Optimization of Reverse Osmosis Performance

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Abstract

A condensed description of my work.

Acknowledgements

These people helped me a lot with my work.

Contents

Dictionary

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

Feed: The water entering the membrane system

Permeate: The purified water leaving the membrane as product water

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

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

RO: Reverse Osmosis - the principle of the membrane behavior

Pressure:

Flow:

Semi-permeable membrane:

Conductivity:

:

Drain:

Drain:

1

Introduction

1.1 Background

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

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

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

1.2 Motivation

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

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

1.3 Goal

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

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

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

Framing of questions

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

1.4 Method

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

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

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Theory

2.1 Semi-permeable membrane

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

2.2 Osmosis

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

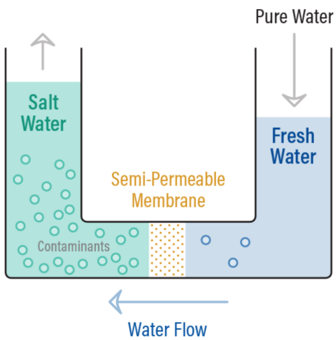


Figure 2.1 Osmosis

2.3 Reverse osmosis

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

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

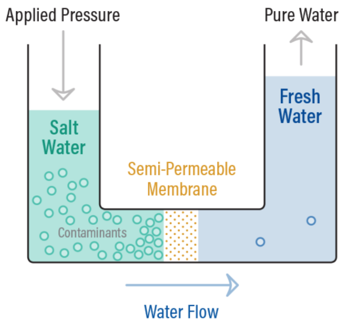


Figure 2.2 Reverse Osmosis

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

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

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

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

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

Fouling

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

2.4 Mathematical modeling of reverse osmosis

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

Figure 2.2 shows the main process.

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

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

and recovery ratio:

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

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

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

and:

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

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

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

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

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

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

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

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

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

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

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

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

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

Equations from DOW

$$Q_p = A_i \pi_i S_E (TCF)(FF)(P_{fi} - \frac{\Delta P_{fcj}}{2} - P_{pi} - \pi + \pi_p) \tag{2.10}$$

$$\pi_f = 1.12(273+T)\sum m_j \tag{2.11}$$

$$TCF = \begin{cases} e^{2640(\frac{1}{298} - \frac{1}{273+T})}, T \geq 25 \\ e^{3020(\frac{1}{298} - \frac{1}{273+T})}, T \leq 25 \end{cases} \tag{2.12}$$

$$pf_i = e^{0.7Y_i} \tag{2.13}$$

$$Y = \frac{Q_p}{Qf} \tag{2.14}$$

$$C_p = B(C_{fc})(pf_i)(TCF)\frac{S_E}{Q_i} \tag{2.15}$$

$$A(\pi) = \begin{cases} 0.125, \pi \leq 25 \\ 0.125 - 0.011(\frac{\pi-25}{35}), 25 \leq \pi \leq 200 \\ 0.07 - 0.0001(\pi - 200), 200 \leq \pi \leq 400 \end{cases} \tag{2.16}$$

2.5 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.

Linear Quadratic Gaussian control (LQG)

Linear Quadratic Gaussian is considered being a combination of a Kalman filter, linear quadratic estimator (LQE) with a linear quadratic regulator (LQR). The method is called LQG since the regulator is linear, works with quadratic criterias and the noise is normally distributed, Gaussian. LQG control applies to both linear time-invariant systems as well as linear time-varying systems. The controller is a dynamic system and often has the same state dimensions as the system it is controlling. The optimum problem is separable in two independent parts: to calculate the optimum estimated states, the kalman filter, and to calculate the optimum feedback from the estimated states. Below describes briefly how a LQG controller is designed for a continuous system. The system can be displayed as:

$$\begin{aligned} \dot{x}(t) &= A(t)x(t) + B(t)u(t) + v(t) \\ y(t) &= C(t)x(t) + w(t) \end{aligned} \tag{2.17}$$

where x(t) represents the vector of state variables in the system, u(t) the vector of control inputs and y(t) the vector of measured outputs available for feedback. The v(t) is white Gaussian system noise and the w(t) is white Gaussian measurement noise, both affecting the system. If searching for the

$$u(t) = -F_y(p)y(t) \tag{2.18}$$

that minimize

$$V = \|z\|_{Q_1}^2 + \|u\|_{Q_2}^2 \tag{2.19}$$

for a positive definit matrice Q_2 and a positive semi definit matrice Q_1. The regulator is assumed causal. The optimum linear controller is:

$$\begin{aligned} u(t) &= -L\hat{x}(t) \\ \dot{\hat{x}} &= A\hat{x} + Bu(t) + K(y(t) - C\hat{x}(t)) \end{aligned} \tag{2.20}$$

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. [**PID**]

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:

$$G_{cl}(s) = \frac{e^{-sL}}{1 + sT_{cl}} \tag{2.21}$$

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. **??**

3

Equipment

3.1 Reverse Osmosis Membrane

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

3.2 Pumps

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

3.3 Drain valve

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

3.4 Simscape/Simulink

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

The system control is implemented in Simulink.

3.5 Speedgoat Real-Time Target Machine

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

3.6 Measurement instruments

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

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

Conductivity sensor block

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

Temperature sensor

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

Pressure sensor

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

Flow meter

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

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

4

Method/Implementation

4.1 Flowchart investigation

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

Pressure drop over the membrane is high

Flow through membrane is high

The model shall contribute with the following:

Permeate conductivity (minimized)

Fouling on the membrane (minimized)

Temperature dependencies

Waste water going through drain (minimized)

Mainly two different systems containing two pumps were considered:

System 1

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

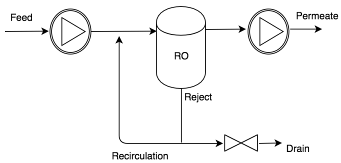


Figure 4.1 System 1

System 2

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

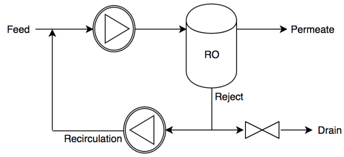


Figure 4.2 System 2

4.2 Tests

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

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

Table 4.1 Testcases

4.3 Modeling

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

4.4 Implementation Test Rig

Current System

In order to run all tests a physical rig was built. A first version to meet the specifications of the system used in the current water device were built according to Figure 4.3, with all the measurement sensors implemented and tests were executed. In order to log all signals and to run the system the Real-Time Target Machine described in section 3.5 were connected with all significant signals. Different interfaces, as i^2c, Analog I/O, Digital inputs, PWM were used to implement the communication between the Real-Time Target Machine and measurement instruments. Circuits were built to transform voltage supply to required level for each component. All implementation of the communication and power supply can be seen in Figure 5.35 - 5.38.

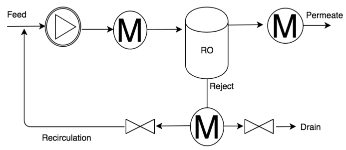


Figure 4.3 Current System, with measurement sensors

System 2 "Comparing system"

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

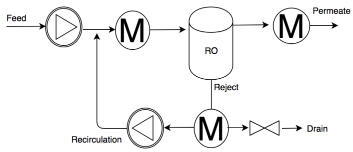


Figure 4.4 System 2, with measurement sensors

4.5 Mapping

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

4.6 Design of control algorithms

Investigating tests on System 2, Figure 4.2, were executed prior the design of the control algorithms to recieve required reference signals to the pumps and drain valve. During the tests one parameter at a time changed while the others were kept constant. In test 1, seen in Figure 5.41 the pump in recycle path were the changing parameter and in Test 2, seen in Figure 5.42 the pressurizing pump on inlet side were the changing parameter.

Control algoritms were developed in Matlab - Simulink.

