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

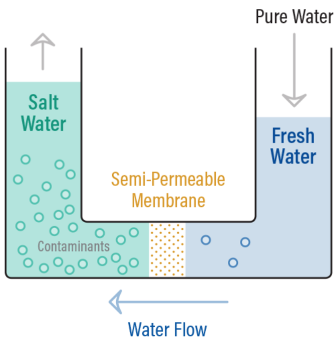

Figure 2.1 Osmosis

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

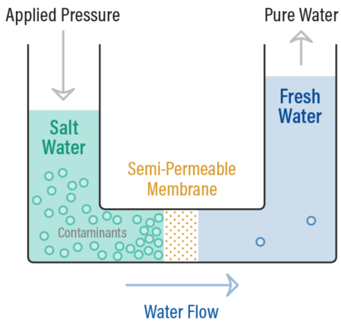

Figure 2.2 Reverse Osmosis

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.

2.5 Control theory

The system is considered a slow system

3

Equipment

3.1 Reverse Osmosis Membrane

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

3.2 Pumps

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

3.3 Drain valve

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

3.4 Simscape/Simulink

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

The system control is implemented in Simulink.

3.5 Speedgoat Real-Time Target Machine

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

3.6 Measurement instruments

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

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

Conductivity sensor block

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

Temperature sensor

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

Pressure sensor

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

Flow meter

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

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

4

Method/Implementation

4.1 Flowchart investigation

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

Pressure drop over the membrane is high

Flow through membrane is high

The model shall contribute with the following:

Permeate conductivity (minimized)

Fouling on the membrane (minimized)

Temperature dependencies

Waste water going through drain (minimized)

Mainly two different systems containing two pumps were considered:

System 1

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

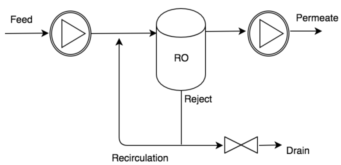

Figure 4.1 System 1

System 2

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

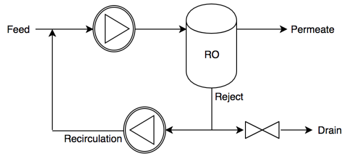

Figure 4.2 System 2

4.2 Tests

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

4.3 Modeling

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

4.4 Implementation Test Rig

Current System

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

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

Table 4.1 Testcases

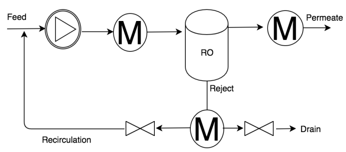

Figure 4.3 Current System, with measurement sensors

System 2 "Comparing system"

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

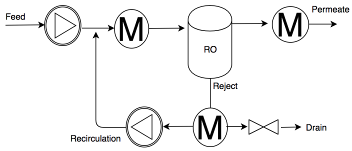

Figure 4.4 System 2, with measurement sensors

4.5 Connections

4.6 Mapping

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

4.7 Design of control algorithms

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

Control algoritms were developed in Matlab - Simulink.

4.8 Control simulations

INSERT PICTURES

4.9 Improvements

5

Results

5.1 Flowchart investigation

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

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

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

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

The two comparing systems were set to:

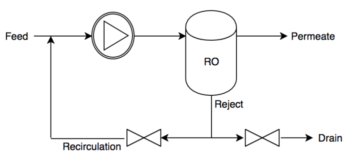

Figure 5.1 Current System

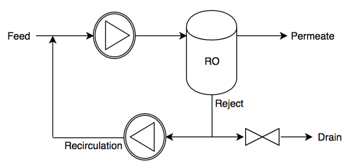

Figure 5.2 System 2

5.2 Tests

Current system

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

Room temperature:

