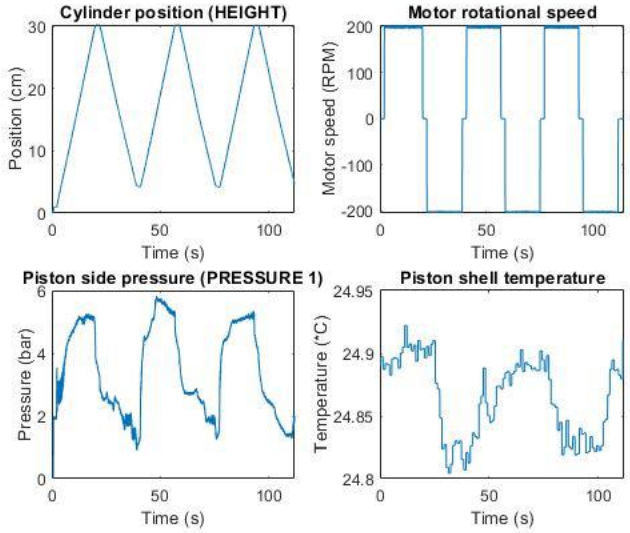
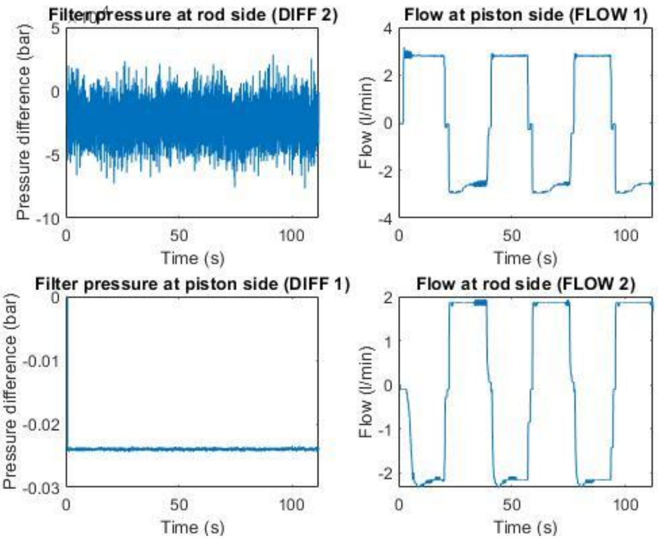
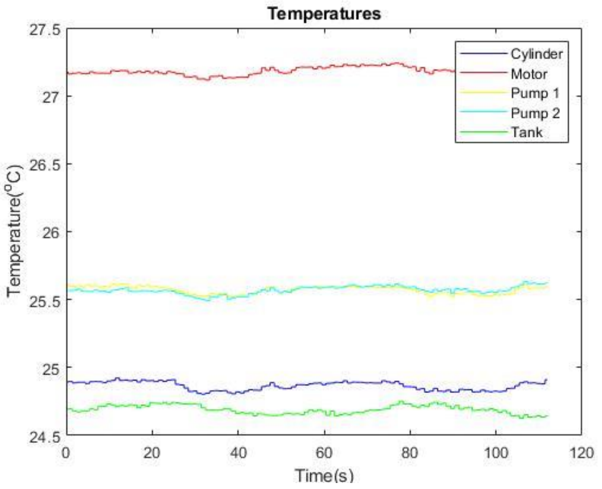
ATTACHMENT