5

Results

5.1 Modeling

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

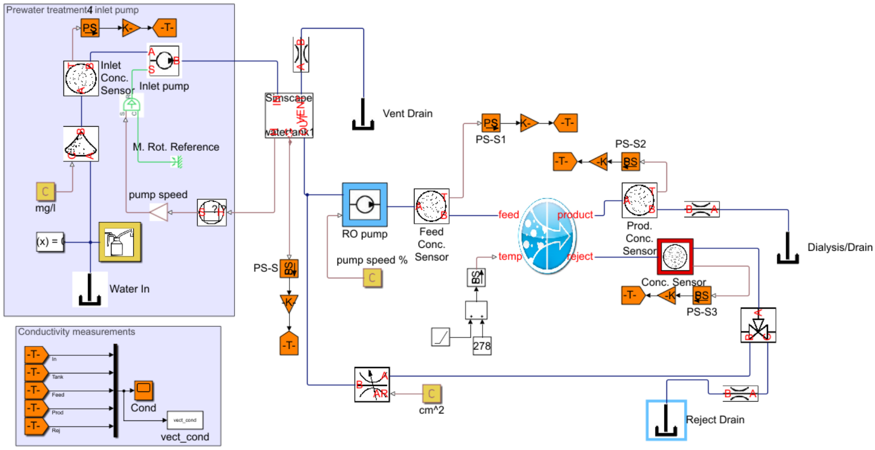


Figure 5.1 Model made in Matlab tool Simscape

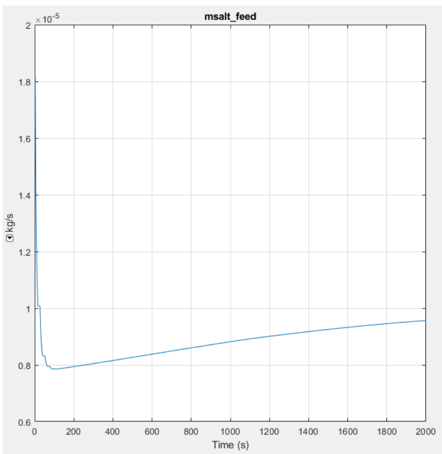


Figure 5.2 Salt concentration feedwater

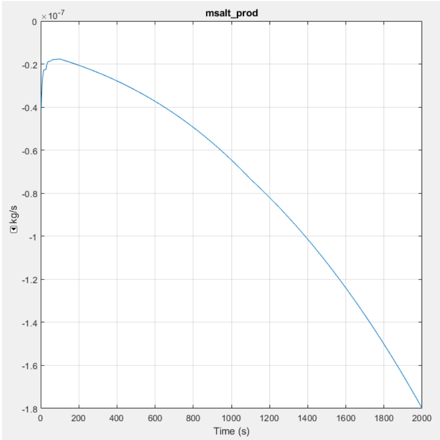


Figure 5.3 Salt concentration productwater

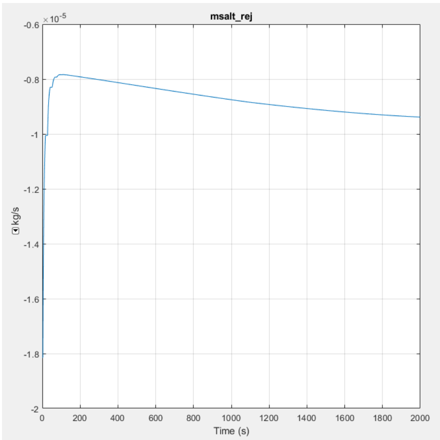


Figure 5.4 Salt concentration reject water

5.2 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 1.3, for an updated version.

One pump system, figure 4.1, The one pump system was designed to use both a tank and the recirculation loop as a water source and to create pressure by generat-

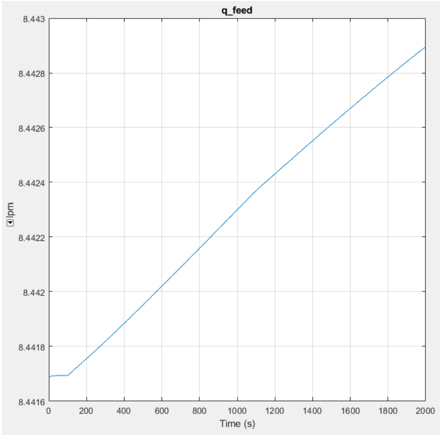


Figure 5.5 Flow feed side

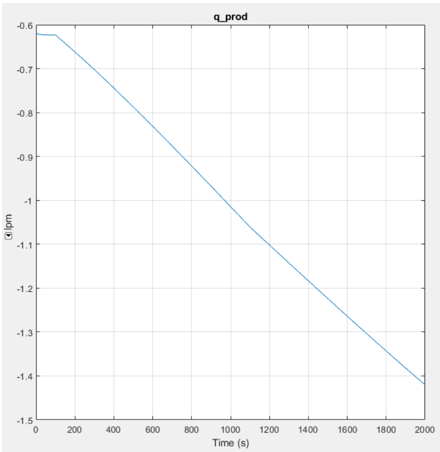


Figure 5.6 Flow product side

ing a large flow over the membrane and recirculation restrictor.

Two pump system, figure 4.2, In the two pump system the water path was modified so that the feed pump only used a tank as a source and pressureized the entire recirculation loop. The recirculation pump was used to recirculate the already pressureized water within the recirculation loop.

An overview of the systems can be seen below.

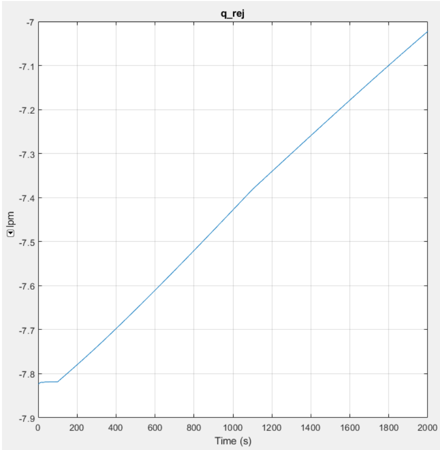


Figure 5.7 Flow reject side

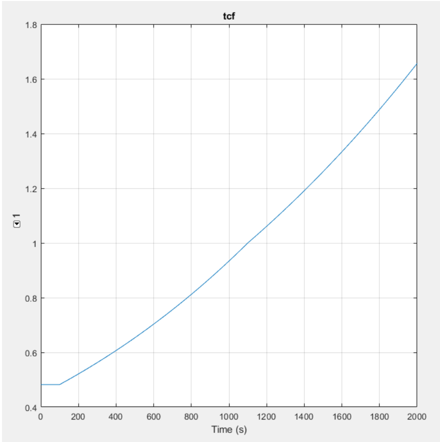


Figure 5.8 Temperature correction factor

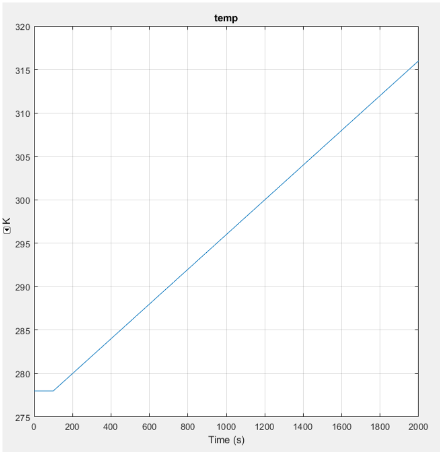


Figure 5.9 Temperature

5.3 Investigation

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 tests were conducted by changing the temperature, recirculation conductivity and pump speed and meassure how the system behaved once it had reached

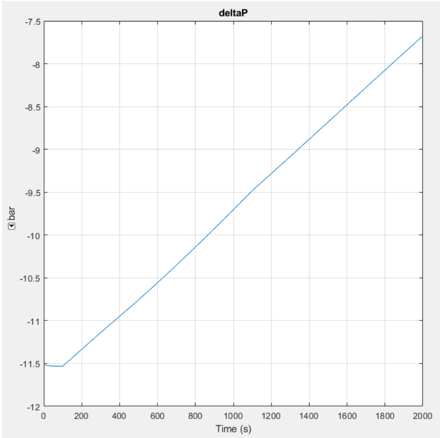


Figure 5.10 Pressure drop feed side to product side

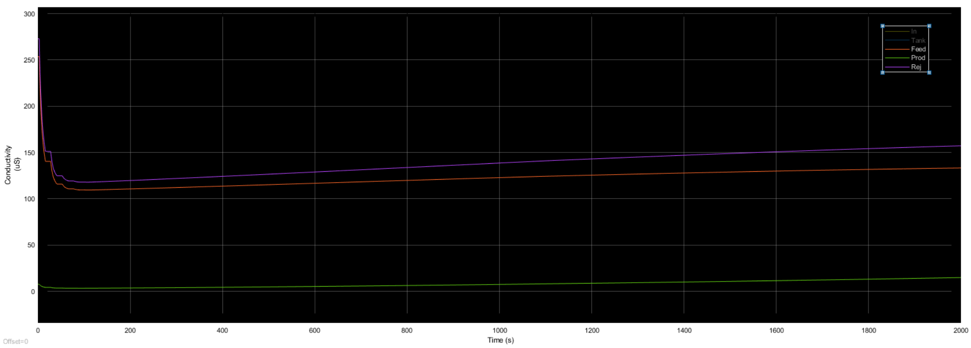


Figure 5.11 Conductivity in feed, reject and product side

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.

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.

