Proof of concept study on a continuous filtering system

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Preface

This thesis is written to conclude a Bachelor of Science degree in General Mechanical Engineering at the department of Mechanical and Marine Engineering at Western Norway University of Applied Sciences (WNUAS). The thesis represents 20 credit points, representing 540 working hours for each student. The topic of the thesis is given by Associate Professor Saeed Bikass, in cooperation with Monmic Solutions AS.

The intention of this article is to assess Monmic Solutions' patented continuous filtering system, and to consider the appropriate parameters for mechanical removal of particles from wastewater.

While working on this thesis, we have got a lot of assistance and support from several individuals and companies. We would like to thank our supervisor Associate Professor Saeed Bikass for his guidance in this project. We would also like to thank Monmic Solutions for good cooperation, and Senior Department Engineer Harald Moen at WNUAS for his professional expertise.

Bergen, May 2020

Abstract

The need to filter wastewater is increasing globally due to environmental awareness, and businesses around the world are searching for more reliable and economical filtering methods. An important type of filter when removing particles from wastewater, is the mechanical filtration technique, more specifically the granular filter. Granular filtering will be the focus in this thesis. This kind of filter is effective for its purpose, but has room for improvement when it comes to automation and cost-effectiveness. This is where the Monmic Operations continuous filter system comes into the picture. This filtration solution makes it possible to have an automated and maintenance-free filtration process, making the process more cost efficient. This thesis is based on a literature review and several filter experiments, with a focus on understanding relevant parameters for Monmic's filter.

Several comparable filter types are identified and described in the literature review, including membrane filters, granular bed filters, chemical filters etc. This gives a wider understanding of the filtration techniques used in industry for various purposes. The capture mechanisms in a mechanical filter is of great importance when researching filtration techniques. Also, cake formation is critical for filtration efficiency. The filter cake itself contributes to the filtration in the filter, while also decreasing liquid flow. Furthermore, the following parameters are identified as important: Bed depth, grain size and filter material.

Depending on the filtration criteria and the industry where the filter is applied, the filter parameters need to be adjusted. When choosing the filter materials of interest, there are several aspects to consider. The surface roughness of the filter material affects the filtration efficiency. Of importance is also the shape and density of the filter material. Finally price, availability and the material's ability to be cleaned and recycled are crucial when choosing a filter material to be used in the patented filtration system.

Lab experiments were conducted to investigate various parameter effects, before applying the acquired experience to the patented filtration system, along with applicable theory. To be able to compare the filtration efficiency of the experiments, turbidity is used as a measurement of particle concentration in the wastewater before and after filtration. To be able to compare the flowrates, cumulative volume of filtrate were recorded as time passed.

The results show that the patented continuous filter system is effective at removing particles from wastewater, with promising results regarding both filtration efficiency and flowrate. Further work is necessary to investigate the effect of parameters such as grain size, filter materials and other parameters. Expectedly there will also be need of a system for cleaning and recycling the filter material, and the possibility to design such a system also needs investigation.

Samandrag

Behovet for å filtrere gråvatn aukar globalt grunna større fokus på miljø. Dette gjer at bedrifter over heila verda er på jakt etter meir økonomiske og sikrare måtar å filtrere på. Ein filtertype som er viktig når det kjem til å fjerne partiklar frå gråvatn er mekaniske filter, og då særleg kornfilter. Desse filtera er effektive til sin bruk, men har forbetringspotensiale når det kjem til kostnadseffektivitet og automatisering av prosessen. Det er her Monmic Operations sitt kontinuerlege filtersystem kjem inn. Dette er eit filtersystem som gjer det mogleg å ha ein vedlikehaldsfri og autonom filtreringsprosess, noko som gjer prosessen meir kostnadseffektiv. Fokuset i denne oppgåva har hovudsakleg vore å få ei forståing av parameter som er relevante for Monmic sitt filter, basert på litteraturstudium og eksperiment.

Fleire samanliknbare filtertypar er skildra i litteraturstudien, inkludert membranfilter, kornfilter, kjemiske filter osb. Dette gir ei betre forståing av filtreringsteknikkane brukt i dagens industri på forskjellige bruksområde. Mekanismane for partikkelfanging i mekaniske filter er særs viktige når ein undersøker filtreringsteknikkar. I tillegg er filterkakedanning essensielt for filtreringseffektivitet, ettersom filterkaka i seg sjølv bidreg med filtrering av partiklar i filteret, samstundes som den reduserer volumstraumen. Vidare er følgjande parameter viktige for å forstå filtrering: høgda på filtersøyla, kornstorleik og filtermateriale.

Avhengig av filtreringskriteria og bransjen sine behov må filterparametera bli justerte for kvart bruksområde. Når ein vel eit filtermateriale, er det fleire punkt å vurdere. Ruheit på overflata er viktig, då det påverkar filtreringseffektiviteten. I tillegg er form og eigenvekta til materiale viktig. Til slutt er pris, tilgjenge og høvet til reinsking og resirkulering av materialet viktig når ein skal velje filtermateriale som skal brukast i det kontinuerlege filtersystemet.

Lab-eksperiment vart utførte for å undersøke effekten av forskjellige parameter, før ein brukte erfaringar derifrå, saman med teori, til eksperiment på prototypen til det patenterte filtersystemet. For å kunne samanlikne resultata er turbiditet brukt som ein målemetode for partikkelinnhald i gråvatnet før og etter filtrering. For å samanlikne volumstraum vart kumulativt volum av filtrat notert i lag med tid.

Resultata frå eksperimenta viser at det patenterte filtersystemet effektivt fjernar partiklar frå gråvatn, med gode resultat både når det gjeld filtreringseffektivitet og volumstraum. Vidare arbeid er naudsynt for å undersøke effekten av parameter slik som kornstørrelse, filtermaterial og andre parameter. I tillegg bør filtersystemet sin eigenskap til å kontinuerleg byte ut filtermateriale undersøkast vidare, og det same gjeld høvet til å utvikle eit system til å reinske og resirkulere filtermateriale.

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Nomenclature & Terminology

µm	=	Micrometer, unit of length [$1x10^{-6}$ m]
BAR	=	Unit of pressure [$1x10^{5}$ Pa]
BARG	=	Gauge pressure, in BAR
Filtrate	=	The fluid that passes through the filter
Filtration efficiency	=	The filters capability to remove particles [%]
g	=	Grams, unit of weight
Hydraulic Diameter	=	Calculated value for simplifying cross-sections to circular cross sections
kg	=	Kilogram, unit of weight [$1x10^{3}$ g]
l	=	Liter, unit of volume [$1x10^{-3}$ m^3]
min.	=	Minute, unit of time
mm	=	Millimeters, unit of length [$1x10^{-3}$ m]
NTU	=	Nephelometric Turbidity Unit
P	=	Pressure [kg/m^2]
Permeability	=	The ability of a solid, porous material to let fluid pass through it [m^2]
s	=	Seconds, unit of time
Turbidity	=	The concentration of particles in a liquid (NTU)
ρ	=	Density [kg/m^3]

1. Introduction

1.1 Motivation

Today, clean water is considered a limited resource around the globe. Industries are consuming vast amounts of water every day in the production of various products and services. Industries that want to be "water smart" must reconsider their water usage. The industries need to evaluate the amount of water consumed, how wastewater is filtered and the possibility to reuse some of the wastewater that the industries are producing in their processes. As the environmental awareness is rising among the end consumers, pressure is added on businesses and producers to act in a more environmentally friendly way when it comes to the production, packing and transportation of the goods in industries. For industries consuming great amounts of water in their production, the more environmentally friendly way to act will be to reduce the amount of water consumed, and have a stricter filtration and control of the wastewater.

Wastewater is today mainly filtered through traditional mechanical water filters, such as a granular filter. After a specific period of operation, the filter medium needs to be either replaced or backwashed. To replace the filter medium, the filtration system and production needs to be halted to undergo the maintenance process required to replace the filter medium. Any halt in the production causes a decrease in production, which also has an economic impact on the business. To make this process more automated, an inline filter is needed which replaces the filtering material during the operation process. The new solution patented by Monmic Operations A/S is a system where wastewater is continuously filtered without needing to stop the process for maintenance. This is an interesting idea which can be cost-effective for the industry.

The team in this thesis is going to take a closer look into the process of greywater filtration. The team need to get a deeper understanding of greywater filtration to be able to compare this solution for filtration to other solutions available on the market today. The team will look at the rate of filtration of the water and the effectiveness of the filtration process. The plan in this project is to do laboratory experiments to look at filter materials and level of particles that are left in the wastewater after the filtration process. The team will also do testing on the general flow through the filter to make sure the filter is not restricting the flow from the production system. All this to make sure that this solution will be effective to replace today's traditional solutions.

1.2 Objective

The main objective of this project is to investigate the filtration solutions in Monmic Operations A/S patented mechanical filtering system for filtration of wastewater. The patented filtration system will be reviewed and compared to solutions available on the market today.

Sub-objectives:

- Analyze different filter materials and granule sizes to be able to find an effective solution.
- Investigate various filtration parameters and its effects.
- Investigate filtration mechanisms, and key factors for filtration.
- Test the theoretical solutions with the available prototype in the lab.
- Compare the filtration results of the project to commonly used filtration systems used in industry today.

2. Literature Review

Filtration is a process where solids are separated from a fluid in a mixture, using a filter medium built up with a complex structure to only let the fluid pass through.

2.1 Available technology

There are several ways to filtrate wastewater, depending on the composition of the wastewater and how the wastewater is disposed of. In this project, the focus will be on mechanical filtration. Unlike chemical and biological filtration, one will not have the same possibility to remove bacteria. A mechanical filter will primarily remove dirt and particles from the wastewater. One of the most common forms of mechanical filters is the granular bed filters, where granular materials are being used to filter the wastewater as it runs through the filter. Some of the reasons for the popularity of the granular bed filters is the high efficiency and low cost. Most granular bed filters are built for easy maintenance where it is possible to close the flow to the filter and regenerate or clean the filter with a backwash effect where fluidization of the bed is necessary as well as the removal of the collected particles from the filter material and collection of the particles in a separate single-use filter or tank.

For a granular bed filter, several parameters will affect the filtration efficiency:

- The depth of the filter bed, often referred to as the length, *L*, of the filter.
- The mean grain size/diameter referred to as, *d*.
- It is also possible to change the efficiency of a filter by adding several layers of different grain size filter elements, where the coarser filter material at the top filters out the larger particles and the lower levels are then able to filter out finer particles without clogging the filter.
- For most mechanical granular bed filters one of the main problems is the collection of a filter cake at the top of the filter, which results in a higher head-loss in the filter, and lower efficiency of the filter itself. To design a filter with longer running time before the filter cake is too thick, a filter with larger diameter is necessary, this makes it possible to collect a larger filter cake before reaching the same height of the cake [1].

2.1.1 Chemical filters

Chemical filtration is a filtration process where the effect of different chemicals is utilized to remove unwanted bacteria from wastewater. Often, wastewater is filtered through a bed of either active carbon, zeolite, oxide or resin, depending on the kind of bacteria needed to be removed from the fluid. There is a mechanical filter effect to this filter type since the filter media will form a granular bed where you have filtration of particles when they get trapped in the filter media [2], [3].

2.1.2 Biological filters

Biological filters utilize biomass attached to the filter material to remove organic particles and pollutants from water and wastewater but can also be used to clean air. According to the authors of “Biofilter in Water and Wastewater Treatment”: “Any type of filter with attached biomass on the filter media can be defined as a filter media” [4]. This means that sand filters or filters with granular activated carbon used in water treatment plants are considered biological filters. In “Biofilter in Water and Wastewater Treatment”, it is concluded that biofilters can be used economically to filter wastewater effectively [4].

2.1.3 Membrane filters

Membrane filters are a mechanical filter where the filtration is done through a membrane. The fine mesh of the membrane filter is stopping the particles in the flow. Due to the fine pore sizes of the membrane, the filters normally have a very low flow rate. Another consideration about the membrane filter, it is to be considered a "surface filter" where the filtering is happening on the top of the filter and not in the depth of a filter bed as other filters, this is leading to a build-up of particles on the filter top leading to a clogging of the filter, thereby regular maintenance is required. A membrane filter can be made of a material with chemical filtrations properties, which also will help on the filtration of bacteria [5]–[7].

2.1.4 Granular bed filters

A granular bed filter is a mechanical filter where granular media is added as the filter material in the filter housing. The main purpose of a granular bed filter is to remove particles in the wastewater. Depending on the filter media selected it is possible to kill certain bacteria in the wastewater as stated in 2.1.1 in this thesis. Normal applications for a granular bed filters range from slow sand filtration, gravel filtration and to hypergeometric media filters. Using a granular bed filter one will have the possibility to either use gravity to feed the wastewater in the filter, or to pressurize the system to benefit from the effect of added pressure [8], [9].

2.1.5 Moving granular bed filters

Moving bed filters are mainly used for filtration of gases, due to the nature of the design of most moving granular bed filters. These filters have many similarities to regular granular bed filters. The main difference is that the fluid flow passes through the filter horizontally, instead of vertically. The filter material is fed into the filter housing from the top and is moving downward as the fluid passes through the filter horizontally. The filter material is then removed at the bottom. This design means that filtrating liquid is difficult, as the liquid behaves different to gases. For filtration of gases, the filter has high efficiency and pressure drop [10]. These types of filters has some similarities to the patented continuous filter discussed in this article, but the patented filter from Monmic Operations AS has the advantage of making liquid filtration possible.

2.1.6 Rotating drum/disc filters

The rotating drum/disc filter is available in different configurations, but their working principles are the same. The filters operate in a way where a series of discs and drums spin. The wastewater is fed into the filter in a manner where it will flow through the discs or drum to get the highest possible filtration. As the wastewater is filtrated through the filter, there is a build-up of filter cake at the disc and drum, as the filter is rotating the filter cake is removed from the filter element. The rotating speed of the filter element is slow, with about 10 – 80 revolutions per hour. The discs or drum are customizable to best suit the filtration needs for each unit [11], [12].

2.2 Filtration mechanisms

Particle size in a liquid from an industrial filtration process can range from nanoscale up to a few millimeter depending on the liquid being filtered. In this section, the mechanisms for particle capture and cake formation will be discussed.

2.2.1 Particle capture

There are several methods of capture mechanisms involved in the filtration processes. Each of the methods is illustrated in Figure 1. It is assumed that the liquid is behaving with laminar flow in most cases in industrial processes, and therefore follows a smooth streamline through the filter.

1. **Straining or sieving**
   This method is one of the most important methods of particle capture in a granular or membrane filter. If the particle is larger than the openings in the filter medium, it will be stopped.
2. **Inertial impaction**
   This happens when the particle does not follow the fluid streamline and intercepts with the filter medium. This is dependent on the momentum of the particle (i.e. the fluid velocity).
3. **Interception**
   A mechanism very similar to inertial impaction, but this time the particle follows the fluid streamline and comes into contact with the filter medium. This capture mechanism is dependent on the ratio of particle to pore size.
4. **Sedimentation, or gravity settling**
   Although not exactly a filtration method, the settling of larger particles in a filtration system is important to note. Sedimentation is often used in a filtration plant before or after a filter, such as in a water treatment plant.
5. **Electrostatic deposition**
   If the surface charge of the particle is opposite of the filter medium, the particle path may divert and it may cling to the filter medium.
6. **Brownian motion**
   Small particles relative to the mean particle size may be influenced by the fluid streamline as well as Brownian motion (random motion of molecular particles in the fluid). This may direct the particles onto the filter medium [13].