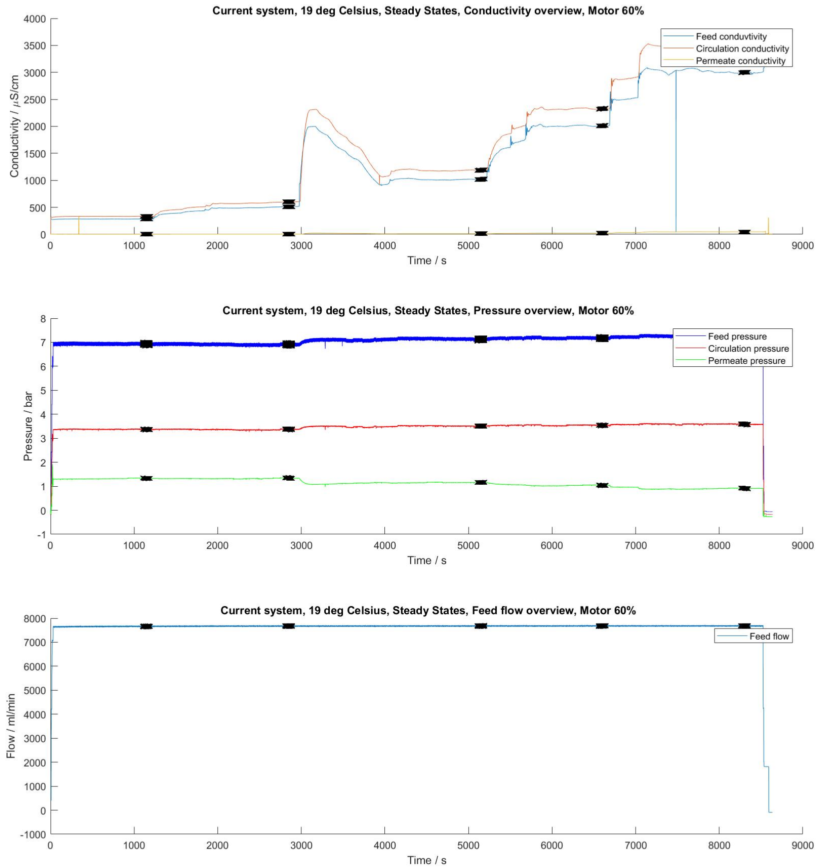

Figure 5.3 Connections Pressure sensors

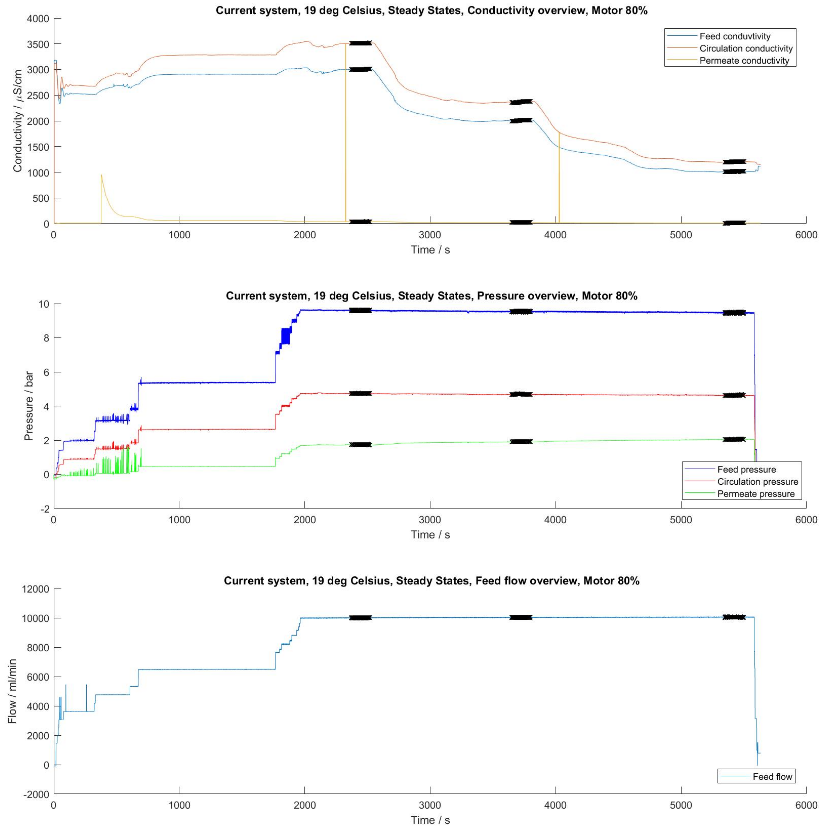

Figure 5.4 Connections Pressure sensors

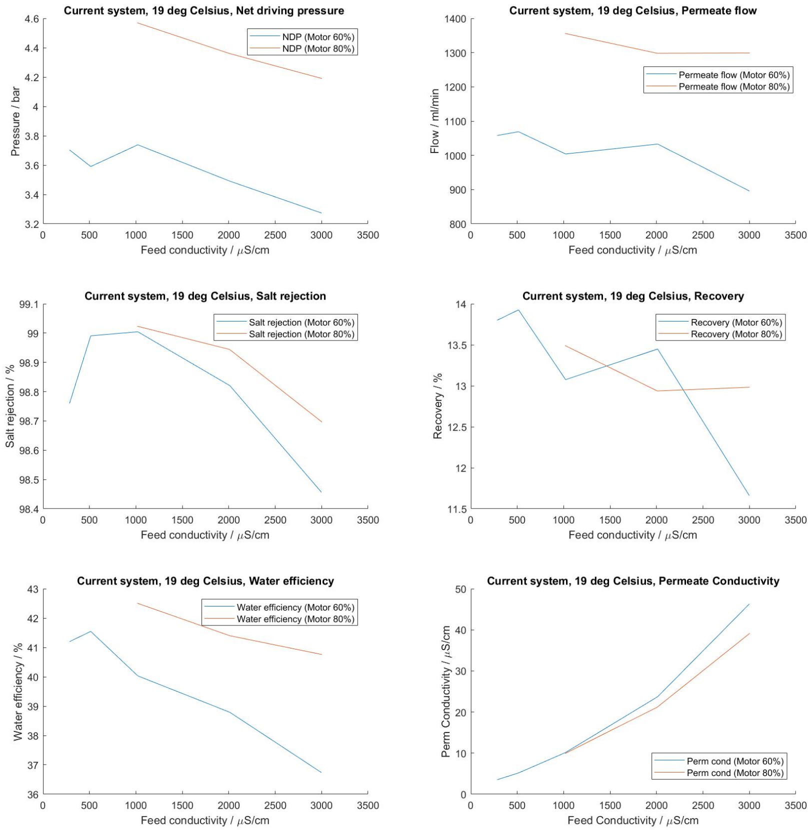

Figure 5.5 Connections Pressure sensors

short explanation of tests.

Tests conducted at 30 deg C.

