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OPERATIONAL APPLICABILITY OF CERAMIC NANO- AND MICROFILTRATION FOR MUNICIPAL WASTEWATER REUSE.

HZ UNIVERSITY OF APPLIED SCIENCES

evides industriewater

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Operational applicability of ceramic nano- and microfiltration for municipal wastewater reuse.

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Abstract

The Rotterdam Innovative Nutrients, Energy & Water management (RINEW) project aims to realize an innovative and sustainable closed circulation of (waste-)water, nutrients and energy (NEWater) within the Port of Rotterdam, researching alternative wastewater treatment techniques. During experimental research for the RINEW project at the pilot location in Rotterdam, the utilization of tubular ceramic nano- and microfiltration (cNF; cMF) membranes in a municipal wastewater treatment system was analyzed with regard to specific aspects of membrane technology. These specific aspects include the characteristics, applicability and economic feasibility of the membranes.

During membrane characterization analyses, the retention behavior of the cNF membranes was observed to be lower in March 2016 compared to earlier measurements in 2014 and 2015, indicating the occurrence of membrane degradation. Additionally, the average pore size of the cMF membranes was observed to be 0.06 µm in April 2016, disagreeing with the supplier's given pore size for the membranes of 0.15-0.20 µm. While operating the filtration system at set fluxes for the cNF and cMF membranes of 30 and 150 $\frac{\mathrm{l}}{\mathrm{h*m^2}}$, the average duration of a filtration cycle was observed to be 28 and 5 hours, respectively. Per filtration cycle, average volumes of 6.5 and 3.7 m^3 feed water and 3.7 and 3.1 m^3 of permeate water were processed and produced while utilizing the cNF and cMF membranes, respectively.

Due to the occurrence of membrane fouling, specific cleaning procedures were employed in order to restore the membrane's permeability. The cleaning procedures were observed to consume similar amounts of chemical solutions during the employment of both the cNF and cMF membranes. However, the total chemical consumption was observed to be higher while employing the cMF membranes, due to the higher frequency of required membrane cleaning procedures in comparison with the employment of cNF membranes. The total electrical consumption of the filtration unit while employing either cNF or cMF membranes was estimated at 36300 and 24462 kWh per year, resulting in 32 and 14 kWh/m^3 produced permeate product, respectively.

Further analysis on the utilization of cMF membranes should be conducted in order to make a clear comparison with the operational specifications of cNF membranes. The filtration unit should be tested at a recovery rate of 50% while utilizing cMF membranes, potentially increasing the duration of a filtration cycle due to relatively lower membrane fouling rates, thus increasing permeate production rates. Furthermore, chemically enhanced backwashes should be further investigated as a suitable membrane cleaning procedure and compared to other membrane cleaning techniques in order to more effectively restore the initial permeability of the cMF membranes.

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List of Abbreviations

Abbreviation	Definition	Specification
cNF	Ceramic Nanofiltration	Membrane technology
cMF	Ceramic Microfiltration	Membrane technology
vRO	Vertical Reverse Osmosis	Membrane technology
MWCO	Molecular Weight Cut Off	Lowest (90%) retention weight
CIP	Clean-in-Place	Chemical membrane cleaning procedure
PEG	Polyethylene glycol	Synthetic ethylene oxide polymer
PES	Polystyrene	Synthetic aromatic styrene polymer
TMP	Transmembrane Pressure	Membrane pressure gradient
CF	Cross Flow	Feed water flow recirculation
Da	Dalton	Mass unit
H2020	Horizon 2020	Development program
COD	Chemical Oxygen Demand	Measure for oxidizable organic compounds
BOD	Biochemical Oxygen Demand	Required oxygen to stabilize present organic compounds
CP	Concentration Polarization	Concentration overpotential
RINEW	Rotterdam Innovative Nutrients, Energy and Water management	Development program
DAF	Dissolved Air Flotation	Suspended matter removal
P&ID	Piping and Instrumentation Diagram	Technical schematic drawing of a process installation
CWF	Clean Water Flux	Membrane performance test
TSS	Total Suspended Solids	Portion of the TS retained on a filter with a specified pore size, after being dried at a specific temperature (TS – TDS)
TDS	Total Dissolved Solids *Electrical Conductivity (EC)*	Organic and inorganic colloidal or ionized substances contained in a liquid (TS – TSS)
TS	Total Solids	TSS + TDS
EC	Electrical Conductivity	A substance's ability to conduct an electric current
TOC	Total Organic Carbon	Total amount of carbon in an organic compound
SS	Settleable Solids	Suspended solids settling out of a stagnant fluid
Total-N	Total Nitrogen	Sum of NO_3-N, NO_2-N, NH_3-N and organically bonded nitrogen
Total-P	Total Phosphorus	Sum of dissolved (ortho-), inorganic and organically bound phosphates
CEB	Chemically Enhanced Backwash	Chemical membrane cleaning procedure
FB	Filter Backwash	Membrane cleaning procedure

1. Introduction

1.1 Background

Evides Waterbedrijf N.V. is a water supply company, supplying safe and clean drinking water to 2.5 million customers and companies in Zeeland, the south-western parts of Zuid-Holland and the area of the Brabantse Wal (Evides, 2016). As a specific branch within the company of Evides Waterbedrijf N.V., Evides Industriewater B.V. specializes in process water production and wastewater treatment for several industrial companies in the Netherlands, Belgium and Germany, including customized water services for companies like Dow Chemical, Exxon and Akzo Nobel (Evides, 2016).

Multiple changing factors, such as climate change, soil pollution and the presence of contaminants, influence the quantity and quality of the water source (Evides, 2016). Because of this, water treatment techniques and distribution methods that are currently being used by Evides Industriewater will require innovation in order to be applicable in the future for water treatment processes. Evides Industriewater started the research project ‘H2020’ in 2014, specifically looking at the possibilities and challenges in the future regarding water treatment and distribution.

The H2020 project is divided into several coherent research projects (Evides, 2014). One of these projects, named Rotterdam Innovative Nutrients, Energy & Water management (RINEW), aims to realize an innovative and durable closed circulation of (waste-)water, nutrients and energy (NEWater) within the Port of Rotterdam, as shown in figure 1.

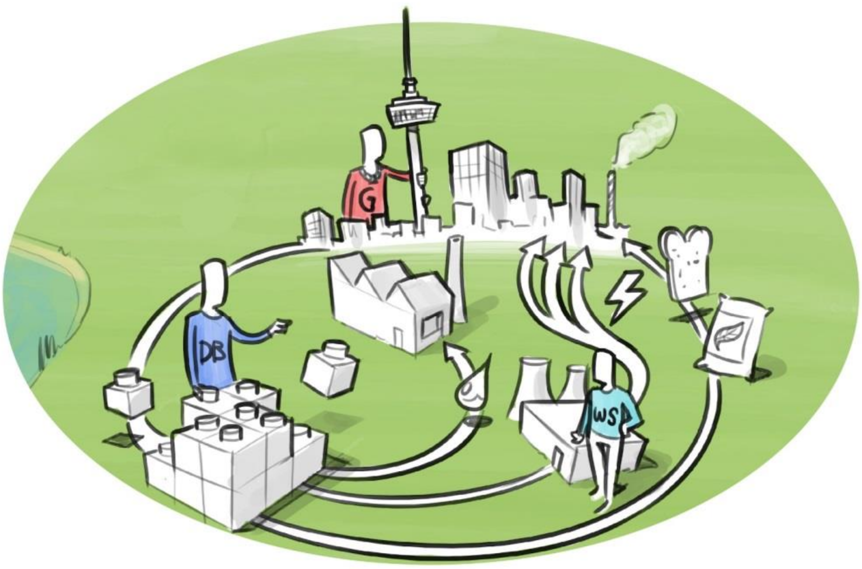

Figure 1: The RINEW project; focusing on the development and implementation of wastewater treatment processes and water circulation techniques in the Port of Rotterdam (Evides, 2014).

Within the RINEW project, alternative suitable wastewater treatment techniques are investigated meeting the project's requirements, regarding the reclamation of water, nutrients and energy. During experimental research for the RINEW project at the pilot location in Rotterdam, the utilization of tubular ceramic nano- and microfiltration (cNF; cMF) membranes in a municipal wastewater treatment system is analyzed with regard to specific aspects of membrane technology. These specific aspects include the characteristics, applicability and economic feasibility of the membranes.

In the coming decades the Municipality of Rotterdam will be transforming old harbor areas of the Port of Rotterdam into modern living and working areas (Evides, 2014). Phased redevelopment will take place in the Port of Rotterdam, near Delfshaven, due to the migration of port activities to the western part of the port. During this development, it is possible to implement the recently developed water treatment and circulation techniques in these areas. Centralized and decentralized wastewater treatment solutions both have their own benefits, depending on the location. Knowledge of and experience with the different centralized and decentralized treatment methods offer the possibility to make well informed choices during the development of specific areas, based on the situation. Furthermore, the knowledge and experience gained in the Netherlands can be exported to other countries with water and sanitation issues regarding wastewater treatment processes. The development of suitable alternative forms of wastewater treatment techniques will ultimately improve sustainable and conscious use of chemicals, such as phosphates, and the availability of safe and clean water sources.

The parties primarily involved within the RINEW project are the Municipality of Rotterdam (responsible for the collection of Rotterdam's urban wastewater and the redevelopment of the Port of Rotterdam), Hoogheemraadschap van Delfland (HHD; responsible for the wastewater treatment in the Delfland area), Hoogheemraadschap van Schieland en de Krimpenerwaard (HHSK; responsible for the wastewater treatment in the area of Schieland and the Krimpenerwaard), Waterschap Hollandse Delta (WHD; executor of the wastewater treatment at Dokhaven) and Delft University of Technology in association with the Stichting voor de Technische Wetenschappen (TU Delft, STW; responsible for content related research projects and subsidizing the RINEW project) (Evides, 2014). In 2012 and 2015, partnership agreements were signed by the aforementioned parties and Evides Waterbedrijf N.V., subsequently involving HHSK in 2015.

1.2 Problem analysis

The RINEW project mainly focuses on the municipal wastewater stream (Evides, 2014). The research project aims to investigate alternative wastewater treatment techniques to make it possible to reclaim specific nutrients and biogas from municipal wastewater, while producing demineralized water. Traditional wastewater treatment plants are not designed to reclaim the aforementioned products, while on the other hand the development of alternative wastewater treatment techniques could potentially result in new methods on how specific products from the municipal wastewater can be reclaimed. However, the practical full scale applicability and economic feasibility of alternative wastewater treatment processes still need to be optimized. Experimental research gives essential feedback for potential optimization in order to increase the operational efficiency of the alternative wastewater treatment process.

The aim of the RINEW project is to determine the opportunities for efficient resource reclamation by implementing membrane filtration. Increasing the efficiency of the wastewater treatment technique includes comparing the results of the research conducted on ceramic nanofiltration with those of ceramic microfiltration (cNF and cMF, respectively), while taking into account the applicability and economic feasibility of both wastewater treatment techniques. The use of ceramic material (Al_2O_3) results in a higher chemical, thermal and mechanical stability of the cNF and cMF membranes as opposed to polyamide based membranes. A simplified model of the closed water loops that will be used for the experiments during the RINEW project is shown in figure 2.

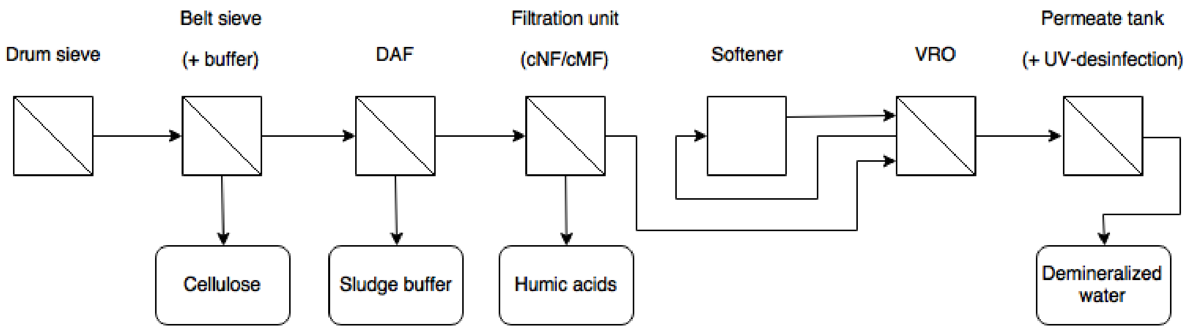

Figure 2: Simplified model of the closed water loops that will be tested during the RINEW project, including Dissolved Air Flotation (DAF), Vertical Reverse Osmosis (VRO) and Ultraviolet disinfection (UV).

1.3 Problem definition

Evides Waterbedrijf N.V. has set up the H2020 project in order to determine the applicability and economic feasibility of treating municipal wastewater while reclaiming the resources it contains (Evides, 2016). One of the several coherent research projects within H2020 is the RINEW project, located in the Port of Rotterdam, aiming to realize an innovative and sustainable water recirculation system. The main goal of the RINEW project is to investigate developments in alternative wastewater treatment technology in order to efficiently reclaim cellulose, demineralized water, specific nutrients and energy from municipal wastewater streams.

During the RINEW project, research will be conducted on the applicability and economic feasibility of the cNF and cMF membranes within the RINEW project. This research will include a cost-benefit analysis, membrane characterization tests and the operational specifications regarding permeate production and nutrient/organism recovery.

The results of this research will provide a comparison between the utilization of cNF and cMF membrane filtration techniques as a pretreatment method for the VRO step in the RINEW project's pilot condition municipal wastewater treatment process.

1.4 Research objective

The objective of this research is to compare the operational performance of cNF and cMF membranes with regard to the applicability and economic feasibility of these specific membrane filtration techniques as a pretreatment method for the VRO step in the current process of municipal wastewater treatment at the RINEW project.

Research questions

According to the aforementioned research objective, the following primary research question has been derived.

How do cNF and cMF membrane filtration techniques compare with regard to applicability and economic feasibility as a pretreatment method for the VRO step in the current municipal wastewater treatment process?

With the following secondary research questions.

Characterization, comparison of cNF and cMF

1. What are the MWCO values of the cNF and cMF membranes?
2. What is the fresh water permeability of the cNF and cMF membranes?

Applicability

1. What is the chemical and biological composition of the feed water, cross, permeate and concentrate flows during municipal wastewater treatment at the RINEW project during the cNF and cMF membrane filtration processes?
2. What is the average permeate production rate of the municipal wastewater treatment process at the RINEW project while employing the cNF or cMF membranes?
3. What is the average run time of the municipal wastewater membrane filtration process cycle at the RINEW project, in between two CIP procedures, while employing the cNF or cMF membranes?

Economic feasibility

1. How do cNF and cMF membranes compare with regard to variable and fixed operational costs of the municipal wastewater treatment process?
2. What is the potential yearly revenue of the municipal wastewater treatment process, regarding the produced permeate, while employing the cNF or cMF membranes?

2. Theoretical Framework

2.1 Membrane filtration

Selective separation

Membrane processes are based on the principle of dividing the feed flow into two streams, the concentrate stream and the permeate stream (Mulder, 1996). Membrane filtration is used as a wastewater treatment technique by driving the feed flow of the wastewater stream through a thin layer of semi-permeable material, separating specific substances, as shown in figure 3 (Mallevialle et al., 1996). Selective separation of specific substances from liquids or gasses makes it possible to purify, concentrate and fractionate the feed flow. After selective separation, the concentrate flow contains the residue of the filtration process, while the permeate flow contains the filtrate. Both the concentrate and permeate flow will be the product stream of the water treatment process if the goal is to reclaim nutrients, energy and demineralized water from the municipal wastewater stream.

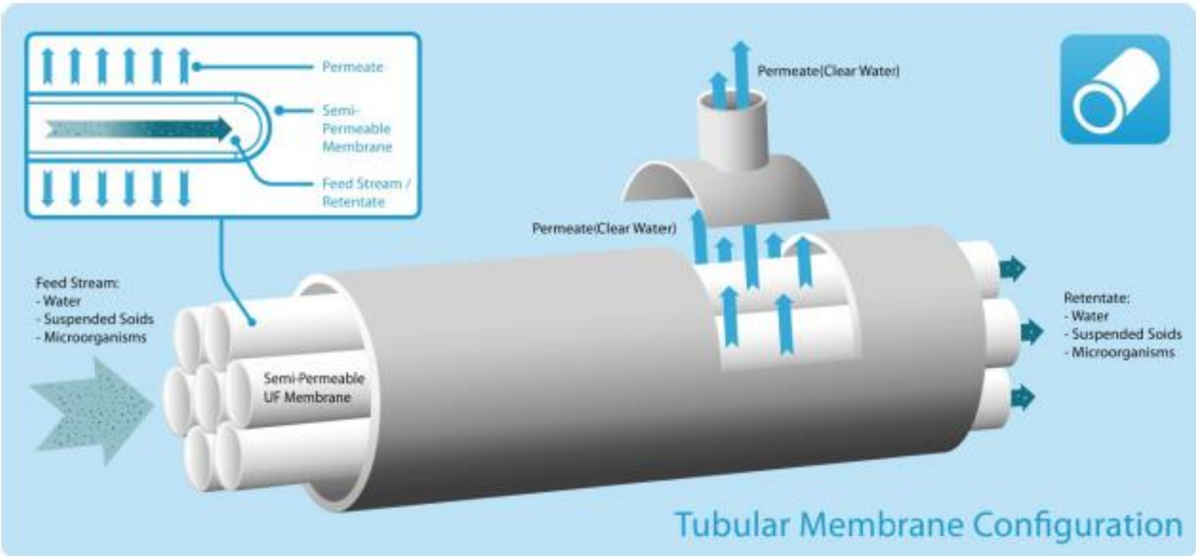

Figure 3: Tubular membrane configuration (Koch, 2013).

The selective separation of membrane filters is based on the permeability or mass transfer coefficient of the membrane (MTC). The MTC correlates to the pressure difference between the feed flow and permeate flow, also known as the trans-membrane pressure (TMP) and specific correction factors for velocity and temperature, which are installation specific. In other words, the performance and efficiency of a specific membrane is determined by its selectivity and flow through the membrane. The logarithmic trend in the retention behavior of the tubular membranes relates to the occurrence of particle retention and elution in a cross flow filtration system, correlating to particle size distribution. Hereby, particles are eluted from the membrane's channels in order of increasing mass.

Molecular weight cut off

Membrane filtration can be used in order to remove specific organic and inorganic material from the feed flow, such as particulates, microorganisms, viruses and chemical compounds (Jacangelo, 1997). The specific atomic mass of the molecular weight cut off (MWCO), measured by the amount of Dalton, is related to the retention behavior of a membrane and determined at a compound retention rate of 90%

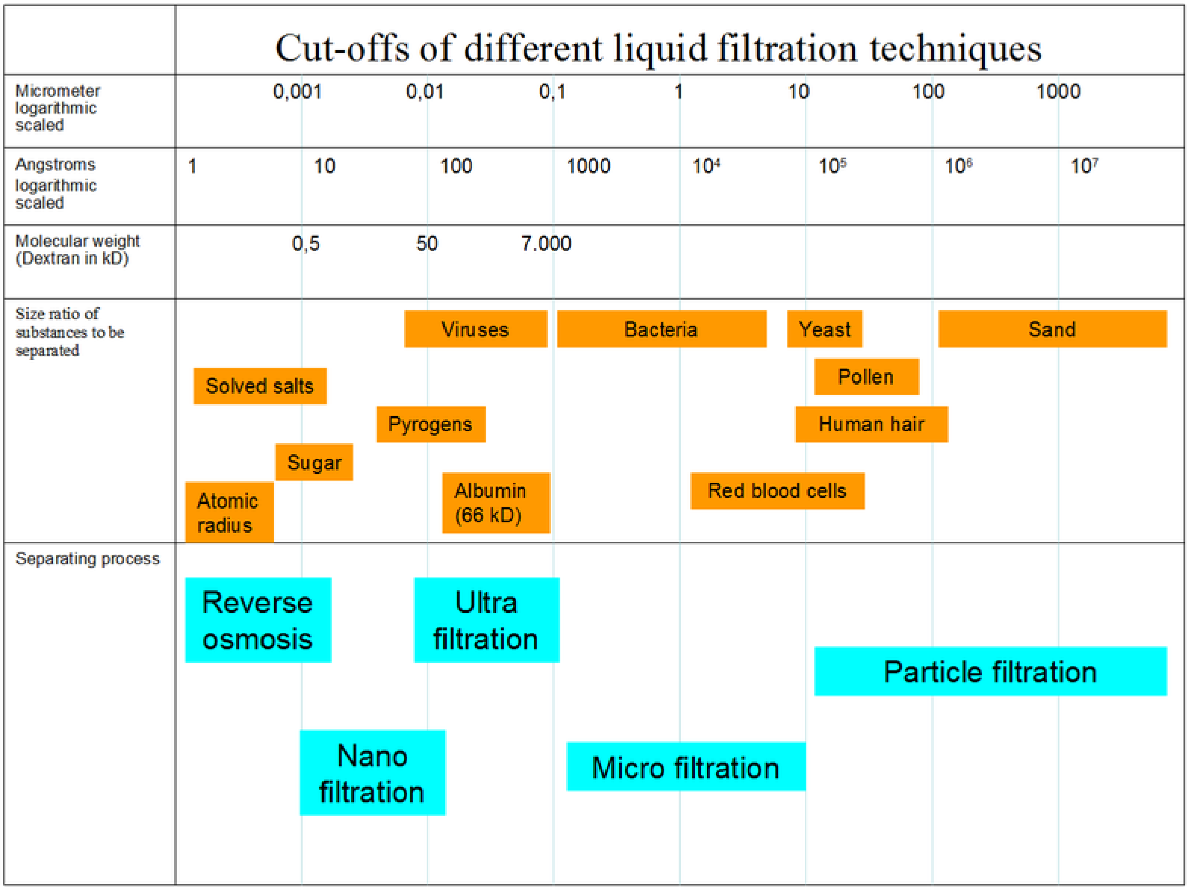

Figure 4: MWCO values of several specific separating processes (Koch, 2016).

Reverse osmosis has the lowest MWCO, followed by nanofiltration, ultrafiltration, microfiltration and particle filtration, as described in figure 4. The different types of filtration can be set up in series during the treatment process, using the selective membrane pore size and charge to increase the efficiency at which organic and inorganic compounds are removed or reclaimed from the feed flow during the wastewater treatment (Koch, 2016).

The specific MWCO for each type of membrane filtration makes it possible to precisely determine the characteristics of the permeate product, as is shown in figure 5 (Koch, 2016).

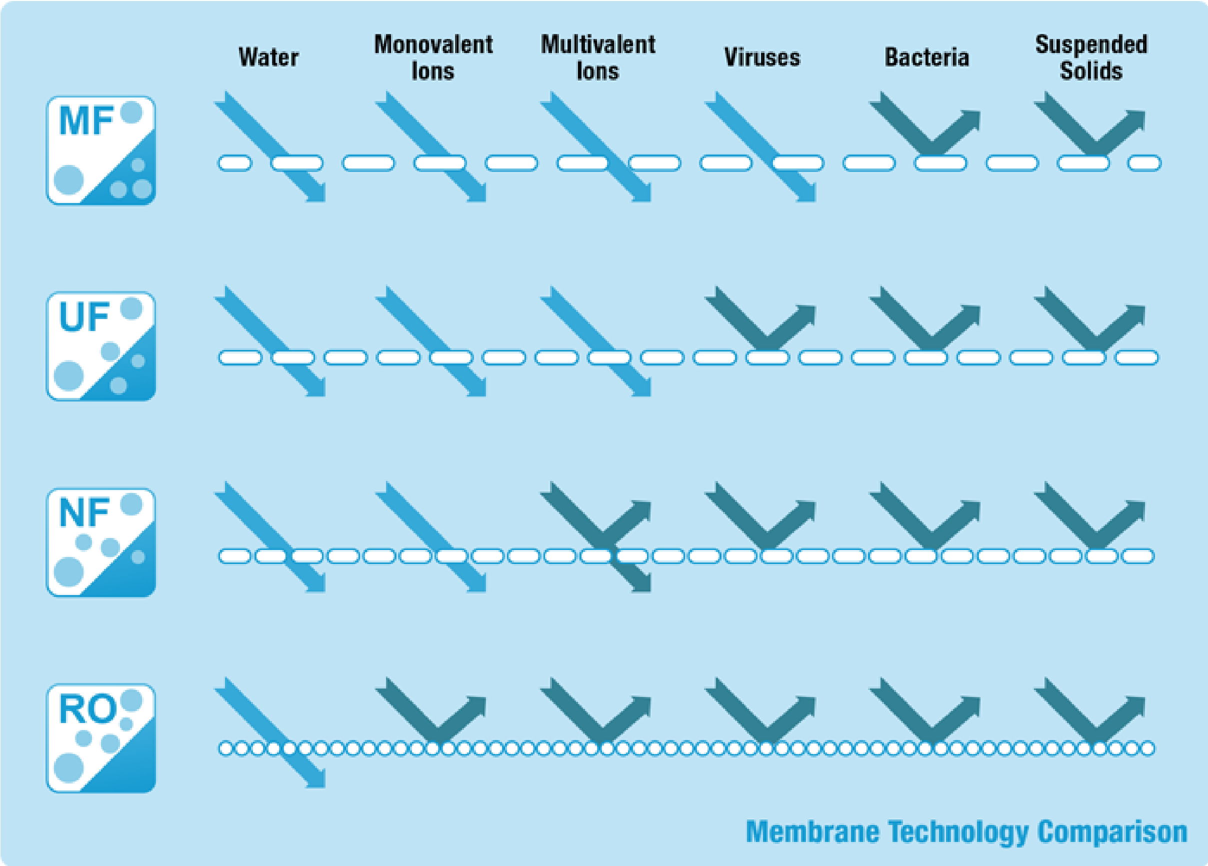

Figure 5: Specific membrane filtration technique limitations (Koch, 2016).