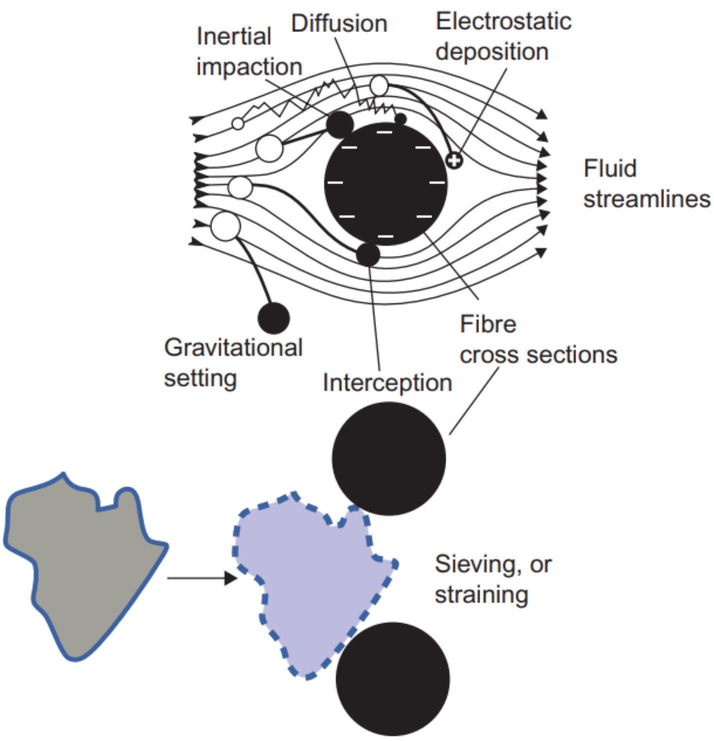

Figure 1: Particle capture mechanisms [13]

2.2.2 Cake formation

The formation of a filter cake on the surface of the filter medium is of great importance to the filters ability to effectively trap particles. A single particle entering a filter has a high possibility of passing through, but when hundreds or thousands of particles are competing to pass through the filter at the same time, the particles will be jammed, and a filter cake will be formed at the surface of the filter as illustrated in Figure 2. The established filter cake acts as filter medium itself and is often far more effective at trapping particles than the base filter medium, but at the same time limiting flow [13].

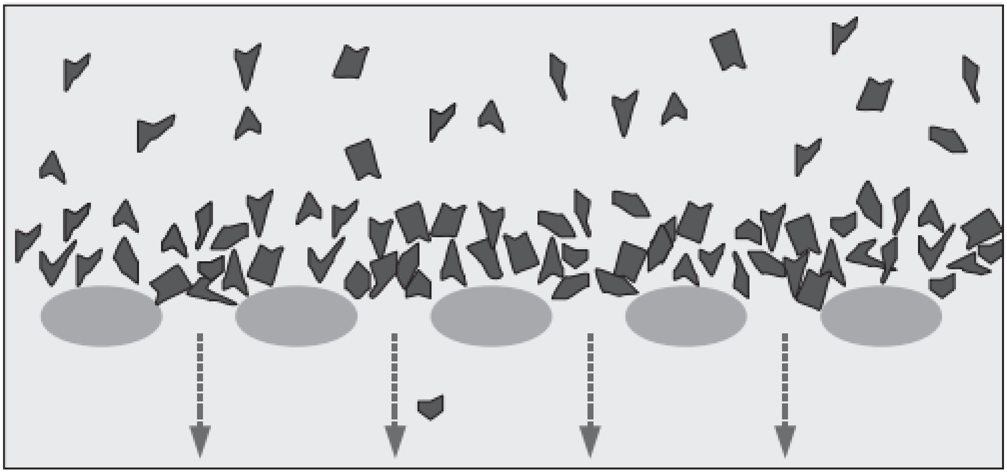

Figure 2: Formation of a filter cake [13].

As a cake is formed, it is possible to predict the relationship between volume of filtered liquid and time. For most filtration cases it can be approximated to:

$$V \propto \sqrt{t}$$

Equation 1

Where:
V = Cumulative volume filtrate
t = Time

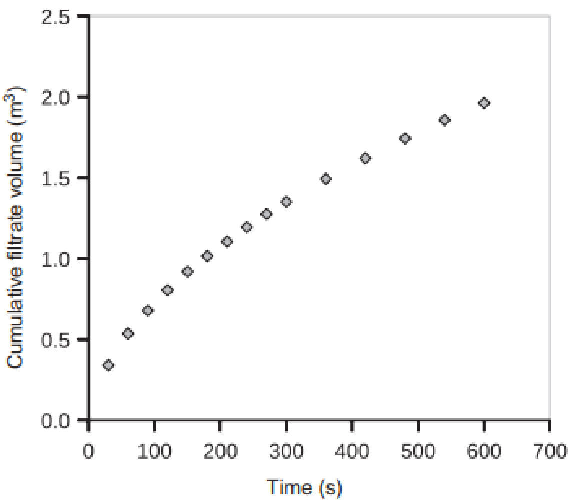

Figure 3: Cumulative volume filtrate collected vs time. This figure illustrates the approximation that: $V \propto \sqrt{t}$ [13]

This means that as the filter cake accumulates, the liquid flow rate is reduced. It takes 4 times as long to double the volume filtrate as the filtration process is under way as seen in [13]. This approximation is correlating well to the results from the lab experiments in this report in section 4.5.3.

2.3 Filtration criteria

According to Bergen municipality water and wastewater divisions main plan for drainage and aquatic environment, wastewater should be "Environmental toxins and other harmful substances must be removed at the source", i.e. before entering the municipal sewage system. This also applies to substances that create problems for the transport system or cleaning process, which results in more pollution being relieved in overflow to vulnerable water bodies [14]. According to this the main criteria for defining the efficiency for the filtration process will be the removal of elements that might be harmful to the environment, as well as particles of a greater size that might cause problems in the local transport pipes for wastewater. In this report investigation of particle removal will be done, and not the level of bacteria in the wastewater. Filtration of bacteria or environmental toxins is a complicated process where it is necessary to have a clear understanding of what bacteria or toxins is present in the wastewater to be able to choose a process suited for the filtration needs in the application.

According to Worlds Health Organizations standards for drinking water published in 1993, the turbidity, measured in NTU, is to be below 5 NTU and preferably below 1 NTU to be classified as drinking water [15]. In these experiments, it is not expected to get any results within this quality range. A result that is comparable with the requirements for drinking water may suggest that there is something wrong with the testing procedure. A more typical result for wastewater is about 100-400 NTU [16].

The filtration technologies listed in chapter 2.1 do have multiple uses and are easily modified to fit different filtration needs. Most technologies can filter both gases and liquids and can be modified with different mesh sizes/filter material diameter, to be able to filter specified sizes of particles. Depending on the operator's criteria for filtration, different filter technology and filter materials will be better suited for the different uses.

When jet fuel is being handled, there are strict guidelines for how to handle it. For instance, the filtration of fuel is necessary after transportation. Before fueling an aircraft or a helicopter, the expected filtration quality of the fuel is to have no particles greater than 2 microns. The normal setup for a jet fuel system includes a water separation filter and a membrane filter in a "high capacity cartridge filter" normally made of cellulose or fiberglass [17].

Another example is in the process of drilling an oil well, a drilling fluid (mud) with the correct characterizations is necessary. The need for a well-controlled mud is related to the stability of the well being drilled. The process of mixing the mud is what gives the stability of the well, the filtration of mud is a different process. The filtration of mud is related to the drilling fluid returning from the well and consists of drill cuttings. The drill cuttings will when returned to the drill floor to be separated from the drilling fluid, making it possible to reuse the drilling fluid. The process of filtering the mud is done with the use of first a vibrating membrane filter (shale shaker) which separates the larger particle out of the mud. Then into a centrifugal separator, and to protect the pumps in the system there is a mesh filter to remove particles of certain sizes that might have passed through the previous filters. The need for filtration in this process is necessary to remove as much drill cuttings from the mud as possible to control the mixture of the mud to protect and clean the well [18].

2.4 Desirable filter material

To be able to decide which filter media is to be tested in the lab experiments, previous research must be reviewed, and parameters and specifications must be defined. The most used granular filter media in water treatment is sand, but other materials are used as well. Coal, pumice, plastics, ceramics, garnet, ilmenite, alumina and magnetite are just a few of the filter media being used for this purpose [19].

Important physical properties of the filter media that is essential for filtration are size, shape, density, the specific surface area of each grain, surface roughness, filter bed depth and surface diameter of the filter to mention the most important parameters and specifications.

Another consideration when deciding which filter media to choose is its ability to be cleaned and recycled. Some media are harder to clean than others (i.e. sand vs. steel balls). This is an important parameter, as a media that is hard or expensive to recycle will be inappropriate for the patented filtration system discussed in this thesis. The process of cleaning out a filter material is a process called regeneration. Some materials, such as sand, is difficult to regenerate. Filters made up of sand and other materials with small diameter < 0.8 mm typically uses a backwash system. This backwash is done by sending water in from the outlet of the filter, which fluidizes the filter bed, and in the process, transports captured particles out in a separate container or an easy to replace single-use paper filter. Since sand is a relatively cheap filter material, it is not cost-efficient to recycle and is normally discarded.

Eventually, the only reliable way of testing the filter media to be used in this project is empirical data from pilot lab tests [20], followed up by full-scale tests in the available prototype of the filtration device.

2.5 Research of wastewater

Wastewater is found in multiple compositions. Wastewater and greywater are normally buildups of particles distributed in different sizes and bacteria. When selecting a wastewater substitute to use for testing, a fluid that will have a consistent distribution of the same particles is necessary. Regular household wastewater is built up of different solids in the water and will vary depending on the household. Other fluids will have more known particle distribution and size, in chapter 3.3 this will be discussed further for different kinds of coffee and tea. Another example of fluid that could be considered for making wastewater for testing would be an ISO – standard test dust of different compositions suited for ones need [18], [21]. According to ISO 12103-1:2016[22] A2, Fine Test Dust would be a suited candidate for diluting in water for making a wastewater equivalent with consistency.

For urban wastewater a mixture consisting of total phosphor, BOF5, nitrogen, bacteria and viruses are common. To determine the efficiency of a filter with wastewater of this quality more advanced measuring technics for the filtrate will be needed to evaluate the results against the applicable standard for small wastewater treatment systems NS-EN 12566-3:2005 [23].

2.6 Effect of parameters

2.6.1 Effect of pressure

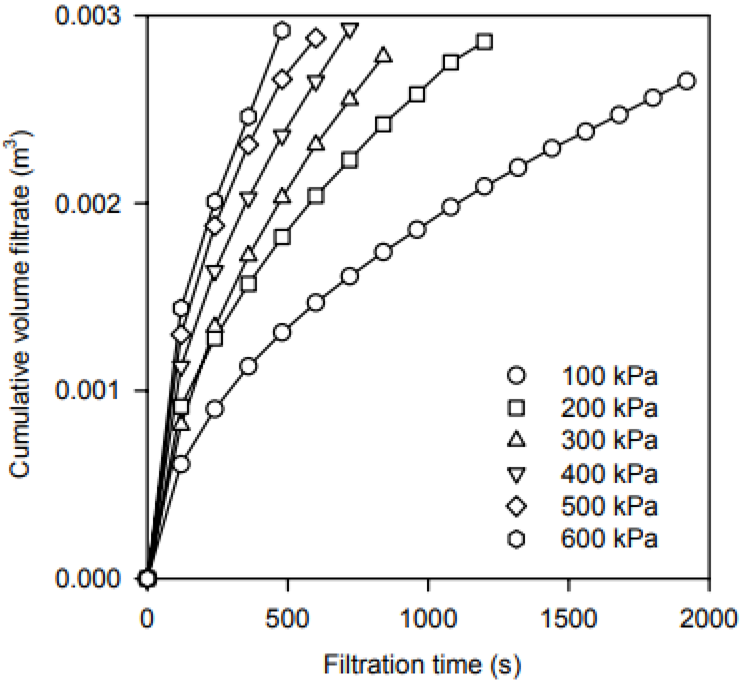

Figure 4 - Effect of pressure on cumulative volume filtrate [24].

According to the model in Figure 4 it is clear that a higher pressure at the filter leads to a quicker and more effective filtration process. The pressure build-up at the top of the filter material leads to a higher filtration rate. When using filter materials with small grain sizes like sand, it is useful to pressurize the filter to increase flow through the much denser filter bed [25].

2.6.2 Effect of filter material diameter

In the experiments done by Yu Et Al[9], grain sizes ranging from 3 to 10 mm were tested as shown in Figure 5. The results of the experiments are clear, the smallest grain size, 3 mm, had the highest filtration effect but also the largest pressure drop. In the other end, the largest 10 mm grains had the lowest filtration effect but had a much lower pressure drop. The 5 mm grains had a great effect on the filtration of the particles, and the pressure drop of this size was considerably lower than the smaller 3 mm grains.

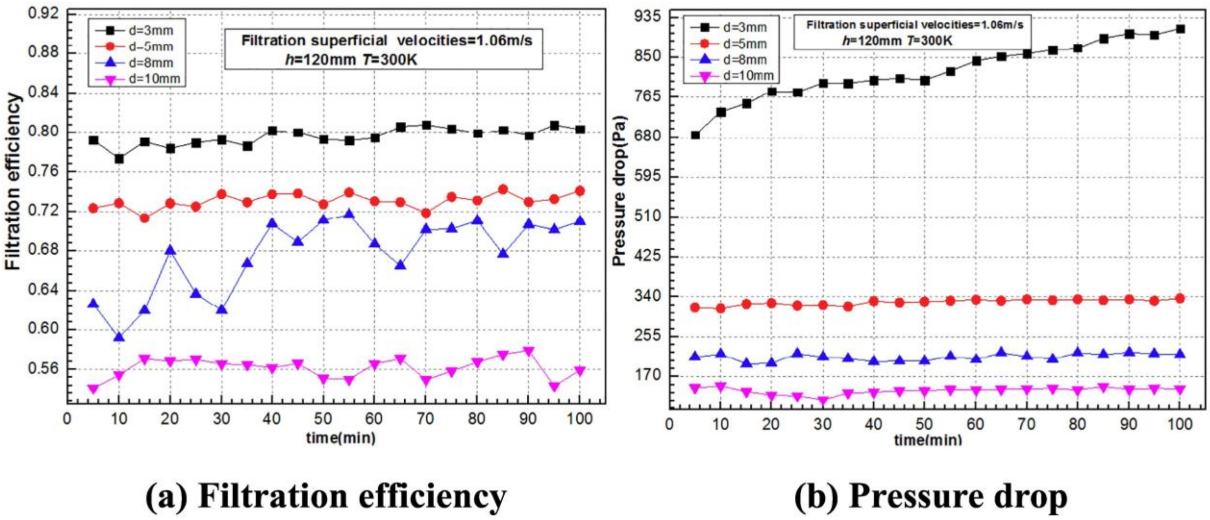

Figure 5: Results from Yu Et Al experiments [9]

2.6.3 Effect of filter media surface

The geometric form and size of the filter media will have an impact on the filtration efficiency in a filtration set up. Different materials will have different porosity which also will affect the filtration. A filter media with a rougher surface will trap particles more efficiently. When designing a filter with a more coarse filter medium the advantage in the filter media surface can be used to make the filter with a smaller bed depth, or keep the same bed depth to increase the filtration efficiency [26].

2.6.4 Effect of filter bed depth

The depth of the filter material layer will be of the parameters that impact the flowrate and the filtration efficiency of a filter system. In the industry it is desirable to achieve a L/d ratio of 1200 [26]. This ratio tells something about the filter bed depth compared to the effective diameter of the filter material, where a filter material with a smaller effective diameter will need a smaller bed depth to accomplish the same results regarding filtration. By this ratio it is possible to calculate the filter bed depth from the effective diameter of the filter material. For depth filtration the particles in the wastewater is smaller than the filter material, this allows the particles to be captured in the pores in the filter, a filter with more depth will have more pores to collect particles before it becomes clogged, and will have a longer operating time [13].

