Optimization of Reverse Osmosis Performance

Angelica Persson and Pontus Lundberg

LUND UNIVERSITY

Department of Automatic Control

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Department of Automatic Control
Lund University
Box 118
SE-221 00 LUND
Sweden

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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 is a company that developes medical devices and water purification devices that is used in medical applications. In this thesis a new flow path is investigated that replaces a single feed water pump with to independant pumps. The goal is to investihgate the advantages with this setup and to design a control application that is able to optimize the performance of the system for all operating conditions within the operating range.

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

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Acknowledgements

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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.

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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: The purified water stream leaving the membrane as product water.

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

Drain: 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 uS/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 permetate over the mebrane while blocking other substances.

3

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 remove impurities, as salt and inorganic molecules from the water[Company, 2018].

In a RO-system the feed water is pressurized by a pump and forced through the RO-membrane to overcome the osmotic pressure. The RO-membrane is a semi-permeable membrane and let water passes freely true the membrane creating a purified product stream. This product water is used by the dialysis machine in order to give the patients a safe treatment. If the water is not pure enough the patient is exposed to a high risk and it is of great importance that the purification plant, e.g the water device delivers good quality on the water at all times.

The water device has a current system containing 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 has a significant impact on the membrane behaviour in order to deliver pure water.

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 optimise 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 dependancies 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 component should be investigated and tested.

The temperature dependencies of the RO-membrane should be added into the current simscape model.
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 implementet 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 minimising 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 a high spectra of 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 optimise 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 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.
- Improve if possible.

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 three streams: feed, permeate and reject. Main concern in the process boundary is the semipermeable barrier that selectively allows the passage of some components but not others. [R, 2015]

4.2 Osmosis

The osmosis process occurs when two solutions of different chemical concentration are separated by a semi-permeable membrane. The two different solutions will try to reach equilibrium. The solution with less concentration will have a natural tendency to migrate through the membrane over to the side with higher concentration. Osmosis is a naturally occurring phenomenon and one of the most important processes in nature. The pressure that occurs is called the osmotic pressure. The phenomenon can be seen in Figure 4.1. The fresh water on right side inte figure wants to contract through the semi-permeable membrane in order to reach a 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 salute concentration in the fresh and salt water creates the flow. A greater difference in concentration creates a higher osmotic pressure than lower concentration difference.

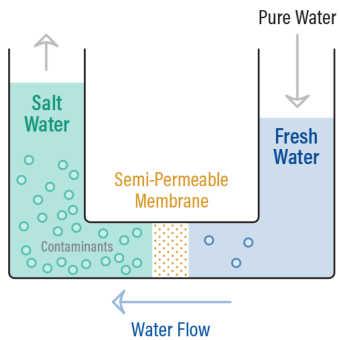

Figure 4.1 Osmosis

4.3 Reverse osmosis

The reverse osmosis(RO) process is the reverse process of the osmosis. The idea is putting a pressure on the high concentration side in order 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 true. The amount of pressure required depends on the salt concentration of the water. In order to gain reverse osmosis the pressure applied must be greater than the osmosis pressure. The membrane employs cross filtration rather than standard filtration. With cross filtration, the solution passes through the filter with two outlets. One solution passes true the membrane and is called permeate and is the filtered, pure, solution. The other solution can be drained or fed back into the filtering system, and is called reject. This can be seen in figure 4.3.

The contaminants build up att the surface area and it is of great importance to try to sweep them away and hold the surface clean. If the contaminants builds up the performance of the membrane will decrease, and cleaning with chemicals or heat water might be necessary[*What is reverse osmosis*]. The phenomenon of reverse osmosis can be seen in 4.2. The water on left side is pressured through the membrane to the right side since the applied pressure is higher than the osmotic pressure. The result is a pure water with only small amount of contaminants in the fresh water stream.

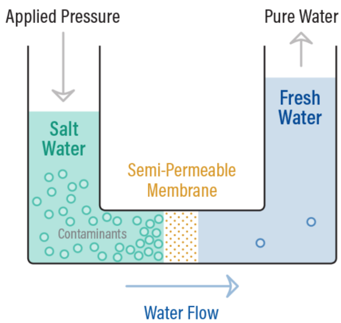

Figure 4.2 Reverse Osmosis

Fouling

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

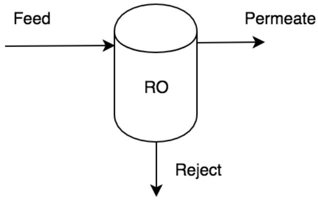

Figure 4.3 RO-system

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 is 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 is 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

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

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

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

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

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

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

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

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 the systems aims for different types of controlling. There exists different control methods to meet the differences in the characteristics of the systems. The control theory is basically split in two, linear and non-linear. In order to design a controller that is capable of regulating the system parameters 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.

Step-response: The time behaviour of the outputs of a general system when the input is changed from zero to one in a very short time.
Rise Time: The time it takes for the plant output to rise beyond 90 % of the desired level for the first time
Overshoot: How much the peak level is higher than the steady state, normalized against the steady state.
Settling time: The time it takes for the system to converge to steady state.
Steady-state error: the difference between the steady-state output and the desired output.
Transfer function: Gives the system output for each possible input.

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 a optimal system response. It has a robust performance in a wide range of operating conditions. The parameters needs 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 with the controller.

To achieve good performance of the controller the requirements of the system needs 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 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 to high an oscillation system behavior is expected and the system will become unstable if the proportional gain is set too high.

Integral component (I) The integral component (I) sums 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 Steady-State error never reaches zero 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. [M., 2001]

Windup and methods to avoid it

Windup occurs when the steady-state error never reaches zero and 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. [**clamping**]

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 saturate and limits the integrating part until saturation is no longer experienced.[**clamping**]

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 is presented below.

Ziegler-Nichols method The Ziegler-nochols method is a popular method of tuning a PID controller and conducts proposed rules for determining values of the gain (K) as: $K_P, K_I and K_D$ based on the transient step response of a plant. The relationship between $K_P, K_I and K_D$ are important and when tuning the system some rules of thumb can be used:

- Adjust K_P to decrease the rise time.
- Adjust K_I to eliminate steady-state error.
- Adjust K_D to reduce overshoot and settling time.

Ziegler-Nichols tuning method is considered good as a initial tuning for PID-control for unknown systems. For the design of the gain parameter there are some guidelines to be followed:
Use a closed loop system with a proportional controller, K_P. Start with a low value of the gain, K_P, increase until a steady-state oscillation occurs and note the value as K_{cr}. The parameters $K_P, T_i and T_d$ can be estimated with this help parameter, K_{cr} and P_{cr} which is the period time(s) of the oscillations, as follows: $K_P = 0.6K_{cr}$, $T_i = 0.5P_{cr}$, $T_d = 0.125P_{cr}$ **??**.

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 system pole for stable processes and without cancellation of system pole 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 choosed 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. **??**

5

Method/Implementation

5.1 Overview Method

The method of this master thesis has an iterative flowchart since decisions on next step where made during the time for the thesis. Some tasks were performed in parallell with each other.

First, studies of theory and on previous work on the field where made in order to investigate requirements. After that flowchart investigations and test planning were made in parallell. Thereafter modelling in Simscape and building of the test rig were done before the first test serie, on current system were performed.

Analysis of data were made and the rig for test serie 2 on the next system were built in parallell with modelling in Simscape for the second system.

After both test series were done comparison of membrane behaviour and improvements were done. In 5.1 an overview of the method can be seen to get a better overview.

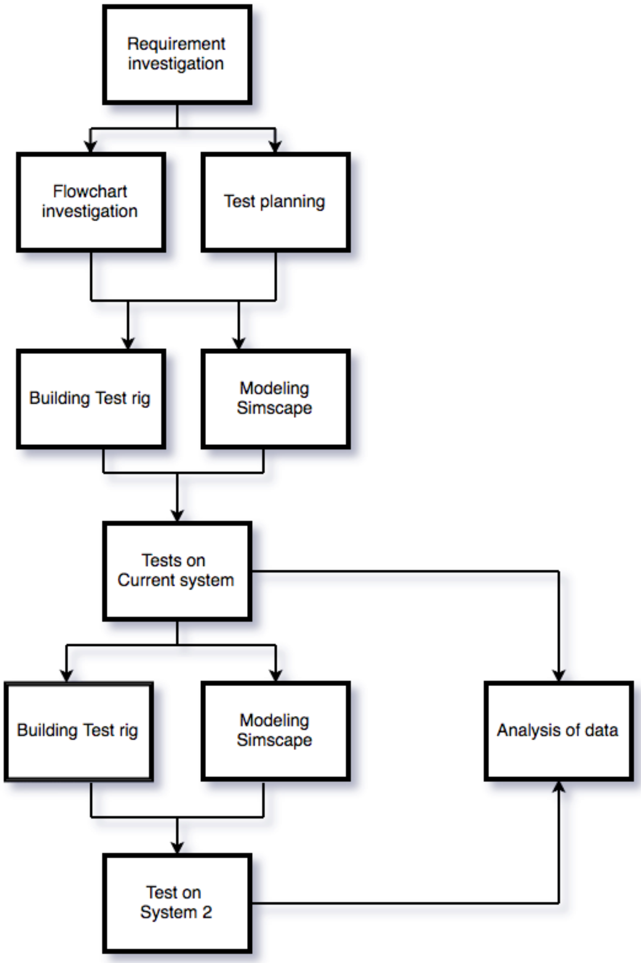

Figure 5.1 Overview over method

5.2 Modeling

Simscape software tool described in section Appendix A is used to do a physical model in order to achieve the characteristics of the membrane. The isolated system with pump, pipes, valves and water supply(tank) is implemented. Mass balance equations from section 4.4 is used together with equations from 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 polariztion 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, temperature are received from the simulations, and can be seen in section 6.1

5.3 Flowchart investigation

Today, a system containing one pump is used. The pump is implemented at feed side of the membrane. The pump creates a pressure to overcome the osmotic pressure end create a flow from feed to permeate side. The system can be seen in 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.

This limits the possibility for the water device to adapt itself to different working

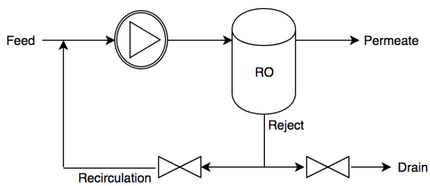

Figure 5.2 One pump system

conditions and changes in inlet water quality and also if the membrane surface is fouling. This is an admired feature to implement to the Water Device if to use at markets with seasonal variations that can change the quality and temperature on the inlet water during water production. If the membrane performance could be improved at all conditions end especially when the conditions is variated over time the freedom of controlling the pumps and valve is desirable to optimise the performance of the membrane.