Because of the multidisciplinary character of membrane filtration technology, it is applicable in a wide variety of separation processes (Mulder, 1996). The main advantages of using membrane filtration in separation processes include the possibility for continuous water treatment, upscaling and hybrid processing, making it possible to combine membrane filtration with other separation processes.

Compound retention

Compound retention caused by steric separation is based on steric interactions between uncharged compounds and the membrane's surface. The membrane's performance regarding steric separation processes is defined by the membrane's pore size or MWCO. Steric separation is limited by the permeability of the membrane for a specific compound size, either rejecting or allowing a compound to pass through the pores of the membrane.

The production of the ceramic membranes is physically limited to MF pore size ranges, requiring special coating in order to be able to achieve a lower MWCO than the MWCO values of cMF membranes (Evides, 2016). This special coating is applied to the membrane using TiO_2, giving the membrane surface a specific charge, which is related to the pH of the feed flow (Van Gestel, 2002). Depending on the charge of the membrane's surface layer, electrolytes will either be rejected or attracted, also known as the Gibbs-Donan effect. Electrostatic compound rejection is caused by the repulsion of co-ions, whereby the charge of the specific compound is the same as the charge of the membrane's TiO_2-layer. In contrast, electrostatic compound retention or adsorption of counter-ions occurs due to the difference in the charge of the ions present in the feed flow compared to the membrane's TiO_2- layer in order to maintain electron-neutrality.

The selectivity of a membrane is defined by either the retention (R) or the separation factor (α), relating to the membrane's effectiveness in retaining a specific organic or inorganic compound, calculated by using formula 1 and 2, respectively (Mulder, 1996).

$$R = \left(1 - \frac{c_p}{c_f}\right) * 100 \qquad (1)$$

with

R	=	Retention of the membrane	(%)
c_p	=	Compound concentration in the permeate flow	(mg/l)
c_f	=	Compound concentration in the feed flow	(mg/l)

$$\alpha_{A/B} = \frac{(y_A/y_B)}{(x_A/x_B)} \qquad (2)$$

with

$\alpha_{A/B}$	=	Selectivity factor of the membrane	
y_A	=	Concentration of component A in the permeate flow	(mg/l)
y_B	=	Concentration of component B in the permeate flow	(mg/l)
x_A	=	Concentration of component A in the feed flow	(mg/l)
x_B	=	Concentration of component B in the feed flow	(mg/l)

Another essential aspect of a membrane's selectivity is defined by the recovery rate of the filtration process. The concentration of certain compounds in the feed flow differ from the concentrate flow, relating to the recovery (S). The recovery is defined as the fraction of a specific compound which has passed through a membrane, calculated by using formula 3.

$$S = \left(\frac{q_p}{q_f}\right) * 100 \qquad (3)$$

with

S	=	Recovery of the membrane filtration process	(%)
q_p	=	Permeate flow rate	(m^3/h)
q_f	=	Feed flow rate	(m^3/h)

The flow through a membrane is often defined by the flux rate, relating to the permeate flow per hour per square meter of the membrane's surface, calculated by using formula 4 (Mulder, 1996).

$$Flux = \left(\frac{Q_{v,p}}{A_m}\right) * 1000 \qquad (4)$$

with

$Flux$	=	Membrane flux rate	$\left(\frac{l}{h}/m^2\right)$
$Q_{v,p}$	=	Permeate flow per hour in cubic meters	(m^3/h)
A_m	=	Total membrane surface	(m^2)

Calculating a membrane's flux rate makes it possible to calculate the permeability of the membrane during the filtration process by using formula 5, relating to the pressure difference between the feed and permeate flow (TMP) which can be calculated by using formula 6.

$$TMP = \left(\frac{P_f + P_c}{2}\right) - P_p \qquad (5)$$

with

TMP	=	Transmembrane Pressure	(bar)
P_f	=	Feed flow pressure	(bar)
P_c	=	Concentrate flow pressure	(bar)
P_p	=	Permeate flow pressure	(bar)

$$Permeability = \left(\frac{Flux}{TMP}\right) * C_{T20} \qquad (6)$$

with

$Permeability$	=	Membrane permeate passage per area per time	$\left(\frac{l}{h*m^2*bar}\right)$
$Flux$	=	Membrane flux rate	$\left(\frac{l}{h}/m^2\right)$
TMP	=	Transmembrane Pressure	(bar)
C_{T20}	=	Correction factor temperature (T = 20°C)	(1.02)

2.2 Membrane fouling

Organic and inorganic membrane fouling

The Gibbs-Donan effect also causes charged compounds with a molecular weight lower than the MWCO of the specific membrane to be retained. Due to charged compound retention, membrane fouling of inorganic compounds can occur during the filtration process, also known as concentration polarization (CP) (Moitsheki, 2003). Besides the CP of inorganic compounds, biological fouling can occur on a membrane's surface due to the presence of colloidal biological particles. These membrane fouling phenomena eventually cause the formation of a cake layer on the membrane's surface consisting of specific organic and inorganic compounds, as shown in figure 6, depending on the MWCO value of the membrane (Howe, 2002). Specific wastewater characteristics, regarding organic and inorganic compounds, make it more difficult to concentrate the raw waste water (Heijman, 2014). The presence and load of certain organic and inorganic compounds cause an increased amount of cake layer formation.

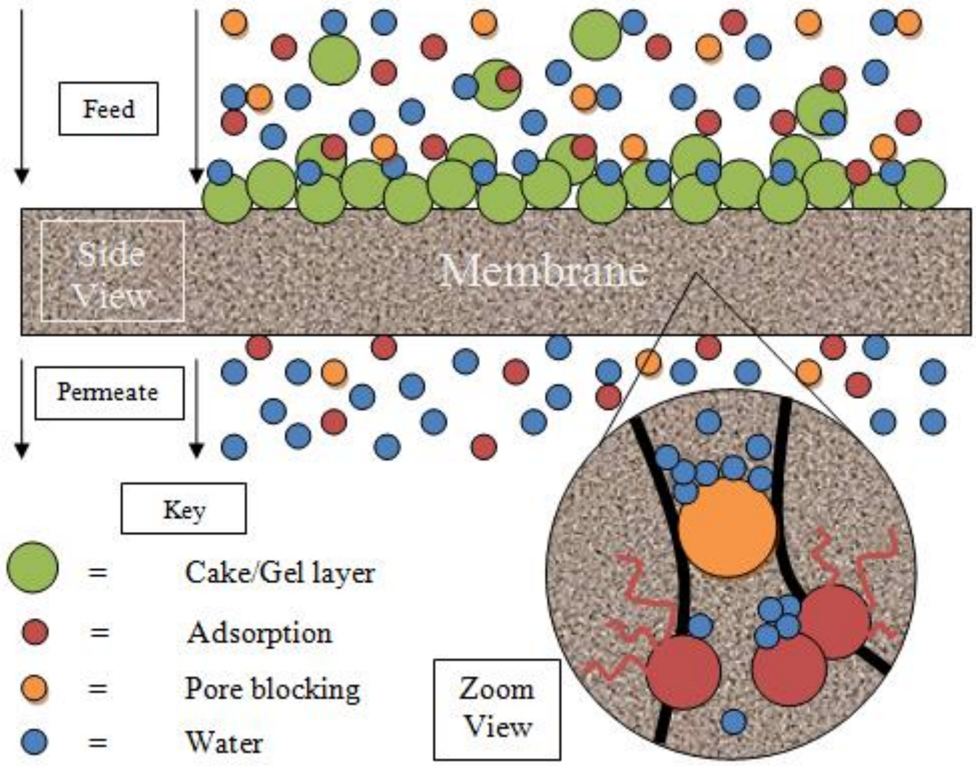

Figure 6: Membrane fouling, including cake layer formation, pore blocking and adsorption (Howe, 2002).

Decreased permeate passage

The formation of a cake layer on the membrane's surface, consisting of either organic or inorganic colloidal particles, affects the membrane's performance by lowering the permeability of the membrane, causing decreased levels of permeate passage (Moitsheki, 2003). The permeate passage can be restored by increasing the feed pressure of the filtration process, resulting in a higher TMP value. However, increasing the TMP of a filtration system causes increased membrane fouling rates, ultimately resulting in a continuous rise of the TMP requirement throughout the filtration process. At a certain TMP value a break-even point is reached, where further increasing the value for TMP would result in lower economic feasibility of the installation's operational use.

2.3 Membrane cleaning procedures

In order to remove reversible fouling from the membrane's surface, specific cleaning procedures are employed, as explained below and shown in figure 7.

Clean-in-place

The wastewater filtration process will be interrupted in order to remove the fouling layer from the membrane's surface. The membrane's surface is cleaned by making use of a chemical cleaning protocol named 'clean-in-place' (CIP) (Evides, 2016). The first step of the CIP protocol consists of a caustic cleaning process, employing sodium hypochlorite (NaOCl) and caustic soda (NaOH) solutions. In this process, the alkaline chemical solutions are added to a closed system including the membrane filter for a specific amount of time in order to soak into the fouling layer. The addition of the chemical solution causes the pH in the system to raise to 12, removing reversible biological and organic fouling. Subsequently, in the second step, the system is rinsed from alkaline chemicals by adding tap or demineralized water, consequently lowering the pH in the system to 9. The third step of the CIP protocol consists of a caustic cleaning process, employing a hydrochloric acid (HCl) solution. In this process, the acidic chemical solution is added to a closed system including the membrane filter, lowering the pH in the system to a value lower than 2, for which the protocol is comparable to the alkaline procedure, in order to remove reversible inorganic fouling.

Chemically enhanced backwash

During this membrane cleaning procedure, the filtration process will be interrupted as well in order to remove the fouling layer from the membrane's surface. During the chemically enhanced backwash (CEB) cleaning protocol, chemicals are added to a separate permeate tank filled with either tap or demineralized water, either raising the pH of the mixture to 12 with a caustic soda (NaOH) solution or lowering the pH to 2-4 with a hydrochloric acid (HCl) or citric acid ($C_6H_8O_7$) solution. The permeate flow is then reversed and the liquid from the separate permeate tank will be pumped through the membrane in order to remove either reversible biological and organic, or reversible inorganic fouling, depending on the chemicals that have been used in the cleaning procedure.

Monitoring membrane permeability

The efficiency of the CIP and backwash procedures, regarding the permeability, is monitored by fresh water permeability tests. During a fresh water permeability test, specific measurements will be taken with regard to pressure, flow rate, temperature and pH, while operating the filtration unit with tap or demineralized water and a set value for the flux in the system. Ultimately, the observed measured values in the system will determine the permeability of the membrane.

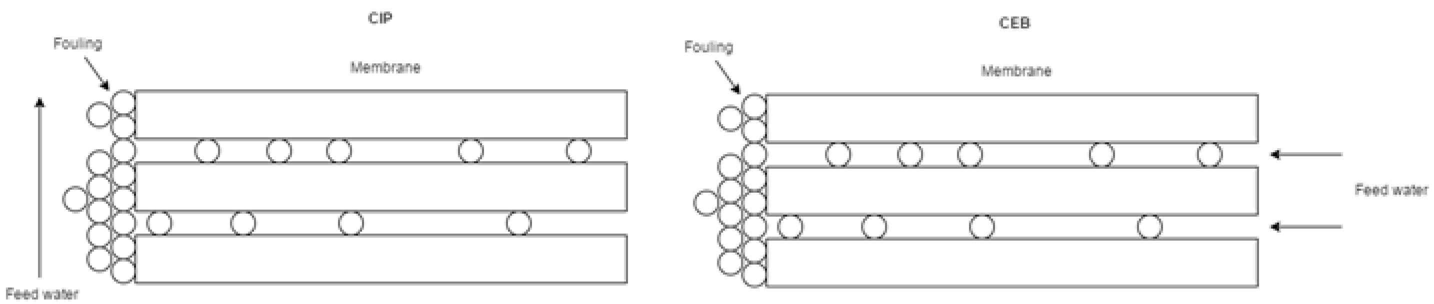

Figure 7: Illustration of the CIP and CEB chemical membrane cleaning procedures.

3. Materials and Methods

3.1 Research facility

Experiments will be conducted in the RINEW project's research facility provided by Evides Industriewater in Rotterdam (Evides, 2014). The research facility provides the possibility to combine theoretical and practical aspects of multiple research projects by exploring custom wastewater treatment installations.

3.2 Experimental setup

The cNF and cMF membranes are tested at the RINEW research hall in Rotterdam. A tubular module is fitted in the pilot installation, containing 37 membranes with a length of 1200 mm each. The cNF membranes contain 19 channels per membrane, with an internal channel diameter of 3.5 mm. The cMF membranes contain 4 channels per membrane, with an internal channel diameter of 7.8 mm.

The filtration unit is designed to operate in continuous mode. During continuous mode operation, the filtration unit's operational system operates filtration and CIP processes automatically according to set parameters in the operational system's matrix. While the filtration unit is operating in continuous mode, influent filtration experiments are performed automatically.

In order to be able to conduct batch tests regarding membrane characterization and specific operational performance, the initial continuous mode of the pilot installation can be modified to operate in batch mode. Hereby, the filtration system is operated with tap or demineralized water, as opposed to the continuous mode, whereby the DAF unit's effluent is utilized instead. While operating in batch mode it is possible to recirculate the concentrate and permeate flows.

The piping and instrumentation diagram (P&ID) of the experimental setup that will be used during the practical research is given in appendix II 'Filtration unit'. The pilot installation's settings can be modified via its operating system. The pilot installation's operation system is based on the P&ID of the experimental setup and can be subdivided into three specifications; the influent line, filtration line and backwash line.

3.3 Operational specifications

3.3.1 Wastewater treatment system specifications

During the process of purifying municipal wastewater specific types of installations are utilized in order to efficiently treat the influent stream. The specifications of these installations are described below.

Drum sieve
The first step in purifying the municipal wastewater influent entering this closed water loop is filtering the feed flow by using a drum sieve in order to remove particles >250µm (Evides, 2016). The drum sieve works with a constant flow of 4 m^3/h.

Belt sieve
In the following step, the permeate flow of the drum sieve is directed through the belt sieve, removing particles >120 µm (Evides, 2016). The belt sieve works with a constant flow of 3 m^3/h.

DAF unit
The permeate flow of the belt sieve then enters the Dissolved Air Flotation (DAF) unit (Evides, 2016). The DAF unit is located in between the belt sieve and the cNF and cMF unit in order to reduce the amount of remaining suspended and colloidal particles. By dosing $FeCl_3$ (40%), flocculation occurs with iron. The exact dose will be determined experimentally with the COD and phosphate mass balance. After the formation of flocks, the particles and colloidal organics then float towards the surface by injecting pressurized air into the tank, forming air bubbles.

cNF/cMF
The permeate flow of the DAF unit is then pumped through either the cNF or cMF membranes, depending on the experimental stage of the research project (Evides, 2016).

The cNF membranes have a pore size of 0.9 nm with a MWCO (Molecular Weight Cut Off) of 450 Dalton (Da) (Inopor, 2016). The cNF membranes are used to filter organic and inorganic material from the feed flow, ranging from bacteria and viruses to certain chemical compounds.

According to the manufacturer Philips, the cMF membranes have a pore size ranging from 150 to 200 nm with MWCO values greater than 1.000.000 Da. The cMF membranes are used to filter particles from the feed flow, including sand, silt, clay, algae and specific bacterial species. It is, however, not possible to filtrate viruses from the feed flow by using cMF membranes.

The concentrate flow from the membrane filtration is then recycled to the DAF unit in order to increase the efficiency of the total nutrient reclamation during the treatment process (Evides, 2016).

VRO
The permeate flow of the membrane filtration is then purified by using Vertical Reverse Osmosis (VRO) (Evides, 2016). The pore size of the membrane is 0.1-1.0 nm, making it possible to remove nearly all remaining inorganic compounds. The first results of practical research during the RINEW project have shown a salt retention within the expected range of 10%. The VRO unit effectively removes all organic compounds from the feed flow, including bacteria and viruses.

3.3.2 *Filtration unit specifications*

The Inopor cNF membrane elements are fitted in the pressure vessel, in which a cross flow velocity of 1.5 to 3.5 m/s is applied. Hereby the cross flow velocity is related to an 80% recovery rate during the filtration process, which is based on 190 and 150 l/h feed and permeate flows, respectively (Evides, 2016). This generates a flux through the membrane, ranging from 15 to 30 $l * h^{-1} * m^{-2}$. According to the manufacturer Philips, the flux capacity of the cMF membranes ranges from 150 to 200 $l * h^{-1} * m^{-2}$. Furthermore, the permeability of the membranes correlates to the pressure at which the filtration process is operating and a specific correction factor for temperature. During experimental batch test procedures, while employing cNF or cMF membranes, the applied pressure in the filtration system amounted to ~1.5 bar, with temperature correction factors ranging from 1.02 to 1.19.

Decreasing the amount of fouling on the membrane's surface is related to lowering the costs for the chemical cleaning process, also known as clean-in-place (CIP). The CIP cleaning protocol uses acidic and alkaline chemicals in order to remove the layer of colloidal particles and precipitate from the membrane's surface. These chemicals include hydrochloric acid (HCl, 10%), citric acid ($C_6H_8O_7$, 50%), sodium hydroxide (NaOH, 32%) and sodium hypochlorite (NaOCl, 15%) solutions. The chemicals NaOCl and NaOH are part of an alkaline cleaning process, which is then followed by an acidic cleaning process including the chemical compound HCl, reducing the amount of organic and inorganic fouling present on the membrane's surface, respectively. Further specifications of the CIP process' procedures will be described in paragraph 2.3, 'Chemical cleaning'.

Initially, the wastewater treatment process installation at the RINEW project's pilot plant also included an additional backwash installation besides the CIP procedure in order to prevent the buildup of fouling on the membrane's surface by reversing the permeate stream (Hoek, 2016). However, experiments conducted during the RINEW project regarding the cNF membrane's permeability have shown no significant improvement in permeate production rate while employing the backwash installation (Santos, 2014). In order to save permeate product and operational time, the backwash process is no longer applied in the municipal wastewater treatment process at the RINEW project's pilot location. However, if a decreased permeability of the cMF membranes is observed while CIPs are employed during membrane cleaning procedures, the use of CEBs should be tested, utilizing the same chemical solutions.

Furthermore, besides a robust ceramic aluminum oxide (Al_2O_3) layer, a coated titanium dioxide (TiO_2) layer is included in the cNF membrane's support structure, resulting in a higher chemical, thermal and mechanical stability of the cNF membranes as opposed to polyamide based membranes (Urbanowska, 2014). The characteristics of these layers increase the cNF membrane's resistance to aggressive chemicals, high temperatures and organic solvents during operational use.

3.4 Operational performance analysis

The research project will focus mainly on the operational performance of the filtration unit during continuous municipal wastewater filtration processes. The operational performance of the filtration unit will be analyzed with regard to the following aspects of the filtration process, summarized in table 1.

Aspect	Specifics	Unit
Filtration cycle	Flux (set value)	$\frac{l}{h * m^2}$
	Recovery (set value)	%
	Permeability/TMP progress over time during filtration process	$\frac{l}{h * m^2 * bar}$
	Time in between two CIP procedures	h
	Processed feed	m^3
	Produced permeate	m^3
Operational costs	Electricity	kWh/m^3
	HCl	kg
	NaOH	kg
	NaOCl	kg
Product revenue	Processed feed	m^3
	Produced permeate	m^3

Table 1: Operational performance parameters.

Water composition
Due to stringent 'not-to-exceed' discharge requirements for wastewater treatment installations, substance analyses regarding the water composition are essential to the treatment process of municipal wastewater flows (Tchobanoglous et al., 2003). The parameters that have been measured during the continuous municipal wastewater filtration processes, as listed in appendix I 'Water composition', are indicators of organic and inorganic substances present in the water and can be used to determine the substance removal rate of the filtration unit. Appendix I "interrelationships of solids in (waste-)water samples" shows a more detailed description of solid compounds in wastewater.

Membrane performance
The performance of a specific membrane, regarding compound retention, is based on steric and electrostatic separation processes (Klemm, 2015). Due to the presence of both charged and uncharged compounds in the filtration unit's feed flow, a combination of these interactions influences the performance of the membrane. Compound retention caused by steric and electrostatic interactions depends on the concentration of both charged and uncharged compounds in the liquid, the temperature and electrical potential of the feed flow and the applied pressure in the filtration unit (Mulder, 1996).

During practical research, data is gathered by analyzing specific parameters, which are indicated by the corresponding measurement instruments that have been installed in the pilot installation, as listed in appendix II 'Filtration unit'. The values for each of these parameters will be processed in Excel.

3.5 Experimental data

In order to answer the research questions of this project, practical research will be conducted by utilizing the experimental setup of the pilot installation. During this practical research, the main focus of experimental activities lies on the subjects of characterization, applicability and economic feasibility of the cNF and cMF membrane filtration processes.

Characterization, comparison of cNF and cMF
Characterization tests will be carried out to determine the MCWO of the cNF and cMF membranes. During the characterization tests specific organic and inorganic compounds are added to the filtration system in order to determine the MWCO of the membranes by measuring the rejection behavior of the membranes for these specific compounds.

1. *What are the MWCO values of the cNF and cMF membranes?*

Characterization tests for the cNF membranes include the chemical compounds potassium phosphate (K_3PO_4), polyethylene glycol 400, 600 and 1000 (PEG 400, PEG 600 and PEG 1000, respectively), with molecular weights ranging from 400 to 1000 Da. These chemical compounds will be added and recirculated in the filtration unit in separate experiments. During each experiment, samples will be taken from the feed, permeate, cross and concentrate flows at 0, 15, 30 and 45 minutes during the first measurement and at 0 and 30 minutes during the second, third and fourth measurements. After the first measurement, the pH level in the system will be lowered stepwise from 7-8 to 2.5-3 by dosing HCl solution to tank (T-01), influencing the amount of electrostatic particle interactions. Due to the organic nature of PEG compounds, measuring the COD of a sample indicates the change in the PEG concentration at a specific sampling point during the experiments. The PEG concentrations are therefore related to the COD content, which will be measured by utilizing spectrophotometry (DR-2800), in combination with specific testing kits (HACH LANGE). By making use of a calibration curve, it is possible to calculate the actual PEG concentration in the samples, ultimately resulting in the rejection behavior of the cNF membranes for these specific compounds.

Characterization tests for the cMF membranes include polystyrene particle solutions, with specific molecule sizes of 100 and 200 nm (PES 100; PES 200). These inorganic chemical compounds will be added and recirculated in the filtration unit in separate experiments. During each experiment, duplo samples will be taken from the feed, permeate, cross and concentrate flows at 0 and 60 minutes during the first measurement and at 0, 60, 90 and 120 minutes during the second measurement after adding one of the specific PES compounds. The first measurement in each experiment will be a blanco measurement, indicating the amount of particles present in the system before the addition of the specific PES solution. The pH level of the system will not be altered, due to the absence of a coating layer, limiting the cMF membrane to steric particle interactions. The concentration of the particles in each specific sample will be determined by a particle counter analysis (NanoCount 50+, Lighthouse Worldwide Solutions).

2. *What is the fresh water permeability of the cNF and cMF membranes?*

During different stages of the experiment, the clean water permeability of the cMF membranes will be tested. The results of the clean water flux permeability tests indicate the effect of specific actions that have been taken on the permeability of the membranes and the potential need for adjustments during experimental procedures. After the system has been chemically cleaned by the CIP process, a clean water flux test (CWF) will be carried out by using tap or demineralized water to check reversibility. Hereby the system is operated in batch mode for half an hour, while the permeate recovery is measured over time in order to determine the reference state of the membrane regarding its permeability, before starting the next filtration cycle.