3. Key Factors

This chapter will discuss influence that contributes to the result as this article will consist of two different experiments. The first experiment will be a lab approach where the objective of the experiments will be to get an understanding of the ideal grain size, filter material, bed depth and the effect of pressure in the filter system. This knowledge will later be used to optimize the experiments in the scaled prototype filter system available from Monmic Operations. The results from the lab experiments will also be compared to the results that will be gathered from the scaled prototype to determine if the design of the continuous filtering system will function sufficiently.

3.1 Defining filter materials

The following materials will be tested in the lab experiments:

- Plastic balls
- Sand
- Gravel

For the testing, the team investigated the use of both plastic balls and steel ball. Due to the high density of the steel balls, about 7500 – 8500 kg/m^3 it was considered to be not suitable for use in the prototype due to restrains in the design.

When conducting the experiments with plastic balls, there are some extra considerations that must be done. As some plastics such as polypropylene has a density of 905 kg/m^3, it is lighter than water and other liquids. With density lower than water, it will most likely result in the filter material floating at the top of the water, and not sitting in the filter as a solid filter bed as the other materials tested. Other plastic types such as polyoxymethylene has a higher density of 1410 kg/m^3. This makes it heavier than water, and the simulated wastewater (see chapter 3.3). Due to these constraints polyoxymethylene is a desirable material for plastic balls as a filter material.

3.2 Filter materials and sizes

The suggested filter material and grain sizes for the experiments are presented in Table 1.

Table 1: Selected filter material and sizes

Material	Size range	Testing pressure	Eq. hydraulic diameter
Plastic balls	3mm, 5mm, 7 mm and 10 mm	Atm and 2 Bar	Actual diameter
Sand	Coarse sand 0.2 – 6 mm	Atm and 2 Bar	1.08mm±0.17mm
Gravel	Medium coarse gravel 11 – 16 mm	Atm and 2 Bar	9.7mm ±1mm

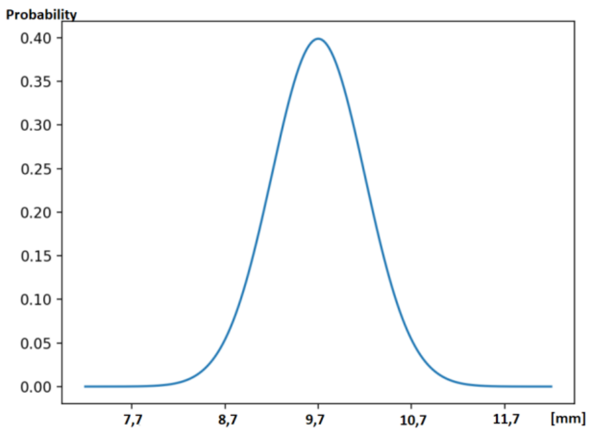

Figure 6: Grain Size distribution for gravel

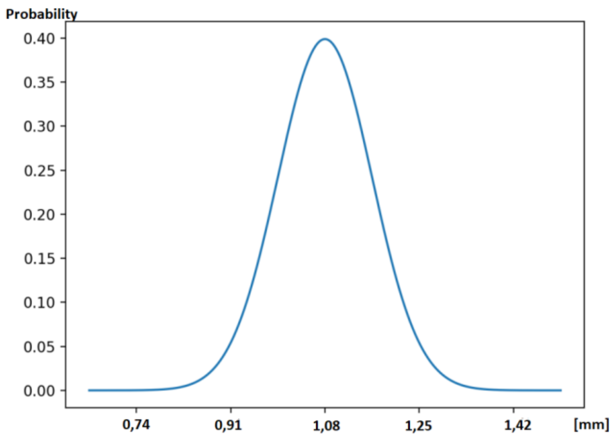

Figure 7: Grain Size distribution for sand

As the grain sizes distributed in both sand and gravel are of different shapes, it is necessary to calculate the equivalent hydraulic diameter of the grains. A small but representative sample of both the sand and gravel was measured for size, and a hydraulic diameter was calculated using an assumption that the grain shape was ellipse shaped. After the grains were measured and the hydraulic diameter was calculated, a graph showing the distribution of the grains were to be calculated. Due to the small sample size and the assumption that the grains are normally distributed, an unknown variance a Student's T-distribution was calculated. Figure 6 and Figure 7 shows the distribution of the grain sizes in gravel and sand from these calculations. With a 95%

confidence interval in the grain size distribution, the results read 9.7mm ± 1 mm for gravel and 1.08 mm ± 0.17 mm for sand.

3.3 Defining wastewater used in the experiment

In the experiment to be performed a simulated wastewater must be defined before performing tests. The wastewater needs to have particle sizes similar to wastewater being filtered in the industry today. According to Kusnierz and Wiercik, wastewater particle sizes range from 30 µm to 550 µm in raw sewage from the wastewater treatment plants tested in their article [27], Figure 9 shows the distribution in the test data collected from the sewage plants. This indicates what the size distribution the produced wastewater used in the experiments in this article should be.

Coffee is a wastewater alternative with particle size from 20 to 1300 µm (see Figure 8), depending on the type of grinding [28]. This is a good wastewater alternative, as it has a wide span of particle sizes. Another property of coffee as the wastewater is the density. When mixed as described in "Preparing of wastewater" the density of this wastewater is 1022.4 kg/m^3.

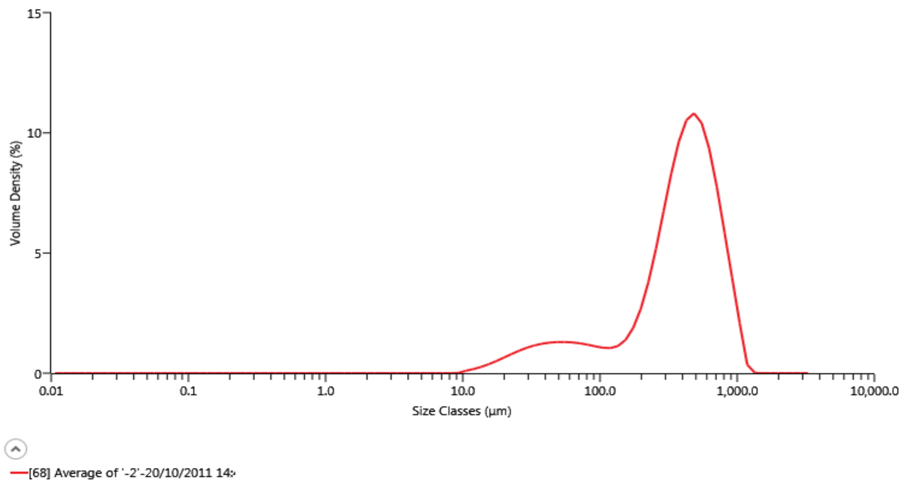

Figure 8: Coffee particle size distribution [27].

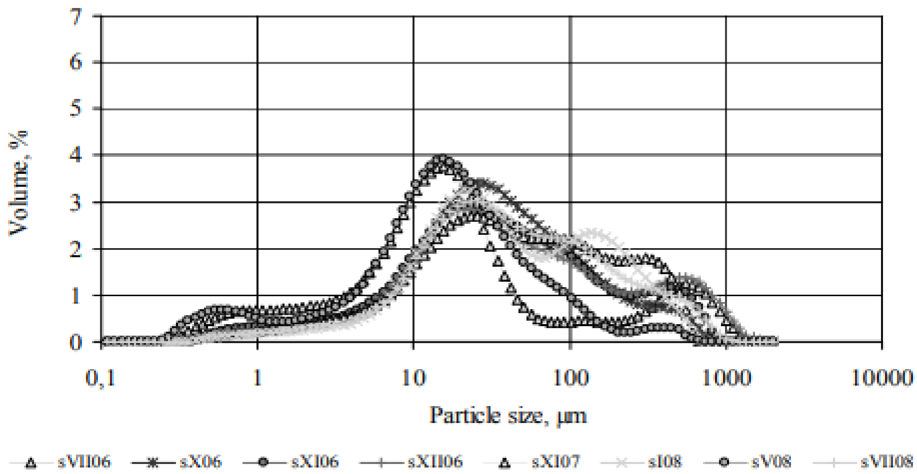

Figure 9: The percentage share of particles of diameter d, in the total volume of raw sewage samples collected from the WWTP 1 plant [27].

Other wastewater alternatives would be products such as tea, colored water, water with cement dust etc. Due to the range of particle sizes, cost and convenience, coffee is chosen as the wastewater alternative in this experiment.

When conducting turbidity measurements of different wastewater alternatives (See 3.4 for results), a coffee/water mix of 40g/l seems suitable for this purpose, as it has a turbidity value of approximately 750 NTU. These values are within the turbidity values wanted for simulating wastewater according to A.R. Mels finds in his report [16].

Preparing of wastewater

The wastewater necessary to conduct the experiments in this project is defined in 3.3. When making the wastewater, Luxus filter ground coffee from the low-cost grocery store Europris is used, due to price and availability.

Procedure for preparing wastewater:

1. Put 40 g Luxus filter ground coffee per liter water into a separate water container
2. Add the wanted quantity of hot water at approx. 60 °C to a separate water container.
3. Mix coffee and hot water together.
4. Wait 15 min. for the settling of bigger particles in a separate water container.
5. Top off the wastewater into the supply water container.

3.4 Introduction to Turbidity

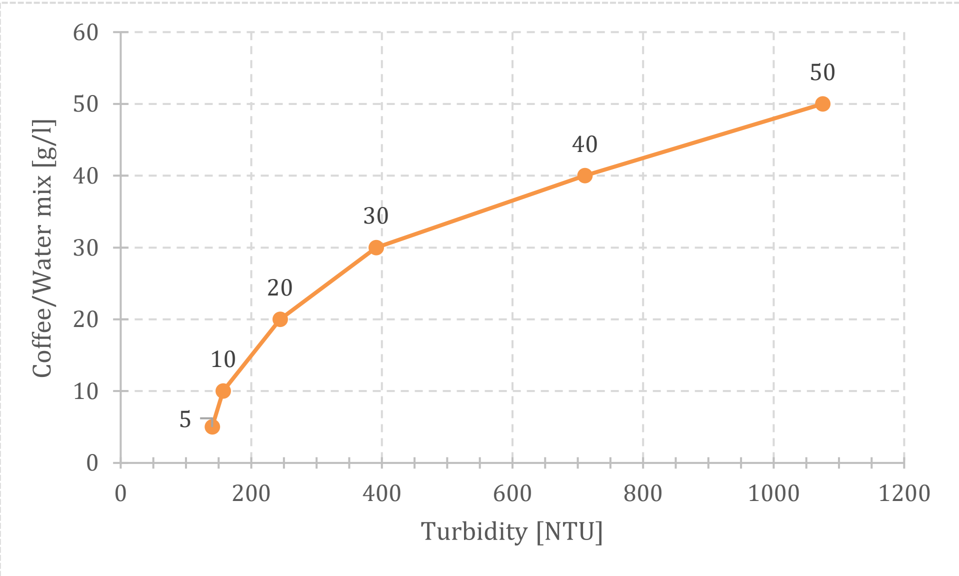

Figure 10: Coffee/Water mix vs Turbidity.

In Figure 10 the results from turbidity measurement of a coffee/water mix are shown. Six samples of the mix were tested, ranging from 5 g/l to 50 g/l. It is clearly seen that the turbidity increases as the amount of coffee in the mix increases. This gives the reader an indication of the turbidity of such a mix when a turbidimeter is unavailable, or inconvenient to use.

To get a more practical view of the level of turbidity, Figure 11 was made to illustrate this more clearly for the reader. The illustration follows the datapoints in Figure 10, from left to right, with 5 g/l to 50 g/l. When reaching a turbidity of about 400 NTU, 30 g/l it is harder to visually separate the samples from each other.

Figure 11: Visual Turbidity Scale

Results from initial turbidity measurements

Measurements were conducted with the turbidity measurement apparatus Aqua Lytic AL450T-IR, of the following liquids, for later reference. See Table 2.

Table 2: Results from turbidity testing of various liquids for comparison

Measured Liquid	Measurement [NTU]
Tap Water @ ambient temp.	0.39
Tea @ 40°C	56
Luxus filter ground coffee, filtered @ 55°C	194
Unfiltered beer, stout @ ambient temp.	272
Luxus filter ground coffee 50g/l, unfiltered @ 55°C	1075

4. Experimental tests

As a full-scale test of filter materials for the patented continuous filter system requires a lot of time and resources, a small scale lab test where different filter materials and sizes are tested is necessary to be able to decide which materials qualifies for the full-scale test in the available prototype. In this test, filtration efficiency and flow rate will be the main evaluation criteria when evaluating the filter materials. The tests will give valuable information when designing the tests and deciding filter media for the tests in the prototype filter.

4.1 Lab preparation

In Figure 12, the inspiration for the lab setup planned in this project is shown. In this diagram from K. J. Ives “Specifications for granular filter media” [19], a suggestion for an apparatus to test a materials filterability is proposed. The main components of this apparatus are its sample funnel, inlet pipe, test tube, and outlet pipe. In addition, the apparatus has manometers at the inlet and outlet pipes, and a rotameter to measure flow at the outlet pipe. The lab setup in this project will have many similarities to K.J. Ives setup, but with significant differences shown in Figure 13.

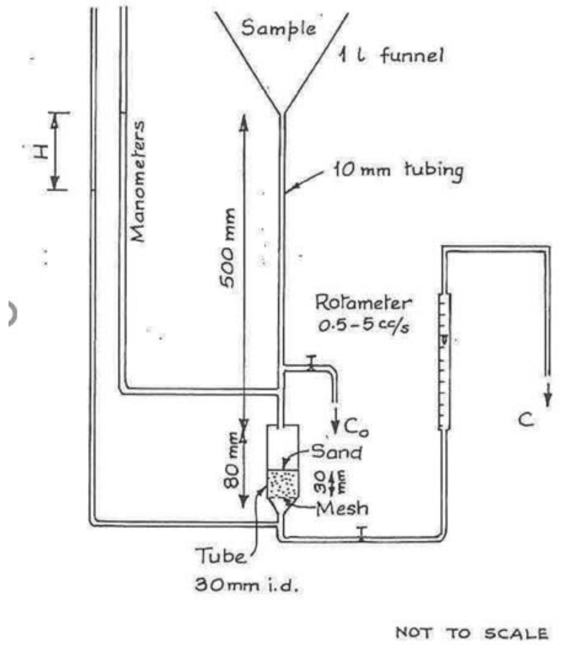

Figure 12: Diagram of filterability apparatus [19]

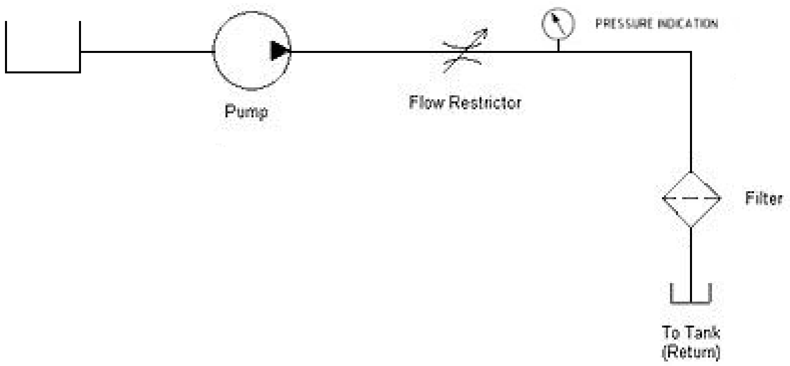

Figure 13: Hydraulic Schematic of a laboratory setup

When deciding the layout of the system used to test the filter, different kind of models presented in EN 13443-2:2005 +A1:2007 were taken into consideration alongside the setup from K. J. Ives in Figure 12. From Figure 46 (in appendix) and Figure 12 the setup to be used for the tests were designed. The pressurized water supply is replaced by a pump and there will be no flow metering device, but there will be a measuring scale on the supply container which in combination with a stopwatch can be used to calculate flow rates, as described in 4.3. In Figure 14 the final laboratory setup is shown.