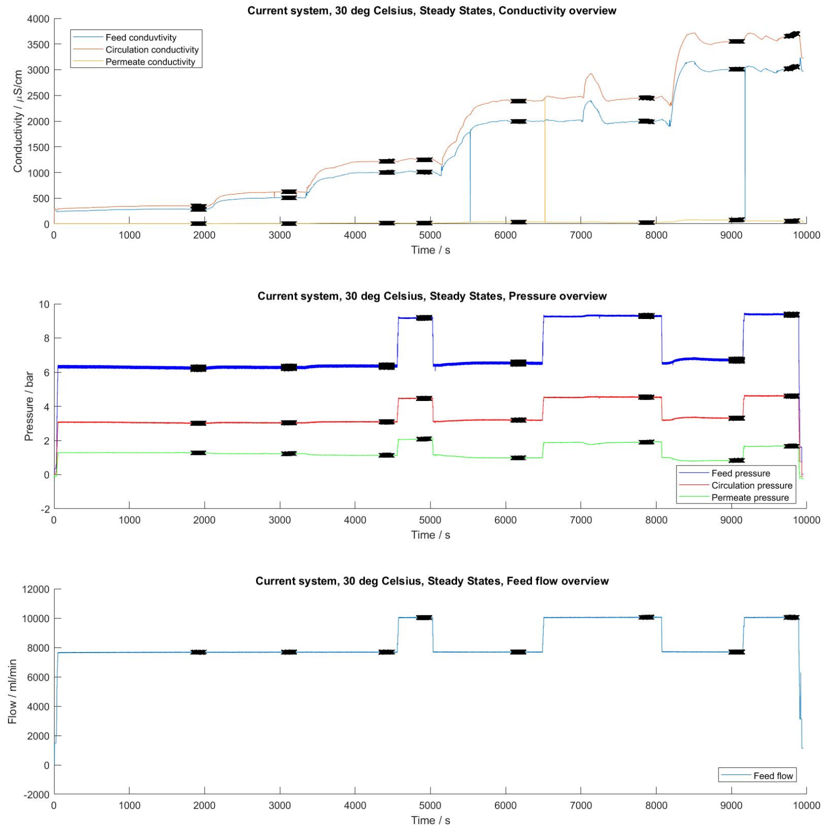

Figure 5.6 Connections Pressure sensors

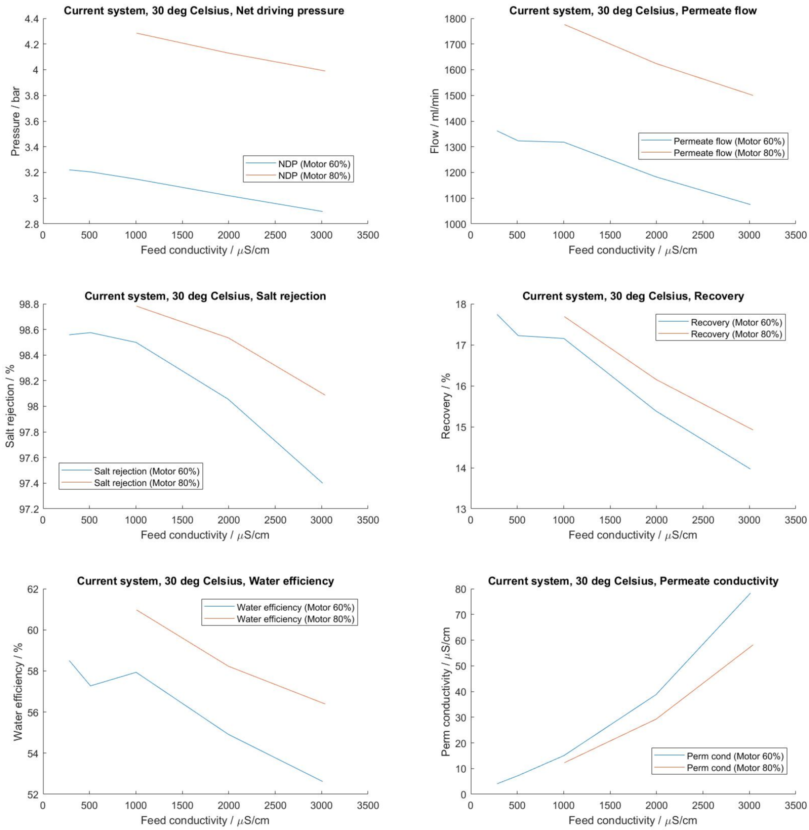

Figure 5.7 Connections Pressure sensors

Tests conducted at 40 deg C.”

