Optimization of Reverse Osmosis Performance

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Abstract

Reverse osmosis is one of the most common water purification techniques and is used in applications ranging from salt water desalination plants to medical devices. Baxter develops medical devices and water purification devices used in medical applications using the reverse osmosis technique.

In this thesis a new flow path design is investigated. By replacing a single feed water pump with two independent pumps investigations of the possibilities of optimizing the performance of the membrane is done. The goal is to investigate any advantages with the new setup and to design a control system that is able to optimize the performance of the system for all operating conditions within the operating range. The optimization is isolated to the performance of the reverse osmosis membrane used in the water device by Baxter.

Theory of the reverse osmosis identifies two important parameters that can improve the membrane performance, pressure and flow. Two parameters that affect the purity of the product water delivered by the water device is conductivity and temperature, which has a high negative impact of the membrane performance.

The second pump offers another degree of freedom which allows the pressurisation and flow over the membrane to be independently controlled.

The method for the investigations includes both modelling in Simscape and real test series on a physical rig built at Baxter. Tests on current setup used by Baxter today and the two pump system is performed.

Results showed that it is possible to improve the performance of the system by using the two pump solution. Especially in critical working areas as high temperature or high conductivity, or a combination of both.

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During the thesis work we have always felt like a part of the team at the Water Technologies department and many have contributed to our thesis and have made us feel welcome.

We would also like to thank MathWorks for their help and for supplying the necessary licenses to program the rig.

We hope that Baxter will be able to use our research to continue delivering life saving care to patients and we wish you the best with your future endeavours.

Angelica Persson and Pontus Lundberg

Contents

Dictionary

Inlet water: The water that is pumped into the system from the tank.

Feed water: The pressurized water stream that i pushed into the feed inlet of the membrane.

Permeate water: Purified water stream leaving the membrane as product water.

Reject water: The brine water leaving the RO-module. The reject water can either be recirculated or rejected through the drain valve.

Drain water: The water wasted, e.g. water leaving the flow path through the drain valve.

Recirculation loop: Recirculation path from the reject stream of the RO-module into the feed stream.

Membrane flux: Flow through the surface of the membrane.

Pressure: System pressure, measured in Bar.

Flow: Water flow in the flow path. Measured in ml/min.

Conductivity: The electrical conductivity of the water is used to determine the amount of dissolved salts in the fluid. Measured in (µS/cm).

RO: Short for Reverse Osmosis

Semi-permeable membrane: Physical property of the membrane that describes how the membrane is able to let some substances permeate over the mebrane while blocking other substances.

Recovery: Percentage of feed water that permeate across the membrane into the permeate stream.

DOW: The DOW chemical company is the manufacturer of the Reverse Osmosis membrane investigated in the thesis.

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Introduction

3.1 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 not to harm the patients when using the final product. The water systems used for water purification are using the reverse osmosis (RO) method as the first stage in the purification process. It removes impurities, as salt and inorganic molecules from the water[**1**].

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 that lets water pass freely through the membrane creating a purified product stream. The product water is used by the dialysis machines in order to give the patients a safe treatment. If the water is not pure enough the patient is exposed to high risk and it is of great importance that the purification plant, e.g the water device delivers good quality water at all times.

The current water device system is implemented with one pump, which 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. Both flow rate and pressure have a significant impact on the performance of the membrane.

3.2 Motivation

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

Currently there is a simulink model of the RO-membrane from an earlier masters thesis. However, this model does not include the temperature dependencies of the membrane and therefor these dependencies should be investigated and added to the model.

3.3 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. The positioning of the pumps, membrane and other components should be investigated and tested.

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 and implemented on a physical test setup. This algorithm, should be able to control the flow and pressure over the RO-membrane to maximize the performance of the membrane while minimizing waste water and energy consumption.

Framing of questions

- **Is it possible to upgrade the RO-membrane model to include temperature dependencies?**
  Due to the fact that the membrane is temperature dependent and considered non linear in different temperatures, is it possible to implement the temperature dependencies in full range or is it preferable to limit the membrane to work in a set range in order to handle the temperature dependencies linearly?

- **Is it possible to control the system with two pumps instead of one?**
  Will the two pump system increase the performance of the membrane under all circumstances, or even some? Will it ensure the quality on the water in a higher range than today?

- **Is it possible to design a control algorithm using two pumps that will optimize the performance of the membrane while reducing waste water, power and possibly noise? (In comparison with the current system)**
  The belief is that the two pump system will give a higher degree of freedom to control pressure and flow in the system. However, parameters as the amount of waste water, the uses energy to deliver pure water and even noise level is parameters that can be improved by a two pumps system.

3.4 Method

In order to investigate the performance of the current system and to compare it with the new model the 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.

- Implementation in a test rig to verify the performance of the system.

- Run tests to determine the performance.

4

Theory

4.1 Semi-permeable membrane

A membrane is defined as a barrier between two homogeneous phases. The process is a continuous steady-state operation consisting of three streams: feed, permeate and reject. The main component in the process boundary is the semipermeable barrier that selectively allows the passage of some components but not others. [2]

4.2 Osmosis

The osmosis process occurs when two solutions of different chemical concentrations are separated by a semipermeable 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 4.1. The fresh water on the right side in the figure wants to pass through the semi-permeable membrane in order to reach equilibrium with the salt water on the left side. This creates a stream of water from right side of the membrane to the left side. The osmotic pressure created by the different solute concentrations in the fresh and salt water creates the flow. A greater difference in concentration creates a higher osmotic pressure than a lower concentration difference.

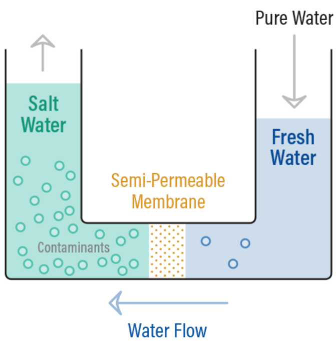

Figure 4.1 Osmosis (https://puretecwater.com/reverse-osmosis/what-is-reverse-osmosis)

4.3 Reverse osmosis

The reverse osmosis (RO) process is the reverse process of osmosis. By generating a pressure on the high concentration side it is possible to overcome the osmotic pressure, created by the difference in contaminant concentration. When pressure is applied to a semipermeable membrane, the water molecules are forced through the semipermeable membrane and the contaminants are not allowed through. The amount of pressure required depends on difference in salt concentration over the membrane. In order to achive 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 leaves the RO-unit in two streams. One stream pass through the membrane and is called permeate, this is the filtered purified solution. The other stream contains the contaminants that did not pass through the membrane and is called reject or brine. This can be seen in figure 4.3.

The contaminants build up on the membrane surface and it is of great importance to try to sweep them away to maintain a clean surface. If the contaminants build up the performance of the membrane will decrease, and cleaning with chemicals or heat might be necessary [**3**]. The phenomenon of reverse osmosis can be seen in 4.2. The water on the pressurized side is pushed through the membrane to the permeate side because the applied pressure is greater than the osmotic pressure. The result is a stream of pure water with only small amounts of contaminants.

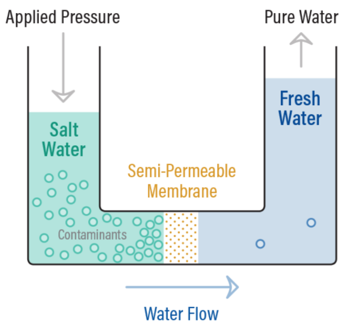

Figure 4.2 Reverse Osmosis, https://puretecwater.com/reverse-osmosis/what-is-reverse-osmosis

Fouling

Fouling occurs when contaminants accumulate on the surface of the membrane. Fouling contributes to a pressure drop that will decrease the performance of the membrane and reduce the permeate flow. Fouling will happen eventually to some extent given the fine pore size of the membrane but a high reject flow and proper

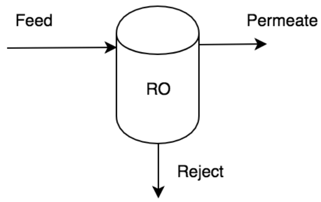

Figure 4.3 RO-system

pretreatment will extend the operational time between cleaning procedures of the membrane [**3**].

4.4 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 4.2 shows the main process. The mass balance equations are applied to feed, permeate and reject side, as in figure 4.3.

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 are rejection ratio:

$$R = 1 - \frac{C_p}{C_f} \tag{4.1}$$

and recovery ratio:

$$Y = \frac{Q_p}{Q_f} \tag{4.2}$$

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

$$Q_f = Q_p + Q_r \tag{4.3}$$

and:

$$C_f Q_f = C_p Q_p + C_r Q_r \tag{4.4}$$

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

$$J_w = \frac{Q_p}{A_m} = A(\Delta P - \Delta\pi) \tag{4.5}$$

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:

$$J_s = B(C_f - C_p) \tag{4.6}$$

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

$$C_p = \frac{C_f}{1 + \frac{A}{B}(\Delta P - \Delta\pi)} \tag{4.7}$$

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

$$Q_p = Q_f Y \tag{4.8}$$

The four mass balance equations (4.3 - 4.6) 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:

$$\Delta\pi = b(C_f - C_p) \tag{4.9}$$

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.

Equations from DOW

$$Q_p = A_i \pi_i S_E (TCF)(FF)(P_{fi} - \frac{\Delta P_{fcj}}{2} - P_{pi} - \pi + \pi_p) \tag{4.10}$$

$$\pi_f = 1.12(273 + T)\sum m_j \tag{4.11}$$

$$TCF = \begin{cases} e^{2640(\frac{1}{298} - \frac{1}{273+T})}, T \geq 25 \\ e^{3020(\frac{1}{298} - \frac{1}{273+T})}, T \leq 25 \end{cases} \tag{4.12}$$

$$pf_i = e^{0.7Y_i} \tag{4.13}$$

$$Y = \frac{Qp}{Qf} \tag{4.14}$$

$$C_p = B(C_{fc})(pf_i)(TCF)\frac{S_E}{Q_i} \tag{4.15}$$

$$A(\pi) = \begin{cases} 0.125, \pi \leq 25 \\ 0.125 - 0.011(\frac{\pi-25}{35}), 25 \leq \pi \leq 200 \\ 0.07 - 0.0001(\pi - 200), 200 \leq \pi \leq 400 \end{cases} \tag{4.16}$$

4.5 Control theory

Control theory deals with the behaviour of dynamical systems. The inputs and outputs may vary in numbers, and the reference signal, output is controlled by manipulating the input signal to obtain the desired output of the system. The characteristics of a system determines which control algorithms that are suitable. In order to design a controller that is capable of regulating the system parameters such as speed, linearity/non-linearity, complexity and robustness needs to be analysed before a specific method is chosen. Below, some key words and different types of control principles are presented.

PID control

The PID controller is the most commonly used algorithm for process control. PID control consists of three basic coefficients, P (proportional), I (integral) and D (derivative) which are varied to recieve an optimal system response. It has a robust performance in a wide range of operating conditions. The parameters need tuning in order to giva an ideal response.

The basic idea behind a PID controller is to read a signal from a sensor, compute the desired actuator output by calculate the P,I and D response and sum them to compute the output of the controller. The controller needs a given set point and a measured process value from the system. A closed loop system provides feedback to the control system and the offset between the set point and the measured value is compensated by the controller.

To achieve good performance of the controller the requirements of the system need to be identified. The control system performance can be measured by applying a step function as the set point command variable, and then measure the response of the process variable.

Proportional component (P) The proportional component (P) depends on the difference between the set point and the process variable. The difference between them is referred to as the Error. The proportional gain determines the ratio of output response to the error signal. Increasing the proportional gain increases the speed of the control system response. If the gain is set too high an oscillative system behaviour is expected and the system will become unstable if the proportional gain is set too high.

Integral component (I) The integral component (I) sums up the error over time. A small error term will cause the integral component to increase slowly. The response will continuously increase over time as long as the error is not zero. A windup phenomenon may occur if the control signal is saturated and an implementation of an anti-windup is often needed. If an anti-windup system is not implemented the controller keeps increasing the integral component without the controller driving the error signal towards zero.

Derivative component (D) The derivative component (D) causes the output to decrease if the process variable increases rapidly. The response is proportional to the rate of change of the process variable. Increasing the derivative time parameter will cause the control system to react more strongly to changes in the error term and will increase the overall control system response. [**4**]

Windup and methods to avoid it

Windup occurs when the integrating component increases and saturates the control signal. Below, two different ways of implementing anti-windup, conditional integration and Back-calculating, to avoid wind-up is presented.

Conditional Integration Conditional Integration is an anti-windup method that stops the integration process when the output has reached a saturation limit. The method ensures that while the controller is experiencing saturation there is no further increase in the value of the output. When or if the the error reduces below certain level, making the output come out of saturation level, the integrator start again [**5**].

Back-calculating Back-calculating is a method that uses a PID controller on parallell form with a back-calculation factor calculated from a model of the actuator model. The back-calculating method uses one parameter to calculate if the output signal has saturated and limits the integrating part until saturation is no longer experienced. [**5**].

Tuning

The process of setting the optimal gains for the P, I and D component is called tuning. The components shall be designed in order to get an ideal response from the system. There are many concepts on how to tune a PID-controller. Some are presented below.

Lambda method for tuning PI controllers Lambda tuning is an approximative pole placement method. The tuning method has the potential to be a simple straight forward tuning method. The theory of the Lambda method is based on two assumptions. The first one where the process is modeled as a first order process with dead time. The second one where the closed loop transfer function is specified as:

$$G_{cl}(s) = \frac{e^{-sL}}{1 + sT_{cl}} \tag{4.17}$$

where T_{cl} is the time constant of the closed loop, T is the time constant and L is the time delay.

The lambda method can be used with cancellation of a system pole for stable processes and without cancellation of system poles for stable or unstable processes. The lambda method requires only one tuning parameter, T_{cl} that is the desired closed loop constant. The choice of T_{cl} is a key decision in order to get a well performed system. T_{cl} can be choosen to any value, but in practice, an arbitrary choice can lead to poor performance or even instability, since the simple process models are only valid in certain frequency regions. Therefore the closed loop constant shall be related to the process dynamics, e.g. time constant (T) and time delay (L). To obtain a fast response with good rejection of disturbances it is desirable ta have a small value of T_{cl}. A large value of T_{cl} gives a system that is more insensitive to parameter variations.

If there is limited knowledge about the system dynamics it would be appropriate to use a relatively high value of $T_{cl} = T\lambda$, where λ is the adjustable parameter. If the system is considered having a little deadtime, a relatively small T_{cl} is appropriate. The T_{cl} can be determined by $L\lambda$ in integrating processes. [**6**]

5

Method/Implementation

5.1 Overview Method

The working method during the thesis have been based on model based design in which a model and a physical system have been built in parallel.

First, studies of theory and on previous work in the field were made in order to investigate requirements. After that, a flow chart investigation and test planning were made in parallel. Thereafter, modelling in Simscape and the construction of the first test rig, a rig using only one pump, was done. Afterwards, the one pump system was tested and the data from all the sensors were gathered.

Analysis of the data was made and the rig was modified with two pumps to simulate the proposed two pump system. This was done in parallel with the modelling of the two pump system.