To be able to investigate the performance of the feasibility to replace the one pump solution with to pumps in order to control the flow and pressure over the membrane two different ideas were considered. Desirable outputs for increasing the membrane performance is:

1. Pressure drop over the membrane is high
2. Flow through membrane is high

The expected results of an optimisation is that: the permeate conductivity is minimised, fouling on the membrane surface is minimised, the temperature dependencies is taken care of, waste water is minimised 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 is handled with control
3. Waste water is minimised
4. Energy efficiency is improved compared to current one pump solution

Mainly two ideas of systems containing two pumps considered to give the system this extra degree of freedom and is presented below:

System 1

The first system with one with pump on feed side and one pump on permeate side, as seen in Figure 5.3. This setup contributes with the ability to create a net pressure over the membrane with a low, or even a under pressure on permeate side, whilst the feed pump creates a "high" pressure on feed side. Benefits with this implementation is the low energy consumption due to the ability to create negative pressure on permeate side. A high net driving pressure(pressure difference from feed to permeate side) can be achieved with rather low pressur on feed side. The withdrawal might be the implementation of the pump on permeate side. The water is used to feed dialysis machines and has high requirements on its purity. This sets high requirements on the pump, to not soil the purified water.

System 2

The second system considered with one pump on feed side and one pump on reject side, in recirculation path, seen in Figure 5.4. The feed pump is used to create a high pressure on feed side and the pump in the recirculation path is used to control the flow in recirculation path. This contributes to control the recovery rate. Due to

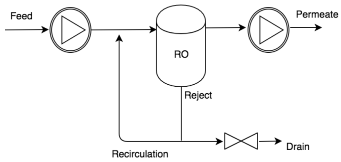

Figure 5.3 System 1

theory the membrane behaviour is dependent on feed and flow characteristics over the membrane, salt concentration and temperature. with this two pump solution the flow and pressure can be controlled independently and the membrane behaviour can be improved. The quality of the permeate water is ensured.

System 1 and System 2 contributes with the ability to control pressure and flow

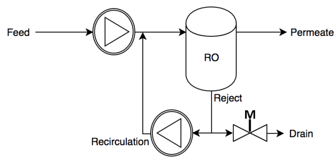

Figure 5.4 System 2

characteristics over the membrane. The big withdrawal with the implementation of a pump on permeate side is considered a high risk implementation and might put patients to high risks. System 1 is therefore precluded.

5.4 Mapping

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

Due to lack of instruments that could measure the flow under the high pressure some mapping of the flow from the pumps were done. The flow stream through the pumps were measured at different RPM 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 mapped flow has an accuracy of $\pm 10\%$.

5.5 Implementation Test Rig

Current System

In order to run all tests a physical rig was built. A first version to meet the specifications of the system used in the current water device were built according to Figure 5.5, with all the measurement sensors implemented. The rig contained, at the first stage: 1 pump with power supply, 1 RO-membrane, 3 needle valve, 1 drain valve, 1 water bath, three measurement sensors, pipes and couplings. The water bath is used to simulate different inlet water temperatures. The needle valves is 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 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 connected to the rig. All control and feedback signals to and from the rig is handled in a built Simulink workspace where it is able to log and export all data to be able to analyse the system behaviour. All signals are filtered and displayed in real-time on a screen.

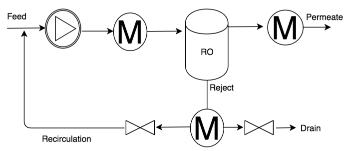

Figure 5.5 Current System, with measurement sensors

System 2 "Comparing system"

The second system, System 2, were built by modifying the first rig, according to Figure 5.6. The second rig build contains: 2 pumps with power supply, 1 RO-membrane, 3 needle valve, 1 drain valve, 1 water bath, 1 flow meter, 3 measurement sensors, pipes and couplings. The water bath is used to simulate different inlet water temperatures. The needle valves is 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 signal from the rig. All signals is 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 6.18 - 6.21.

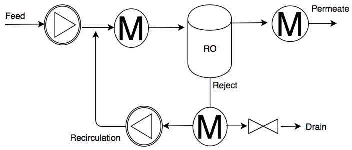

Figure 5.6 System 2, with measurement sensors

5.6 Test setup for membrane behaviour

In order to compare results of the current system, furthermore called "Current System" and the updated system, System 2, some test will be done on the current setup. Reasonable values are investigated in order to meet requirements of the Water device. Corresponding points will be tested on the comparing system to evaluate any improvements on the membrane performance. The critical operational areas for the membrane is considered high temperatures (over 30 °C) and high conductivity (over 2000 µS). The tests are performed in a range from 280-3000 µS and from 18-40 °C.

Points to be investigated can be seen in Table 5.1. Same tests is performed on Current system and System 2 in order to analyse the difference in performance and membrane behaviour.

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

Table 5.1 Testcases

5.7 Design of control algorithms

Investigating tests on System 2, Figure 5.4, were executed prior the design of the control algorithms to receive required reference signals to the pumps and drain valve. During the tests one parameter at a time changed while the others were kept constant. In test 1, seen in Figure **??** the pump in recycle path were the changing parameter and in Test 2, seen in Figure **??** the pressurising pump on inlet side were the changing parameter.

6

Results

6.1 Modeling

A physical model of the membrane were 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 temp. The temp node gives freedom to simulate the behaviour of the membrane in different temperature ranges.

The model consists of the pump, pipes, valves and tank. The water in the tank can be set to contain any salt koncentration 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 shows expected behaviour due to the theory about membrane behaviour when temperature rising. Flow and conductivity on permeate/product side is 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 is considered being significant due to theory of the membrane. More details of the parameters in the model can be seen in subsections below.

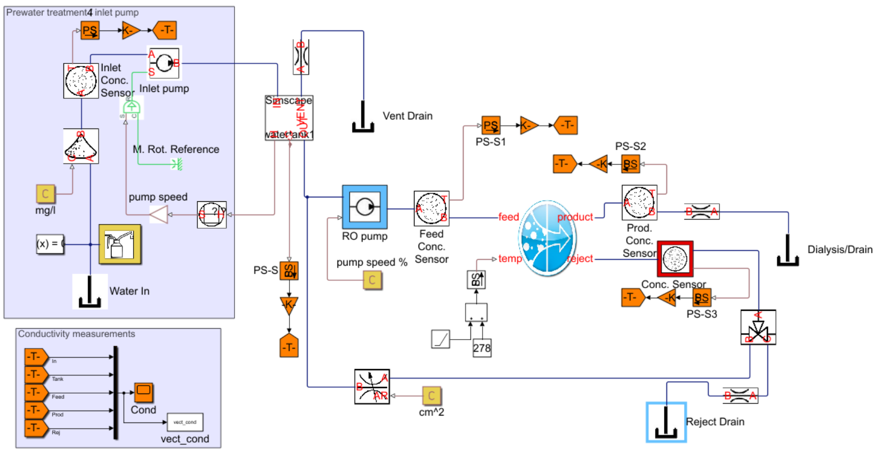

Figure 6.1 Model made in Matlab tool Simscape

Temperature

In figure 6.2 the simulated temperature, 278-316 K is shown. All plots 6.4 - 6.1 shows 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 dependent 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.

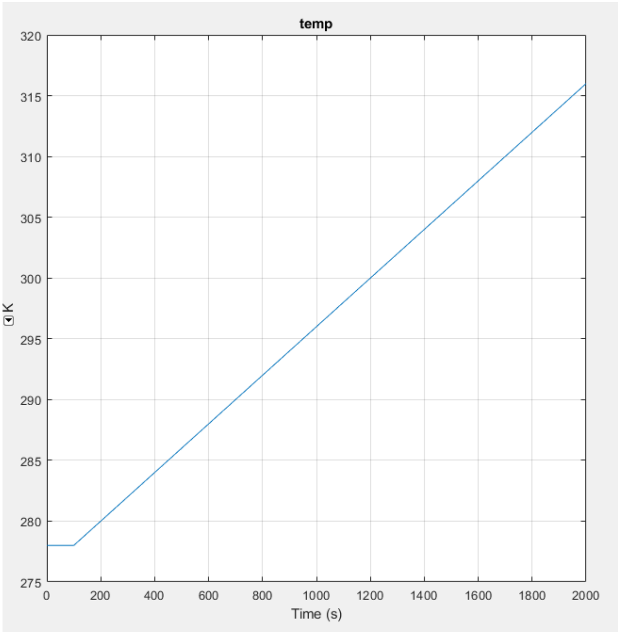

Figure 6.2 Temperature range in simulations, from 278-316 K

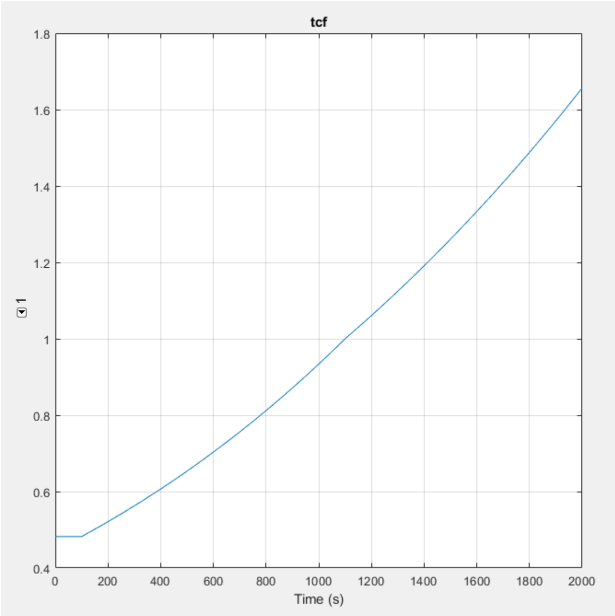

Figure 6.3 Temperature correction factor, TCF, when temperature is simulated from 278-316 K

Salt concentration

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

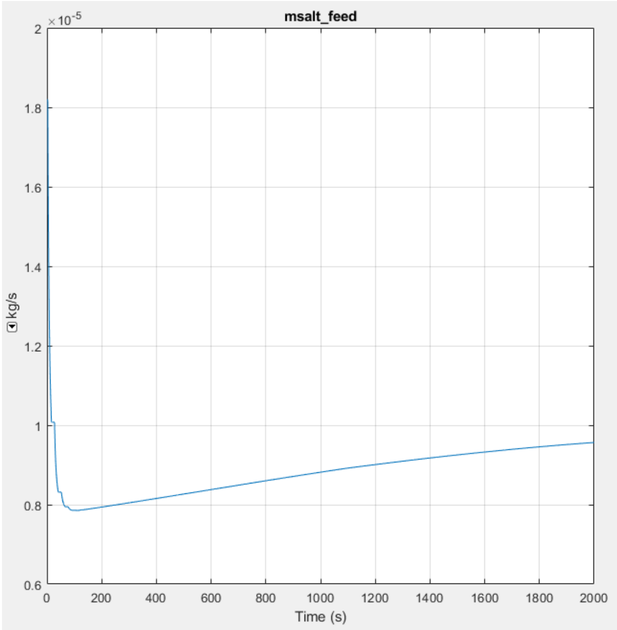

Figure 6.4 Salt concentration feed water, when temperature is simulated from 278-316 K

Flow

Figure 6.7 - 6.9 shows 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 temperature rising.

