Reverse osmosis temperature control

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Abstract

Baxter develops medical devices that take advantage of reverse osmosis to purify water that's being used in dialysis fluids. Reverse osmosis is a commonly used water purification process that removes unwanted particles from the water.

The membrane that is used to purify the water has a temperature dependency that changes the performance of the membrane when the temperature is changed. When lowering the temperature of the water the purification of the water is increased. In this thesis the possibilities of lowering and controlling the temperature of the water was investigated. The goal was to implement a solution on a physical water device and to analyse the performance.

Several solutions for the problem was presented where one of the solutions was selected for implementation on the real system. The final solution was a Peltier assembly which transfer heat from a flow of water and dissipating the heat through a second flow of water. The heart of the solution was a Peltier module which is a solid state heat pump that has no moving parts.

A test rig was set up in a lab at Baxter with the water device and other components. In order to control the temperature of the water a controller was implemented and tuned. To analyse the performance several tests were performed.

The results showed that the temperature could be lowered but not as much as the initial goal. A major issue was the low flow of the dissipating water. The effect of the low water flow was that the efficiency of the Peltier assembly was decreased.

Acknowledgement

First of all I would like to thank my supervisor at Baxter, Peter Sendelius, who has guided and supported me from the start to the finishing of this master thesis. Your passion and ambition to the work has been a huge inspiration and it has been a joy to work together with you. The knowledge and ideas you have shared have been invaluable for the project.

I would like to thank Tore Hägglund, faculty of Engineering at LTH, who has been my supervisor at LTH. Your knowledge and support has been a major help to me. You have always been there and proceeded every problem with open arms.

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Dennis Dalenius

Contents

Dictionary

Feed water: The water that is fed into the RO-membrane

Reject water: The water that is rejected by the RO-membrane

Permeate water: The water that is purified by the RO-membrane

Product water: The water that is produced by the water device, note! not same as permeate water

RO: Abbrevation of reverse osmosis

Recovery (%) : $\frac{\text{Permeate water flow}}{\text{Feed water flow}} * 100$

Salt passage (%) : $\frac{\text{Concentration of salt in permeate water}}{\text{Concentration of salt in feed water}} * 100$

Salt rejection (%) : 100 – Salt passage

CWP: Central water plant

1

Introduction

1.1 Background

The Water technologies department at Baxter develops water systems that purifies water used by dialysis machines. The water systems are using reverse osmosis (RO) to purify water. Reverse osmosis is just one part of the whole process and will be the main focus for this master thesis.

In a simple manner the reverse osmosis process is performed by pressurising water which will be forced through a semipermeable membrane, called RO-membrane, where most of the impurities are rejected at the membrane surface. The feed water is divided into reject water and permeate water where the permeate water is the purified water passing through the membrane.

The performance of the RO-membrane has a significant temperature dependency. By controlling the temperature the performance of the water systems can be improved in several ways.

1.2 Motivation

The results from the master thesis “Optimization of Reverse Osmosis Performance” gave inspiration to the idea of controlling the temperature of the RO-membrane [1]. By lowering the temperature of the water passing by the RO-membrane, the following effects can be achieved:

Lower temperature:

- Increased salt rejection in the RO-membrane. Means that the permeate/product water will have lower concentration of impuritiesDialk. This means that less pure water could be used.

- Less scaling on RO-membrane due to that solubility of $CaCo_3$ is increased with lower temperature [2].
- Less bacterial growth due to biological activity is lower at lower temperatures.

1.3 Goal

The purpose of the Master Thesis is to come up with different solutions of how to lower and control the temperature of the water passing through the RO-membrane, evaluate the solutions and implement at least one of the solutions on a real system.

1.4 Method

- Literature studies
- Analyse current designs of Water devices and CWP
- Identify project requirements
- Evaluate different solutions for the temperature control
- Decide which solution to proceed with
- Implement at least one solution on a prototype and analyse the performance.

2

Theory

This chapter will explain basic functions of the system in order to understand the problem and to understand the working basics of the system. The function of the RO-membrane is fundamental in this thesis and to understand how the RO-membrane works some basics about osmosis and reverse osmosis is explained. After that the system is explained in a basic way with a simplified flowchart. Some theory about heat transfer and heat capacity is explained and also the parts used for the solutions are explained. Last the control methods used are explained.