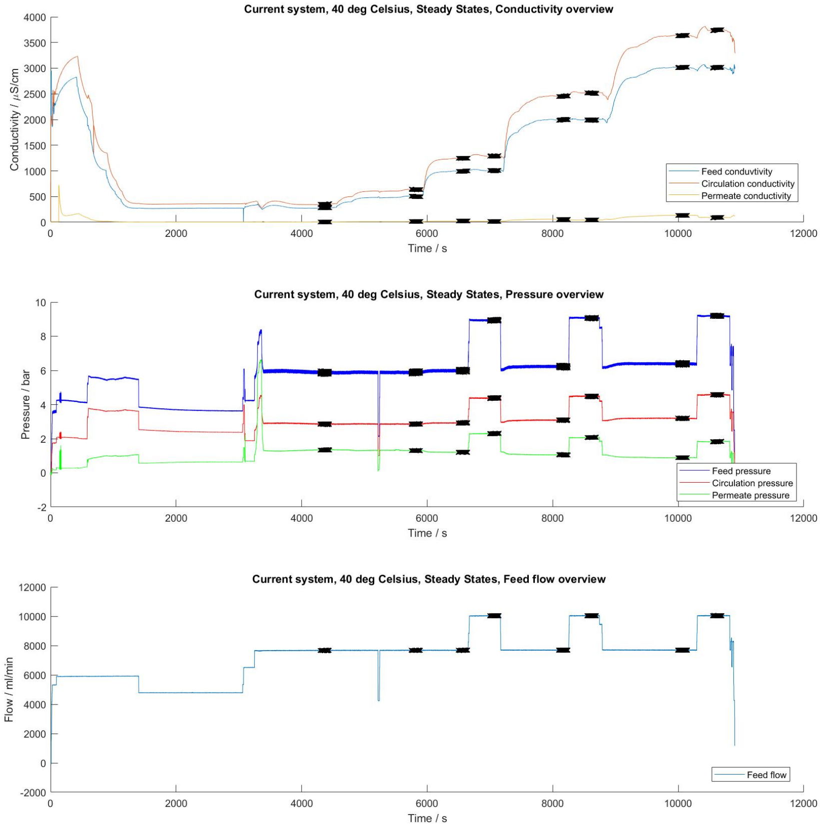

Figure 5.8 Connections Pressure sensors

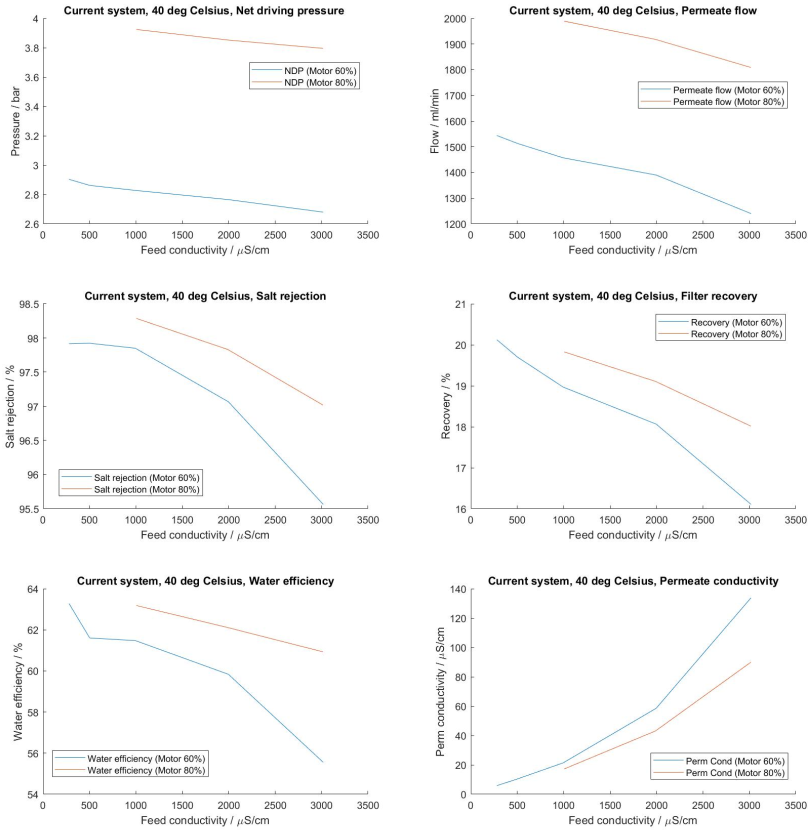

Figure 5.9 Connections Pressure sensors

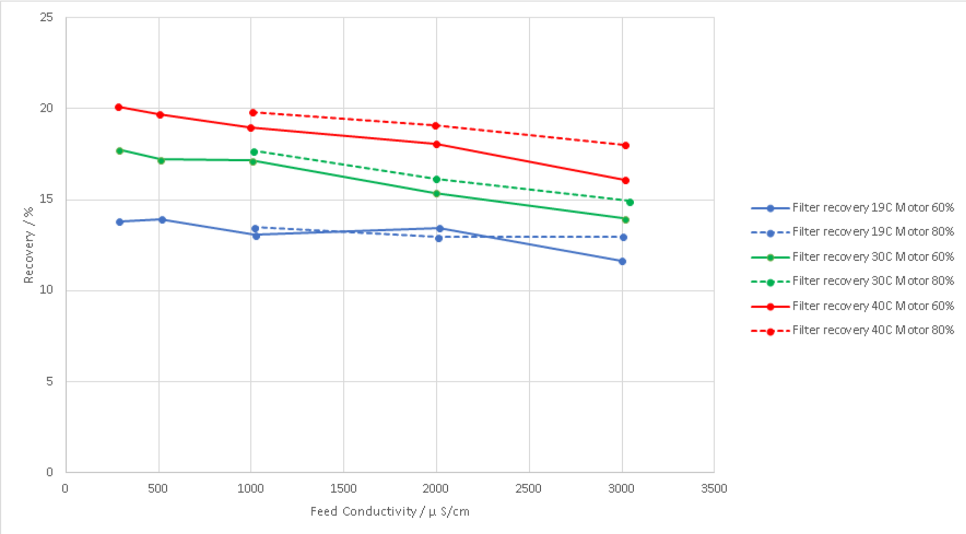

Figure 5.10 Connections Pressure sensors

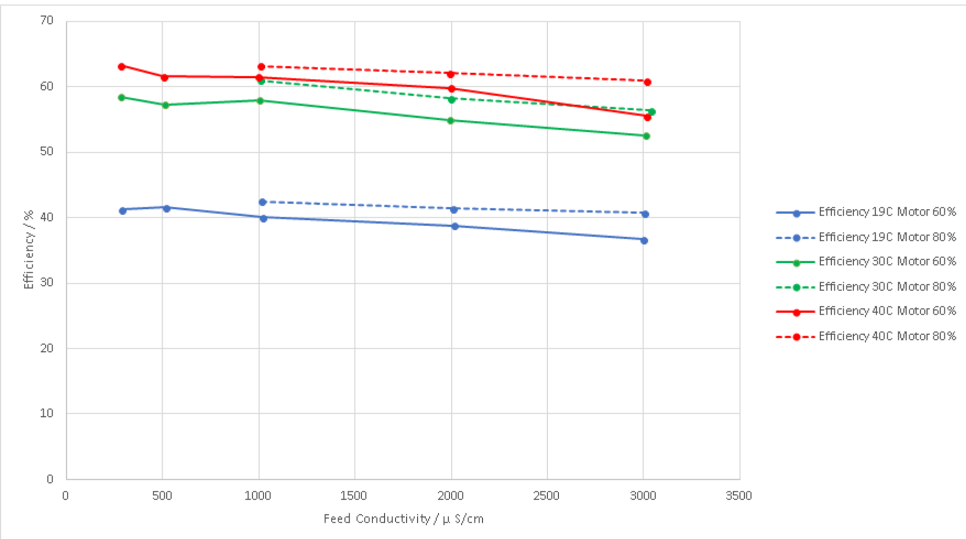

Figure 5.11 Connections Pressure sensors