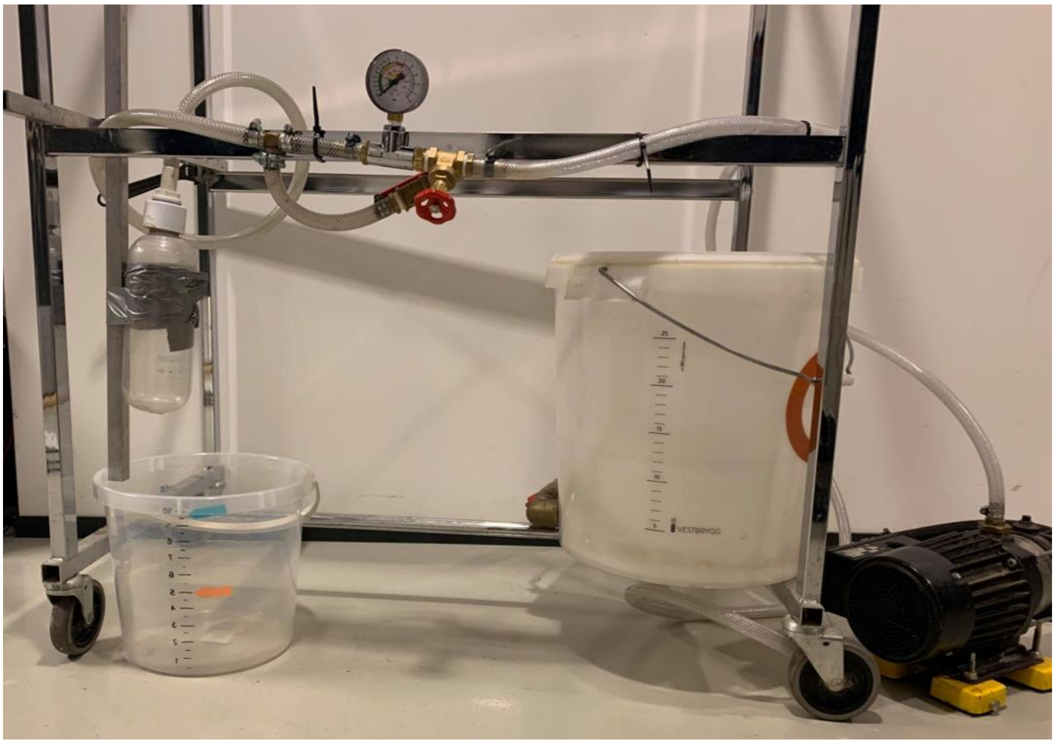

Figure 14: Laboratory experiment setup

4.1.1 Required Components for lab setup

When doing the experimental lab tests, the following parts are needed in addition to the mentioned parts above.

- 5 m, ½" reinforced hose
- 1 pcs gate valve with ½" coupling
- 1 pcs bushing to ½" hose coupling
- 1 pcs manometer (1-12 bar) with ¼ " coupling.
- 1 pcs adapter 1/2" pipe coupling to 1/2" hose coupling, male/male
- 1 pcs T-section with 1/2" coupling
- Grundfos water pump, see Figure 45 in appendix for specifications
- Thread sealant

To make the experiments as accurate and consistent as possible, suitable equipment needs to be chosen. To be able to adjust the flow, a gate valve will be installed between the pump and the filter housing. As the Grundfos water pump is a centrifugal pump there will not be a need for a bleed of valve in the system with the desired operation pressure.

4.1.2 Procedure for the atmospheric pressured lab experiment

When conducting the atmospheric pressured lab experiment, a consistent procedure must be defined.

1. Add desired bed depth of desired filter material in the filter housing.
2. Prime filter housing with water before the start of the experiment.
3. Place liquid collection unit underneath filter housing.

4. Pour 2 l of wastewater through the filter housing reservoir (see 3.3 for the making of wastewater), collecting the filtered liquid in the liquid collection unit.

4.1.3 Procedure for the pressurized lab experiment

When conducting the pressurized lab experiment, a consistent procedure must be defined.

1. Add desired bed depth of filter material in the filter housing.
2. Prime filter housing with water before the start of the experiment.
3. Add 12 l wastewater to the water reservoir (see 3.3 for the making of wastewater).
4. Place liquid collection unit underneath filter housing.
5. Start the water pump to initiate flow through the system.
6. Adjust line pressure to wanted pressure with the gate valve and manometer.
7. Stop water pump when 10 l indicator in collecting unit for filtrate is reached.

4.2 Input Parameters

The following parameters are considered when performing the tests. The parameters are divided into input and output parameters. These parameters will be considered when designing both the laboratory experiment and the full-scale prototype test later in this article.

Top priority input parameters:

1. Turbidity [NTU]

   In this project, a turbidity measurement unit is used to define the particle concentration in the liquid measured. Western Norway University of Applied Sciences (WNUAS) has kindly allowed the authors of this article to use an apparatus from the manufacturer Aqua Lytic, model name: AL450T-IR. This apparatus measures turbidity according to EN ISO 7027. Measuring range: 0.01 to 1100 NTU. Operation of the apparatus is according to the user manual of the device [29].

   According to Aqua Lytic, the device can be used in different areas, from drinking water to wastewater [30]. Mels, Spanjers and Klapwijk mention in their research article about turbidity monitoring that turbidity is a reliable measuring unit to measure particles in wastewater [16]. Additionally, it is stated that municipal wastewater measurements range from 100-400 NTU during the dry season, and 100 to >1000 NTU during rainy periods (Wageningen, The Netherlands). These numbers are interesting for comparison when the measurements in this project are analyzed. The turbidity is measured before and after filtration for comparison and analyzed to calculate the filtration efficiency.

2. Inlet pressure [barg]

   The manometer is placed between the valve and the filter. This is measured in bar. The inlet pressure range of interest in this test is 0 – 2,5 barg.

3. Grain size [mm]

   Caliper measurement control / stated information from the producer (depending on filter material). See Figure 6 and Figure 7 for grain size range.

   When measuring spherical grains such as plastic balls, the spherical diameter can be measured. Gravel and sand are harder to measure due to its random shape. Because of this, a consistent measurement procedure must be defined. In this case, it has been decided to calculate the hydraulic diameter equivalent of an ellipse. Se Figure 45 the appendix.

4. Bed depth [mm]

   The depth of the filter bed measured from the bottom of the filter housing to the topmost level of the filter material.

Other Input Parameters:

- Grain shape (spherical, cylindrical, random)
- Grain density (kg/m^3)
- Temperature (°C)

The input parameters discussed above will be evaluated in the range presented in Table 3.

Table 3: Input parameter range

Parameter	Range	Unit
Turbidity	800-1100	NTU
Inlet pressure	0-2,5	barg
Grain size	0-16	mm
Bed depth	0 -200	mm

4.3 Output Parameters

The measurement method of each parameter relevant to the experiments is defined in the following section.

Top priority output parameters:

1. Turbidity [NTU]
   - See the input parameters, 4.2. This parameter will be compared to the input turbidity.

2. Flow rate [l/min]
   - Measured by analyzing videotape of the experiment. The cumulative volume filtrate is noted at each ½ l, and flowrate is calculated based on this and time.
3. Cumulative volume filtrate [l]
   - Measured by scales on the liquid collection unit.

Other output parameters:

- L/D – ratio (Bed depth / grain diameter) [Dimensionless]

The output parameters discussed above will be evaluated in the range presented in Table 4.

Table 4: Output parameter range

Parameter	Range	Unit
Turbidity	50-1100	NTU
Flow Rate	0-33	l/min
Cum. vol. filtrate	0-10	l

4.4 Sources of error

When defining sources of error, one can divide them into two main categories of errors, random errors and systematic errors. Random errors may be caused by small variations in the environment, an instrument or the way measurements are read. These random errors will over time affect the results different every time. To address this form of errors the utilization of replication, repeating a measurement several times using the average result, is used to get a more accurate result from the experiment.

- **Systematic errors:** Often comes from limitations of either the measuring instruments or in the procedure. These errors will give measurements that are constantly different from the true value of the result. This may come from a bad calibration of an instrument or the bias of a researcher.
- **Instrumental errors:** The calibration of the turbidity measurement apparatus and the scales on the measuring equipment.
- **Procedural errors:** The authors are working as a team. This gives a risk that it is not always the same team member doing the same calculations so there will be a chance for a different rounding of the calculations and the results will not be the same.
- **Environmental errors:** as possible the first series of experiments will be conducted in one of the laboratories at WNUAS, where there is a stable environment, with little to non-variations in temperature, no windows and no traffic of people in the room to distract the results.
- **Human errors:** One of the greatest human errors is estimation error, which is the way a measurement or instrument is read. Another is transcriptional errors, which occurs when data is recorded or written down incorrectly, this will also include when one forgets to register a number in the dataset in the computer for further investigation of the results.

After discussing the above-mentioned sources of errors, there is one trend in the errors. The consistency of the operator is vital for the correct collection and processing of the data from the experiments. To eliminate as many errors here as possible, the operators will be assigned different tasks only they will conduct, to prevent the data to be inconsistent due to different operators. Other errors are harder to eliminate the impact of, as the calibration and scales of the measuring equipment are harder to control but could be taken care of in a costly manner, of replacing it with better equipment.

4.5 Results and discussion

Before testing the set up with filter material, a baseline for what the selected equipment and design was able to deliver is necessary. The first test conducted determined the maximum flow rate of the filter housing with 1 mm holes in the bottom of it. After pouring 1 liter of water through the filter housing and measuring the time of it with a stopwatch, the time ended up at 15.1 seconds, resulting in a max. available flowrate of 0.07 l/s at atmospheric pressure.

When testing the baselines for the pressurized system, the tests were conducted in the test rig. Clean tap water was used. The test results from 1.0 barg and 1.4 barg pressure is shown Table 5.

Table 5: Results from flow test of setup

Pressure [barg]	Filtrate amount [l]	Time [s]	Calculated Flowrate [l/s]
0 / ATM	1	15.1	0.07
1.0	5	11.11	0.45
1.4	5	10.10	0.50

4.5.1 Results from flow testing of filter house w/ gravel

To get a baseline for evaluating the filtration of wastewater a test with gravel as filter material was concluded to get results from the flow rate. The results are presented in Table 6 and will create a comparison bias for the results from the filtration of wastewater.

Table 6: Test results from test of filter with water

Pressure [barg]	Bed Depth [mm]	Filtrate amount [l]	Time [s]	Calculated Flowrate [l/s]
1.0	110	5	11.98	0.42
1.0	200	5	14.49	0.35

4.5.2 Notes from preliminary experiments

During testing with sand (0,2 – 6 mm) as the filter material, a sandwich solution must be applied to prevent clogging of filter house in the bottom and to prevent "crater" build-up. Sand and gravel must be cleaned before conducting the experiments.

4.5.3 Results from the lab experiments

A total of 11 different lab experiments will be conducted. There will be two tests for each material, size and bed depth. One with the pressurized setup, and one with the gravity setup.

Table 7: Input and output parameters. Filter medium: Sand.

Parameters	Input	Output
Turbidity [NTU]	1075	431
Bed Depth [mm]	185	
Grain Size, hydraulic eq. [mm]	1,08 ± 0,17	
Cum. Vol. filtrate vs time		See Figure 15
Pressure [barg]	0	

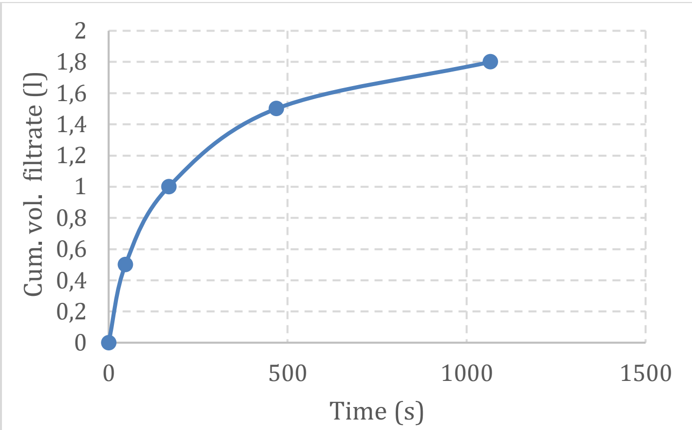

Figure 15: Cumulative volume filtrate vs time. Filter medium: Sand. Pressure: Atmospheric. Bed depth: 185 mm

Table 8: Input and output parameters. Filter medium: Sand.

Parameters	Input	Output
Turbidity [NTU]	1080	1050
Bed Depth [mm]	100	
Grain Size, hydraulic eq. [mm]	1,08 ± 0,17	
Cum. Vol. filtrate vs time		See Figure 16
Pressure [barg]	0	

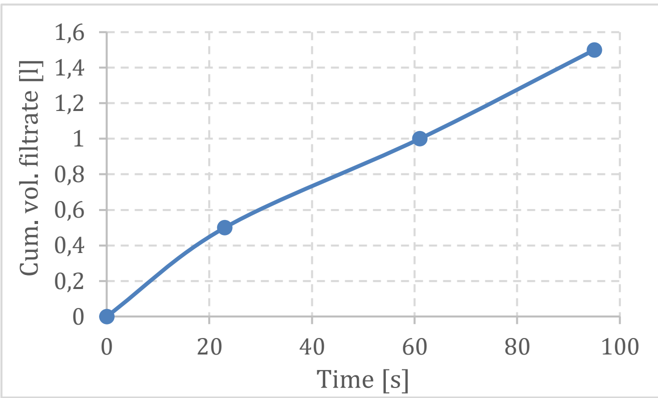

Figure 16: Cumulative volume filtrate vs time. Filter medium: Sand. Pressure: Atmospheric. Bed depth: 100 mm

Table 9: Input and output parameters. Filter medium: Sand.

Parameters	Input	Output
Turbidity [NTU]	1080	472
Bed Depth [mm]	185	
Grain Size, hydraulic eq. [mm]	1,08 ± 0,17	
Cum. Vol. filtrate vs time		See Figure 17
Pressure [barg]	2	

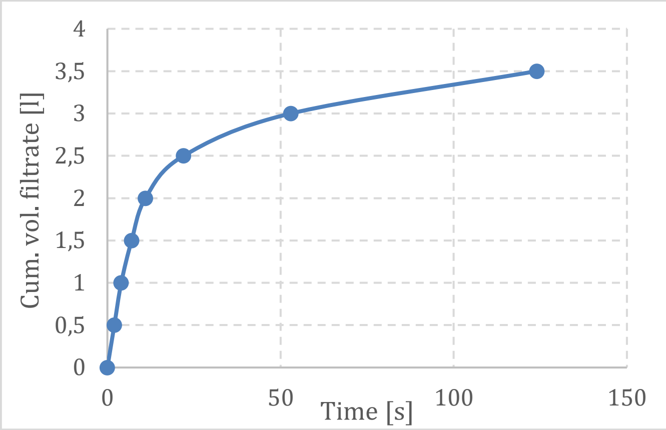

Figure 17: Cumulative volume filtrate vs time. Filter medium: Sand. Pressure: 2 barg. Bed depth: 185 mm.

