Optimization of Reverse Osmosis Performance

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Abstract

A condensed description of my work.

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Dictionary

In: The water coming in to the system from a tank

Feed: The water entering the membrane system

Permeate: The purified water leaving the membrane as product water

Reject: The water leaving the membrane and can be wasted or recurculated

Drain: The water wasted, e.g. let out in the canalization

RO: Reverse Osmosis - the principle of the membrane behavior

Pressure:

Flow:

Semi-permeable membrane:

Conductivity:

:

Drain:

Drain:

1

Introduction

1.1 Background

The Water Technologies department at Baxter develops water systems for use in mixing fluid for dialysis treatments. The water quality is important in order to not harm to the patients when using the final product. The water systems used for water purification are using the reverse osmosis (RO) method as the finest level of filtration. It remove impurities, as salt and inorganic molecules from the water[Company, 2018].

In a RO-system the feed water is pressurized by a pump and forced through the RO-membrane to overcome the osmotic pressure. The RO-membrane is a semi-permeable membrane and let water passes freely true the membrane creating a purified product stream.

The pump in the current system has two purposes, creating a pressure to overcome the osmotic pressure and creating a flow on the reject side of the RO-membrane to prevent aggregation of impurities on the membrane surface.

1.2 Motivation

By using two pumps instead of one in the RO-system it will be possible to control the pressure on the module and the flow on the reject side independently and thus get better possibility to optimize the performance of the RO-system, focusing on reducing impurities and water consumption.

As the current model does not take temperature dependencies in concern, the model will be redesigned in order to handle temperature dependencies.

1.3 Goal

The purpose of this masters thesis is to evaluate the feasibility of replacing the main RO-pump with two pumps, one for controlling the flow through the membrane and one for controlling the pressure.

To achieve good performance it will be necessary to design a realistic model of the system, once the model has been designed and tested a control algorithm is to be developed. This algorithm, should be able to control the flow and pressure over the RO-membrane to maximize the efficiency of the filter while minimizing the amount of waste water that is produced.

The temperature dependencies will be taken in concern in the new model.

Framing of questions

- Is it possible to upgrade the RO-membrane model to include temperature dependencies?
- Is it possible to control the system with two pumps instead of one, which is used today?
- Is it possible to control the two pumps in order to gain better efficiency in reducing water waste, noise or performance? (In comparison with the current system).

1.4 Method

In order to investigate the performance of the current system and to compare it with the new model following steps will be evaluated:

- Research on the RO-membrane that is implemented in the system
- Research on previous work on the field
- Modelling of the system to identify suitable component properties and design of the flow path
- Design of control algorithms
- Control simulations
- Implementation in a test rig to verify the performance of the system
- Run tests to determine the performance
- Improve if possible

2

Theory

2.1 Semi-permeable membrane

A membrane is defined as a barrier between two homogeneous phases. The process is a continuos steady-state operation consisting three streams: feed, permeate and reject. Main concern in the process boundary is the semipermeable barrier that selectively allows the passage of some components but not others. [R, 2015]

2.2 Osmosis

The osmosis process occurs when two solutions of different chemical concentration are separated by a semi-permeable membrane. The two different solutions will try to reach equilibrium. The solution with less concentration will have a natural tendency to migrate through the membrane over to the side with higher concentration. Osmosis is a naturally occurring phenomenon and one of the most important processes in nature. The pressure that occurs is called the osmotic pressure. The phenomenon can be seen in Figure 2.1

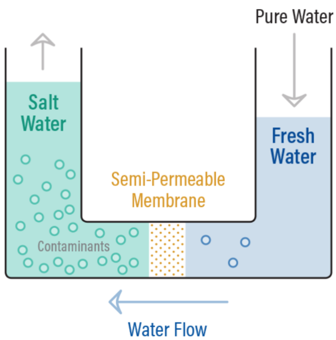

Figure 2.1 Osmosis

2.3 Reverse osmosis

The reverse osmosis(RO) process is the reverse process of the osmosis. When pressure is applied to a semipermeable membrane, the water molecules are forced through the semipermeable membrane and the contaminants are not allowed true. The amount of pressure required depends on the salt concentration of the water. In order to gain reverse osmosis the pressure applied must be greater than the osmosis pressure. The membrane employs cross filtration rather than standard filtration. With cross filtration, the solution passes through the filter with two outlets. One solution passes true the membrane and is called permeate and is the filtered solution.

The other solution can be drained or be fed back into the filtering system. The contaminants build up att the surface area and it is of great importance to try to sweep them away and hold the surface clean. If the contaminants builds up the performance of the membrane will decrease, and cleaning with chemicals or heat water might be necessary[*What is reverse osmosis*]. The phenomenon of reverse osmosis can be seen in 2.2. In order to obtain good performace over the RO membrane there

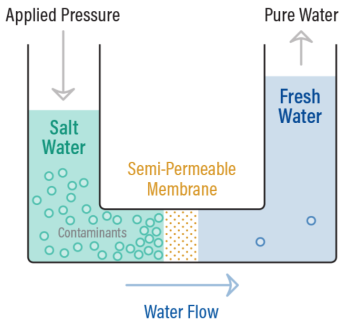

Figure 2.2 Reverse Osmosis

are some parameters that should be taken in consideration when designing a RO system. These are:

Pressure: feed (P_f), permeate (P_p), reject, (P_r)

Conductivity: feed, C_f, permeate (C_p), reject (C_r)

Flow: feed (Q_f), permeate (Q_p), reject(Q_r)

Temperature: feed (T_f), permeate (T_p), reject (T_r)

Fouling

Fouling occurs when contaminants accumulate on the surface of the membrane. The fouling contributes to a pressure drop that will decrease the performance of the membrane and cause less permeate flow. Fouling will happen eventually to some extent given the fine pore size of the membrane. A high reject flow and proper pretreatment will extend the operational time between cleaning procedures of the membrane[*What is reverse osmosis*].

2.4 Mathematical modeling of reverse osmosis

There are different models to describe the flow of solutes and solvents in the reverse osmosis process. The mass balance equations are central in modeling the process.

Figure 2.2 shows the main process.

A hydraulic pressure is applied to to the feed stream of concentration, C_f and results in a flow rate Q_f. Some of the solvent, pure water, passes through the RO-membrane characterized by solvent permeability, solute permeability and surface area. The product water (purified water), is called permeate and has the concentration C_p and flow Q_p. The concentration, called reject has the concentration C_r with flow Q_r. The study objective of this basic RO-modeling is to calculate output concentrations and flow rates in terms of input and operation conditions. Parameters used to evaluate the performance of the RO-membrane is rejection ratio:

$$R = 1 - \frac{C_p}{C_f} \tag{2.1}$$

and recovery ratio:

$$Y = \frac{Q_p}{Q_f} \tag{2.2}$$

which express the quality and quantity of the solvent product respectively.
Mass balance in the system gives:

$$Q_f = Q_p + Q_r \tag{2.3}$$

and:

$$C_f Q_f = C_p Q_p + C_r Q_r \tag{2.4}$$

Solvent flux per unit time per unit membrane surface area is described by:

$$J_w = \frac{Q_p}{A_m} = A(\Delta P - \Delta\pi) \tag{2.5}$$

where $\Delta\pi = \pi_f - \pi_p$ is the osmotic pressure difference between feed and permeate side and A_m is membrane surface area. Solute flux is given by:

$$J_s = B(C_f - C_p) \tag{2.6}$$

where B is the solute permeability.
The permeate concentration can be described by:

$$C_p = \frac{C_f}{1 + \frac{A}{B}(\Delta P - \Delta\pi)} \tag{2.7}$$

where A is solvent permeability. Permeate flow is described by:

$$Q_p = Q_f Y \tag{2.8}$$

The four mass balance equations (2.3 - 2.6) make the RO process mathematically solvable.

In order to model the osmotic pressure the van't Hoff principle can be used. It gives the osmotic pressure:

$$\Delta\pi = b(C_f - C_p) \tag{2.9}$$

where b is a proportionality. In van't Hoff's equation b=RT, where R is the gas constant and T is the absolute temperature om the membrane system.

2.5 Control theory

The system is considered a slow system

3

Equipment

3.1 Reverse Osmosis Membrane

The membrane used is a reverse osomosis membrane manufactured by the DOW chemicals company. It is a custom made membrane for Baxter AB.

3.2 Pumps

The pumps used in the system are magnet drive rotary vane pump TSSS401 from Fluid-o-Tech. They are designed to deliver a smooth flow reliably and optimized to reduce noise and power consumption. They are made for a maximum static pressure of 20 bar and has a speed limit of 1725 rpm. The nominal flow rate is 400 l/h.

3.3 Drain valve

A proportional valve were implemented on drain side to be able to control the drain flow out from the membrane. It is a motorized angle seat control valve with high capacity. It has an integrated positioner and control the amount of flow going through the valve.

3.4 Simscape/Simulink

Simscape is a graphical programming tool within the Matlab simulink environment designed to model and simulate physical systems. A model of the RO-membrane and the flow path is designed using simscape and the simulated system could then be controlled using a control algorithm running in Simulink, a Matlab software too. The RO-membrane model encorporate separete mathematical models of the most important system dependencies, such as temperature , flow, pressure and conductivity.

The system control is implemented in Simulink.

3.5 Speedgoat Real-Time Target Machine

Speedgoat is a realtime target machine used for development. It is an FPGA I/O module with Simulink driver blocks. It is capable of simultaneous sampling and is used to drive the system rig. It contains an Intel 2.0 GHz quad core CPU.

3.6 Measurement instruments

Different instruments used to measure pressure, flow, temperature and conductivity in the physical rig.

Figure 3.1 Speedgoat (Speedgoat real time simulation and testing, 2018)

Conductivity sensor block

A conductivity sensor block built by Gambro Lundia AB, called C3 is used to measure the water conductivity. In order to measure the required range two of the blocks where adjusted and calibrated. Two of the blocks, implemented in feed and recirculation path measures in range 0-3000 μS. The sensors cell implemented on permeate side measures up to 1500 μS.

Temperature sensor

The C3 cell described in section 3.6 contains sensors for temperature measurements and are used fro the temperature measurements in the system.