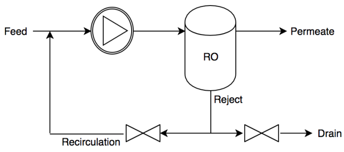


Figure 5.12 One pump system

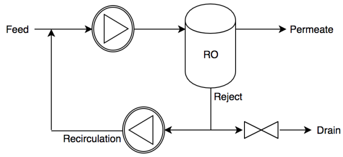
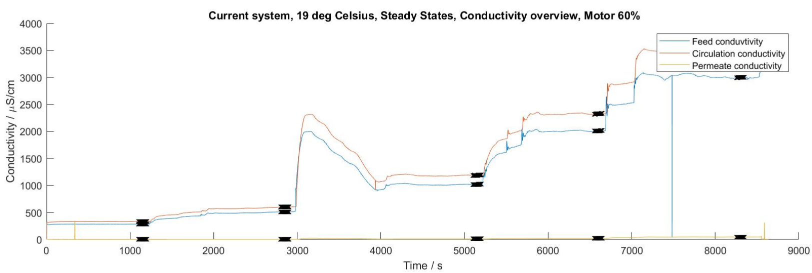


Figure 5.13 Two pump system

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 5.1 Testcases



Current system, Test sequence 1, part 2

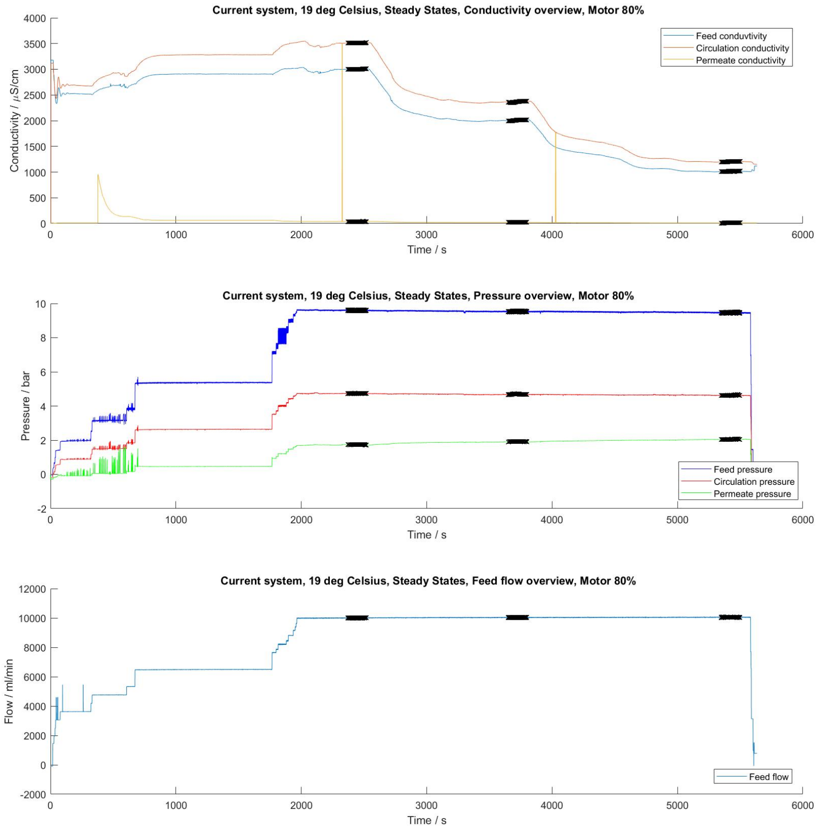


Figure 5.15 Test 1, Current system, 18 degrees celsius. Steady states 1.4, 1.6 and 1.8

By post-procesing the data from test one in Matlab it was possible to visually show how the system parameters were affected by the changed pump speed and feed conductivity.

insert table, results on how the different graphs changed!!!

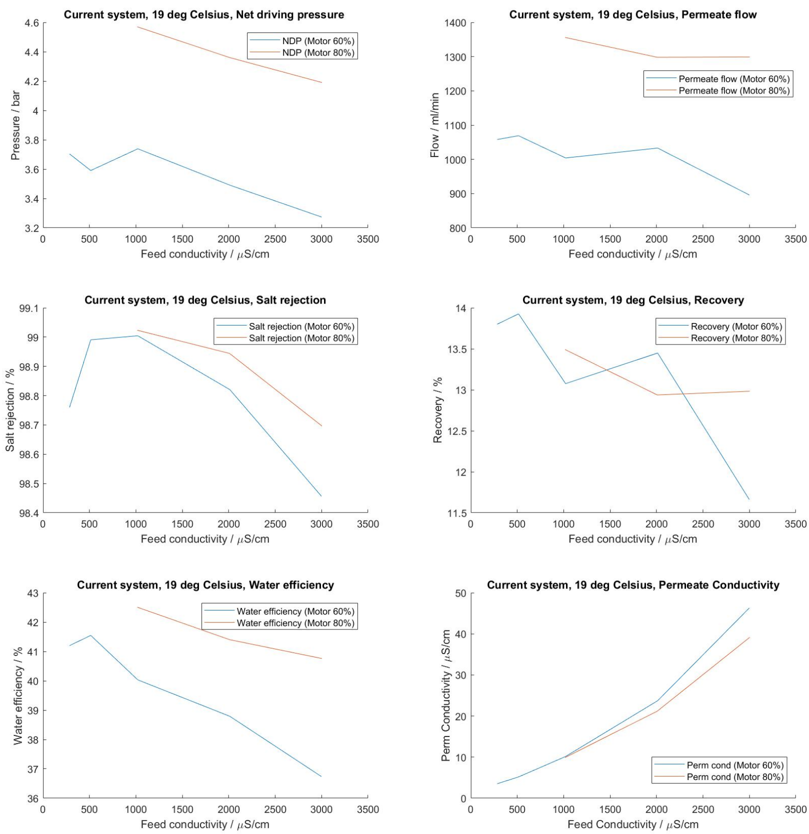


Figure 5.16 Connections Pressure sensors

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 contimous test.

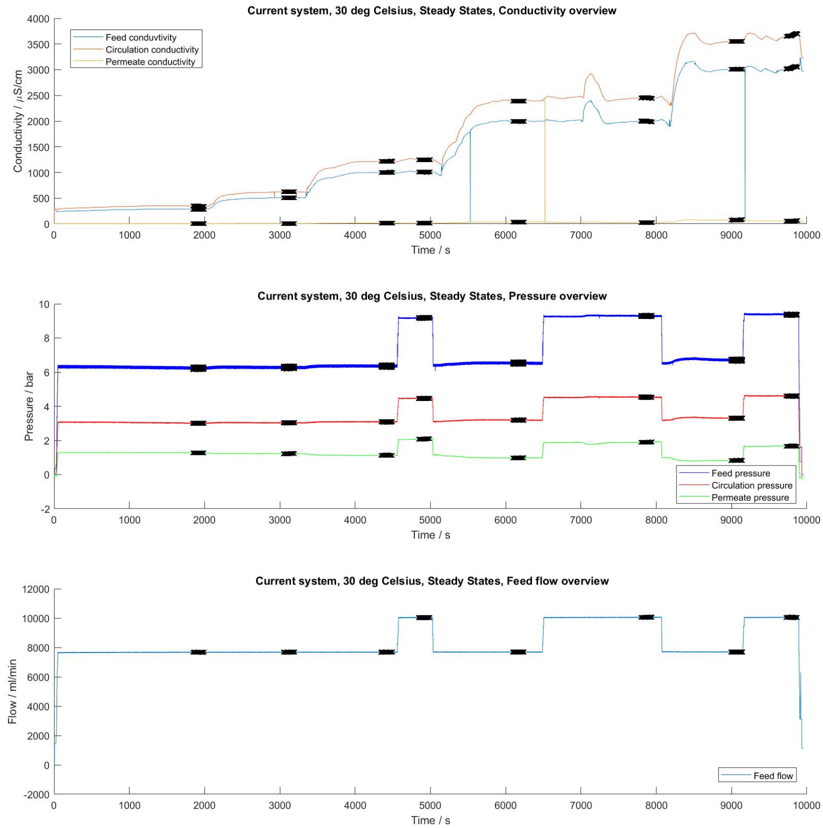


Figure 5.17 Test 2, Current system, 30 degrees celsius. Steady states 1.1, 1.2, 1.3, 1.4 1.5, 1.6, 1.7 and 1.8

The data from the test was post proccesed in Matlab in exactly the same way as the previous test.