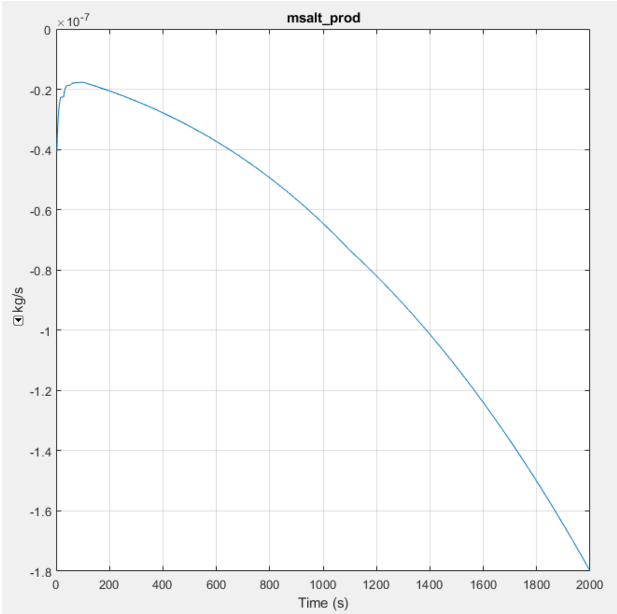

Figure 6.5 Salt concentration product water, when temperature is simulated from 278-316 K

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 are increasing and let more water flow through the membrane which contributes with the lower pressure.

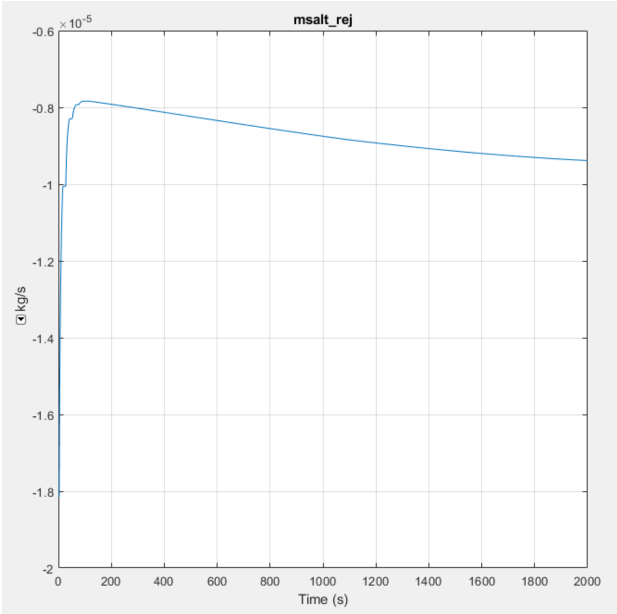

Figure 6.6 Salt concentration reject water, when temperature is simulated from 278-316 K

Conductivity

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

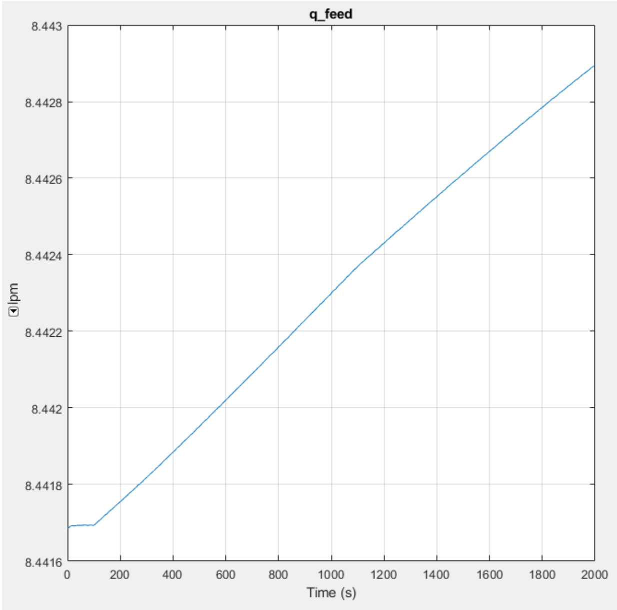

Figure 6.7 Flow feed side, when temperature is simulated from 278-316 K

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.

One pump system, seen in figure 5.3. The one pump system 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.

Two pump system, figure 5.4. In the two pump system 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 is used to pressurise water within the recirculation loop, control the flow rate in the recirculation loop.

Two ideas of the two pump system were considered and the system with one pump

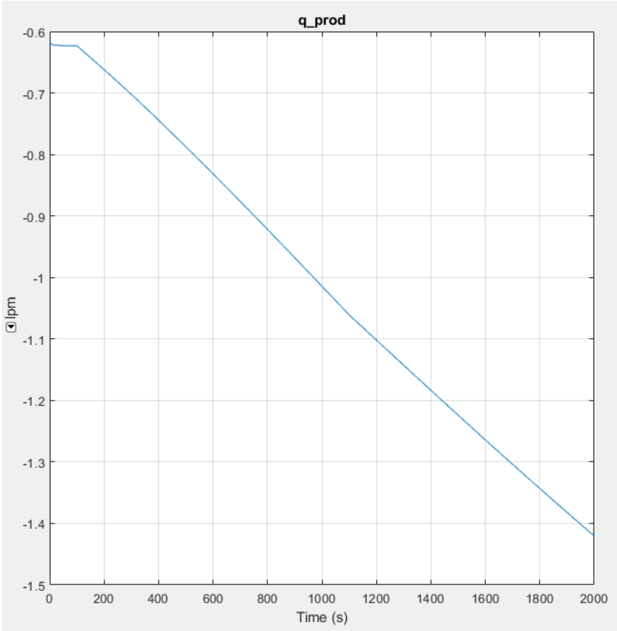

Figure 6.8 Flow product side, when temperature is simulated from 278-316 K

in recirculation path was chosen. The big withdrawal with the implementation of a pump on permeate side, discussed in **??** is considered a high risk implementation and might put patients to high risks. System 1 was therefore precluded, and System 2 with one pump on feed side and one in recirculation loop were chosen.

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

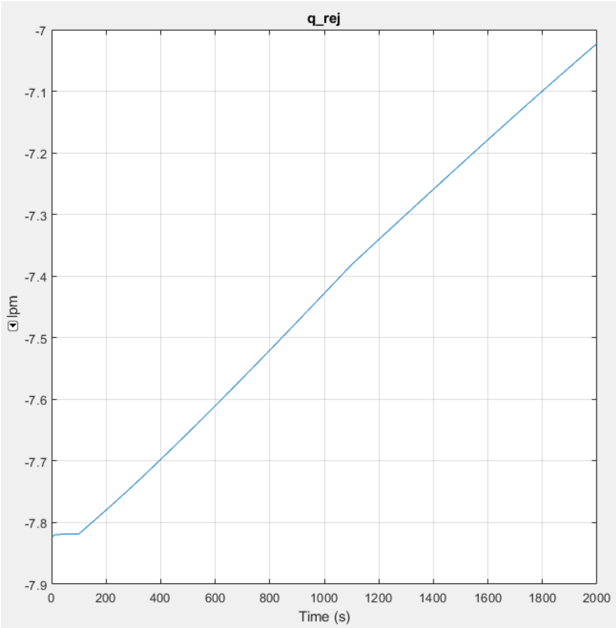

Figure 6.9 Flow reject side, when temperature is simulated from 278-316 K

6.3 Mapping

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

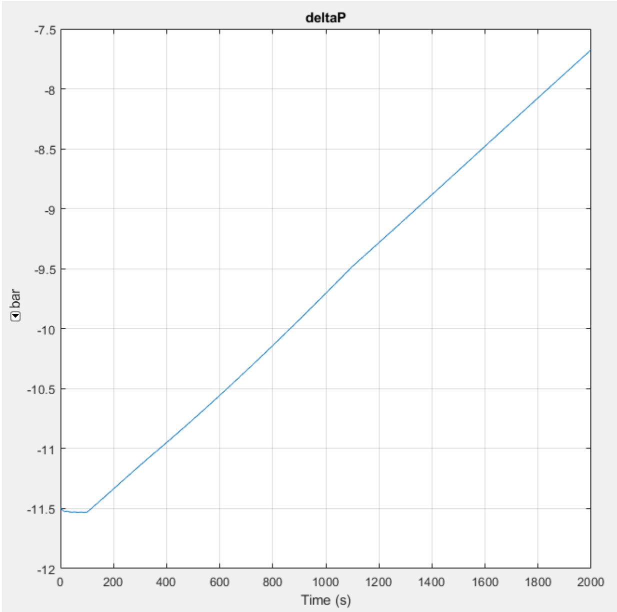

Figure 6.10 Pressure drop feed side to product side, when temperature is simulated from 278-316 K

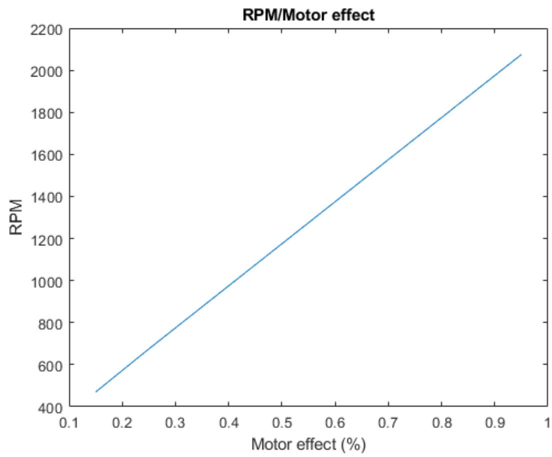

Figure 6.14 RPM of the Pumps at different control signals/duty cycles

The RPM was measured by receiving input from hall sensors in the pump. The flow rate was measured by investigations of different RPM of the pump, different