After the tests on both systems were completed, an extensive comparison of the two systems were made. In figure 5.1 an overview of the work flow can be seen to get a better overview.

The data gathered from the tests could then be used to design an optimal control algorithm.

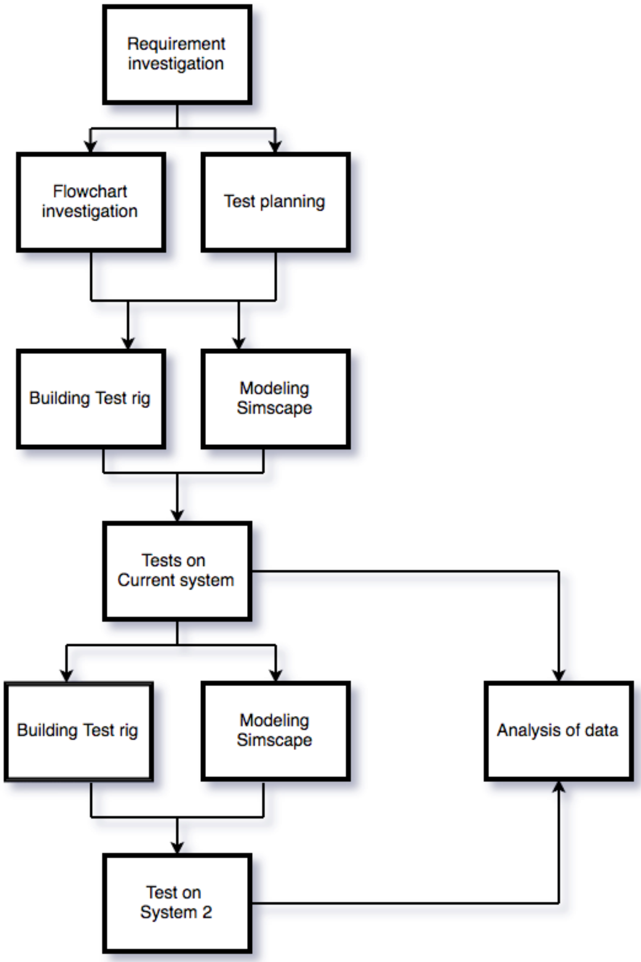

Figure 5.1 Overview of method

5.2 Modeling

The Simscape software tool described in section Appendix A is used to do a physical system model in order to model the characteristics of the membrane. The isolated system with pump, pipes, valves and water supply (tank) is implemented. The matematical equations used in the simulation can be seen in chapter 4.4. The temperature correction factor, TCF is implemented with equation 4.12 to simulate the temperature dependency of the membrane. The osmotic pressure, P_{osm} is implemented in the model by equation 4.11. The polarization factor, P_f that describes the polarization along the membrane surface is implemented with equation 4.13.

Dimensions on valves and pipes are implemented as the dimensions in the water device. Water quality, and temperature can be adjusted to simulate different conductivity and temperatures, to represent real values. The pump speed can be adjusted in the model to represent an actual value. Plots of characteristics of pressure, flow, salt concentration and temperature are generated from the simulations and can be seen in section 6.1

5.3 Flowchart investigation

Today, a system containing one pump is used by Baxter. The pump is positioned at the feed side of the membrane. The pump creates a pressure to overcome the osmotic pressure and creates a flow from feed to permeate side. The system can be seen in figure 5.2. The pump is used at two different set points on speed depending of the water quality (conductivity). There are no control implemented to adjust the speed (besides these two set points) of the pump in order to create different pressure and flow characteristics over the membrane to increase performance due to these different conditions. The valve in the recirculation path is adjusted when installing the water device at the clients and is not adjustable after that, other than by a service technician.

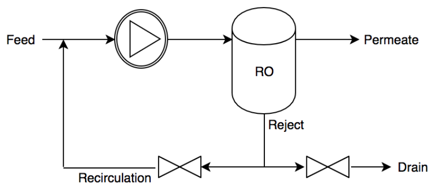

Figure 5.2 One pump system

This limits the possibility for the water device to adapt itself to different working conditions and changes in inlet water quality and also if the membrane surface is fouling. Overcoming these issues would enable the water device to adapt to seasonal variations and changing temperature and tap water quality. If the membrane performance could be improved in all conditions and especially when the conditions vary over time the freedom of controlling the pumps and valve is desirable to optimize the performance of the membrane.

To be able to investigate the performance and the feasibility of replacing the one pump system with a two pump system in order to control the flow and pressure over the membrane two different ideas were considered. Desirable outputs for increasing the membrane performance are:

1. Pressure drop over the membrane is high

2. Flow through membrane is high

The expected results of an optimization is that: the permeate conductivity is minimized, fouling on the membrane surface is minimized, the temperature dependencies is taken care of, waste water is minimized and the energy efficiency of the system is increased. In this thesis the investigations are limited to:

1. Permeate conductivity is kept under 30 μS

2. The temperature dependencies are handled with control asystem

3. Waste water is minimized

4. Energy efficiency is improved compared to current one pump solution

Different system setups were considered to implement the second pump. The two most promising ideas are presented below.

System 1

The first system has one pump on the feed side and one pump on the permeate side, as seen in figure 5.3. This setup contributes with the ability to create a greater net pressure over the membrane with a low, or even a negative gauge pressure on permeate side, while the feed pump creates a high pressure on feed side. Benefits with this implementation is the low energy consumption due to the ability to create negative pressure on the permeate side. A high net driving pressure (pressure difference from feed to permeate side) can be achieved with rather low pressure on the feed side. The disadvantage might be that the second pump may contaminate the permeate stream.

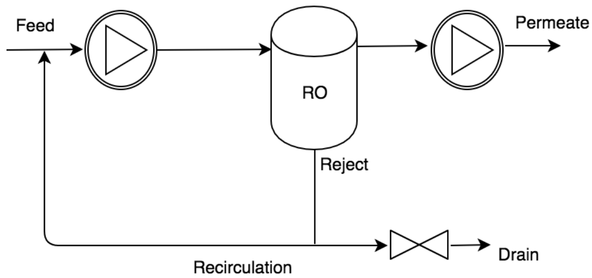

Figure 5.3 System 1

System 2

The second system considered has one pump on the feed side and one pump in the recirculation loop, as seen in figure 5.4. The feed pump is used to create high pressure on the feed side and the pump in the recirculation path is used to control the flow in the recirculation path. As a result, the recovery rate can be controlled. According to theory the membrane behaviour is dependent on feed and flow characteristics over the membrane, salt concentration and temperature.

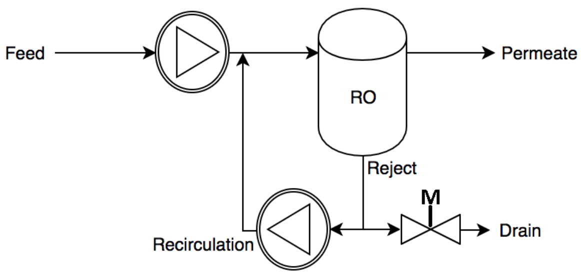

Figure 5.4 System 2

Both system 1 and system 2 enables the ability to control pressure and recirculation flow independently.However, one big disadvantage with system 1 is that one of the pumps is positioned on the permeate side and this could potentially contaminate the permeate. System 1 was therefore precluded.

5.4 Flow measurements using the pumps

In order to investigate the performance of the membrane, the pressure, flow, conductivity and temperature are measured and logged. The test rig should be able to operate at 15 bar and this made it difficult to find sensors that were able to function at such high pressure. The solution was to build our own sensor blocks and to use the feedback from the hall sensors in the pumps to measure the flow.

Due to lack of instruments that could measure the flow under the high pressure some mapping of the flow from the pumps was made. The flow stream through the pumps were measured at different RPMs and with different pressure resistance on the outlet. The flow is depending on the RPM with negligible difference depending on the applied outlet pressure from the pump. The results from the mapping can be seen in the results chapter.

5.5 Implementation Test Rig

Current System

In order to run all tests a physical rig was built. A first version was built to simulate the system used today, see figure 5.5, with all the measurement sensors implemented. The first version of the rig contained one pump with power supply, one RO-membrane, three needle valves, one drain valve, one heating bath, three measurement sensors, pipes and couplings. The heating bath is used to simulate different inlet water temperatures. The needle valves are used to adjust the pressure in the system to correspond with the real pressure characteristic in the water device.

In order to log all signals and to run the system on the Real-Time Target Machine described in Appendix A is connected with all significant signals. A GUI designed in Simulink to control the rig is also connected to the rig. All control and feedback signals to and from the rig is handled in Simulink. After a test all measurements could be downloaded to a computer for analysis. Selected signals and calculations could also be displayed on a separate screen in real-time.

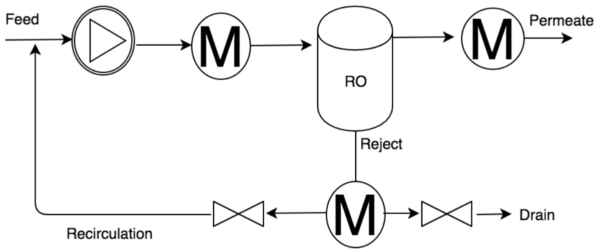

Figure 5.5 Current System, with measurement sensors

System 2

The second system, System 2, was built by modifying the first rig, according to figure 5.6. The second rig contains: two pumps with power supply, one RO-membrane, three needle valves, one drain valve, one heating bath, one flow meter, three measurement sensors, pipes and couplings. The heating bath is used to simulate different inlet water temperatures. The needle valves are used to adjust the pressure in the system to correspond with the real pressure characteristic in the water device. The flow meter is used to measure the permeate flow from the membrane.

The Simulink workspace, and the GUI was modified to be able to log all signals from the rig. All signals are displayed in real time as in the previous rig edition. Data is sampled and logged to be able to analyse the behaviour in the two pump system.

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 6.19 - 6.22.

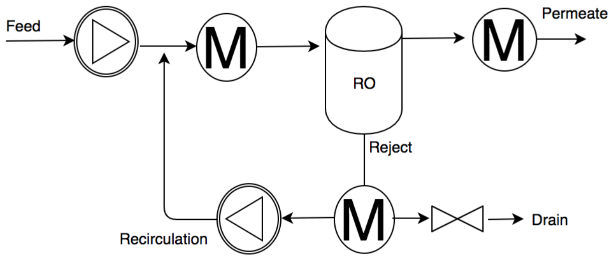

Figure 5.6 System 2, with measurement sensors

5.6 Test setup

In order to compare the results from the current one pump system with the proposed two pump system, system 2, similar tests will be carried out on both systems. Measurements of interest are investigated in order to understand the how different working conditions affect the membrane. The same working conditions will be tested on both the current one pump system and on the two pump system. The critical operational areas for the membrane are considered to be high temperatures (over 30 °C) and high conductivity (over 2000 µS)/cm. The tests are performed in a range from 280-3000 µS and from 20-40 °C.

The working conditions that are to be investigated can be seen in Table 5.1. The motor effect column is only valid for the one pump system.

Steady state	Temperature (°C)	Feed Conductivity (µS/cm)	Motor effect (%)
1.1	20	280	60
1.2	20	500	60
1.3	20	1000	60
1.4	20	1000	**80**
1.5	20	2000	60
1.6	20	2000	**80**
1.7	20	3000	60
1.8	20	3000	**80**
2.1	30	280	60
2.2	30	500	60
2.3	30	1000	60
2.4	30	1000	**80**
2.5	30	2000	60
2.6	30	2000	**80**
2.7	30	3000	60
2.8	30	3000	**80**
3.1	40	280	60
3.2	40	500	60
3.3	40	1000	60
3.4	40	1000	**80**
3.5	40	2000	60
3.6	40	2000	**80**
3.7	40	3000	60
3.8	40	3000	**80**

Table 5.1 Testcases for the investigations of the membrane behaviour. Each case represents one steady state in the experiments.

6

Results

6.1 Modeling

A physical model of the membrane was made and the given results can be seen below. In figure 6.1 the flowchart is given. The RO-membrane is simulated with three nodes; feed, product and reject, and an extra input for specifying the temperature. The temperature node gives freedom to simulate the behaviour of the membrane at different temperatures.

The model consists of the pump, pipes, valves and a tank. The water in the tank can be set to contain any salt concentration to be able to simulate different conductivity values. The speed of the pumps can be changed to change the flow and pressure characteristic over the membrane in the model.

All plots in this section show expected behaviour according to the theory about membrane behaviour when the temperature is rising. Flow and conductivity on permeate/product side are increasing which is desirable to control in the system, and to be kept at limited values in order to have the water device to handle these differences in working conditions. The results of the simulations are considered to be realistic accrding to the theory of the membrane. More details of the parameters in the model can be seen in subsections below.

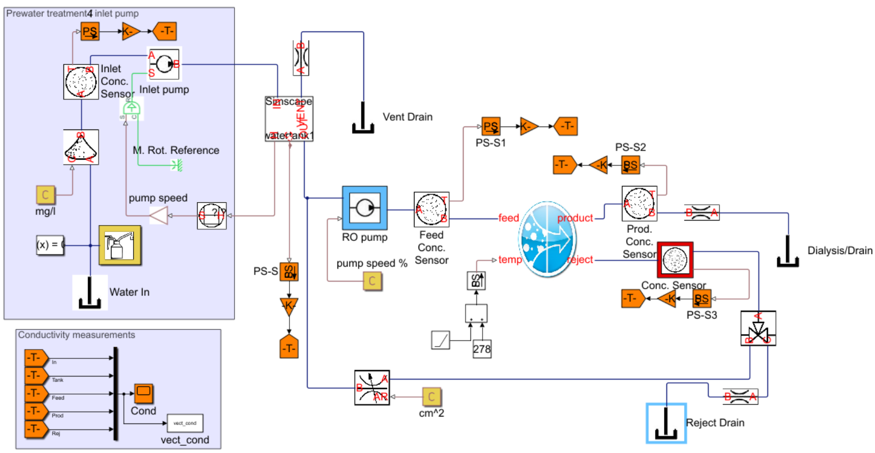

Figure 6.1 Model made in Matlab tool Simscape

Temperature

In figure 6.2 the simulated temperature, 278-316 K is shown. Plots 6.3 - 6.11 show the behaviour over a simulated time of 2000 s and a temperature range of 278-316 K. Pump speed is kept constant. The temperature correction factor, TCF, in figure 6.3 is the temperature dependant parameter implemented in the simulated model to receive the differences of the behaviour of the membrane. At 298 K TCF is equal to 1. Below and above it is adjusted to compensate for the differences of the membrane behaviour.