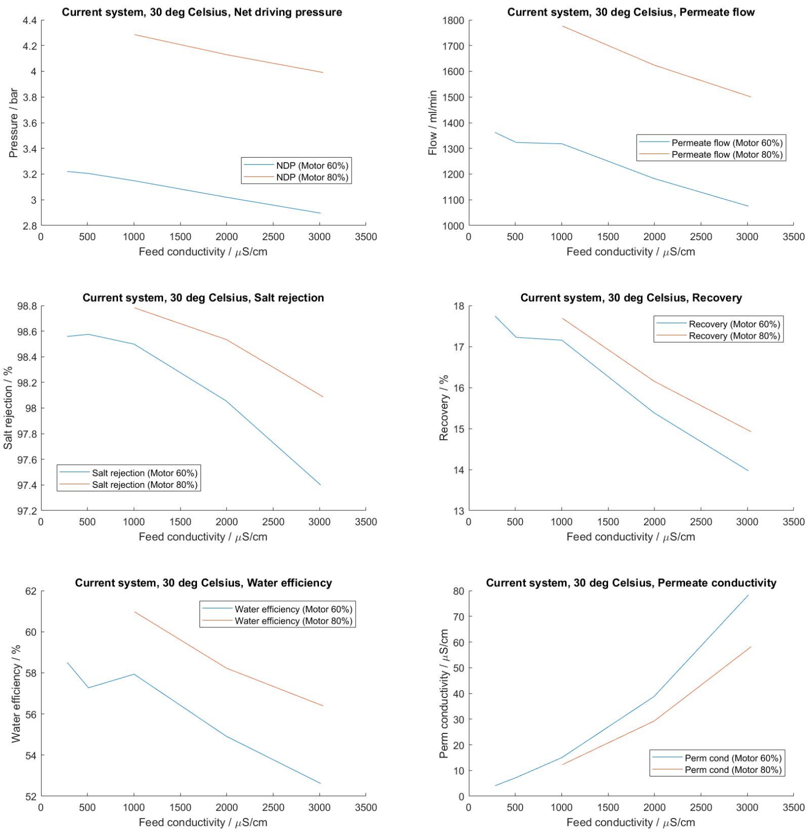


Figure 5.18 Connections Pressure sensors

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.

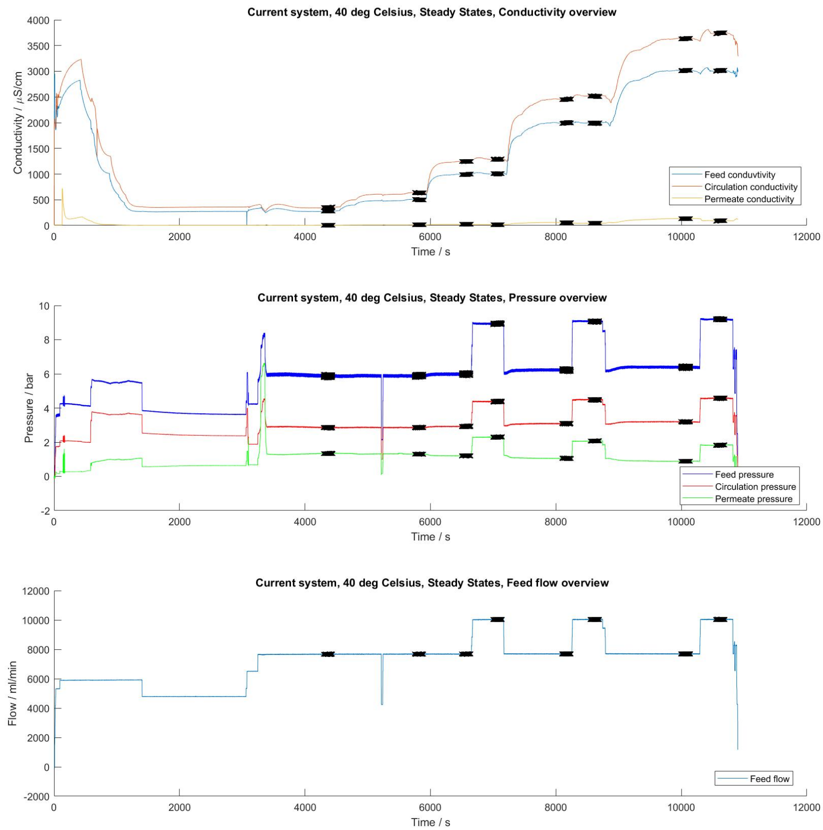


Figure 5.19 Connections Pressure sensors

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

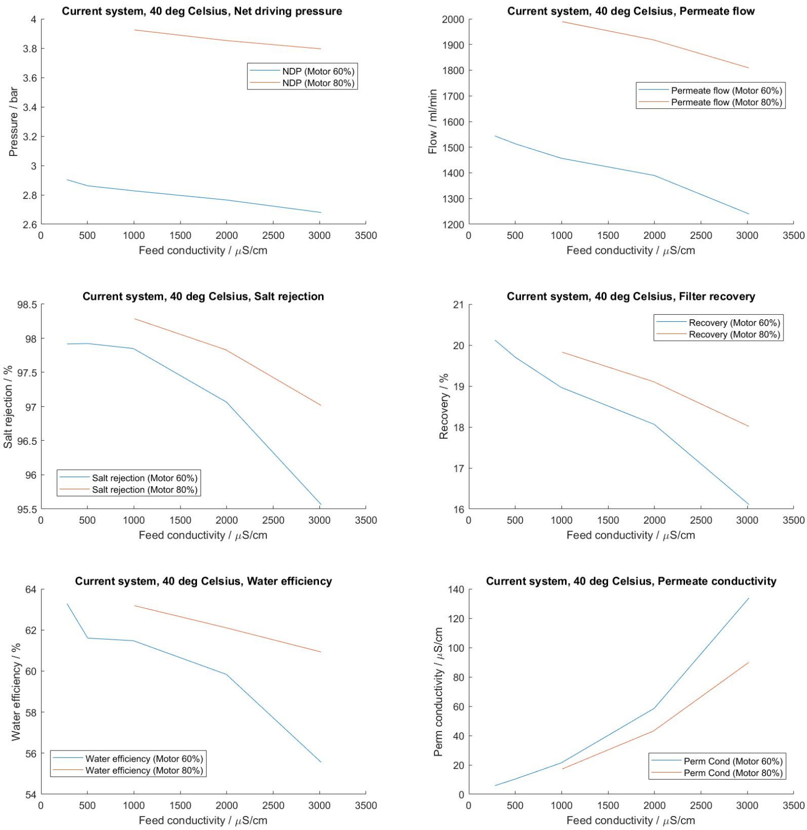


Figure 5.20 Connections Pressure sensors

In order to understand how the system current performed in different working conditions all plots from the post processing in Matlab was put togheter.

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.