Table 10: Input and output parameters. Filter medium: Sand.

Parameters	Input	Output
Turbidity [NTU]	1060	716
Bed Depth [mm]	100	
Grain Size, hydraulic eq. [mm]	1,08 ± 0,17	
Cum. Vol. filtrate vs time		See Figure 18
Pressure [barg]	2	

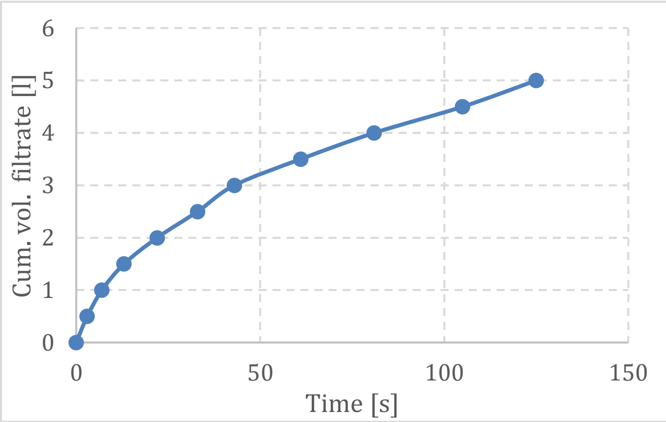

Figure 18: Cumulative volume filtrate vs time. Filter medium: Sand. Pressure: 2 barg. Bed depth: 100 mm

Table 11: Input and output parameters. Filter medium: Gravel.

Parameters	Input	Output
Turbidity [NTU]	1060	1000
Bed Depth [mm]	185	
Grain Size, hydraulic eq. [mm]	9,7 ± 1,0	
Cum. Vol. filtrate vs time		See Figure 19
Pressure [barg]	0	

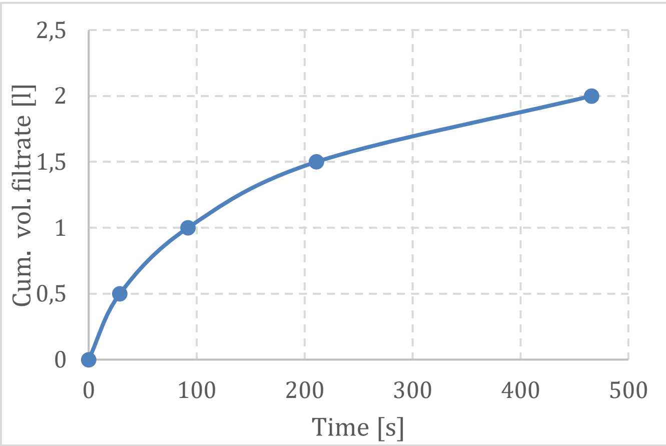

Figure 19: Cumulative volume filtrate vs time. Filter medium: Gravel. Pressure: Atmospheric. Bed depth: 185 mm

Table 12: Input and output parameters. Filter medium: Gravel.

Parameters	Input	Output
Turbidity [NTU]	1080	1080
Bed Depth [mm]	100	
Grain Size, hydraulic eq. [mm]	9,7 ± 1,0	
Cum. Vol. filtrate vs time		See Figure 20
Pressure [barg]	0	

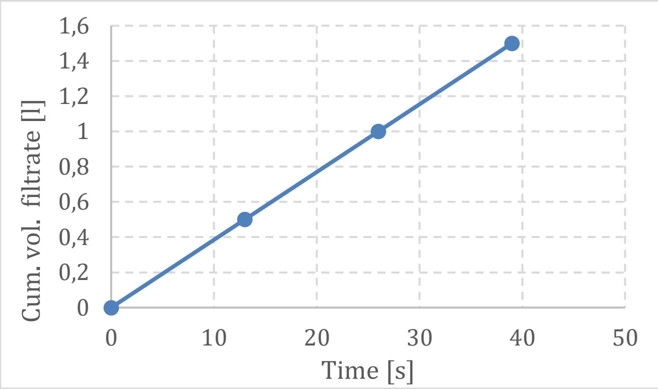

Figure 20: Cumulative volume filtrate vs time. Filter medium: Gravel. Pressure: Atmospheric. Bed depth: 100 mm

Table 13: Input and output parameters. Filter medium: Gravel.

Parameters	Input	Output
Turbidity [NTU]	1075	1060
Bed Depth [mm]	185	
Grain Size, hydraulic eq. [mm]	9,7 ± 1,0	
Cum. Vol. filtrate vs time		See Figure 21
Pressure [barg]	2	

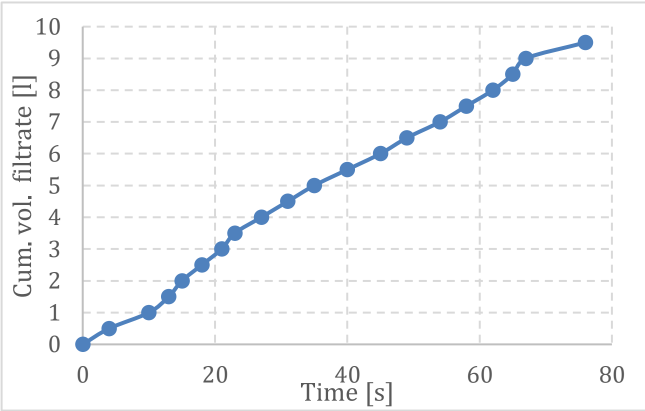

Figure 21: Cumulative volume filtrate vs time. Filter medium: Gravel. Pressure: 2 barg. Bed depth: 185 mm

Table 14: Input and output parameters. Filter medium: Plastic Balls, 3 mm

Parameters	Input	Output
Turbidity [NTU]	924	780
Bed Depth [mm]	185	
Grain Size, hydraulic eq. [mm]	3	
Cum. Vol. filtrate vs time		See Figure 22
Pressure [barg]	0	

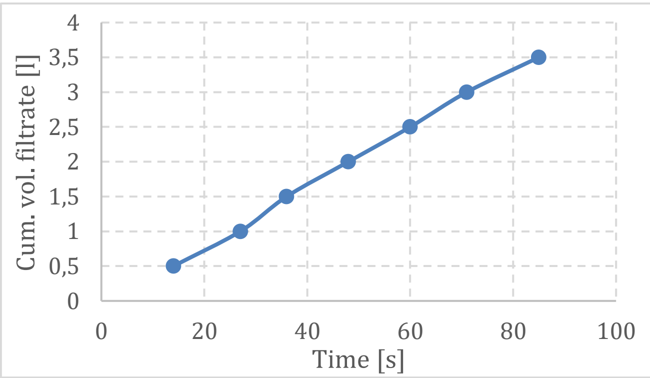

Figure 22: Cumulative volume filtrate vs time. Filter medium: Plastic Balls, 3 mm. Pressure: Atmospheric. Bed depth: 185 mm

Table 15: Input and output parameters. Filter medium: Plastic Balls, 5 mm

Parameters	Input	Output
Turbidity [NTU]	830	830
Bed Depth [mm]	185	
Grain Size, hydraulic eq. [mm]	5	
Cum. Vol. filtrate vs time		See Figure 23
Pressure [barg]	0	

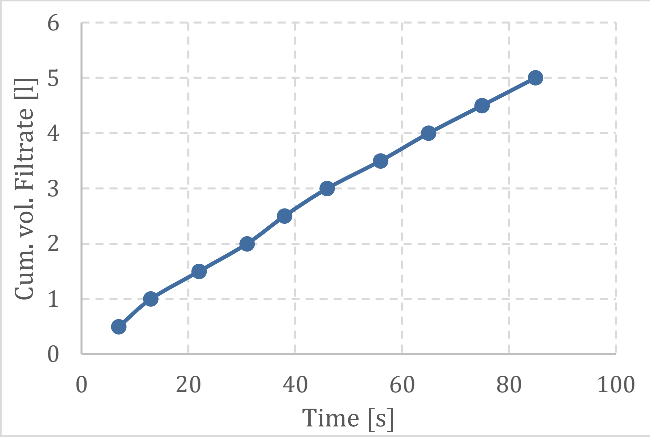

Figure 23: Cumulative volume filtrate vs time. Filter medium: Plastic Balls, 5 mm. Pressure: Atmospheric. Bed depth: 185 mm

Table 16: Input and output parameters. Filter medium: Plastic Balls, 7 mm

Parameters	Input	Output
Turbidity [NTU]	973	840
Bed Depth [mm]	185	
Grain Size, hydraulic eq. [mm]	7	
Cum. Vol. filtrate vs time		See Figure 24
Pressure [barg]	0	

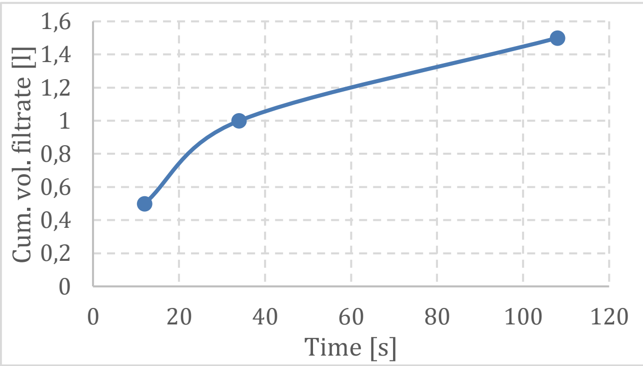

Figure 24: Cumulative volume filtrate vs time. Filter medium: Plastic Balls, 7 mm. Pressure: Atmospheric. Bed depth: 185 mm

Table 17: Input and output parameters. Filter medium: Plastic Balls, 10 mm

Parameters	Input	Output
Turbidity [NTU]	982	981
Bed Depth [mm]	185	
Grain Size, hydraulic eq. [mm]	10	
Cum. Vol. filtrate vs time		See Figure 25
Pressure [barg]	0	

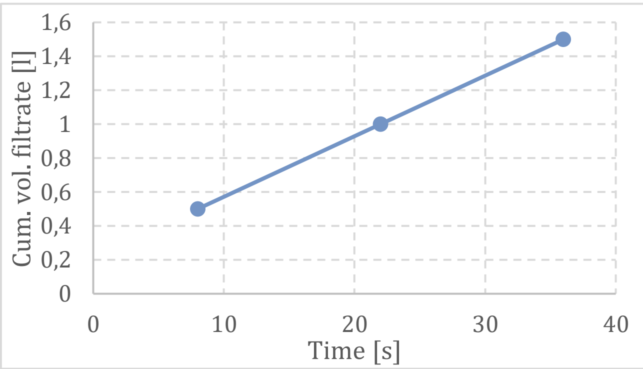

Figure 25: Cumulative volume filtrate vs time. Filter medium: Plastic Balls, 10 mm. Pressure: Atmospheric. Bed depth: 185 mm

Note: Due to clogging in gravel with pressure setup, and 100 mm bed depth, the test did not give any reasonable result and is therefore not shown in this report.

4.5.4 Comparison of the pressure effect in various filter materials and bed depths

Gravity vs. Pressure. (Filter medium: Gravel. Bed depth: 185 mm) When comparing the results of the gravel tests seen in Figure 26, where atmospheric pressure is compared to 2 bar pressure with a 185 mm filter bed depth, it is clear that the flowrate in a pressurized setup is far greater than that of an atmospheric setup. The pressurized setup have a linear time/volume curve, while the atmospheric setup have a declining curve resembling an approximated square root curve as discussed in chapter 2.2. The filtration efficiency results of these tests are very similar, with the atmospheric being slightly more efficient than the pressurized setup with 6% and 2% respectively.

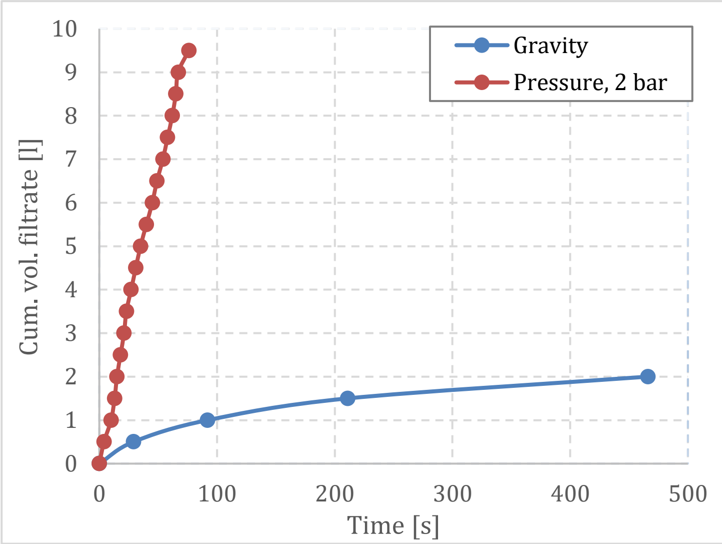

Figure 26: Comparison of the effect of pressure vs gravity. Filter medium: Gravel. Bed depth: 185 mm

Gravity vs. Pressure. (Filter medium: Sand. Bed depth: 185 mm) As seen in Figure 27, where the results from sand as the filter medium, and a bed depth of 185 mm is shown, it is clear that the flowrate of the pressurized setup is far greater, and that the total volume possible to filter is greater than that of the atmospheric setup due to clogging. The curve of the pressurized setup is fairly linear until 2 l is filtered, from there it starts declining due to clogging. The atmospheric curve is declining from the start of the filtration process, and is reasonably similar to the approximated root curve discussed in ch. 2.2, meaning that a filter cake has been building up, and slowly starts clogging the filter. Filtration efficiency of sand is good, at 60% for atmospheric pressure, and 56% at 2 bar pressure.

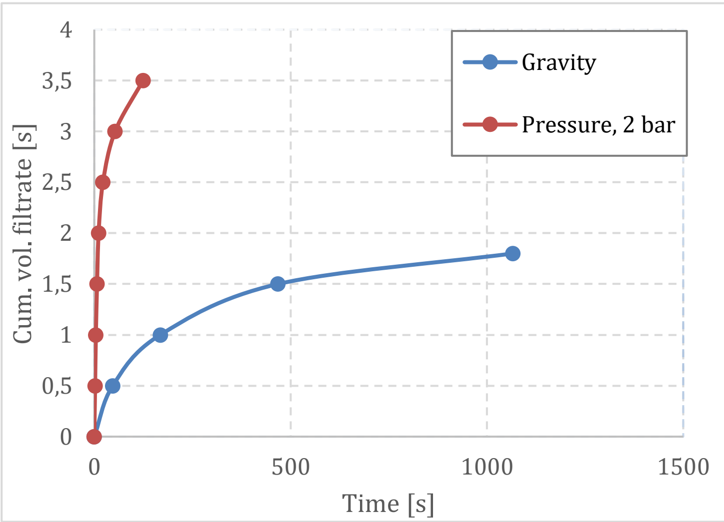

Figure 27: Comparison of the effect of pressure vs gravity. Filter medium: Sand. Bed depth: 185 mm.

Gravity vs. Pressure. (Filter medium: Sand. Bed depth: 100 mm)

In Figure 28 When testing with sand as the filter medium with a bed depth of 100 mm, it is apparent that the flow rate increases as the filter bed depth decreases compared to the 185mm bed depths in Figure 27. The curve for the atmospheric test is fairly linear, while the pressurized test flattens out over time, indicating a filter cake build up. Filtration efficiency is decent at 32.5% for the pressurized test, while the atmospheric test got a result of 2.8% which is far lower.