Applicability

1. *What is the chemical and biological composition of the feed water, cross, permeate and concentrate flows during municipal wastewater treatment at the RINEW project during the cNF and cMF membrane filtration processes?*

Determining the chemical and biological composition of the feed, cross, permeate and concentrate flows includes taking samples of these streams and analyzing the samples by utilizing specific testing kits (HACH&LANGE) in combination with spectrophotometry (DR-2800).

2. *What is the average permeate production rate of the municipal wastewater treatment process at the RINEW project while employing the cNF or cMF membranes?*

The average permeate production rate of the municipal wastewater filtration process can be determined by measuring the produced permeate stream over a specific amount of time.

3. *What is the average run time of the municipal wastewater membrane filtration process cycle at the RINEW project, in between two CIP procedures, while employing the cNF or cMF membranes?*

The average run time of the filtration process cycle, in between two CIP procedures, will also be measured. The average run time of the filtration process cycle depends on the time it takes until chemical cleaning processes are required in order to continue efficient operation of the filtration process. This ultimately depends on the membrane fouling rate of the cNF and cMF membranes, which is related to the chemical and biological composition of the influent. In addition to that, the chemical cleaning processes of the cNF and cMF membranes may differ from each other with regard to the required procedures, potentially causing a difference in the duration or frequency of the chemical cleaning procedures. The permeability, or TMP, will be measured over time during multiple filtration cycles. During the filtration process, the flux and recovery of the filtration unit will be set to specific values, while the duration of the filtration cycles in between two CIP procedures will be monitored. Furthermore, the duration and number of CIP procedures will be analyzed as well.

Economic feasibility

1. *How do cNF and cMF membranes compare with regard to variable and fixed operational costs of the municipal wastewater treatment process?*

The total consumption of energy and chemicals during the continuous municipal wastewater filtration processes will be monitored and converted to the total operational costs of the filtration unit and the total costs per cubic meter produced permeate product.

2. *What is the potential yearly revenue of the municipal wastewater treatment process, regarding the produced permeate, while employing the cNF or cMF membranes?*

Experimental data regarding the amount of processed influent water and produced permeate water will determine the potential revenue of the municipal wastewater treatment process. The processed feed and produced permeate flows during the filtration cycles will be quantified and formalized as the specific revenue of these production values per year.

4. Results

4.1 Membrane characterization

4.1.1 Experimental conditions

During the characterization of the membranes, operational conditions of the filtration unit, including the recovery, feed pressure, flux, TMP, permeability and temperature, have been kept as constant as possible in order to accurately determine the MWCO of the specific membrane. In order to do so, the pump capacity of the pumps (P-02/07) and the manual permeate valve were adjusted accordingly. The operational conditions of the filtration unit during the conducted batch test experiments are included in appendix III 'Membrane characterization' and listed in table 2.

		cMF		cNF			
Parameter	**Unit**	**PES 100**	**PES 200**	**PEG 400**	**PEG 600**	**PEG 1000**	**PO_4-P**
Recovery	[%] ± St. Dev.	50.0 ± 0.0	50.0 ± 0.0	45.5 ± 2.0	53.4 ± 2.5	52.5 ± 2.2	53.3 ± 2.3
Feed pressure	[bar] ± St. Dev.	1.47 ± 0.0	1.47 ± 0.01	1.11 ± 0.08	1.55 ± 0.01	1.57 ± 0.01	2.02 ± 0.01
Flux	$\left[\frac{\mathrm{l}}{\mathrm{h}}/\mathrm{m}^2\right]$ ± St. Dev.	114.80 ± 0.0	114.37 ± 0.99	26.94 ± 0.88	18.10 ± 0.99	19.40 ± 1.24	30.76 ± 0.88
TMP	[bar] ± St. Dev.	0.92 ± 0.01	0.90 ± 0.03	1.01 ± 0.11	0.93 ± 0.06	0.99 ± 0.06	1.54 ± 0.07
Permeability	$\left[\frac{\mathrm{l}}{\mathrm{h} * \mathrm{m}^2 * \mathrm{bar}}\right]$ ± St. Dev.	149.89 ± 2.02	152.01 ± 6.54	32.20 ± 4.31	23.3 ± 2.48	23.40 ± 2.81	23.83 ± 1.53
Temperature	[°C] ± St. Dev.	20.5 ± 1.0	20.7 ± 2.3	19.1 ± 2.6	15.7 ± 2.5	18.1 ± 1.8	18.0 ± 1.5

Table 2: Operational conditions membrane characterization batch test experiments.

4.1.2 cMF retention behavior and MWCO determination

The retention behavior of the cMF membranes has been analyzed by utilizing a Nanocount 50+ liquid particle counter. Hereby, the cumulative amount of particles present in the batch test samples (n = 8) was measured continuously over a period of 10 minutes up to 0.05, 0.10, 0.15 and 0.20 µm. This analysis resulted in a logarithmic retention curve for the cMF membrane, as shown in figure 8.

The average retention behavior of the cMF membrane regarding the PES 100 and PES 200 particles amounts to 94.02 ± 3.55% and 99.25 ± 0.58%, respectively. According to the literature research, the pore size of the membrane is determined at a specific compound retention rate of 90%, resulting from the following logarithmic trend line equation relating to the experimental data, as shown in figure 9. Hereby, the average pore size of the cMF membrane unit amounts to 0.06 µm.

$$\text{Pore size} = e^{\left(\frac{90-111.4}{7.5464}\right)} = 0.06\ \mu\text{m}$$

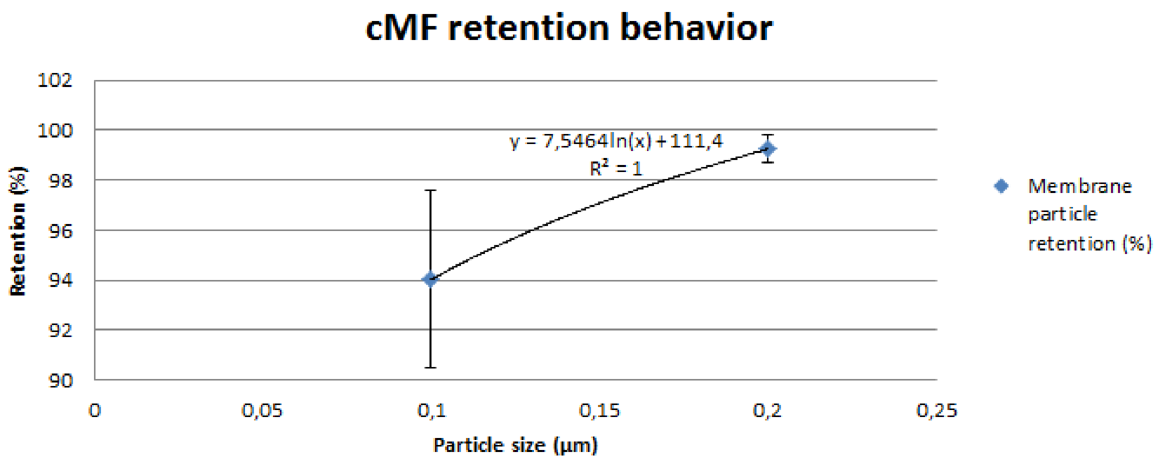

Figure 8: Retention behavior of the cMF membrane regarding particle size during batch test experiments, including a logarithmic trend line.

4.1.3 cNF retention behavior and MWCO determination

The retention behavior of the cNF membranes has been analyzed during the specific retention batch test experiments by measuring the COD concentration in the batch test samples and converting the specific values to the PEG concentration by making use of a calibration curve. This resulted in a retention curve for the cNF membrane, as shown in figure 9. Additionally, the membrane characterization results from previously conducted batch test experiments are included as well in order to indicate the occurrence of membrane degradation.

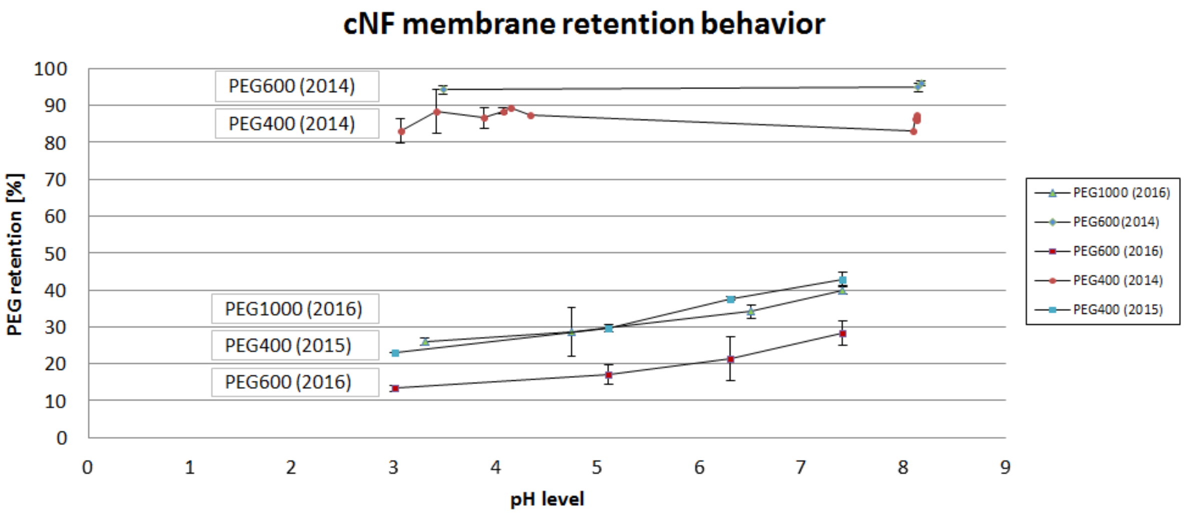

Figure 9: Retention behavior of the cNF membrane regarding PEG particles at varied pH conditions during batch test experiments.

The combined average retention behavior of the cNF membrane unit at different pH levels in March 2016, regarding the PEG 600 and PEG 1000 particles, amounts to 20.01 ± 6.44% and 32.13 ± 6.15%, respectively. According to the literature research, paragraph 2.1 ‘Membrane filtration’, the MWCO of the membrane is determined at a specific compound retention rate of 90%, resulting from the following logarithmic trend line equation relating to the experimental data, as shown in figure 10. Hereby, the average MWCO of the cNF membrane unit was roughly estimated to be 1 x 10^4 g/mol.

$$\text{MWCO} = e^{\left(\frac{90+131.77}{23.726}\right)} = 1 \text{ x } 10^4 \text{ g/mol}$$

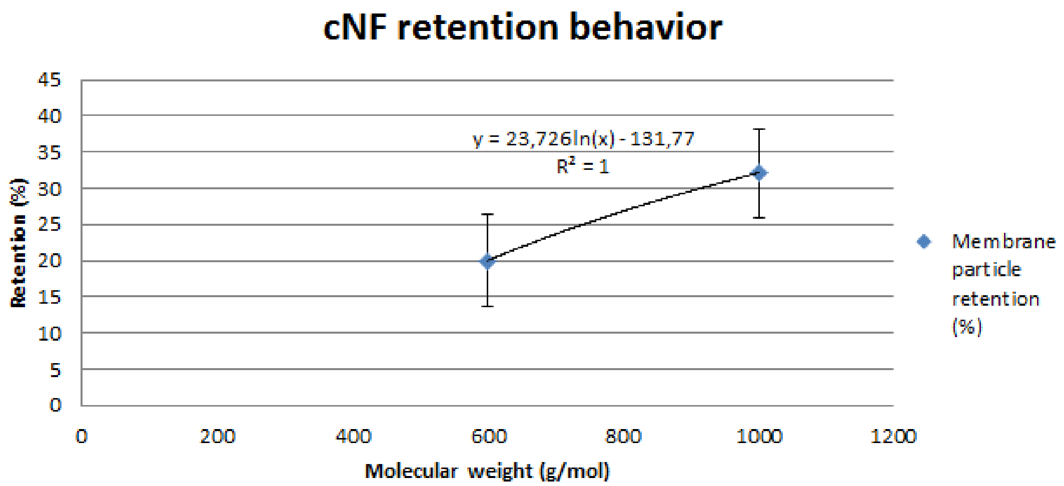

Figure 10: Retention behavior of the cNF membrane regarding PEG particles at varied pH conditions during batch test experiments, including a logarithmic trend line.

The retention behavior of the cNF membranes regarding phosphate (PO_4^{3-}-P) has been analyzed during specific batch test experiments as well. Hereby, the retention of phosphates is observed to proportionally decrease depending on the acidity of the feed flow, ranging from 13.81 ± 9.91% at a pH of 6.7 to 1.04 ± 0.43% at a pH of 2.9, as shown in figure 11. Additionally, the results from previously conducted phosphate retention tests are included as well in order to further analyze the occurrence of membrane degradation. These results, however, do not include error margins due to the lack of duplicate experiments.

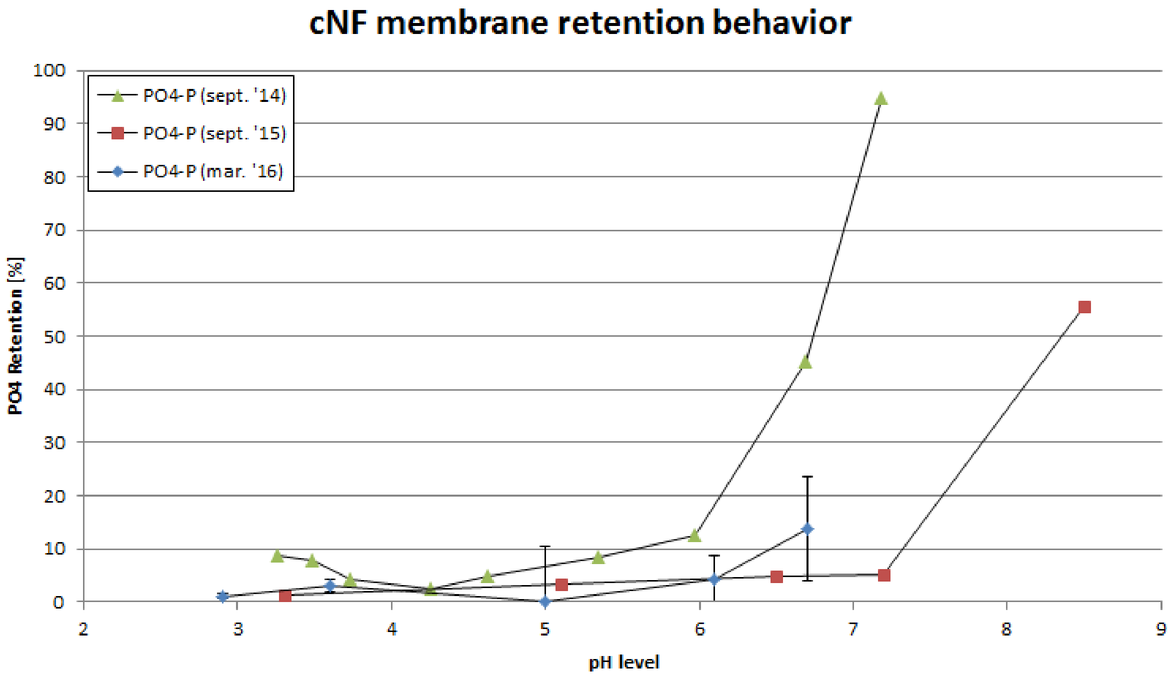

Figure 11: Retention behavior of the cNF membrane regarding phosphate particles at varied pH conditions during batch test experiments.

4.2 cMF membrane clean water permeability

During different stages of the experiment, the clean water permeability of the cMF membranes was tested with tap (TW) and demineralized water (DW) while operating the filtration system at low feed pressure conditions of ~1.5 bar with recovery rates of ~50 or ~80% . The results of the clean water permeability tests indicate the effect of specific actions that have been taken on the permeability of the cMF membranes and the potential need for adjustments during experimental procedures, as shown in table 3.

cMF				
Date (2016)	**Liquid (TW/DW)**	**Recovery [%] ± St. Dev.**	**Permeability $\left[\frac{\mathbf{l}}{\mathbf{h} * \mathbf{m}^2 * \mathbf{bar}}\right]$ ± St. Dev.**	**Notes**
31-03	TW	85.99 ± 4.97	1302.27 ± 35.19	Broken membrane
		50.90	1304.65	
07-04	DW	80.00 ± 1.66	1120.61 ± 151.23	
		52.64 ± 7.57	1310.74 ± 72.28	
	TW	78.68	1155.20	
		51.57	1295.22	
19-04	DW	83.19 ± 2.42	124.29 ± 2.61	Before PES 200 retention test
		50.00	127.33	
19-04	DW	82.28 ± 1.88	127.50 ± 0.65	After PES 200 retention test
		52.13	123.44	
02-05	TW	55.48	31.80	Permeability not recovered after multiple CIP cycles
04-05	TW	77.68 ± 7.32	56.91 ± 1.45	After filtrate backwash (FB) (demineralized water)
		46.88	58.14	
04-05	DW	83.16	88.56	After acidic CEB (citric acid)
		46.88	84.78	
	TW	78.35 ± 2.25	68.12 ± 10.51	
		48.42 ± 1.54	70.56 ± 10.30	
04-05	TW	77.74	108.01	After basic CEB (sodium hydroxide)
		52.17	107.98	

Table 3: Clean water permeability during different stages of the filtration unit analyses.

4.3 Operational filtration cycle analysis

The period of operational filtration analyses ranged from the 29th of January until the 14th of August 2015 for the cNF membranes and from the 20th of April until the 7th of May 2016 for the cMF membranes.

cNF

During the employment of the cNF membranes, the filtration system was analyzed for a period 197 days 5 hours and 31 minutes, while the total filtration time amounted to 83 days 8 hours and 49 minutes. The average run time of a filtration cycle in between two cleaning procedures was observed to be 27 hours and 56 minutes. The initial permeability of the cNF membranes could be restored by the CIP procedures, as is shown in appendix IV ‘Operational filtration cycle analysis’, by utilizing NaOH, HCl and NaOCl solutions.

cMF

During the employment of the cMF membranes, the filtration system was analyzed for a period of 16 days 11 hours and 21 minutes, while the total filtration time amounted to 5 days 9 hours and 38 minutes. The average run time of a filtration cycle in between two cleaning procedures was observed to be 5 hours and 11 minutes. The initial permeability of the cMF membranes could not be fully restored by employing standard protocol CIP procedures. Additionally, to little or no avail, alternative CIP procedures have been tested, including the utilization of a citric acid ($C_6H_8O_7$) solution instead of a hydrochloric acid (HCl) solution. The employment of CEB procedures in order to restore the cMF membrane’s initial permeability showed promising results.

4.3.1 Energy consumption

While utilizing the cNF and cMF membranes, the average energy consumption per filtration cycle amounted to 14 and 9 kWh, respectively, while the total energy consumption of the filtration unit, including membrane cleaning procedures, was estimated at 36300 and 24462 kWh per year, respectively. The energy consumption during filtration cycles was observed to progress linearly, as described in appendix IV ‘Operational filtration cycle analysis’.

4.3.2 Chemical consumption

The measured chemical consumption of specific compound solutions during the automatically conducted CIP procedures, while employing the cNF and cMF membranes for municipal wastewater filtration procedures, is listed in appendix IV ‘Operational filtration cycle analysis’.

It was observed that the amount of chemicals used per CIP procedure is not specifically related to the type of membrane which is being employed in the filtration unit. This is due to the fact that the amount of chemicals required to alter the pH in the filtration system remains equal while employing either type of membrane. The total amount of chemicals used over time during the operational analyses was, however, related to the frequency of membrane cleaning procedures, which was higher during the utilization of cMF membranes.

4.3.3 *Operational analysis (2016)*

An increased drop in the permeability of the cMF membranes was observed during the operational analysis, as is shown in figure 12, even though CIP procedures with NaOH, HCl and NaOCl solutions were conducted after completed filtration cycles. The run time of a filtration cycle was not specifically related to the permeability of the membrane, but rather mainly to the composition of the influent, as described in appendix IV “Chemical analysis”. In order to restore the permeability of the cMF membranes, CEB’s have been used as a membrane cleaning procedure. During consecutive CEB procedures, chemical compound solutions containing NaOH, HCl and $C_6H_8O_7$ have been utilized in order to remove reversible membrane fouling. The permeability was measured by clean water flux tests after each CEB, showing an increase in membrane permeability after each CEB procedure. As shown in figure 12, the permeability was restored after the CEB’s, however decreasing rapidly during the first filtration cycle. The standard protocol CIP procedures that followed were not able to fully restore the membrane’s initial permeability.

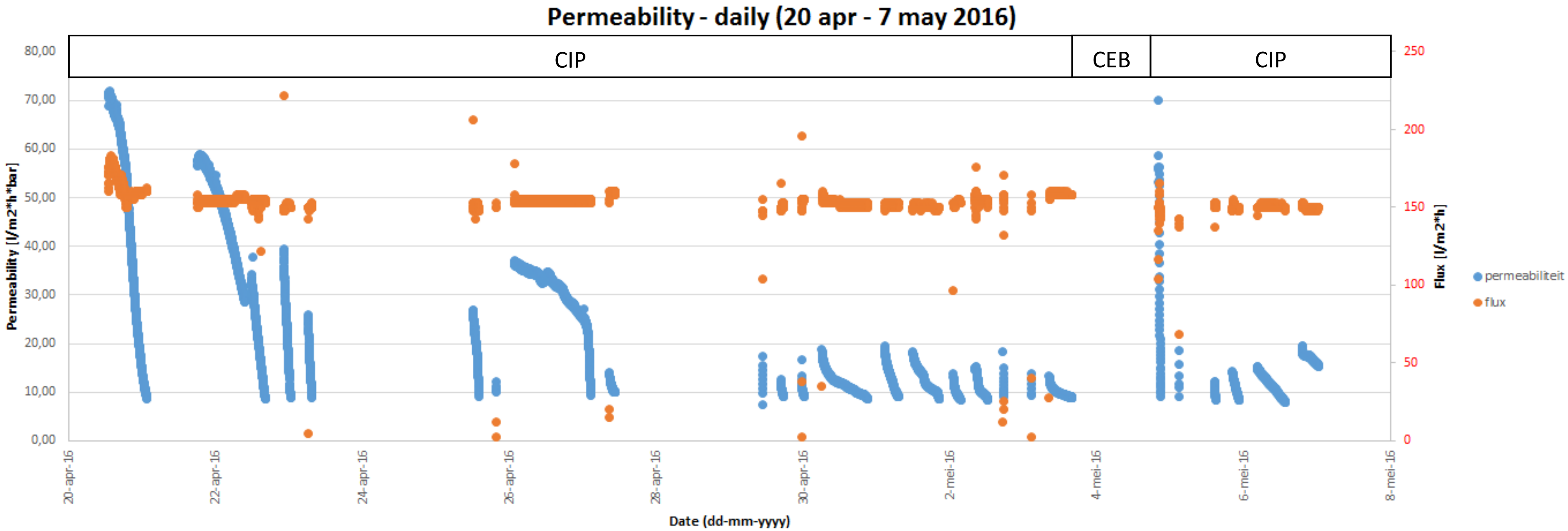

Figure 12: Measured flux and membrane permeability during continuous municipal wastewater filtration procedures from the 20th of April to the 7th of May 2016 while utilizing cMF membranes.

4.3.4 Filtration cycle analyses

Further analysis regarding the filtration cycles during municipal wastewater filtration procedures while utilizing the cNF and cMF membranes shows a different TMP progression trend over time for both membranes, as illustrated in figure 13 and 14. However, this trend could only be observed when the permeability of the membranes was restored, as is shown in appendix IV ‘Operational filtration cycle analysis’. The membrane fouling rate of the cMF membranes showed an increase throughout the operational analysis whenever the TMP reached a certain value, ranging from 3-5 bar, as opposed to the more linear TMP progression of the cNF membranes, as is shown in appendix IV ‘Operational filtration cycle analysis’.