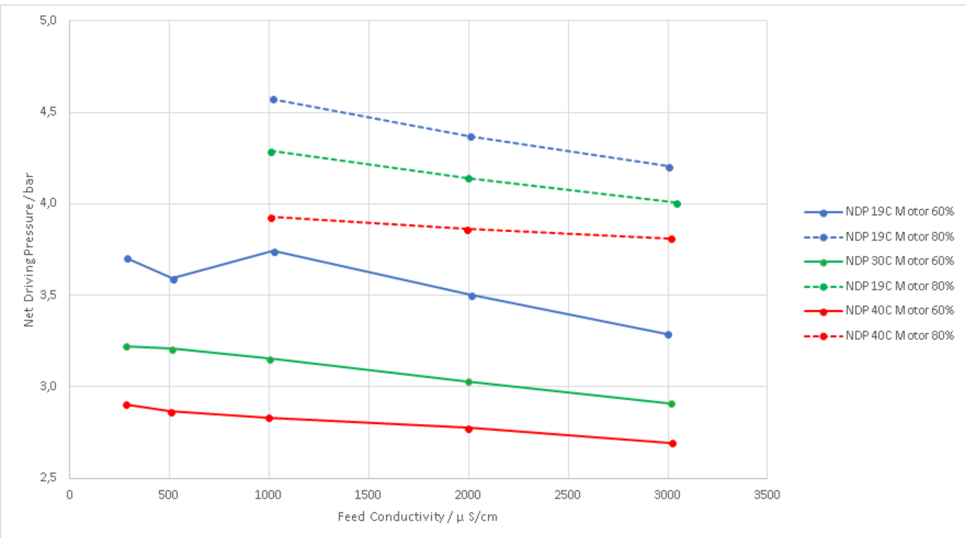


Figure 5.21 Connections Pressure sensors

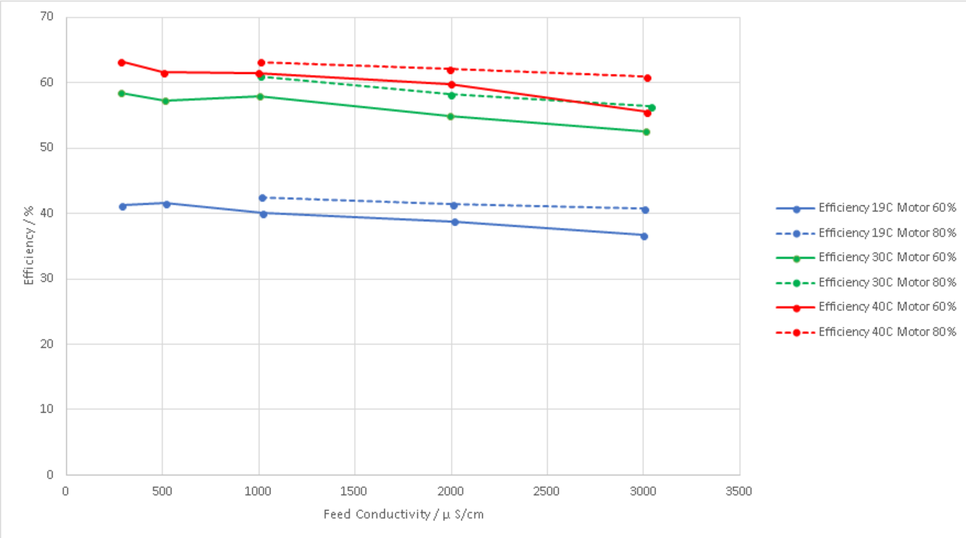


Figure 5.22 Connections Pressure sensors

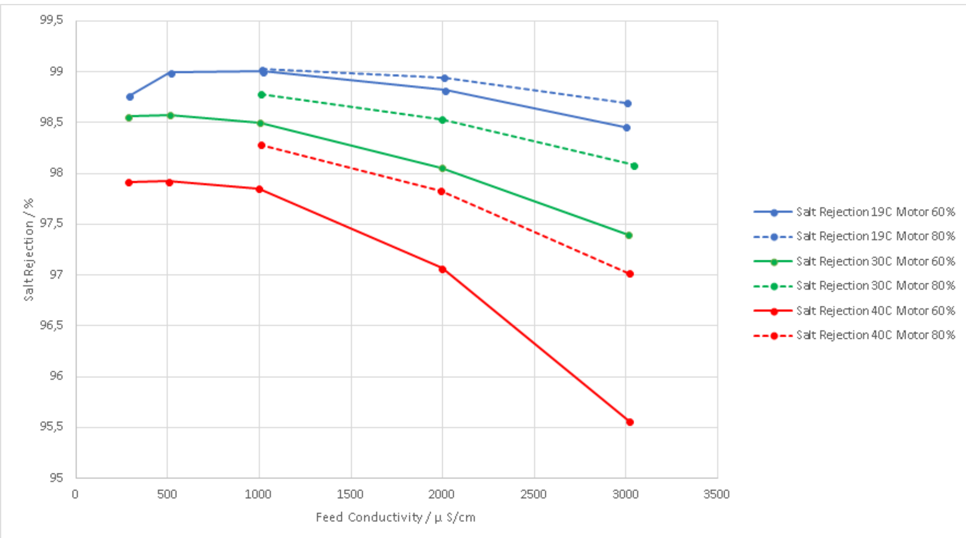


Figure 5.23 Connections Pressure sensors

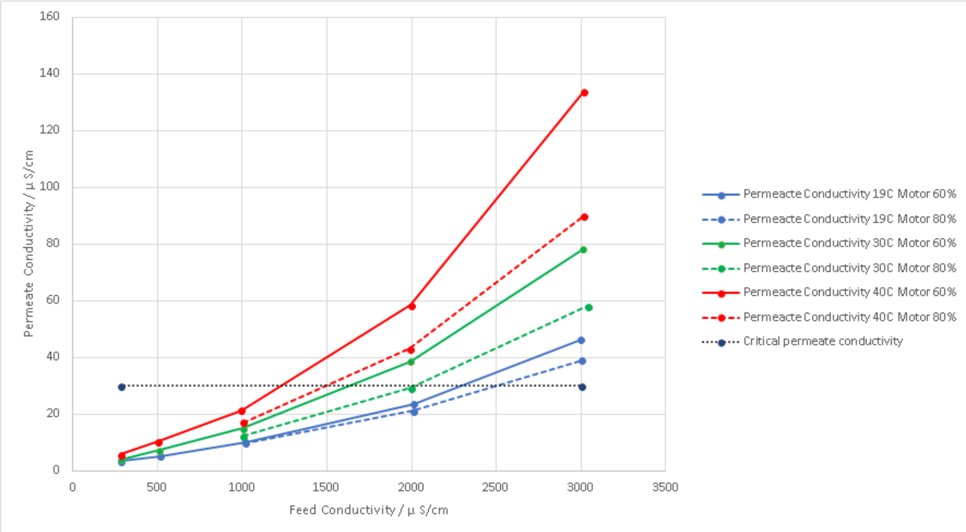


Figure 5.24 Connections Pressure sensors

Summary results 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 net driving pressure.