Pressure sensor

Pressure sensors where implemented in the C3 block, described in section 3.6, and calibrated in order to achieve the pressure at feed, recirculation and permeate side of the membrane. The pressure sensors range is between 0-20 bar.

Flow meter

A flowsensor from Bronkhorst High-Tech B.V is used to measure the flow on permeate side. The flowmeter works in 4-1500 ml/min range and 0-100 bar with water as liquid flowing through. It has an accuracy of +- 1 ml/min.

Figure 3.2 Flowmeter (BRONKHORST HIGH-TECH B.V.)

4

Method/Implementation

4.1 Flowchart investigation

To obtain a system to run tests on some different flowchart are considered. The current pump will be replaced by two pumps. Following requirements will be desirable when obtaining a updated model of the flowchart:

Pressure drop over the membrane is high

Flow through membrane is high

The model shall contribute with the following:

Permeate conductivity (minimized)

Fouling on the membrane (minimized)

Temperature dependencies

Waste water going through drain (minimized)

Mainly two different systems containing two pumps were considered:

System 1

The first system with one with pump on feed side and one pump on permeate side, as seen in Figure 4.1. This setup contributes with the ability to create a net pressure over the membrane with a low, or even a under pressure on permeate side, whilst the feed pump creates a "high" pressure on feed side.

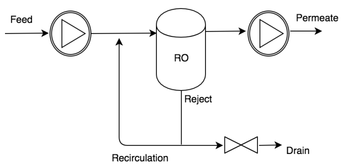

Figure 4.1 System 1

System 2

The second system considered with one pump on feed side and one pump on reject side, in recirculation path, seen in Figure 4.2. The feed pump is used to create a high pressure on feed side and the pump in the recirculation path is used to control the flow in recirculation path. This contributes to control the recovery rate.

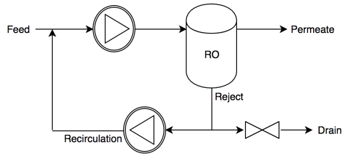

Figure 4.2 System 2

4.2 Tests

In order to compare results of the current system, furthermore called "Current System" and the updated system, some test will be done on the current setup. Reasonable values were investigated in order to meet requirements of the Water device. Corresponding points will be tested on the comparing system to evaluate any improvements on the membrane performance. Points to investigate can be seen in Table 4.1:

4.3 Modeling

Simscape software tool described in section 3.4 is used to do a physical modeling in order to achieve the characteristics of the membrane. Mathematical equations from the manufacturer of the membrane and physics of the solution-diffussion model described in section 2.4 were used and implemented.

4.4 Implementation Test Rig

Current System

In order to run all tests a physical rig was built. A first version to meet the specifications of the system used in the current water device were built according to Figure 4.3, with all the measurement sensors implemented and tests were executed. In order to log all signals and to run the system the Real-Time Target Machine described in section 3.5 were connected with all significant signals. Different interfaces, as i^2c, Analog I/O, Digital inputs, PWM were used to implement the communication between the Real-Time Target Machine and measurement instruments. Circuits were built to transform voltage supply to required level for each component. All implementation of the communication and power supply can be seen in Figure 5.24 - 5.27.

Steady state	Temperature	Feed Conductivity	Motor effect
1.1	18 °C	280 µS	60 %
1.2	18 °C	500 µS	60 %
1.3	18 °C	1000 µS	60 %
1.4	18 °C	1000 µS	**80 %**
1.5	18 °C	2000 µS	60 %
1.6	18 °C	2000 µS	**80 %**
1.7	18 °C	3000 µS	60 %
1.8	18 °C	3000 µS	**80 %**
2.1	30 °C	280 µS	60 %
2.2	30 °C	500 µS	60 %
2.3	30 °C	1000 µS	60 %
2.4	30 °C	1000 µS	**80 %**
2.5	30 °C	2000 µS	60 %
2.6	30 °C	2000 µS	**80 %**
2.7	30 °C	3000 µS	60 %
2.8	30 °C	3000 µS	**80 %**
3.1	40 °C	280 µS	60 %
3.2	40 °C	500 µS	60 %
3.3	40 °C	1000 µS	60 %
3.4	40 °C	1000 µS	**80 %**
3.5	40 °C	2000 µS	60 %
3.6	40 °C	2000 µS	**80 %**
3.7	40°C	3000 µS	60 %
3.8	40°C	3000 µS	**80 %**

Table 4.1 Testcases

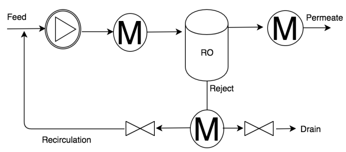

Figure 4.3 Current System, with measurement sensors

System 2 "Comparing system"

A new, second system were built, according to Figure 4.4 in order to do the tests for the modified system including two pumps. Same membrane, measurement senors were used.

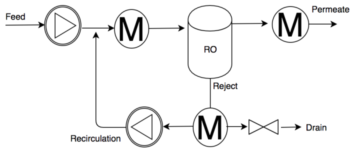

Figure 4.4 System 2, with measurement sensors

4.5 Connections

4.6 Mapping

In order to investigate the performance of the membrane pressure, flow, conductivity and temperature is to be measures. In the systems there are critical values of high pressure on feed side and reject side which makes it difficult to find measurement equipment that can handle both the high pressure and relatively low flows with no loss of pressure and required accuracy. Therefore some mapping of the flow were done and used.

4.7 Design of control algorithms

Investigating tests on System 2, Figure 4.2, were executed prior the design of the control algorithms to recieve required reference signals to the pumps and drain valve. During the tests one parameter at a time changed while the others were kept constant. In test 1, seen in Figure 5.30 the pump in recycle path were the changing parameter and in Test 2, seen in Figure 5.31 the pressurizing pump on inlet side were the changing parameter.

Control algoritms were developed in Matlab - Simulink.

4.8 Control simulations

INSERT PICTURES

4.9 Improvements

5

Results

5.1 Flowchart investigation

Two different setups for a comparing system to the current system were investigated, section 4.1, and System 2 were chosen to be the comparing system. Both Systems were considered fulfilling most of the requirements, section 1.3, for an updated version.

In order to choose one comparing system benefits and disadvantages with the two system were investigated.

System 1, figure 4.1, is considered capable of creating a high pressure drop over the membrane. The hypothesis is also that it is capable of creating the biggest pressure drop with the least amount of energy needed. A disadvantage is considered that implementing a pump in the purified water path will increase the risk that the pump may release particles into purified water which is, from a patient safety perspective, a high risk factor.

System 2, figure 4.2, is considered capable of creating a high pressure drop over the membrane. It is also capable of controlling the recovery factor which, due to theory increases the membrane life time and performance. It might also be capable of minimize the salt concentration close to membrane surface area if increasing recirculation flow, e.g, create turbulence close to the membrane surface.

The two comparing systems were set to:

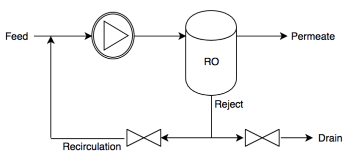

Figure 5.1 Current System

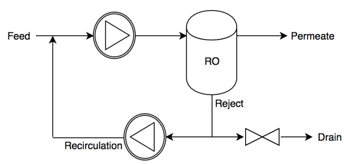

Figure 5.2 System 2

5.2 Tests

Current system

Results for the test on the current system, figure **??**:

Room temperature:

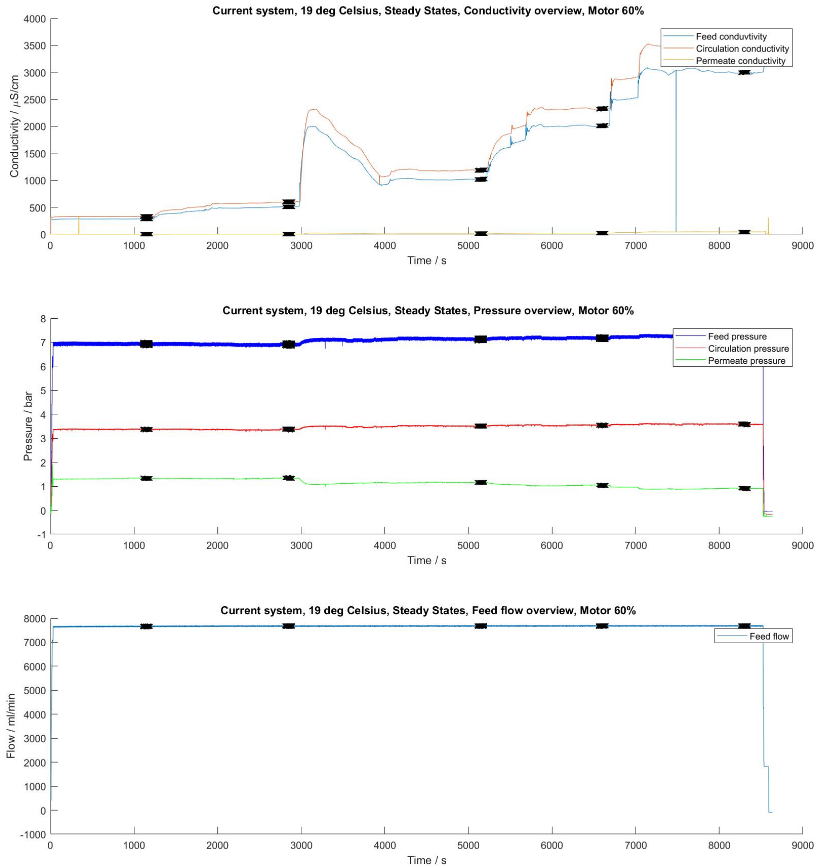

Figure 5.3 Connections Pressure sensors

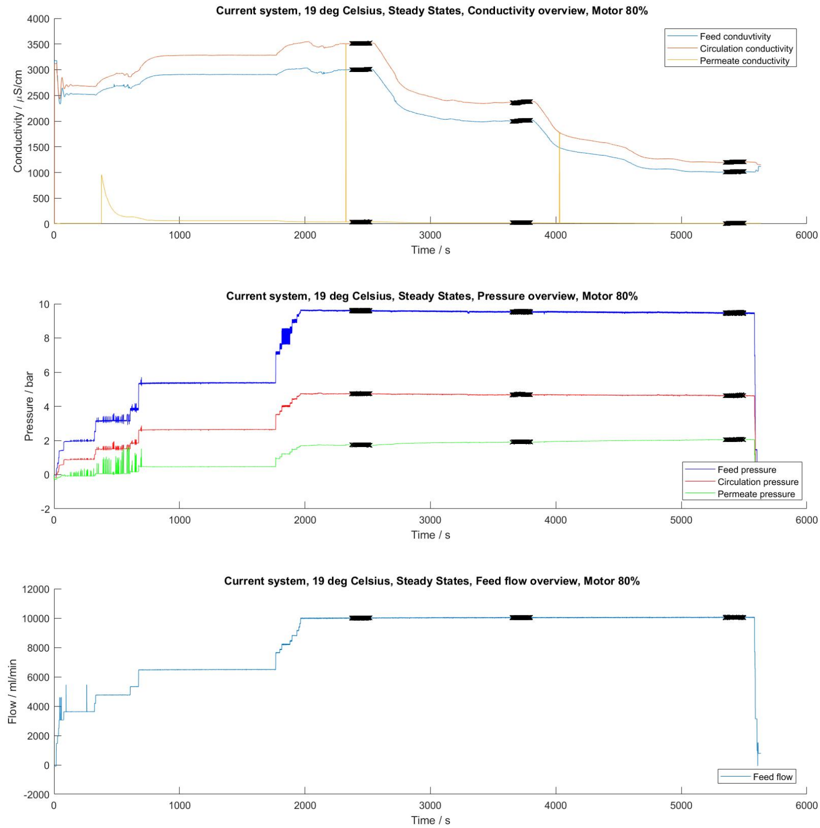

Figure 5.4 Connections Pressure sensors

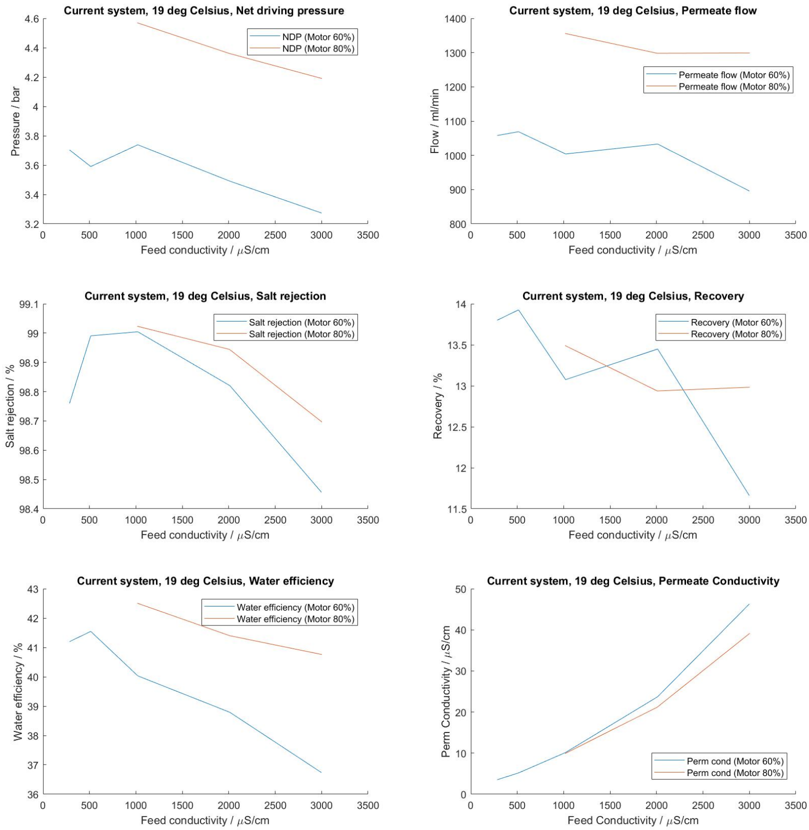

Figure 5.5 Connections Pressure sensors

short explanation of tests.

Tests conducted at 30 deg C.

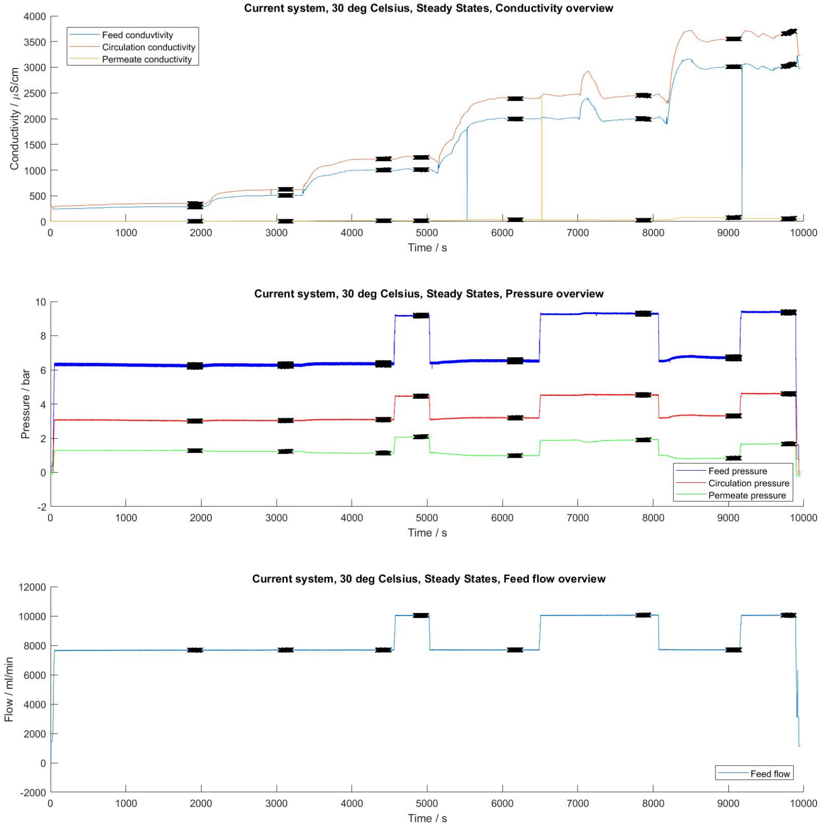

Figure 5.6 Connections Pressure sensors

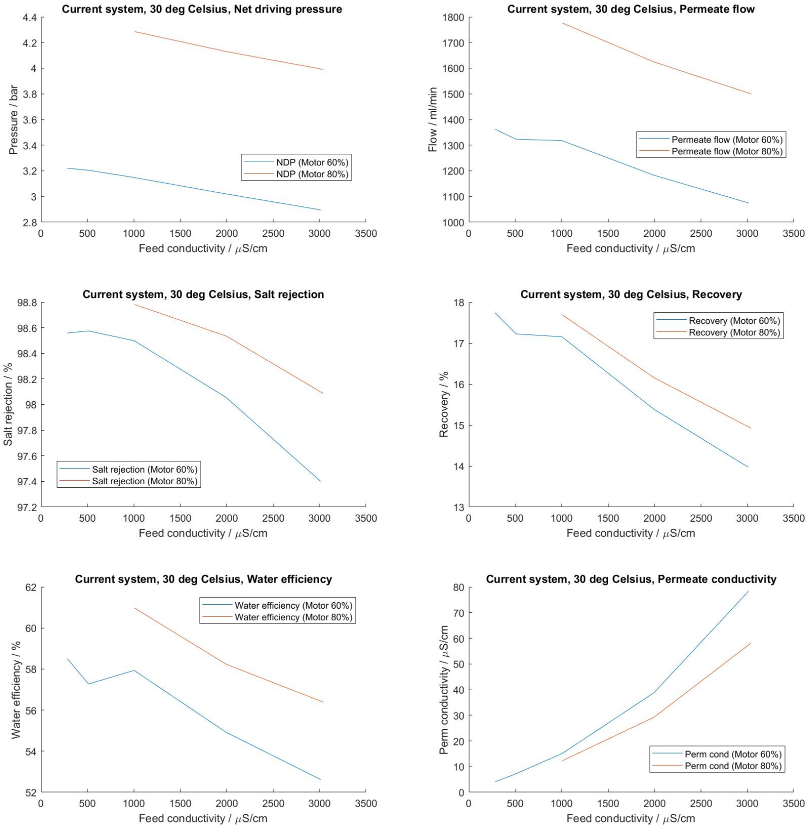

Figure 5.7 Connections Pressure sensors

Tests conducted at 40 deg C."