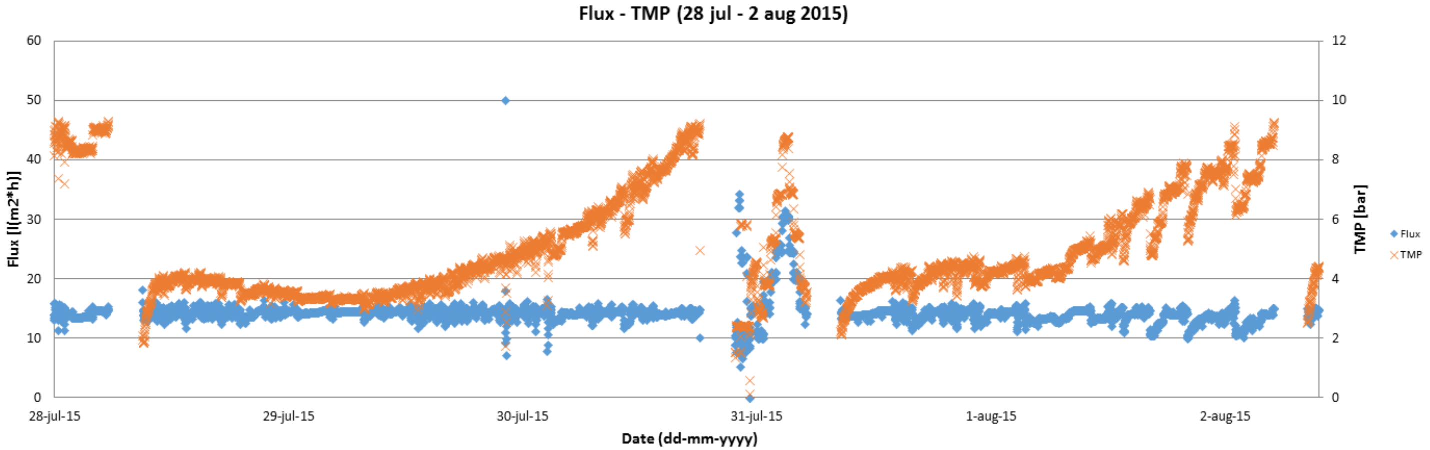

Figure 13: Measured flux and TMP during continuous municipal wastewater filtration procedures from the 28th of July to the 2nd of May 2015 while utilizing cNF membranes.

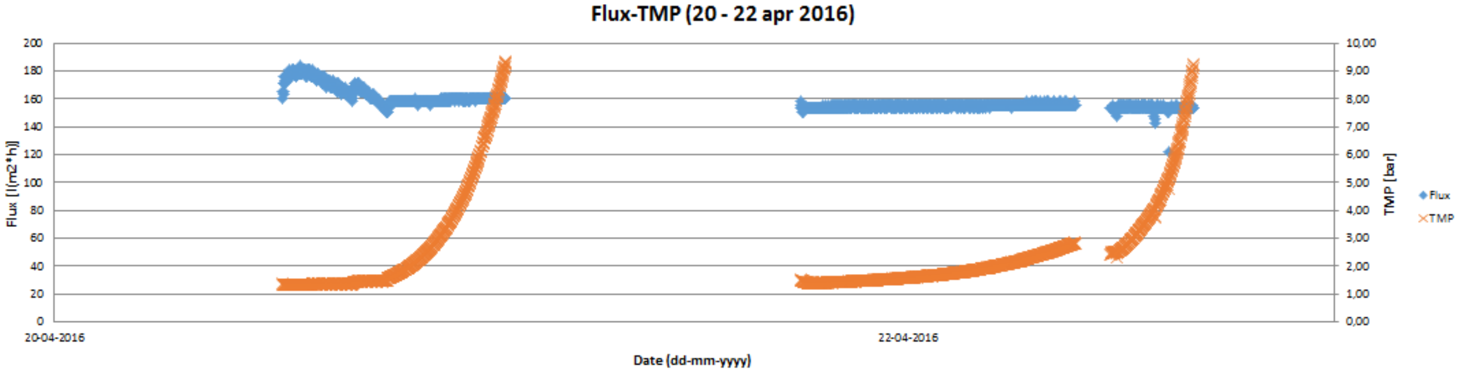

Figure 14: Measured flux and TMP during continuous municipal wastewater filtration procedures from the 20th of April to the 22th of April 2016 while utilizing cMF membranes.

4.3.5 Operational production analyses

While utilizing cNF membranes in wastewater filtration procedures with a set flux of 30 $\frac{l}{h*m^2}$, the values for processed feed water and the produced permeate water amounted to 6.5 and 3.7 m^3 per filtration cycle in between two chemical cleaning procedures, respectively, as is shown in figure 15.

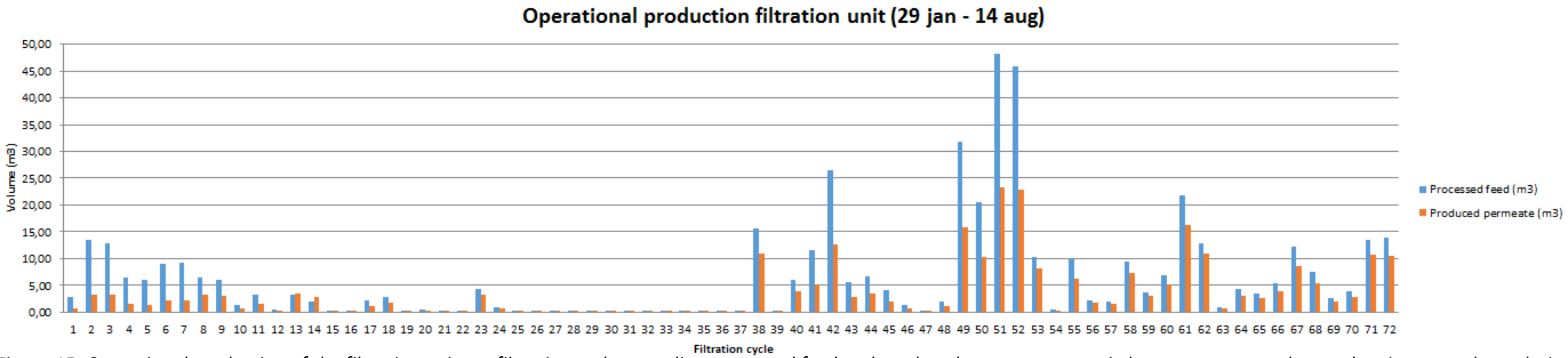

Figure 15: Operational production of the filtration unit per filtration cycle regarding processed feed and produced permeate water in between two membrane cleaning procedures during continuous municipal wastewater filtration procedures from the 29th of January to the 14th of August 2015 while utilizing cNF membranes.

While utilizing cMF membranes in wastewater filtration procedures with a set flux of 150 $\frac{l}{h*m^2}$, the values for processed feed water and the produced permeate water amounted to 3.7 and 3.1 m^3 per filtration cycle in between two chemical cleaning procedures, respectively, as is shown in figure 16.

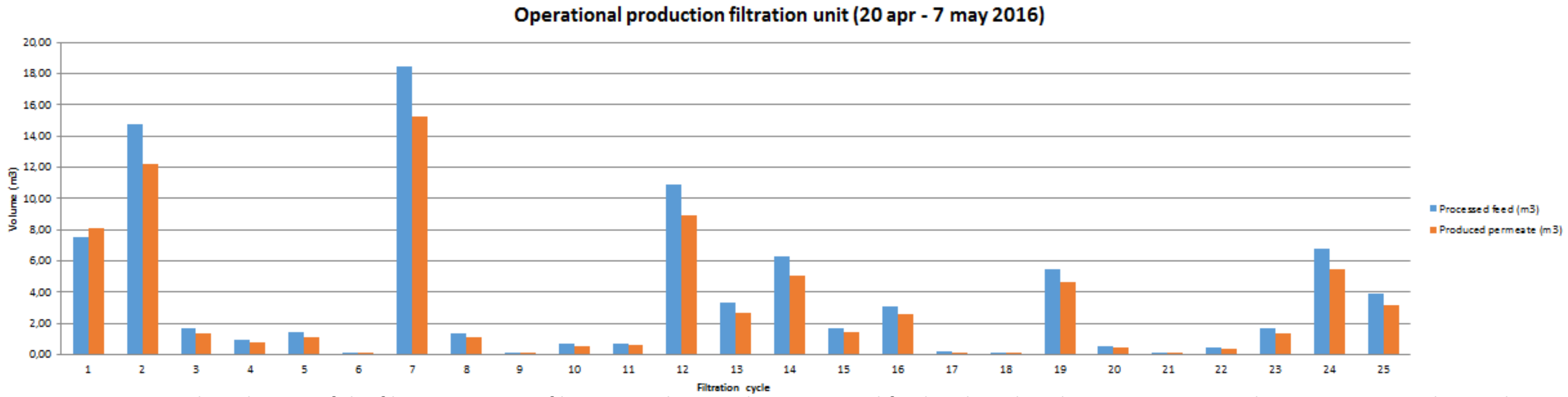

Figure 16: Operational production of the filtration unit per filtration cycle regarding processed feed and produced permeate water in between two membrane cleaning procedures during continuous municipal wastewater filtration procedures from the 20th of April to the 7th of May 2016 while utilizing cMF membranes.

4.3.6 VRO unit

During the employment of the cMF membranes an increased drop was observed in the diffusive mass transfer coefficient (MTC) of the VRO unit's membranes, as shown in figure 17.

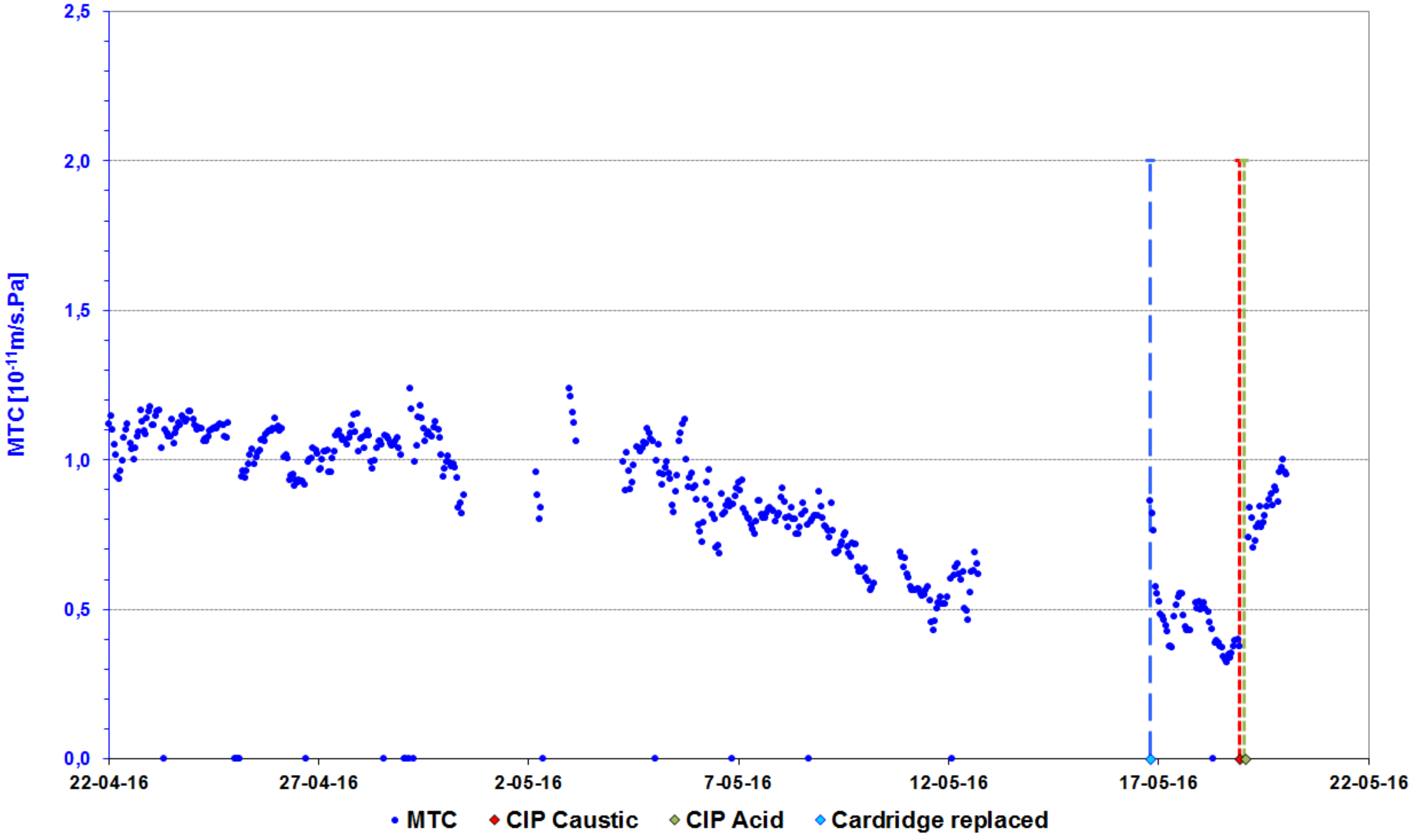

Figure 17: Operational analysis measurements of the VRO unit the employment of the cMF membranes (2016).

5. Discussion

Membrane characterization

The retention behavior of the cNF membranes in March 2016 decreased in comparison with earlier membrane characterization tests in 2014 and 2015, indicating the occurrence of membrane degradation. Further analysis during visual inspection of the cNF membranes while replacing them with the cMF membranes in March 2016 indicated damage to the top and support layers, as shown in appendix V ‘Visual observations’.

Literature research suggested that in order to characterize the cMF membranes with regard to retention behavior and subsequently determining the average pore size, a particle counter analysis would be a suitable method compared to alternative membrane characterization techniques. The first batch tests experiments, however, showed unanticipated results. During the particle counter analysis, nearly equal values for the concentrations of particles ranging from 0.05 to 0.20 µm were observed in concentrate and permeate samples. After further investigation, the results of clean water permeability tests regarding the membrane’s permeability indicated damage to the cMF membrane. By opening the membrane unit and reversing the permeate flow, it was possible to determine which specific membrane was broken. The batch test experiment was repeated after the broken membrane was replaced, subsequently showing results in the expected range. The cMF membrane characterization test results indicated an average membrane pore size of 0.06 µm, disagreeing with the supplier’s given pore size of 0.15-0.20 µm. However, the results of the cMF membrane characterization tests have also shown that these type of retention tests suffice and should be utilized in consecutive batch test experiments regarding the cMF membrane retention behavior.

Operational analyses

Analyses of continuous operational wastewater filtration, while employing the cNF and cMF membranes, showed meaningful results regarding the performance of the membranes and what type of adjustments should be made in order to improve the permeate production rate of the membranes.

The most notable observation during the employment of the cNF and cMF membranes is the average run time of a filtration cycle and the amount of wastewater being processed during these filtration cycles. While operating the filtration system during the cNF and cMF membrane analyses, set fluxes of 30 and 150 $\frac{\mathrm{l}}{\mathrm{h*m^2}}$ have been applied, respectively. The difference in set flux values was mainly caused by the difference in total membrane surface area, amounting to 9.28 m^2 and 3.92 m^2 for the cNF and cMF membranes, respectively. Even though the average permeability of the cNF membranes was lower than that of the cMF membranes at the start of the filtration cycles during the operational analyses, amounting to ~20 and ~125 $\frac{\mathrm{l}}{\mathrm{h*m^2*bar}}$, respectively, at a recovery rate of ~80%, the average duration of the filtration cycles while employing cMF membranes was observed to be shorter at higher flux rates compared to the cNF membrane analysis. The average duration of a filtration cycle while employing cNF and cMF membranes amounted to ~28 and ~5 hours, with almost equal permeate production rates of 3.7 and 3.1 m^3 per filtration cycle, respectively. Furthermore, increased membrane fouling rates were observed whenever the TMP reached a certain value. This observation could potentially confirm the findings of the membrane characterization tests regarding the actual pore size of the cMF membranes and suggests that the cMF membranes should be operated at a lower, more suitable flux rate.

Retention behavior

Even though the production rate per filtration cycle of the cNF and cMF membrane units is comparable with regard to volume, the quality of the produced permeate water differentiates. The decreased quality of the permeate water ultimately caused the TMP in the VRO unit to increase more rapidly due to increased membrane fouling rates while utilizing the cMF membranes as opposed to the cNF membranes. The root cause for this increased membrane fouling rate could be the increased presence of Fe^{2+} ions in the feed flow of the filtration unit due to inconsistencies in operating the DAF unit. Higher retention rates of the cNF membrane for Fe^{2+} ions compared to cMF membranes could explain the increase in membrane fouling rates for the VRO unit. However, the amount of solids present in the filtration unit's wastewater samples was not measured and has been excluded from this specific research due to inaccurate working methods, leading to inconsistent results.

Membrane performance

Improving the efficiency of all corresponding procedures, while utilizing the cMF membranes for municipal wastewater filtration procedures will improve permeate production rates of the filtration system. The shorter average duration of filtration cycles while employing cMF membranes causes the amount of feed and permeate water being processed and produced per day to be lower compared to when cNF membranes are employed, caused by the increased frequency of membrane cleaning procedures during the employment of cMF membranes. Furthermore, these membrane cleaning procedures use almost equal amounts of chemicals, subsequently increasing the total chemical consumption over time while utilizing cMF membranes for municipal wastewater filtration procedures.

Alternative membrane cleaning procedures

Thus far, alternative membrane cleaning procedures in the form of CEBs showed more promising results regarding the restoration of the cMF membrane's initial permeability than the conducted CIP procedures and should be further investigated. The difference in efficiency of these membrane cleaning procedures with regard to restoring the initial permeability of the membranes could be explained due to the fact that particles which have been absorbed in the membrane are not released during CIP membrane cleaning procedures, instead solely removing the constructed layer of contaminants on the membrane's surface. By utilizing CEBs as a membrane cleaning procedure it is, however, possible to remove these type of particles as opposed to CIPs.

However, further analysis of the operational performance of the cMF membranes should be conducted in order to confirm the aforementioned arguments based on a sufficient amount of data. As of yet, it is not possible to make a clear comparison between the cNF and cMF membranes regarding their performance in the operational procedures of municipal wastewater filtration.

6. Conclusion

Based on the conducted research it can be concluded that:

6.1 Characterization, comparison of cNF and cMF

1. *What are the MWCO values of the cNF and cMF membranes?*

The MWCO of the cNF membranes was observed to be $1x10^4$ g/mol in March 2016, indicating the occurrence of membrane degradation since previously conducted membrane characterization tests in 2014 and 2015. The occurrence of membrane degradation was later confirmed by visual inspection of the cNF membranes.

The average pore size of the cMF membranes was observed to be 0.06 µm in April 2016, disagreeing with the supplier's given pore size for the membranes of 0.15-0.20 µm.

2. *What is the fresh water permeability of the cNF and cMF membranes?*

The fresh water permeability of the cNF membranes in March 2016 was determined to be 19.67 ± 0.51 $\frac{\mathrm{l}}{\mathrm{h}*\mathrm{m}^2*\mathrm{bar}}$ at a recovery of 80.59 ± 0.54% regarding demineralized water.

The fresh water permeability of the unemployed cMF membranes in April 2016 was determined to be 124.29 ± 2.61 $\frac{\mathrm{l}}{\mathrm{h}*\mathrm{m}^2*\mathrm{bar}}$ at a recovery of 83.19 ± 2.42% regarding demineralized water.

6.2 Applicability

1. *What is the chemical and biological composition of the feed water, cross, permeate and concentrate flows during municipal wastewater treatment at the RINEW project during the cNF and cMF membrane filtration processes?*

During specific batch test experiments in March 2016, the phosphate retention behavior of the cNF membranes was observed to proportionally decrease depending on the acidity of the feed flow, ranging from 13.81 ± 9.91% at a pH of 6.7 to 1.04 ± 0.43% at a pH of 2.9.

The chemical composition of the feed, permeate, cross and concentrate flows regarding the concentration of specific nutrients in the filtration system during the employment of the cMF membranes can be found in appendix IV "Chemical analysis data".

2. *What is the average permeate production rate of the municipal wastewater treatment process at the RINEW project while employing the cNF or cMF membranes?*

While utilizing cNF membranes in wastewater filtration procedures with a set flux of 30 $\frac{\mathrm{l}}{\mathrm{h}*\mathrm{m}^2}$, the values for processed feed water and the produced permeate water amounted to 6.5 and 3.7 m^3 per filtration cycle in between two chemical cleaning procedures, respectively.

With cMF membranes with a set flux of 150 $\frac{\mathrm{l}}{\mathrm{h}*\mathrm{m}^2}$, the values for processed feed water and the produced permeate water amounted to 3.7 and 3.1 m^3 per filtration cycle in between two chemical cleaning procedures, respectively.

3. *What is the average run time of the municipal wastewater membrane filtration process cycle at the RINEW project, in between two CIP procedures, while employing the cNF or cMF membranes?*

The average run time of a filtration cycle during operational wastewater filtration procedures with the cNF membranes amounted to 27 hours and 56 minutes.

With the cMF membranes this amounted to 5 hours and 11 minutes.

6.3 Economic feasibility

1. *How do cNF and cMF membranes compare with regard to variable and fixed operational costs of the municipal wastewater treatment process?*

The operational costs of the filtration system while utilizing cNF and cMF membranes for municipal wastewater treatment mainly differ with regard to chemical use. The chemical cleaning procedures were observed to use similar amounts of chemicals during employment of cNF and cMF membranes. However, while utilizing the cMF membranes for municipal wastewater treatment, shorter filtration cycles were observed in comparison with the cNF membranes, ultimately resulting in an increase of chemical cleaning procedures.

The total energy consumption of the cNF filtration unit, including membrane cleaning procedures, was estimated at 36300 kWh per year, resulting in 32 kWh/m^3 produced permeate product.

The total energy consumption of the cMF filtration unit, including membrane cleaning procedures, was estimated at 24462 kWh per year, resulting in 14 kWh/m^3 produced permeate product.

2. *What is the potential yearly revenue of the municipal wastewater treatment process, regarding the produced permeate, while employing the cNF or cMF membranes?*

While utilizing cNF membranes in wastewater filtration procedures with a set flux of 30 $\frac{\mathrm{l}}{\mathrm{h*m^2}}$, the yearly revenue of the produced permeate water ranged from 1040 to 1150 m^3, depending on recovery rates ranging from ~80 to ~50%, respectively (Hoek, 2016).

While utilizing cMF membranes in wastewater filtration procedures with a set flux of 150 $\frac{\mathrm{l}}{\mathrm{h*m^2}}$, the yearly revenue of the produced permeate water was estimated at 1716 m^3 at a recovery rate of ~80%.

7. Recommendation

The findings in the conducted research recommend that:

- The filtration system should be tested at a recovery rate of 50% while utilizing cMF for municipal wastewater filtration procedures. Lowering the recovery rate could potentially lower the membrane fouling rate and increase the average run time of the filtration cycles in between two chemical cleaning procedures. This could ultimately result in a higher average permeate production rate of the cMF membranes due to a relatively higher total uptime of the filtration system compared to operating the system at a higher recovery rate.

- Further research should be conducted on the use of CEB's as a membrane cleaning procedures during employment of cMF membranes for municipal wastewater treatment. The use of CEB's as a membrane cleaning procedure should be analyzed with regard to their ability to restore membrane permeability. The results of this practical analysis should be compared to other membrane cleaning procedures in order to determine a suitable membrane cleaning procedure for the cMF membranes.

References

Cho, R. (2013). 'Phosphorus: Essential to Life – Are We Running Out?'. State of the Planet. http://blogs.ei.columbia.edu/2013/04/01/phosphorus-essential-to-life-are-we-running-out/

Evides (2014). 'Projectplan RINEW'. Evides Waterbedrijf.

Evides (2016). 'Onderzoeksprogramma rond zuiveringstechnologie en distributie'. Evides Waterbedrijf.
https://www.evides.nl/over-evides/paginas/onderzoek-en-innovatie-.aspx

Evides (2016). 'Over Evides Waterbedrijf'. Evides Waterbedrijf.
https://www.evides.nl/over-evides/Paginas/default.aspx

Evides (2016). 'Research committee RINEW – UJES Meeting'. Evides Waterbedrijf.

FAO (2016). 'How to Feed the World in 2050'. Food and Agriculture Organization of the United Nations.
http://www.fao.org/fileadmin/templates/wsfs/docs/expert_paper/How_to_Feed_the_World_in_2050.pdf

Heijman, B. (2014). 'Ceramic nanofiltration as the key step for sustainable wastewater treatment with reuse of water, energy and nutrients. Delft University of Technology.
http://www.citg.tudelft.nl/nl/over-faculteit/afdelingen/watermanagement/secties/sanitary-engineering/research/new-projectsgrants/ceramic-nanofiltration-as-the-key-step-for-sustainable-wastewater-treatment-with-reuse-of-water-energy-and-nutrients/

Hoek, T. (2016). 'Upscaling cNF – Research report'. Evides Industriewater, Den Hoorn, the Netherlands.

Howe, K., Clark, M. (2002). 'Fouling of Microfiltration and Ultrafiltration Membranes by Natural Waters'. Environmental Science Technology, vol. 36, pp. 3571 – 3576.

Jacangelo, J.G., et al. (1997). 'Membrane Filtration for Microbial Removal'. American Water Works Association Research Foundation and American Water Works Association, Denver.

Klemm, B. (2015). 'Ceramic nanofiltration for municipal wastewater reuse'. Evides Industriewater, Den Hoorn, the Netherlands.