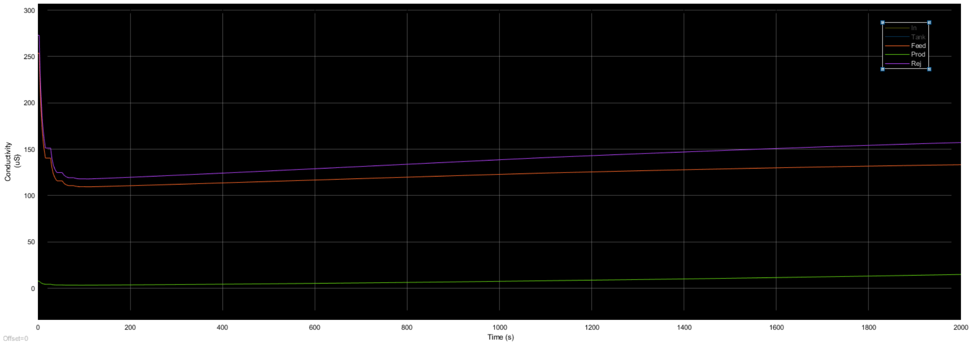

Figure 6.11 Conductivity in feed, reject and product side, when temperature is simulated from 278-316 K

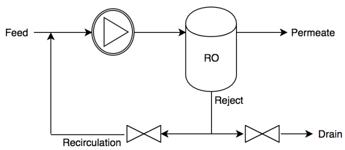

Figure 6.12 One pump system, as the current setup used in the Water Device today

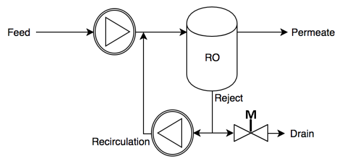

Figure 6.13 Two pump system, with one pump on feed side and one pump in recirculation loop

pressure values of the outlet and scaling of the amount of water delivered by the pumps. Plots, and functions of the flow rate due to the RPM of the pumps were implemented in the control workspace in Simulink.

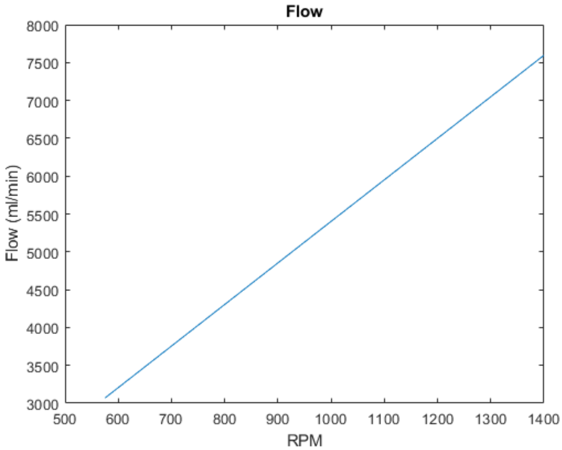

Figure 6.15 Flow rate at different control signals/duty cycles

6.4 Implementation Test Rig

Connections

In Figure (6.18-6.21) all connections in the test rig is displayed. The whole rig can be seen in 6.16 and 6.17

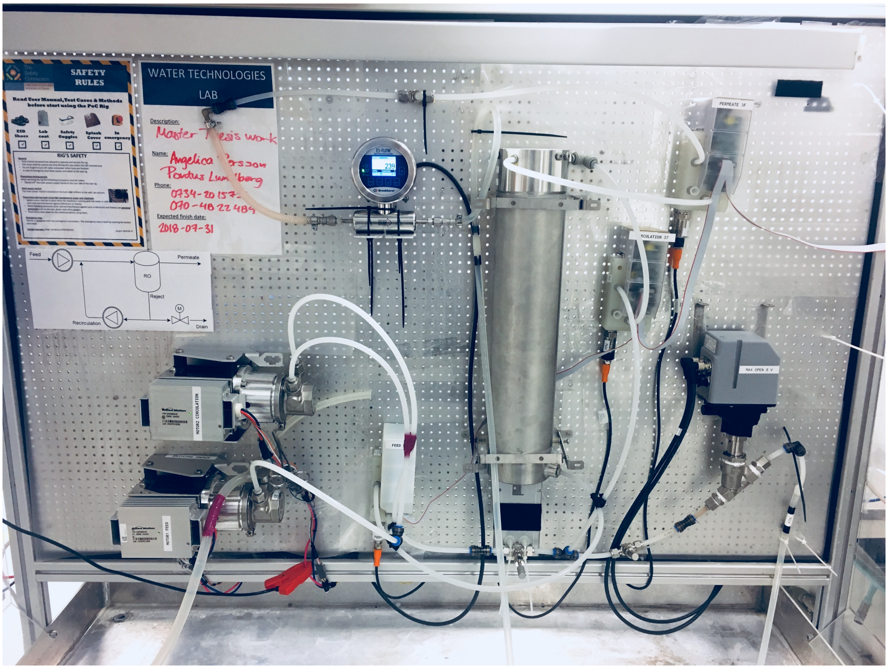

Figure 6.16 The rig built at Baxter Lund AB, with RO-membrane, pumps, pipes, flowmeter, measurement sensors and valves

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

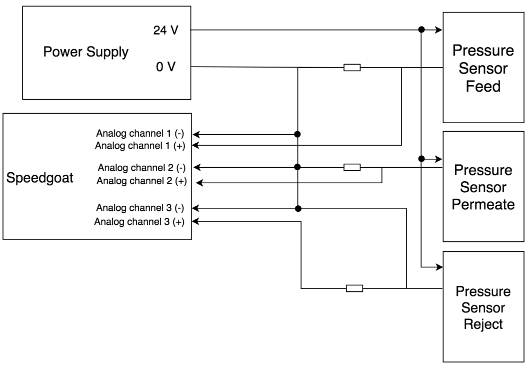

Figure 6.18 Connections Pressure sensors

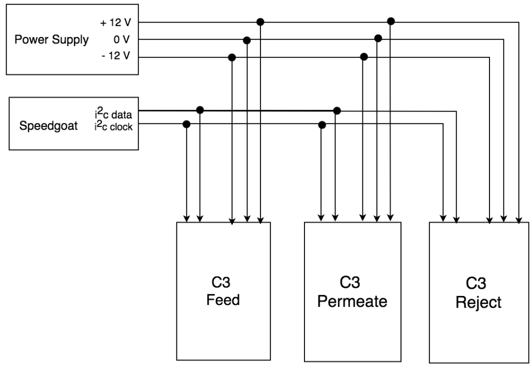

Figure 6.19 Connections measurement blocks, C3

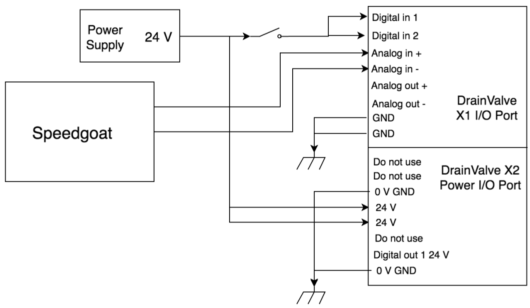

Figure 6.20 Connections Drain Valve

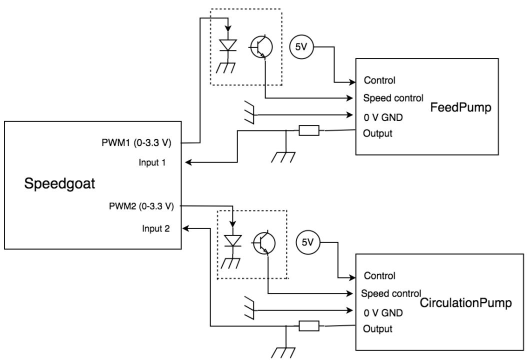

Figure 6.21 Connections Pumps

Figure 6.22 The Display with all key values, read from sensors in the rig, and calculated

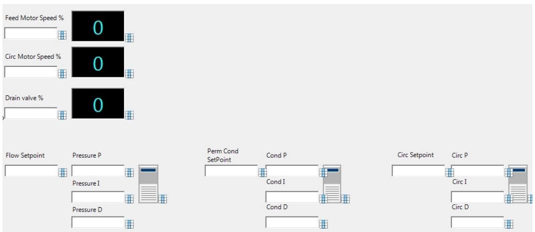

Figure 6.23 The GUI implemented in Simulink and used to control the rig

6.5 Investigation on 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.

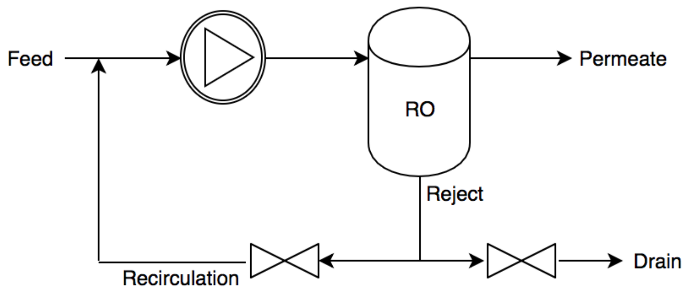

Figure 6.24 One pump system, the current setup used in the Water Device today

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

Table 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 in the tank was heated 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 6.25 and 6.26 show an overview of the tests conducted at 20 C. The parts of the curves that has been marked with black are the steady states points. To be able to get good measurements an average was calculated from these marked values. Note that the three subplots within figure 6.25 and 6.26 share the same timeline so that the marked areas in all three plots are different measurements collected simulataneously.