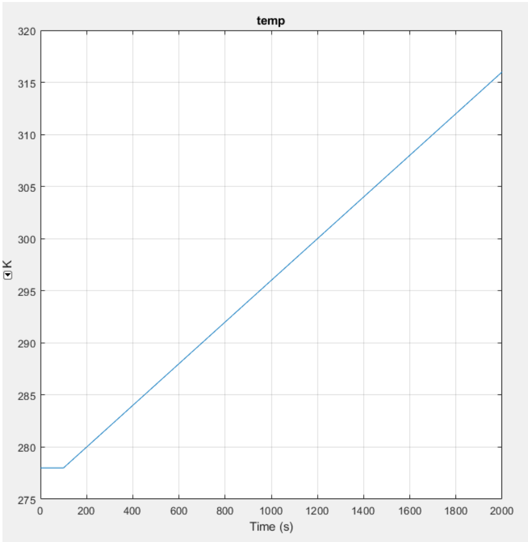

Figure 6.2 Temperature range in simulations, from 278-316 K

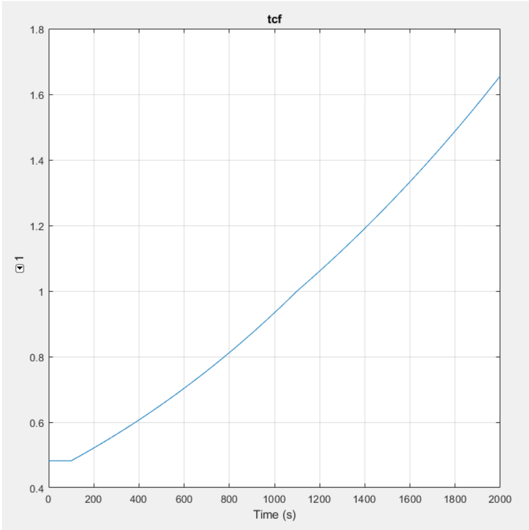

Figure 6.3 Temperature correction factor, TCF, when temperature is simulated from 278-316 K

Salt concentration

In figure 6.4 the salt concentration in kg/s on the feed side of the membrane is shown. The salt concentration increases with increasing temperature. In figure 6.5 the salt concentration in the product water is shown. Due to the mass balance equation in 4.4 the sign is negative, and the concentration increases with temperature. Figure 6.6 shows the salt concentration on the reject side. It increases a little with temperature (negative sign due to the mass balance equations).
The salt concentration in the feed water increases from 0.8 kg/s to 0.96 kg/s. The product water concentration increases from (-) 0.2 to 1.8 kg/s. The reject salt concentration increases from (-) 0.8 to 0.96 kg/s.

The salt concentration characteristics is in line with the expected values of the system for the simulations and is considered to be realistic for the model.

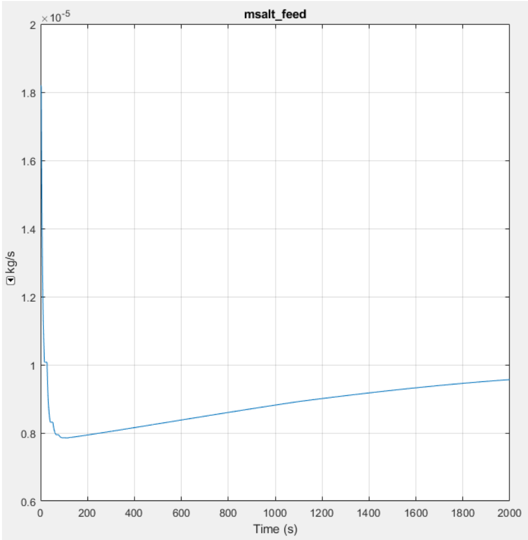

Figure 6.4 Salt concentration in feed water, when temperature is simulated from 278-316 K

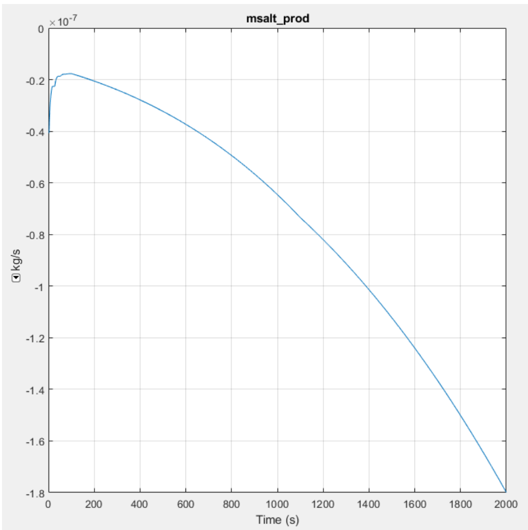

Figure 6.5 Salt concentration in product water, when temperature is simulated from 278-316 K

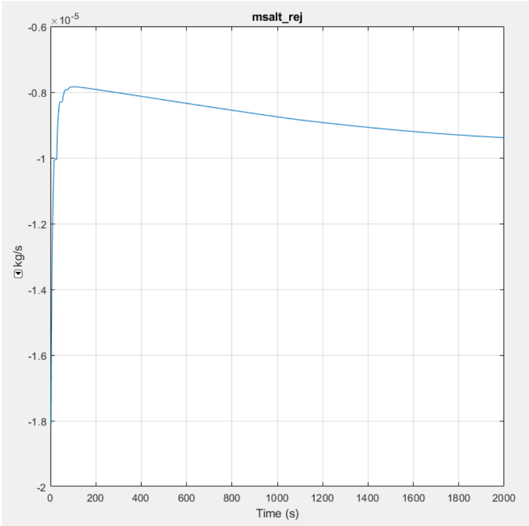

Figure 6.6 Salt concentration in reject water, when temperature is simulated from 278-316 K

Flow

Figure 6.7 - 6.9 show the flow in the three nodes; feed, product and reject. The mass balance equation in 4.4 gives negative sign on reject and product side. The feed water flow increases negligible from 8.441-8.444 l/min. Product/permeate water flow increases from (-) 0.62-1.42 l/min. Reject water flow decreases from (-) 7.82-7.2 l/min.

The plots show expected behaviour of the flow in the system. The membrane pore size is increasing with temperature and the permeate flow is increasing with rising temperature.

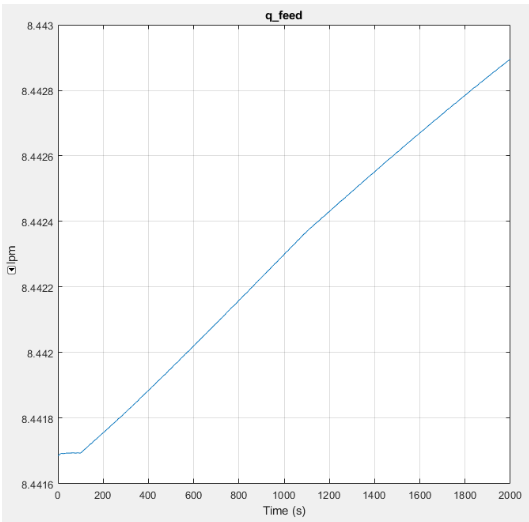

Figure 6.7 Flow feed side, when temperature is simulated from 278-316 K

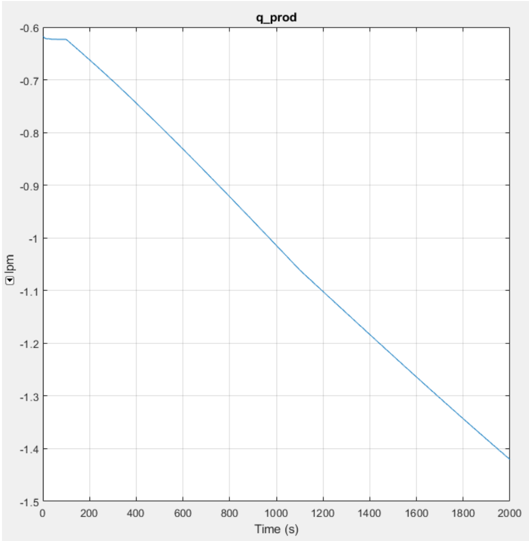

Figure 6.8 Flow product side, when temperature is simulated from 278-316 K

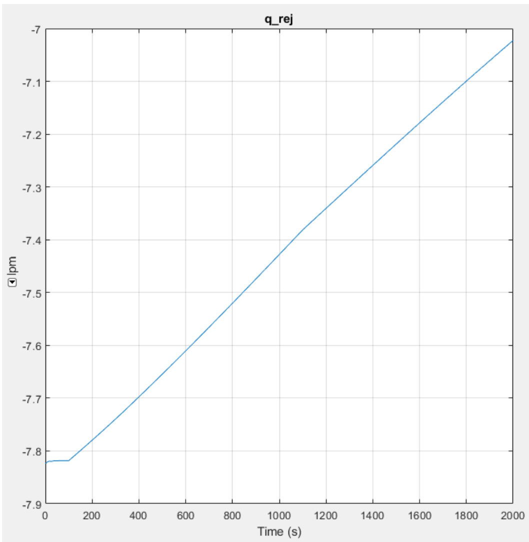

Figure 6.9 Flow reject side, when temperature is simulated from 278-316 K

Pressure

Figure 6.10 shows pressure difference from feed side to product side. The pressure decreases from (-) 11.5-7.7 bar when temperature changes from 278-316 K which is expected when temperature is rising. This is due to the temperature dependency of the membrane. When temperature is rising, the membrane pore size is increasing and let more water flow through the membrane which contributes with the lower pressure.

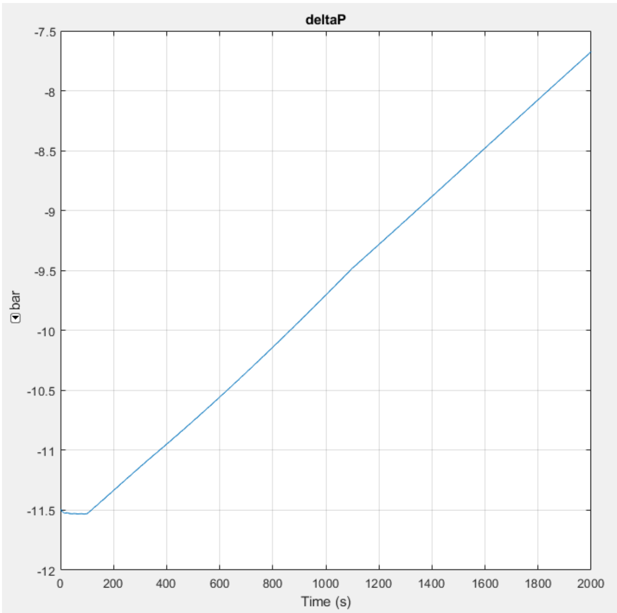

Figure 6.10 Pressure drop feed side to product side, when temperature is simulated from 278-316 K

Conductivity

Figure 6.1 displays the conductivity in feed, product and reject side. The conductivity in all nodes increases during the simulation.

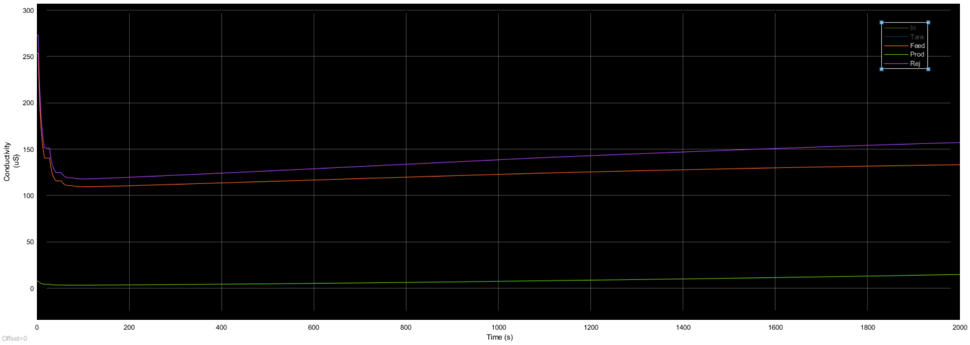

Figure 6.11 Conductivity in feed, reject and product side, when temperature is simulated from 278-316 K

6.2 Flowchart investigation

By changing the flow path in the test setup both the one pump system and two pump system could be investigated and their performance could be compared. Both systems were considered fulfilling most of the requirements, section 3.3, for an updated version.

The one pump system, seen in figure 5.3, was designed to use both a tank and the recirculation loop as a water source and to create pressure by generating a large flow over the membrane and recirculation restrictor with the pump implemented. The pump creates the flow, and together with the needle valve in the recirculation path the pressure over the membrane.

In the two pump system, seen in figure 5.4, the water path was modified so that the feed pump only used a tank as a source and pressurised the entire recirculation loop. The recirculation pump was installed instead of the needle valve used in the recirculation path. The pump was used to create the necessary flow within the recirculation loop.

Two ideas of the two pump system were considered and the system with one pump in recirculation path was chosen. The big disadvantage with the implementation of a pump on the permeate side was that it might contaminate the permeate stream. Therefore, System 1 was precluded and System 2 with one pump on the feed side and one in the recirculation loop was chosen.

An overview of the systems compared in this report can be seen below.

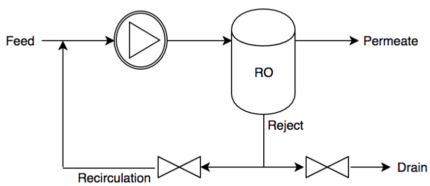

Figure 6.12 One pump system, as the current setup used in the water device today

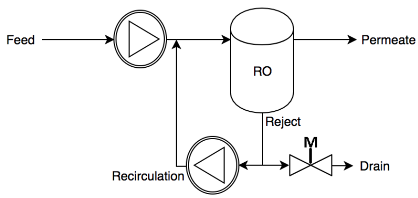

Figure 6.13 Two pump system, with one pump on feed side and one pump in the recirculation loop

6.3 Flow monitoring using the pumps

The mapping of the pumps RPM and flow rate can be seen in 6.14 and 6.15.

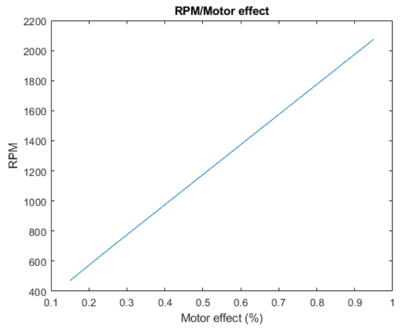

Figure 6.14 RPM of the Pumps at different control signals/duty cycles

The RPM was measured by the hall sensor in the pump. The flow rate was calculated by investigating the flow at different RPMs and outlet pressures. From the gathered data it was possible to calculate the flow at any given RPM in real-time. This could then be used by the simulink program to measure the flow in the system at any given time.

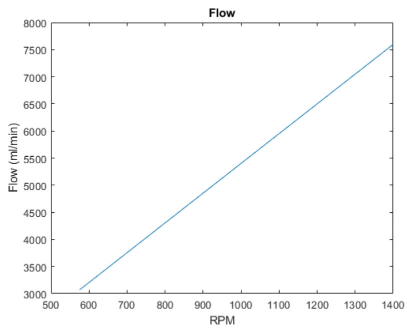

Figure 6.15 Flow rate at different control signals/duty cycles

6.4 Building the test rig

A test rig was built to be able to investigate the performance of both the one pump system and the two pump system. Initially, the one pump system was implemented and once all the testing on that system had been completed the flow path was changed according to 5.4.