Koch (2013). 'Membrane Filtration Technology: Meeting Today's Water Treatment Challenges'. Koch Membrane Systems, Massachusetts, United States of America.
http://www.kochmembrane.com/PDFs/Other-Documents/Membrane-Filtration-Technology---Koch-Membrane-Sys.aspx

Koch (2016). 'Membrane Technologies'. Koch Membrane Systems, Massachusetts, United States of America.
http://www.kochmembrane.com/Learning-Center/Technologies.aspx

Mallevialle, J., et al. (1996). ‘Water Treatment Membrane Processes’. McGraw-Hill Companies, New York, United States of America.

Moitsheki (2003). ‘Nanofiltration: Fouling and chemical cleaning’. University for Christian Higher Education.

Mulder, M. (1996). ‘Basic Principles of Membrane Technology’. Center for Membrane Science and Technology, University of Twente, Enschede, the Netherlands.

Santos, H. (2014). ‘Afvalwaterzuivering met directe keramische nanofiltratie’. Evides Industriewater, Den Hoorn, the Netherlands.

Schindler, D., Schindler, V., John, R. (2004). ‘Over fertilization of the World's Freshwaters and Estuaries’. University of Alberta Press, p. 1.

Swaminathan, M., et al. (2013). ‘Advanced Oxidation Processes for Wastewater Treatment’. Department of Chemistry, Annamalai University, India.

Tchobanoglous, G., et al. (1985). ‘Water quality: characteristics, modeling, modification’. Pearson Education, United States.

Tchobanoglous, G., et al. (2003). ‘Wastewater Engineering, Treatment and Reuse’. McGraw-Hill Companies, New York, United States of America.

Tilley, E., et al. (2014). ‘Compendium of Sanitation Systems and Technologies – (2nd Revised Edition). Swiss Federal Institute of Aquatic Science and Technology (Eawag), Duebendorf, Switzerland. p. 175. ISBN 978-3-906484-57-0.

Urbanowska, A., et al. (2014). ‘Influence of operating conditions on performance of ceramic membrane used for water treatment’. Chemical Papers, p. 190-196.

Van Gestel, T., et al. (2002). ‘Salt retention in nanofiltration with multilayer ceramic TiO_2 membranes’. Journal of Membrane Science, p. 379-389.

Appendix I – Water composition

1. Water composition parameters

Parameters indicating specific constituents present in wastewater samples, as listed in table 4.

Parameter	Substance	Method	Measurement
Chemical Oxygen Demand (COD)	Organic matter	Chemical oxidation	HACH LANGE; DR-2800 LCK 114; LCK 414
Total Solids (TS)	Organic + inorganic matter	The residue remaining after a wastewater sample has been evaporated and dried at a specified temperature (103 to 105°C).	TS = TSS + TDS
Total Suspended Solids (TSS)		Portion of the TS retained on a filter with a specified pore size, measured after being dried at a specified temperature (105°C).	
Total Dissolved Solids (TDS)		Those solids that pass through the filter, and are then evaporated and dried at specified temperature.	TS – TSS *Electrical conductivity (EC)*
Settleable Solids (SS)		Suspended solids that accumulate in the bottom of the cone after 60 min, reported as ml/l	Imhoff cone
Nitrogen (Total-N)	Total-N	Kjeldahl	HACH LANGE; DR-2800 LCK 138
	Free ammonia	NH_4^+	HACH LANGE; DR-2800 LCK 304
Phosphorus (Total-P)	Organic + inorganic P		HACH LANGE; DR-2800 LCK 350; LCK 349
	Inorganic P	Orthophosphate (PO_4^{3-}P)	
Metallic constituents	Anions Cations HCO_3^- Ca^{2+} CO_3^{2-} Mg^{2+} Cl^- Fe^{2+} SO_4^{2-}		

Table 4: Water composition parameters.

2. Interrelationships of solids in (waste-)water samples

Constituents of solids present in wastewater, including the methods in order to analyze each specific constituent with regard to weight per volume wastewater sample, as shown in figure 18 (Tchobanoglous, 1985).

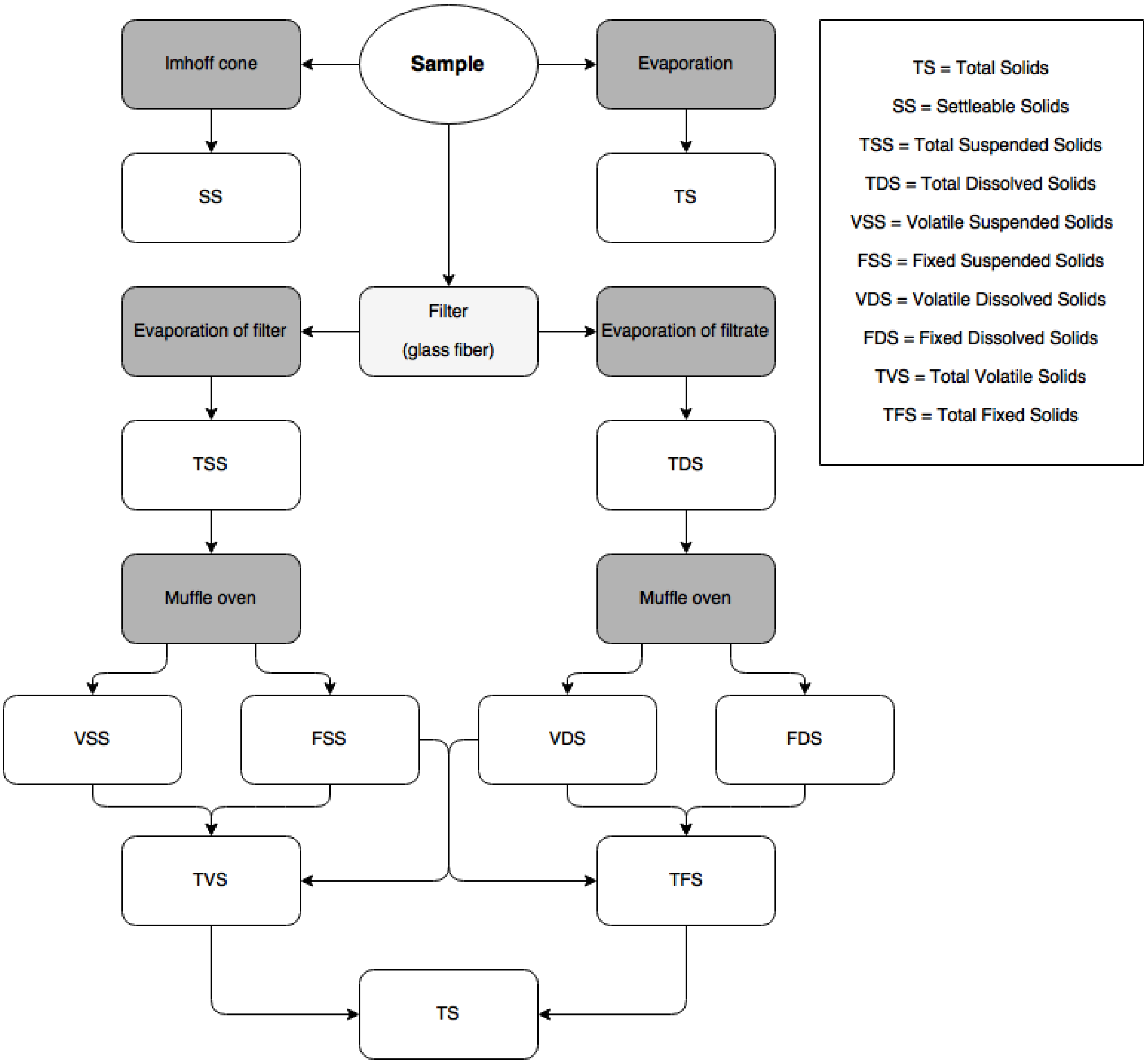

Figure 18: The interrelationships of solids found in (waste-)water samples, including analysis procedures (Tchobanoglous, 1985).

Appendix II – Filtration unit

1. Piping and instrumentation diagram

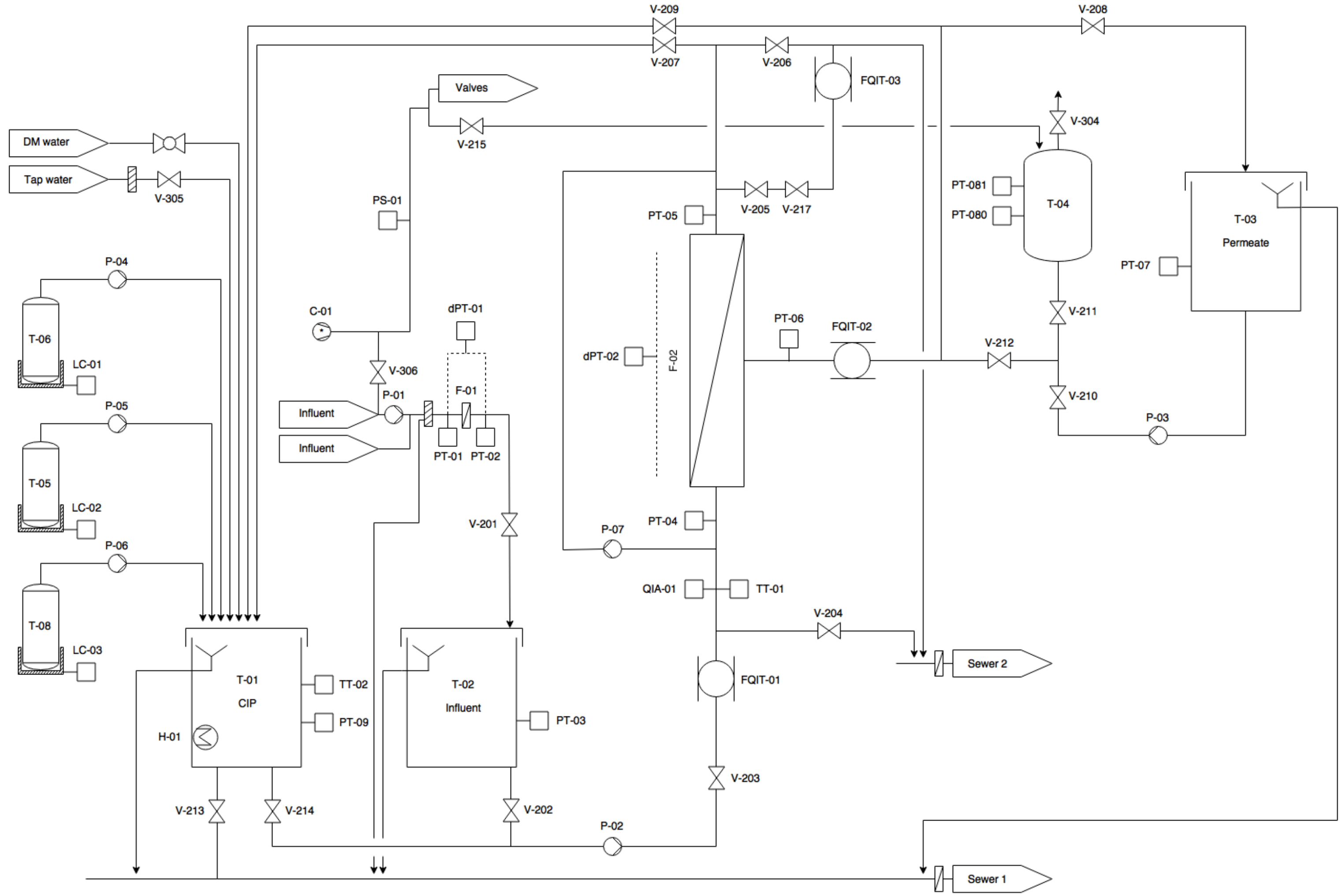

Figure 19: Piping and instrumentation diagram (P&ID) of the experimental filtration unit setup.

The pilot installation's operation system is based on the P&ID, shown in figure 20, of the experimental setup and can be subdivided into three specifications; the influent line, filtration line and backwash line.

Influent line
Both tap and demineralized water sources are connected to tank (T-01), also referred to as the 'CIP tank', in order to be able to complete specific steps during batch test experiments. During these procedures, tap or demineralized water is directed to tank (T-01) by opening valve (V-305) or by opening the manual valve after redirecting the demineralized water tube to tank (T-01). Operating heater (H-01) enables temperature regulation in tank (T-01). Furthermore, the chemical tanks (T-05/06/08), operated by pumps (P-04/05/06), contain the chemical compounds that are used during the CIP process and certain experimental procedures.

Filtration line
In the filtration line, the feed flow is directed through the membrane unit (F-02). The first step in operating the filtration line is opening the valves (V-203/205/206/207/217). Valve (V-217) can be modified to operate at a specific capacity, allowing only a certain percentage of the concentrate flow to pass through the pipe.

Backwash line
Before operating pumps (P-02/07) in the filtration line, valve (V-209) must be opened in the backwash line. Pumps (P-02/07) may only be operated once all of the aforementioned valves are opened. Furthermore, pump (P-07) may only be operated once pump (P-02) has been turned on. Pumps (P-02/07) can be modified to operate at a specific working capacity, making it possible to control the flow rate in the system in combination with the operational modifications of valve (V-217).

Batch mode
During batch mode operation, the concentrate and permeate streams are redirected towards the CIP tank by opening the valves (V-207/209). When stopping batch mode, it is crucial pumps (P-02/07) are turned off before closing the valves (V-203/205/206/207/209/217). During this procedure it is important that pump (P-07) is turned off first, followed by pump (P-02). Operating valve (V-213) allows the system to discharge its contents via the CIP tank into Sewer 1.

2. Measurement instruments

Instruments employed in the filtration unit, indicating values for specific parameters, as listed in table 5.

Instrument	Stream	Type	Unit
FQIT-01	Feed	Flow	m^3/h
FQIT-02	Permeate	Flow	m^3/h
FQIT-03	Concentrate	Flow	l/h
PT-04	Concentrate	Pressure	bar
PT-05	Feed	Pressure	bar
PT-06	Permeate	Pressure	bar
TT-01	Feed	Temperature	°C
TT-02	T-01/CIP tank	Temperature	°C
PT-09	T-01/CIP tank	Height	m
P-02 (set)	Pump	Frequency	Hz
P-07 (set)	Pump	Frequency	Hz
QIA-01	Feed	pH	-
Manual	T-01/CIP tank	pH	-
LC-01	Chemical tank	Weight	g
LC-02	Chemical tank	Weight	g
LC-03	Chemical tank	Weight	g

Table 5: Specifications measurement instruments.

The flow rates in the system, measured by the flow meters (FQIT-01/02/03), are related to the feed, permeate and concentrate flows, respectively. Pressure indicators (PT-04/05/06) indicate the feed, concentrate and permeate site pressures, respectively. The feed flow temperature in the filtration line is measured by a heat sensor (TT-01), whereas the temperature of the contents present in tank (T-01), or CIP tank, is measured by heat sensor (TT-02). Additionally, the water level of the CIP tank is indicated by sensor (PT-09). The set frequencies of the pumps (P-02/07) indicate the rate at which the pumps are operating.

Chemical modifications to the filtration system are indicated by a pH sensor (QIA-01), measuring the pH of the feed flow, and manual pH measurements in the CIP tank. The amount of chemical compounds present in the chemical tanks (T-05/06/08) is indicated by the scales (LC-01/02/03).

3. Filtration unit data summary

a. *Operational data summary 2016*

Cyclus	Begin tijd	Eind tijd	Tijdsduur [uu:mm]	Bruto Flux [l/m2*h]	Recovery [%]	Permeabiliteit Begin [l/m2*h*bar]	Permeabiliteit Eind [l/m2*h*bar]	*RWA / DWA	TMP bereikt [bar]	Vol filtr. cyclus afgerond ja/nee	Per cyclus Voeding verwerkt m^3/cycle	Per cyclus Permeaat geproduceerd m^3/cycle
1	20-04-16 12:50	21-04-16 1:24	12:34	82	81	69,05	8,80	RWA	9,35	ja	7,52	8,07
2	21-04-16 18:00	22-04-16 16:06	22:06	79	80	56,70	8,68	RWA	9,25	ja	14,74	12,18
3	22-04-16 21:59	23-04-16 0:21	2:22	79	80	39,53	8,90	RWA	9,22	ja	1,71	1,38
4	23-04-16 6:06	23-04-16 7:20	1:14	79	79	26,05	9,02	RWA	9,20	ja	0,91	0,73
5	25-04-16 11:58	25-04-16 13:51	1:53	79	80	27,01	9,13	RWA	9,12	ja	1,39	1,13
6	25-04-16 19:23	25-04-16 19:27	0:04	76	64	12,20	10,17	RWA	9,11	ja	0,06	0,03
7	26-04-16 1:22	27-04-16 2:29	25:07	79	80	36,46	9,55	RWA	9,27	ja	18,42	15,22
8	27-04-16 8:34	27-04-16 10:21	1:47	79	80	14,05	10,16	RWA	9,22	ja	1,32	1,11
9	29-04-16 10:36	29-04-16 10:44	0:08	76	71	7,57	9,89	RWA	9,08	ja	0,10	0,08
10	29-04-16 16:35	29-04-16 17:30	0:55	79	80	12,66	9,36	RWA	9,21	ja	0,68	0,55
11	29-04-16 23:17	30-04-16 0:16	0:59	78	78	16,88	9,24	RWA	9,22	ja	0,69	0,56
12	30-04-16 6:00	30-04-16 20:49	14:49	79	80	18,95	8,80	RWA	9,24	ja	10,89	8,90
13	1-05-16 2:29	1-05-16 6:57	4:28	79	80	19,56	9,20	RWA	9,22	ja	3,28	2,68
14	1-05-16 11:45	1-05-16 20:20	8:35	79	80	18,32	8,65	RWA	9,24	ja	6,31	5,08
15	2-05-16 0:57	2-05-16 3:16	2:19	79	80	13,91	8,63	RWA	9,22	ja	1,71	1,40
16	2-05-16 8:00	2-05-16 12:10	4:10	79	80	15,12	8,46	RWA	9,23	ja	3,07	2,54
17	2-05-16 17:11	2-05-16 17:32	0:21	75	79	18,57	10,59	RWA	6,49	nee	0,16	0,11
18	3-05-16 2:20	3-05-16 2:25	0:05	71	62	14,07	9,45	RWA	8,79	ja	0,07	0,04
19	3-05-16 8:16	3-05-16 15:42	7:26	79	80	13,46	8,95	RWA	9,23	ja	5,47	4,61
20	4-05-16 20:00	4-05-16 20:45	0:45	78	80	58,73	9,34	RWA	8,78	ja	0,56	0,44
21	5-05-16 2:34	5-05-16 2:39	0:05	69	66	11,86	9,22	RWA	8,70	ja	0,06	0,05
22	5-05-16 14:12	5-05-16 14:44	0:32	79	80	12,40	8,55	RWA	8,99	ja	0,40	0,33
23	5-05-16 20:09	5-05-16 22:28	2:19	79	80	14,38	8,45	RWA	8,99	ja	1,71	1,38
24	6-05-16 4:12	6-05-16 13:28	9:16	79	80	15,25	8,07	RWA	8,99	ja	6,81	5,48
25	6-05-16 18:52	7-05-16 0:11	5:19	79	80	19,68	15,47	RWA	4,70	nee	3,88	3,11

Total	
Voeding verwerkt m^3	Permeaat geproduceerd m^3
91,93	77,19
per dag	per dag
5,6	4,7
per cycle	per cycle
3,7	3,1

	april		mei		Totaal	
	Voeding verwerkt	Permeaat geproduceerd	Voeding verwerkt	Permeaat geproduceerd	Voeding verwerkt	Permeaat geproduceerd
Total volume (m3)	58,43	49,94	33,50	27,25	91,93	77,19
Volume per day	5,65	4,83	5,67	4,62	5,58	4,69
Volume per cycle	5,31	4,54	2,79	2,27	3,68	3,09
Total days analysis		10,33		5,90		16,24
Total natural days operational		9		7		16
Total duration filtration cycles		83:58		45:40		129:38
Average duration filtration cycle		7:38		3:48		5:11

Table 6: Summary of the processed operational filtration unit data (2016).