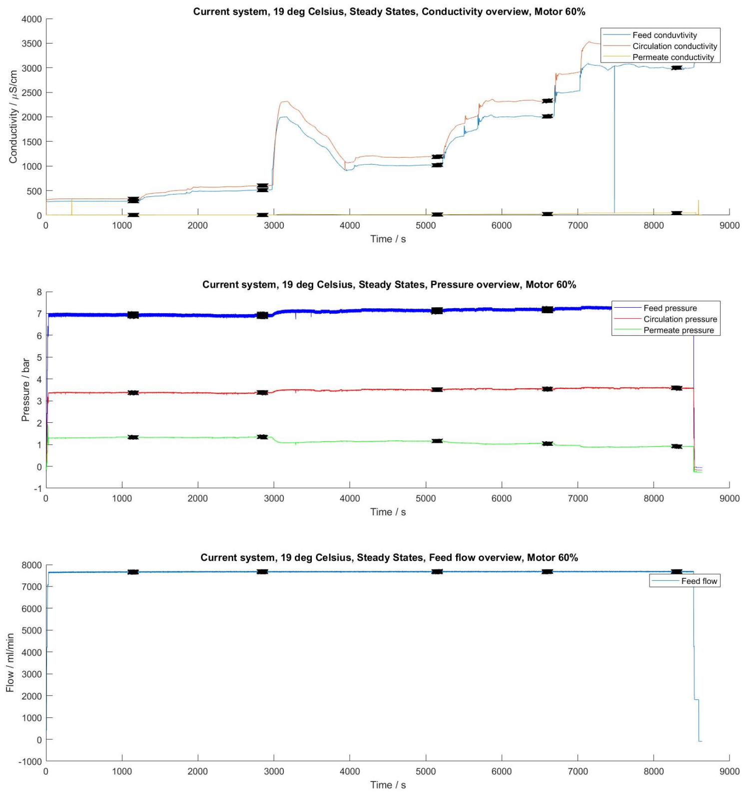

Figure 6.25 Test 1, Current system, 18 degrees celsius. Steady states 1.1, 1.2, 1.3, 1.5 and 1.7

Current system, Test sequence 1, part 2

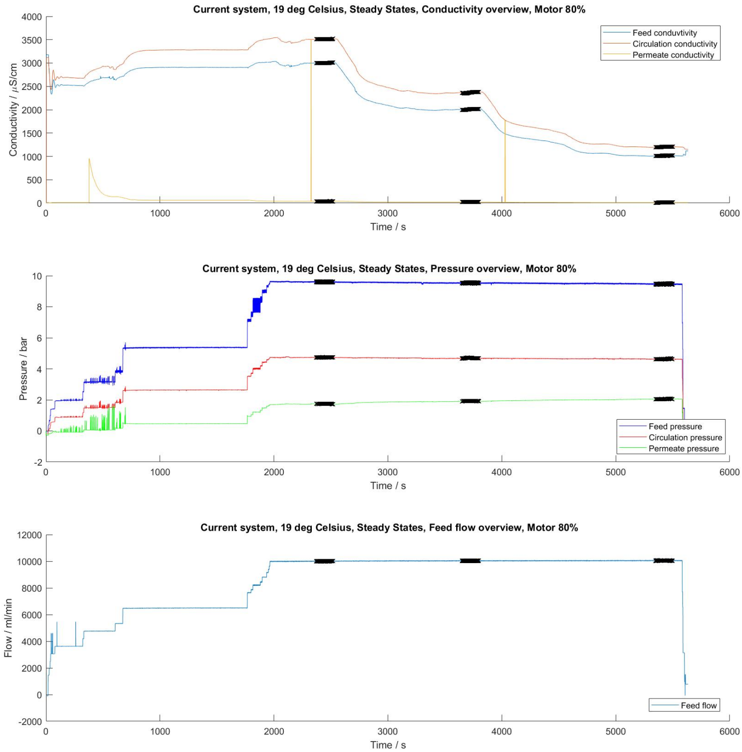

Figure 6.26 Test 1, Current system, 18 degrees celsius. Steady states 1.4, 1.6 and 1.8

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 6.27.

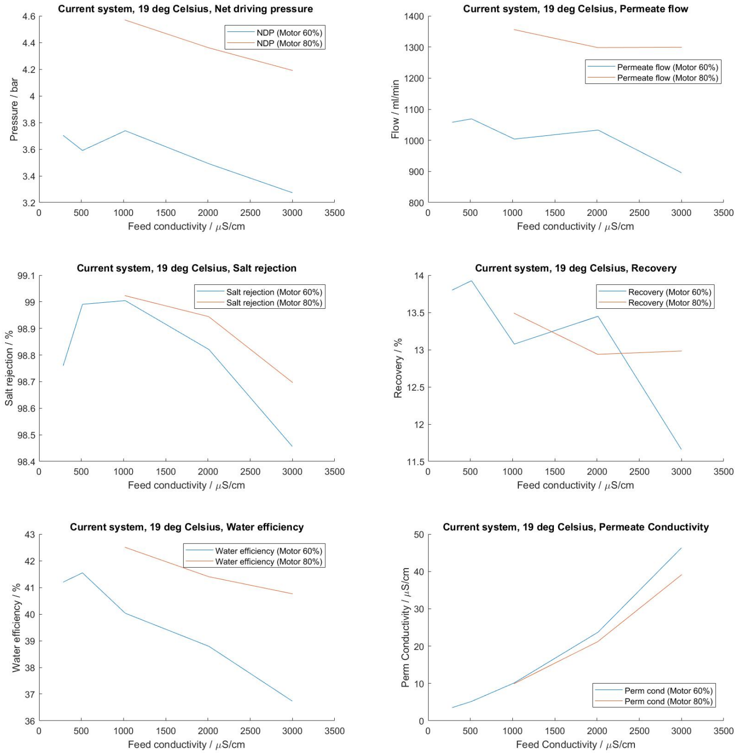

Figure 6.27 Caption missing

Current system, Test sequence 2

The second test was carried out by setting the heater bath to 30 degrees celsius 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.

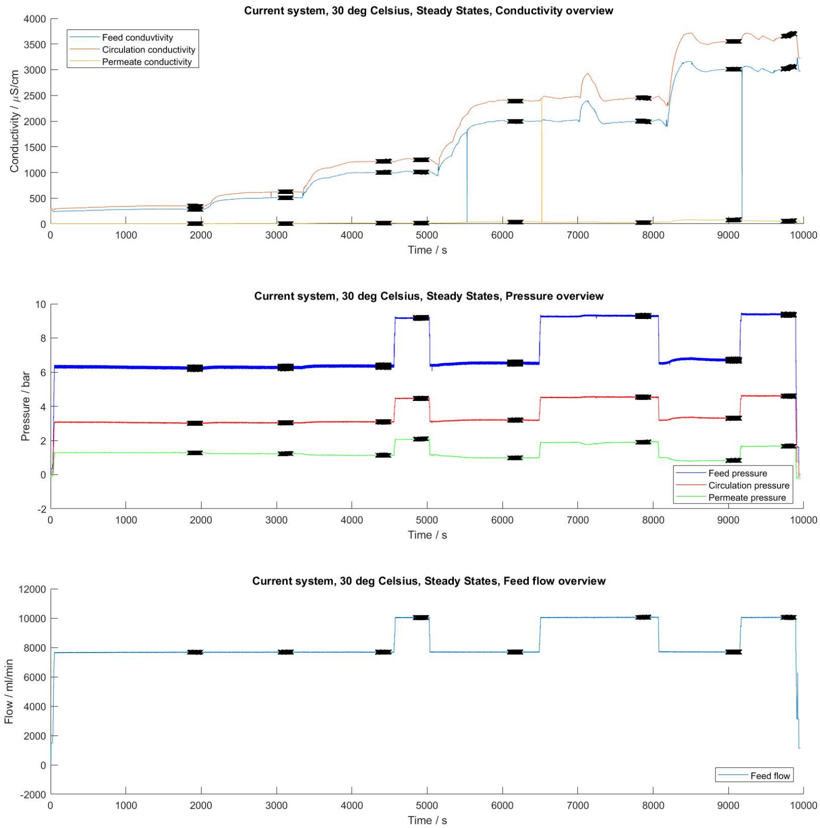

Figure 6.28 Test 2, Current system, 30 degrees celsius. Steady states 1.1, 1.2, 1.3, 1.4 1.5, 1.6, 1.7 and 1.8

The data from the test was post processed in Matlab in exactly the same way as the previous test. The results are displalayed in figure 6.29.

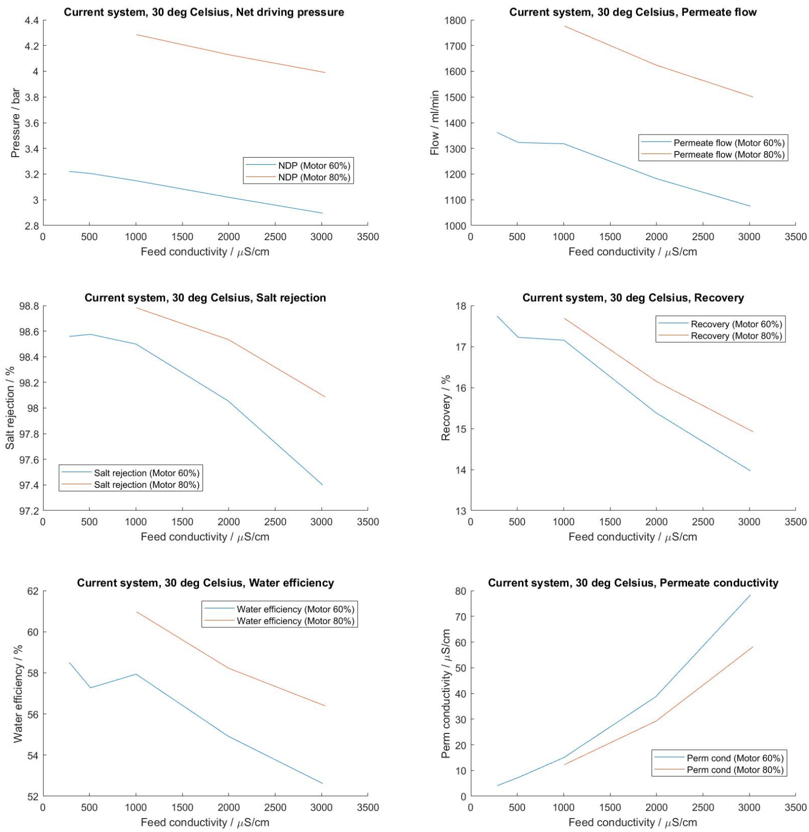

Figure 6.29 Caption missing

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.