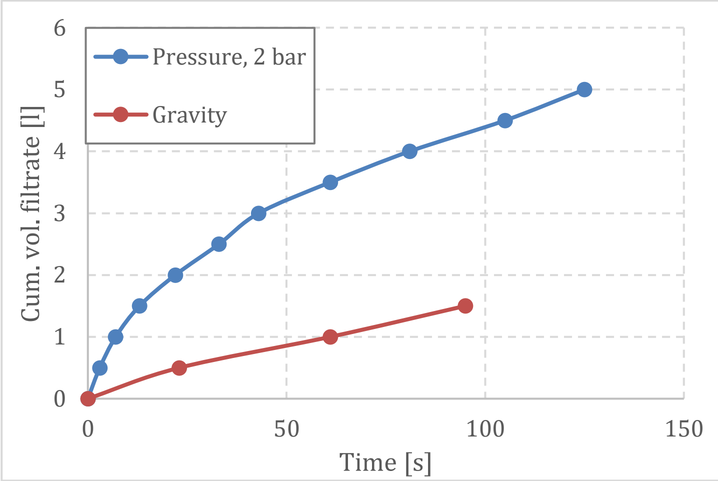

Figure 28: Comparison of the effect of pressure vs gravity. Filter medium: Sand. Bed depth: 100 mm.

4.5.5 Comparison of filter materials and flowrate

Comparison of filter materials. (Pressure: 2 bar. Bed depth: 185 mm)

In Figure 29, the two filter materials sand and gravel is compared, with other parameters equal. The pressure is 2 bar, while the bed depth is 185mm. It is clear from the figure that gravel has a much higher flowrate, and a linear volume/time-curve, while the sand follows the approximated root curve discussed earlier with a significantly declining flow rate over time, due to clogging. When measuring the filtration efficiency of the two materials, the sand is far superior to the gravel, with 56.3% and 1.4% respectively.

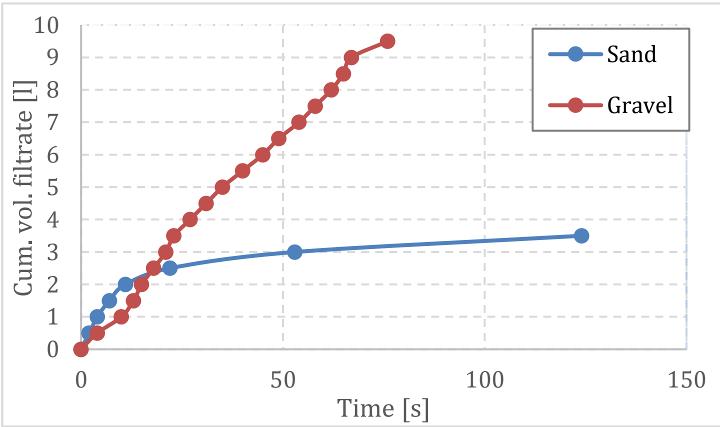

Figure 29: Comparison of filter materials and flowrate. Pressure: 2 bar. Bed depth: 185mm.

Comparison of filter materials. (Pressure: Atmospheric. Bed depth: 185 mm)

In Figure 25, sand, gravel, and four sizes of plastic balls is compared with other parameters equal. The pressure is atmospheric, while the bed depth is 185 mm. Based on these results, sand and gravel have the lowest flowrate of the six materials, while plastic balls in sizes of 3 and 5 mm have the highest flowrate. In theory, the plastic balls of sizes 7 and 10 mm should have the same, or higher flowrate than 3 and 5 mm balls, but due to clogging of the filter house when testing these filter materials, the flow rate was restricted.

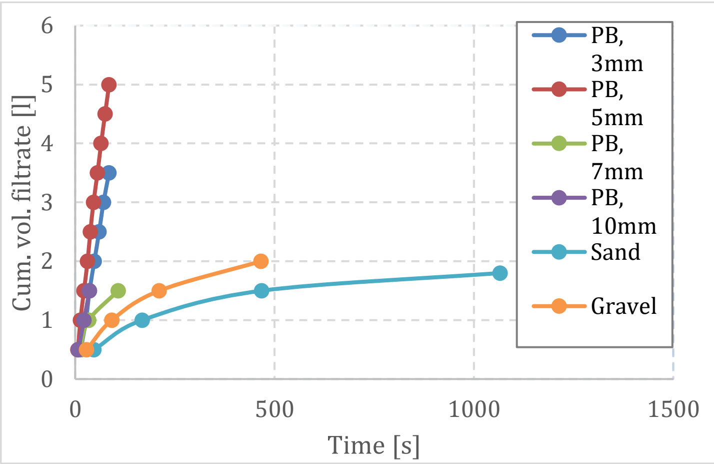

Figure 30: Comparison of filter materials and flowrate. Pressure: Atmospheric. Bed depth: 185mm. PB = Plastic Balls

Filtration efficiency of the filter materials tested is shown in Figure 31. Sand has superior filtration efficiency at 56%, but 3 and 7 mm plastic balls shows promising results at 16% and 14% respectively. However, due to filter house restriction in this test, the results from 7 mm plastic balls may prove false. It is important to consider Figure 25 and Figure 31 together when considering the results to choose a suitable filter material for its purpose, considering filtration efficiency and flowrate together. For instance, 3 mm plastic balls shows good filtration efficiency, without sacrificing major flowrate restriction.

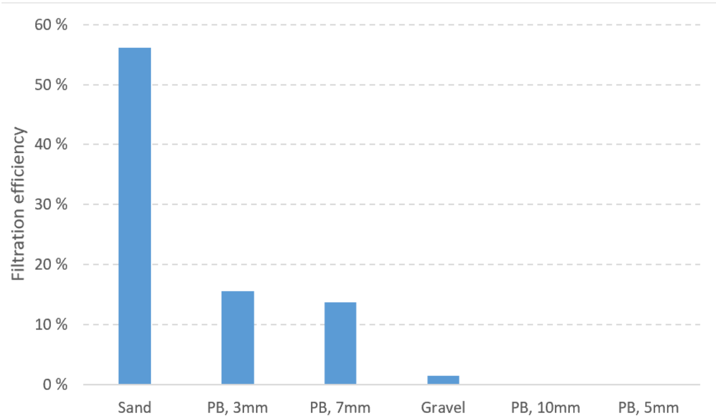

Figure 31: Comparison of filtration efficiency of various filter materials. Pressure: Atmospheric. Bed depth: 185mm. PB = Plastic Balls

Comparison of filter materials. (Pressure: Atmospheric. Bed depth: 100 mm)

When comparing sand and gravel in Figure 32, with other parameters equal, with atmospheric pressure and a bed depth of 100 mm, both curves seem to be fairly linear. Gravel has a steeper curve compared to sand, meaning that the flowrate is higher throughout the test. The filtration efficiency of the two materials in this test is 2.8% for sand and 0% for gravel. It is clear that the lower bed depth has a significant influence on the filtration efficiency, when these results are compared to the results in Figure 30.

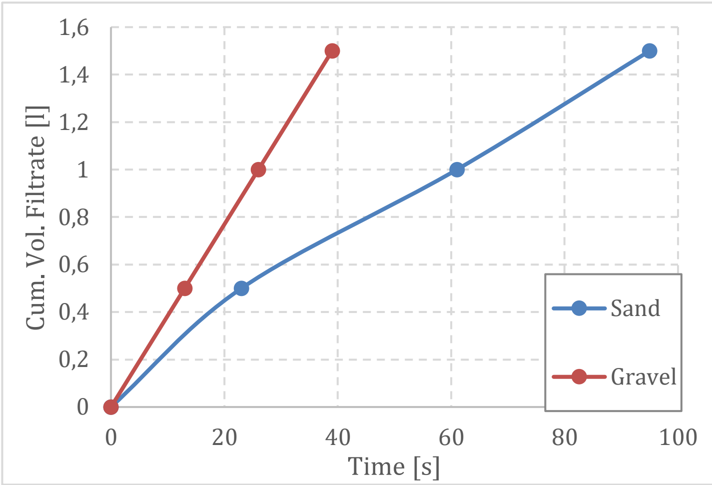

Figure 32: Comparison of filter materials and flowrate. Pressure: Atmospheric. Bed depth: 100mm

4.6 Design of Experiments

To get an effective system to evaluate the testing, the design of the experiment approach is set up to be able to control the input and output parameters of the testing and help get some more conclusions from the tests. The following subchapters will further discuss how the testing will be set up regarding different effects, and considerations. This approach is done by following the examples given in the book "Design of experiments for engineers and scientists" by Antony[31].

4.6.1 The objective of the experiment

The objective of the experiment is to identify the significant filtering parameters and determine the optimal parameter settings which give the optimum filtration efficiency.

4.6.2 Selection of the response function

The response of interest for the experiments is the turbidity of the filtrate, measured in NTU after one round of filtration.

4.6.3 List of factors and interactions of interest for the experiment

After a brainstorming session, the following process variables presented in Table 18 where identified. Each process variable will be studied at 2-levels as a part of an initial investigation, their levels can also be found in Table 18.

Table 18: List of process parameters and their levels

Parameter	Label	Low	High	Unit
Filter Bed Depth	A	100	185	mm
Pressure	B	0	2	Barg
Grain Size	C	2	9	mm

4.6.4 Choice of design and experimental layout

The most suited design to analyze all the two-facto interactions will be a 2^3 full factorial experiment, as it will cover the required degrees of freedom in this study. This will allow one to estimate all the main effects and interactions in the study independently. To minimize the noise in the results each trail condition was randomized, so any effect of irregularities in the particle distribution of the simulated wastewater will be filtered out. The order the test actually were conducted in after randomization is displayed in the parentheses. Due to cost restrictions and a limited time frame each trail condition was not replicated more than one time, to get a more accurate estimate this should be recreated at least three times. The test matrix for the order of the randomized tests is found in Table 19. The following objectives were set before performing the experiment.

1. Which main effect or interactions might affect the filtration efficiency?
2. Which main effects or interactions might influence variability in filtration efficiency?
3. What is the optimal filtration set up?

Table 19: Design matrix for the experiment

Trail no.	Bed Height	Pressure	Grain Size	Filtration Efficiency	Flow rate [l/min]
1 (3)	Low	Low	Low	0.028	1.067
2 (7)	High	Low	Low	0.599	0.275
3 (4)	Low	High	Low	0.325	3.724
4 (2)	High	High	Low	0.563	4.543
5 (1)	Low	Low	High	0	2.368
6 (6)	High	Low	High	0.057	0.445
7 (8)	Low	High	High	N/A	N/A
8 (5)	High	High	High	0.014	8.611

Filtration efficiency is calculated by:

$$Filtration\ Efficiency = 1 - \left(\frac{NTU_{After}}{NTU_{Before}}\right)$$

Equation 2

The average flow rate is calculated from:

$$Avrage\ Flow\ Rate = \frac{Total\ Volume}{Total\ Time}$$

Equation 3

There is no results available for trail 7, 100mm bed depth, gravity pressure with gravel due to the fact that the filter became clogged within a short time of operation. The observation of this result is shown in Figure 33. The filter became clogged within 1/3 of the desired volume of filtrate, this set up will be defined as not desirable, and should be avoided.

Figure 33: Observations from 100mm bed depth, gravity pressure with gravel

4.6.5 Results

Filtration efficiency

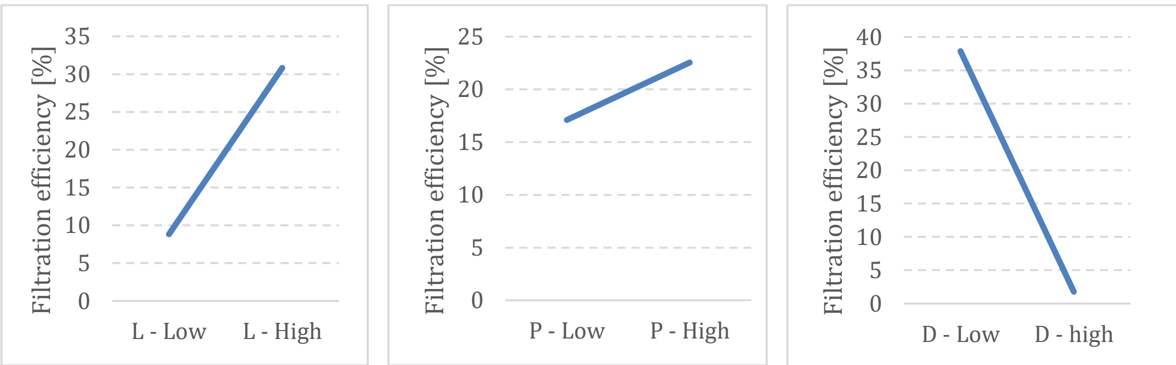

Figure 34: Filtration efficiency parameter effect

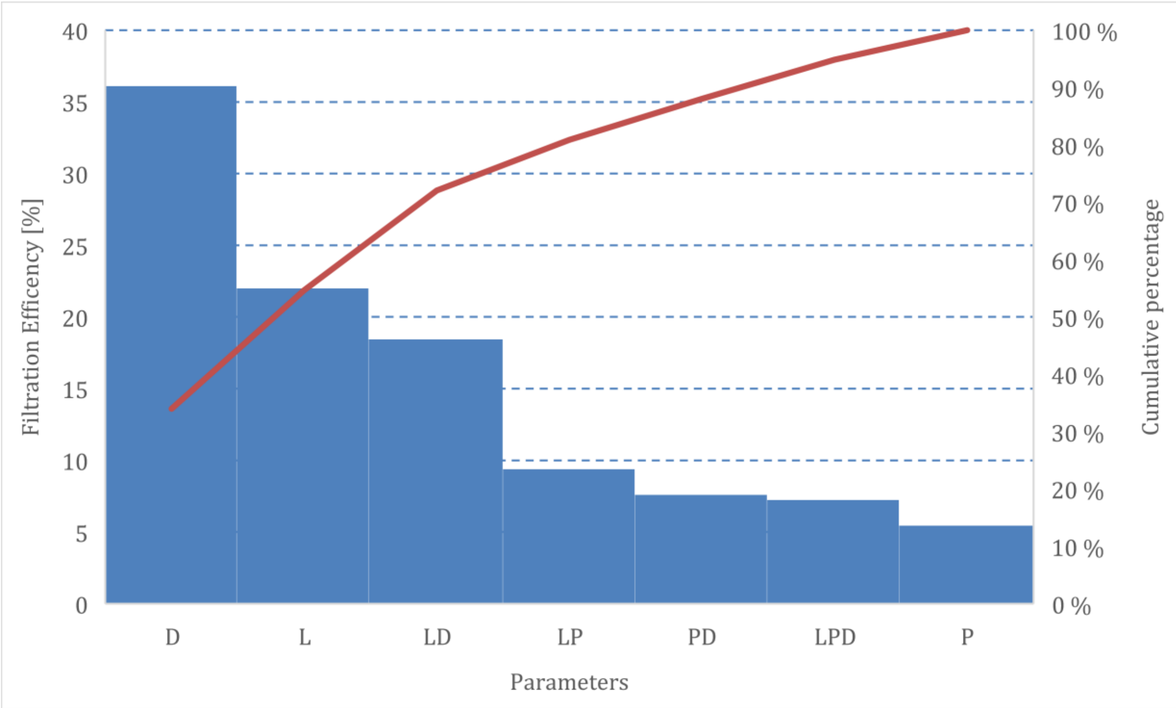

Figure 35: Filtration efficiency pareto plot4

From the above graphs the results from filtration efficiency is represented. From Figure 34 the effect from the different parameters in the setup is evaluated. To maximize the filtration efficiency each setting should be selected at the level giving the highest efficiency. For this experiment the ideal setup is filter bed at high level, pressure at high level and the grain size at low level. From Figure 35 the different parameters and interactions are evaluated from how much the parameter affect the filtration efficiency. The most important parameter is the grain size for the filtration efficiency, this indicates that at smaller grain size gives a higher level of efficiency.