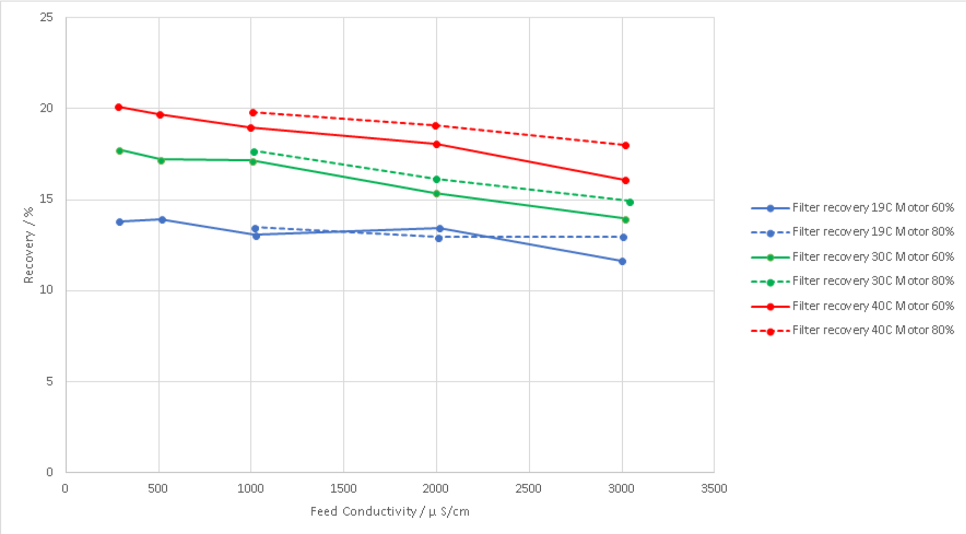


Figure 5.25 Connections Pressure sensors

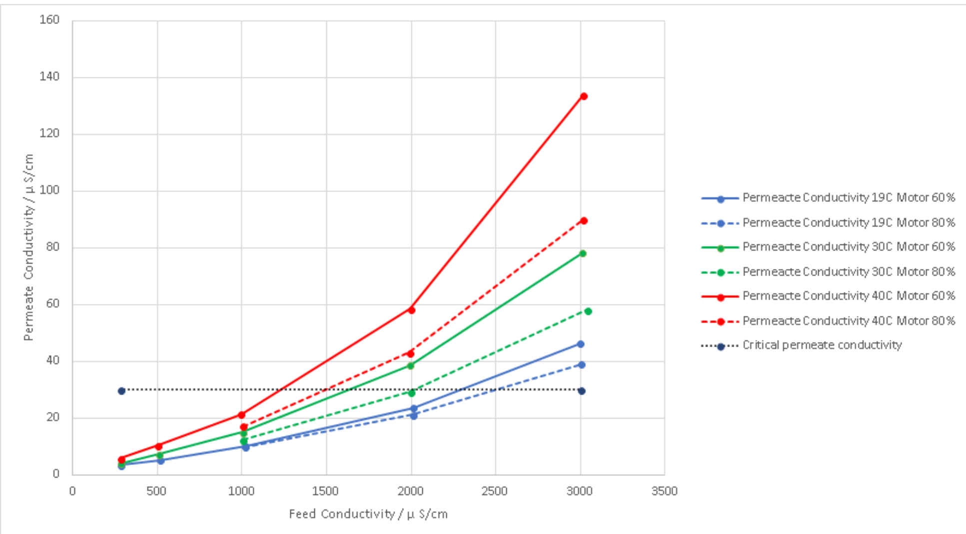


Figure 5.26 Connections Pressure sensors

System 2

Test: increased feed pressure

21

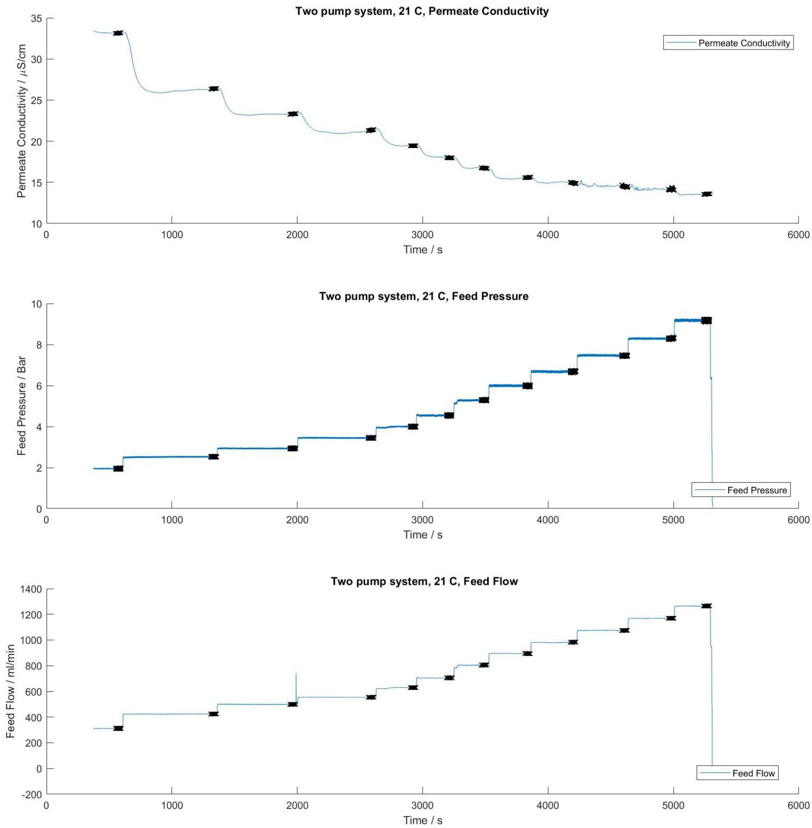


Figure 5.27 Connections Pressure sensors

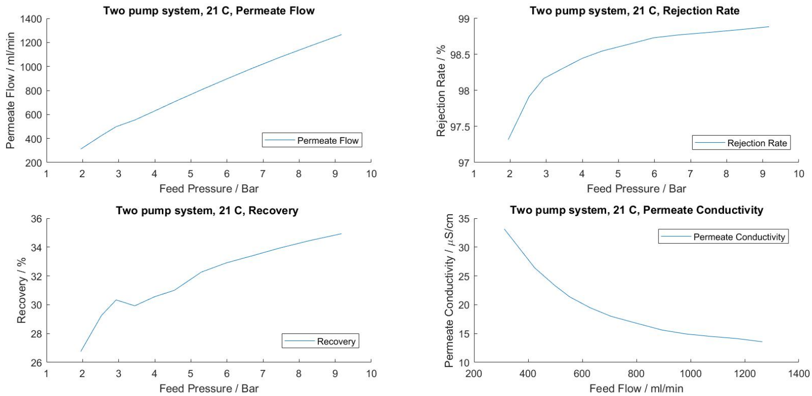


Figure 5.28 Connections Pressure sensors

30

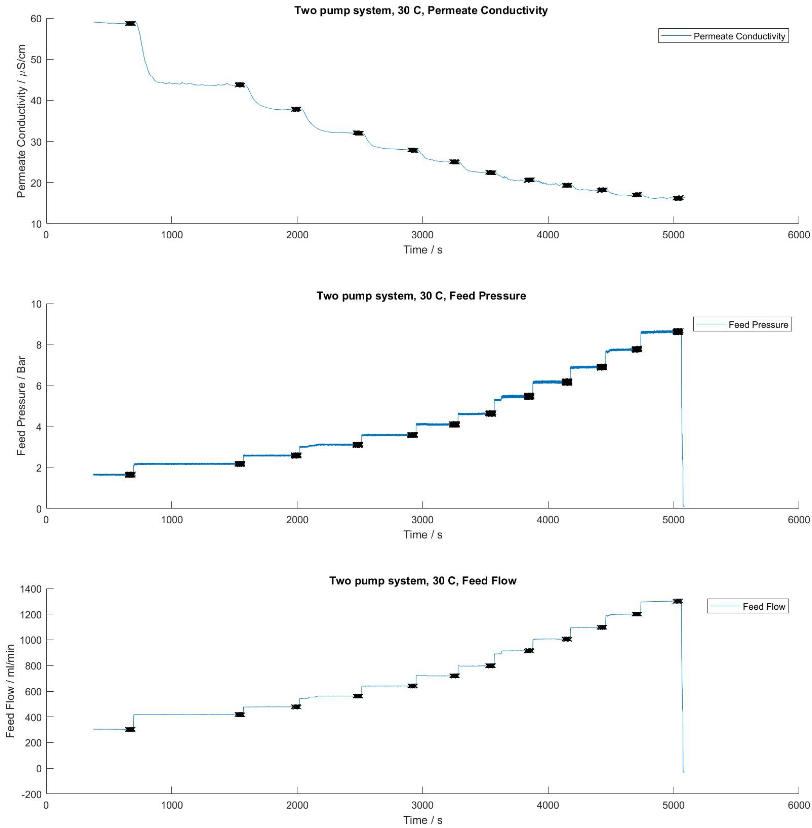


Figure 5.29 Connections Pressure sensors

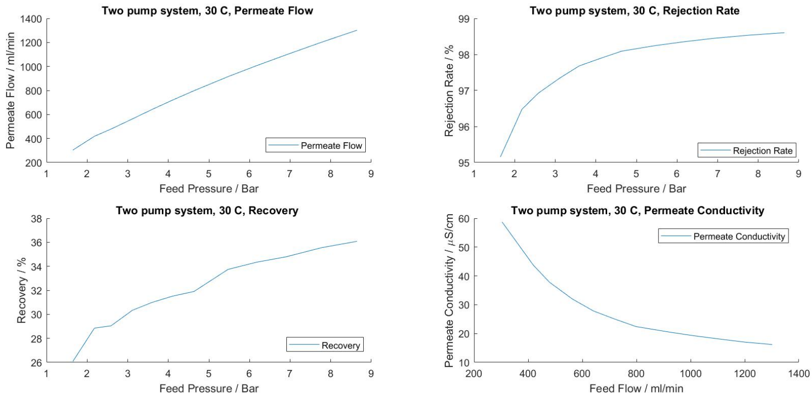