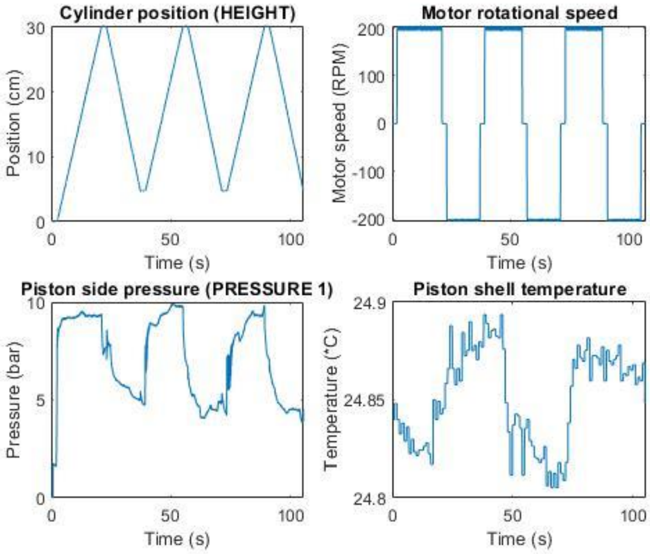
200rpm, 0kg, 0bar

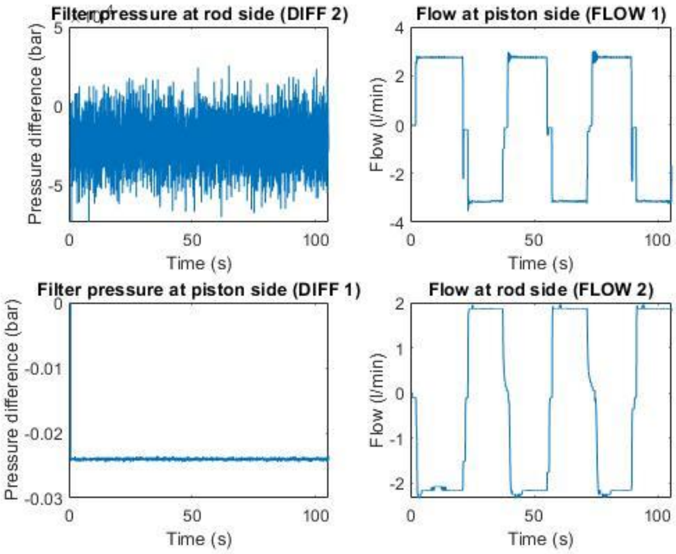


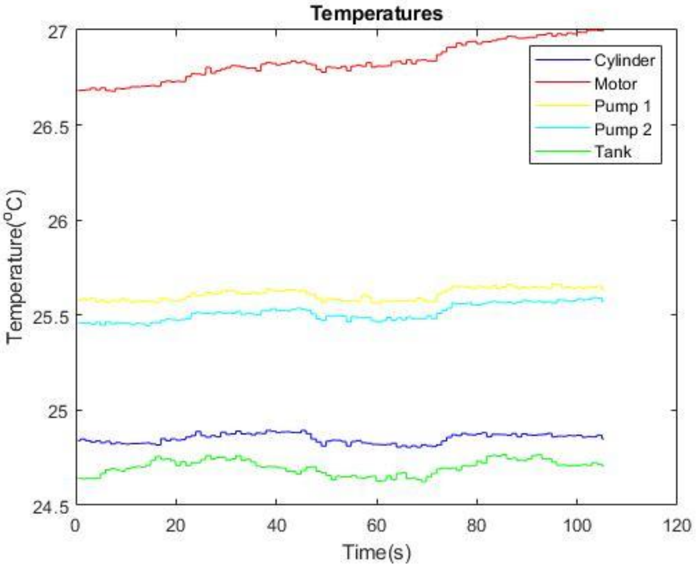




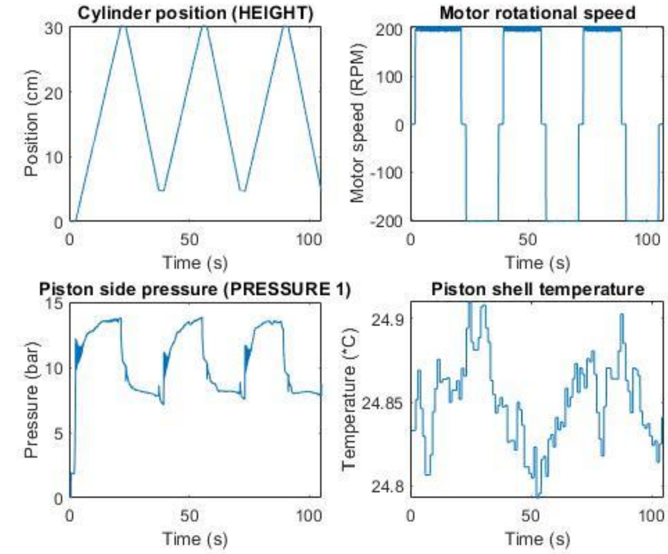
200rpm, 50kg, 0bar

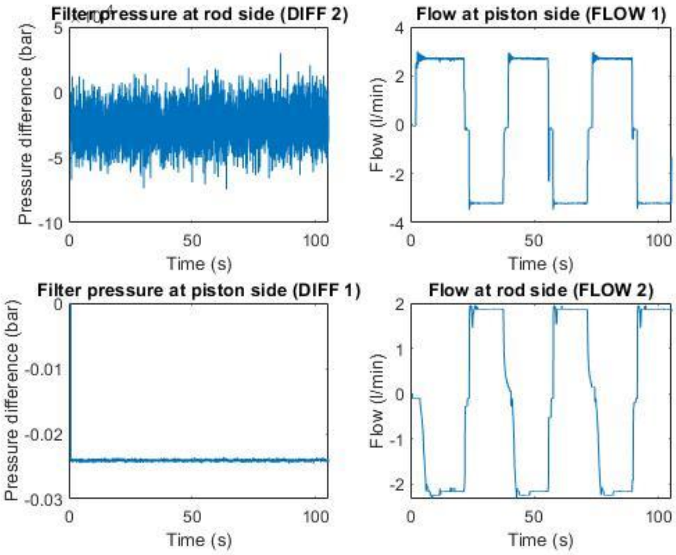


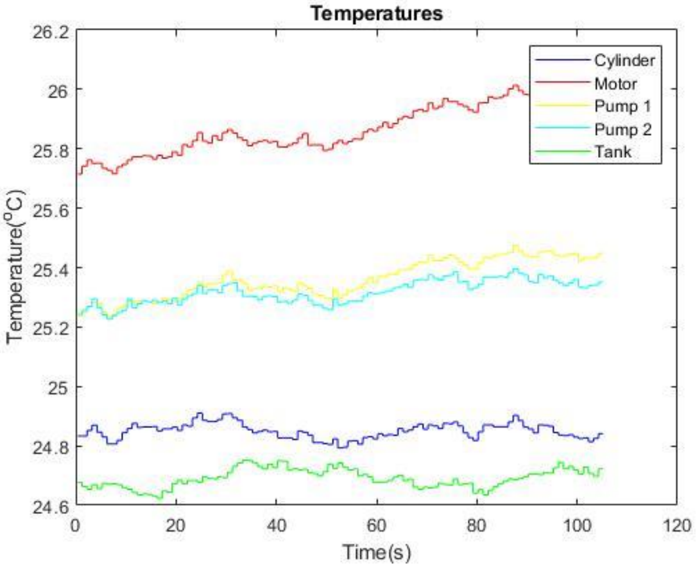




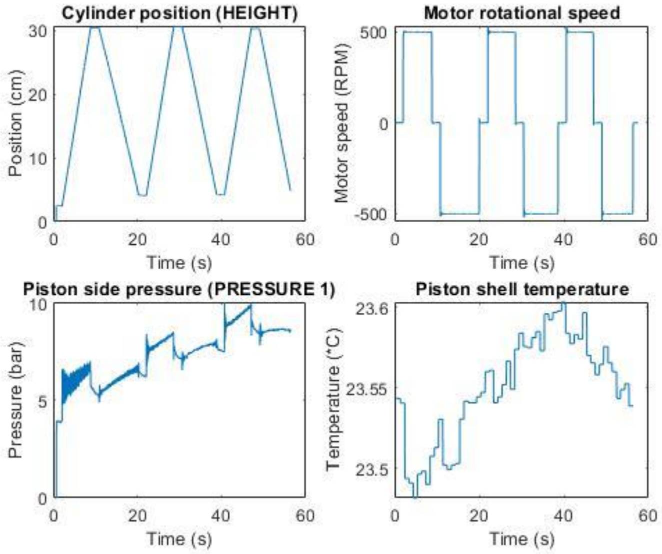