2.1 Osmosis

Osmosis is a natural phenomenon that occurs when two solutes with different concentrations are separated by a semi-permeable membrane. A semi-permeable membrane is a membrane that will pass molecules up to a specific size and stop larger molecules from passing. The effect will be that the weaker solute migrate to the side with the higher concentration. Due to the semi-permeable membrane separating the solutes only certain particles small enough will pass the membrane. Figure 2.1 shows an example of this. The water on the right side will migrate to the left side. The salt molecules is bigger than the water molecules and the membrane is in this case designed to stop most of the salt molecules. This will result in a decrease of concentration on the left side and increase on the right side.

2.2 Reverse osmosis

The reverse osmosis is exactly the osmosis process in reverse. Figure 2.2 shows the previous system but this time with reverse osmosis. Here the water from the left side passes the membrane and the membrane stops the salt from passing. This will increase the concentration on the left side and decrease the concentration on the right side. In order for this to happen some kind of energy must be applied to the system and in this system a pressure is applied to the left side. In order for

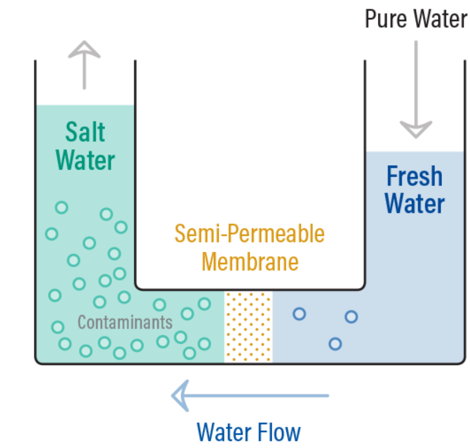

Figure 2.1 Natural occuring osmosis with salt water [3]

this to happen the pressure must be greater than the naturally occurring osmotic pressure [3].

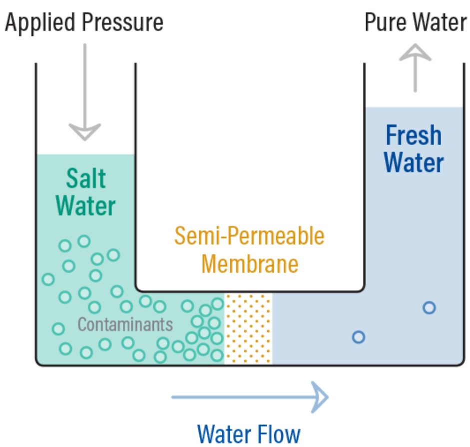

Figure 2.2 Reverse osmosis with salt water [3]

2.3 Conductivity

A way of monitoring the concentration of dissolved salt in the water is to measure the conductivity of the water. The SI unit of conductivity is siemens (S). The conductivity is a measurement on how capable the water is to transfer flow of electrons. This is depending on the amount of conductive ions which mostly comes from dissolved salts and other inorganic materials. High conductivity could mean that the water contains high amount of salt particles [4].

2.4 RO-membrane

A RO-membrane is a membrane that is working on the principle of reverse osmosis. The membrane is made of a material that is semi permeable which means that small enough particles can pass through the material and bigger particles don't pass. Water molecules are small enough to pass the material which means the water can be purified. The membrane has one port where water enters and two ports where the water leaves the membrane, one port for the purified water and one for the rejected water.

Temperature dependency of RO-membrane

The information of the temperature dependency is provided by the RO-membrane supplier. When increasing the temperature of the water the viscosity of the water is decreased and the pores inside the membrane increase in size. The effect of this is that water pass through the membrane easier. The supplier has a rule of thumb that the permeate flow increase by 3% for every 1°C increased and the salt passage in the membrane increases by 6% for every 1°C increased.

With the use of a Simscape model over the system, constructed by previous master thesis students [1], the system is simulated where the temperature is decreased from 30 to 20 °C. Figure 2.3 shows how the conductivity of the water decreases when the temperature is decreased. The bottom graph is showing a sudden increase of the relative conductivity decrease at around 230 seconds. The cause of this increase is unknown and could be a unwanted artifact caused by the simulation.

2.5 Simplified system

The water device is a rather complex system with many actuators and sensors. To not confuse the reader the system is simplified and explained briefly. Figure 2.4 shows a simplified system model of the water device. The numbers in the figure represent different functions in the system.

1. Water enters the system and fills up a tank when V1 is open. C1 and T1 are sensors that measure the temperature and the conductivity of the water.

2. A pump (PuRO) is moving the water into the RO-membrane and building up a pressure to overcome the osmotic pressure.

3. The reject water flows to the left back to the pump and to the right where a constant flow valve (CFV2) reduces the flow and keeps the flow constant.