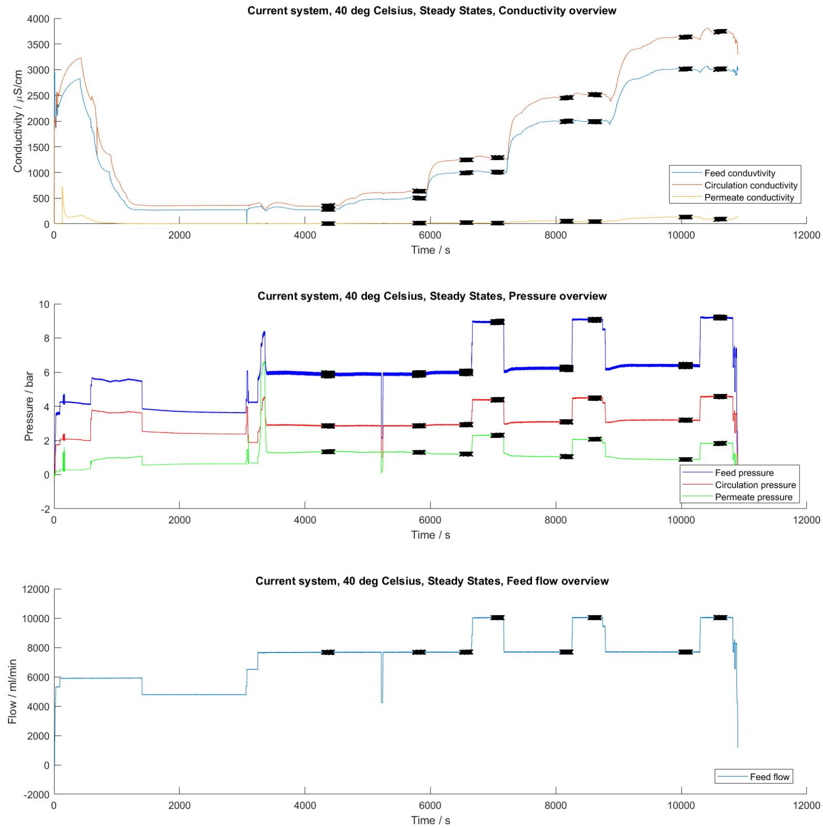

Figure 5.8 Connections Pressure sensors

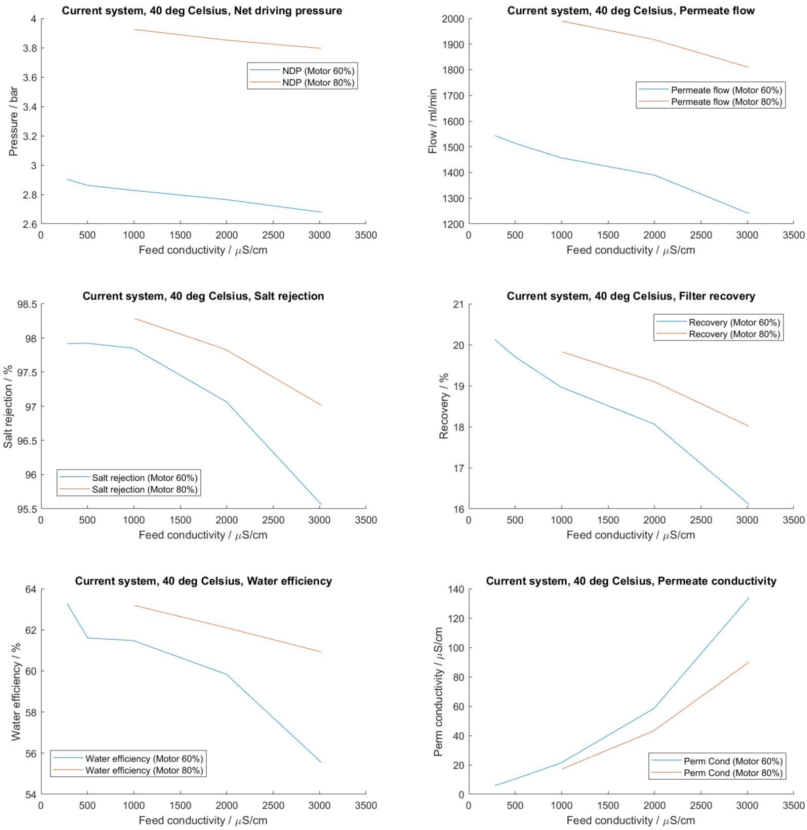

Figure 5.9 Connections Pressure sensors

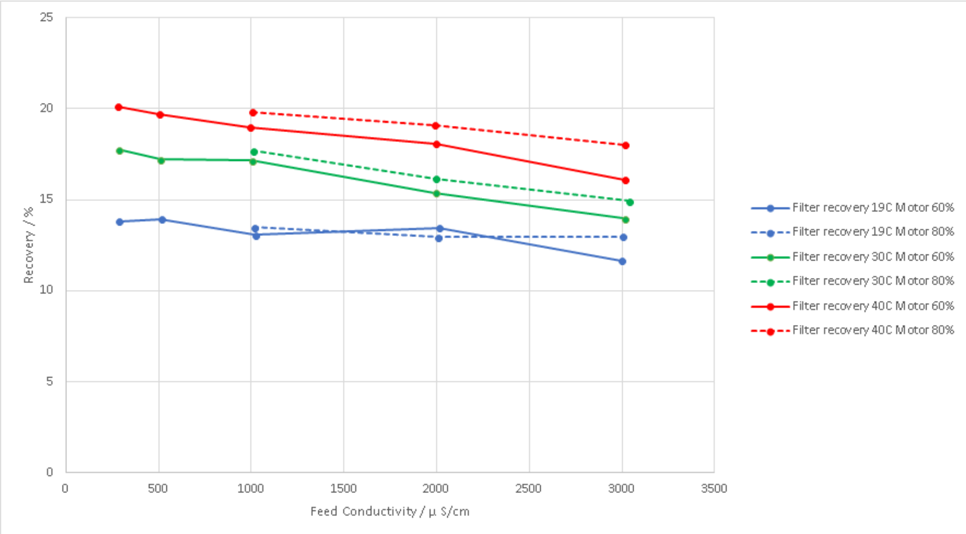

Figure 5.10 Connections Pressure sensors

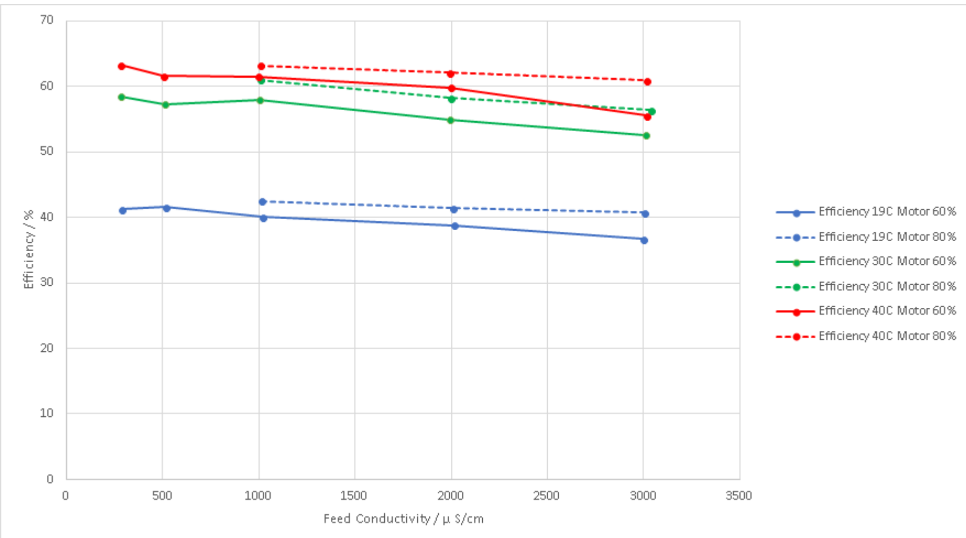

Figure 5.11 Connections Pressure sensors

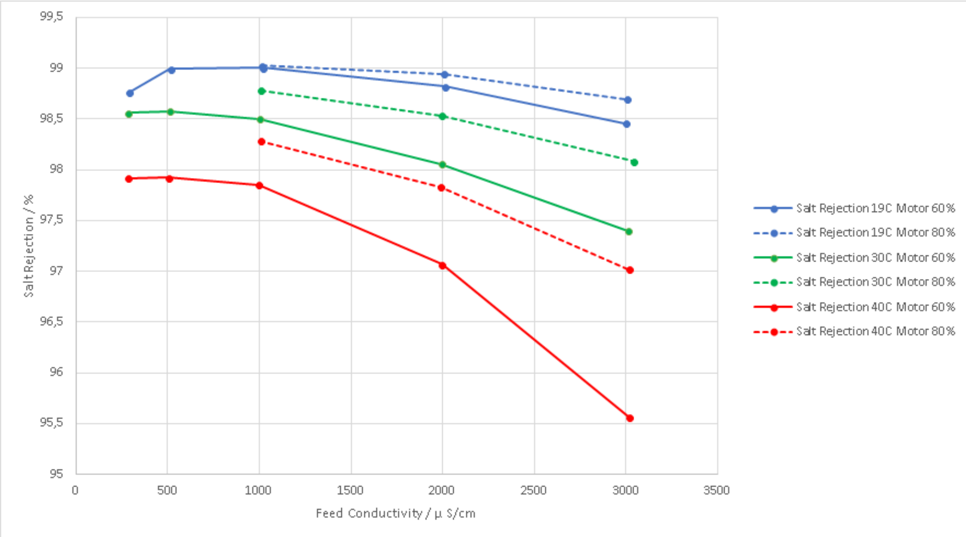

Figure 5.12 Connections Pressure sensors

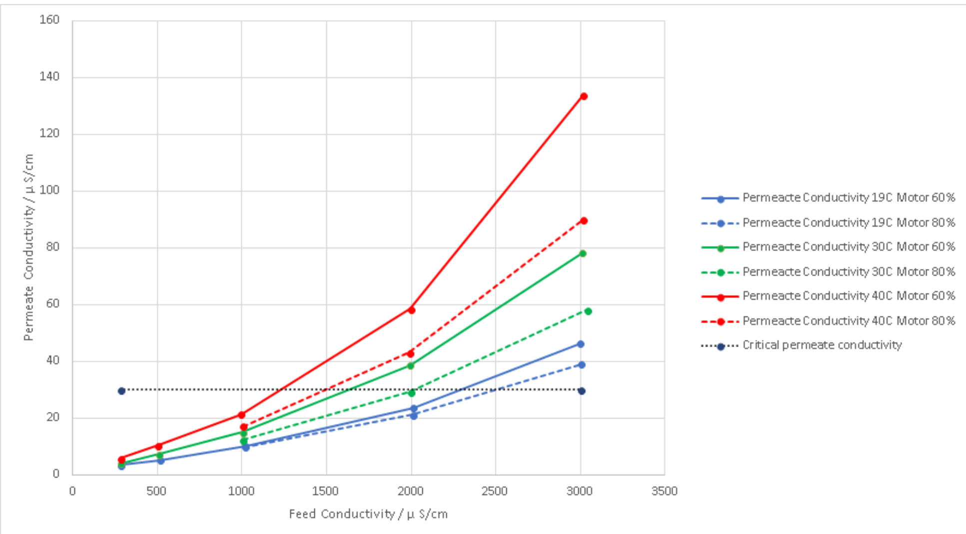

Figure 5.13 Connections Pressure sensors

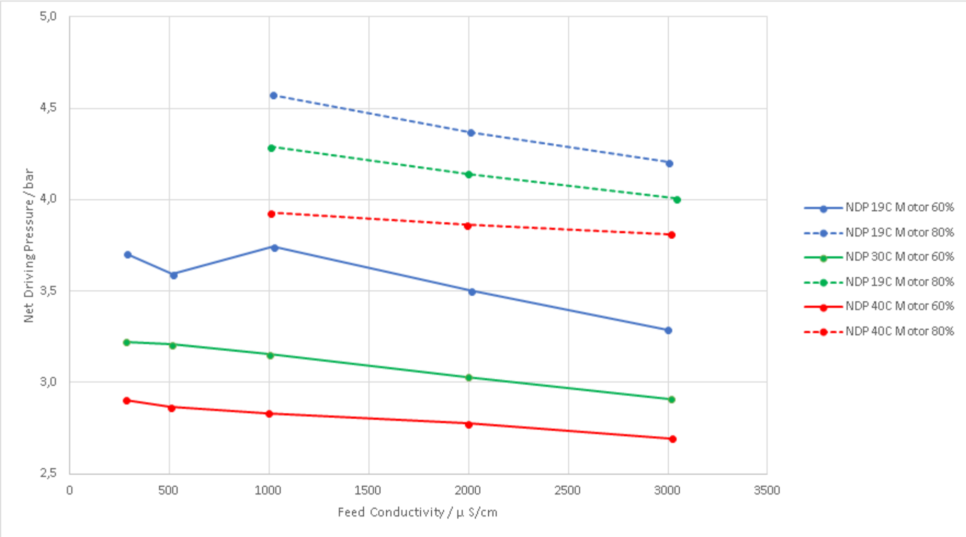