200rpm, 100kg, 0bar

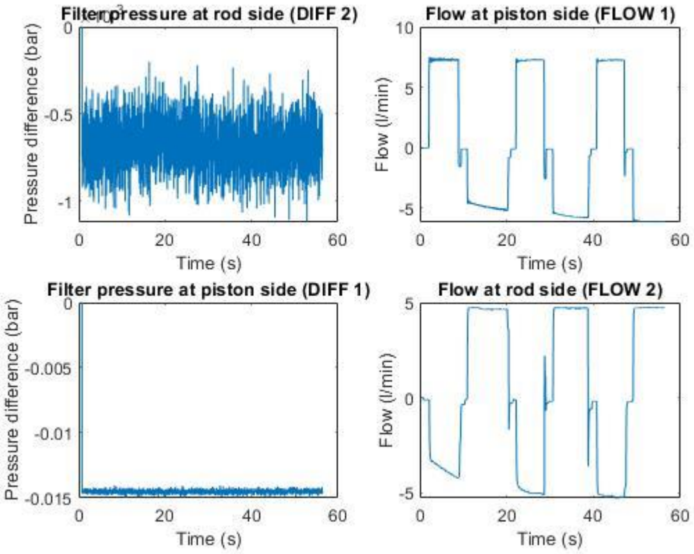


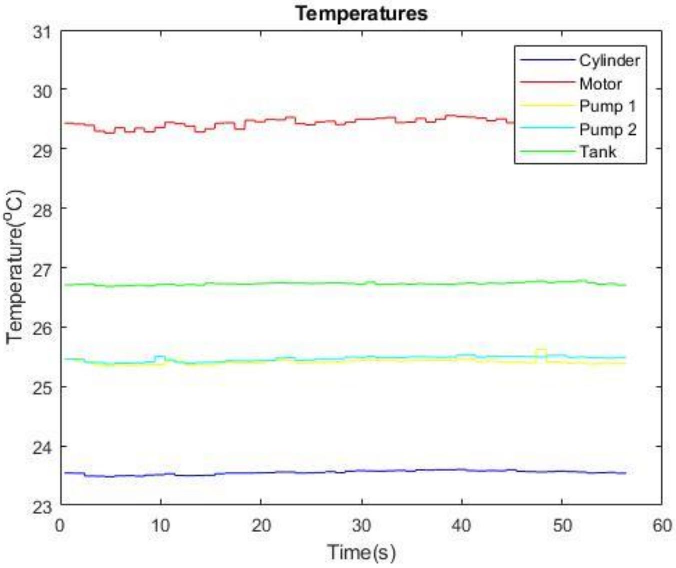




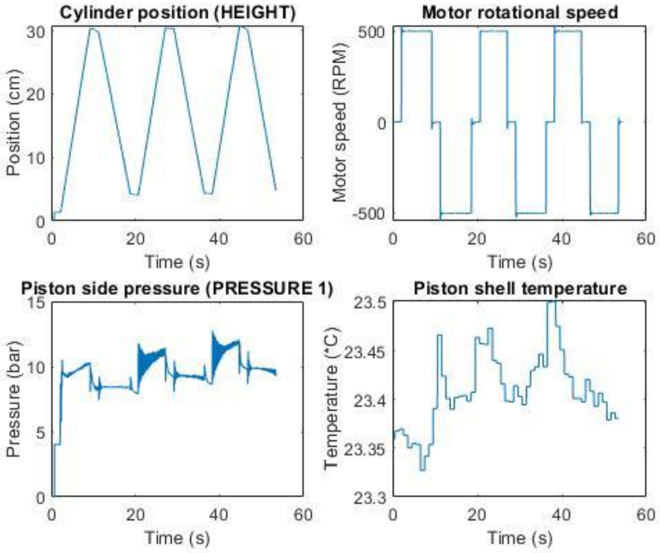
500rpm, 0kg, 0bar

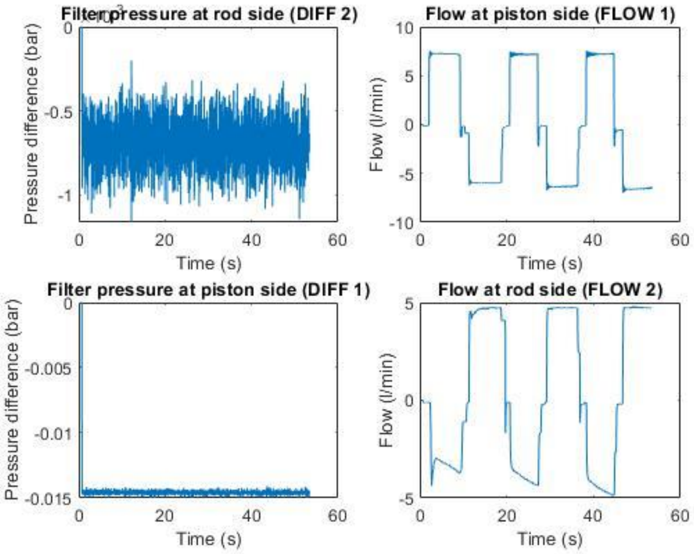


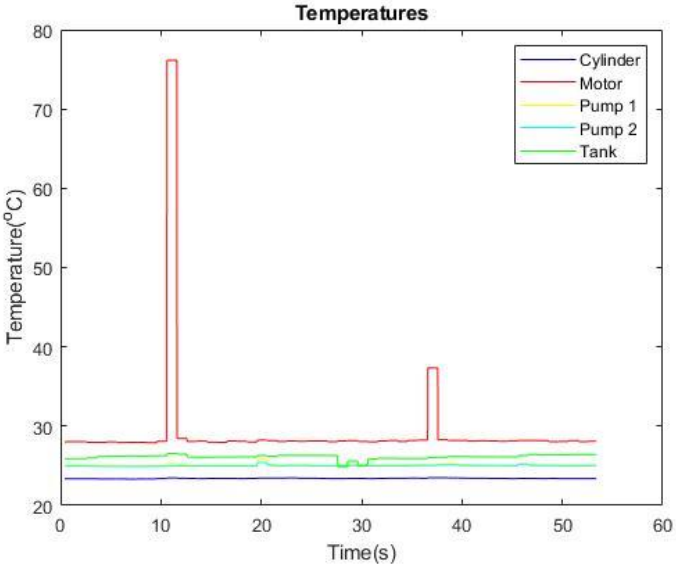




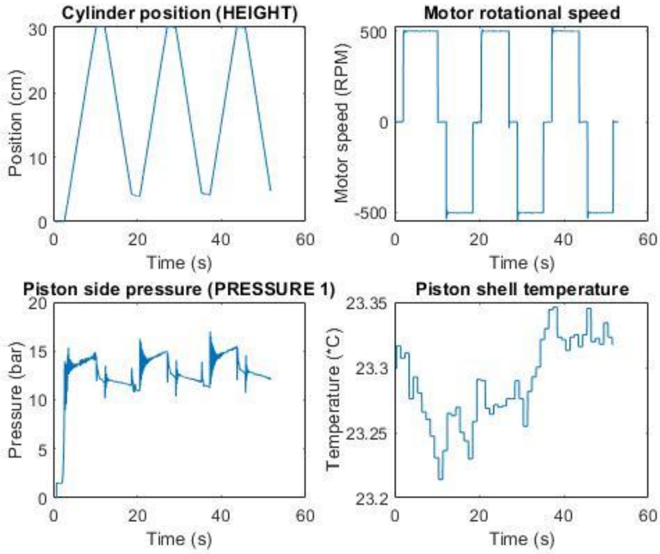
500rpm, 50kg, 0bar

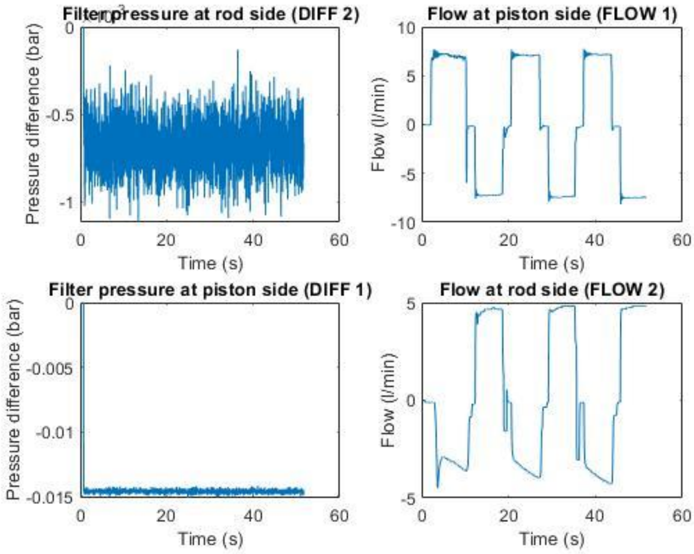