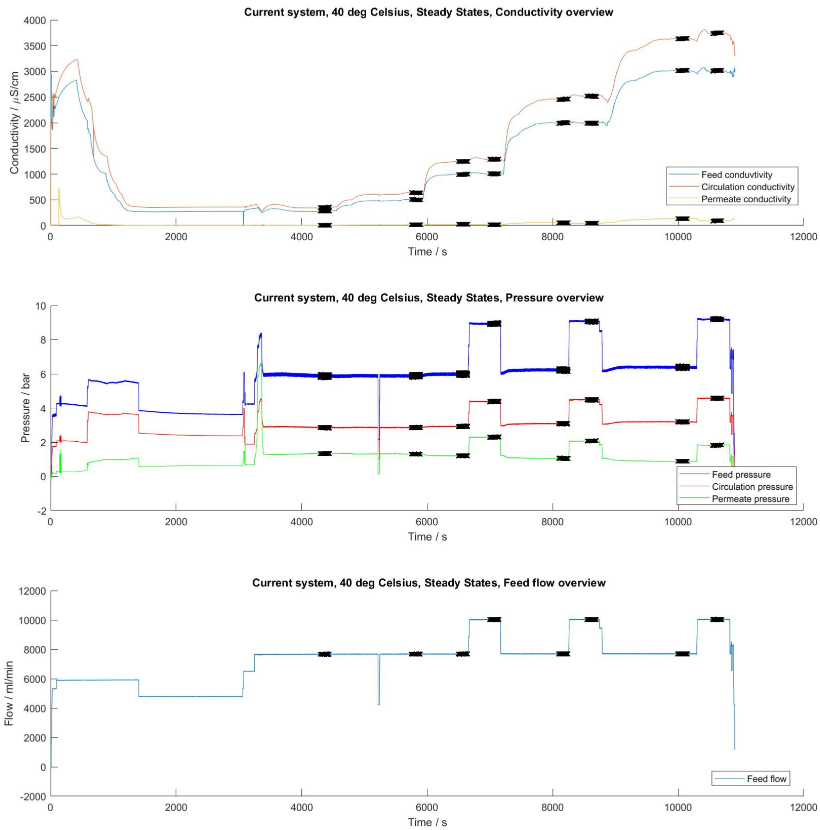

Figure 6.30 Caption missing

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

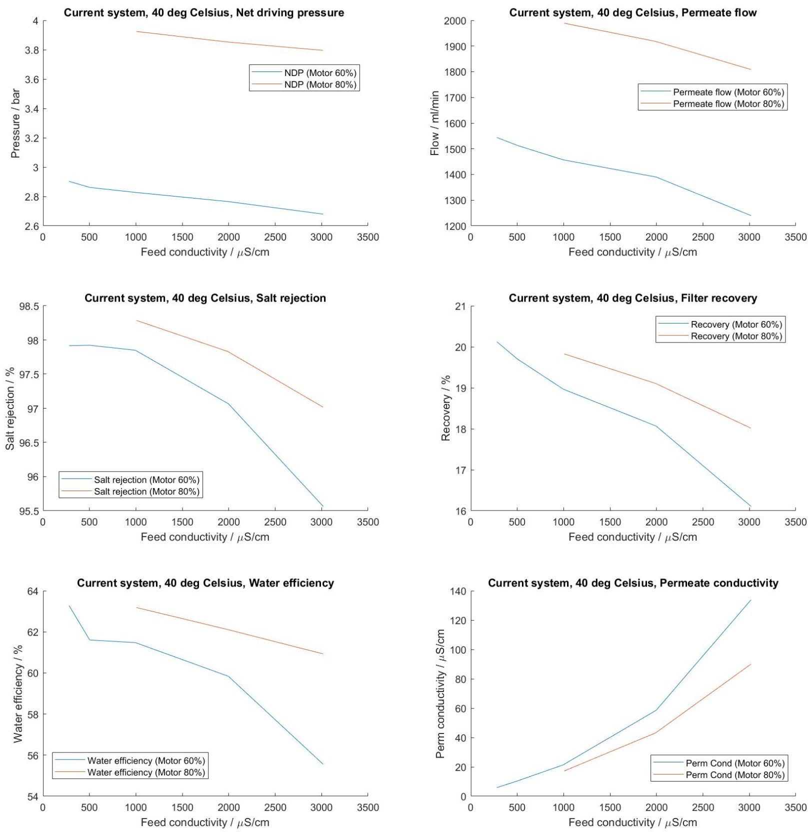

Figure 6.31 Caption missing

In order to understand how the current system performed in different working conditions all plots from the post processing in Matlab was put togeheter. By doing this, it was possible to visuallize 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.

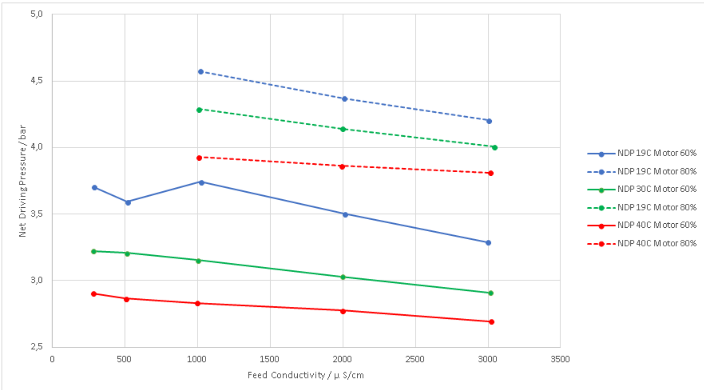

Figure 6.32 Net Driving Pressure, NDP (Pressure difference from feed to permeate side of the membrane)

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

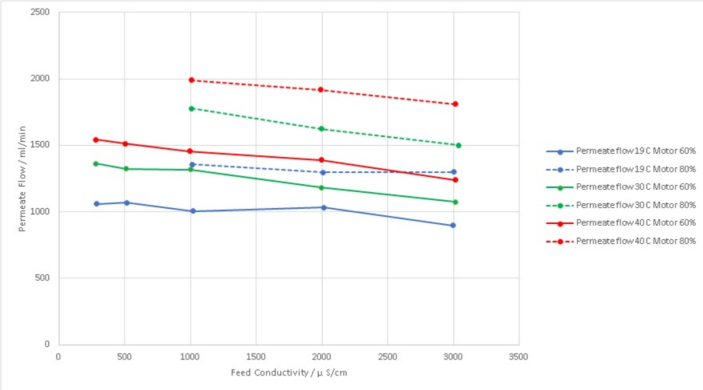

Figure 6.33 Permeate Flow (ml/min)

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.

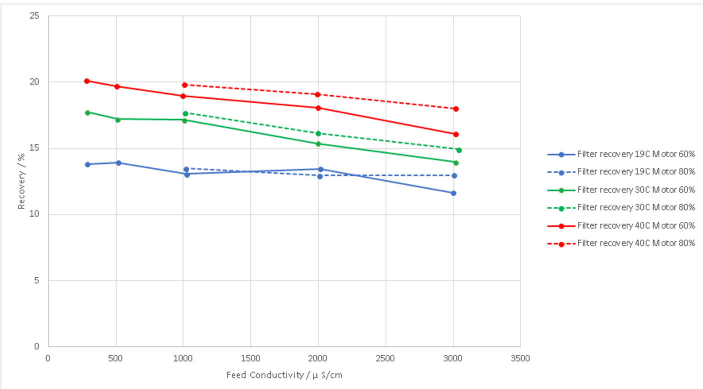

Figure 6.34 Recovery rate (%)

Salt rejection

By looking at figure 6.35 and 6.36 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 30C, 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 3000uS/cm at 19C and 40C 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 that at high temperature and high feed conductivity.

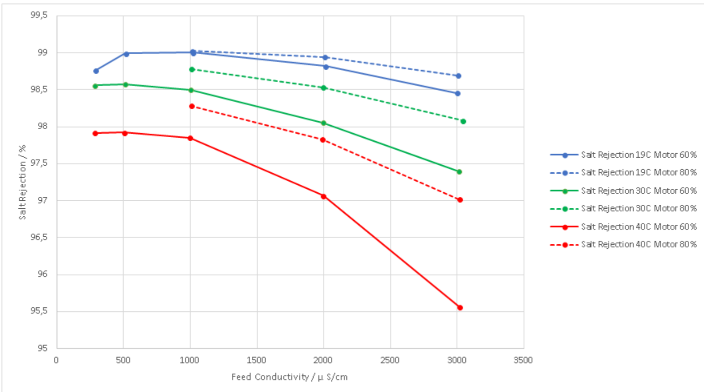

Figure 6.35 Salt Rejection (%)

Permeate conductivity

Permeate conductivity was directly proportional to salt rejection at a certain temperature and feed conductivity. The black line in figure 6.36 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.

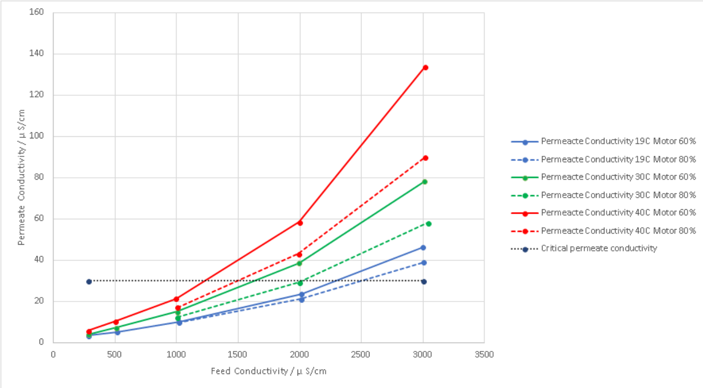

Figure 6.36 Permeate conductivity (µS)

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.

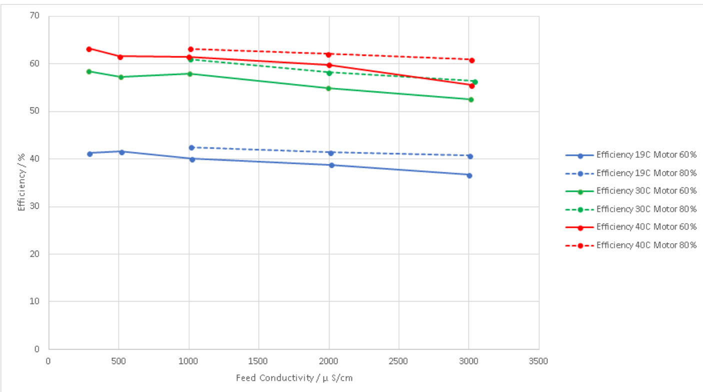

Figure 6.37 Water Efficiency

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 6.38. 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.

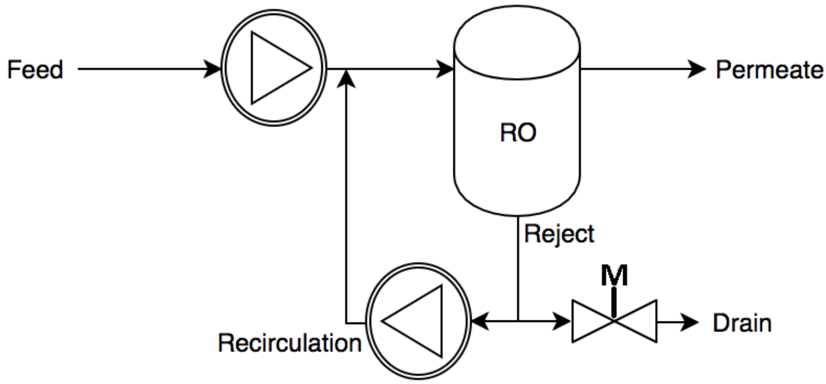

Figure 6.38 Two pump system, with one pump on feed side and one pump in the recirculation loop

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 6.39 show 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.