4. The amount of water returned to the tank is depending on the water quality entering the system. A low value at C1 means that the quality of the water is high. With high quality water more water is returned to the tank and with lesser quality more water gets drained. This is controlled by changing the position of V2.

5. The filtered water (permeate water) enters the heater which keeps the water at a temperature of 30°C. T2 and C2 measure the temperature and conductivity so the values meet the requirements.

6. The valve (VM1) is adjusted to keep the product water flow at a specific flow and to protect the system if the pressure at P1 gets to high.

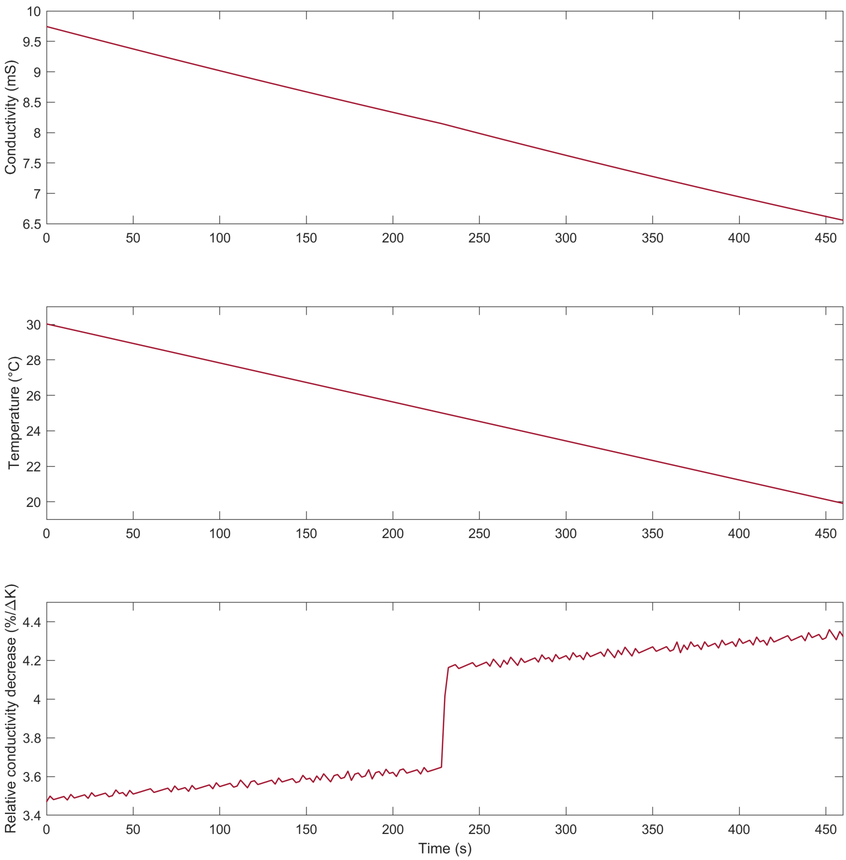

Figure 2.3 Conductivity of permeate water from simulated model

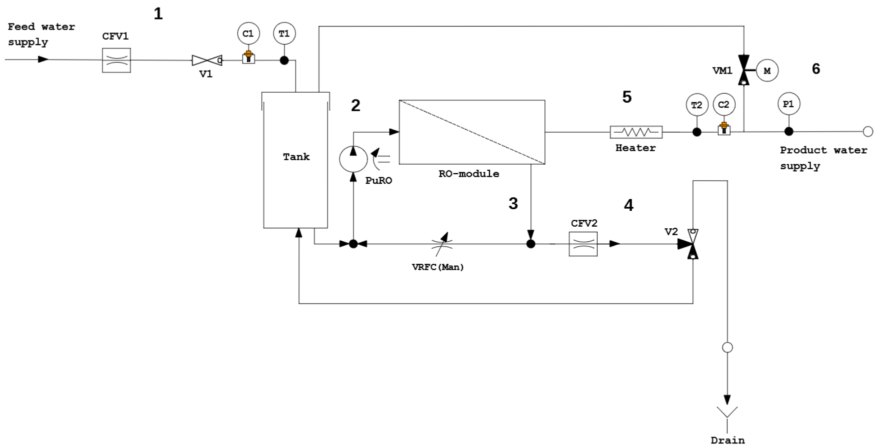

Figure 2.4 Simplified flowchart

2.6 Heat capacity and power

Heat capacity is a measure of how good a specific material is to store thermal energy. The higher the value the better the material is at storing energy. Heat capacity also tells how much energy is needed to heat up a certain material. For water (25°C) the heat capacity is 4.190 kJ/(kg*K). This means it takes 4.190 kJ to heat up one kg of water one degree kelvin. To cool down the same amount of water one degree kelvin, 4.190 kJ needs to be removed from the water.