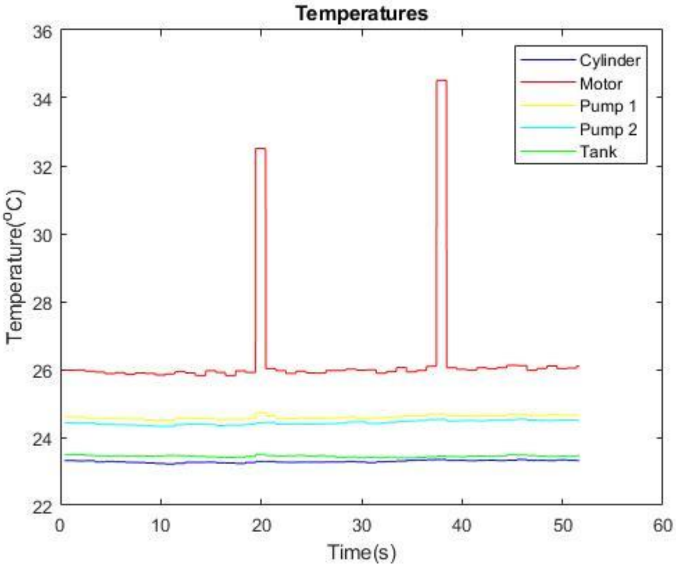




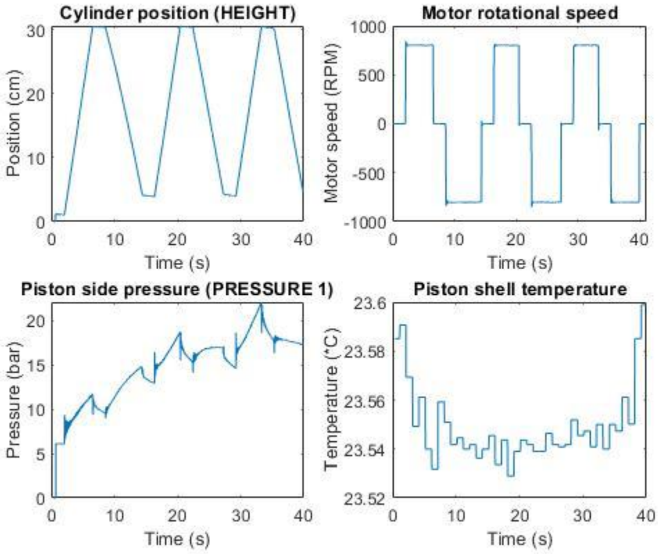
500rpm, 100kg, 0bar

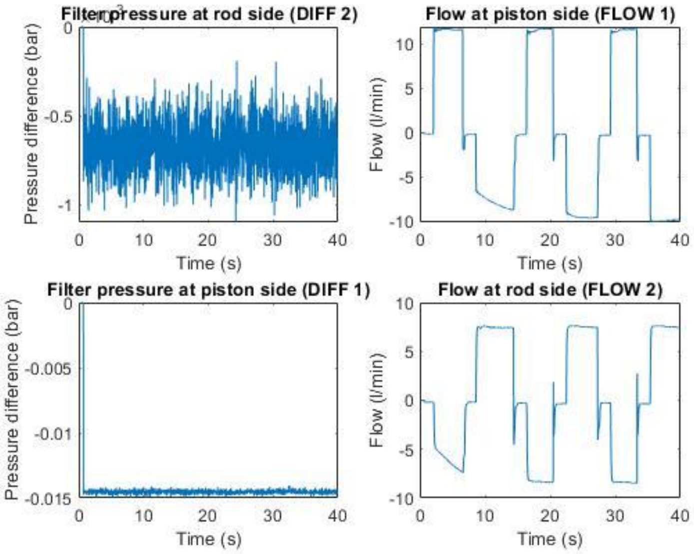


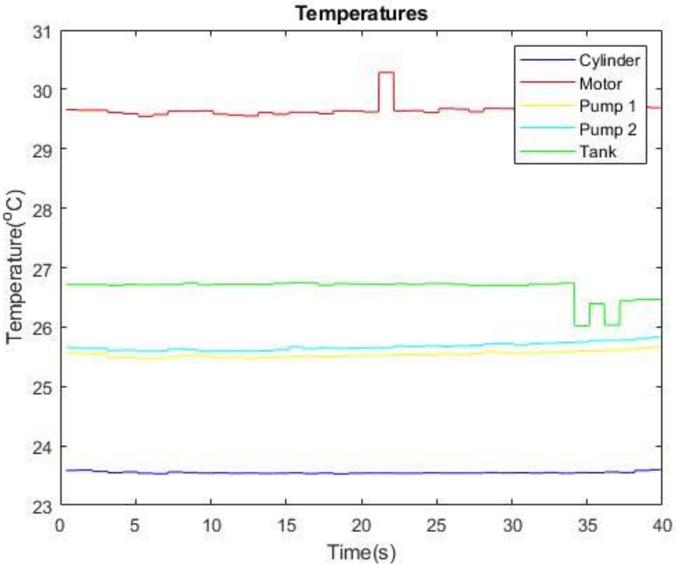




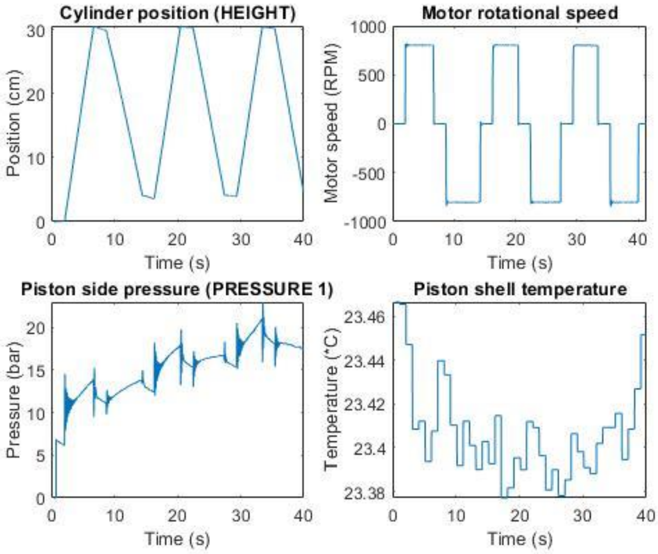
800rpm, 0kg, 0bar

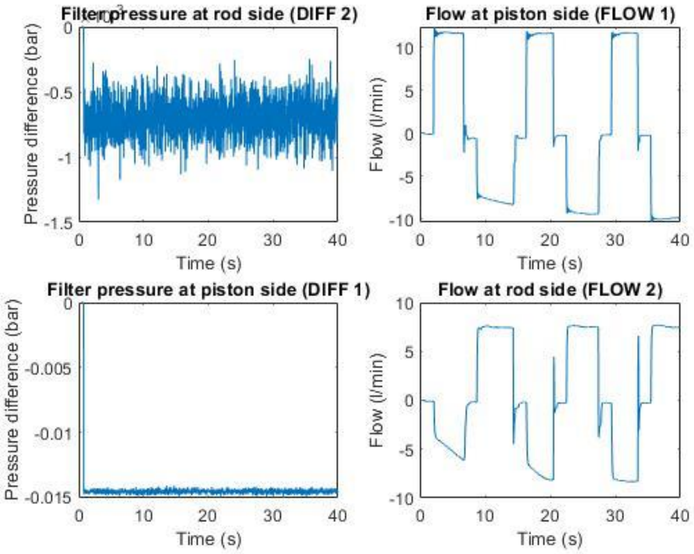


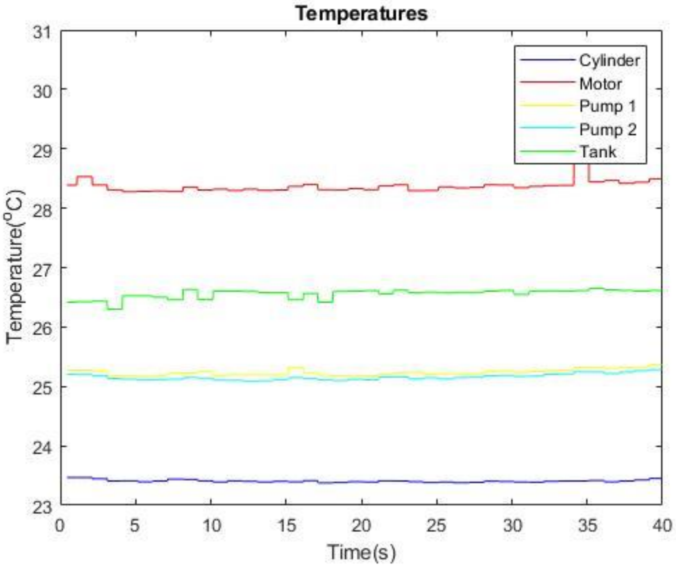