b. Operational data summary 2015

'15 juni cyclus	Cyclus	Begin tijd	Eind tijd	Tijdsduur [uu:mm]	Bruto Flux [l/m2*h]	Recovery [%]	Permeabiliteit Begin [l/m2*h*bar]	Permeabiliteit Eind [l/m2*h*bar]	*RWA / DWA	TMP bereikt [bar]	Vol filtr. afgerond ja/nee	Per cyclus: Voeding verbruikt m³/cycle	Per cyclus: Permeaat geproduceerd m³/cycle		Total: Voeding verm m³	Total: Permeaat geproduc m³
	1	29-01-15 10:21	29-01-15 14:17	3:56	20	25	6,10	2,90	RWA	9,30	ja	2,86	0,77		470,64	266,14
	2	31-01-15 0:02	1-02-15 12:48	36:46	10	24	1,64	1,12	RWA	10,15	ja	13,58	3,31		per dag	per dag
	3	4-02-15 14:28	5-02-15 13:41	23:13	15	25	6,36	1,63	RWA	10,15	ja	12,76	3,25		7,9	4,5
	4	5-02-15 20:42	6-02-15 8:31	11:49	15	25	5,09	1,82	rwa	10,09	ja	6,49	1,65		per cycle	per cycle
	5	6-02-15 13:28	7-02-15 4:14	14:46	11	25	2,82	1,06	rwa	9,94	ja	5,95	1,46		6,5	3,7
	6	7-02-15 10:06	8-02-15 10:18	24:12	10	24	5,18	1,12	rwa	10,07	ja	8,95	2,18			
	7	8-02-15 14:40	9-02-15 15:27	24:47	10	24	4,92	1,10	dwa	10,10	ja	9,16	2,23			
	8	9-02-15 19:48	10-02-15 13:16	17:28	20	51	4,33	2,36	dwa	9,81	ja	6,46	3,31			
	9	10-02-15 21:52	11-02-15 14:00	16:08	20	51	6,93	2,19	dwa	10,06	ja	5,97	3,06			
	10	13-02-15 14:32	13-02-15 18:10	3:38	20	51	14,78	4,16	dwa	5,33	nee	1,35	0,69			
	11	16-02-15 16:24	17-02-15 1:04	8:40	20	51	6,55	2,32	dwa	10,08	ja	3,20	1,64			
	12	17-02-15 14:07	17-02-15 15:37	1:30	20	51	10,25	3,27	dwa	4,31	nee	0,56	0,29			
	13	18-02-15 9:27	18-02-15 18:32	9:05	20	50	8,70	2,09	dwa	9,78	ja	3,31	3,43			
	14	19-02-15 11:10	19-02-15 16:21	5:11	20	50	5,06	2,30	dwa	9,84	nee	1,91	2,93			
	15	19-02-15 20:46	19-02-15 21:02	0:16	7	19	2,20	1,63	dwa	10,20	nee	0,08	0,02			
	16	20-02-15 9:18	20-02-15 9:36	0:18	5	13	1,82	1,08	RWA	8,72	nee	0,12	0,02			
	17	20-02-15 13:59	20-02-15 19:54	5:55	11	27	7,21	2,15	RWA	5,85	nee	2,19	1,10			
	18	23-02-15 9:47	23-02-15 19:54	10:07	12	39	5,14	3,14	RWA	4,81	nee	2,78	1,85			
	19	24-02-15 10:48	24-02-15 12:02	1:14	9	5	2,99	0,92	rwa	9,67	nee	0,28	0,15			
	20	25-02-15 10:01	25-02-15 10:56	0:55	26	49	9,84	3,57	rwa	9,08	nee	0,46	0,31			
	21	25-02-15 12:09	25-02-15 12:37	0:28	25	46	17,39	3,02	rwa	8,80	nee	0,23	0,15			
	22	25-02-15 18:39	25-02-15 19:01	0:22	26	49	7,31	6,02	rwa	5,22	nee	0,19	0,10			
	23	26-02-15 14:40	27-02-15 5:58	15:18	15	50	7,38	3,88	RWA	3,60	nee	4,28	3,28		9,228156732	
	24	27-02-15 9:01	27-02-15 12:39	3:38	15	50	6,23	3,71	RWA	4,66	nee	1,03	0,71		cross flow pomp was not working	
	25	27-02-15 12:50	27-02-15 13:14	0:24	14	49	3,76	1,79	RWA	8,30	ja	0,11	0,07		cross flow pomp was not working	
	26	27-02-15 18:52	27-02-15 20:04	1:12	14	48	0,00	1,91	RWA	8,97	ja	0,33	0,19		cross flow pomp was not working	
	27	28-02-15 2:05	28-02-15 2:56	0:51	14	47	0,00	1,91	rwa	8,97	ja	0,23	0,12		cross flow pomp was not working	
	28	28-02-15 8:54	28-02-15 9:56	1:02	14	47	0,00	1,05	rwa	8,15	ja	0,28	0,15		cross flow pomp was not working	
	29	28-02-15 15:45	28-02-15 16:48	1:03	14	48	0,00	1,75	rwa	8,84	ja	0,29	0,16		cross flow pomp was not working	
	30	28-02-15 22:15	28-02-15 22:59	0:44	14	47	0,00	1,79	rwa	8,68	ja	0,20	0,11		cross flow pomp was not working	
	31	1-03-15 3:28	1-03-15 3:58	0:30	14	47	0,00	1,88	RWA	8,96	ja	0,14	0,07		cross flow pomp was not working	
	32	1-03-15 8:22	1-03-15 8:54	0:32	13	46	0,00	1,79	RWA	8,89	ja	0,15	0,07		cross flow pomp was not working	
	33	1-03-15 13:07	1-03-15 13:46	0:39	13	46	0,00	1,40	RWA	8,65	ja	0,17	0,08		cross flow pomp was not working	
	34	1-03-15 17:54	1-03-15 18:24	0:30	13	46	0,00	1,61	RWA	8,95	ja	0,14	0,06		cross flow pomp was not working	
	35	1-03-15 22:31	1-03-15 22:59	0:28	12	44	0,00	1,76	RWA	8,89	ja	0,13	0,05		cross flow pomp was not working	
1	36	2-03-15 3:10	2-03-15 3:35	0:25	14	47	9,35	1,78	RWA	8,93	ja	0,12	0,05		cross flow pomp was not working	
2	37	2-03-15 7:43	2-03-15 8:13	0:30	13	48	0,00	1,77	RWA	9,05	ja	0,14	0,06			
3	38	2-03-15 17:14	5-03-15 16:54	71:40	15	50	9,77	2,35	RWA	6,95	nee	15,5	11,0			
4	39	6-03-15 14:21	6-03-15 15:14	0:53	12	47	0,00	3,43	RWA	4,53	nee	0,23	0,11			
5	40	9-03-15 11:39	10-03-15 10:43	23:04	15	50	6,55	3,25	RWA	5,37	nee	6,02	3,84			
1	41	31-03-15 15:15	3-04-15 7:00	63:45	19	60	16,10	4,21	RWA	3,60	nee	11,53	5,18	415,4		
2	42	2-04-15 14:28	6-04-15 10:05	91:37	20	64	18,46	3,82	RWA	4,27	nee	26,54	12,67			
3	43	8-04-15 15:04	9-04-15 11:19	20:15	15	50	7,76	4,08	RWA	2,84	nee	5,68	2,86			
4	44	9-04-15 15:28	10-04-15 15:41	24:13	15	50	4,00	3,13	RWA	4,39	nee	6,75	3,55			
5	45	13-04-15 8:39	13-04-15 23:59	15:20	14	48	2,80	2,90	RWA	4,74	nee	4,16	2,03			
6	46	15-04-15 9:17	15-04-15 14:08	4:51	17	52	6,41	2,76	RWA	5,52	nee	1,43	0,75			
7	47	16-04-15 12:55	16-04-15 13:40	0:45	40	63	11,89	9,46	RWA	4,22	nee	0,28	0,18			
8	48	17-04-15 16:27	17-04-15 23:22	6:55	15	50	8,74	5,53	RWA	2,55	nee	1,94	1,07			
9	49	20-04-15 13:09	25-04-15 7:20	114:11	15	50	11,58	1,41	RWA	9,44	ja	31,85	15,94			
10	50	25-04-15 11:06	28-04-15 14:14	75:08	15	50	6,45	1,52	RWA	9,30	ja	20,44	10,25			
1	51	29-04-15 14:00	7-05-15 8:29	186:29	15	50	5,15	2,00	DWA	7,38	nee	48,27	23,22	logiticon visit		
2	52	11-05-15 14:02	18-05-15 10:38	164:36	15	50	5,87	1,74	RWA	8,41	ja	45,90	22,96			
3	53	20-05-15 11:54	22-05-15 11:36	47:42	15	79	3,52	1,67	DWA	7,94	nee	10,32	8,18	gebrek aanvoer		
4	54	26-05-15 16:42	26-05-15 19:01	2:19	15	78	5,15	3,33	DWA	3,72	nee	0,41	0,32			
4	55	28-05-15 14:52	30-05-15 12:50	45:58	17	80	4,34	1,51	DWA	9,42	ja	10,13	6,34			
5	56	30-05-15 16:23	31-05-15 4:53	12:30	15	80	4,93	2,44	DWA	6,09	nee	2,16	1,73			
1	57	5-06-15 11:07	5-06-15 22:25	11:18	15	79	5,58	3,57	RWA	3,74	nee	1,96	1,62			
2	58	8-06-15 9:34	10-06-15 16:26	54:52	16	78	8,43	1,72	DWA	7,77	nee	9,46	7,37			
3	59	11-06-15 15:05	12-06-15 12:06	21:01	15	79	4,98	3,14	DWA	9,05	ja	3,79	2,97			
4	60	22-06-15 12:44	24-06-15 5:43	40:59	14	79	7,62	3,64	RWA	3,77	nee	6,91	5,27			
	61	25-06-15 12:09	1-07-15 10:25	142:16	15	80	3,80	2,28	DWA	5,28	nee	21,71	16,20			
1	62	14-07-15 9:43	17-07-15 13:46	76:03	15	76	1,52	0,96	DWA	9,24	ja	12,91	10,96			
2	63	20-07-15 10:43	20-07-15 14:39	3:56	19	78	5,21	3,02	DWA	9,02	ja	0,85	0,67			
3	64	20-07-15 18:08	21-07-15 15:18	21:10	16	74	5,54	3,07	DWA	9,32	ja	4,27	3,00			
4	65	22-07-15 8:42	24-07-15 18:59	58:17	14	76	6,30	1,94	DWA	6,13	nee	3,57	2,64			
5	66	27-07-15 9:25	28-07-15 17:35	32:10	14	77	2,13	1,36	RWA	9,29	ja	5,35	3,96			
6	67	28-07-15 21:06	31-07-15 17:08	68:02	15	75	7,01	3,29	RWA	3,56	nee	12,13	8,63			
7	68	31-07-15 20:37	2-08-15 17:01	44:24	14	75	5,87	1,28	DWA	9,23	ja	7,54	5,48			
8	69	2-08-15 20:26	3-08-15 12:10	15:44	14	77	4,42	2,46	DWA	5,40	nee	2,68	2,05			
9	70	5-08-15 16:02	6-08-15 15:19	23:17	14	77	3,11	1,32	DWA	9,30	ja	3,96	2,31	B05,afvoer pomp broken		
10	71	6-08-15 18:44	10-08-15 2:45	80:01	14	77	5,16	0,85	DWA	8,85	ja	13,52	10,76			
11	72	10-08-15 14:08	14-08-15 15:46	97:38	14	77	3,42	4,08	RWA	4,30	nee	13,94	10,42			

maart		april		mei		juni		juli		augustus			juli-aug			
Voedin	Permea	Voeding	Permea	Voedin	Permea	Voeding ve	Permeaat (	Voedin	Permea	Voedin	Permeaat gepr		Voedin	Permeaat geproduceerd		
m³	m³	m³	m³	m³	m³	m³	m³	m³	m³	m³	m³		m³	m³	netto	cips
22,03	15,03	110,58	54,48	117,19	62,73	43,83	33,43	46,61	35,35	34,10	26,13		80,71	61,48	43,48	9
per dag	per dag	per dag	per dag	per dag	per dag	per dag	per dag	per dag	per dag	per dag	per dag		per dag	per dag		
3,1	2,1	3,9	1,9	4,7	2,5	2,4	1,9	2,7	2,1	2,6	2,0		2,7	2,0	1,4494	
per cycle	per cycle	per cycle	per cycle	per cycle	per cycle	per cycle	per cycle	per cycle	per cycle	per cycle	per cycle		per cycle	per cycle		
4,4	3,0	12,3	6,1	23,4	12,5	14,6	11,1	7,8	5,9	11,4	8,7		8,1	6,1		
				dagen	dagen	dagen	dagen	dagen	17	dagen	13		dagen	30		
				25	25	18	18	uren	304	uren	216		uren	522		
								net dage	12,667	net dage	9		net dage	21,75		
													netto permeaat productie			9 cips
													18			
													1,4494			
										17,4						

Table 7: Summary of the processed operational filtration unit data (2015).

Appendix III – Membrane characterization

1. cMF membrane retention behavior

1.1 PES 100

Experiment name			**PES 100 retention**											
Installation			RINEW - ceramic microfiltration											
Date			19 april 2016											
Researchers			Ractyte, J; Janse, B.J.											
Test #			**1 (I)**	**1 (II)**	**2 (I)**	**2 (II)**	**3**	**4**	**5 (I)**	**5 (II)**	**6 (I)**	**6 (II)**	**7 (I)**	**7 (II)**
Time			18:38	18:38	19:38	19:38	19:50	20:20	21:20	21:20	21:50	21:50	22:20	22:20
Proces alterations														
PES100 supplement		[mL]	0	0	0	0	1	0	0	0	0	0	0	0
pH ceramic filter		[]	6,06	6,06	6,09	6,09	6,07	6,08						
Measurements														
Sample time		[min]	*0*	*0*	*60*	*60*	-	*0*	*60*	*60*	*90*	*90*	*120*	*120*
Feed	Particles	[n/l]					-	-						
	Conc.	[mg/l]					-	-						
	pH	[]					-	-						
Cross	Particles	[n/l]					-	-						
	Conc.	[mg/l]					-	-						
	pH	[]					-	-						
Permeate	Particles	[n/l]					-	-						
	Conc.	[mg/l]					-	-						
	pH	[]					-	-						
Concentrate	Particles	[n/l]					-	-						
	Conc.	[mg/l]					-	-						
	pH	[]					-	-						
Plant data			**1 (I)**	**1 (II)**	**2 (I)**	**2 (II)**	**3**	**4**	**5 (I)**	**5 (II)**	**6 (I)**	**6 (II)**	**7 (I)**	**7 (II)**
Sample time		[min]	*0*	*0*	*60*	*60*	-	*0*	*60*	*60*	*90*	*90*	*120*	*120*
Supply flow	FQ1	[m³/h]	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9
Permetaat flow	FQ2	[m³/h]	0,45	0,45	0,45	0,45	0,45	0,45	0,45	0,45	0,45	0,45	0,45	0,45
Concentrate flow	FQ3	[m³/h]	0,45	0,45	0,45	0,45	0,45	0,45	0,45	0,45	0,45	0,45	0,45	0,45
Pres. after filter	pT-04	[bar]	1,51	1,51	1,5	1,5	1,5	1,5						
Pres. before filter	pT-05	[bar]	1,47	1,47	1,47	1,47	1,47	1,46						
Permetaat pres.	pT-06	[bar]	0,56	0,56	0,57	0,57	0,58	0,58						
Temp. Before filter	TT-01	[°C]	19,3	19,3	20,9	20,9	21,1	21,6						
Temp. CIP tank	TT-02	[°C]	18,4	18,4	20	20	20,2	20,7						
Level CIP tank	pT-09	[m]	0,5	0,5	0,48	0,48	0,46	0,46						
Feed pump	P-02	[Hz]	15	15	15	15	15	15	15	15	15	15	15	15
Cross-flow pump	P-07	[Hz]	20	20	20	20	20	20	20	20	20	20	20	20
pH ceramic filter	QIA-01	[pH]	6,06	6,06	6,09	6,09	6,07	6,08						
Notes														
(I); (II)	Duplo measurement indication													
1	Blanco demineralized water 0-min													
2	Blanco demineralized water 60-min													
3	Addition of 1 mL PES100													
4	After 30 min of mixing (0-min)													
5	PES200/demineralized water 60-min													
6	PES200/demineralized water 90-min													
7	PES200/demineralized water 120-min													

Table 8: Operational data during the PES 100 retention test (2016).

1.2 PES 200

Experiment name			**PES 200 retention**											
Installation			RINEW - ceramic microfiltration											
Date			19 april 2016											
Researchers			Ractyte, J; Janse, B.J.											
Test #			**1 (I)**	**1 (II)**	**2 (I)**	**2 (II)**	**3**	**4**	**5 (I)**	**5 (II)**	**6 (I)**	**6 (II)**	**7 (I)**	**7 (II)**
Time			13:04	13:04	14:04	14:04	14:16	14:46	15:46	15:46	16:16	16:16	16:46	16:46
Proces alterations														
PES200 supplement		[mL]	0	0	0	0	1	0	0	0	0	0	0	0
pH ceramic filter		[]	6,3	6,3	6,28	6,28	6,29	6,31	6,2	6,2	6,2	6,2	6,2	6,2
Measurements														
Sample time		[min]	*0*	*0*	*60*	*60*	-	*0*	*60*	*60*	*90*	*90*	*120*	*120*
Feed	Particles	[n/l]					-	-						
	Conc.	[mg/l]					-	-						
	pH	[]					-	-						
Cross	Particles	[n/l]					-	-						
	Conc.	[mg/l]					-	-						
	pH	[]					-	-						
Permeate	Particles	[n/l]					-	-						
	Conc.	[mg/l]					-	-						
	pH	[]					-	-						
Concentrate	Particles	[n/l]					-	-						
	Conc.	[mg/l]					-	-						
	pH	[]					-	-						
Plant data			**1 (I)**	**1 (II)**	**2 (I)**	**2 (II)**	**3**	**4**	**5 (I)**	**5 (II)**	**6 (I)**	**6 (II)**	**7 (I)**	**7 (II)**
Sample time		[min]	*0*	*0*	*60*	*60*	-	*0*	*60*	*60*	*90*	*90*	*120*	*120*
Supply flow	FQ1	[m³/h]	0,88	0,88	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9
Permetaat flow	FQ2	[m³/h]	0,44	0,44	0,45	0,45	0,45	0,45	0,45	0,45	0,45	0,45	0,45	0,45
Concentrate flow	FQ3	[m³/h]	0,44	0,44	0,45	0,45	0,45	0,45	0,45	0,45	0,45	0,45	0,45	0,45
Pres. after filter	pT-04	[bar]	1,51	1,51	1,51	1,51	1,5	1,5	1,49	1,49	1,49	1,49	1,49	1,49
Pres. before filter	pT-05	[bar]	1,48	1,48	1,48	1,48	1,47	1,47	1,46	1,46	1,46	1,46	1,45	1,45
Permetaat pres.	pT-06	[bar]	0,55	0,55	0,57	0,57	0,57	0,58	0,6	0,6	0,61	0,61	0,61	0,61
Temp. Before filter	TT-01	[°C]	17,1	17,1	19,1	19,1	19	20,6	22	22	22,8	22,8	23,4	23,4
Temp. CIP tank	TT-02	[°C]	16,3	16,3	18,1	18,1	18,7	19,7	21,1	21,1	21,7	21,7	22,4	22,4
Level CIP tank	pT-09	[m]	0,51	0,51	0,49	0,49	0,47	0,47	0,47	0,47	0,45	0,45	0,44	0,44
Feed pump	P-02	[Hz]	15	15	15	15	15	15	15	15	15	15	15	15
Cross-flow pump	P-07	[Hz]	20	20	20	20	20	20	20	20	20	20	20	20
pH ceramic filter	QIA-01	[pH]	6,3	6,3	6,28	6,28	6,29	6,31	6,2	6,2	6,2	6,2	6,2	6,2
Notes														
(I); (II)	Duplo measurement indication													
1	Blanco demineralized water 0-min													
2	Blanco demineralized water 60-min													
3	Addition of 1 mL PES200													
4	After 30 min of mixing (0-min)													
5	PES200/demineralized water 60-min													
6	PES200/demineralized water 90-min													
7	PES200/demineralized water 120-min													

Table 9: Operational data during the PES 200 retention test (2016).

1.3 Particle counter analysis

PES 100

0-min (Blanco) Perm I PES 100

	0.05	0.1	0.15	0.2
5-9-2016 14:46:04	4694	259	17	5
5-9-2016 14:47:04	5231	299	22	14
5-9-2016 14:48:04	6061	394	37	18
5-9-2016 14:49:04	4983	373	50	24
5-9-2016 14:50:04	2805	290	49	23
5-9-2016 14:51:04	2320	289	45	21
5-9-2016 14:52:04	1941	278	49	25
5-9-2016 14:53:04	2089	394	70	38
5-9-2016 14:54:04	1607	310	60	28
5-9-2016 14:55:04	1173	290	57	25

60-min Perm I PES 100

	0.05	0.1	0.15	0.2
5-9-2016 15:48:04	3301	391	50	25
5-9-2016 15:49:04	3468	446	74	33
5-9-2016 15:50:04	2897	473	97	49
5-9-2016 15:51:04	2110	418	98	38
5-9-2016 15:52:04	1394	347	61	27
5-9-2016 15:53:04	1324	371	80	36
5-9-2016 15:54:04	1258	398	83	33
5-9-2016 15:55:04	1495	474	103	50
5-9-2016 15:56:04	1230	408	83	36
5-9-2016 15:57:04	1314	404	93	46

120-min Perm I PES 100

	0.05	0.1	0.15	0.2
5-9-2016 14:23:04	18876	691	46	19
5-9-2016 14:24:04	15655	773	52	17
5-9-2016 14:25:04	10141	713	56	25
5-9-2016 14:26:04	6707	574	74	28
5-9-2016 14:27:04	5408	598	81	34
5-9-2016 14:28:04	5155	717	107	39
5-9-2016 14:29:04	3619	597	98	39
5-9-2016 14:30:04	3056	523	85	39
5-9-2016 14:31:04	2907	607	100	41
5-9-2016 14:32:04	4080	804	114	57

120-min Conc I PES 100

	0.05	0.1	0.15	0.2
5-9-2016 13:59:04	692760	49641	1343	501
5-9-2016 14:00:04	575686	34081	1005	411
5-9-2016 14:01:04	561159	31336	896	359
5-9-2016 14:02:04	633060	37252	1147	474
5-9-2016 14:03:04	710705	50651	1476	542
5-9-2016 14:04:04	733235	49114	1389	544
5-9-2016 14:05:04	797719	74476	1680	650
5-9-2016 14:06:04	689598	52668	1354	530
5-9-2016 14:07:04	728735	62613	1484	579
5-9-2016 14:08:04	615701	40649	1071	398

0-min (Blanco) Conc I PES 100

	0.05	0.1	0.15	0.2
5-9-2016 15:22:04	5425	2771	496	205
5-9-2016 15:23:04	6550	3224	608	229
5-9-2016 15:24:04	4585	2311	410	163
5-9-2016 15:25:04	5291	2640	543	217
5-9-2016 15:26:04	6422	3066	575	243
5-9-2016 15:27:04	6502	3122	608	247
5-9-2016 15:28:04	8392	3958	834	337
5-9-2016 15:29:04	7639	3588	693	285
5-9-2016 15:30:04	6497	3184	600	217
5-9-2016 15:31:04	4325	2087	383	146

60-min Conc I PES 100

	0.05	0.1	0.15	0.2
5-9-2016 16:13:04	662072	47492	1103	435
5-9-2016 16:14:04	774305	71744	1466	515
5-9-2016 16:15:04	693092	54701	1138	407
5-9-2016 16:16:04	676983	52563	1185	439
5-9-2016 16:17:04	797083	72537	1657	595
5-9-2016 16:18:04	716931	60837	1281	467
5-9-2016 16:19:04	843883	89372	1754	684
5-9-2016 16:20:04	711610	56155	1288	476
5-9-2016 16:21:04	721297	57485	1360	496
5-9-2016 16:22:04	755842	62135	1365	459

120-min Perm II PES 100

	0.05	0.1	0.15	0.2
5-9-2016 16:59:04	19642	699	55	20
5-9-2016 17:00:04	19736	1103	79	35
5-9-2016 17:01:04	14798	893	113	50
5-9-2016 17:02:04	11041	850	123	43
5-9-2016 17:03:04	6363	629	101	41
5-9-2016 17:04:04	5780	709	100	35
5-9-2016 17:05:04	5589	720	111	42
5-9-2016 17:06:04	5324	797	139	62
5-9-2016 17:07:04	4199	689	92	34
5-9-2016 17:08:04	6086	970	142	67

120-min Conc II PES 100

	0.05	0.1	0.15	0.2
5-9-2016 16:38:04	518751	22204	771	307
5-9-2016 16:39:04	549807	23096	813	313
5-9-2016 16:40:04	550650	22303	846	340
5-9-2016 16:41:04	568025	24551	919	330
5-9-2016 16:42:04	582029	24982	889	318
5-9-2016 16:43:04	584898	25714	918	361
5-9-2016 16:44:04	585119	25206	939	371
5-9-2016 16:45:04	685713	48767	1238	489
5-9-2016 16:46:04	610268	32056	988	361
5-9-2016 16:47:04	587714	29136	920	347

PES 200

0-min (Blanco) CIP I PES 200

	0.05	0.1	0.15	0.2
5-9-2016 10:07:04	1663	611	138	67
5-9-2016 10:08:04	1378	531	120	43
5-9-2016 10:09:04	1273	461	120	68
5-9-2016 10:10:04	1641	539	122	55
5-9-2016 10:11:04	1391	469	113	47
5-9-2016 10:12:04	1422	519	114	48
5-9-2016 10:13:04	1348	477	108	62
5-9-2016 10:14:04	1572	599	125	60
5-9-2016 10:15:04	1374	519	119	56
5-9-2016 10:16:04	1298	515	138	74

0-min (Blanco) Perm I PES 200

	0.05	0.1	0.15	0.2
5-9-2016 12:30:04	679	333	50	15
5-9-2016 12:31:04	652	295	44	14
5-9-2016 12:32:04	898	386	71	28
5-9-2016 12:33:04	569	275	47	21
5-9-2016 12:34:04	613	277	51	30
5-9-2016 12:35:04	596	284	61	29
5-9-2016 12:36:04	565	261	58	28
5-9-2016 12:37:04	569	269	55	21
5-9-2016 12:38:04	589	283	64	34
5-9-2016 12:39:04	636	303	78	35

120-min Perm I PES 200

	0.05	0.1	0.15	0.2
5-9-2016 11:41:04	944	544	46	12
5-9-2016 11:42:04	1148	620	71	15
5-9-2016 11:43:04	1158	621	42	9
5-9-2016 11:44:04	1293	589	81	15
5-9-2016 11:45:04	1200	555	64	18
5-9-2016 11:46:04	1067	455	54	15
5-9-2016 11:47:04	1063	433	58	20
5-9-2016 11:48:04	818	326	41	18
5-9-2016 11:49:04	800	309	52	26
5-9-2016 11:50:04	1149	393	62	27

120-min Conc I PES 200

	0.05	0.1	0.15	0.2
5-9-2016 10:52:04	169920	103419	11619	1740
5-9-2016 10:53:04	181663	113985	9920	1525
5-9-2016 10:54:04	221532	140157	18213	2857
5-9-2016 10:55:04	209405	135921	11992	1618
5-9-2016 10:56:04	202423	131948	10659	1373
5-9-2016 10:57:04	224418	148126	13696	1798
5-9-2016 10:58:04	201637	129124	15135	2335
5-9-2016 10:59:04	202575	127332	14150	2086
5-9-2016 11:00:04	193346	122051	11716	1751
5-9-2016 11:01:04	214789	142688	11697	1554

0-min (Blanco) Perm II PES 200

	0.05	0.1	0.15	0.2
5-9-2016 13:06:04	571	257	65	42
5-9-2016 13:07:04	651	312	105	61
5-9-2016 13:08:04	759	328	112	69
5-9-2016 13:09:04	743	359	116	59
5-9-2016 13:10:04	661	314	94	38
5-9-2016 13:11:04	650	304	77	43
5-9-2016 13:12:04	629	301	84	51
5-9-2016 13:13:04	643	299	91	45
5-9-2016 13:14:04	674	335	97	46
5-9-2016 13:15:04	574	288	86	53

120-min Perm II PES 200

	0.05	0.1	0.15	0.2
5-9-2016 12:06:04	1333	634	75	26
5-9-2016 12:07:04	1294	559	76	28
5-9-2016 12:08:04	1401	557	92	38
5-9-2016 12:09:04	1158	431	84	34
5-9-2016 12:10:04	1276	407	71	31
5-9-2016 12:11:04	1270	435	77	35
5-9-2016 12:12:04	1079	383	60	37
5-9-2016 12:13:04	1038	349	66	42
5-9-2016 12:14:04	958	328	54	23
5-9-2016 12:15:04	893	286	54	26

120-min Conc II PES 200

	0.05	0.1	0.15	0.2
5-9-2016 11:17:04	182962	113700	10430	1404
5-9-2016 11:18:04	203920	131136	10925	1248
5-9-2016 11:19:04	204560	133385	10311	1112
5-9-2016 11:20:04	212909	138722	12612	1610
5-9-2016 11:21:04	222158	144420	12245	1475
5-9-2016 11:22:04	225361	145841	14629	2043
5-9-2016 11:23:04	215201	140707	10737	1238
5-9-2016 11:24:04	220318	146584	10669	1058
5-9-2016 11:25:04	225378	148528	14263	1780
5-9-2016 11:26:04	253263	168819	19501	2943

Table 10: Raw data particle counter analysis (2016).