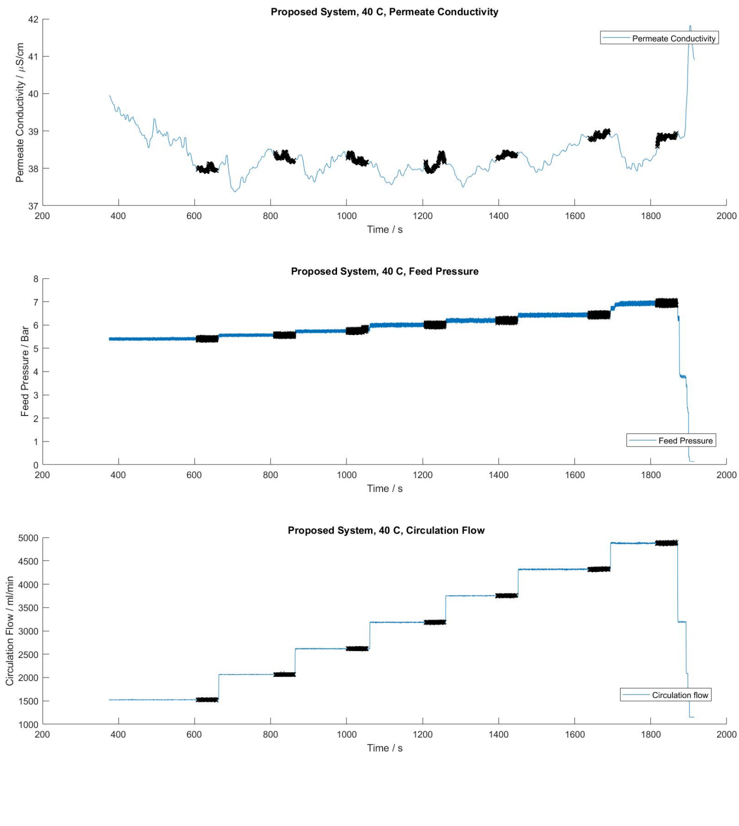

Figure 6.39 Caption missing

More information about how the system performed during the test was calculated and can be seen in figure 6.40. The Recovery decreased from 22% to 14% but salt rejection and permeate conductivity did only slightly increase.

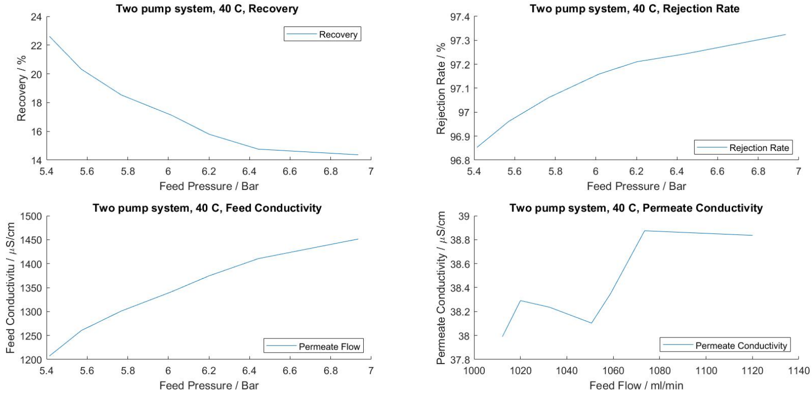

Figure 6.40 Caption missing

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 6.41 and the key parameters calculated after the test can be seen in figure 6.42.

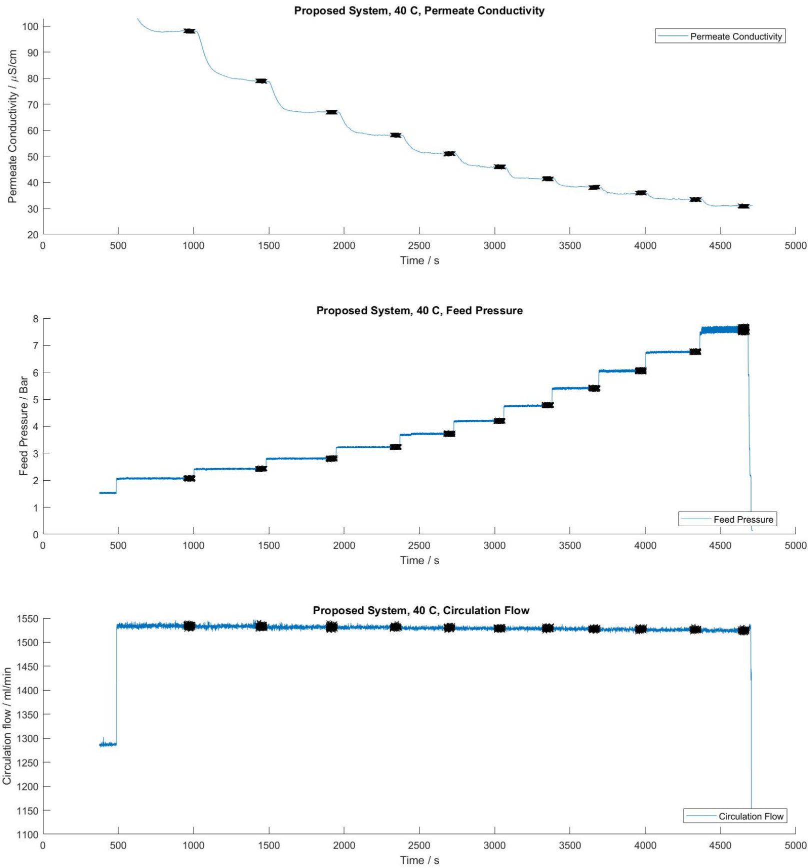

Figure 6.41 Caption missing

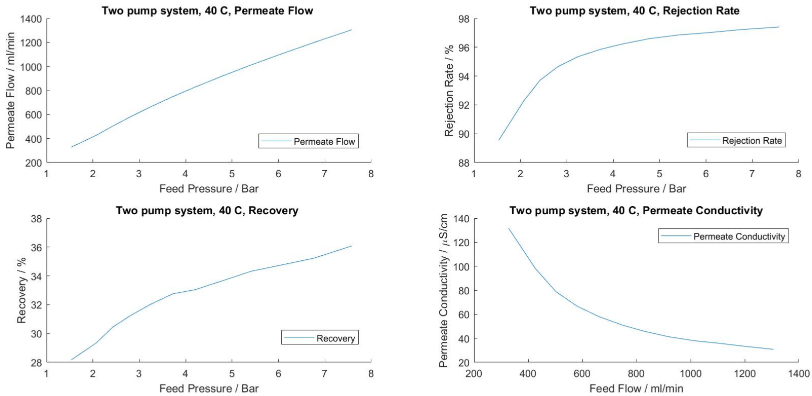

Figure 6.42 Caption missing

From figure 6.41 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 uS/cm to 30 uS/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 consumtion were to be minimized salt rejection would decrease and then more water must be rejected. As a result, increased water efficiency will increase energy consumtion 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 6.32) and that decreased feed pressure reduced salt rejection (see figure 6.35) it could be concluded that using a fixed value setpoint 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. Therefor, 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 uS/cm (25 to 31 uS/cm) while maintaining a recovery of at most 20%. The test was conducted by first adjusting the temperature in the heating bath to 20 deg C and then add salt so that the conductivity of the water in the bath was roughly 275 uS/cm. Afterwards, the feed and circulation pump were adjusted to obtain a permeate conductivity of $\sim$ 30 uS/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 uS/cm. The feed conductivity was increased in small steps and the same procedure was repeated until the conductivity reached 3000 uS/cm. The same procedure was repeated using 30 C and 40 C inlet water. The raw data from the test was noted in table 6.43. 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 30uS/cm. If the feed conductivity was high, depending on temperature, it proved to be impossible to generate 30uS/cm permeate. The measurements that allowed $\sim$ 30uS/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 6.43 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 uS/cm). All relevant pressures, flows, conductivities and other key parameters has been added

By plotting when it was possible to maintain ∼30uS/cm as a function of temperature and feed conductivity it was possible to estimate the working range of the membrane. Figure 6.44 is a 2D representation of the data contained in 6.43. The blue dots are the measurement points were ∼30 uS/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 uS/cm permeate if the feed conductivity was below ∼1292 uS/cm and when the temperature was decreased to 20 C the feed conductivity could be increased to 2101 uS/cm and still produce ∼30uS/cm permeate.

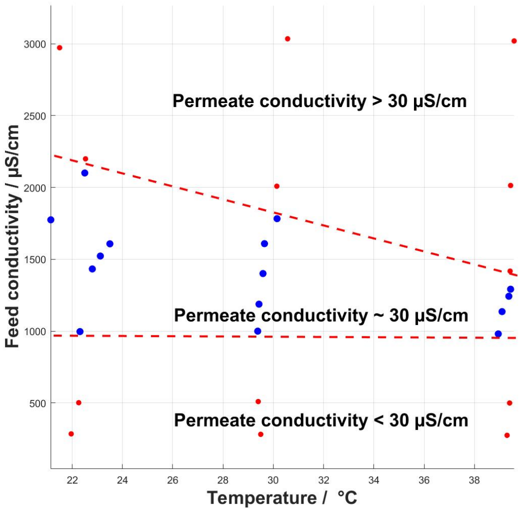

Figure 6.44

Since the idea behind the algorithm was to find an optimal permeate flow for feed conductivities between 275-3000 uS/cm and temperatures between 20 and 40 C a Z axis containing the minimum required to achieve $\sim$ 30uS/cm permeate flow was added to plot 6.44. The blue dots represents the points where good permeate quality could be achieved. By looking at 6.43 it is possible to determine what permeate flow corresponds to the individual points in figure 6.45.