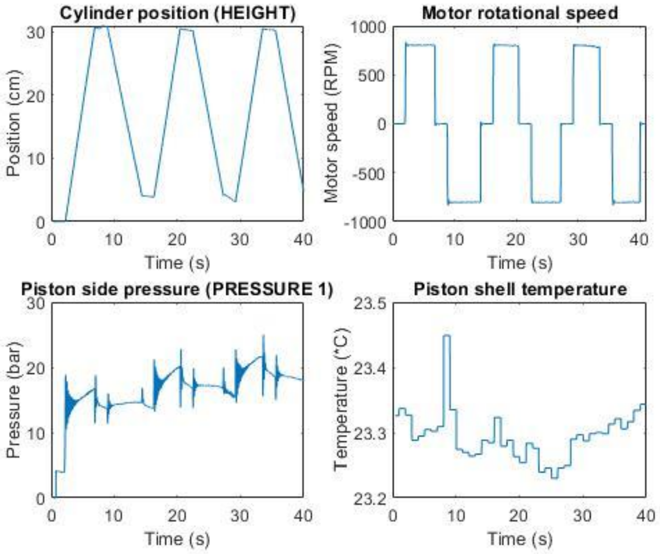
800rpm, 50kg, 0bar

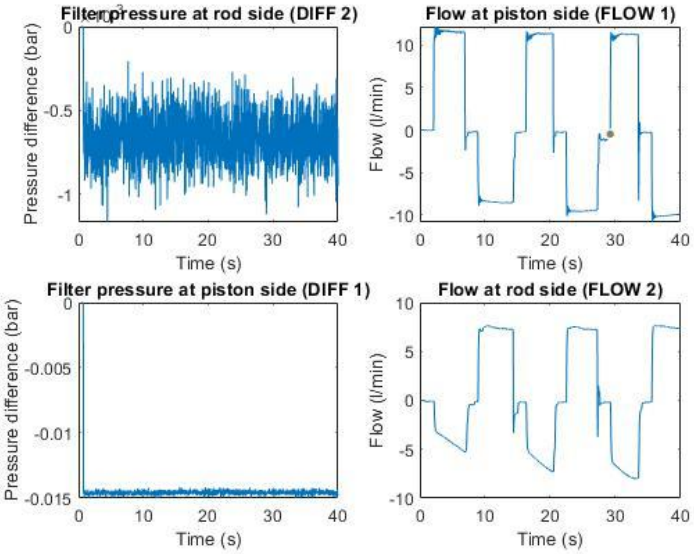


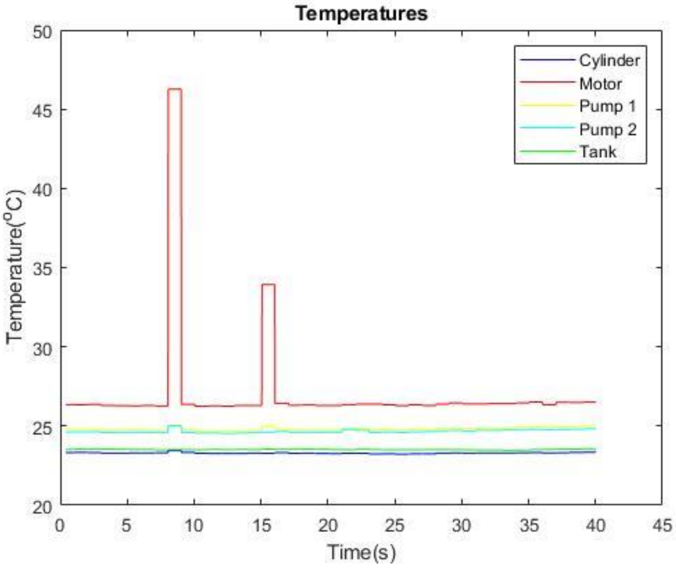




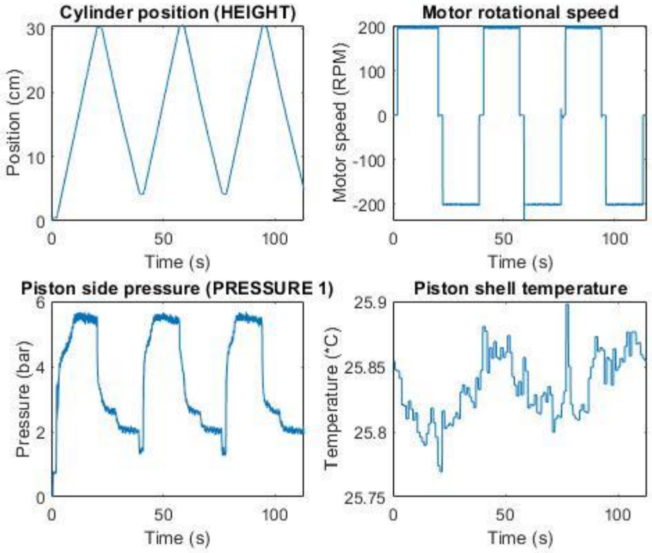
800rpm, 100kg, 0bar

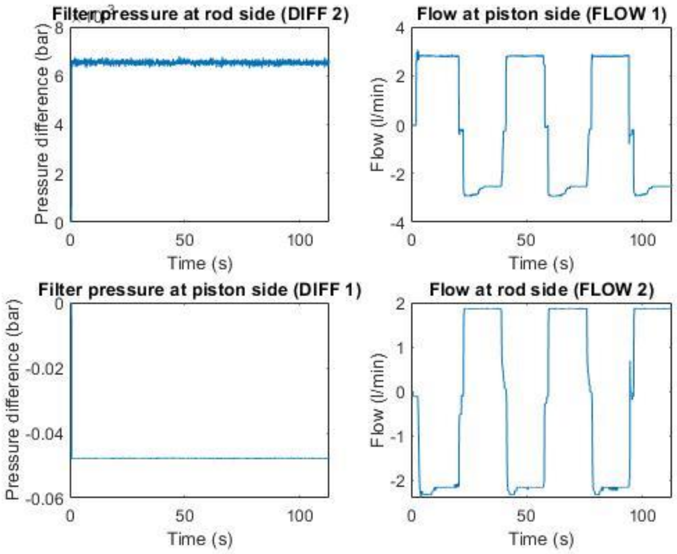


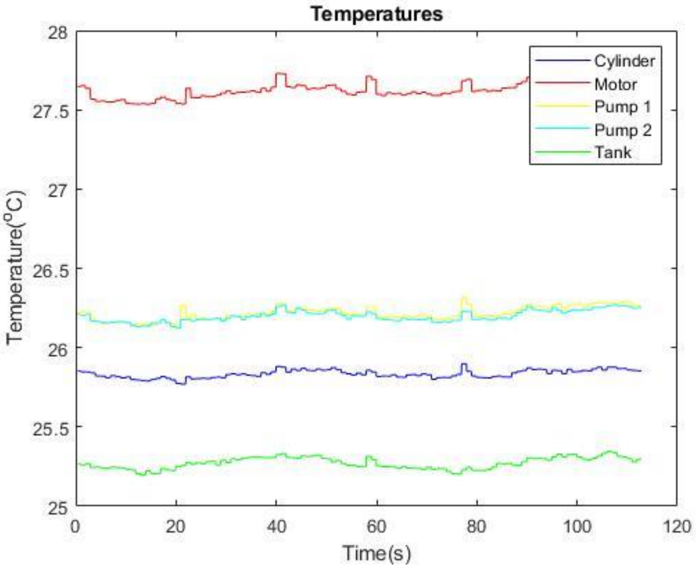




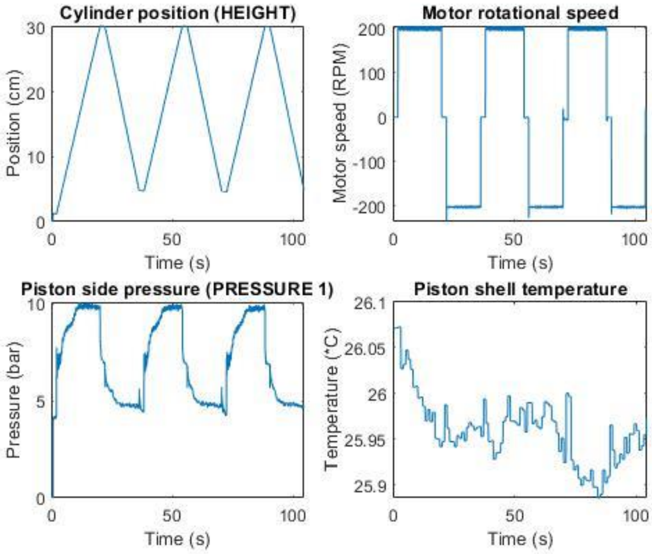