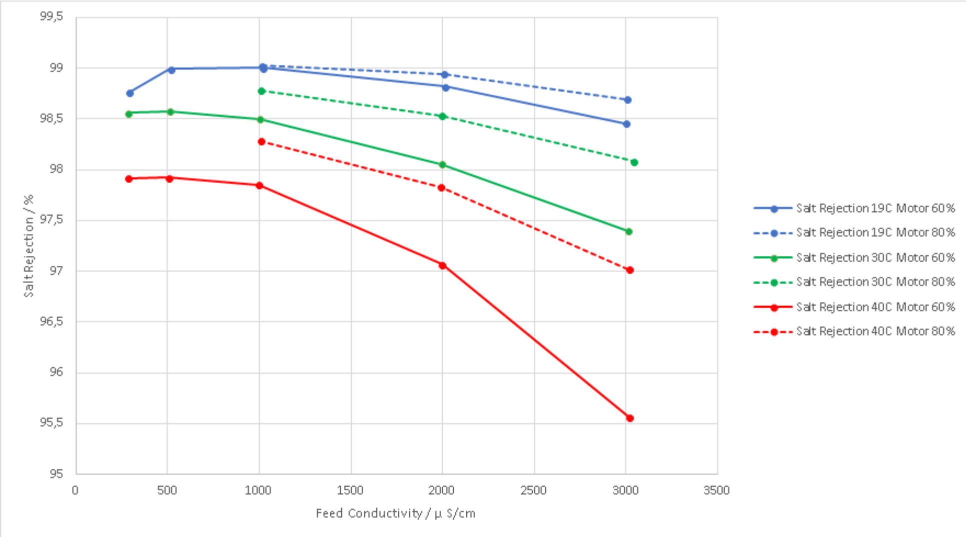

Figure 5.12 Connections Pressure sensors

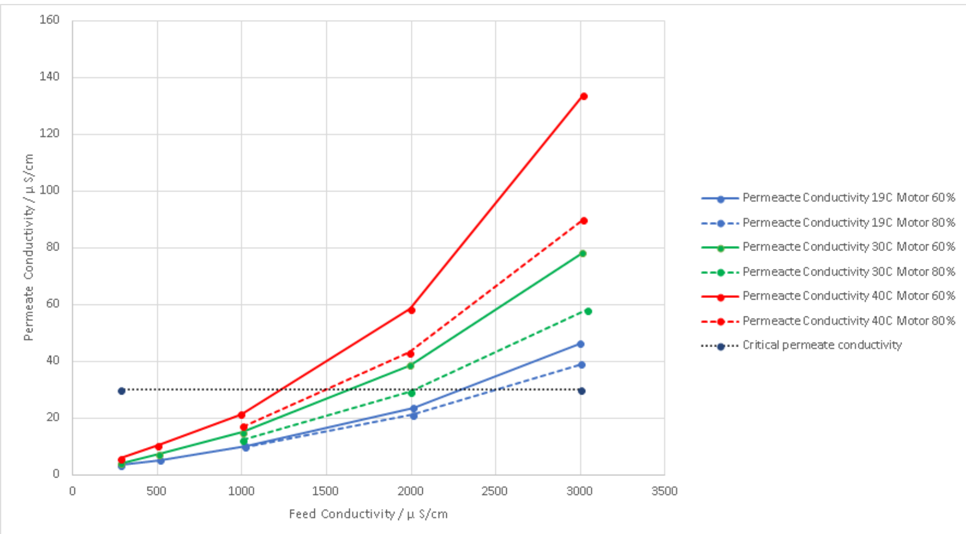

Figure 5.13 Connections Pressure sensors

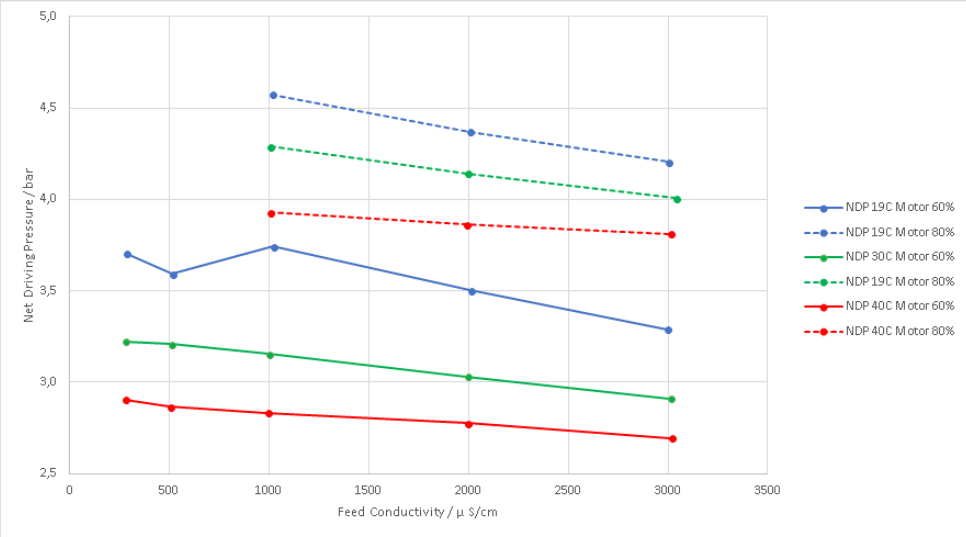

Figure 5.14 Connections Pressure sensors

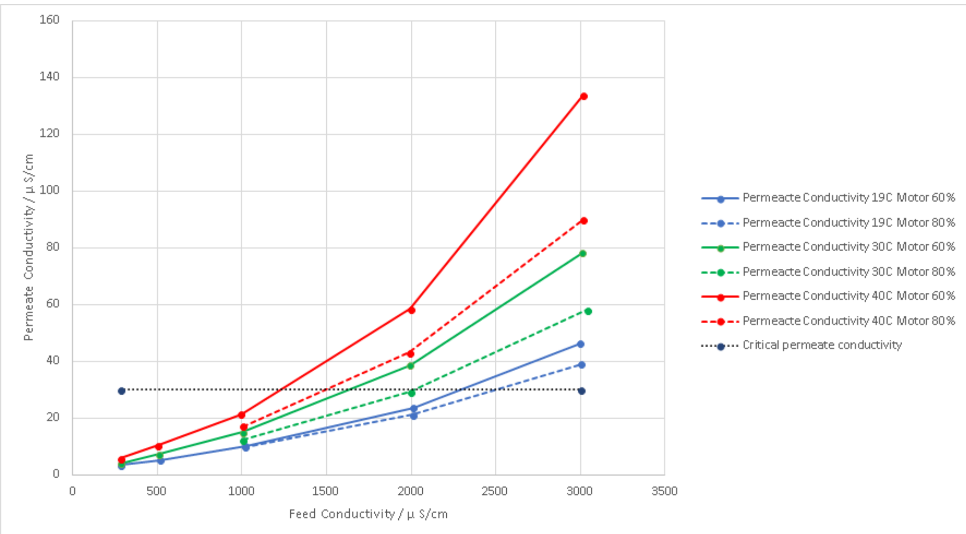

Figure 5.15 Connections Pressure sensors