Figure 5.14 Connections Pressure sensors

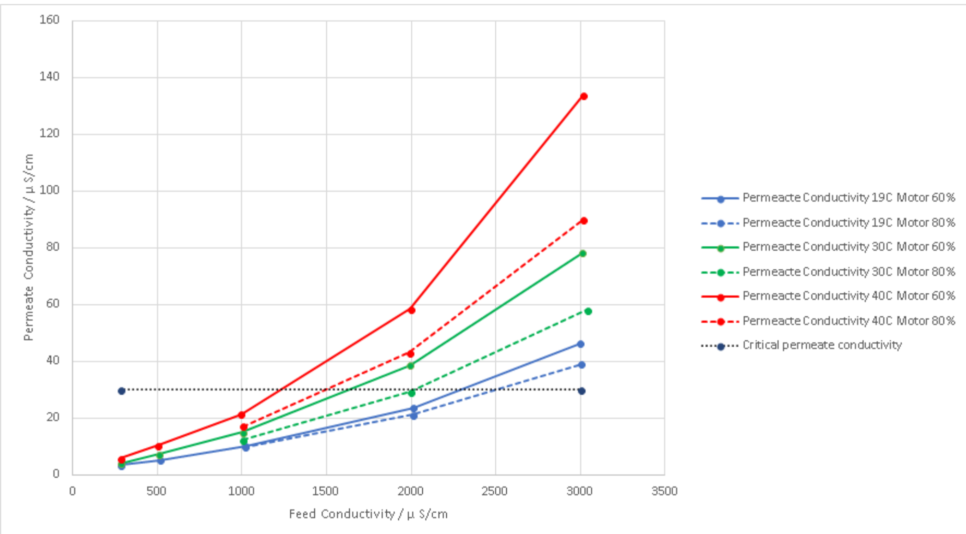

Figure 5.15 Connections Pressure sensors

System 2

Test: increaed feed pressure

21

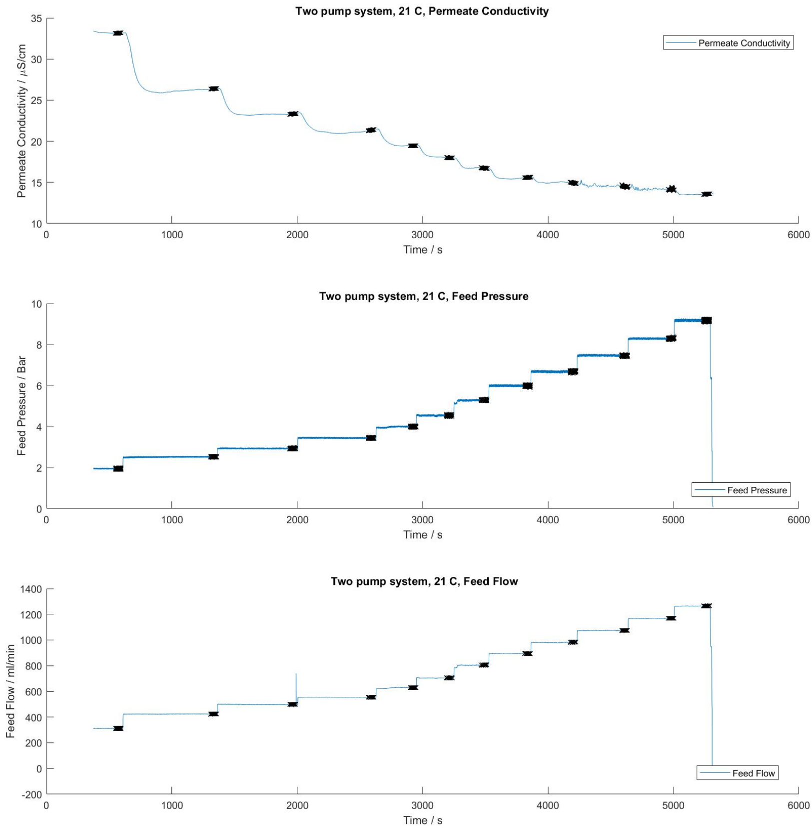

Figure 5.16 Connections Pressure sensors

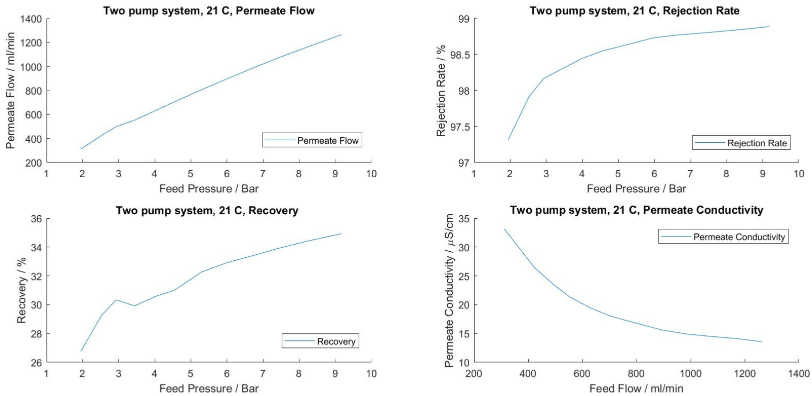

Figure 5.17 Connections Pressure sensors

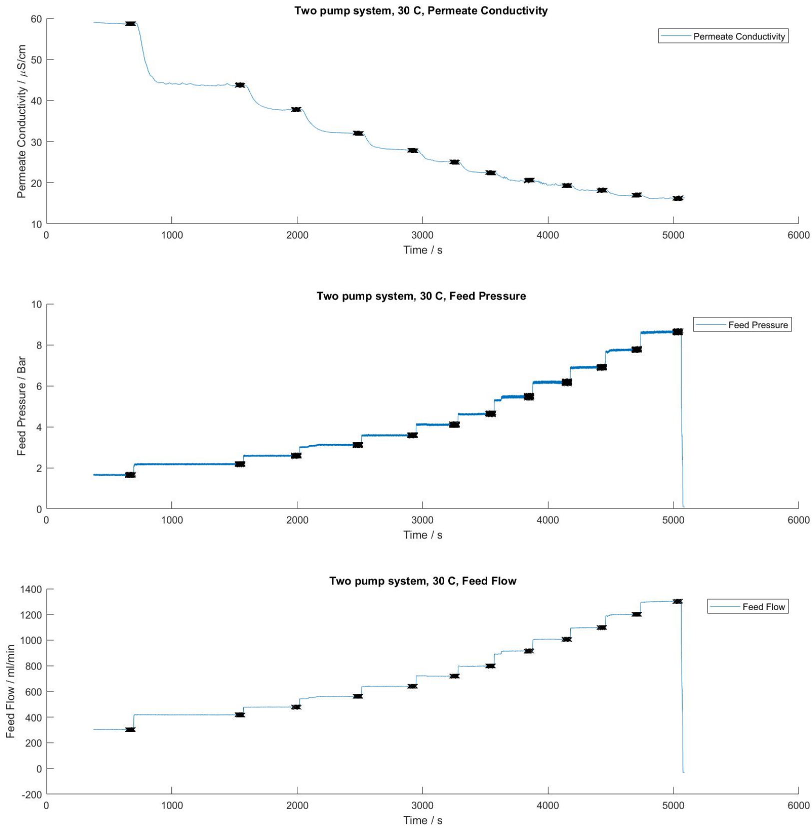

Figure 5.18 Connections Pressure sensors

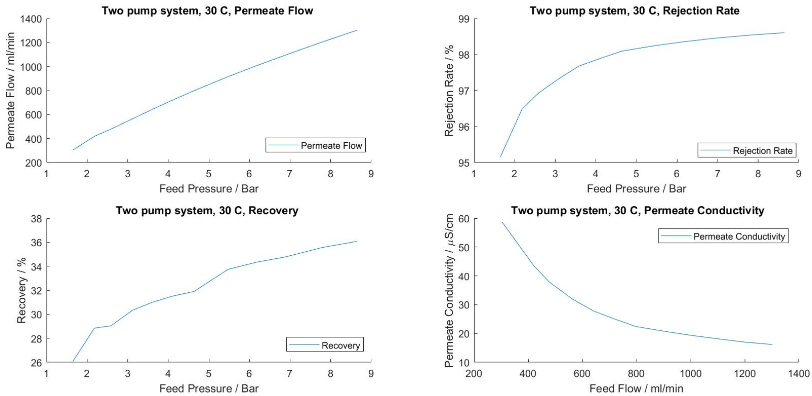

Figure 5.19 Connections Pressure sensors

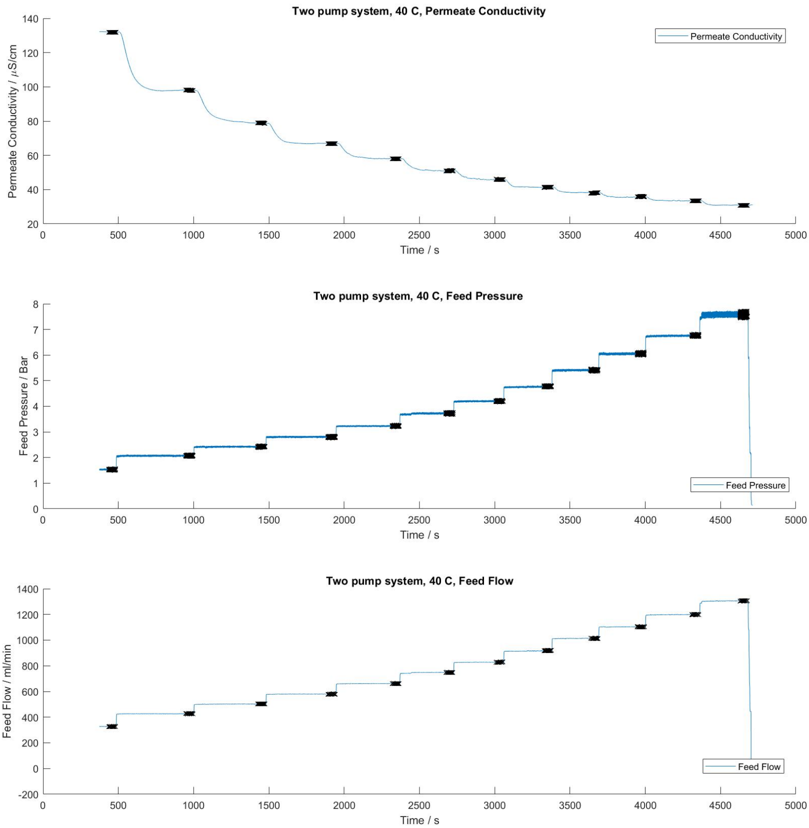