200rpm, 0kg, 5bar

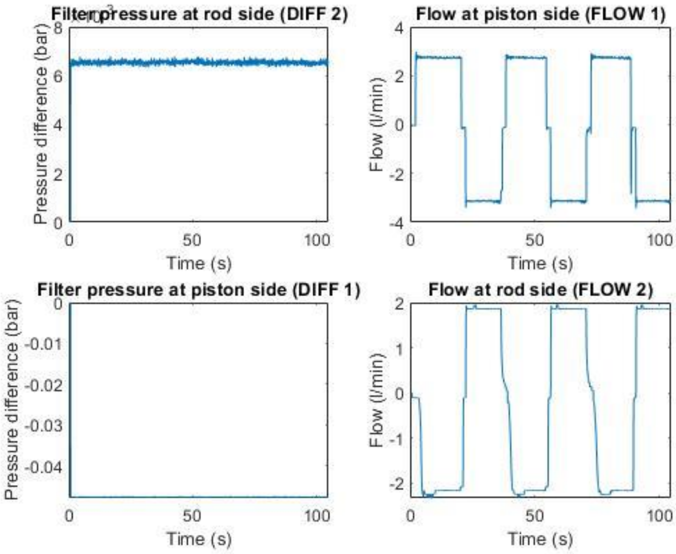


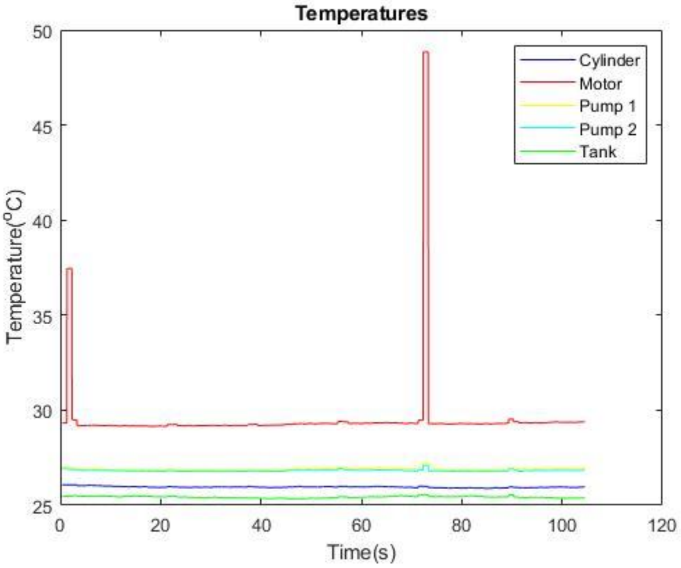




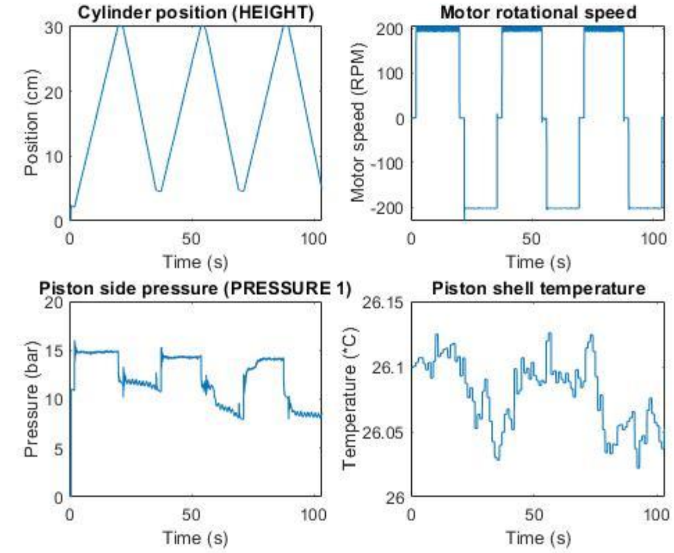
200rpm, 50kg, 5bar

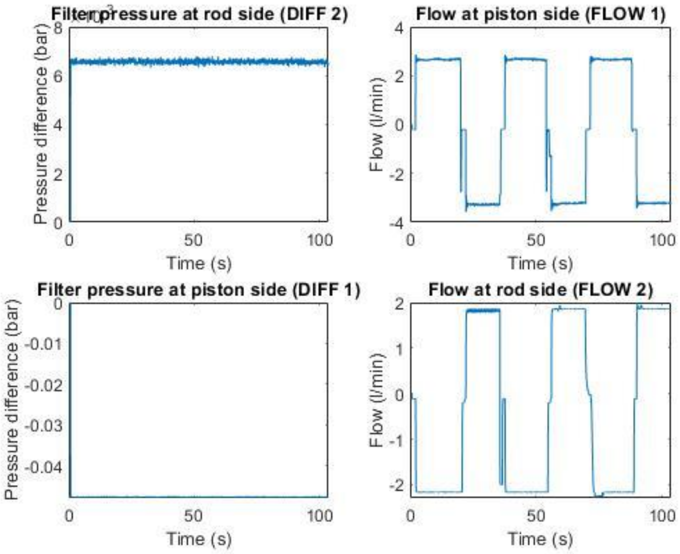


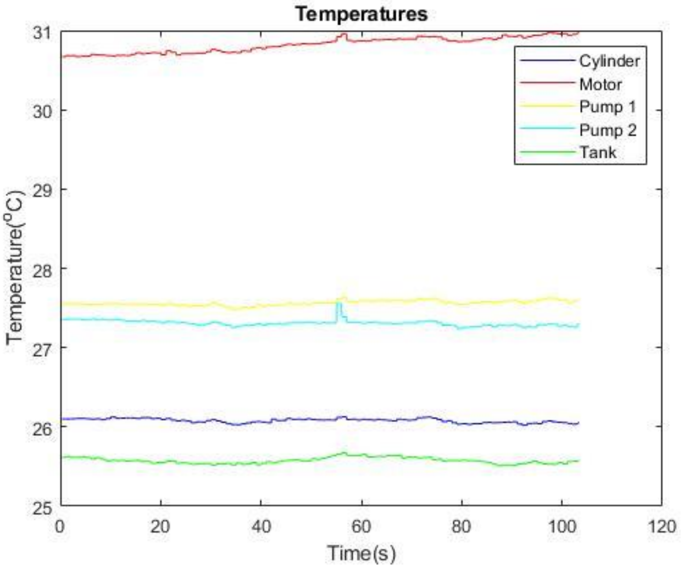




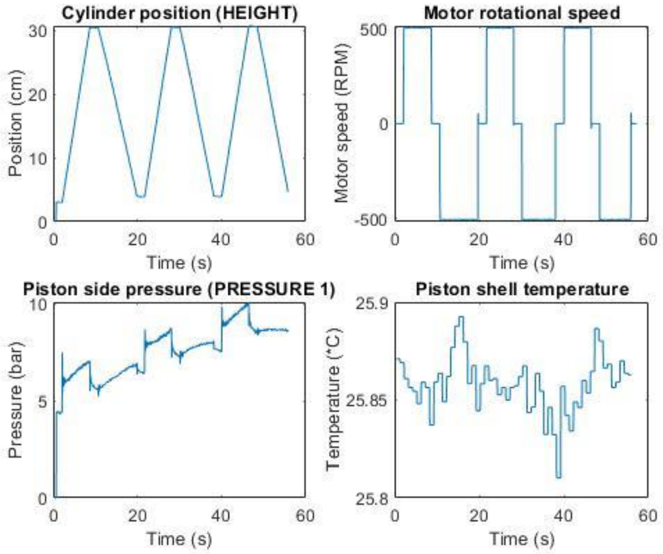
200rpm, 100kg, 5bar

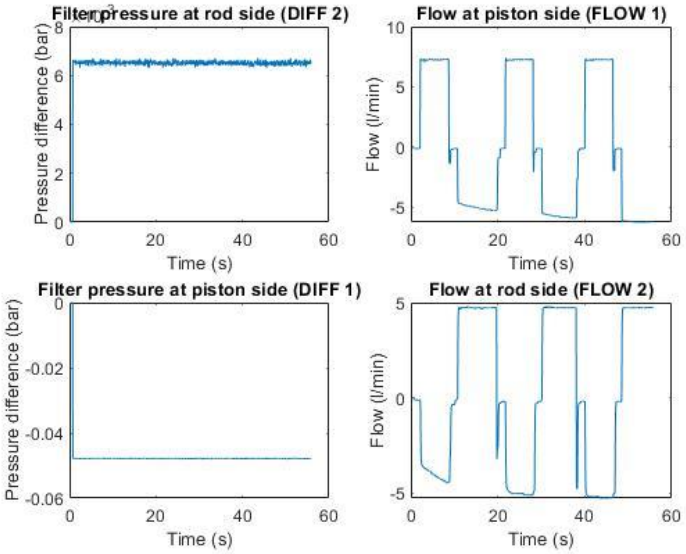