The biggest challenge when building the rig was the high pressure on the feed side of the membrane. It was difficult to find components that would be able to function up to 15 bar and the solution was to modify sensors used in old prototype machines. A sensor block that was able to measure temperature, conductivity and pressure at high pressure was built and can be seen in figure 6.16 (the rectangular blocks in the feed, reject and permeate stream). The hall sensors in the pumps were used to measure the flow in the pressurized parts of the system and a standard flow sensor was used to measure the permeate flow. A motorized valve was used as a drain valve, this valve can be seen in figure 6.16 (bottom right)

The full system setup can be seen in figure 6.17. The computer to the left displays the control GUI and the simulink program. The heating bath was located in front of the rig. The display to the right was connected to the real time target computer and display important system information in real time.

Safety systems were implemented to immediately shut down the rig if the pressure reached above 12 bar. This system was very useful not to accidentally destroy the system. The back side of the rig was also covered in plastic sheets not to allow a water leakage to reach the power supplies.

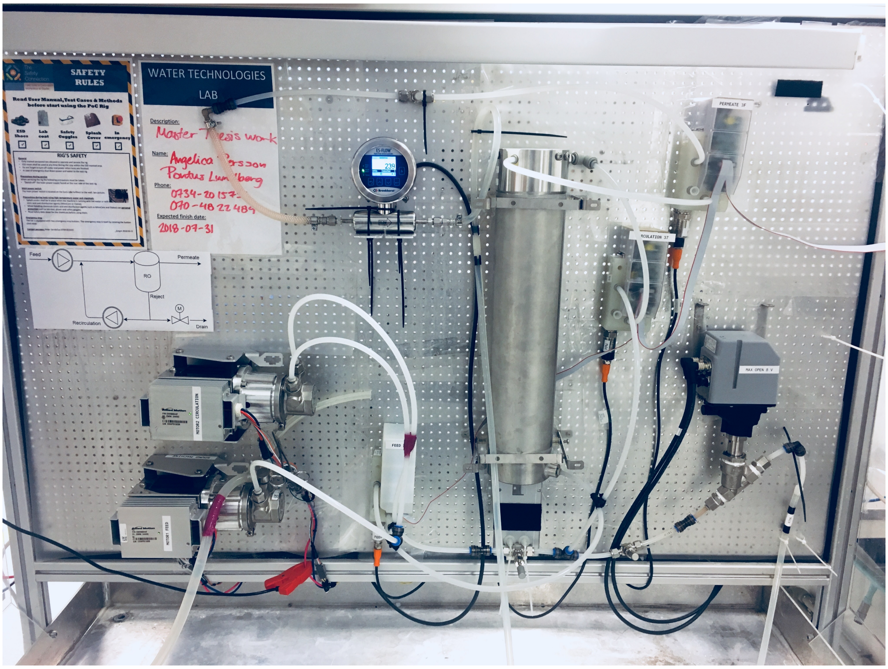

Figure 6.16 The rig built at Baxter Lund AB, with RO-membrane, pumps, pipes, flowmeter, measurement sensors and valves.

Figure 6.17 The full setup built at Baxter Lund AB, with Simulink implementation, GUI, display and water bath.

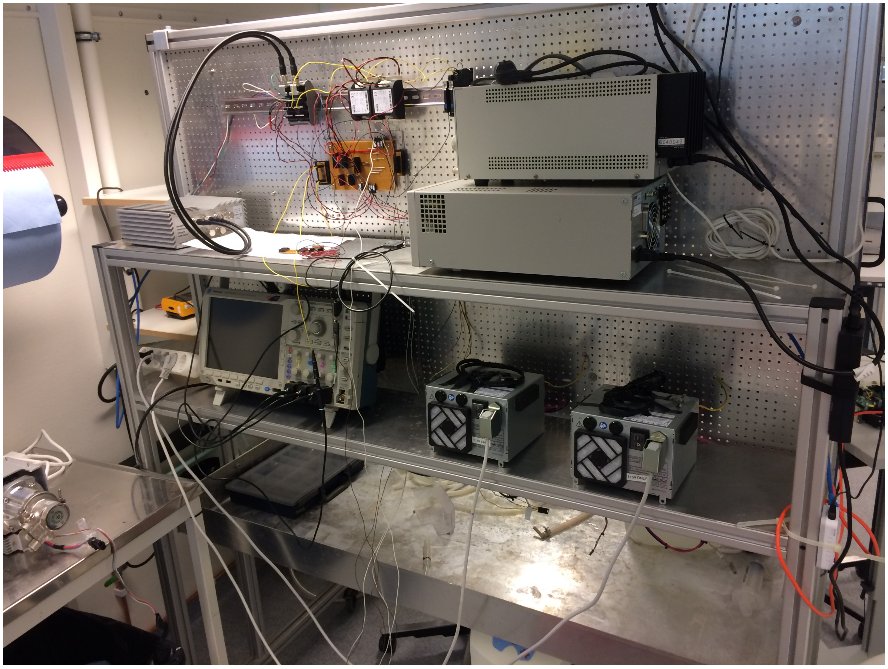

Figure 6.18 Back side of the rig, top shelf: Speedgoat, power supplies and electronics to measure the sensors and control the motors and drain valve. Bottom shelf: power supplies connected to the motors.

Connections

The electrical connections in the rig was done according to 6.19 - 6.22. Figure 6.23 and 6.24 show the GUI and the real-time data display screen from the rig.

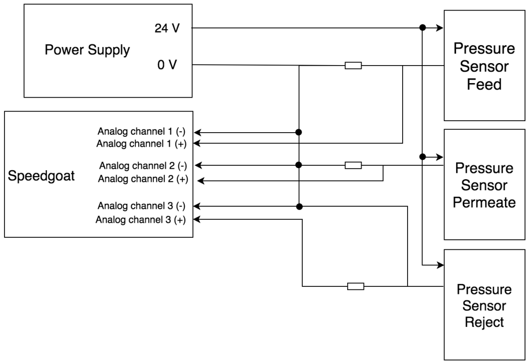

Figure 6.19 Connections Pressure sensors

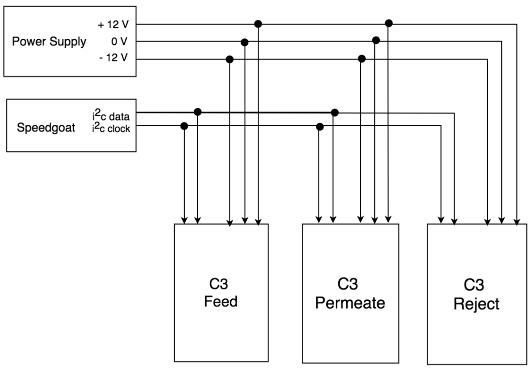

Figure 6.20 Connections measurement blocks, C3

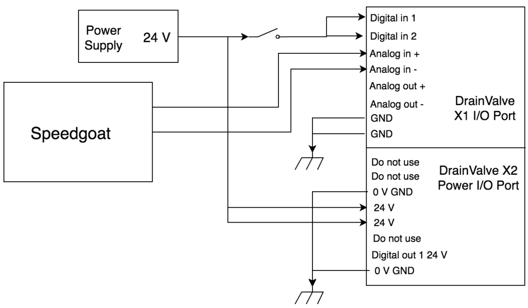

Figure 6.21 Connections Drain Valve

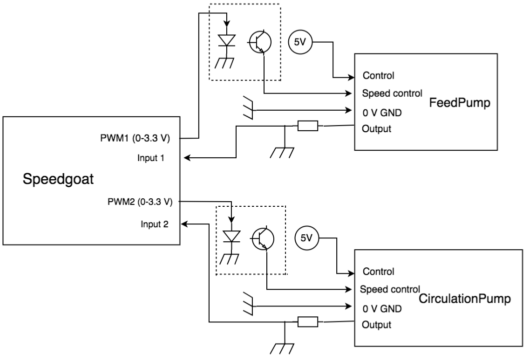

Figure 6.22 Connections Pumps

Figure 6.23 The Display showing rig data in real-time.

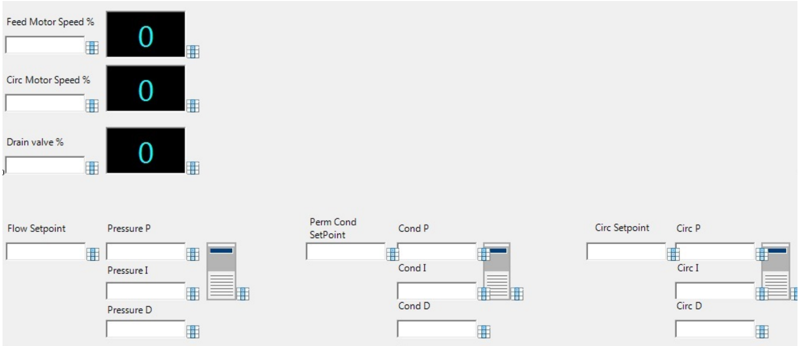

Figure 6.24 The GUI implemented in Simulink to control the rig.

6.5 Investigation of membrane behaviour

In order to compare the two systems and understand how the membrane performed in different working conditions both systems needed to be tested. The tests were conducted by controlling the temperature, pumps and the conductivity in the recirculation loop and log how the different conditions affected the system and the membrane. The current one pump system was tested first.

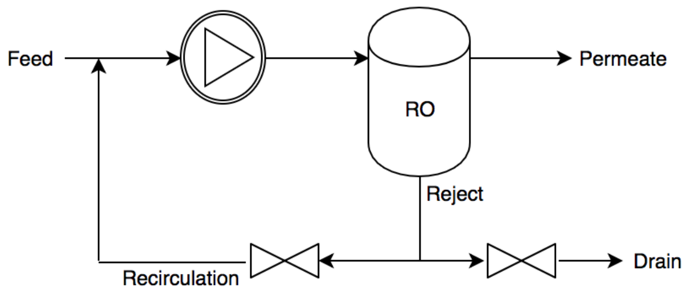

Figure 6.25 One pump system, the current setup used in the Water Device today

The tests were conducted by changing the temperature, recirculation conductivity and pump speed and measure how the system behaved once it had reached steady state. The tests were divided into three test sequences. One test sequence was performed with room temperatured water (20 °C), one with water heated to 30 °C and in the last test sequence the water was heated to 40 °C. Every test sequence included data from 8 steady state points with different settings on feed conductivity and pump speed. The test sequences are displayed in the table below. Each case represents one steady state point were data of the membrane behaviour was collected.

Data collected:

- Pressure (bar): feed, reject and permeate
- Flow (ml/min): feed, reject, permeate and drain
- Conductivity (µS/cm): inlet, feed, reject and permeate
- Temperature (°C): feed, reject and permeate

From this, key values the following system parameters were calculated: net driving pressure, permeate flow, salt rejection, recovery, water efficiency and permeate conductivity. Table 6.1 contains the tests planned for the system.

Steady state	Temperature (°C)	Feed Conductivity (μS/cm)	Motor effect (%)
1.1	20	280	60
1.2	20	500	60
1.3	20	1000	60
1.4	20	1000	**80**
1.5	20	2000	60
1.6	20	2000	**80**
1.7	20	3000	60
1.8	20	3000	**80**
2.1	30	280	60
2.2	30	500	60
2.3	30	1000	60
2.4	30	1000	**80**
2.5	30	2000	60
2.6	30	2000	**80**
2.7	30	3000	60
2.8	30	3000	**80**
3.1	40	280	60
3.2	40	500	60
3.3	40	1000	60
3.4	40	1000	**80**
3.5	40	2000	60
3.6	40	2000	**80**
3.7	40	3000	60
3.8	40	3000	**80**

Table 6.1 Testcases for the investigations of the membrane behaviour. Each case represents one steady state in the experiments.

Current system, Test sequence 1, part 1

The water tank was heated by the ambient temperature in the room while the test was running. Because of this, the test was split up in two parts, first the motor was set to 60% and steady state 1.1, 1.2, 1.3, 1.5 and 1.7 were investigated. In the part 2, the motor was set to 80 % and steady state 1.4, 1.6 and 1.8 were investigated. Figure 6.26 and 6.27 show an overview of the tests at 20 °C. The parts of the curves that have been marked with black are the steady state points. To be able to get good measurements an average was calculated from these marked values. Note that the three subplots within figure 6.26 and 6.27 share the same timeline so that the marked areas in all three plots are different measurements collected simulataneously.

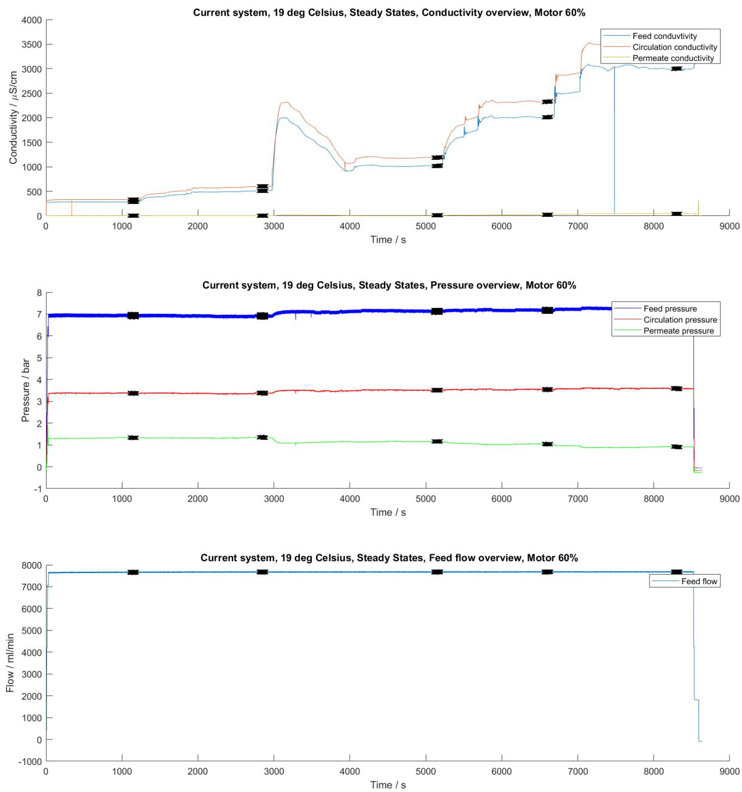

Figure 6.26 Test 1, Current system, 20 °C. Steady states 1.1, 1.2, 1.3, 1.5 and 1.7

Current system, Test sequence 1, part 2

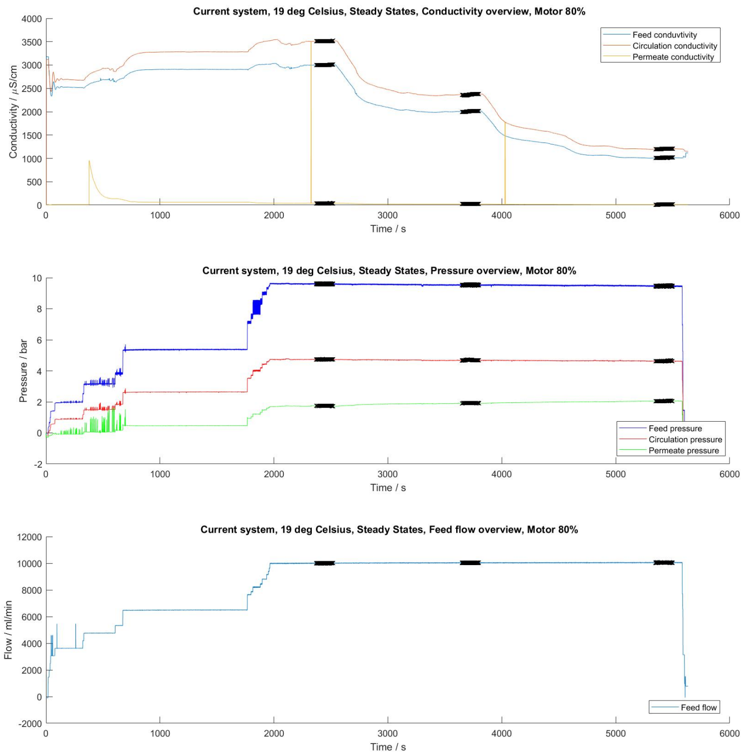

Figure 6.27 Test 1, Current system, 20 °C. Steady states 1.4, 1.6 and 1.8

By post-proccesing the data collected at the different steady states in test sequence 1 in Matlab it was possible to visually show how the system parameters were affected by the changed pump speed and feed conductivity. The results can be seen in figure 6.28.