Figure 5.20 Connections Pressure sensors

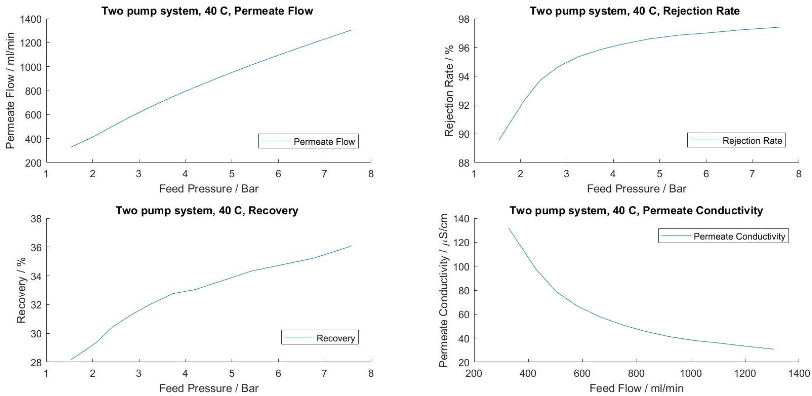

Figure 5.21 Connections Pressure sensors

Recovery Increase

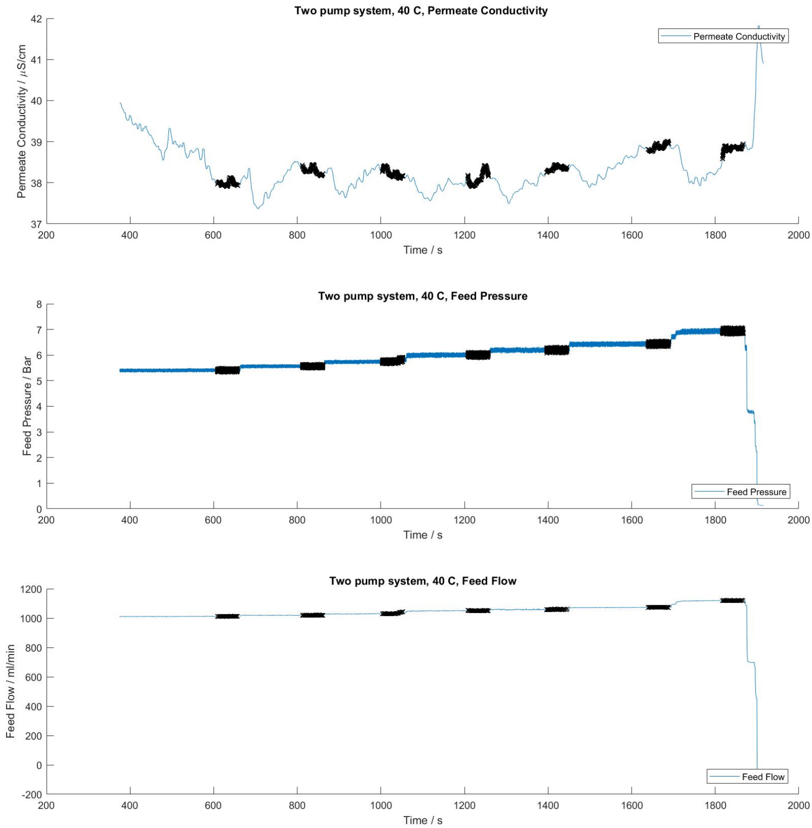

Figure 5.22 Connections Pressure sensors

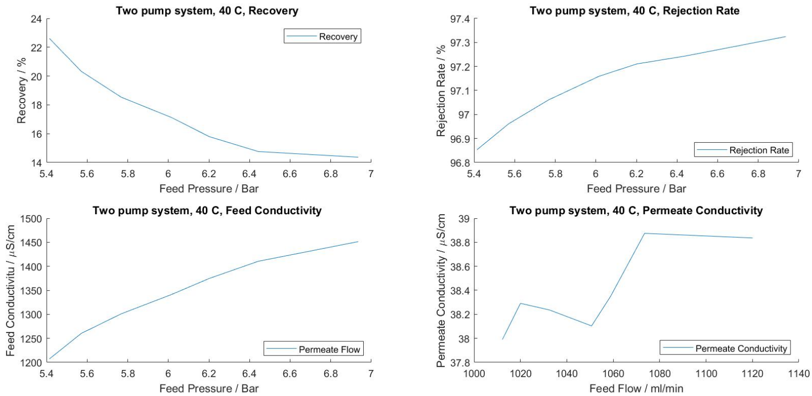

Figure 5.23 Connections Pressure sensors

5.3 Modeling

A physical model of the membrane were made and the given results can be seen in:

5.4 Implementation Test Rig

Connections

In Figure (5.24-5.27) all connections in the test rig is displayed.