Figure 5.30 Connections Pressure sensors

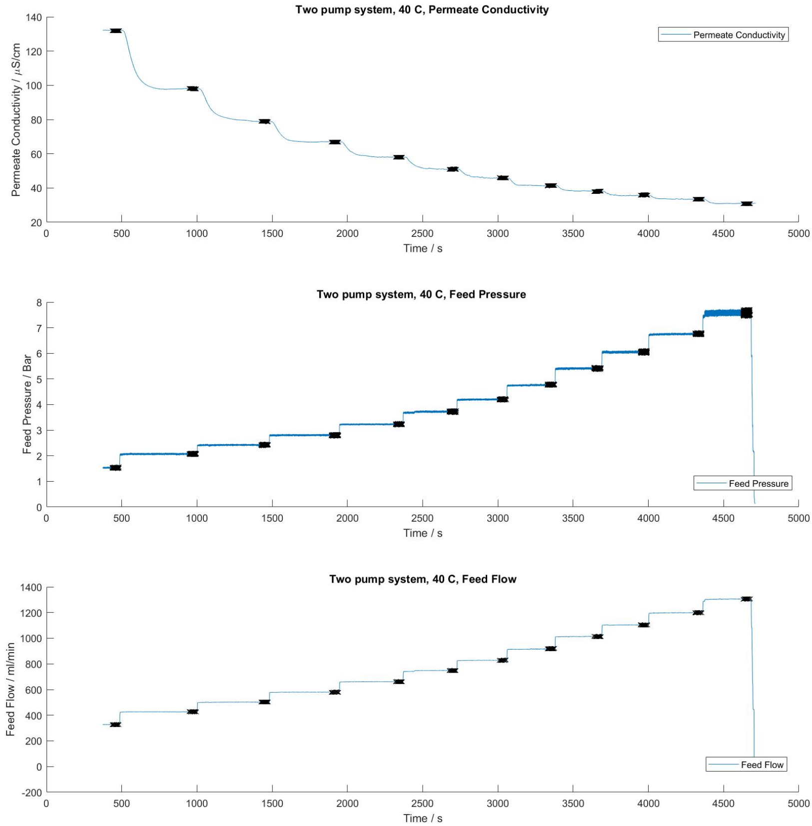


Figure 5.31 Connections Pressure sensors

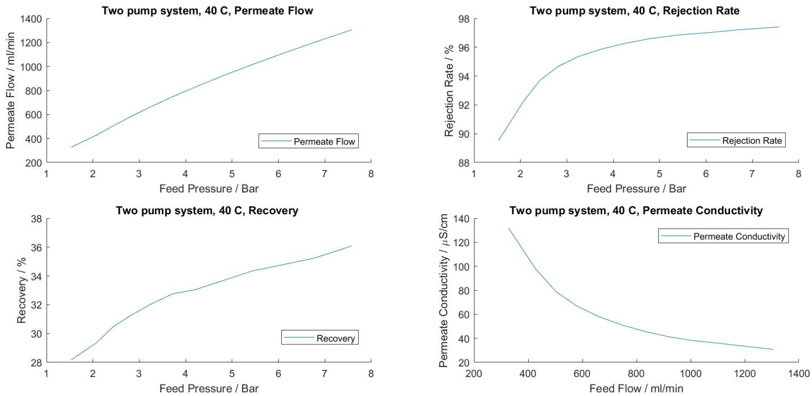


Figure 5.32 Connections Pressure sensors

Recovery Increase

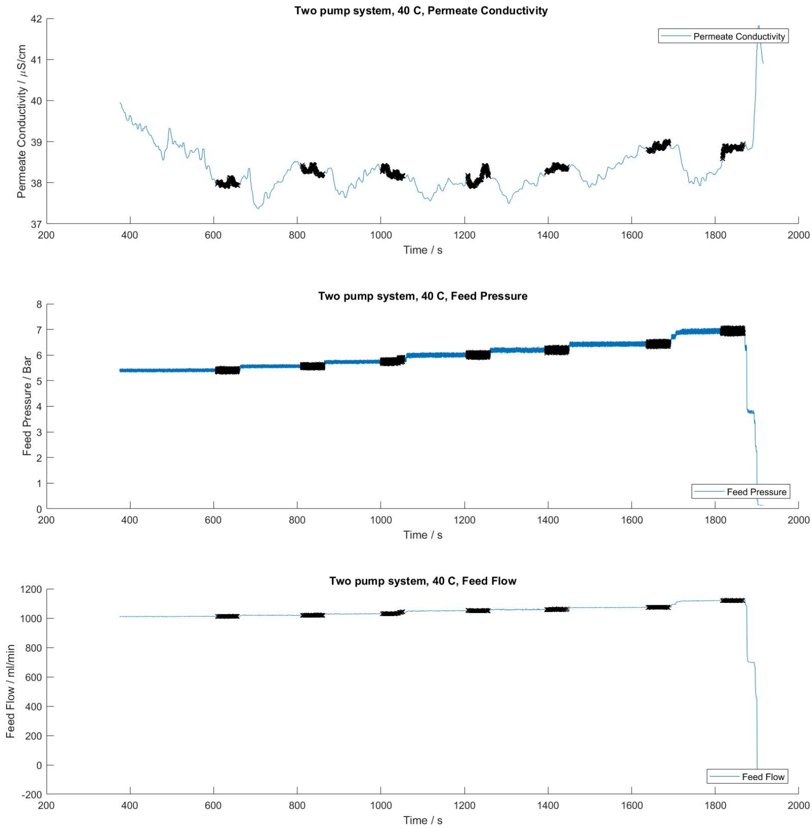


Figure 5.33 Connections Pressure sensors

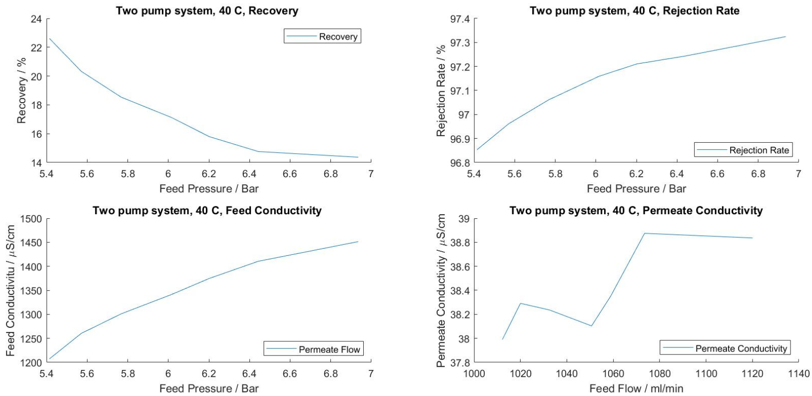


Figure 5.34 Connections Pressure sensors

5.4 Implementation Test Rig

Connections

In Figure (5.35-5.38) all connections in the test rig is displayed.