PES 100

0-min (Blanco) Perm I PES 100				
	0.05	0.1	0.15	0.2
Avg.	3290	318	46	22
St. dev.	1765	50	16	9

0-min (Blanco) Conc I PES 100				
	0.05	0.1	0.15	0.2
Avg.	6163	2995	575	229
St. dev.	1281	563	131	55

	0.05	0.1	0.15	0.2
Retention	65,19274	90,41265	92,65227	91,19522

60-min Perm I PES 100				
	0.05	0.1	0.15	0.2
Avg.	1979	413	82	37
St. dev.	904	41	17	9

60-min Conc I PES 100				
	0.05	0.1	0.15	0.2
Avg.	735310	62502	1360	497
St. dev.	56950	12299	214	84

	0.05	0.1	0.15	0.2
Retention	99,73157	99,34356	94,29919	93,02282

120-min Perm I PES 100				
	0.05	0.1	0.15	0.2
Avg.	7560	660	81	34
St. dev.	5587	93	24	12

120-min Perm II PES 100				
	0.05	0.1	0.15	0.2
Avg.	9856	806	106	43
St. dev.	6083	148	27	14

120-min Perm PES 100				
	0.05	0.1	0.15	0.2
Avg.	8708	733	93	38
St. dev.	5835	120	25	13

120-min Conc I PES 100				
	0.05	0.1	0.15	0.2
Avg.	673836	48248	1285	499
St. dev.	75445	13282	246	90

120-min Conc II PES 100				
	0.05	0.1	0.15	0.2
Avg.	582297	27802	924	354
St. dev.	44498	7977	127	52

120-min Conc PES 100				
	0.05	0.1	0.15	0.2
Avg.	628067	38025	1104	426
St. dev.	59971	10630	187	71

	0.05	0,10	0,15	0,20	0,1
Retention	98,63247	98,10927	92,20172	91,74559	94,018861
	0.05	0,10	0,15	0,20	0,1
Retention	98,63247	98,10927	92,20172	91,74559	95,172262

PES 200

0-min (Blanco) CIP I PES 200				
	0.05	0.1	0.15	0.2
Avg.	1436	524	122	58
St. dev.	139	50	10	10

0-min (Blanco) Perm I PES 200				
	0.05	0.1	0.15	0.2
Avg.	637	297	58	26
St. dev.	100	37	11	7

0-min (Blanco) Perm II PES 200				
	0.05	0.1	0.15	0.2
Avg.	656	310	93	51
St. dev.	61	28	16	10

0-min (Blanco) Perm PES 200				
	0.05	0.1	0.15	0.2
Avg.	646	303	75	38
St. dev.	80	33	13	9

	0.05	0.1	0.15	0.2
Retention	90,51161	90,80876	88,42073	85,73034

120-min Perm I PES 200				
	0.05	0.1	0.15	0.2
Avg.	1064	485	57	18
St. dev.	163	117	13	6

120-min Perm II PES 200				
	0.05	0.1	0.15	0.2
Avg.	1170	437	71	32
St. dev.	171	113	13	6

120-min Perm PES 200				
	0.05	0.1	0.15	0.2
Avg.	1117	461	64	25
St. dev.	167	115	13	6

120-min Conc I PES 200				
	0.05	0.1	0.15	0.2
Avg.	202171	129475	12880	1864
St. dev.	17063	13593	2464	447

120-min Conc II PES 200				
	0.05	0.1	0.15	0.2
Avg.	216603	141184	12632	1591
St. dev.	18244	14152	2879	565

120-min Conc PES 200				
	0.05	0.1	0.15	0.2
Avg.	209387	135330	12756	1727
St. dev.	17654	13872	2671	506

	0.05	0,10	0,15	0,20	0,2
Retention	99,46937	99,66073	99,50078	98,58745	99,249652
	0.05	0,10	0,15	0,20	0,2
Retention	99,46937	99,66073	99,50078	98,58745	99,304581

Table 11: Processed data particle counter analysis (2016).

2. cNF membrane retention behavior

2.1 K_3PO_4

Experiment name	K3PO4 retention
Installation	RINEW - ceramic nanofiltration
Date	9 maart 2016
Researchers	Ractyte, J; Janse, B.J.

Test #			0			1		2		3		4	
Time			10:28	10:43	10:58	11:12	11:42	12:12	12:42	13:31	14:01	14:33	15:03
Proces alterations													
K3PO4 supplement		[g]	5			0		0		0		0	
HCl supplement		[ml]	0			30		75		150		75	
pH ceramic filter		[]	6,7			6,1		5,0		3,6		2,9	
Measurements													
Sample time		[min]	*0*	*15*	*30*	*15*	*30*	*15*	*30*	*15*	*30*	*15*	*30*
Feed	PO4	[mg/L]	5,51	5,16	5,07	4,80	5,32	5,41	5,53	5,66	5,51	5,45	5,20
	pH	[]	6,77	6,86	6,86	6,19	6,31	4,99	5,31	3,55	3,56	2,81	2,85
Cross-flow	PO4	[mg/L]	6,19	5,48	5,39	5,18	5,57	5,75	5,72	5,73	5,71	5,66	5,38
	pH	[]	6,86	6,80	6,85	6,29	6,31	5,11	5,30	3,54	3,54	2,85	2,85
Permeate	PO4	[mg/L]	4,14	4,60	4,78	4,74	4,92	5,80	5,11	5,43	5,38	5,41	5,13
	pH	[]	6,85	6,85	6,74	6,68	6,30	5,81	5,31	3,61	3,58	3,03	2,86
Concentrate	PO4	[mg/L]	6,13	5,63	5,43	5,47	5,63	5,57	5,84	5,81	5,72	5,85	5,30
	pH	[]	6,86	6,90	6,86	6,30	6,36	5,17	5,33	3,54	3,54	2,85	2,85
Average	PO4	[mg/L]	5,49	5,22	5,17	5,05	5,36	5,63	5,55	5,66	5,58	5,59	5,25
	pH	[]	6,84	6,85	6,83	6,37	6,32	5,27	5,31	3,56	3,56	2,89	2,85
Plant data													
Level CIP tank	pT-9	[m]	0,8	0,79	0,79	0,78	0,77	0,75	0,76	0,76	0,75	0,74	0,74
Temp. CIP tank	TT-02	[°C]	14,8	15,1	15,3	15,6	16,2	16,6	17,3	17,7	18,2	18,6	18,8
Feed pump	P-02	[Hz]	17	17	17	17	17	17	17	17	17	17	17
Cross-flow pump	P-07	[Hz]	22	22	22	22	22	22	22	22	22	22	22
Concentrate valve	V-217	[]	41	41	41	41	41	41	41	41	41	41	41
Temp. Before filter	TT-01	[°C]	16	16,4	16,6	16,9	17,4	17,9	18,4	19	19,5	19,9	20,1
Pres. after filter	pT-04	[bar]	1,95	1,95	1,95	1,94	1,94	1,94	1,94	1,94	1,94	1,94	1,94
Pres. before filter	pT-05	[bar]	2,03	2,02	2,02	2,02	2,02	2,02	2,01	2,01	2,01	2,01	2,01
Permetaat pres.	pT-06	[bar]	0,37	0,37	0,38	0,39	0,4	0,43	0,44	0,5	0,5	0,53	0,53
Suply flow	FQ1	[m³/h]	0,5	0,51	0,51	0,51	0,53	0,53	0,55	0,56	0,56	0,57	0,57
Permetaat flow	FQ2	[m³/h]	0,28	0,28	0,28	0,28	0,3	0,28	0,28	0,28	0,29	0,3	0,29
Concentrate flow	FQ3	[m³/h]	0,26	0,26	0,26	0,26	0,26	0,26	0,26	0,26	0,26	0,26	0,26
pH CIP tank	T-01	[]	6,8	6,83	6,8	5,95	6,33	4,68	5,14	3,51	3,49	2,77	2,85
pH before membrane	QIA-01	[]	6,65	6,64	6,64	6,12	6,12	5,01	5,2	3,66	3,69	3,08	3,05

Notes	
11:01 II HCl	16612 -> 16556 -> pH 5,95 (at 11:11, 16607) = 5g HCl supplement
11:53 III HCl	16584 -> 16483 -> pH 4,68 (at 12:12, 16550) = 34g HCl supplement
12:59 IV HCl	16550 -> 16455 -> pH 3,51 (at 13:26, 16483) = 67g HCl supplement
14:07 V HCl	16500 -> 16421 -> pH 3,00 (at 14:15, 16449) = 51g HCl supplement
14:16 V HCl	16449 -> 16404 -> pH 2,90 (at 14:23, 16434) = 15g HCl supplement
14:24 V HCl	16434 -> 16376 -> pH 2,77 (at 14:33, 16370) = 64g HCl supplement (51 + 15 + 64 = 130g HCl supplement)

K3PO4 retention

09-03-2016

Data pick-up						
Measurement graph pH						
test #	0	1	2	3	4	Culum
Titel	Run 0 pH 6,7	Run 1 pH 6,1	Run 2 pH 5	Run 3 pH 3,6	Run 4 pH 2,9	
pH	6,70	6,10	5,00	3,60	2,90	
0	6,84					11
15	6,85	6,37	5,27	3,56	2,89	
30	6,83	6,32	5,31	3,56	2,85	
Measurement graph PO4						
test #	0	1	2	3	4	Culum
0	5,49					
15	5,22	5,05	5,63	5,66	5,59	10
30	5,17	5,36	5,55	5,58	5,25	
PO4 levels permeaat						
test #	0	1	2	3	4	Culum
0	4,14					
15	4,60	4,74	5,80	5,43	5,41	7
30	4,78	4,92	5,11	5,38	5,13	
Ava.	4,51	4,83	5,46	5,41	5,27	
PO4 levels feed						
test #	0	1	2	3	4	Culum
0	5,51					
15	5,16	4,80	5,41	5,66	5,45	3
30	5,07	5,32	5,53	5,51	5,20	
Ava.	5,25	5,06	5,47	5,59	5,33	
PO4 levels crossflow						
test #	0	1	2	3	4	Culum
0	6,19					
15	5,48	5,18	5,75	5,73	5,66	5
30	5,39	5,57	5,72	5,71	5,38	
Ava.	5,69	5,38	5,74	5,72	5,52	

Retention calculation					
PO4 retention related to feed [%]					
test #	*0*	*1*	*2*	*3*	*4*
Titel	Run 0 pH 6,7	Run 1 pH 6,1	Run 2 pH 5	Run 3 pH 3,6	Run 4 pH 2,9
pH	6,7	6,1	5,0	3,6	2,9
0	24,86	#DEEL/0!	#DEEL/0!	#DEEL/0!	#DEEL/0!
15	10,85	1,25	-7,21	4,06	0,73
30	5,72	7,52	7,59	2,36	1,35
Ava.	13,81	4,38	0,19	3,21	1,04
PO4 retention related to cross-flow [%]					
test #	*0*	*1*	*2*	*3*	*4*
0	33,12	#DEEL/0!	#DEEL/0!	#DEEL/0!	#DEEL/0!
15	16,06	8,49	-0,87	5,24	4,42
30	11,32	11,67	10,66	5,78	4,65
Ava.	20,16	10,08	4,90	5,51	4,53
First experiment (sept. '14)					
test #	*0*	*1*	*2*	*3*	*4*
pH	7,19	6,69	5,97	5,35	4,63
Ava.	94,72	45,33	12,48	8,58	4,92
test #	*5*	*6*	*7*	*8*	
pH	4,26	3,74	3,49	3,26	
Ava.	2,63	4,25	7,77	8,75	
Second experiment (sept. '15)					
test #	*0*	*1*	*2*	*3*	*4*
pH	8,50	7,20	6,50	5,10	3,30
Ava.	55,54	5,06	4,86	3,35	1,32

PO4 retention related to feed (2016) [%]					
pH	6,7	6,1	5,0	3,6	2,9
St. dev	9,909168881	4,432708863	10,46787385	1,205092104	0,432897059

Table 12: Processed data phosphate retention tests (2014-2016).

2.2 PEG 400

Experiment name			**PEG 400 retention**										
Installation			RINEW - ceramic nanofiltration										
Date			29 oktober 2015										
Researchers			Ractyte, J; Hoek, T										
Test #			**0**	**1**				**2**		**3**		**4**	
Time			12:00	12:30	12:45	13:00	13:15	14:00	14:20	15:30	15:50	16:30	16:55
Proces alterations													
HCl supplement		[gr]	0	0				80		100		200	
pH ceramic filter		[]	7,47	7,47				6,33		4,17		2,74	
Measurements													
Sample time		[min]	0	*0*	*15*	*30*	*45*	*0*	*30*	*0*	*30*	*0*	*30*
Feed	COD	[mgO/l]	1166	663	667	661	663	668	655	652	648	650	644
	Conc.	[mg/l]	1113	630	634	628	630	635	623	620	616	618	612
	pH	[]	7,17	7,71	7,72	7,7	7,71	6,77	6,75	4,31	4,31	2,63	2,62
Cross-flow	Conc.	[mgO/l]		757	753	736	736	737	721	705	697	686	678
	Conc.	[mg/l]		720	717	700	700	701	686	671	663	652	645
	pH	[]		7,75	7,68	7,69	7,72	6,71	6,74	4,30	4,42	2,65	2,64
Permeate	Conc.	[mgO/l]		536	559	556	565	565	564	602	594	610	605
	Conc.	[mg/l]		508	530	528	536	536	535	572	564	579	575
	pH	[]		7,74	7,71	7,71	7,76	6,84	6,75	4,67	4,34	2,63	2,63
Concentrate	Conc.	[mgO/l]		757	752	741	741	728	724	702	697	688	688
	Conc.	[mg/l]		720	716	705	705	693	689	668	663	654	654
	pH	[]		7,81	7,71	7,67	7,75	6,76	6,70	4,22	4,37	2,63	2,67
Plant data													
Suply flow	FQ1	[m^3/h]	0,5					0,55		0,58		0,57	
Permetaat flow	FQ2	[m^3/h]	0,24					0,25		0,25		0,26	
Concentrate flow	FQ3	[m^3/h]	0,3					0,3		0,3		0,3	
Pres. after filter	pT-04	[bar]	1,56					1,56		1,56		1,54	
Pres. before filter	pT-05	[bar]	1,59					1,57		1,55		1,56	
Permeataat pres.	pT-06	[bar]	0,45					0,5		0,62		0,65	
Temp. Before filter	TT-01	[°C]	15,6					18,6		20,6		21,5	
Feed pump	P-02	[Hz]	15										
Cross-flow pump	P-07	[Hz]	20										

PEG 400 test

29-10-2015

Data pick-up PEG 400					
test #	1	2	3	4	Row
Titel	Run 1 - pH 7	Run 2 - pH 6,2	Run 3 - pH 4,2	Run 4 - pH 3,2	
pH	**7,7**	**6,8**	**4,4**	**2,6**	
Dye concentration feed [mg/l]					
test #	1	2	3	4	Row
0	630	635	620	618	
15	634				
30	628	623	616	612	3
45	630				
Ava.	631	629	618	615	
Dye concentration crossflow [mg/l]					
test #	1	2	3	4	Culum
0	720	701	671	652	
15	717				
30	700	686	663	645	6
45	700				
Ava.	709	694	667	649	
Dye concentration concentrate [mg/l]					
test #	1	2	3	4	Culum
0	720	693	668	654	
15	716				
30	705	689	663	654	12
45	705				
Ava.	712	691	666	654	
Dye concentration permeate [mg/l]					
test #	1	2	3	4	Culum
0	508	536	572	579	
15	530				
30	528	535	564	575	9
45	536				
Ava.	526	536	568	577	

Retention calculation PEG 400				
PEG 400 retention related to feed [%]				
test #	*1*	*2*	*3*	*4*
Titel	Run 1 - pH 7	Run 2 - pH 6,2	Run 3 - pH 4,2	Run 4 - pH 3,2
pH	7,7	6,8	4,4	2,6
0	19,37	15,59	7,74	6,31
15	16,40			
30	15,92	14,13	8,44	6,05
45	14,92			
Ava.	17,23	14,86	8,09	6,18
St. Div.	1,86	1,04	0,49	0,19
PEG 400 retention related to cross-flow [%]				
test #	*1*	*2*	*3*	*4*
0	29,44	23,54	14,75	11,20
15	26,08			
30	24,57	22,01	14,93	10,85
45	23,43			
Ava.	26,70	22,77	14,84	11,02
St. Dev.	2,49	1,08	0,13	0,24
First experiment (sept. '14)				
test #	*1*	*2*	*3*	*4*
pH	**8,093**	**8,11**	**8,12**	**8,12**
Old ava.	83,28	86,49	86,64	86,01
New ava.	16,72	13,51	13,36	13,99
test #	*5*	*6*	*7*	*8*
pH	**8,14**	**4,334**	**3,417**	**3,063**
Old ava.	87,53	87,45	88,29	83,06
New ava.	12,47	11,15	10,48	14,46
test #	*9*	*10*	*11*	*12*
pH	**3,9**	**4,067**	**4,14**	
Old ava.	86,60	88,54	89,40	
New ava.	13,40	11,46	10,60	

Table 13: Processed data PEG 400 retention tests (2014-2015).

2.3 PEG 600

Experiment name			PEG 600 retention										
Installation			RINEW - ceramic nanofiltration										
Date			1 maart 2016										
Researchers			Ractyte, J; Janse, B.J.										
Test #			0		1		2		3		4		5
Time			11:30	12:05	12:25	12:40	13:10	13:40	14:20	14:50	16:00	16:30	
Proces alterations													
HCl supplement		[gr]	0	0	0	0	124	0	62	0	57	0	0
pH ceramic filter		[]	7,79				6,4	6,3	14:20	16:00	2,91	3,14	
Measurements													
Sample time		[min]	0	*15*	*30*	*45*	*0*	*30*	0	30	0	30	0
Feed	COD	[mgO/l]	1458	796	687	700	662	663	657	703	673	730	
	Conc.	[mg/l]											
	pH	[]	7,85	7,89	7,92	7,80	6,70	6,51	3,77	5,45	3,05	3,18	
Cross-flow	COD	[mgO/l]	459	770	785	795	758	766	761	785	758	808	
	Conc.	[mg/l]											
	pH	[]	7,89	7,87	7,86	7,85	6,65	6,50	5,23	5,28	3,26	3,15	
Permeate	COD	[mgO/l]	0	247	479	547	554	545	566	588	590	634	
	Conc.	[mg/l]											
	pH	[]	7,83	7,73	7,92	7,88	6,77	6,50	6,1	5,56	4,68	3,26	
Concentrate	COD	[mgO/l]	351	781	786	794	762	783	758	784	757	821	
	Conc.	[mg/l]											
	pH	[]	7,91	7,88	7,90	7,84	6,57	6,50	5,23	5,24	3,28	3,18	
Plant data													
Suply flow	FQ1	[m³/h]	0,3	0,3	0,3	0,31	0,31	0,32	0,33	0,32	0,33	0,33	
Permetaat flow	FQ2	[m³/h]	0,15	0,16	0,17	0,16	0,18	0,17	0,17	0,17	0,18	0,17	
Concentrate flow	FQ3	[m³/h]	0,16	0,16	0,162	0,162	0,162	0,161	0,161	0,161	0,161	0,161	
Pres. after filter	pT-04	[bar]	1,58	1,53	1,53	1,53	1,56	1,56	1,52	1,53	1,52	1,52	
Pres. before filter	pT-05	[bar]	1,55	1,55	1,56	1,56	1,53	1,53	1,55	1,55	1,55	1,55	
Permetaat pres.	pT-06	[bar]	0,5	0,57	0,59	0,6	0,62	0,62	0,65	0,64	0,67	0,67	
Temp. Before filter	TT-01	[°C]	9,1	14,1	15,8	16,2	16,6	16,8	17	17,1	17,2	17,4	
Level CIP tank		[m]											
Feed pump	P-02	[Hz]	15	15	15	15	15	15	15	15	15	15	
Cross-flow pump	P-07	[Hz]	20	20	20	20	20	20	20	20	20	20	
pH CIP tank	T-01	[pH]	7,79				6,4	6,3	14:20	16:00	2,91	3,14	

Notes	
1. II 13:00 HCl	13899 -> 13775 + NaOH (II = 124 gr) (possibly 13899 - 13628 = 271 gr)
2. III 14:00 HCl	13628 -> 13566 + NaOH (III = 62 gr) (possibly 13628 - 13505 = 123 gr)
3. IV 15:14 HCl	13505 -> 13448 (IV = 57 gr) -> look back in system measurement files for later HCl tank weight
I Feed	Conc. Over range -> 1 ml demi + 1 ml sample -> 729 mg/l = 1458 mg/l
I Permeate	Conc. Under range -> LCK 414 -> Conc. Under range = 0 mg/l

PEG 600 test

07-03-2016

Data pick-up PEG 600					
test #	1	2	3	4	Row
Titel	Run 1 - pH 7,79	Run 2 - pH 6,3	Run 3 - pH 5,1	Run 4 - pH 3,0	
pH	**7,8**	**6,4**	5,1	**3,0**	
PEG 600 concentration feed [mg/l]					
test #	1	2	3	4	Row
15	796	662	657	673	3
30	687	663	703	730	
45	700				
Ava.	728	663	680	702	
PEG 600 concentration crossflow [mg/l]					
test #	1	2	3	4	Culum
15	770	758	761	758	6
30	785	766	785	808	
45	795				
Ava.	783	762	773	783	
PEG 600 concentration concentrate [mg/l]					
test #	1	2	3	4	Culum
15	781	762	758	757	12
30	786	783	784	821	
45	794				
Ava.	787	773	771	789	
PEG 600 concentration permeate [mg/l]					
test #	1	2	3	4	Culum
15	247	554	566	590	9
30	479	545	588	634	
45	547				
Ava.	424	550	577	612	

Retention calculation PEG 600				
PEG 600 retention related to feed [%]				
test #	*1*	*2*	*3*	*4*
Titel	Run 1 - pH 7,79	Run 2 - pH 6,3	Run 3 - pH 5,1	Run 4 - pH 3,0
pH	7,8	6,4	5,1	3,0
15		16,31	13,85	12,33
30	30,28	17,80	16,36	13,15
45	21,86			
Ava.	26,07	17,06	15,10	12,74
St. Div.	5,95	1,05	1,77	0,58
PEG 600 retention related to cross-flow [%]				
test #	*1*	*2*	*3*	*4*
15		26,91	25,62	22,16
30	38,98	28,85	25,10	21,53
45	31,19			
Ava.	35,09	27,88	25,36	21,85
St. Dev.	5,51	1,37	0,37	0,44
First experiment (sept. '14)				
test #	*1*	*2*	*3*	*4*
pH	8,2	8,2	8,1	8,1
Old ava.	96,59	95,52	95,38	95,83
New. Ava.	3,41	4,48	4,62	4,17
test #	*5*	*6*	*7*	*8*
pH	8,1	3,2	3,5	3,6
Old ava.	93,58	95,40	94,04	92,72
New. Ava.	6,42	4,60	5,96	7,28
test #	*9*	*10*	*11*	*12*
pH	3,6			
Old ava.	94,95			
New. Ava.	5,05			
pH	Retention			
8,2	96,06	0,76		
8,1	94,93	1,19		
3,5	94,28	1,18		

29-10-2016

PEG 600 retention related to feed [%]				
test #	1	2	3	4
Titel	Run 1 - pH	Run 2 - pH	Run 3 - pH	Run 4 - pH 3,0
pH	7,4	6,3	5,1	3
15	32,63359	26,77903	17,62295	15,33865
30	30,45977	24,23077	20,27833	12,60331
45	28,84615			
Ava.	30,6465	25,5049	18,95064	13,97098
St. Div.	1,900609	1,80189	1,877637	1,934177
PEG 400 retention related to cross-flow [%]				
test #	1	2	3	4
15	45,01558	37,23917	28,97527	23,14647
30	42,74448	37,95276	30,26087	22,95082
45	41,26984			
Ava.	43,00997	37,59596	29,61807	23,04865
St. Dev.	1,886927	0,504585	0,90906	0,138348

7,4	6,3	5,1	3
30,646504	25,5049	18,95064	13,97098
26,066854	17,05604	15,10465	12,74176
28,356679	21,28047	17,02765	13,35637
3,24	5,97	2,72	0,87

Table 14: Processed data PEG 600 retention tests (2014-2016).