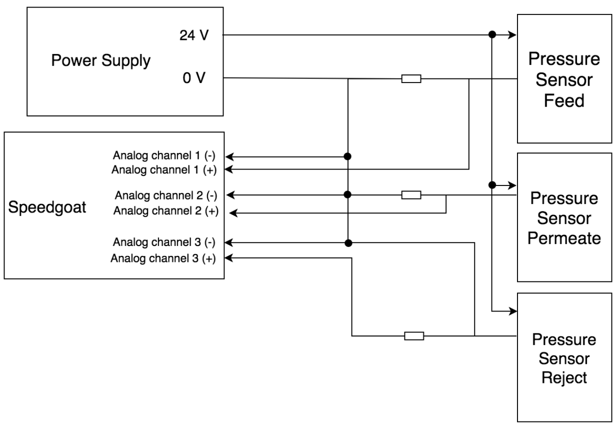

Figure 5.24 Connections Pressure sensors

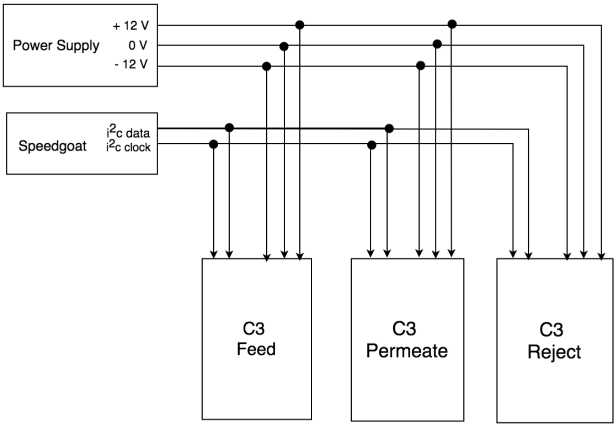

Figure 5.25 Connections measurement blocks, C3

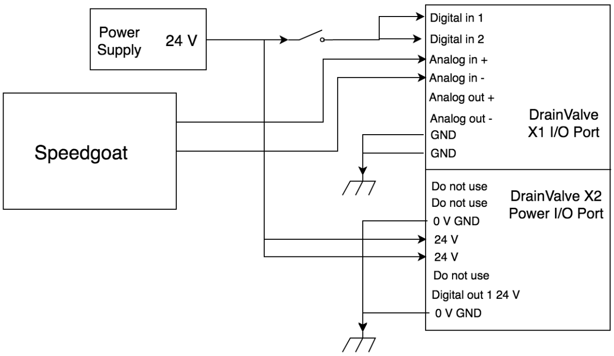

Figure 5.26 Connections Drain Valve

5.5 Mapping

5.6 Design of control algorithms

FIGURES AND PLOTS FROM SIMSCAPE

5.7 Control simulations

5.8 Improvements

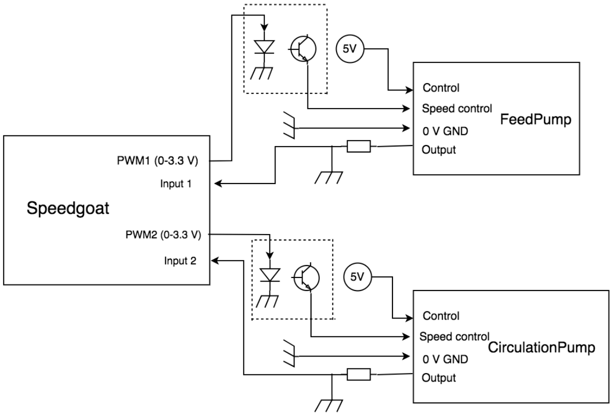

Figure 5.27 Connections pumps

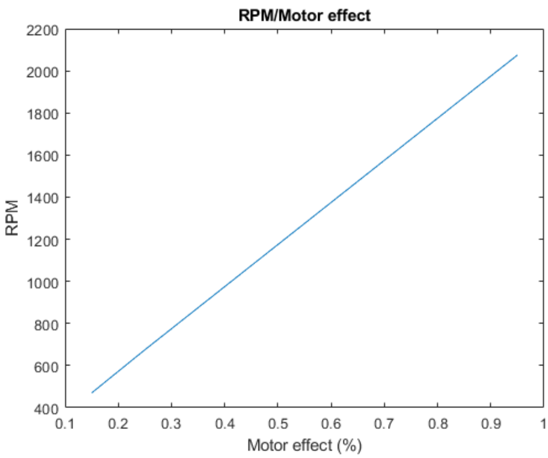

Figure 5.28 RPM Pumps

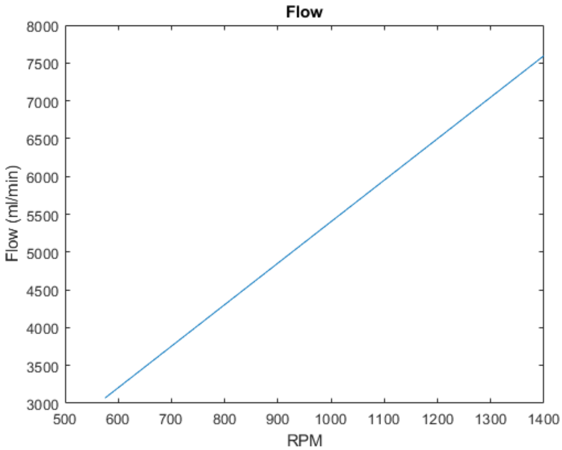

Figure 5.29 Flowrate

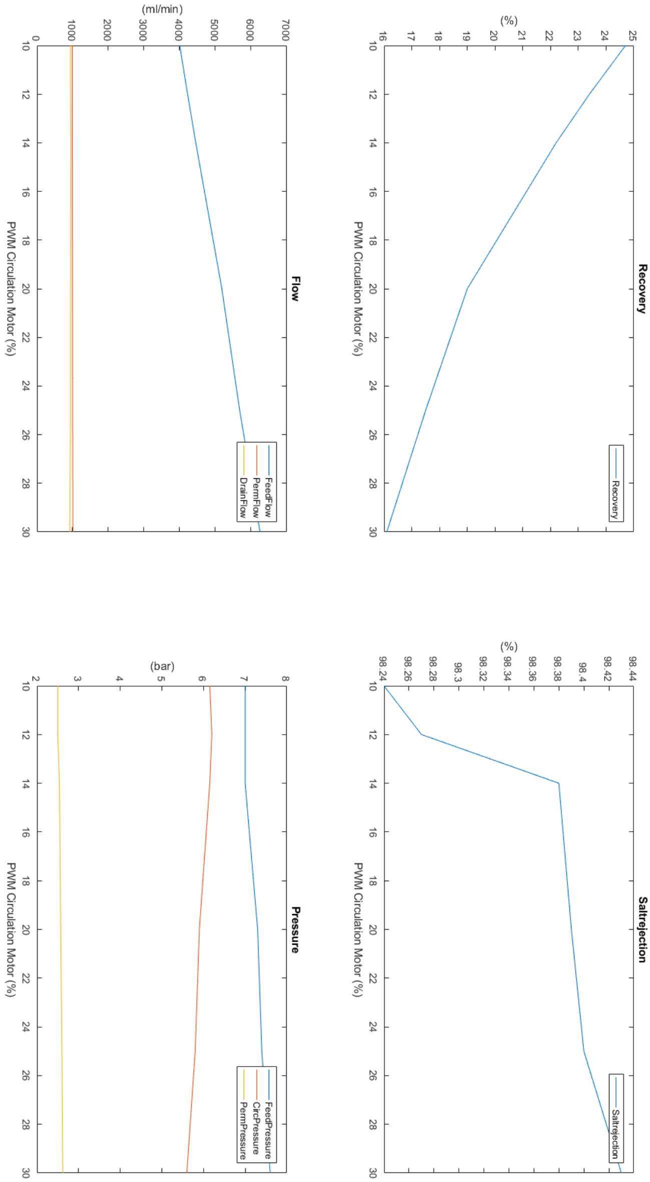

Figure 5.30 Tests with recycle pump as changing parameter

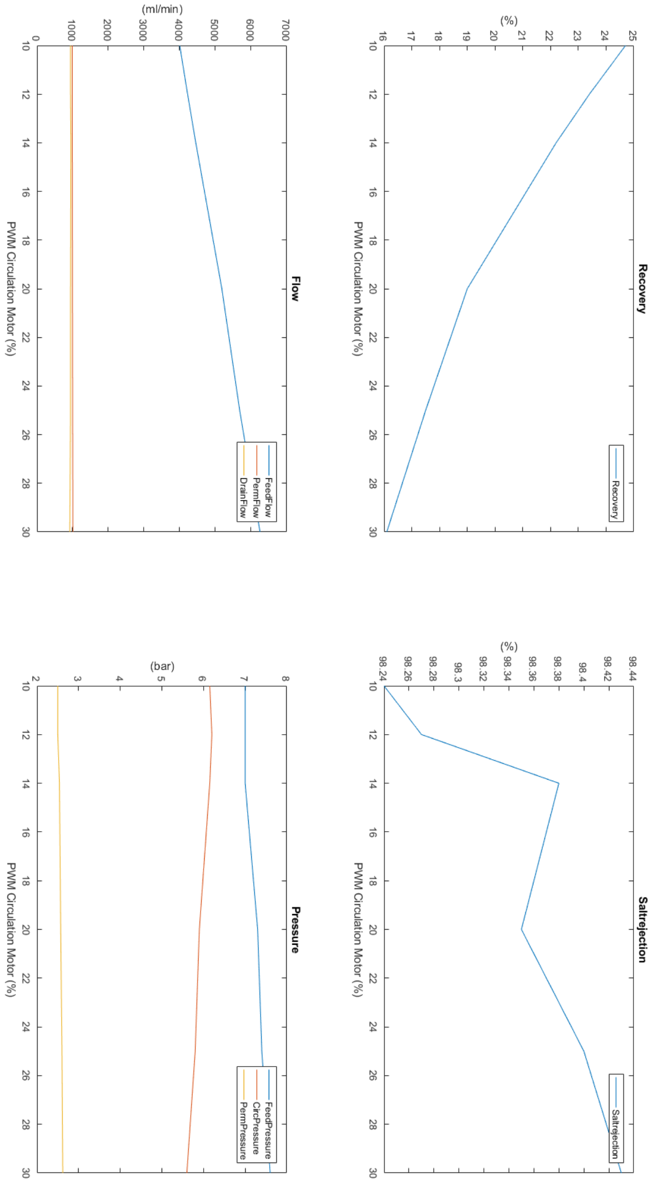

Figure 5.31 Tests with inlet pump as changing parameter

6

Discussion

6.1 System behaviour

The test setup was built to understand how the performance of the reverse osmosis changed while operating in different conditions and by analysis the logs from the tests it was possible to understand the complexity of this multiple input and output system. Testing was mostly carried out by fixing all parameters but one and then change this parameter and log how the system behaved, this proved to be difficult because some parameters, for instance recirculation flow and feed pressure were directly connected to each other. However, analysis of the log files from the tests it was possible to understand how different conditions and setups affected the behaviour of the system.

The main purpose of this thesis was to investigate the advantages of using a two-pump system instead of the current one pump system. We found that there were multiple advantages of using the two-pump system, the overall power consumption and noise levels could be reduced. The new setup also had the unforeseen advantage of reducing the pressure drop over the membrane. This was a result of changing the position of the inlet pump from inside of the recirculation loop to pumping straight into the loop and using the recirculation pump to create the desired flow. The reduced pressure drop causes the membrane to be more evenly pressurized, this should in theory prevent the uneven scaling of the membrane and also create a higher permeate flow at the section of the membrane that is closest to the recirculation stream.

Initially it was believed that a higher recirculation flow would improve the performance of the membrane. The initial theory was that by increasing the flow rate over the membrane surface a more turbulent flow would be achieved causing the high salinity water close to the membrane to mix with water further from the membrane. However, tests showed that this was not the case. The performance did improve by a small amount. However, by increasing the recirculation flow the pressure was also increased and the small improvements that could be observed was most likely caused by the increased pressure, not the increased flow rate over the membrane. Therefore, it was concluded that there was a no possibility of effectively optimizing the membrane by increasing the recirculation flow. According to the membrane manufacturer the recovery rate should not exceed 20 % in order to ensure the longevity of the membrane. Therefore, it was decided to use the recirculation pump to ensure that the recovery remained fixed at 20%.

Feed pressure affect both the salt rejection of the membrane and also the permeate flow. Increasing feed pressure had a direct relationship to permeate flow at a given temperature. Salt rejection also increased with higher feed pressure. This can be seen in figure TBD and from this data it can also be concluded that the increase is nonlinear. The positive effect of an increased feed pressure is greater at low pressure, for instance an increase from 2 to 4 bar has a larger positive effect than an increase from 7 to 9 bar. The physical reason for the improved salt rejection is due to the reason that water passes through the membrane surface at an increasing rate due to the higher pressure and dissolved salts that pass though the membrane is diluted by the larger flow of water. So by increasing the feed pressure and the permeate flow it is possible to improve salt rejection by diluting the passing salts with a higher permeate flow.

The higher temperature of the feed water, the lower is the viscosity of the water. Hot water also has a higher diffusion rate than cold water. Thereby, higher temperatures cause higher permeate flow over the membrane and increased salt passage over the membrane. Temperature is a parameter that cannot be controlled and is completely dependent on the temperature of the tap water where the system is located. Tap water temperature may vary from country to country and can also have seasonal changes. The results from tests concluded that temperature was the most significant quantity that needed to be incorporated in order to design an optimal system.