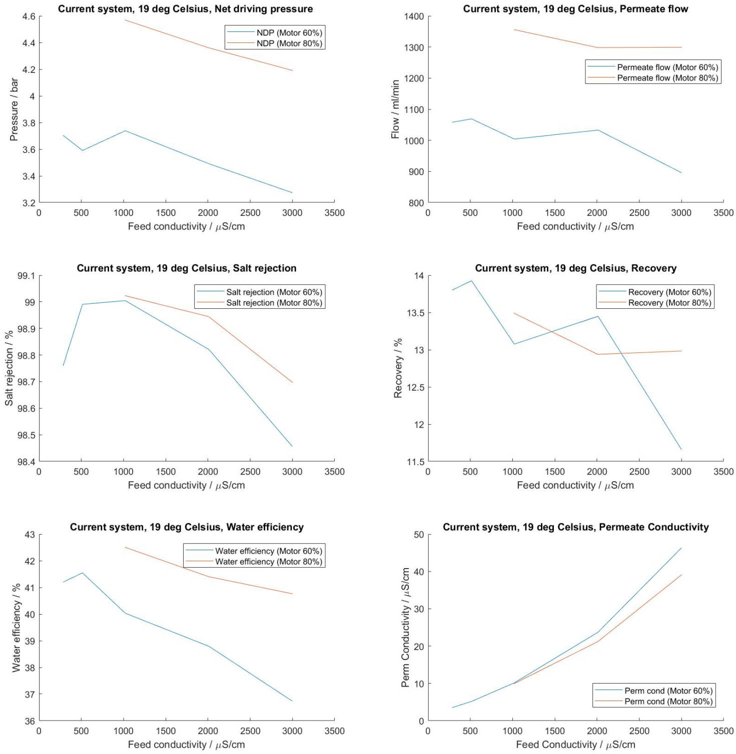

Figure 6.28 Graphs containing information on how the system performed during test sequence 1. The values used in the plots were calculated from the steady state measurements and show how the system changed when the feed conductivity, feed pump RPM was increased.

Current system, Test sequence 2

The second test was carried out by setting the heater bath to 30 °C and and adjusting the conductivity and pump speed according to the test plan. Since the water was much warmer than the air in the room, the heating caused by the pump was not as prominent and allowed all steady states to be examined in one continuous test.

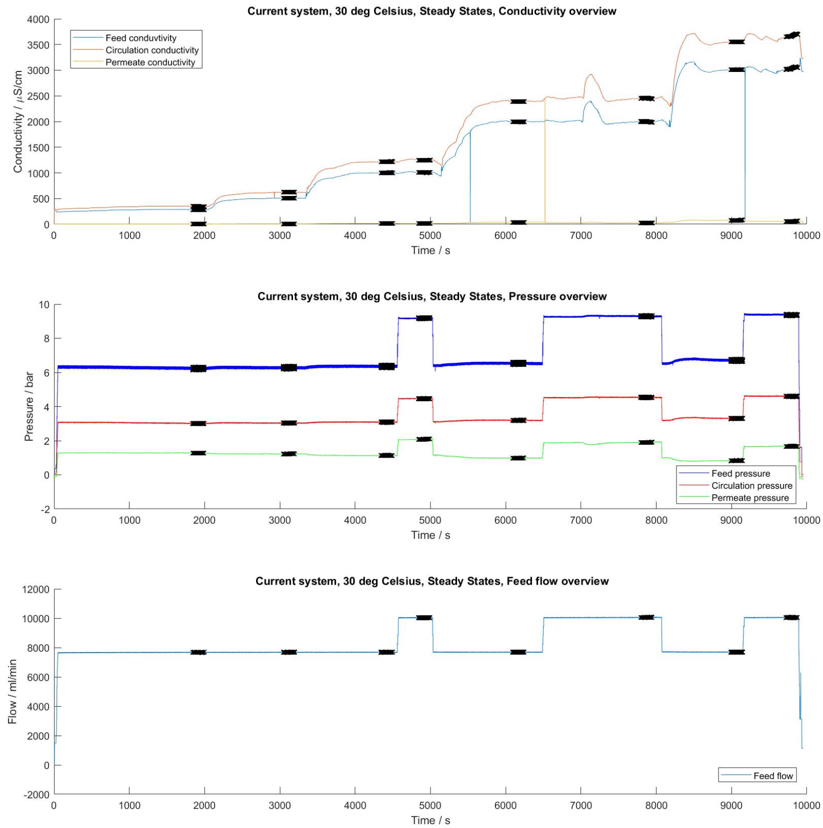

Figure 6.29 Test 2, Current system, 30 °C. Steady states 2.1, 2.2, 2.3, 2.4 2.5, 2.6, 2.7 and 2.8

The data from the test was post processed in Matlab in exactly the same way as the previous test. The results are displayed in figure 6.30.

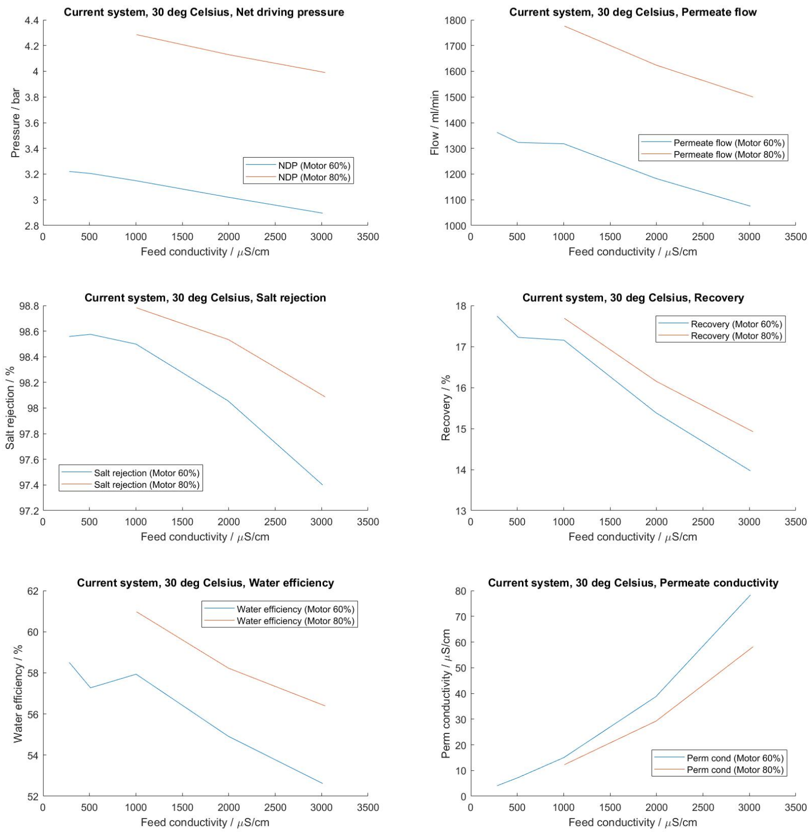

Figure 6.30 Graphs containing information on how the system performed during test sequence 2. The values used in the plots were calculated from the steady state measurements and show how the system changed when the feed conductivity, feed pump RPM was increased.

Current system, Test sequence 3

Finally the heating bath was set to 40 °C and the test sequence was performed just like test sequence 2.

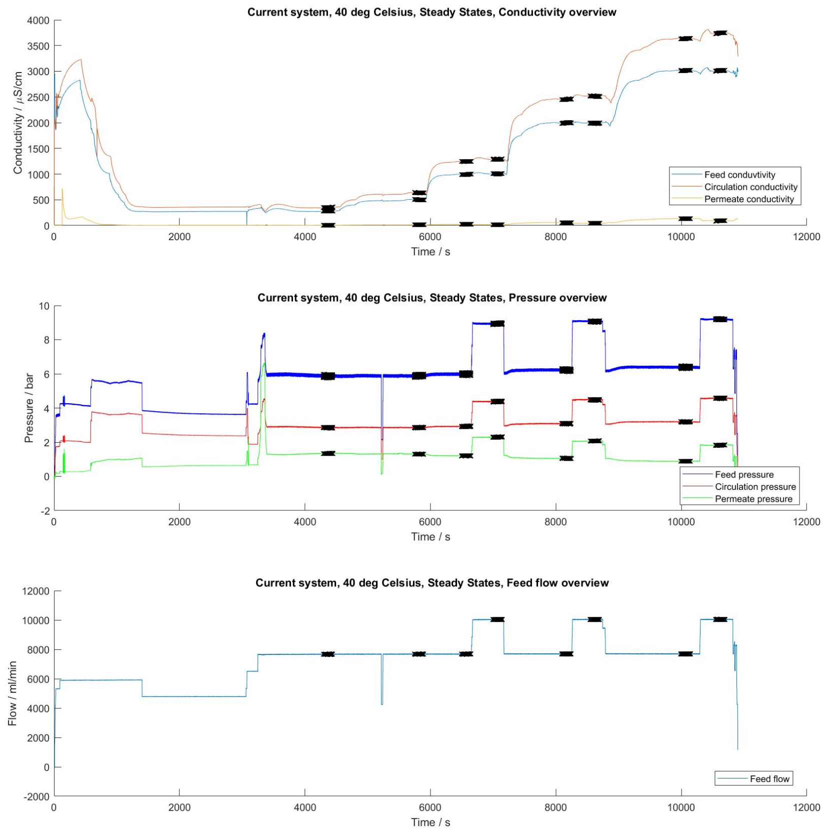

Figure 6.31 Test 3, Current system, 30 °C. Steady states 3.1, 3.2, 3.3, 3.4 3.5, 3.6, 3.7 and 3.8

Post processing in Matlab generated the following data from the steady states.

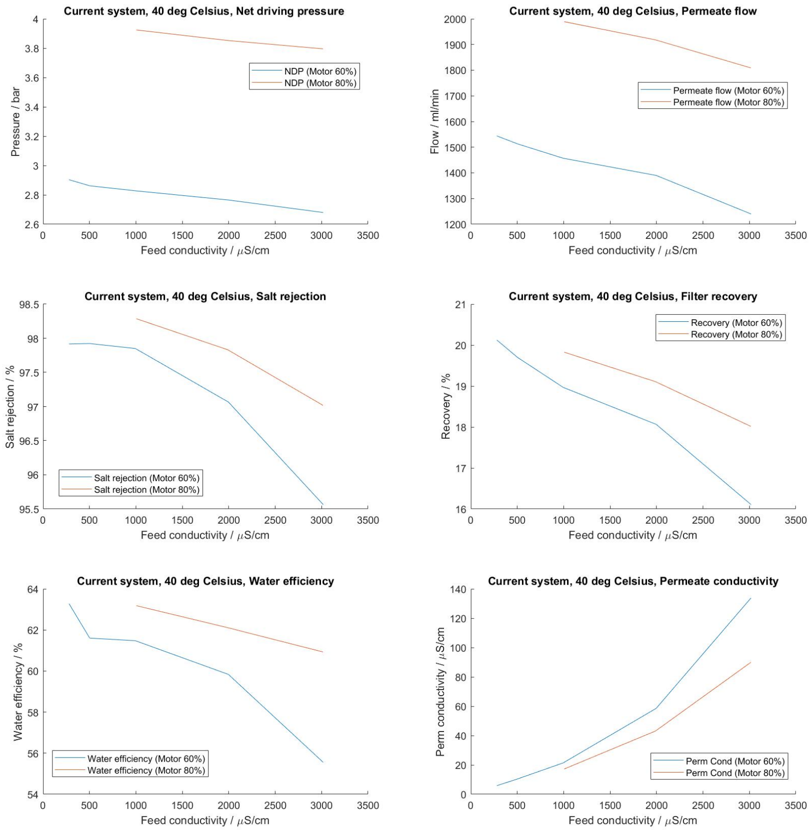

Figure 6.32 Graphs containing information on how the system performed during test sequence 3. The values used in the plots were calculated from the steady state measurements and show how the system changed when the feed conductivity, feed pump RPM was increased.

In order to understand how the current system performed in different working conditions all plots from the post processing in Matlab were put togeheter. By doing this, it was possible to visualize the effect of temperature on the system parameters. The following plots explain in more detail how the system parameters changed when the system temperature, feed conductivity and feed pressure incresed.

Net driving pressure

Net driving pressure was decreased when the temperature was increased. Higher feed conductivity resulted in a decreased net driving pressure. As expected, running the feed pump at a higher RPM also increased the net driving pressure.

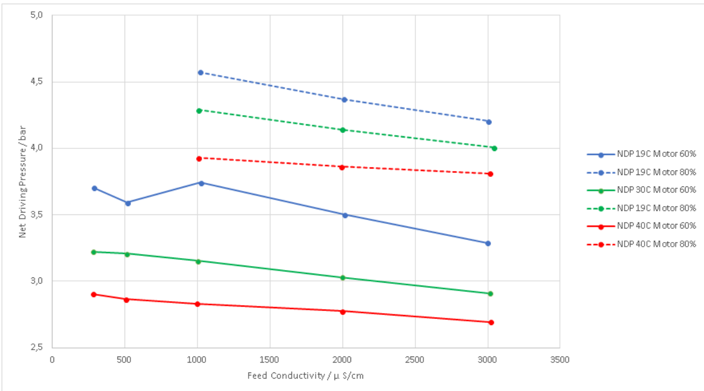

Figure 6.33 Net Driving Pressure, NDP (Pressure difference from feed to permeate side of the membrane minus the osmotic pressure)

Permeate flow

According to theory, net driving pressure has a direct effect on permeate flow. When the feed pump was increased more water was pushed through the membrane. Increased water temperatures caused a higher permeate flow. For instance, the permeate flow increased by around 50% when the temperature was increased from 20 °C to 40 °C and the pump was running at 60%. Due to the increased osmotic pressure, permeate flow decreased when the feed conductivity increased

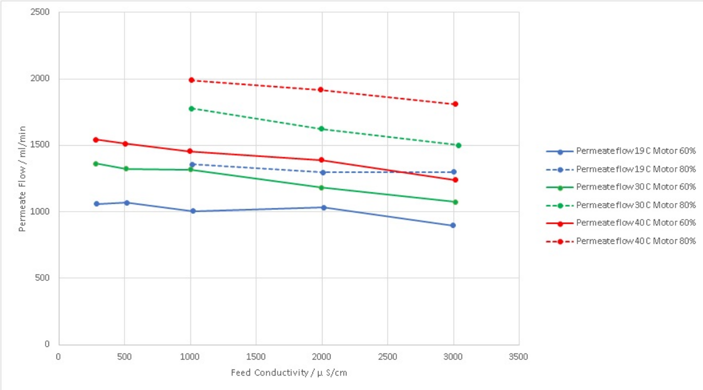

Figure 6.34 Permeate Flow (ml/min)

Recovery

Warmer water enabled more feed water to pass through the membrane and therefore the recovery was increased. Increased conductivity reduced recovery due to the increased osmotic pressure.