System 2

Test: increaed feed pressure

21

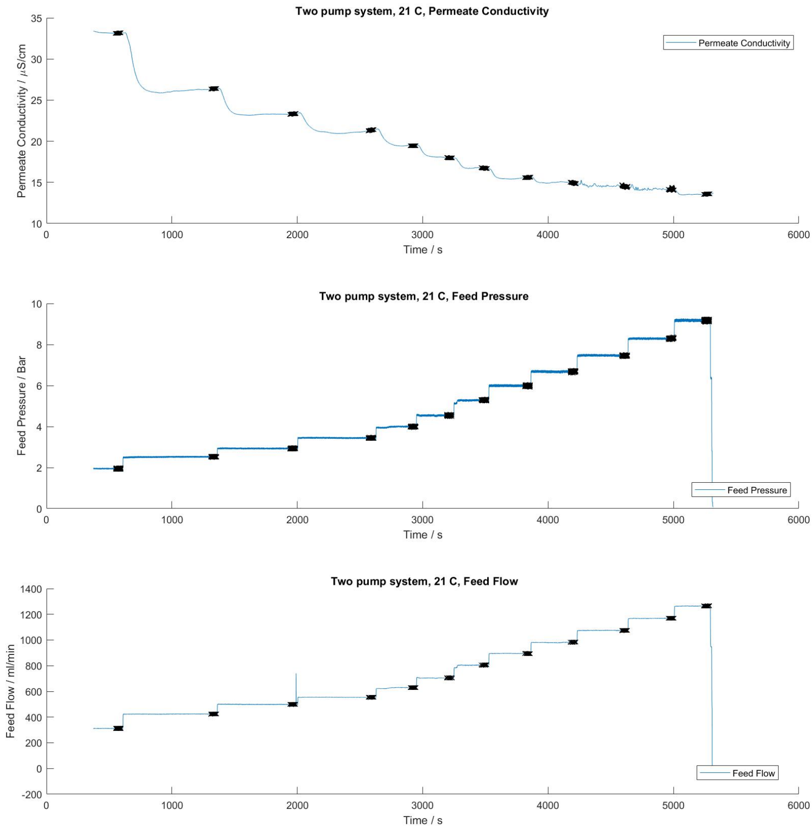

Figure 5.16 Connections Pressure sensors

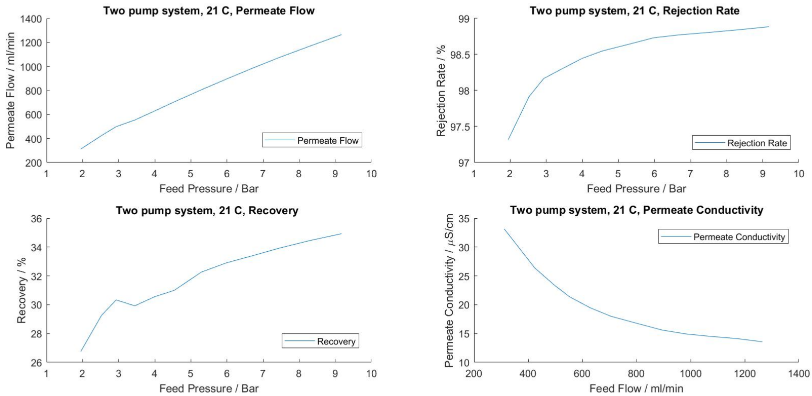

Figure 5.17 Connections Pressure sensors

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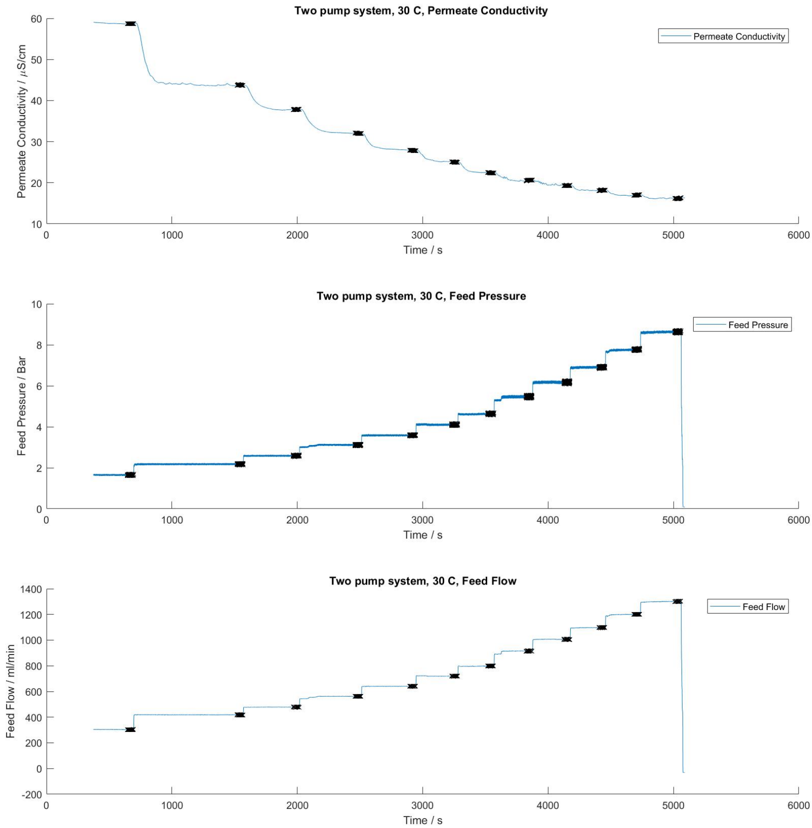