To calculate the power required for this action the amount of time need to be considered. Equation 2.1 is used to calculate the power required where t is in seconds.

$$P = \frac{E}{t} \tag{2.1}$$

2.7 Heat transfer

In this system there are three kinds of heat transfers that can take place. Conduction, convection and radiation.

Conduction

Conduction is heat transfer that takes place when a hot and cold object are in contact. The heat flux is depending on the thermal conductivity of the materials.

Convection

Convection can take place in e.g. fluids and gases when removing or adding heat. The temperature difference will cause a movement of the molecules with higher energy to the area with lower energy. An example of this is when heating up water in a saucepan. When heating the bottom of the saucepan the water will absorb heat and move up to the area with lower energy.

Radiation

Radiation is the electromagnetic radiation caused by objects. Depending on the temperature and the surface of the object different amount of heat is radiated. Higher temperature gives higher radiation and larger surface area gives higher radiation [5].

2.8 Thermoelectric module

A thermoelectric module also called Peltier module, is a solid state heat pump. This means that a Peltier module doesn't have any physical moving parts like a regular heat pump.

Figure 2.5 shows a sketch of a typical Peltier module. The heart of the Peltier module is in the middle and is made with semiconductors of both p and n-type. They are placed in a certain pattern with electrical conductors between some of the semiconductors. This is where the heat transfer is happening. Two cables are also connected to the Peltier module which is where the voltage is applied. Two ceramic insulators screen of the semiconductors and act as an electrical barrier.

When a voltage is applied over an Peltier module, heat will be absorbed from one side and will dissipate through the other side. The heat is transferred through the semiconductors. The amount of heat that can be transferred from the cold to the hot side is highly dependent on the temperature difference between the cold and hot side. A low temperature difference causes more heat to be transferred. This means that the hot side need to have a dissipator that can dissipate much heat in order to maintain a high efficiency. The amount of heat that dissipates from the hot side is the amount of heat transferred plus the power required for the Peltier module. When changing the direction of the current through the Peltier module the hot side becomes the cold side and vice versa [6].

2.9 Cold plate

A cold plate can be used to transfer heat from and to liquids. The base of a cold plate is often made out of aluminium. Inside the aluminium block there is a path for the fluid which can be a metal tube or just a cutout in the block. Figure 2.6 shows

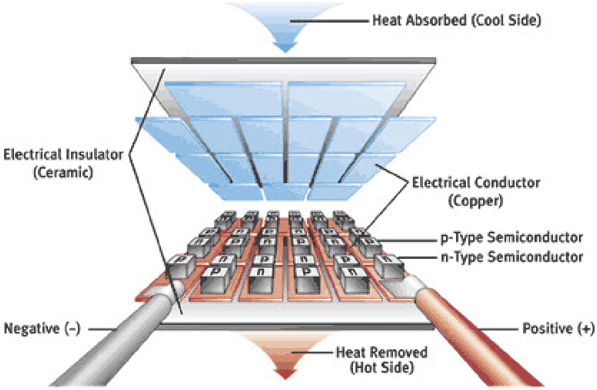

Figure 2.5 A sketch of a Peltier module [7].

a typical cold plate. A usage scenario could be that a hot fluid is running through the cold plate. The cold plate has a lower temperature than the fluid which results in a transfer of the heat. The fluid will loose some heat and the cold block will gain some heat.

The performance of a cold plate is depending a lot on the flow inside the cold plate. A higher flow will give a lower thermal resistance which is good but a higher flow will occur to a increasing pressure due to the water flow resistance. This must be accounted for when using a cold plate in applications. Thermal resistance is explained in section 2.12.

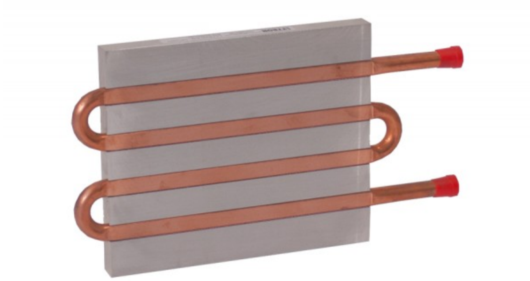

Figure 2.6 A typical cold plate [8]

2.10 Heat sink

A heat sink is used a lot in applications when a material need to be cooled down. The heat sink will absorb heat through the base and dissipate the heat through the fins. Often a fan is placed on top of the fins to dissipate more heat. They are often found in electrical equipment. The thermal resistance of the heat sink tells how well the heat sink can dissipate heat. This depends on several factors such as size, design and material.