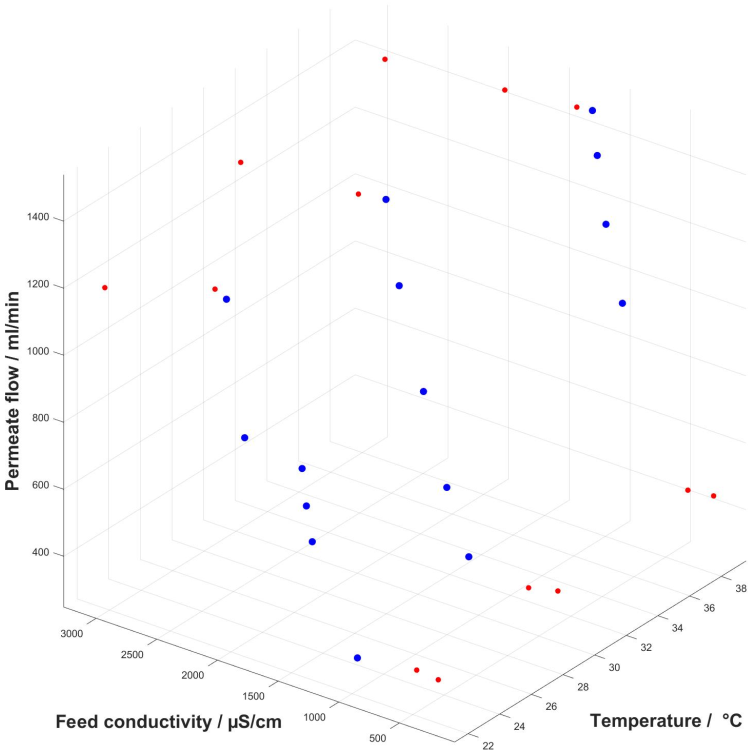

Figure 6.45

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 6.46 . The plane is an estimation of what permeate flow is needed at a given temperature and conductivity to create a permeate quality of ~ 30 uS/cm.

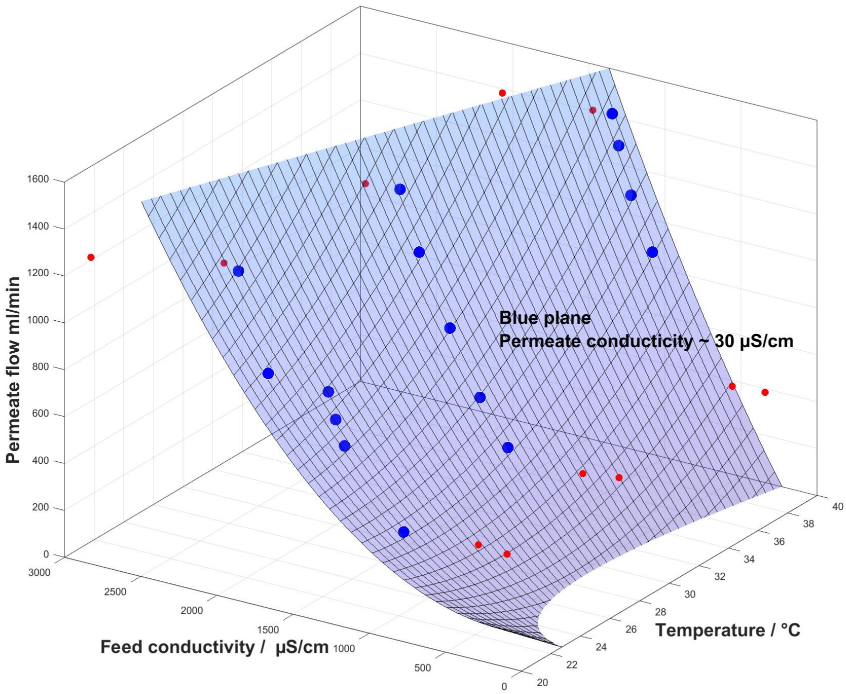

Figure 6.46

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

$$permeate flow = 2349 - 153.9 * t - 1.128 * c + \dots \\ 2.225 * t^2 + 0.05315 * t * c + 0.0002567 * c^2 \quad (6.1)$$

Energy consumtion 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 a algorithm that minimize energy consumtion without wasting more water than necessary. When the system is running at 40 C the maximum allowed conductivity that generates a permeate conductivity of $\sim$ 30 uS/cm is limited to 1292 uS/cm. The proposed optimal function that can be seeb in figure 6.47 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 temperatuer 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.

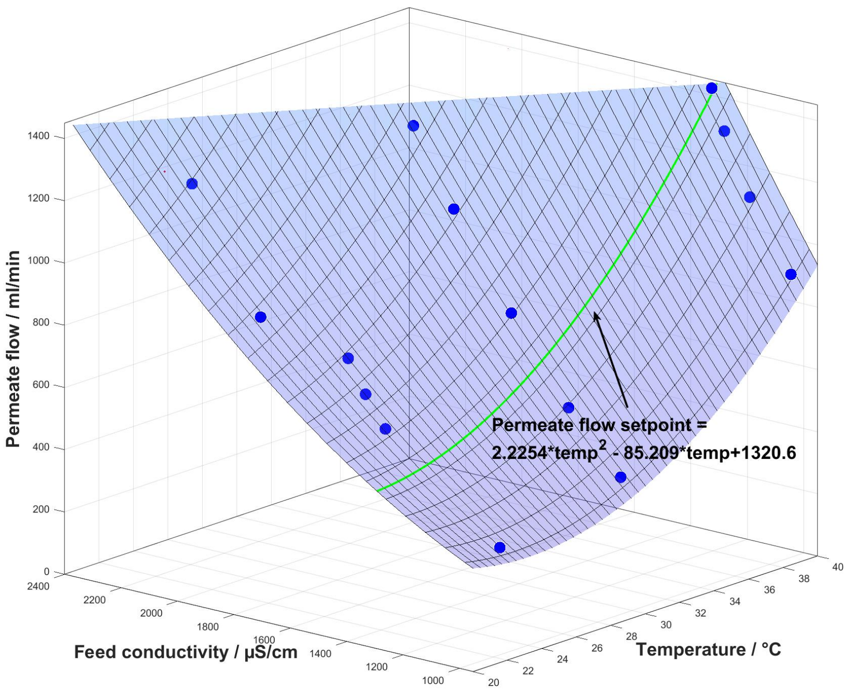

Figure 6.47

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 30uS/cm. Thus, the system will be optimized and operate on the green line in figure 6.47. 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 6.43). The test showed that power consumption of the two pump system ranged from 12 to 194.4 watts depending on the feed conductivity which was far less than what was required when only one pump. Typically, the one pump system used TBD watts when running at 60% and TBD watts when running at 80%. The measured power consumption of the two pump system can be seen in figure 6.48. For example, the two pump system would require % less energy than the one pump system when used in Lund (communal water, temperature 20 C, conductivity 170 uS/cm). Note that the feed pump generate a pressure of 10 bar when running at 25%, the one pump system generate TBD bars when running at 80%.

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 6.48

7

Discussion

7.1 Simulations

When performing the simulations in Simscape the main subjective was to isolate the characteristics to the membrane functionally. The temperature dependencies in flow and pressure was 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 constrains from theory. One important parameter is the temperature correction factor, plotted in 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, water efficiency and noise levels could be reduced without reducing permeate quality. 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 pass through the membrane surface and dilutes the dissolved salts that also pass. This can be seen in figure TBD and 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 become 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 membrane pores is also expanding in 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 was 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 feed 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 when a permeate conductivity of 30 uS/cm can not be maintained. Therefore, the system can adapt to different feed water conductivity by adjusting the water efficiency.

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 an in the authors opinion, the slight decrease in NDP is worth the increase in efficiency. It is possible to increase the feed side pressure by increasing the pump speed. 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 feedpump.

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

A PI controller was used to control the conductivity of the permeate 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 uS/cm. For instance, if the system has a salt rejection of 99% the recirculation loop must hold water with a conductivity of 3000 to obtain a 30 uS/cm permeate. If the system saltrejection change to 96% then the conductivity in the recirculation loop must be 750 uS/cm to achieve the same permeate quality. As can be seen in figure XXXX from the tests withfthe current system, a system with room temperatured inlet water was able to maintain 30 uS/cm permeate water with 2500 uS/cm in the recirculation loop but if the inlet water was heated to 40 degrees Celsius only 1500 uS/cm recirculation conductivity was needed to reach 30 uS/cm. Thereby, controlling the valve position was critical to being able to make sure that the permeate conductivity was 30 uS/cm regardless of operating conditions.

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 slowly the system would overshoot. The only was 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 need to be handled by the controller controlling the pressure in the system. This means that these two controllers are coupled to each other and that it is impossible to change one without influencing the other. 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 a 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 XXXX5.23 and XXXX5.22. From the figures it can be seen that 22 percent recovery caused a pressure of 5.2 TBD bars and a recovery of 14 percent TBD increased the pressure to 6.2 bars. 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 increase inlet 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 5.12 it can be seen that increasing feed pressure has a larger positive effect on salt rejection when the inlet temperature was high and therefor there is no need to waste energy running the system at high pressure. In this scenario, it is better to save energy by running the system at lower pressure and permeate flow.

The system was designed to be able to deliver a stream of permeate water with a conductivity of 30 uS/cm without using more energy and rejected water than necessary, but our tests showed that the only way to increase salt rejection and lower the amount of rejected water was to increase the permeate flow. This 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 uS/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 TBD to TBD depending on the permeate flow set point 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 quieter.

7.8 Membrane size

Membrane size determines the permeate flux at a certain pressure and for smaller systems itt 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 TBD and the temperature to optimal permeate flow function will only work for this membrane TBD. 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 become coated with suspended solids that clogs the surface of the membrane. Using the control design from this thesis, when the membrane surface clogs up more pressure is needed to reach the set point 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 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 optimzed permeate flow for every temperature within the operating range.

By replace the current one pump system without any feedback loops with a system using two pumps and PI regulators and the ability to control the system allows for a more optimzed performance on both water efficiency and energy consumption. As mentioned, the current system does not use any feedback controllers and therefor it cannot adapt to the changing 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 the it can be argued that the system can be optimized by allways applying maximum feed pressure. However, generating pressure costs energy and at low temperatures this extra energy might not be worth the cost even if it improves water efficiency by increasing salt rejection. Consequently, running the system at low pressure will cost less energy but waste more water. Therefore, it is not possible to optimize energy consumption without reducing the water efficiency of the system and vice versa. As a result, any optimization of the system will be regarding which 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.

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 Parameters of concern

Saltrejection Recovery

9.2 Optimization

Energy efficiency Water efficiency

9.3 Mapping

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

- XXX
- XXX

9.4 Membrane size

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

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

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.

The system control is implemented in Simulink.

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 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 fro the temperature measurements in the system.

Pressure sensor

Pressure sensors where 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.)