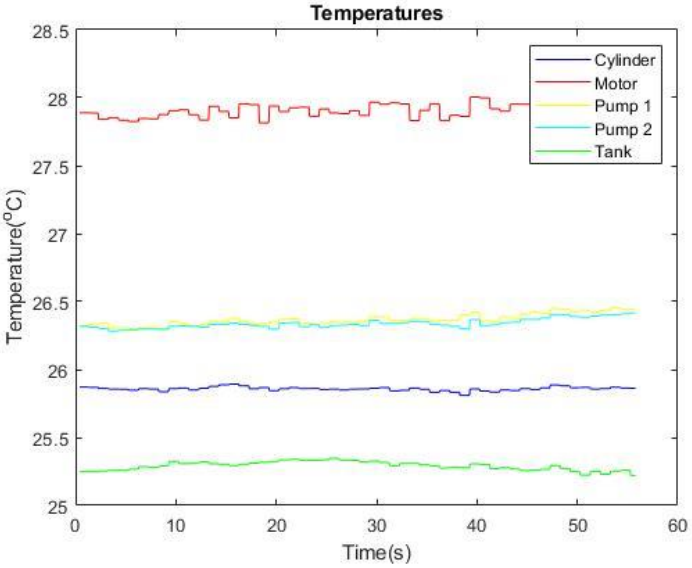




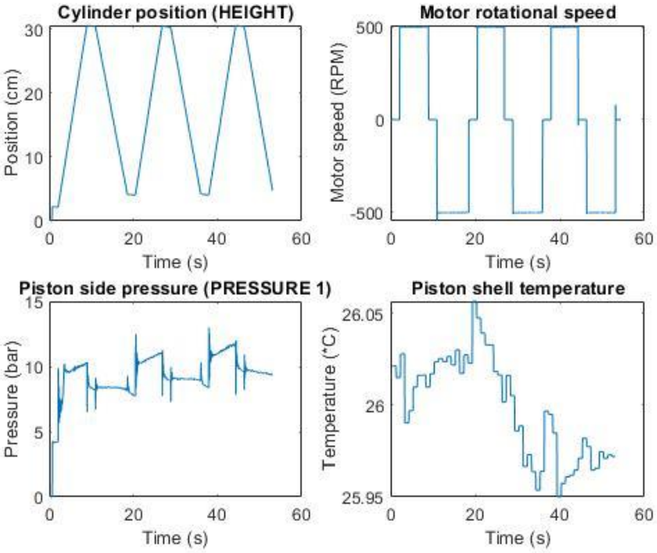
500rpm, 0kg, 5bar

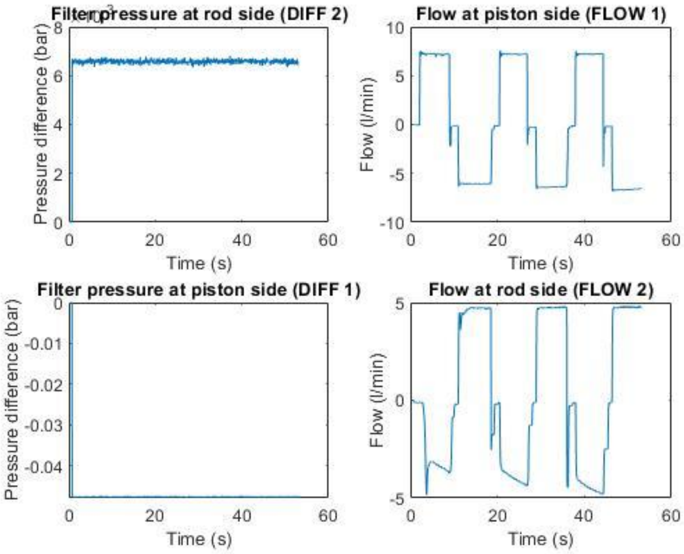


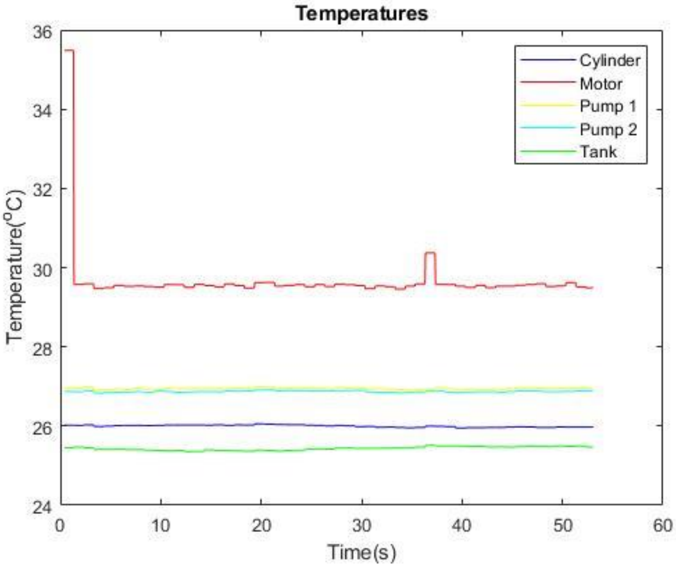




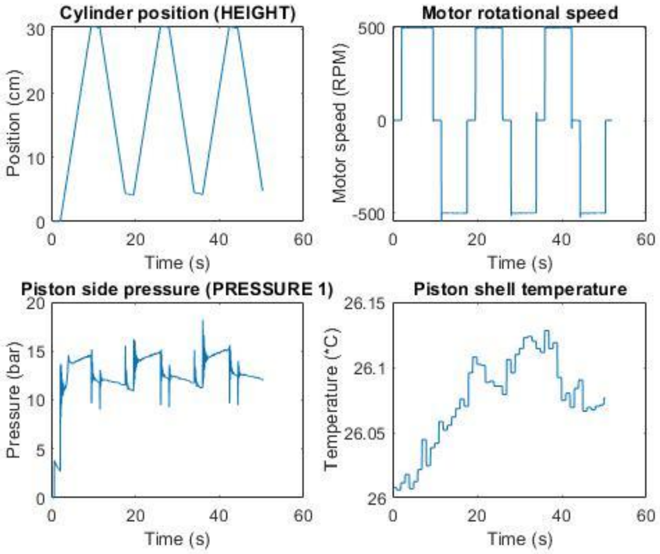
500rpm, 50kg, 5bar

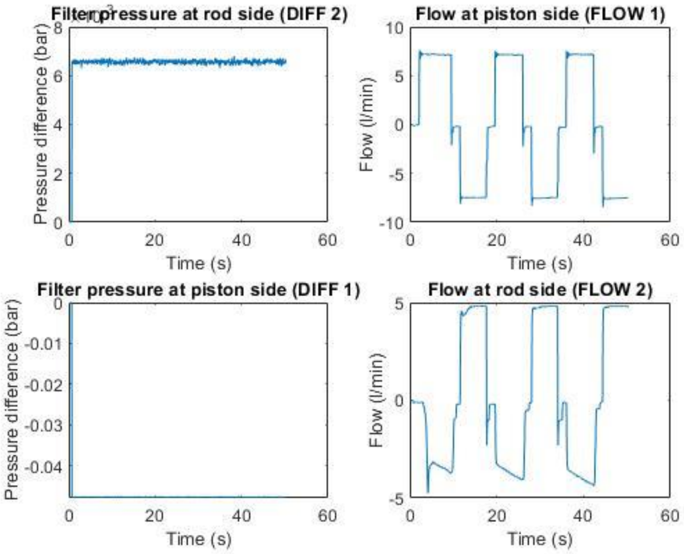


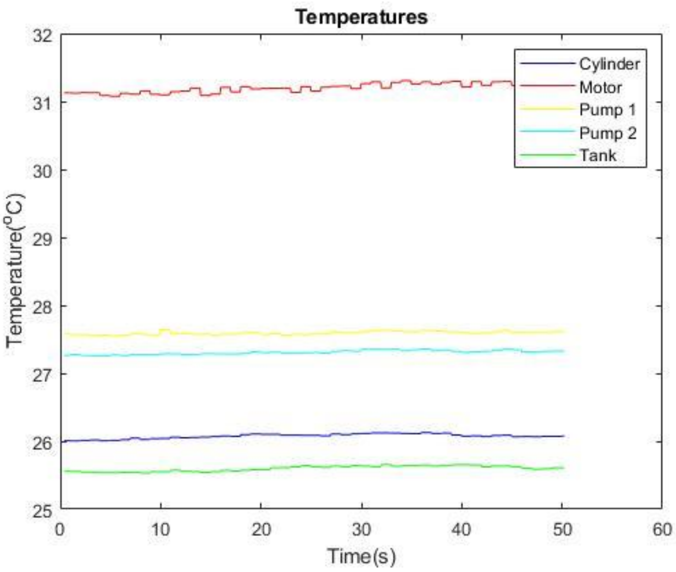