2.11 Heat exchanger

A heat exchanger is used to transfer heat from one liquid to another liquid. It's build by several layers of metal sheets which will transfer the heat between the fluids. They are often used in applications when liquid need to be cooled or heated.

2.12 Thermal resistance

Thermal resistance is a measurement of how resistant a material is to heat transfer. This depends on the geometry and thermal conductivity of the medium. A higher value means that the heat won't transfer that good but instead will end up in heating the medium. Thermal resistance is measured in K/W. In the case for heat sinks and cold plates the value should be as low as possible to be able to transfer most of the heat.

2.13 PI-tuning methods

There are several ways to experimentally tune the parameters for a PI controller and the lambda method is the most common method used in the industry.

The lambda method is a step response method where the static gain K_p, dead time L and time constant T of the process is decided. With those values the amplification K and integral time T_i can be calculated. To perform the experiment the system should be in a steady state and after that a step change in the control signal should be made. The experiment is done when the measurement signal has reached a steady state. Figure 2.7 shows such an experiment. The upper graph shows the measurement signal and the lower graph shows the control signal. The static amplification K_p is decided by dividing the change in measurement signal by the change in the control signal.

$$K_p = \frac{\Delta y}{\Delta u} \tag{2.2}$$

To decide the dead time L following has too be done. First one has to find the biggest derivative of the measurement signal. The point where the tangent crosses the level of the measurement signal before the change in control signal is the end point of the dead time. The time from the step change to the end point is the value of the dead time L. The time constant T is calculated by finding the time it takes for the measurement signal to reach 63 % of the final measurement signal.

K and T_i is given by

$$K = \frac{1}{K_p} \frac{T}{L + \lambda} \tag{2.3}$$

$$T_i = T \tag{2.4}$$

The integral time is set to the time contant T. The lambda method has a parameter which can be set by the user which is λ. A common selection is to set $\lambda = T$ [9].

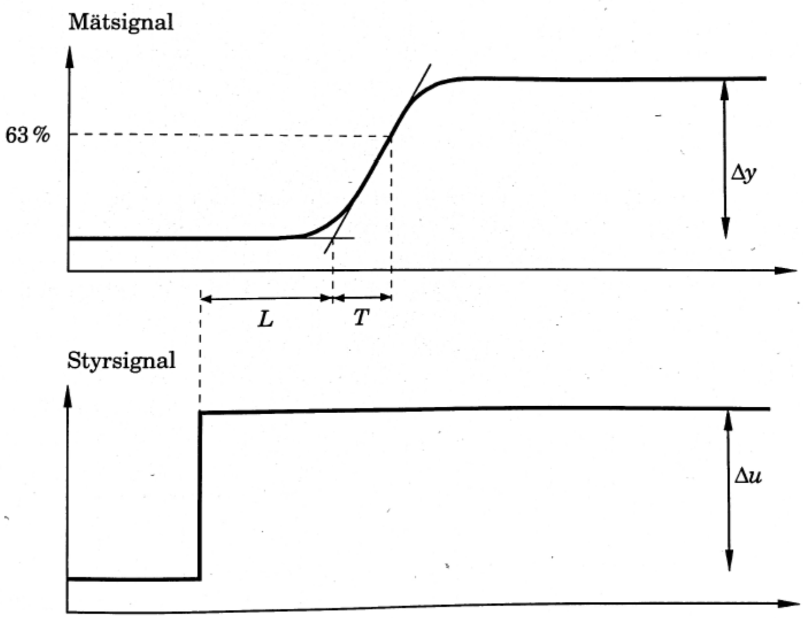

Figure 2.7 Lambda method [9]

3

Initiation phase

3.1 Overview

The outline of the project was early decided to have a specific structure. Roughly the work was split into two parts where the first part was the idea generation and the second part the realisation. The idea generation would end in a meeting where a decision should be taken which solution that should be realised and implemented on the real system.

The idea generation started of by doing a literature study on relevant theory regarding dialysis machines and on previous work. In order to gather the requirements for the solution it was important to understand roughly how the system worked. After the literature study a investigation and gathering of the requirements was made. Once the requirements were gathered the idea generation could start. Here another literature study was made on what techniques that were available for cooling liquid. Parallel to this the water device that was used for the project was set up properly.

Once several solutions had been investigated a decision meeting was held at the company where presentation of the different solutions was made and feedback on the different solutions was gathered. At the meeting it was decided which of the solutions to proceed with and implement on the physical system.