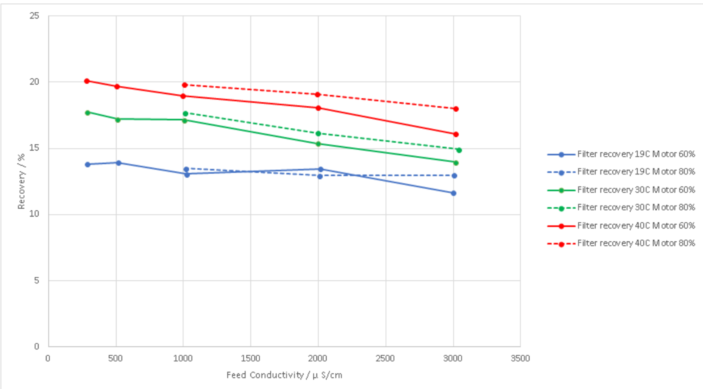

Figure 6.35 Recovery rate (%)

Salt rejection

By looking at figure 6.36 and 6.37 the deterimental effects of both increased temperature and feed conductivity can be seen. The negative effect of increased feed conductivity was much more prominent at 40 °C than 30 °C, which means that the performance of the membrane decreased with higher temperature. Increased feed pump pressure resulted in better salt rejection and the positive effect of increased pump pressure was larger when the system was hotter. Temperature was the parameter that decreased salt rejection the most and by comparing how the system performed when the pump and feed conductivity was set to 60% and 3000 µS/cm at 19 °C and 40 °C it can be seen that the salt rejection decreased from 98.5% to 95.5 %. From the experiment it can also be concluded that the system perform much better at low temperature and low feed conductivity than at high temperature and high feed conductivity.

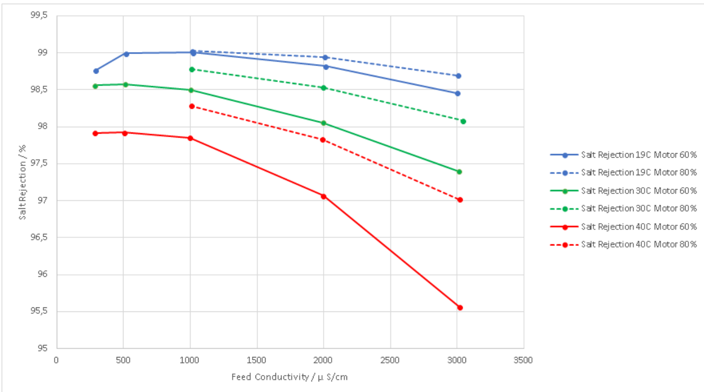

Figure 6.36 Salt Rejection (%)

Permeate conductivity

Permeate conductivity was directly proportional to salt rejection at a certain temperature and feed conductivity. The black line in figure 6.37 show the critical permeate conductivity that the system should be able to maintain and from the plot it is possible to se how high the feed conductivity can be without exceeding this limit.

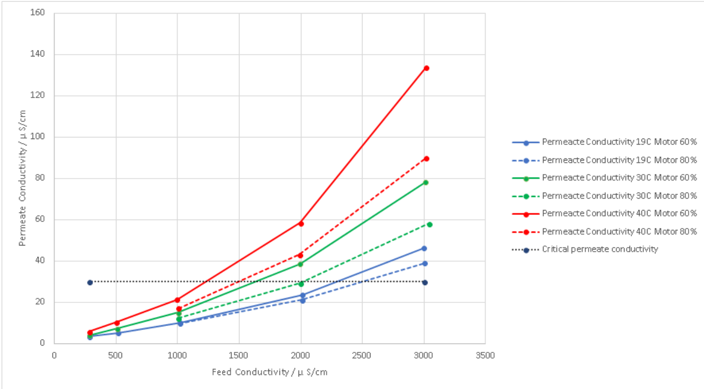

Figure 6.37 Permeate conductivity (µS/cm)

Water efficiency

Water efficiency increased when the temperature increased due to more permeate water being generated by the same feed pressure. Increased feed pressure also increased water efficiency.

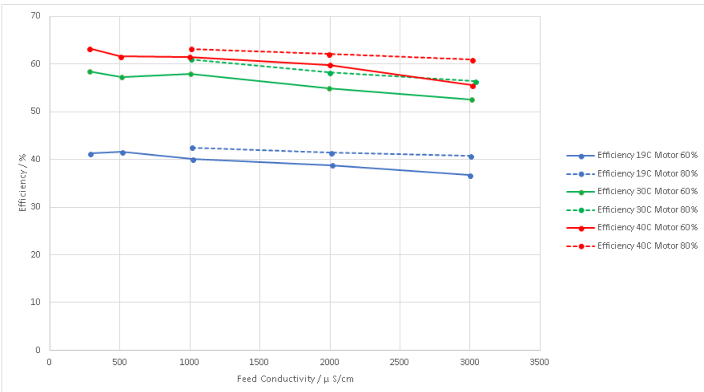

Figure 6.38 Water Efficiency

System 2

The circulation pump, a motorized drain valve and a flow meter on the permeate side was added to the system and the flow path was modified according to figure 6.39. The rig was also reprogrammed to be able to measure all flows in the flow path in real time. This could be done because now both the feed flow, circulation flow and permeate flow could be measured and from this data, the inlet and drain flow could be calculated.

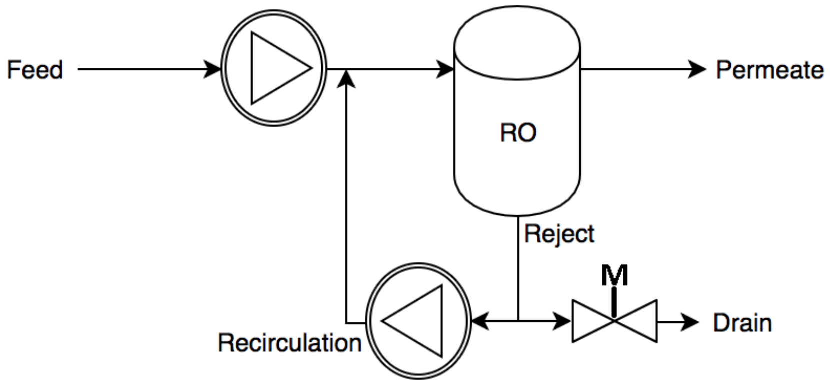

Figure 6.39 Two pump system, with one pump on feed side and one pump in the recirculation loop

Increased circulation The Initial idea for optimising the membrane was to use the circulation pump to create a turbulent flow close to the membrane surface. Therefore, a test was set up to test this idea. During the test, the feed pump and drain valve was set to a fixed value and the circulation pump was increased from 5% to 35%. Figure 6.40 shows the permeate conductivity, circulation flow and feed pressure and 7 steady state points from the test.

The circulation flow was increased from 1500 ml/min to 5000 ml/min and the increased circulation flow caused the pressure to increase from 5.5 to 7 bar. The permeate conductivity remained unchanged.

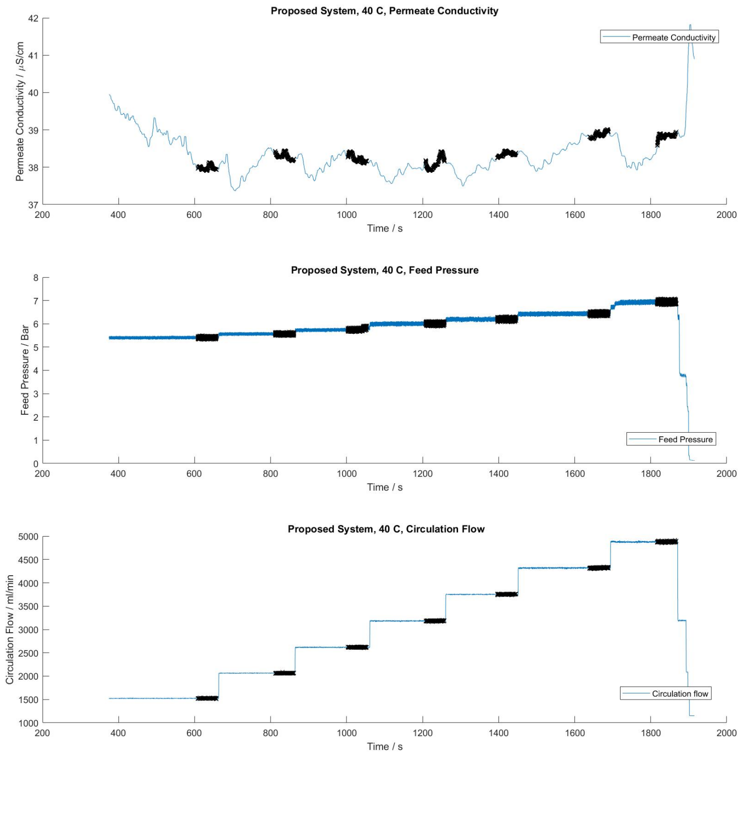

Figure 6.40 Overview of test, The circulation flow was increased with the circulation pump without changing the feed pump.

More information about how the system performed during the test was calculated and can be seen in figure 6.41. The Recovery decreased from 22% to 14% but salt rejection and permeate conductivity did only increase slightly.

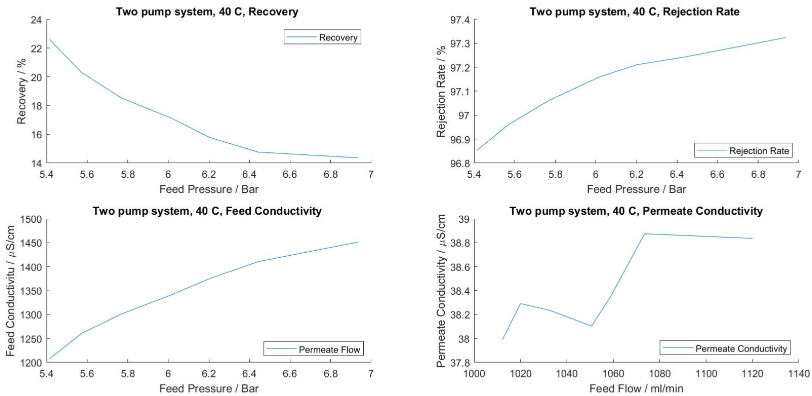

Figure 6.41 The steady state measurements were used to calculate key system parameters when the circulation flow was increased

The test concluded that the initial theory that increased circulation flow would lead to better system performance was false. Increasing the circulation has no measurable positive effect on the system.

Increased feed pressure The next test was set up to investigate the effect of an increased feed pressure. During the test all parameters were kept constant except the RPM of the feed pump. An overview of the test can be seen in figure 6.42 and the key parameters calculated after the test can be seen in figure 6.43.

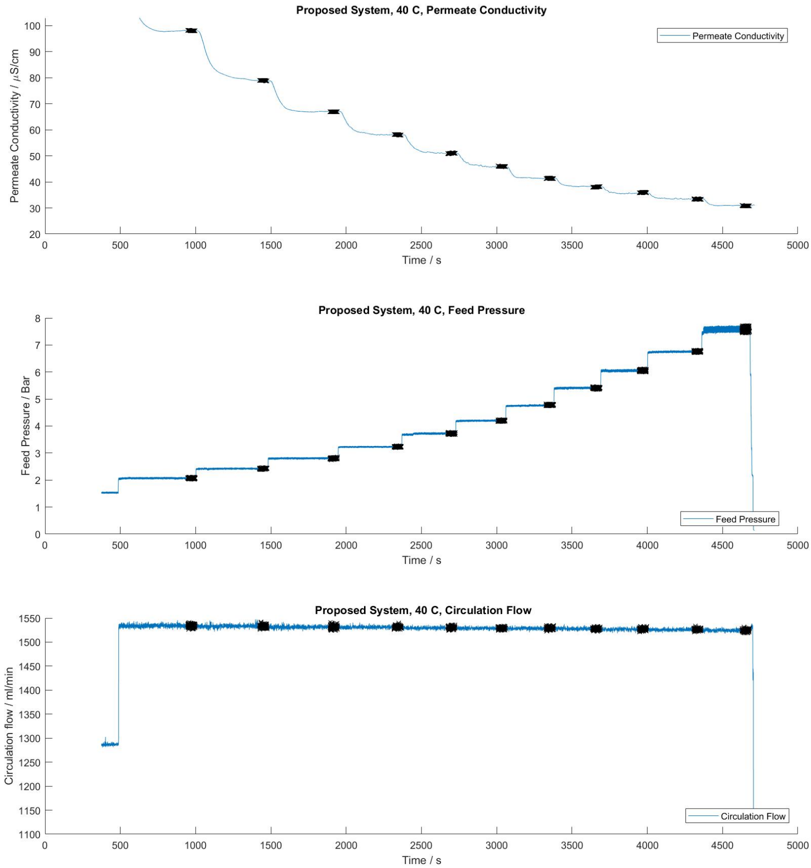

Figure 6.42 Overview of test, feed pressure was increased with the feed pump without changing the circulation flow

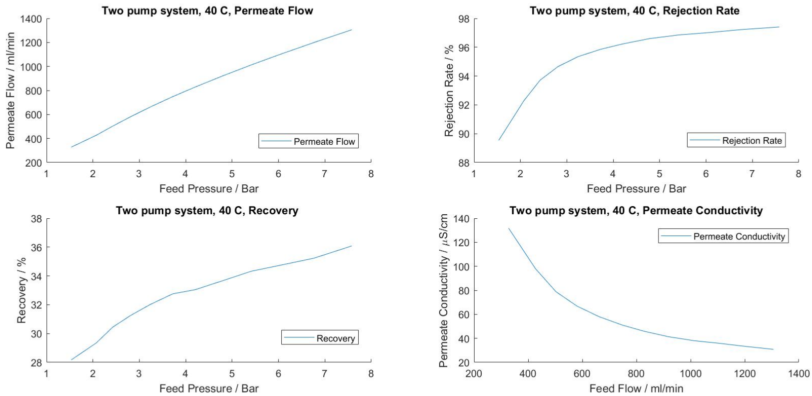

Figure 6.43 The steady state measurements were used to calculate key system parameters when the feed pressure was increased

From figure 6.42 it can be seen that the circulation flow remained constant and that the feed side pressure was increased from 1.5 to 8 bars. The permeate quality increased from 100 µS/cm to 30 µS/cm. As a result, it could be concluded that it was possible to increase the performance of the membrane by increasing feed side pressure without the increased circulation flow. It should be noted that the membrane recovery increased from 28% to 36% during the test and this is far above the maximum limit specified by the manufacturer (20%). Therefore, it should also be concluded that only controlling the feed pump without controlling membrane recovery could damage the membrane.