Figure 5.18 Connections Pressure sensors

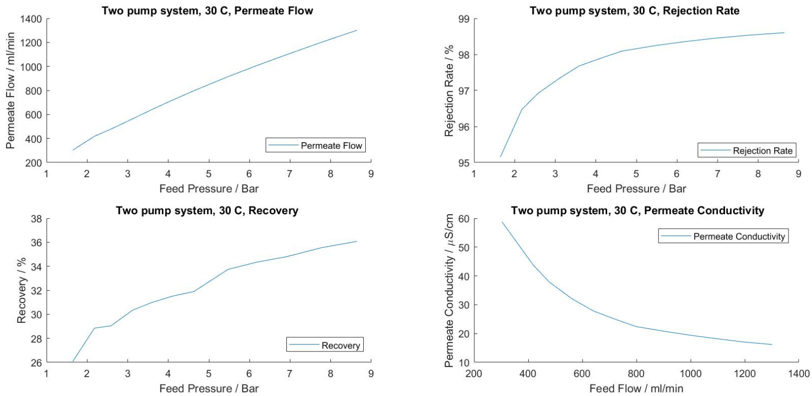

Figure 5.19 Connections Pressure sensors

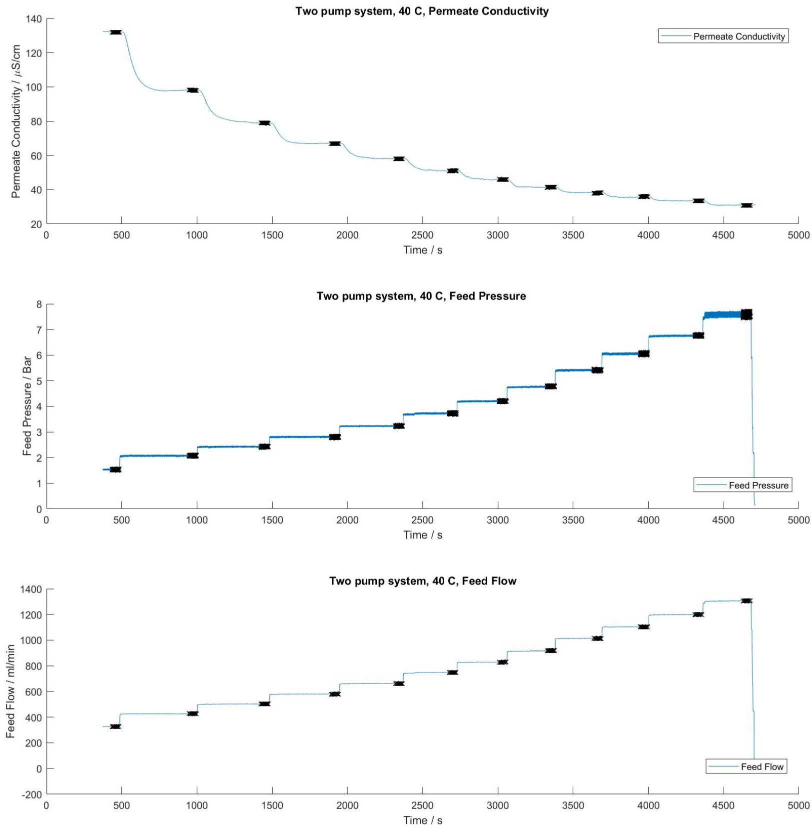

Figure 5.20 Connections Pressure sensors

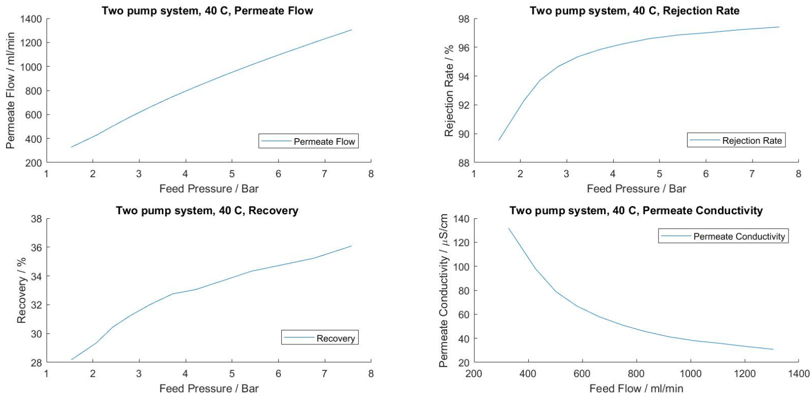

Figure 5.21 Connections Pressure sensors

Recovery Increase

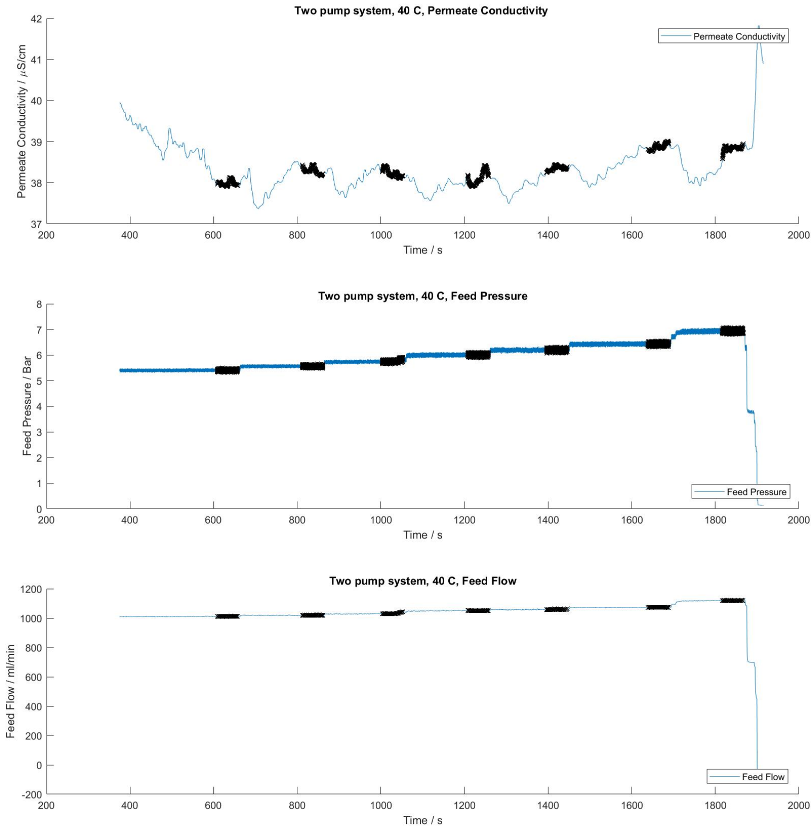

Figure 5.22 Connections Pressure sensors

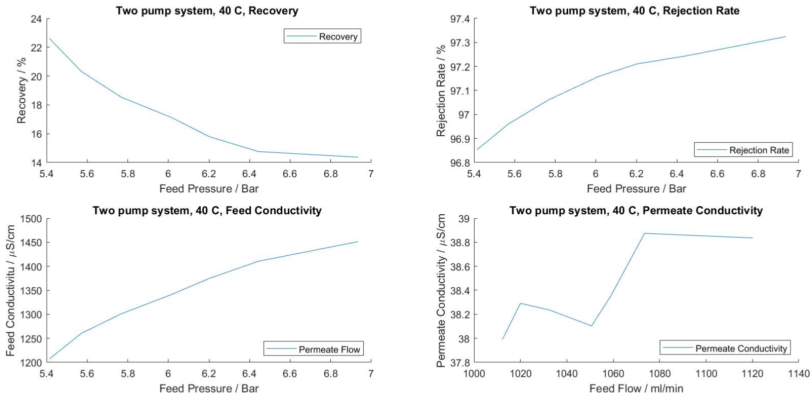

Figure 5.23 Connections Pressure sensors

5.3 Modeling

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

5.4 Implementation Test Rig

Connections

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

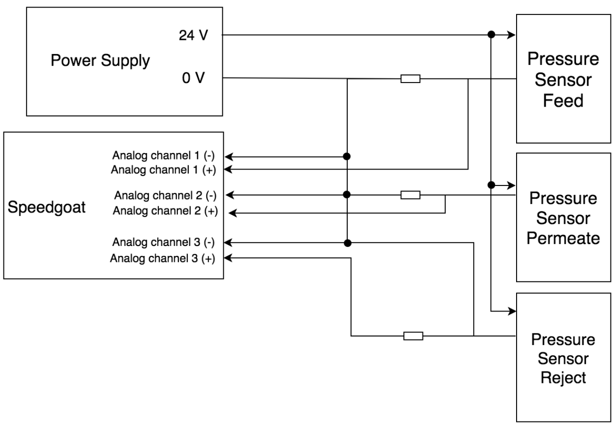

Figure 5.24 Connections Pressure sensors

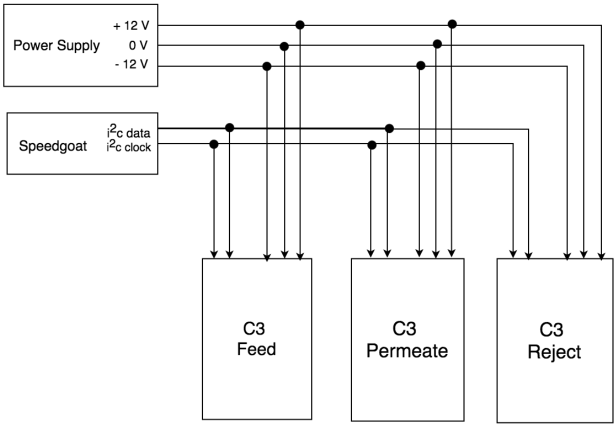