3.2 Requirement gathering

First the constraints on the solution were decided which can be seen below.

- Maximum power: 300W
- Time to reach setpoint: 3 min
- Temperature decrease: 15 °C

- Lifetime: approx 8 years

These requirements were loosely set and calculations would then show if they could be achieved or not. A requirement for Baxter was that the water device and a cycler must be able to be on the same fuse in a regular home. Thereby there was a restriction on the maximum power. The water device is a medical product where reliability is important and that's why lifetime was set to 8 years. The solution is supposed to be installed in the water device so a solution that needs regular maintenance would not be satisfactory.

Information about the water device was then gathered in order to calculate the required cooling power. These were the four important factors that were needed in order to do the calculations.

- Water flow into and out from the water device
- Temperature of water into the water device
- Temperature of water out of the water device
- Energy added to the water by the system

All the necessary information can be seen below.

- Volume
  - Water volume inside water device: ca 2000 ml
- Flow
  - Water in : 200-500 ml/min
  - Product water out : 200 ml/min
  - Drain water out : 0-300 ml/min
- Temperature
  - In water temp: 5-32 °C
  - Out water temp: ca 30 °C

The flow in and out from the water device must always be the same and depending on the water quality the drain water ranging from 0-300 ml/min. When the quality of the water decreases the flow of the drain water increases.

A known source of unwanted energy was the main pump in the system. Measurements on the pump had been performed prior to the start of the project. Those measurements were used to approximate the heating power of the pump. During normal operation the pump varies from 60 to 80% duty cycle where the heating power ranges from 90-170W.

3.3 Cooling power calculations

The analysis of the cooling power required was split up into two parts, initiation and running phase. This was not how the water device operates during normal production but was a thought how to run the water device and to simplify the calculations.

When starting the water device it's filled with water (2 l) and the initiation phase is to lower the temperature of all the water in the water device. The required amount of cooling power is here the power it takes to lower the temperature of 2 liters of water during a specified amount of time. From the theory (section 2.6) we know that the power is depending on the energy required to change the temperature of the material during a specific amount of time.

When the water device produces water (running phase) the water device is emptying water and filling up equal amount of water (200-500 ml/min). The cooling power required during running phase is the amount of cooling power it takes to lower the temperature of 200-500 ml water during a minute. In addition to this the energy that the pump adds to the water needs to be considered. The amount of energy is highly dependent on the duty cycle of the pump.

Calculation of the initiation and running phase:

From the theory we get the following equations that were used to calculate the cooling power:

$$E = C_p * m * \Delta T \tag{3.1}$$

$$P = \frac{E}{t} \tag{3.2}$$

$$P_{tot} = P + P_{pump} \tag{3.3}$$

where:

E = Energy required (J)
C_p = Heat capacity of water (kJ/(kg*K)) = 4.190
m = Mass of water (kg)
ΔT = Temperature difference (°C)
P = Power (W)
P_{pump} = Power the pump adds to the system (W) = 90-170 W
t = Time (s)

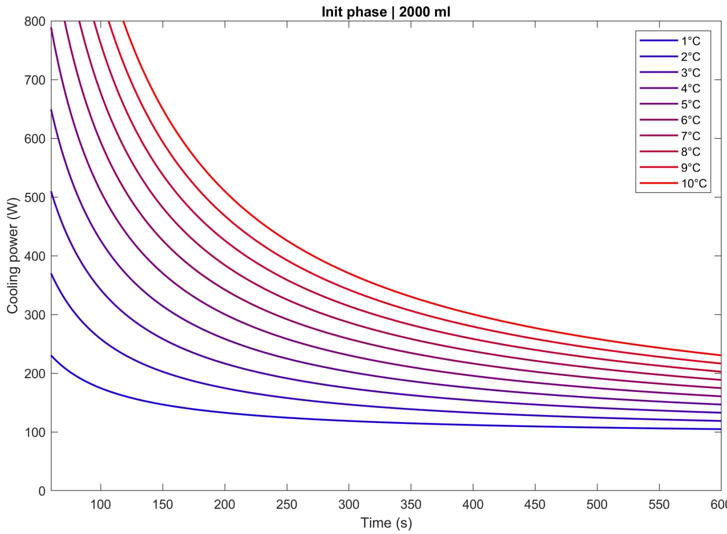

Figure 3.1 Required cooling power for init phase

With the use of equations 3.1-3.3 the required cooling power was calculated. Figure 3.1 shows the cooling power required to lower the temperature x °C during y seconds. The temperature change varies from 1-10 °C and the time varies from 60-600 seconds.