Another important conclusion is that increasing feed pressure results in a higher salt rejection and thus more water can be recirculated instead of being rejected through the drain valve. This means that saving water will cost more energy. On the other hand if energy consumption were to be minimized salt rejection would decrease and then more water must be rejected. As a result, increased water efficiency will increase energy consumption and vice versa.

Optimization algorithm

Previous tests concluded that it was ineffective to increase salt rejection by increasing the circulation flow, that it was possible to increase feed side pressure to increase salt rejection and that water temperature was the parameter that had the largest deterimental effect on salt rejection. Increased feed water conductivity also decreased the performance of the system, but not as much as increased temperature and the negative effect of high conductivity was more prominent at higher temperatures. Increased feed side pressure has a larger positive effect on salt rejection at high temperature. Since test showed that increased temperature decreased net driving pressure (See figure 6.33) and that decreased feed pressure reduced salt rejection (see figure 6.36) it could be concluded that using a fixed setpoint value at either feed side pressure or permeate flow would not work. Instead a set point could be calculated for a given temperature and pressure or permeate flow could be used as a setpoint. By using permeate flow instead of feed side pressure as a set point, factors such as membrane fouling, scaling and individual differences in the membrane could be compensated by the controller. Therefore, permeate flow was selected to be the setpoint for the feed pump controller.

Finding an optimal plane

The purpose of the next test was to find a permeate flow set point that would ensure good quality permeate at all temperatures without wasting more water and energy than needed. Since it was concluded in previous tests that membrane recovery did not improve salt rejection it was determined that this parameter should be set to approximately 20% by controlling the circulation pump.

The goal of the test was to find the lowest permeate flow needed at a given feed conductivity and temperature to achieve a permeate conductivity of $\sim$ 30 µS/cm (25 to 31 µS/cm) while maintaining a recovery of at most 20%. The test was conducted by first adjusting the temperature in the heating bath to 20 °C and then add salt so that the conductivity of the water in the bath was roughly 275 µS/cm. Afterwards, the feed and circulation pump were adjusted to obtain a permeate conductivity of $\sim$ 30 µS/cm and 20% recovery. Once the system had stabilised important parameters were noted. Once the measurements had been obtained, the conductivity was slowely increased and the pumps were modified to once again produce peremate water with a conductivity of 30 µS/cm. The feed conductivity was increased in small steps and the same procedure was repeated until the conductivity reached 3000 µS/cm. The same procedure was repeated using 30 °C and 40 °C inlet water. The raw data from the test was noted in table 6.44. Note that for low feed conductivities the feed pump could be set to the lowest value (3%) and the system would still generate a permeate conductivity of less than µS/cm. If the feed conductivity was high, depending on temperature, it proved to be impossible to generate 30 µS/cm permeate. The measurements that allowed $\sim$ 30 µS/cm permeate to be generated has been colored blue.

Temp (°C)	FeedPWM (%)	CircPWM (%)	FeedP (Bar)	RejP (Bar)	PermP (Bar)	FeedC (µS/cm)	CircC (µS/cm)	PermC (µS/cm)	Salt Rej (%)	FeedQ (ml/min)	PermQ (ml/min)	InletQ (ml/min)	CircQ (ml/min)	DrainQ (ml/min)	Rec (%)
21,96	3	3	1,77	1,27	0,21	285	353	5,85	97,95	2450	380	1151	1299	771	15
22,26	3	3	1,84	1,42	0,21	502	622,97	10,7	97,86	2450	373	1163	1287	790	15,2
22,31	3	3	1,95	1,53	0,17	997	1215	26,93	97,3	2450	346	1161	1289	815	14
22,8	10,5	3	4	3,4	1,01	1433	1899	29,87	97,91	3286	624	2004	1282	1380	18,9
23,12	12,4	5	4,6	3,9	1,35	1523	2014	29,82	98,04	3740	710	2210	1530	1500	19
23,5	14,6	5,5	5,35	4,6	1,7	1608	2160	30,06	98,09	4030	800	2460	1570	1660	19,9
21,15	17,5	8,5	6	5,8	2,3	1775	2483	30,2	98,29	4670	940	1980	2690	1040	20
22,5	25	16,8	10,12	8,3	4,1	2101	2776	30,8	98,53	6410	1273	3633	2777	2360	19,7
22,53	25	16,5	10,4	8,5	4,2	2199,4	3520	34,1	98,45	6500	1290	3710	2790	2420	19,8
21,5	25	16,5	10	8,5	3,82	2973	4100	65,41	97,81	6300	1228	3628	2672	2400	19,2

Temp (°C)	FeedPWM (%)	CircPWM (%)	FeedP (Bar)	RejP (Bar)	PermP (Bar)	FeedC (µS/cm)	CircC (µS/cm)	PermC (µS/cm)	Salt Rej (%)	FeedQ (ml/min)	PermQ (ml/min)	InletQ (ml/min)	CircQ (ml/min)	DrainQ (ml/min)	Rec (%)
29,58	3	3	1,62	1,15	0,24	282	349	5,06	98,2	2450	424	1154	1296	730	16,2
29,4	3	3	1,7	1,2	0,21	510	622,7	11,21	97,79	2450	408	1158	1292	750	16,6
29,38	4	3	2,12	1,6	0,31	1000	1228	28,83	97,11	2646	440	1355	1291	915	16,7
29,43	9,5	3	3,4	2,8	0,97	1188	1524	29,84	97,49	3190	622	1902	1288	1280	19,5
29,59	15	8,5	5,25	4,2	1,9	1401	1799	29,34	97,88	4400	877	2496	1904	1619	19,8
29,65	21	16	7,8	6,15	3,31	1609	2877	29,2	98,2	5900	1165	3165	2735	2000	19,7
30,15	25,3	21	9,9	7,75	4,6	1783	2337	30,7	98,28	6950	1386	3656	3294	2270	19,9
30,14	25,3	21	9,9	7,8	4,5	2009	2887	37,38	98,13	6960	1374	3664	3296	2290	19,7
30,57	25,3	21	10,09	7,9	4,21	3035	4073	85,07	97,19	6970	1328	3678	3292	2350	19

Temp (°C)	FeedPWM (%)	CircPWM (%)	FeedP (Bar)	RejP (Bar)	PermP (Bar)	FeedC (µS/cm)	CircC (µS/cm)	PermC (µS/cm)	Salt Rej (%)	FeedQ (ml/min)	PermQ (ml/min)	InletQ (ml/min)	CircQ (ml/min)	DrainQ (ml/min)	Rec (%)
39,3	3	3	1,51	1,1	0,39	275	336	10,78	96,07	2450	421	1156	1294	735	17,2
39,4	3	3	1,56	1,12	0,34	500	613	22,74	95,4	2450	407	1158	1292	751	16,5
38,95	15	10,5	4,7	3,7	2,02	981	1269	28,23	97,1	4620	918	2488	2132	1570	19,8
39,1	19,5	15,5	6,4	5	3,06	1136	1475	29,61	97,41	5650	1130	2990	2660	1860	19,9
39,37	23,3	20	8	6,2	4	1243	1628	30,06	97,58	6600	1314	3434	3166	2120	19,9
39,44	26,2	22	9,1	7,1	4,78	1292	1702	29,78	97,7	7180	1440	3780	3400	2340	19,9
39,42	26,2	22	9,1	7,1	4,78	1418	1864	34,89	97,54	7180	1435	3785	3395	2350	19,9
39,44	26,2	22	9,25	7,25	4,61	2014	2623	67,3	96,65	7180	1411	3781	3399	2370	19,6
39,58	26,1	22	9,5	7,5	4,4	3020	3910	162,3	94,61	7180	1373	3783	3397	2410	19

Figure 6.44 Raw data from tests at 20, 30 and 40 °C. The blue cells contains information about system performance when it was possible to maintain a permeate quality of ∼30 uS/cm (25 - 31 µS/cm). All relevant pressures, flows, conductivities and other key parameters has been added

By plotting when it was possible to maintain ∼30 µS/cm as a function of temperature and feed conductivity it was possible to estimate the working range of the membrane. Figure 6.45 is a 2D representation of the data contained in 6.44. The blue dots are the measurement points were ∼30 µS/cm could be maintained. As can be seen in the plot, increasing temperature limits the ability to maintain good permeate quality. The two most important findings were that at 40 °C it was possible to maintain ∼30 µS/cm permeate if the feed conductivity was below 1292 µS/cm and when the temperature was decreased to 20 °C the feed conductivity could be increased to 2101 µS/cm and still produce ∼30 µS/cm permeate.

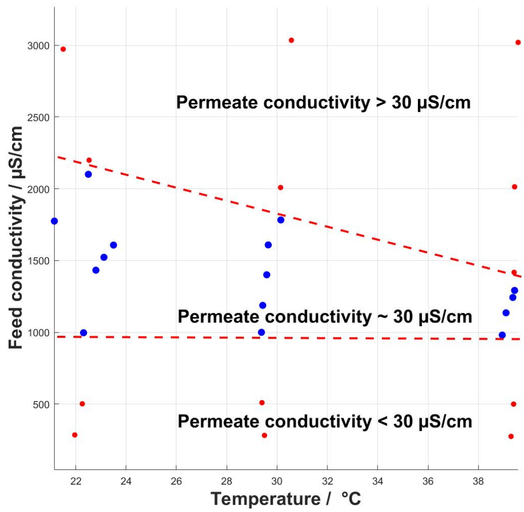

Figure 6.45 The operational area of the membrane, blue dots represents when it was possible to generate a permeate conductivity of ∼30 µS/cm.

Since the idea behind the algorithm was to find an optimal permeate flow for feed conductivities between 275-3000 µS/cm and temperatures between 20 and 40 °C a Z axis containing the minimum required to achieve ∼ 30 µS/cm permeate flow was added to plot 6.45. The blue dots represent the points where good permeate quality could be achieved. By looking at 6.44 it is possible to determine what permeate flow corresponds to the individual points in figure 6.46.

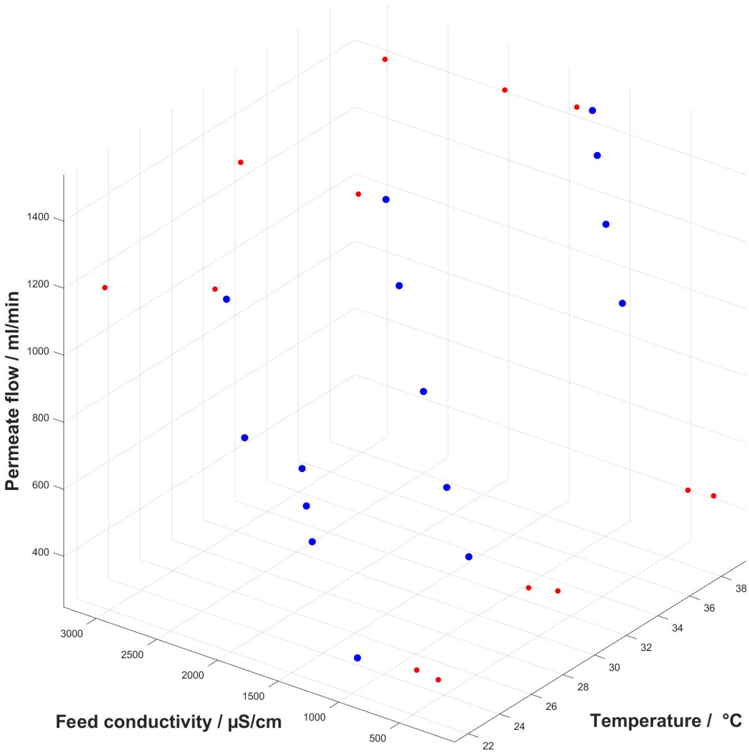

Figure 6.46 3D representation of when it was possible to generate ∼ 30 µS/cm permeate as a function of temperature, feed conductivity and permeate flow.

The points where good permeate conductivity could be attained (blue points) were used as a basis for a second order interpolation to obtain a plane. This plane can be seen in figure 6.47. The plane is an estimation of what permeate flow is needed at a given temperature and conductivity to create a permeate quality of ~ 30 µS/cm.

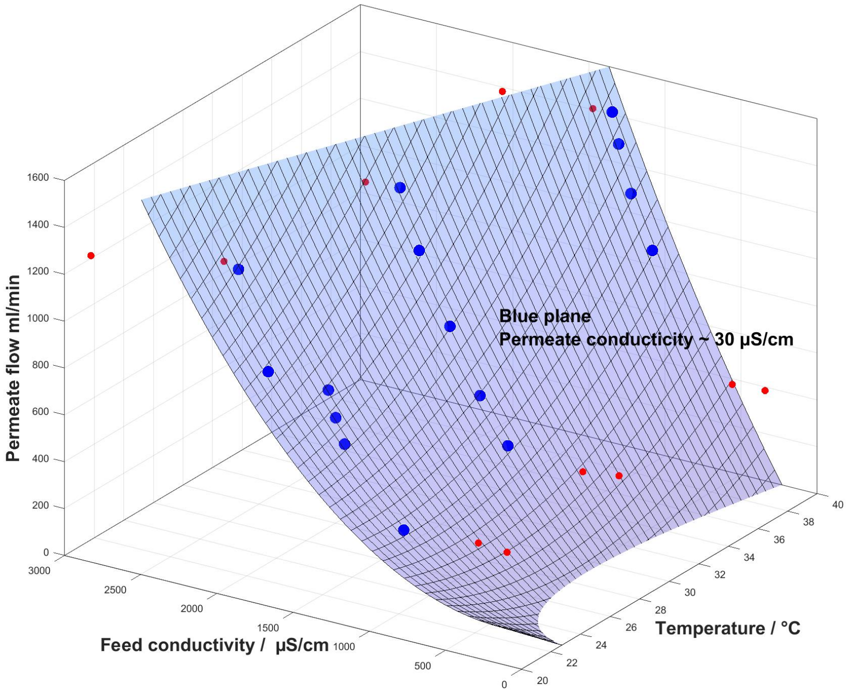

Figure 6.47 Plane created from an interpolation of the measurements in figure 6.46. The plane represents what permeate flow is needed at a given feed conductivity and temperature to generate ~ 30 µS/cm permeate

The equation for the plane can be seen below.
(temperature = t, conductivity = c)

$$
\begin{aligned}
permeateflow = 2349 - 153.9 * t - 1.128 * c + \ldots \\
2.225 * t^2 + 0.05315 * t * c + 0.0002567 * c^2
\end{aligned}
\tag{6.1}
$$

Energy consumption and water efficiency is coupled in a manner such that it is imposible to minimize both at the same time. However, by selecting a curve on the aforementioned plane it is possible to find an algorithm that minimizes energy consumption without wasting more water than necessary. When the system is running at 40 °C the maximum allowed conductivity that generates a permeate conductivity of ∼ 30 µS/cm is limited to 1292 µS/cm. The proposed optimal function that can be seen in figure 6.48 was selected because it would allow the system to function at the maximum allowed conductivity at 40 °C but when the system temperature decrease the system would save energy by reducing the permeate flow. For instance, if the system temperature was 40 °C the function would set a permeate flow setpoint of 1440 ml/min. If the temperature was reduced to 30 °C the algorithm would set the permeate flow setpoint to 767 ml/min and thereby saving energy. If the temperature was furhter reduced to 20 °C the algorithm would set the permate flow setpoint to 506 ml/min.