2.4 PEG 1000

Experiment name			PEG 1000 retention									
Installation			RINEW - ceramic nanofiltration									
Date			3 maart 2016									
Researchers			Ractyte, J; Janse, B.J.									
Test #			0	1			2		3		4	5
Time			10:55	11:10	11:25	11:42	12:10	12:42	13:48	14:18	14:56	15:26	
Proces alterations												
HCl supplement		[gr]	0	0	0	0	110	0	185	0	119	0	0
pH ceramic filter		[]					6,47	6,47	4,67	4,81	3,25	3,27	
Measurements													
Sample time		[min]	0	*15*	*30*	*45*	*0*	*30*	0	30	0	30	0
Feed	COD	[mgO/l]	726	624	620	680	667	631	824	673	692	675	
	Conc.	[mg/l]											
	pH	[]	7,46	7,49	7,53	7,48	6,52	6,69	4,53	4,92	3,15	3,16	
Cross-flow	COD	[mgO/l]	855	866	844	865	841	853	902	862	864	885	
	Conc.	[mg/l]											
	pH	[]	7,48	7,52	7,54	7,54	6,65	6,68	4,73	4,89	3,15	3,17	
Permeate	COD	[mgO/l]	203	326	369	414	448	407	627	449	508	504	
	Conc.	[mg/l]											
	pH	[]	7,49	7,45	7,55	7,52	7,02	6,72	5,56	5,01	3,26	3,17	
Concentrate	COD	[mgO/l]	848	859	843	862	877	843	878	870	868	889	
	Conc.	[mg/l]											
	pH	[]	7,51	7,53	7,55	7,84	6,75	6,69	4,79	4,89	3,15	3,15	
Plant data			I				II		III		IV		
			0	*15*	*30*	*45*	*0*	*30*	0	30	0	30	0
Suply flow	FQ1	[m^3/h]	0,33	0,33	0,33	0,33	0,33	0,35	0,36	0,35	0,36	0,36	
Permetaat flow	FQ2	[m^3/h]	0,17	0,18	0,17	0,17	0,17	0,17	0,19	0,2	0,19	0,19	
Concentrate flow	FQ3	[m^3/h]	0,163	0,163	0,162	0,162	0,162	0,162	0,162	0,163	0,163	0,165	
Pres. after filter	pT-04	[bar]	1,55	1,55	1,54	1,55	1,55	1,54	1,54	1,53	1,53	1,53	
Pres. before filter	pT-05	[bar]	1,59	1,58	1,58	1,58	1,58	1,57	1,57	1,57	1,56	1,56	
Permetaat pres.	pT-06	[bar]	0,51	0,52	0,52	0,53	0,54	0,55	0,6	0,6	0,64	0,64	
Temp. Before filter	TT-01	[°C]	15,7	16,2	16,5	16,8	17,4	18,1	19,3	19,7	20,3	20,7	
Level CIP tank		[m]	0,8	0,79	0,79	0,78	0,78	0,77	0,76	0,76	0,76	0,75	
Feed pump	P-02	[Hz]	15	15	15	15	15	15	15	15	15	15	
Cross-flow pump	P-07	[Hz]	20	20	20	20	20	20	20	20	20	20	
pH CIP tank	T-01	[pH]	7,43	7,38	7,42	7,4	6,4	6,59	4,38	4,84	3,1	3,13	
pH ceramic filter	QIA-01	[pH]					6,47	6,47	4,67	4,81	3,25	3,27	

Notes	
1. II HCl 11:47	10890 - 10830
2. II HCl 11:58	10830 - 10780 (II = 110 gr) (possibly 10890 - 10796 = 94 gr)
3. III HCl 12:49	10796 - 10684 -> pH 5,45
4. III HCl 12:58	10723 - 10644 -> pH 5,21 (10695)
5. III HCl 13:24	10701 - 10611 -> pH 4,38 (10656) (III = 185 gr) (possibly 10796 - 10656 = 140 gr)
6. IV HCl 14:22	10656 - 10554 -> pH 2,94 (10588)
7. IV HCl 14:30	10588 - 10537 (IV = 119 gr) -> look back in system measurement files for later HCl tank weight

PEG 1000 test

07-03-2016

Data pick-up PEG 1000					
test #	1	2	3	4	Row
Titel	Run 1 - pH 7,4	Run 2 - pH 6,5	Run 3 - pH 4,7	Run 4 - pH 3,3	
pH	**7,4**	**6,5**	**4,7**	**3,3**	
PEG 1000 concentration feed [mg/l]					
test #	1	2	3	4	Row
15	624	667	824	692	3
30	620	631	673	675	
45	680				
Ava.	641	649	749	684	
PEG 1000 concentration crossflow [mg/l]					
test #	1	2	3	4	Culum
15	866	841	902	864	6
30	844	853	862	885	
45	865				
Ava.	858	847	882	875	
PEG 1000 concentration concentrate [mg/l]					
test #	1	2	3	4	Culum
15	859	877	878	868	12
30	843	843	870	889	
45	862				
Ava.	855	860	874	879	
PEG 1000 concentration permeate [mg/l]					
test #	1	2	3	4	Culum
15	326	448	627	508	9
30	369	407	449	504	
45	414				
Ava.	370	428	538	506	

Retention calculation PEG 1000				
PEG 1000 retention related to feed [%]				
test #	*1*	*2*	*3*	*4*
Titel	Run 1 - pH 7,4	Run 2 - pH 6,5	Run 3 - pH 4,7	Run 4 - pH 3,3
pH	7,4	6,5	4,7	3,3
15		32,83	23,91	26,59
30	40,48	35,50	33,28	25,33
45	39,12			
Ava.	39,80	34,17	28,60	25,96
St. Div.	0,97	1,88	6,63	0,89
PEG 1000 retention related to cross-flow [%]				
test #	*1*	*2*	*3*	*4*
15		46,73	30,49	41,20
30	56,28	52,29	47,91	43,05
45	52,14			
Ava.	54,21	49,51	39,20	42,13
St. Dev.	2,93	3,93	12,32	1,31

Table 15: Processed data PEG 1000 retention test (2016).

Appendix IV – Operational filtration cycle analysis

1. Chemical analyses

Data sheet regarding the measured concentrations of specific chemical compounds present in wastewater samples.

			20-apr			22-apr			25-apr						26-apr		
			15:00			13:30			12:20								
			I	II	Avg.	I	II	Avg.	I	II	Avg.	I	II	Avg.	I	II	Avg.
COD	Influent	[mg/l]	71,8	60,6	66,2	40,2	42,5	41,35	81,3	81,6	81,45						
	Permeate	[mg/l]	51,5	48,5	50,0	36,6	36	36,3	65,2	67,9	66,55						
	CF	[mg/l]	96,9	99,9	98,4	59,4	66,4	62,9	139	137	138						
	Concentrate	[mg/l]	112,0	97,7	104,85	67,9	64,3	66,1	133	133	133						
			I	II	Avg.	I	II	Avg.	I	II	Avg.	I	II	Avg.	I	II	Avg.
Total-P	Influent	[mg/l]	1	0,971	0,986	0,268	0,3	0,284									
	Permeate	[mg/l]	0,398	0,253	0,326	0,013	0,015	0,014									
	CF	[mg/l]	3,210	3,230	3,220	1,36	1,39	1,375									
	Concentrate	[mg/l]	3,550	3,340	3,445	1,45	1,38	1,415									
			I	II	Avg.	I	II	Avg.	I	II	Avg.	I	II	Avg.	I	II	Avg.
Total-N	Influent	[mg/l]	11,4	10,8	11,1	10,1	10,1	10,1									
	Permeate	[mg/l]	11,1	10,4	10,8	10,8	10,3	10,6									
	CF	[mg/l]	13,2	13,4	13,3	11,8	12,0	11,9									
	Concentrate	[mg/l]	12,6	12,4	12,5	12,4	12,3	12,4									
			I	II	Avg.	I	II	Avg.	I	II	Avg.	I	II	Avg.	I	II	Avg.
Fe	Influent	[mg/l]	1,660		1,660				1,83	1,78	1,805						
	Permeate	[mg/l]	0,297		0,297				0,732	0,702	0,717						
	CF	[mg/l]							3,87	3,84	3,855						
	Concentrate	[mg/l]							4,02	3,96	3,99						
			I	II	Avg.	I	II	Avg.	I	II	Avg.	I	II	Avg.	I	II	Avg.
SO4	Influent	[mg/l]	109	104	106,5	73,5	69,6	71,55									
	Permeate	[mg/l]	104	103	103,5	69,3	68,6	68,95									
	CF	[mg/l]	118	121	119,5	92	85,2	88,6									
	Concentrate	[mg/l]	129	123	126,0	90,7	88,6	89,65									
			I	II	Avg.	I	II	Avg.	I	II	Avg.	I	II	Avg.	I	II	Avg.
PO4-P	Influent	[mg/l]	0,079	0,091	0,085	0,05	0,046	0,048	0,462	0,422	0,442						
	Permeate	[mg/l]	0,015	0,017	0,016	0,018	0,015	0,017	0	0	0						
	CF	[mg/l]	0,329	0,355	0,342	0,191	0,195	0,193	1,77	1,77	1,77						
	Concentrate	[mg/l]	0,356	0,366	0,361	0,2	0,193	0,197	1,76	1,74	1,75						
			I	II	Avg.	I	II	Avg.	I	II	Avg.	I	II	Avg.	I	II	Avg.
Mg	Influent	[mg/l]															
	Permeate	[mg/l]	5,18	5,18	5,18	5,12	5,28	5,2									
	CF	[mg/l]	5,18	5,18	5,18	5,27	5,09	5,18									
	Concentrate	[mg/l]															
			I	II	Avg.	I	II	Avg.	I	II	Avg.	I	II	Avg.	I	II	Avg.
NH4	Influent	[mg/l]	12,7	12,4	12,6	11,0	11,3	11,2	19,6	19,7	19,65						
	Permeate	[mg/l]	12,4	13,0	12,7	11,8	11,5	11,7	19,8	20	19,9						
	CF	[mg/l]	12,3	12,5	12,4	12,1	11,9	12,0	21,4	21,8	21,6						
	Concentrate	[mg/l]	12,4	12,6	12,5	11,8	11,7	11,8	21	20,8	20,9						
			I	II	Avg.	I	II	Avg.	I	II	Avg.	I	II	Avg.	I	II	Avg.
NH4-N	Influent	[mg/l]	9,58	9,64	9,61	8,55	8,81	8,68	15,2	15,3	15,25						
	Permeate	[mg/l]	9,62	10,10	9,86	9,13	8,93	9,03	15,4	15,6	15,5						
	CF	[mg/l]	9,55	9,68	9,62	9,44	9,24	9,34	16,6	17	16,8						
	Concentrate	[mg/l]	9,61	9,80	9,71	9,2	9,09	9,15	16,3	16,2	16,25						

Table 16: Nutrient concentrations at specific sample locations during continuous operational procedures (2016).

2. Energy consumption

Energy consumption measured (t = 1 minute) during each filtration cycle while utilizing cMF membranes for municipal wastewater filtration procedures, as shown in figure 20. The consumption of energy during operational filtration cycles was mainly related to automatic pump frequency adjustments.

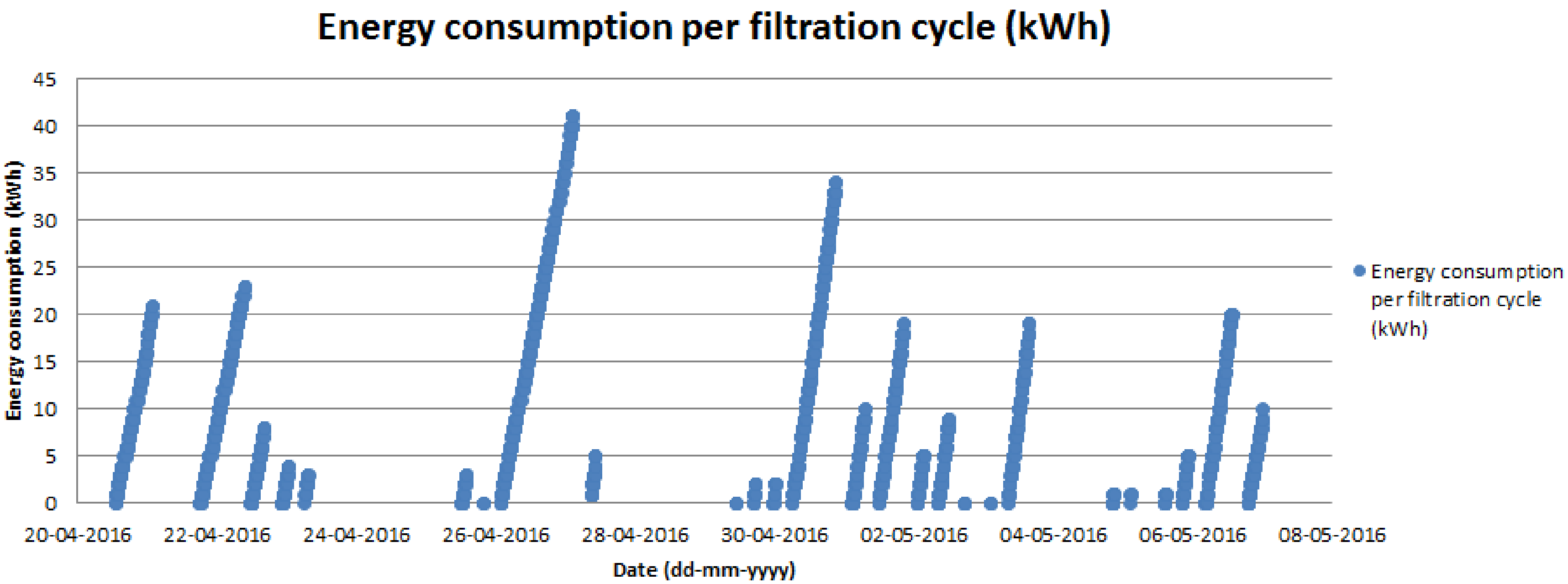

Figure 20: Energy consumption per filtration cycle while utilizing cMF membranes (kWh).

3. Chemical consumption

Chemical consumption measured during the operational filtration cycle analyses, including previously conducted measurements during the employment of the cNF membranes (Hoek, 2016).

cMF				**cNF**			
Date	NaOH (g)	HCl (g)	NaOCl (g)	Date	NaOH (g)	HCl (g)	NaOCl (g)
21-04-2016	3576	2759	117	17-07-2015	3243	2340	145
25-04-2016	3292	2517	156	21-07-2015	3131	1532	145
25-04-2016	3203	2516	101	30-07-2015	2604	1548	111
29-04-2016	3212	2505	151	02-08-2015	3830	2096	100
Average	3321 ± 175	2574 ± 123	131 ± 27	Average	3202 ± 436	1879 ± 350	125 ± 20

Table 17: Measured chemical consumption of the CIP procedures during the utilization of the cNF and cMF membranes.

4. Filtration cycle analysis

Flux and TMP values measured during the employment of cNF and cMF membranes during specific periods of experimental operational research regarding the filtration of municipal wastewater, as shown in figure 21 and 22.

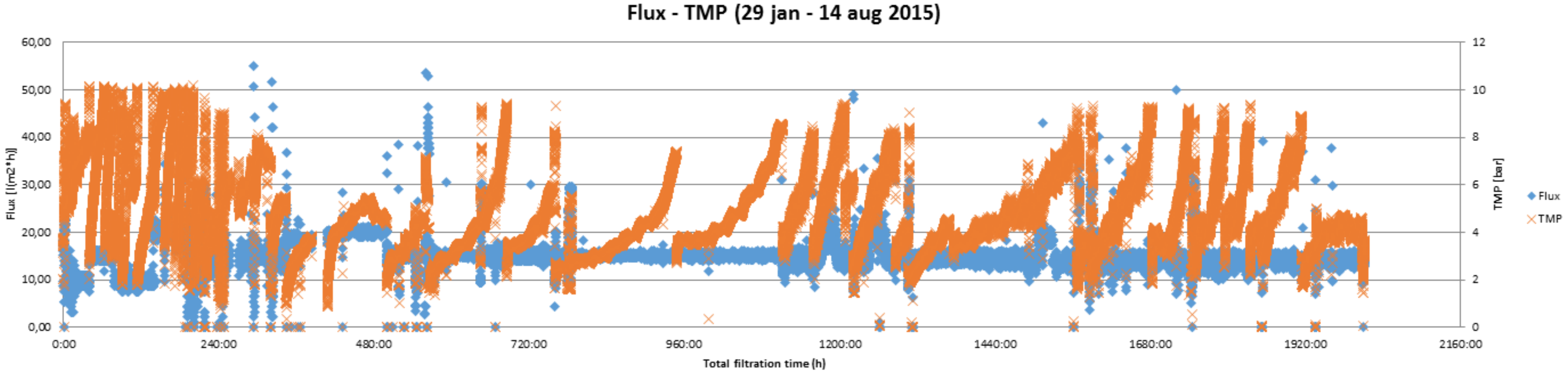

Figure 21: Measured flux and TMP during continuous municipal wastewater filtration procedures from the 29th of January to the 14th of August 2015 while utilizing cNF membranes.

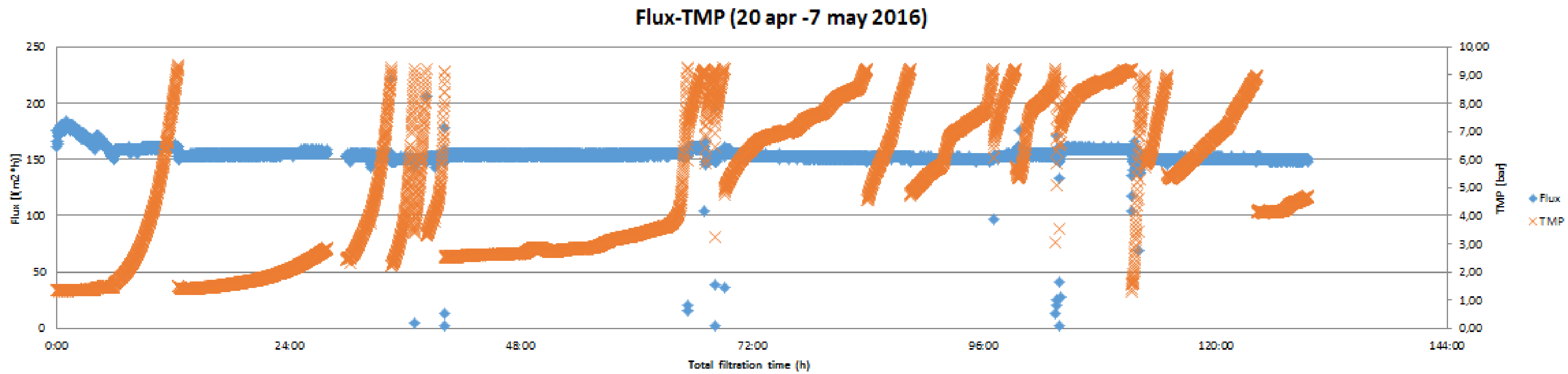

Figure 22: Measured flux and TMP during continuous municipal wastewater filtration procedures from the 20th of April to the 7th of May 2016 while utilizing cMF membranes.

cNF membrane permeability during a specific period of experimental operational research regarding the filtration of municipal wastewater, as shown in figure 23.

Permeability - daily (29 jan - 14 aug 2015)

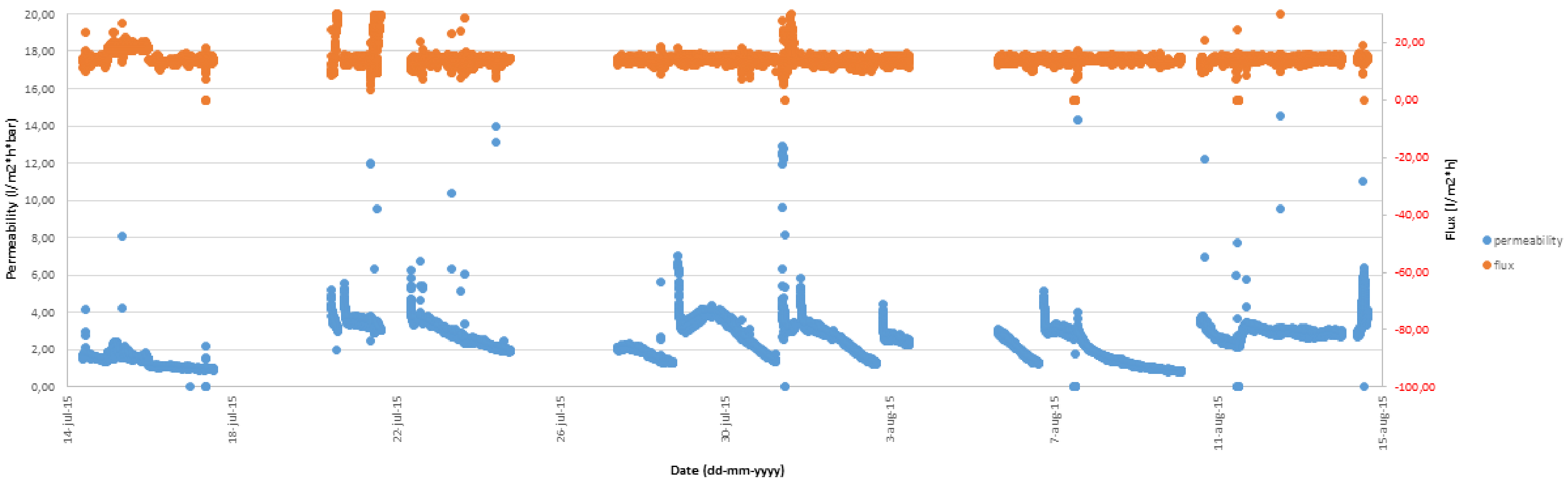

Figure 23: Measured flux and membrane permeability during continuous municipal wastewater filtration procedures from the 29th of January to the 14th of August 2015 while utilizing cNF membranes.

Appendix V – Visual observations

1. Membrane degradation

Figure 24: Damaged top and support layers of a cNF membrane utilized in operational municipal wastewater treatment procedures (2016).

2. Membrane unit

Figure 25: The membrane unit containing the cNF membranes before replacing them with the cMF membranes (2016).

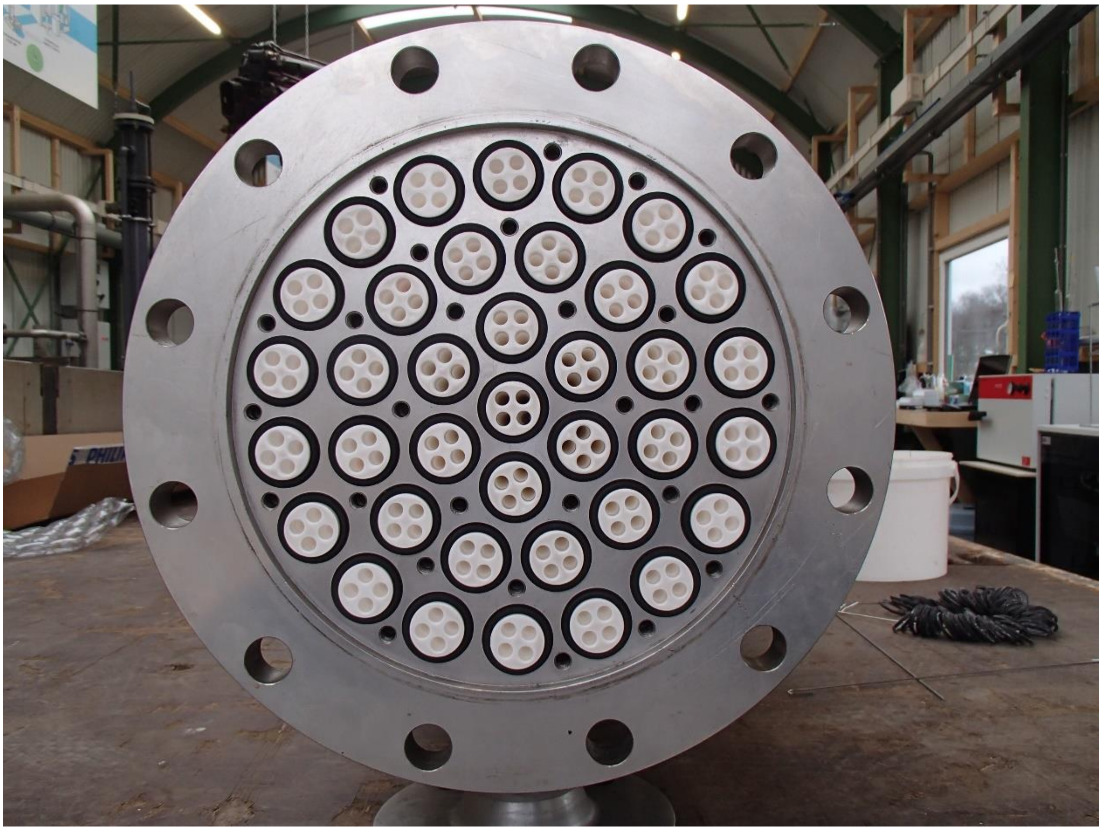

Figure 26: The membrane unit containing the new cMF membranes (2016).