For the running phase the amount of water that needs to be cooled changes between 250-500 ml. When producing water the amount of water is depending on the water quality into the system. If the quality of the water is high less water is rejected which means less water will be inserted to the system. Figure 3.2 shows the required cooling power for different flows and temperature change.

After the calculation of required cooling power it was clear that a temperature change of 15 °C would require too much power. A decision was taken that a change of 5 °C in 5-6 minutes would be a goal much more obtainable than the previous one.

3.4 Idea generation

Once all the requirements were found the idea generation could start. The idea generation included several steps such as finding a suitable technique, analysis of the placement of solution and dimension the solution to meet the requirements. The idea generation ended up with three different solutions.

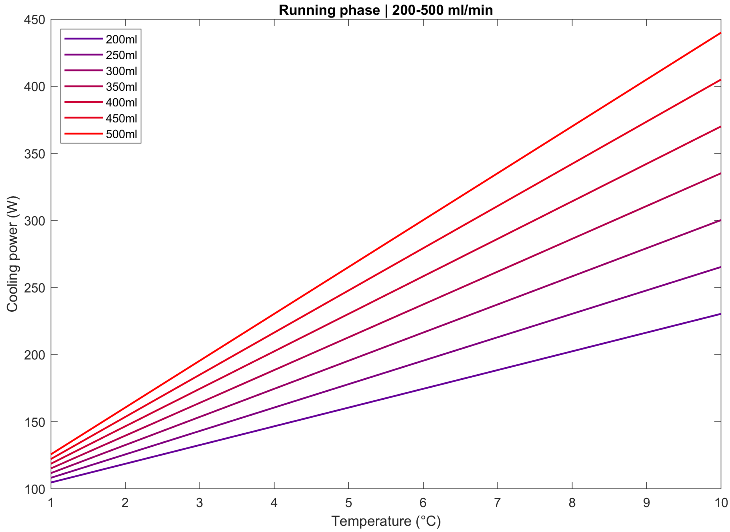

Figure 3.2 Required cooling power for running phase

As explained in section 2.5 the heater heats up the water to 30 °C. This is because the end product water must keep this temperature when proceeding to the next phase. If the heater would be kept at the same place it would work against the cooler so in all the solutions the heater was moved and placed after the return valve (VM1). Figure 3.3 shows the new placement of the heater.

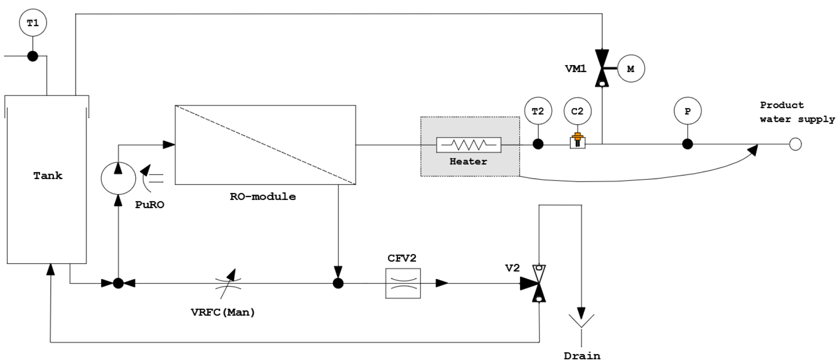

Figure 3.3 New position of the heater

Peltier module water-air

This solution consists of Peltier modules, one cold plate, heat sink and a fan. Figure 3.4 shows a rough sketch of the solution. Water runs through the cold plate where the Peltier module moves the heat from the water to the heat sink. The water gets cooled down and the heat sink is heated. The heat then dissipates from the heat sink with a fan. This solution requires placement of the cooling part inside the flow path and some outlet through the casing for heat dissipation.