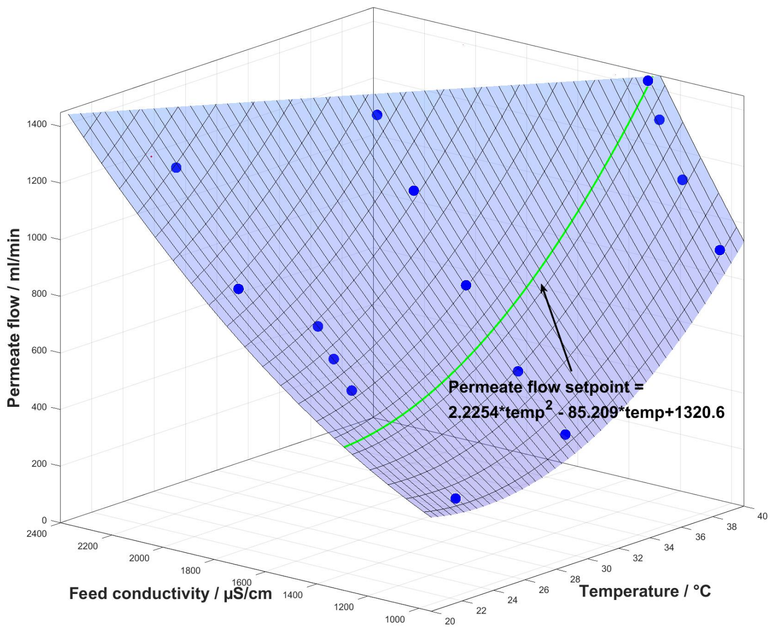

Figure 6.48 The green curve represents the choosen optimization algorithm suggested in this thesis

To summarize, the proposed algorithm for optimizing the membrane is to use the temperature of the inlet water to determine an optimal permeate flow rate. By using the feed pump as the actuator one control loop controls the permeate flow to achieve the setpoint determined by the actuator. The control loop controlling the circulation pump to achieve a recovery of 20%. The last control loop controls the drain valve so that the permeate quality is 30 µS/cm. Thus, the system will be optimized and operate on the green line in figure 6.48. The proposed algorithm to calculate the optimal permeate flow based on system temperature can be seen below (temperatuer = t). Note that the function is only valid within 20 to 40 C and that the allowed permeate flow should be within 500 to 1450 ml/min.

$$permeateflow = 2.2254 * t^2 - 85.209 * t + 1320.6 \tag{6.2}$$

Energy consumption

The current was measured on both motors during the tests with 20 °C inlet water in the optimal plane test case (table 6.44). The test showed that power consumption of the two pump system ranged from 12 to 194.4 Watt depending on the feed conductivity and temperature which was less than what was required when only one pump was used. Typically, the one pump system used 86 Watt when running at 60% and 228 Watt when running at 80%. The measured power consumption of the two pump system can be seen in figure 6.49.

For example, the two pump system would require somewhere between 12 and 36 Watt and the current one pump system would require 86 Watt when used in Lund (communal water, temperature 20 °C, conductivity 170 uS/cm). Since the current system does not ensure a permeate quality of 30 µS/cm it is difficult to compare the two systems. The two pump system will use more power when needed to ensure good permeate quality but the one pump system will use the same power, regardless of the permeate quality.

Note that the feed pump generate a pressure of 10 bar when running at 25% in the two pump system and in the one pump system the feed pump generate 7.5 bars when running at 80%. Because of this, the two pump system can remove more of the salts than in the one pump system but it will use more energy.

Temp (°C)	FeedPWM (%)	CircPWM (%)	FeedP (Bar)	RejP (Bar)	PermP (Bar)	FeedC (µS/cm)	Feed Motor Current (A)	Circ. motor current (A)	Total wattage (W)
21,96	3	3	1,77	1,27	0,21	285	0,4	0,1	12
22,26	3	3	1,84	1,42	0,21	502	0,4	0,1	12
22,31	3	3	1,95	1,53	0,17	997	0,4	0,1	12
22,8	10,5	3	4	3,4	1,01	1433	1,4	0,1	36
23,12	12,4	5	4,6	3,9	1,35	1523	1,8	0,3	50,4
23,5	14,6	5,5	5,35	4,6	1,7	1608	2,2	0,4	62,4
21,15	17,5	8,5	6	5,8	2,3	1775	3,2	0,9	98,4
22,5	25	16,8	10,12	8,3	4,1	2101	6,7	1,4	194,4
22,53	25	16,5	10,4	8,5	4,2	2199,4	6,7	1,4	194,4
21,5	25	16,5	10	8,5	3,82	2973	6,7	1,4	194,4

Figure 6.49 Measurements on system performance at 20 °C

7

Discussion

7.1 Simulations

When performing the simulations in Simscape the main objective was to isolate the characteristics of the membrane functionally. The temperature dependencies in flow and pressure were expected to be implemented in the model. In order to receive good results, equations from DOW, the manufacturer of the membrane, were used. The results from the simulations showed that the membrane behaviour meets the constraints from theory. One important parameter is the temperature correction factor, plotted in figure 6.3. It is used to compensate for the differences in temperature for the membrane performance, both in flow, pressure and conductivity and give the model some realistic behaviour in different temperatures.

The simulations in Simscape showed significant results on the membrane behaviour. The flow characteristics over the membrane, due to changes in temperature, meets the expectations from the theory. Pressure characteristics, seen in figure 6.10 is a bit high, which probably is due to the pump and pipes simulated in the model.

7.2 System behaviour

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 without reducing permeate quality or water efficiency. The new setup also had the unforeseen advantage of reducing the pressure drop over the membrane, from feed to reject side. 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, creating a more uniform permeate flux accross the membrane surface, this could in theory prevent the uneven scaling of the membrane.

Initially, it was believed that a higher recirculation flow would improve the performance of the membrane by increasing the flow rate over the membrane surface and thereby causing a more turbulent flow that would mix high salinity water close to the membrane with less saline water further from the membrane. However, tests showed that this was not the case. The performance did improve by a small amount, but by increasing the recirculation flow, the pressure was also increased and the small improvements that could be observed was more likely caused by the increased pressure on feed side, not the increased flow rate from feed to reject side. Therefore, it was concluded that there was a no possibility of effectively optimize 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. It was decided to use the recirculation pump to ensure that the recovery remained fixed at 20% and not use this parameter for optimization.

Feed pressure has a direct effect on both permeate flow and salt rejection. The physical reason for the improved salt rejection is that a larger volume of water passes through the membrane surface and dilutes the dissolved salts that also passes. This can be seen in figure 6.42, from this data it can also be concluded that salt rejection does not increase linearly with increased pressure and that 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. As a result, improving the performance of the membrane has low cost at low pressures but becomes more and more expensive when the pressure increases.

Hot water has lower viscosity than cold water and also a higher diffusion rate than cold water. The pores of the membrane are also expanding at higher temperatures, causing a higher flow through the membrane from feed to product side. Consequently, higher temperatures cause higher permeate flow over the membrane and increased salt passage through the membrane surface. If both water and salt passage were equaly affected by temperature the rejection rate would not change with changing temperature but high temperatures makes it easier for salts to pass through the membrane surface than water, resulting in a larger flow of water that contains a proportionally larger amount of dissolved salts. In order to improve the salt rejection rate more permeate needs to pass through the surface to dilute the salts and this can be achieved by increasing feed side pressure, causing a higher flow.

The conductivity of the inlet water 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 set point for controlling the drain valve it is possible to optimize the water efficiency of the system and ensure high quality permeate water. Lower conductivity feed water allows the system to recirculate more water without reaching the critical limit where a permeate conductivity of 30 can not be maintained. Therefore, the system can adapt to different feed water conductivity by adjusting the drain valve.

Net driving pressure depends on the feed 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 increases NDP, net driving pressure. However, this drawback is necessary to maintain a high water efficiency and 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, although, 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 on permeate side with a low pressure drop and by using a short flow path.

7.3 One vs two pump system

In the one pump system, the feed pump creates both flow and pressure and these parameter are therefore coupled to each other and cannot be changed independently. The pressure is generated by the resistance in the membrane and also in the recirculation restrictor. As a result, the feed pump must deliver a large amount of water to build the pressure needed to push the water through the membrane surface.

By changing the flow path and adding another pump the feed pump can pressurize the circulation loop without a high water flow. As a result, the feed pump can run at a much lower rpm. The circulation pump creates the flow but does not have to generate any pressure since the circulation loop is pressurized by the feed pump.

7.4 Fine tuning

The PID parameters for the controllers could be changed at runtime in the simulink real time GUI and the PID parameters that were used was found by trial and error. We found that the recirculation, and permeate flow controller could be fast without causing problems. The drain valve controller on the other hand needed to be very slow to not cause oscillations.

No effort was made to try to find the best possbile PID parameters for the control loops. Since the pumps or the drain valve most likely would be changed if there were any further development on the two pump system we choose not to spend time trying to make the system as fast and stable as possible and instead focus on the algorithm.

7.5 Control System Design

There were two main properties that was to be optimized, 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 by opening or closing the drain valve. Salt rejection changes with different temperatures and feed pressure, because of this, the recirculation loop can only hold a certain amount of dissolved salts in order to maintain a permeate of 30 µS/cm. For instance, if the system has a salt rejection of 99% the recirculation loop must hold water with a conductivity of 3000 µS/cm to obtain a 30 µS/cm permeate. If the system saltrejection change to 96% then the conductivity in the recirculation loop must be 750 µS/cm to achieve the same permeate quality. As can be seen in figure 6.37 from the tests with the current system, a system with room temperatured inlet water was able to maintain 30 µS/cm permeate water with 2500 µS/cm in the recirculation loop but if the inlet water was heated to 40 degrees Celsius only 1500 µS/cm recirculation conductivity was needed to reach 30 µS/cm. Thereby, controlling the valve position was critical to being able to make sure that the permeate conductivity was 30 µS/cm regardless of operating conditions.

Opening the drain valve lowers the conductivity in the recirculation loop but it takes time to reach a new steady state. This caused a problem because if the changes were not slow the system would overshoot. The only way to fix this problem was to use a slower controller.

An increase in pressure resulted in more fluid getting pushed out of the drain valve without the position of the valve being changed. 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 needs 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. Because pressure can be changed quickly, this problem could be fixed by using a much faster controller for the controller controlling the feed pressure pump than the drain valve.

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 approximately 20 % which was the recommended recovery from the membrane manufacturer. This regulator had little impact on the regulator controlling the drain valve but when the flow in the recirculation loop increase so does the pressure in the loop. The effect of this can be seen in figure 6.40. From the plots it can be seen that 22 % recovery caused a pressure of 5.5 bars and a recovery of 14 % increased the pressure to 7 bars. Therefore, 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 increased permeate flow. By using the formula to convert feed water temperature to a set point for the permeate flow the salt rejection of the membrane could be optimized. This design allows the system to counter the detrimental effect that increased temperature has on the salt rejection of the membrane at the cost 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 6.36 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. 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 µS/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 means that there is a trade-off between water efficiency and energy efficiency. Running the system on low pressure decreases salt rejection and thereby less salts can be recirculated back into the recirculation loop and this means that more water is wasted. By testing, the lowest permeate flow that generated a permeate conductivity of 30 µS/cm at different temperatures could be found and these results were translated into a function for what permeate flow should be used as a set point at different temperatures.

7.6 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.

7.7 Reduced pump size

When using the two pump system the pump speeds varied from 3% to 25% 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 pumps. 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 more quiet.

7.8 Membrane size

Membrane size determines the permeate flux at a certain pressure and for smaller systems 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.

7.9 Membrane identification method

This report is based on the DOW FilmTec membrane used by Baxter today and the temperature to optimal permeate flow function will only work for this membrane. However, the method for finding this function can be used on any membrane. By following the method outlined in this report this function can be found for any other reverse osmosis membrane and can be modified for other specifications on permeate quality.

7.10 Scaling

One advantage of using a permeate flow set point for the feed pump controller is that it will let the system adapt to scaling. When scaling occur, the membrane surface becomes 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 permeate flow setpoint and this will automatically be achieved by increasing the feed pump. 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 is the maximum allowed recovery and by controlling this parameter with a control loop, the system improves the longevity of the membrane.

7.11 Drain valve

The valve used in the test rig was built for much larger systems and is not intended for fine tuning. This caused problems because it was not possible to make small changes 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.

8

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 optimized permeate flow for every temperature within the operating range.

By replacing the current one pump system without any feedback loops with a system using two pumps and PI regulators and the ability to control the system allow a more optimzed performance on both water efficiency and energy consumption. As mentioned, the current system does not use any feedback controllers and therefore it cannot adapt to the changing behaviour 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 is subjected to more feed side pressure it can be argued that the system can be optimized by always 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. Therefore, it is not possible to optimize energy consumption without reducing the water efficiency of the system and vice versa. As a result, to optimize the system it needs to be determined which one of these parameters is considered to have the highest cost.

The model of the reverse osmosis membrane is build around the theoretical equations presented by DOW. These equations are accurate in describing the flow and pressure characteristics 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.

The two pump system that is proposed in this thesis is more energy efficient in all working condition than the old one pump system. By looking at figure 6.49 it is clear that the gains are substantial.

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

9

Future Prospects

9.1 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 should to be done. The current algorithm will not be optimal from 5 to 20 °C.

9.2 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

[1] The Dow Chemical Company. *Dow Water and Process solutions - Levels of Separation of IX, RO, NF, UF*, The Dow Chemical Company, 2018.

[2] R, Singh *Membrane Technology and Engineering for Water Purification(Second edition)*, Butterworth-Heineman, 2018.

[3] Puretech Industrial Water. *What is reverse osmosis*, *https://puretecwater.com/reverse-osmosis/what-is-reverse-osmosis*, 2018.

[4] Goodwin G. Graebe S. Salgado M. *Control System design*, 2001.

[5] Haugen, F. *Anti-Windup schemes for Proportional Integral and Proportional Resonant Controller*, 2010.

[6] Panagopoulos H Astrom K J Hagglund T. *The Lambda method for Tuning PI Controllers*, 1997.

A

Equipment

A.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.

A.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.

A.3 Drain valve

A proportional valve was 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.

A.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.

A.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.

Figure A.1 Speedgoat (Speedgoat real time simulation and testing, 2018)

A.6 Measurement instruments

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

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 A.6 contains sensors for temperature measurements and are used to measure the temperature in the system.

Pressure sensor

Pressure sensors were implemented in the C3 block, described in section A.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 A.2 Flowmeter (BRONKHORST HIGH-TECH B.V.)