Figure 5.25 Connections measurement blocks, C3

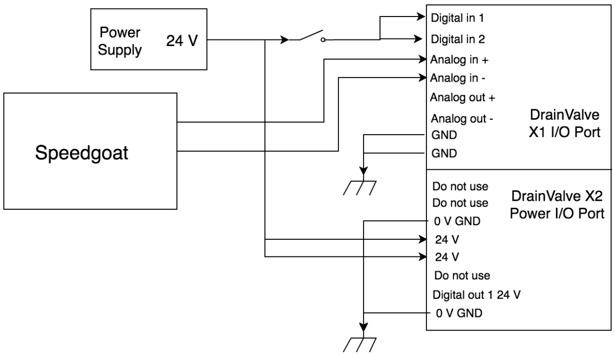

Figure 5.26 Connections Drain Valve

5.5 Mapping

5.6 Design of control algorithms

FIGURES AND PLOTS FROM SIMSCAPE

5.7 Control simulations

5.8 Improvements

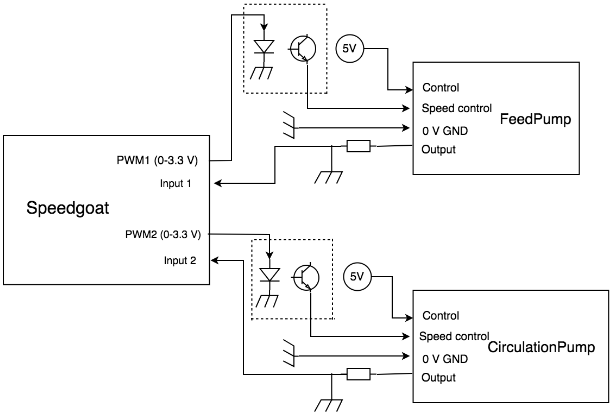

Figure 5.27 Connections pumps

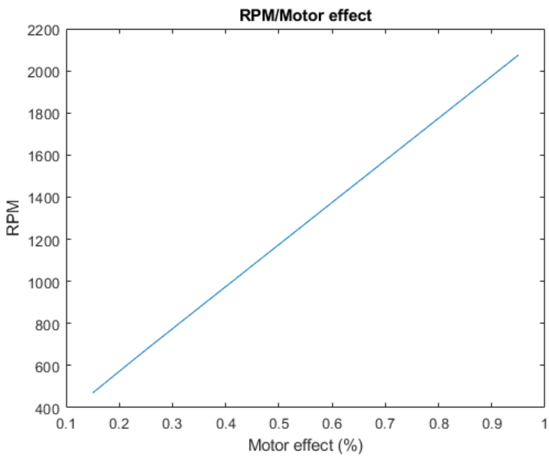

Figure 5.28 RPM Pumps

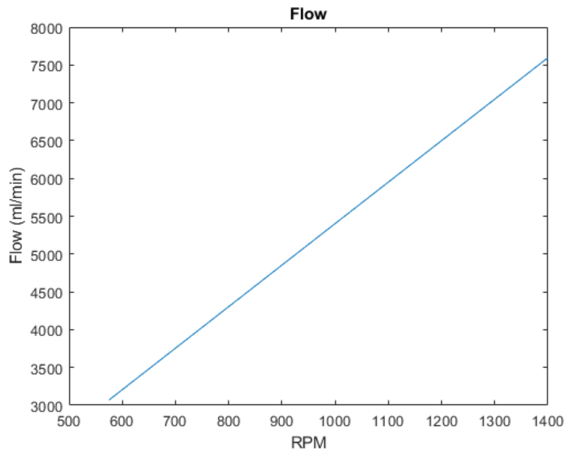

Figure 5.29 Flowrate

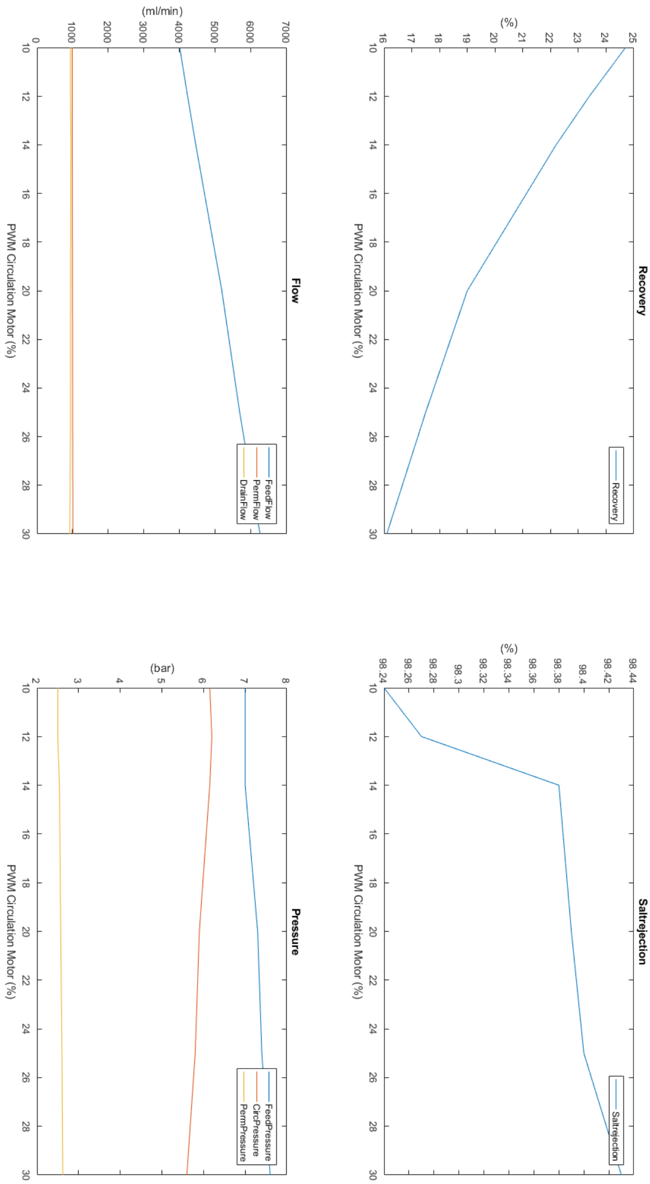

Figure 5.30 Tests with recycle pump as changing parameter

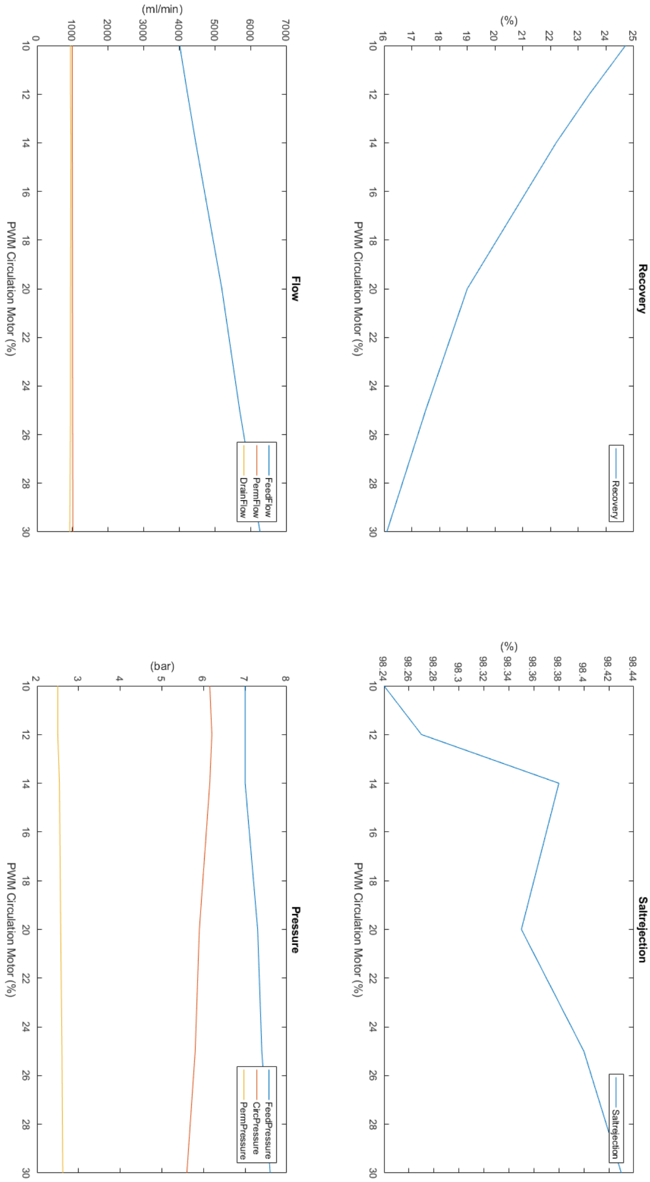

Figure 5.31 Tests with inlet pump as changing parameter

6

Discussion

discuss

7

Conclusion

jj

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