Flow rate

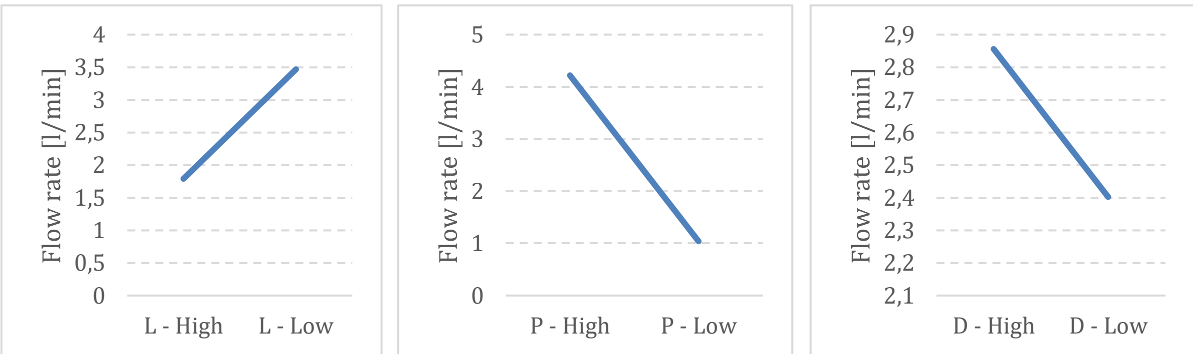

Figure 36: Flow rate parameter effect

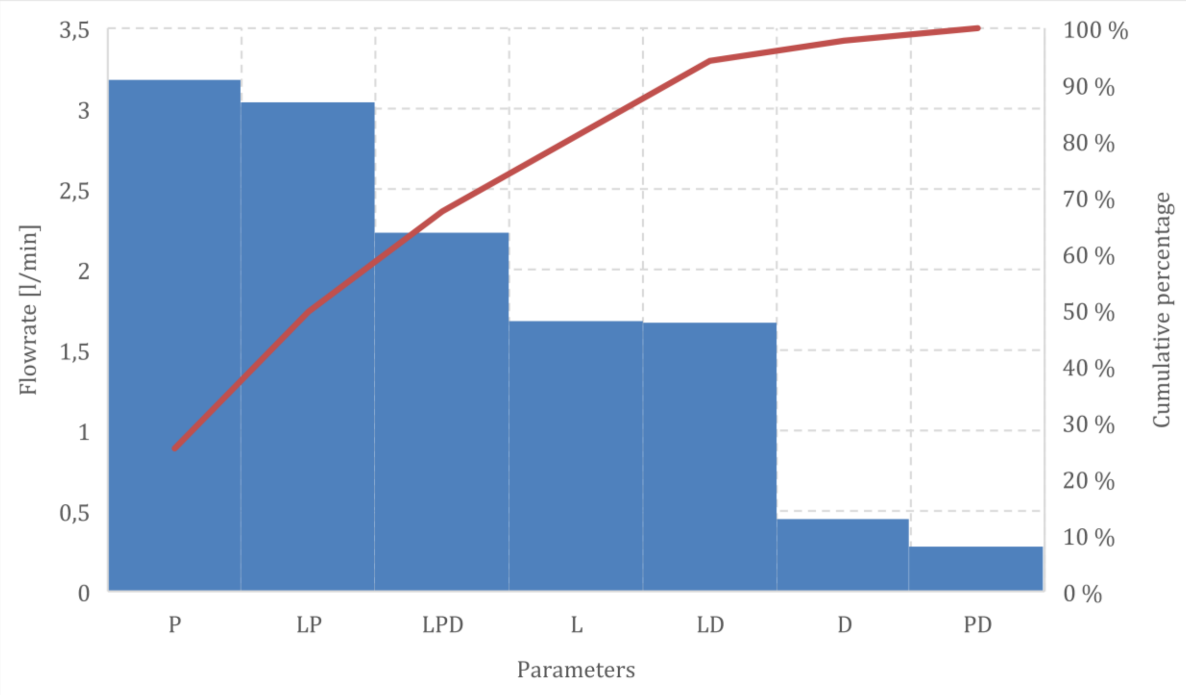

Figure 37: Flow rate pareto plot

Evaluating how the flow rate is affected by the different parameters in Figure 37 show that the pressure is the parameter that have the greatest effect on the flow rate. One interesting result is the flow rate is less effected by the grain size than the height of the filter bed. When selecting the ideal operating conditions based on the flow rate in Figure 36 suggest that the following parameters should be set to: bed height low, pressure high and grain size high.

When comparing the result from ideal operating conditions for both flow rate and filtration efficiency, one can see that the only parameter suggested to remain at the same level are the pressure, at level high. When selecting the two last parameters one need to evaluate the filtration needs in the different systems. Evaluating the parameters effect on the flow rate, the grain size will have a small input on the result, this should suggest keeping the grain size at the low level for general applications to keep a high level of filtration. The filtration needs should be the main consideration to decide the parameters, for an application for coarse filtration, where you need to separate larger particles from the liquid and the flow rate is the most important factor, a filter following the ideal suggestions for a high flow filter could be chosen. When designing a filter that operates at a combination of flow and efficiency one need to take more consideration when deciding the parameters.

5. Scaled Prototype Experiment

This part of the experiments will be based on experience acquired from the previously mentioned lab experiments. This knowledge will be used to minimize the cost of carrying out many experiments with the scaled prototype. This will lead to the test only being performed with the filter material and operation conditions considered to function well in the lab experiments. Due to the design of the scaled prototype built by Monmic, the testing cannot be done in the same manner.

Figure 38: Picture of scaled prototype by Monmic

In Figure 38 one can see the prototyped unit by Monmic. This unit has a built-in programmable logic controller (PLC). This PLC gives a greater advantage in monitoring and controlling of the operating parameters in the filtration operation. This will give the possibility to control the flowrate in an accurate manner.

Another consideration will be the general layout of the filter itself. As the filter is oriented at an angle of about 40 degrees, Monmic's sister product, the continuous brewing system, has a variable angle of 5 to 30 degrees with respect to the horizontal plane [32], and is likely to be the result from a finalized filter unit as well. The effect on the filter bed due to the inclination is not clear. In the finalized filter model, there will be a possibility to adjust this angle. As well as the angle of the filter set up the filter housing also consists of a conveyor screw that helps to transport the filter media in the filter. The effect of this screw and the impact of the flow in the filter will have to be evaluated.

5.1 Working principle of the Monmic Continuous Filter

The idea behind the patented prototype filter by Monmic is to only replace the top layer of the filter material to prolong the service life of the filter material. In a typical setup of a granular bed filter, one will have to replace all the filter material when the buildup of the filter cake is too great and the filter is clogging and the flowrate is declining. Monmic's patent is based on the levelling of the filter material in a screw. The Monmic filter will work as a granular bed filter where a granular filter media is being transported through the filters main screw, from the filter media hopper and feed screw, through the filtration process, before it gets disposed in the filter media outlet, to either be cleaned for reuse in the filter or disposed of in a different way. The operation of this filter will give the advantage of only changing the top layer of the filter media to remove the built-up filter cake and no more filter media than necessary and reduce the build up of low resistance pore in the filter medium [33]. This is time and cost efficient for the user. See Figure 39 for diagram of the filter unit.

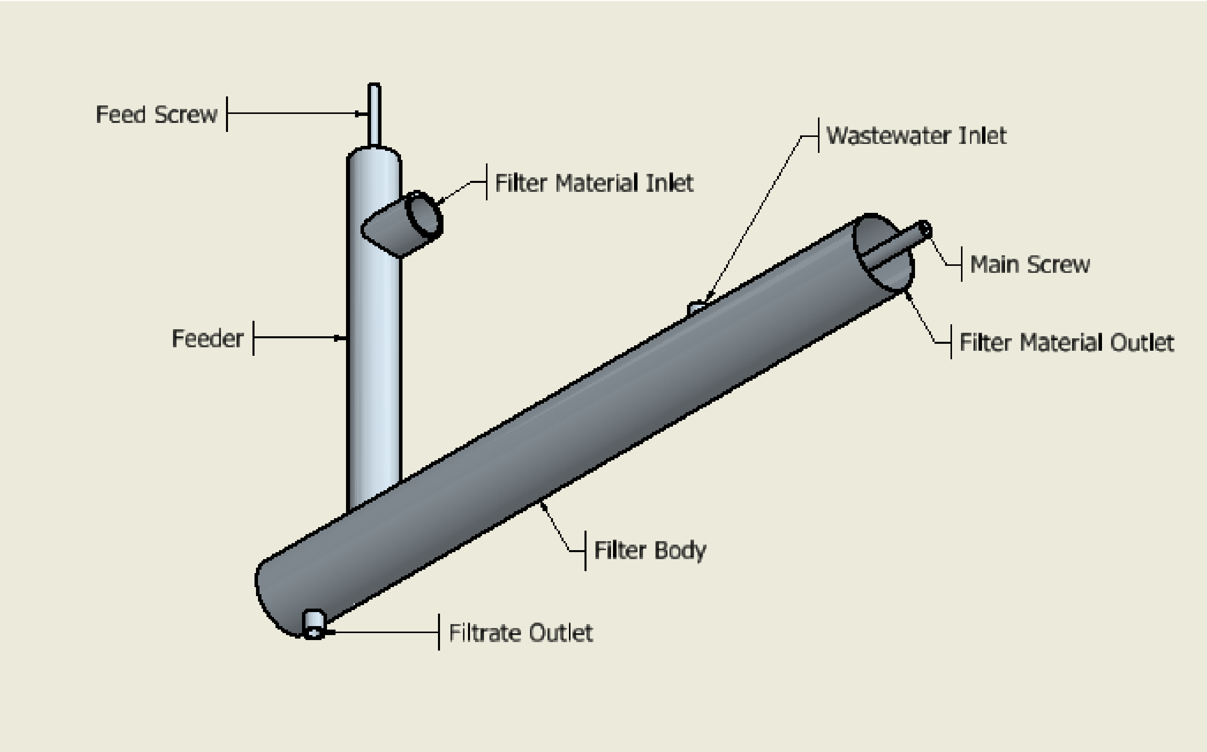

Figure 39: Diagram Monmic prototype filter unit

The wastewater or process water will enter the filter unit at the top of the filter body near the filter material outlet as illustrated. This gives the wastewater a filter bed to travel through before leaving the the filter.

5.2 Setup of the experiments on the scaled prototype

To be able to evaluate the Monmic prototype filter in the best manner possible, the experience from the lab experiments in chapter 4.1 will be taken into account. Most of the designing parameters and procedures will remain the same, as the goal is to evaluate the prototyped filter, and evaluate the effect of it for the same operating conditions. The following sub chapters are updated to suit the prototyped unit.

Due to limitations in time and budget there will not be a possibility to conduct all the same experiments on the prototype. From 4.6.5 Results, there is a suggestion to keep a smaller grain size. From this conclusion the group will be conducting experiments on the prototype with 5mm plastic balls and gravel.

As the tests on this prototype will be conducted as batch filtration, and not as a continuous process where the filter material will be cycled during the process there is a possibility to test the prototype with different bed depths. The team will not focus on this for the following test, as it is difficult to get an accurate reading of the fill level / bed depth of the closed screw chamber.

At the moment of testing the prototype was set up for filtration of process water using active carbon. To best suite this the technicians had the unit set up with a diaphragm pump, to make a slow but steady waterflow to mimic the process of slow sand filtration. This will be a limiting factor to make the filtration process as equal as possible for both testing in the lab and on the prototype.

Setup for Prototype test

When doing the tests on the prototype, the following parts and equipment are needed.

- Wastewater reservoir
- Filtrate collection unit
- Prototype filter unit with PLC control system
- Iwaki diaphragm pump, see Figure 47 in appendix for specifications

Procedure

When conducting the experiment on the prototyped unit, a consistent procedure must be defined.

1. Add filter material to the feed hopper on the prototyped unit
2. Cycle the filter feed screw to fill the filter with filter material
3. Prime the filter with water before the start of the experiment.
4. Add wastewater to the wastewater reservoir (see chapter 3.3 for the making of wastewater).
5. Connect filter outlet to filtrate collection unit.
6. Set the desired pump frequency on the control system.
7. Start the system to initiate flow through the system.
8. Stop system when wanted filtrate volume is reached.

5.3 Parameter measurement

The measurement method of each parameter relevant to the experiments is defined in the following section. The input and output parameters is shown in Table 20 and Table 21.

5.3.1 Input Parameters

1. Turbidity [NTU]

   See the input parameters, 4.2.
2. Grain size [mm]

   See the input parameters, 4.2.
3. Bed depth [mm]

   The bed depth of the prototype unit is measured from the wastewater inlet to the filtered wastewater outlet in the longitudinal direction of the filter housing body.

Table 20: Inlet parameter range

Parameter	Range	Unit
Turbidity	750-900	NTU
Inlet pressure	0	barg
Grain size	0-16	mm
Bed depth	600	mm

5.3.2 Output Parameters

1. Turbidity [NTU]

   See the input parameters, 4.2. This parameter will be compared to the input turbidity.

2. Cumulative volume filtrate vs time

- Measured by analyzing videotape of the experiment. The cumulative volume filtrate is noted at each 1 l, and cumulative volume filtrate is plotted against time as seen in the results section (5.5).

Table 21: Output parameter range

Parameter	Range	Unit
Turbidity	400-500	NTU
Flow rate	0-1.5	l/min
Cum. vol. filtrate	0-20	l

5.4 Sources of error

Most of the sources of error will follow the description in chapter 4.4. As there is a few factors that changed, some new considerations have to be done. One of the major differences is the location used, the experiments on the prototype is no longer conducted in a laboratory, but in an industrial workshop. Monmic's workshop is to be considered a clean workshop due to the work conducted. The activity level is low and will have little to none impact on the results. In the workshop there will be more people around the experiments in process, but none of them will be given any leading task in the process which will impact the results. The equipment used to analyze the results from the prototype will be the same and will not have any further impact on the results. When performing the experiment itself, the use of high quality and trusted equipment is still maintained and should not bring any further errors.

5.5 Results and discussion for the Monmic Prototype filter unit

5.5.1 Results from prototype experiment

Table 22: Input and output parameters. Filter medium: Gravel.

Parameters	Input	Output
Turbidity [NTU]	888	494
Bed Depth [mm]	600	
Grain Size, hydraulic eq. [mm]	9,7 ± 1,0	
Cum. Vol. filtrate vs time		See Figure 40
Pressure [barg]	0	

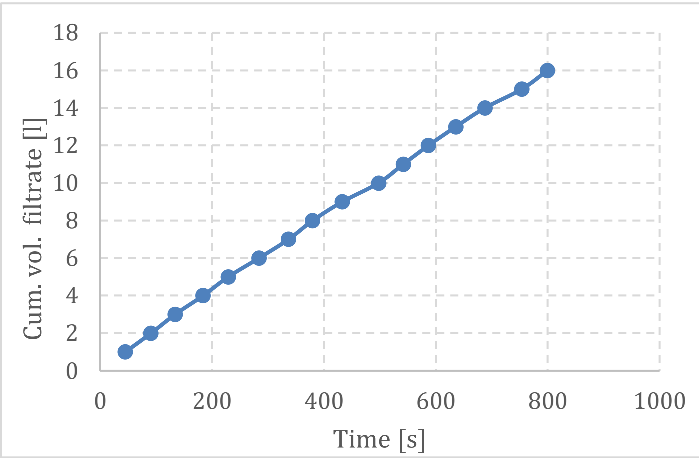

Figure 40: Cumulative volume filtrate vs time. Filter medium: Gravel. Pressure: Atmospheric. Bed depth: 600 mm

Table 23: Input and output parameters. Filter medium: Plastic balls, ø 5 mm.