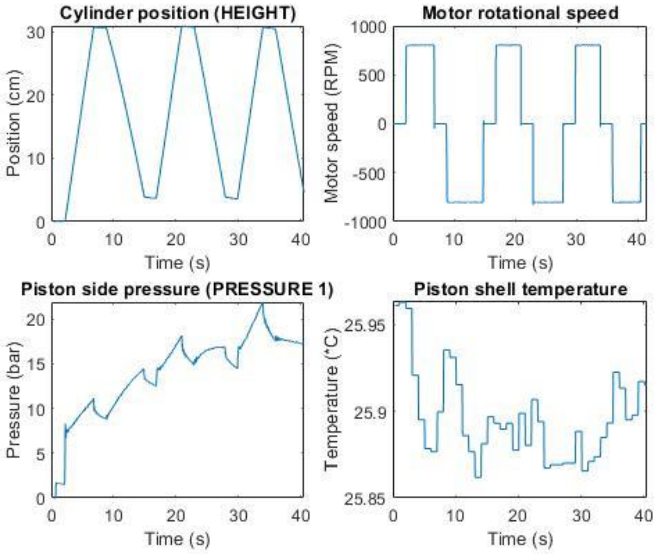
500rpm, 100kg, 5bar

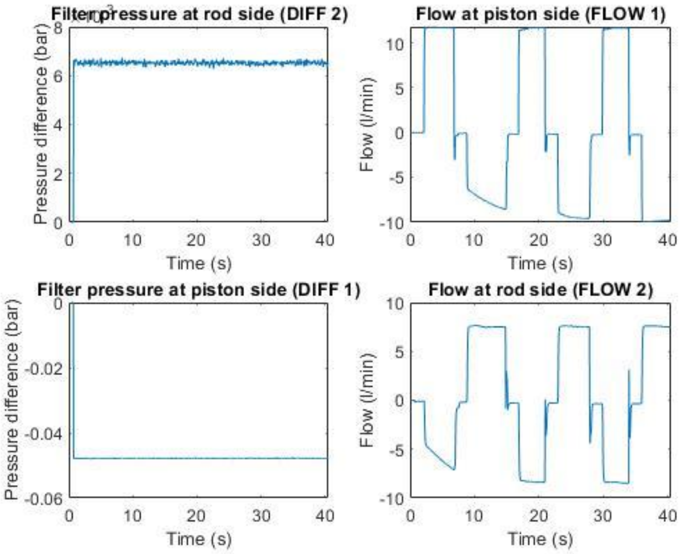


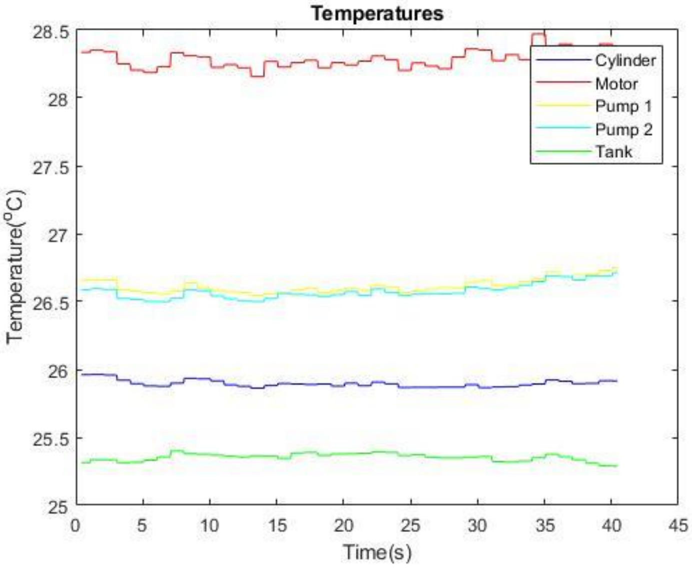




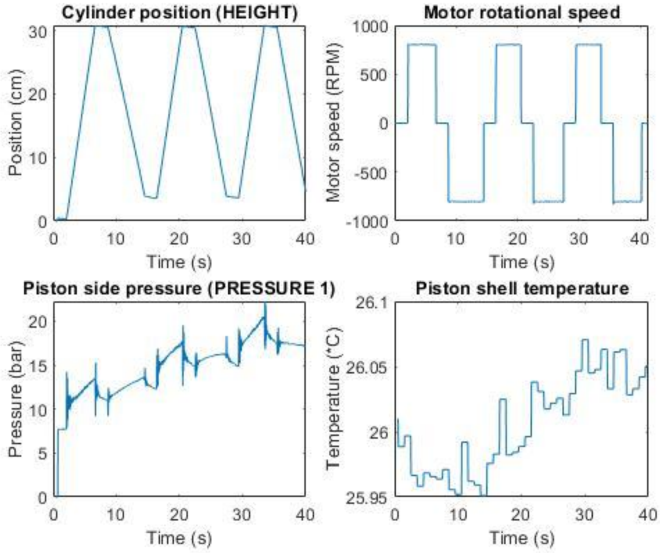
800rpm, 0kg, 5bar

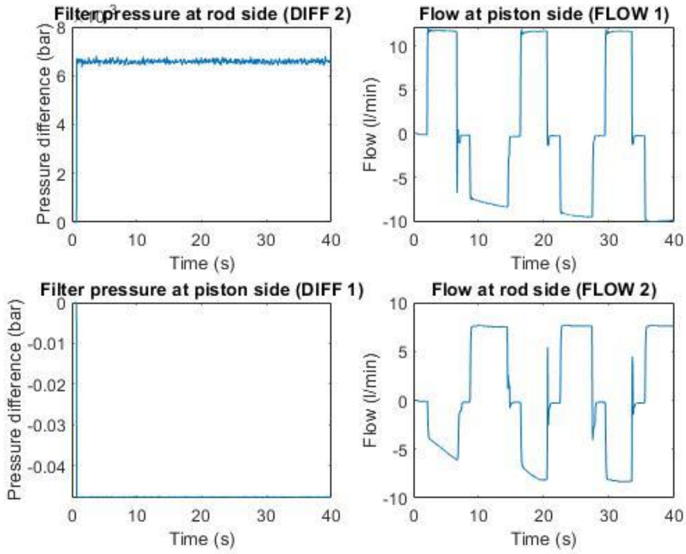


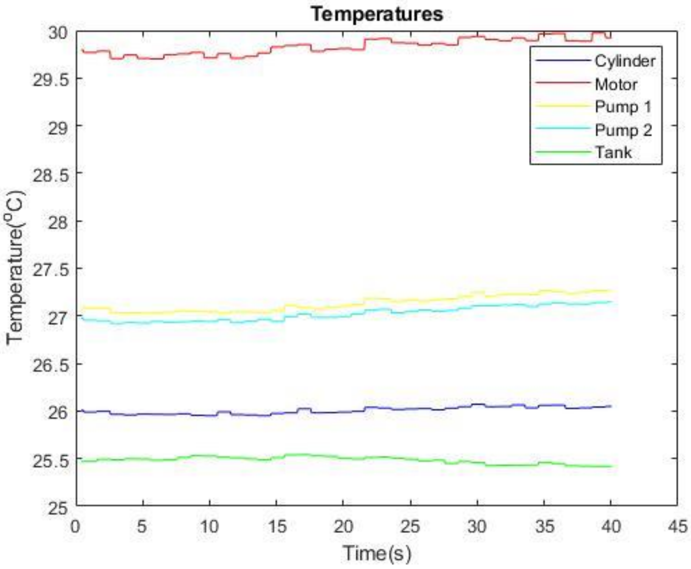




800rpm, 50kg, 5bar







800rpm, 100kg, 5bar