The conductivity of the feedwater is also a quantity that depends on the tap water and determines the lowest possible conductivity of the recirculation loop. By using permeate conductivity as a setpoint for controlling the drain valve it is possible to optimize the water efficiency of the system. Lower conductivity feed water allows the system to recirculate more water without reaching the critical limit when a permeate conductivity of 30 uS/cm could not be maintained. Therefore, the system could adapt to different feed water conductivity by adjusting the water efficiency.

Net driving pressure depends on the feed side pressure in the recirculation loop, permeate side pressure and also the osmotic pressure caused by the different salt concentrations across the membrane. In order to save energy, it is beneficial to have a low permeate side pressure and lower conductivity in the recirculation loop. In order to save water, the control loop controlling the drain valve accumulate high conductivity water in the recirculation loop which decreases NDP. However, this drawback is necessary to maintain a high water efficiency an in the authors opinion, the slight decrease in NDP is worth the increase in efficiency. It is possible to increase the feed side pressure by increasing the pump speed. However, this requires more energy. The only way to improve the NDP of a system without decreasing water efficiency or increasing energy is to decrease the permeate side pressure. This can be done by selecting components with a low pressure drop and by using a short flow path.

6.2 s

imulation

6.3 Model based design

6.4 Control System Design

There three main properties that was to be optimized were water efficiency and energy consumption. The conductivity of the permeate water should also be controlled.

A PI controller was used to control the conductivity of the permeate water by opening or closing the drain valve. Since the salt rejection of the membrane changed due to inlet water temperature and feed pressure there is a point for any salt rejection that generates a permeate conductivity of 30 uS/cm. As can be seen in figure 5.15 from the tests of the current system, a system with room tempered inlet water was able to maintain 30 uS/cm permeate water with 2500 uS/cm in the recirculation loop but if the inlet water was heated to 40 degrees Celsius only 1500 uS/cm recirculation conductivity was needed to reach 30 uS/cm. Thereby, controlling the valve position was critical to being able to make sure that the permeate conductivity was 30 uS/cm regardless of operating conditions.

Since the recirculation loop and the membrane contains about TBD liters of water the response from changing the drain valve was slow, much longer than the other control loops which has an almost immediate effect. Because of this it was necessary for the controller to slow.

An increase in pressure result in more fluid getting pushed out of the drain valve without changing the position of the valve. As a result, changes in pressure will act as a disturbance on this control loop. To counter the effect of this the valve needs to close to make sure that no water is unnecessarily being rejected to drain. However, closing the valve will result in an increased pressure in the system that need to be handled by the controller controlling the pressure in the system. This means that these two controllers are coupled to each other and that it is impossible to change one without influencing the other. Tests showed that increased recovery did not affect the salt rejection of the system. For this reason, it was decided to set the recovery setpoint to 20 % which was a the recommended recovery from the membrane manufacturer. This regulator has little impact on the regulator controlling the drain valve but when the flow in the recirculation loop is increased so is the pressure in the loop. The effect of this can be seen in figure 5.23 and 5.22. From the figures it can be seen that 22 percent recovery caused a pressure of 5.2 TBD bars and a recovery of 14 percent TBD increased the pressure to 6.2 bars. Consequently, the regulator pressurizing the recirculation loop act as a disturbance on the recovery regulator. The last controller was the controller tasked with optimizing the membrane. Warmer inlet temperature increases the amount of salts that pass through the membrane as well as the water. However, the increased temperature increases the salt passage more than the passage of water, resulting in a higher permeate flow with a higher conductivity. The only way to counter this phenomenon and increase salt rejection is to increase the permeate flow by increasing feed pressure and dilute the increased salt in the permeate with more water. By using the formula to convert feed water temperature to a setpoint for the permeate flow the salt rejection of the membrane could be optimized by increasing the feed pump to generate a higher feed pressure and thereby a higher permeate flow. This design allows the system to counter the detrimental effect increase inlet temperature has on the salt rejection of the membrane at the prize of using more energy. The increased salt rejection allows higher conductivity water to be accumulated into the recirculation loop and thereby water efficiency is increased. In figure 5.12 it can be seen that increasing feed pressure has a larger positive effect on salt rejection when the inlet temperature was high and therefor there is no need to waste energy running the system at high pressure because it will have low impact on salt rejection. In this scenario, it is better to save energy by running the system at lower pressure and permeate flow. The system was designed to be able to deliver a stream of permeate water with a conductivity of 30 uS/cm without using more energy and rejected water than necessary, but our tests showed that the only way to increase salt rejection and lower the amount of rejected water was to increase the permeate flow. This meant that there is a trade-off between saving water and wasted energy and vice versa. Running the system on low pressure decreases salt rejection and thereby less salts could be recirculated back into the recirculation loop meaning that more water needed to be wasted. By testing, the lowest permeate flow that generated a permeate conductivity of 30 uS/cm at different temperatures could be found and these results were translated into an optimal function for what permeate flow should be used as a setpoint at different temperatures.

6.5 Noise reduction

An additional positive effect of using two pumps instead of one was that there was a significant reduction in noise. Since this effect was not a part of the initial scope and just a positive side effect of using two pumps no data was gathered to support the claim but the difference could be heard when both systems were tested. The reason for the noise reduction was that both the two pumps were running at much lower rpms when using two pumps than one.

6.6 Reduced pump size

Using the pumps with the new system the pump speed varied from TBD to TBD depending on the permeate flow setpoint which is a reduction from the 60 %and 80 % used when one pump was used. This indicate that it might be possible to use smaller pump. Smaller pumps could allow the system to be smaller and they are often cheaper than larger pumps. This reduction of the prize could reduce the increased cost of buying two pumps instead of one. Smaller pumps might also be quieter.

6.7 Membrane size

membrane size determines the permeate flux and for smaller systems that it might be beneficial to reduce the size of the membrane to make the device smaller and possibly cheaper. In addition to the reduced size and prize a smaller membrane has less pressure drop and more even pressure over the whole membrane.

6.8 Membrane identification method

This report is based on the DOW FilmTec membrane TBD and the temperature to optima permeate flow rate will only work for this membrane. However, the method for finding this curve for any other reverse osmosis membrane is general and easy to follow. By following the method outlined in this report this curve can be found for any other membrane and can be modified for other specifications on the permeate conductivity.

6.9 Scaling

One advantage of using a permeate flow setpoint for the feed pump controller is that it will let the system adapt to scaling. When scaling occurs, the membrane surface become coated with suspended solids that clogs the surface of the membrane. Using the control design from this thesis, when the membrane surface clogs up more pressure is needed to reach the setpoint for the permeate flow and the feed pump will compensate for this by increasing its speed. Membrane fouling is inevitable and eventually the membrane will have to be replaced. Even though Membrane fouling can't be stopped it can be minimized by following the operational guidelines from the membrane manufacturer. One of these guidelines are the maximum allowed recovery the recovery control loop has been implemented.

6.10 Drain valve

The valve used in the test rig was built for much larger systems and not intended for fine tuning. This caused problems because it was not possible to make small changes of the position of the valve and this caused oscillations in the conductivity of the permeate. Because it was clear what caused the oscillation and that it would take a lot of time to find, order and rebuilt the test rig with a new valve we choose to continue using the valve. If there are any further development of the system, the valve should be replaced.

7

Conclusion

The permeate quality of an RO-system is reduced considerably when the system is running on hot water due to the decreased salt rejection. The results from our tests showed that the most effective way of incresing permeate quality was to create a higher permeate flow when the system was hot to dilute the increased salts in the permeate with a larger volume of water. By identifiying what permeate flows are needed at different temperatures it is possible to find an optimzed permeate flow for every temperature within the operating range..

By replace the current one pump system without any feedback loops with a system using two pumps and PI regulators and the abilty to control the system allows for a more optimzed performance on both water efficiency and energy consumption. As mentioned, the current system does not use any feedback controllers and therefor it cannot adapt to the changing behavior of the reverse osmosis membrane that is introduced by changing temperatures. The modified system however, can measure and adapt to changing working condition and improve the performance of the membrane.

Since the performance of the membrane improves when it's subjected to more feed side pressure the it can be argued that the system can be optimized by allways applying maximum feed pressure. However, generating pressure costs energy and at low temperatures this extra energy might not be worth the cost even if it improves water efficiency by increasing salt rejection. Consequently, Running the system at low pressure will cost less energy but waste more water due to the decreased salt rejection. Therefore, it is not possible to optimize energy consumption without reducing the water efficiency of the system. As a result, any optimization of the system will be regarding which of these parameters is considered to have the lowest cost.

The model of the reverse osmosis membrane is build around the teoretcal equations presented by DOW. These equations are accurate in describing the flow and pressure charachteristics at different temperature. However, DOW is using a fixed rejection rate for all temperatures and does not incorporate the diluting effect that occurs when pressure is increased. To be able to make a more accurate model this phenomenon needs to be matematically described and added to the model.

To summarize, the feedback controlled two pump system is a viable soultion with several benefits over the current system and it is possible to optimize water efficiency and power consumtion when using two pumps that would not have been possible with one.

8

Future Prospects

8.1 Parameters of concern

Saltrejection Recovery

8.2 Optimization

Energy efficiency Water efficiency

8.3 Mapping

This work is a first step in investigating the possibility to optimize the performance of the membrane. It can be seen that there are great possibilities, but in order to achieve an optimum performance more mapping is to be done. The main factors that is seen and a proposal for further investigations are:

- XXX
- XXX

8.4 Membrane size

As seen in the tests the permeate water quality is due to the flow and salt rejection rate. In order to design devices that will deliver as clean and purified water as possible it might be beneficial to use smaller membranes when lower permeate flow is needed. Today there are recirculation paths from permeate side back to tank where clean purified water is mixed with inlet water, which might not be neccssary if down scaling the membrane.

Bibliography

Company, T. D. C. (2018). “Dow water and process solutions - levels of separation of ix, ro, nf, uf”. **2**, p. 1.

R, S. (2015). *"Membrane Technology and Engineering for Water Purification(Second edition)"*. Vol. 435, pp. 1–80.

water, P. industrial. *What is reverse osmosis*. URL: `https://puretecwater.com/reverse-osmosis/what-is-reverse-osmosisl`. accessed: 09.02.2018.

A

Appendix A