Parameters	Input	Output
Turbidity [NTU]	760	409
Bed Depth [mm]	600	
Grain Size, hydraulic eq. [mm]	5	
Cum. Vol. filtrate vs time		See Figure 41
Pressure [barg]	0	

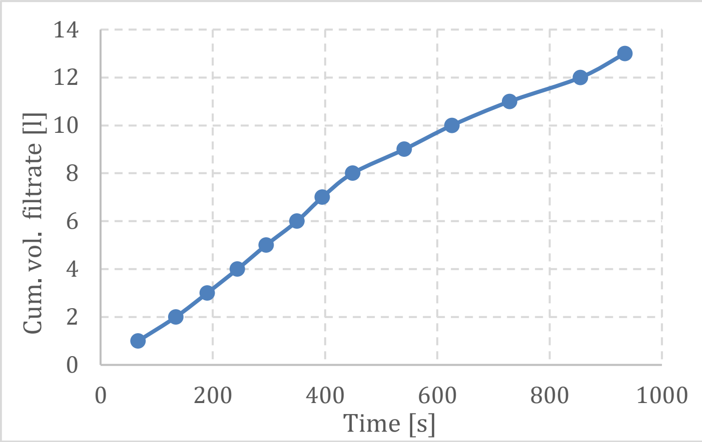

Figure 41: Cumulative volume filtrate vs time. Filter medium: Plastic balls, ø 5 mm. Pressure: Atmospheric. Bed depth: 600 mm

5.5.2 Comparison of filter materials and flowrate

Comparison of filter materials. (Pressure: Atmospheric. Bed depth: 600 mm)

In Figure 42 the results of gravel, and plastic balls (ø5 mm) is compared in the prototype filter unit, with other parameters equal. See Table 22 and Table 23 for input and output parameters. Gravel has a slightly higher flowrate than plastic balls, as seen in the figure. With gravel as the filter material, there is no sign of decline in flowrate due to clogging when 16 l of wastewater is filtered, but with plastic balls, there is a slight decrease occurring from 9 l of filtered wastewater, indicating start of clogging. The filtration efficiency is 46% for the plastic balls, and 44% for the gravel. These results indicate that both gravel and plastic balls have decent filtration capabilities, with fairly similar flow rate.

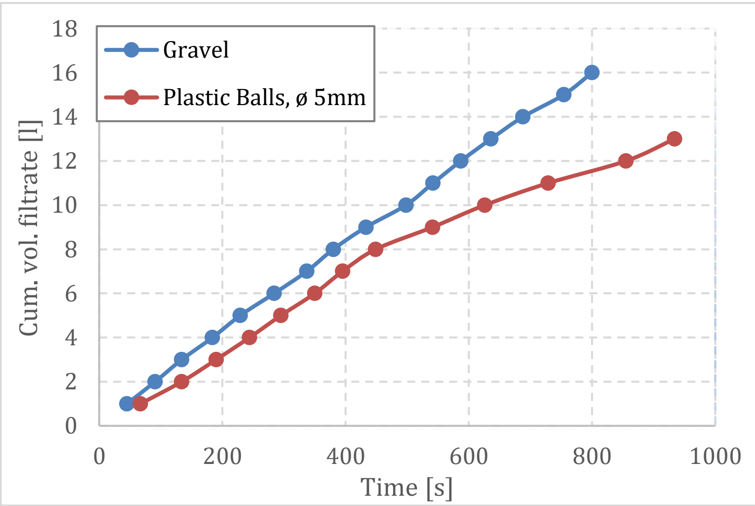

Figure 42: Comparison of filter materials and flowrate. Pressure: Atmospheric. Bed depth: 600mm

6. Comparison of the Laboratory Tests and the Prototype - Discussion

The results from the prototyped unit by Monmic solutions shows a great effectiveness compared to the lab set up. However, there are some considerations to be done when comparing the results presented in Table 24. The easy conclusion to draw from this table is the fact that the prototype has a much higher filtration efficiency than the laboratory unit. This conclusion will not be totally correct. The filter bed of the laboratory filter has a height of 185mm, versus 600mm on the prototyped unit. This gives the prototype a 3.2 times larger bed depth, which will be an advantage for the prototype due to the possibility to trap more particles in the larger pores in the filter. The L/d ratio is not a defined scale where 50 has twice the filtration potential of 25. The improvement in filtration efficiency with a greater L/d ratio gives an indication of the filtering mechanisms in the prototyped unit follows the existing depth filters.

Table 24: Comparison of laboratory test and prototype tests

Material	Size	Pressure	Effectiveness		L/D ratio		Flow rate	
			Lab	Prototype	Lab	Prototype	Lab	Prototype
Gravel	9.7 mm	0 Barg	0%	44%	19	62	0.26 l/min	1.20 l/min
Plastic balls	5 mm	0 Barg	0%	46%	37	120	3.53 l/min	0.83 l/min

Figure 43: Observations done on 185mm bed depth gravel test

The table shows a wide spread in the flow rates for the different set ups. The flowrates could be expected to be lower in the prototyped unit, due to a larger head loss in the longer filter bed. This is, according to the results, not the case. Observations done during the experiments might give a better explanation to the observed results. In Figure 43 one can clearly see how the coffee particles gets trapped in the filter. The particles had penetrated the filter completely, and a buildup of coffee particles in the bottom of the housing where found. The particles in the bottom of the housing where clogging the 1mm drilled holes in the bottom of the filter housing, effectively making large restrictions on the flow rate out of the filter. From the photo one can clearly see that the filter has separated out larger particles from the coffee, but there is still a great amount of finer particles in the filtrate to not have a reduced turbidity value. During a longer filtration run a buildup of a such filter cake in the filter will be beneficial to help filter out more of the finer particles.

In the prototyped unit there are currently not a restriction in the outlet of the filter where particles will clog the process, this will lead to a more consistent and higher flow rate of the filtrate out of the filter.

Due to the geometric shape of gravel, it will have a different packing factor than the spherical plastic balls. The rougher, less defined and often flatter surfaces of the gravels allows them to pack tighter than the plastic balls, leaving less room between the grains. The tighter clearances between the grains helps to collect finer particles in the wastewater.

In the laboratory experiments the plastic balls did not create a large restriction as filter material, and did not have any impact on the filtration efficiency. The observations made in the laboratory leads towards a theory that the gap between the filter material is too large to effectively capture the particles in the coffee.

7. Conclusion and further work

7.1 Conclusion

The aim of this thesis has been to investigate filtration parameters relevant to Monmic Solutions' patented continuous filtering system, considering the effect of filter material, bed depth, pressure and grain size to the filtration efficiency and flow rate of the filter. The use of these parameters makes it possible to compare Monmic's solution to filtering systems available on the market today, and to decide if this kind of filter can replace some of today's solutions for mechanical filters.

From the literature review it is clear that several capture mechanisms play an important role in a mechanical filter, and thus need to be taken into account when designing a filter and defining its parameters. In addition, the formation of a filter cake is vital for the mechanisms of a granular filter, as the filter cake itself contributes to the wastewater filtration.

Analysis of the lab experiments highlights the most important parameters, and how they affect the filtration efficiency and flowrate. These parameters are: bed depth, pressure, and grain size. It is clear that a small grain size is favorable for high filtration efficiency, but it often limits the flowrate of the filter accordingly. A high bed depth is favorable as well for filtration efficiency, with low impact on the flowrate of the filter. A pressurized filter increases flowrate through the filter, but has limited to zero effect on filtration efficiency.

From tests conducted on Monmic's prototype unit, there are promising results regarding filtration efficiency and flow rate. With a filtration efficiency of 44% and 46%, for gravel and 5 mm plastic balls respectively, it is apparent that effective removal of particles is possible with this kind of filter unit.

7.2 Further work

There is a need of more testing to be able to further evaluate the prototype unit's ability to remove particles from wastewater. The prototype should be tested with several grain sizes and filter materials, as well as other parameters discussed in this thesis. This will give Monmic the opportunity to better evaluate the optimal parameter values for the desired area of application.

The main advantage of Monmic's prototype, which is the possibility to replace the filter material continuously, has not been thoroughly reviewed. It would be of great interest to look further into how the filter material replacement mechanism affects the filtration capabilities over time, when filtering large amounts of wastewater over a wider timespan.

Furthermore, the possibility of designing a system able to clean and recycle the filter material is/will be of interest, making the whole filtration process automated. This could relieve the manual work necessary to clean and supply the system with filter material, which makes such a system economically feasible in a full scale unit.

8. References

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Appendix

Geometry	Shape	P/√A
Rectangle	2b, 2a	$\frac{2(\varepsilon+1)}{\sqrt{\varepsilon}}$
Ellipse	b, a	$\frac{4E(\varepsilon')}{\sqrt{\pi\varepsilon}}$
Annulus	r_i, r_o, $r^* = \frac{r_i}{r_o}$	$\frac{2\sqrt{\pi}(1+r^*)}{\sqrt{(1-r^*)}}$
Polygons	b, N = # sides	$2\sqrt{N}\left(\tanh\left(\frac{\pi}{N}\right)\right)^{1/2}$
Isosceles Triangle	2b, 2Φ, $\varepsilon = \frac{h}{2b}$	$\frac{2/\cos\phi + 2\tan\phi}{\sqrt{\tan\phi}}$

Figure 44: Table for equivalent hydraulic diameter [34]

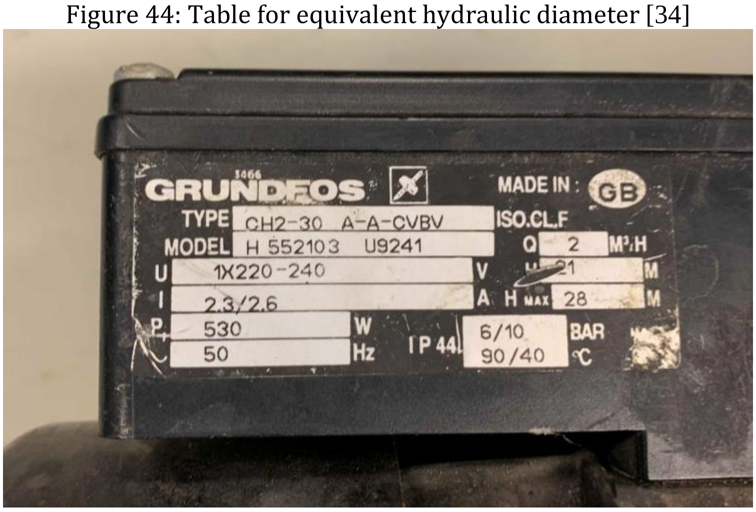
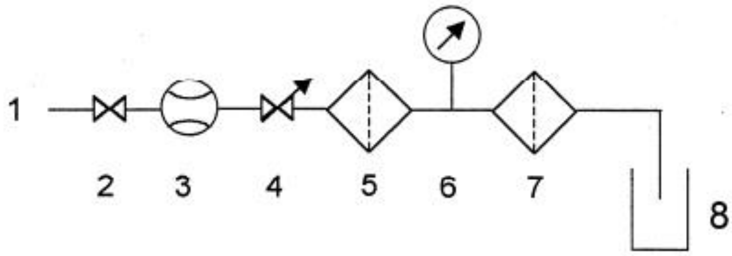


Figure 45 - Specifications of Grundfos pump. Q = 2 m^3/h = 33.3 l/min, Head max 28 m => 2.8 Bar



Key

1 Pressurised water supply
2 Ball valve
3 Flow metering device
4 Flow regulating valve
5 Clean-up filter
6 Pressure indicator
7 Test filter cartridge
8 Clean bottle

Figure 46: Diagram of apparatus to verify cleanliness [35]

標準性能曲線
PERFORMANCE CURVES

1SLK−411 (2)

客先名 PURCHASER	殿
需要者名 USER	殿
機器名称 Equipment Name	
機番 ITEM No.	
工事番号 Job No.	
工事名称 Project Name	

要求仕様 Operating Condition

吐出量 Capacity	/min		
吐出圧力 Dis.Press.	MPa		
液名 Liquid Name			
濃度 Concentration	%	液温 Pumping Temp.	℃
粘度 Viscosity	cp	比重 Specific Gravity	

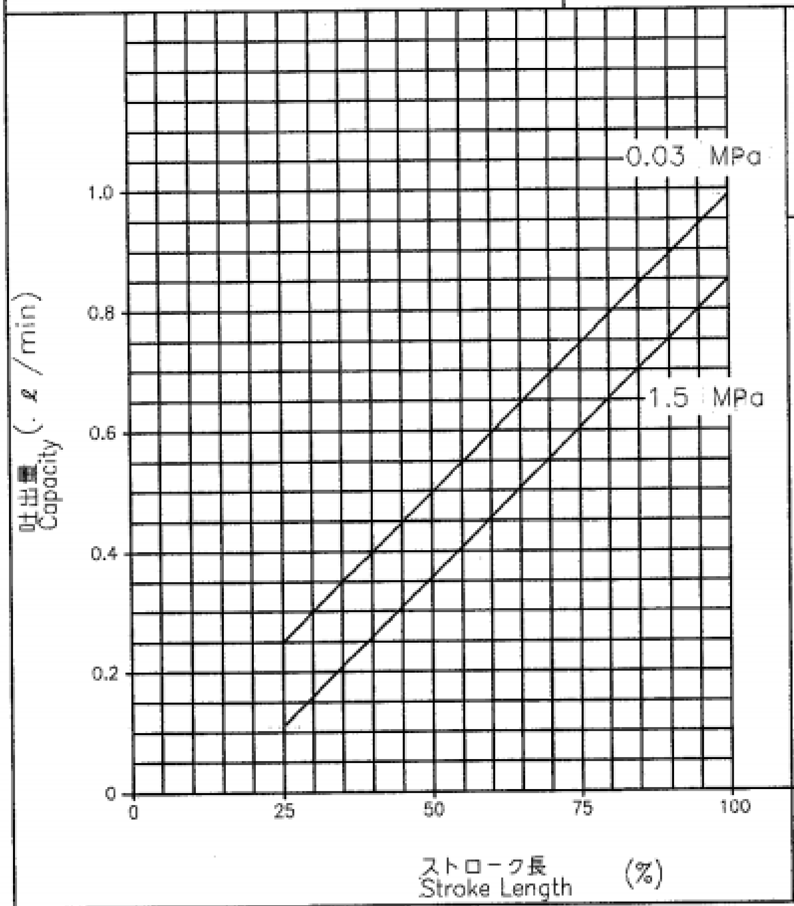
DATE	
EDP NO.	
型式 MODEL	LK−45S
製造番号 MFG.No.	

ポンプ仕様 Pump Specification

周波数 Frequency	50	Hz
プランジャー径 Plunger Dia.	—	mm
ピストン径 Piston Dia.	—	mm
ダイヤフラム径 Diaphragm Dia.	ø72	mm
ストローク長 Stroke Length	6.0	mm
ストローク数 Stroke Speed	48	spm
最大吐出量 Max Capacity	0.85	ℓ/min
最大吐出圧力 Max Dis.Press.	1.5	MPa

モータ仕様 Motor Specification

型式 Model			
周波数 Frequency	50 Hz	出力 Out Put	KW
相数 Phase	3 ø	極数 Poles	4 P



試験仕様 Test Condition

試験液:常温・清水
Test Liq.:Room Temperature
Fresh Water

備考 Remark

承認 Approved By	作成 Made By
K. Suzuki	M. Tatsumi

IWAKI CO.,LTD.

Figure 47: Iwaki diaphragm pump specification