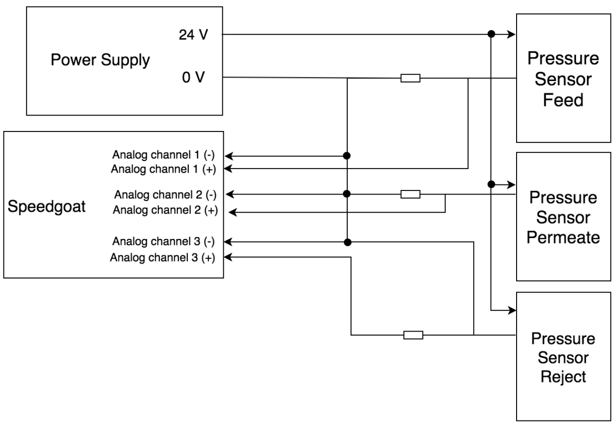


Figure 5.35 Connections Pressure sensors

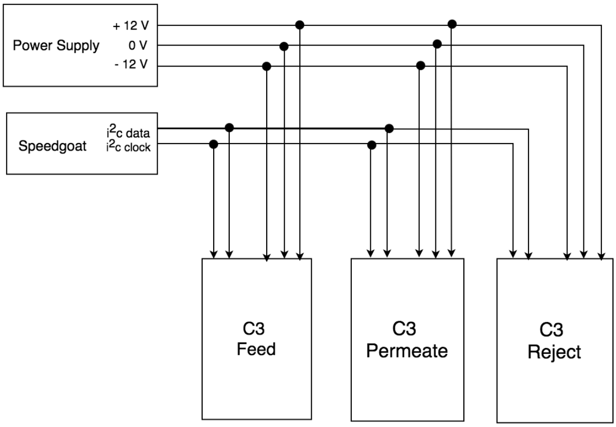


Figure 5.36 Connections measurement blocks, C3

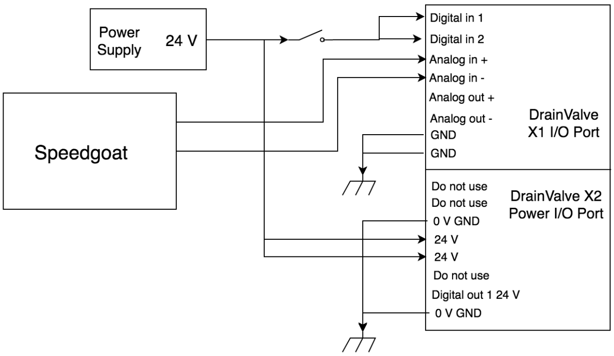


Figure 5.37 Connections Drain Valve

5.5 Mapping

5.6 Design of control algorithms

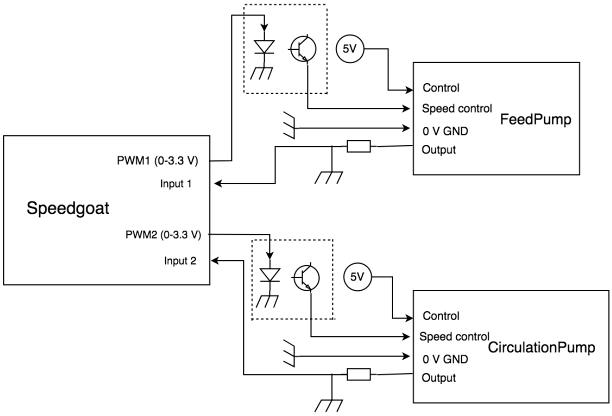


Figure 5.38 Connections pumps

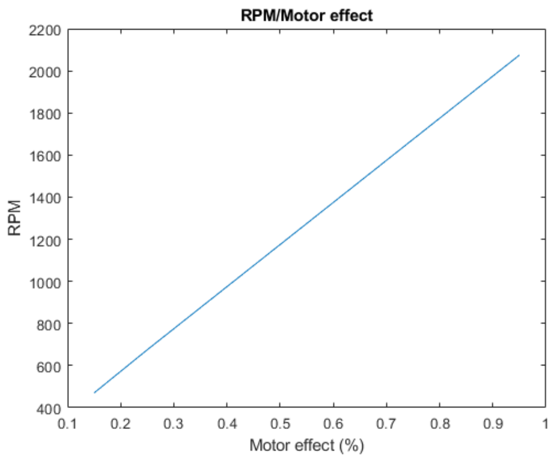


Figure 5.39 RPM Pumps

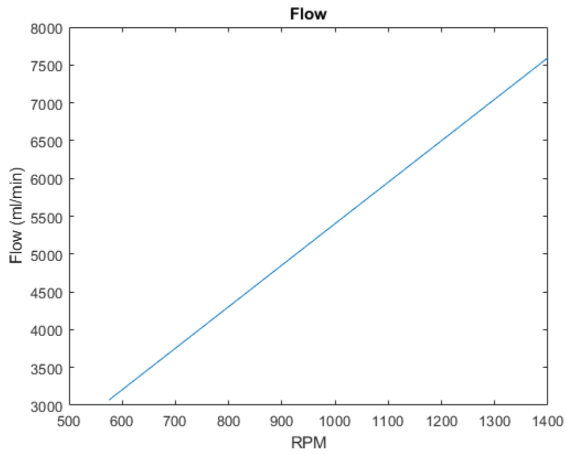


Figure 5.40 Flowrate

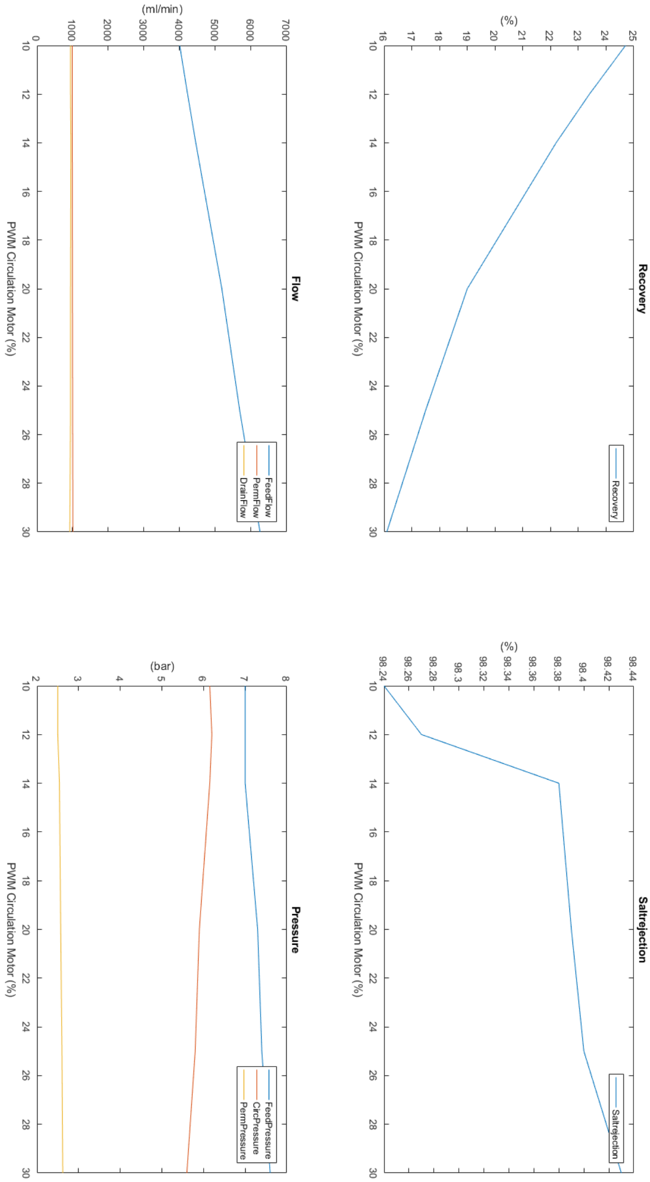


Figure 5.41 Tests with recycle pump as changing parameter

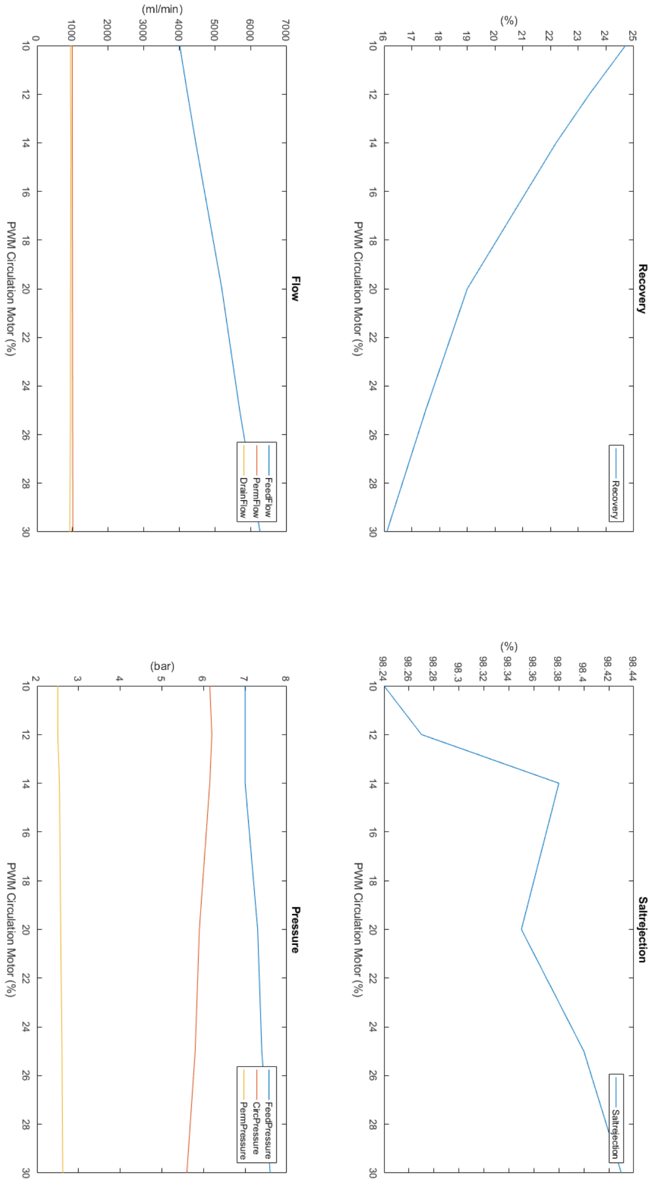


Figure 5.42 Tests with inlet pump as changing parameter

6

Discussion

6.1 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. 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 accros 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 most likely caused by the increased pressure, not the increased flow rate over the membrane. Therefore, it was concluded that there was a no possibility of effectively optimizing the membrane by increasing the recirculation flow.

According to the membrane manufacturer the recovery rate should not exceed 20 % in order to ensure the longevity of the membrane. 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 presure increases.

Hot water has lower viscosity than cold water and also a higher diffusion rate than cold water. Consequently, higher temperatures cause higher permeate flow over the membrane and increased salt passage over 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 salt rejection more permeate needs to pass through the surface to dilute the salts and this can be achived by increasing feed side pressure.

The conductivity of the feedwater is also a quantity that depends on the tap water and determines the lowest possible conductivity of the recirculation loop. By using permeate conductivity as a setpoint for controlling the drain valve it is possible to optimize the water efficiency of the system and ensure high quality permeate. 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. 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 with a low pressure drop and by using a short flow path.

6.2 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 eachother and cannot be changed independantly. 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.

6.3 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 not to cause oscillatons.

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.

6.4 Simulation

6.5 Model based design

6.6 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 5.15 from the tests withf the 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 slowely 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 valcve 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 controling 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 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 5.23 and 5.22. From the figures it can be seen that 22 percent recovery caused a pressure of 5.2 TBD bars and a recovery of 14 percent TBD increased the pressure to 6.2 bars. 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 peremeate flow . By using the formula to convert feed water temperature to a setpoint for the permeate flow the salt rejection of the membrane could be optimized. 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 setpoint at different temperatures.

6.7 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. TBD TBD

6.8 Reduced pump size

When using the two pump system the pump speeds varied from TBD to TBD depending on the permeate flow setpoint which is a reduction from the 60 %and 80 % used when one pump was used. This indicate that it might be possible to use smaller 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.

6.9 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.

6.10 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.

6.11 Scaling

One advantage of using a permeate flow setpoint for the feed pump controller is that it will let the system adapt to scaling. When scaling 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 setpoint and this will automatically be achived 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.

6.12 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.

7

Conclusion

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

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

Since the performance of the membrane improves when it's subjected to more feed side pressure the it can be argued that the system can be optimized by allways applying maximum feed pressure. However, generating pressure costs energy and at low temperatures this extra energy might not be worth the cost even if it improves water efficiency by increasing salt rejection. Consequently, Running the system at low pressure will cost less energy but waste more water. 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 teoretcal equations presented by DOW. These equations are accurate in describing the flow and pressure charachteristics at different temperature. However, DOW is using a fixed rejection rate for all temperatures and does not incorporate the diluting effect that occurs when pressure is increased. To be able to make a more accurate model this phenomenon needs to be matematically described and added to the model.

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

8

Future Prospects

8.1 Parameters of concern

Saltrejection Recovery

8.2 Optimization

Energy efficiency Water efficiency

8.3 Mapping

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

- XXX
- XXX

8.4 Membrane size

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

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Appendix A