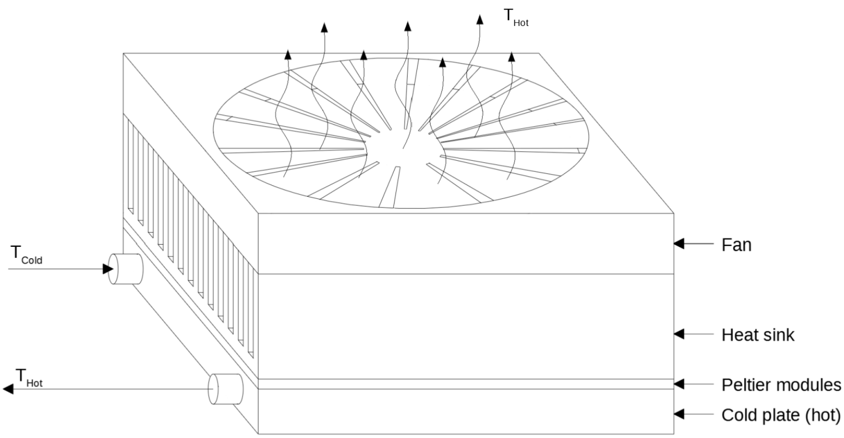

Figure 3.4 Sketch of Peltier module water-air solution

Peltier module water-water

This solution consists of two cold plates and Peltier modules. The difference from previous solution is that this solution uses water instead of air to dissipate the heat. One of the cold plates will cool water and the other will heat water. This solution requires placement of both cooling and heating inside the flow path. Figure 3.5 shows a rough sketch of the solution.

Heat pump

This solution uses a heat exchanger where the cooling medium runs in one of the channels and the water in the other channel. By doing this the heat is transferred

Figure 3.5 Sketch of Peltier module water-air solution

from the warmer water to the colder refrigerant. Solutions like this are often used in larger liquid coolers such as water dispensers and industrial water temperature baths. Figure 3.6 shows a rough sketch of the solution. This solution is similar to the first Peltier module solution as it only needs placement of the cooling inside the flow path.

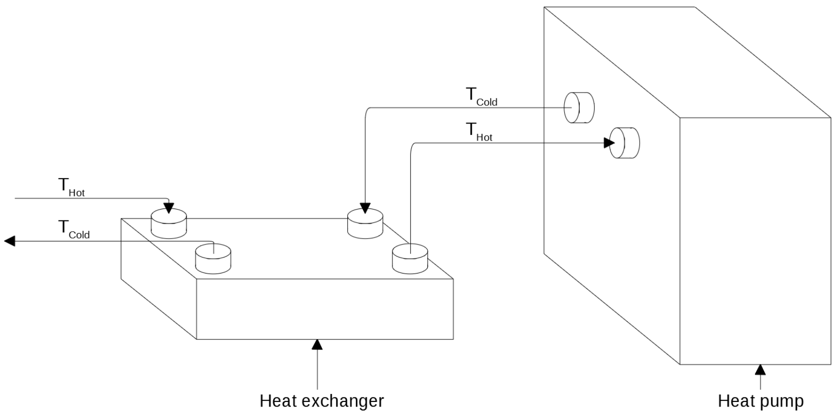

Figure 3.6 Sketch of heat pump solution

3.5 Dimensioning the solutions

The calculations on the solutions was based on a maximum power consumption of 300 W and an upper limit on the heat dissipation temperature of 50 °C due to safety reasons. If the dissipated air or water would be too hot during operation it would be a safety issue.

The solutions which included Peltier modules was calculated with a thermal calculator provided by Laird which can be found on their website https://www.lairdthermal.com/.

Due to some difficulties of finding a suitable solution for the heat pump solution calculations was only performed on the solutions which included Peltier modules.

Using the Laird thermal calculator

The calculator that was used to calculate on the solutions is only valid for Laird products. Below is a brief explanation how to use the calculator.

In order to use the calculator the user needs to specify the temperature difference between the cold side and the ambient temperature. The user must also specify the thermal resistance in the hot and cold side.

When calculating for one Peltier module the user can plug in the values and read the results directly from the calculator. When using more than one Peltier module on a single cold plate or heat sink the thermal resistance needs to be recalculated. This is calculated by multiplying the number of Peltier modules with the thermal resistance of the heat sink or cold plate.

T_{hot} is the temperature on the hot side of the Peltier module. If using a heat sink or cold plate with high thermal resistance this value will get higher. And when using multiple Peltier modules this is calculated by $T_{hot} = T_{ambient} + R_{thermalhot} * P_{dissipated} * N_{Peltier}$.

The last thing that needs to be recalculated is the cooling power and required power, both are calculated by multiplying initial values by the number of Peltier modules.

When calculating on the solutions the temperature difference between the cold side and the ambient temperature was set to 10°C. The ambient temperature was set to 35°C due to the fact that the solution should be placed inside the cabinet where it's warmer than room temperature.

Peltier module water-water

This solution is made with two cold plates and one or several Peltier modules. Calculations on the solutions was made with 1-4 Peltier modules. Table 3.1 and 3.2 shows the calculations made on the four different solutions. Two different flows on the cold side have been used to show the effect of different flows. 1 l/min corresponds to the permeate flow and 5 l/min to the reject flow. When comparing cooling power of the two different flows there is some slight difference with the higher flow having the higher cooling power. One thing to notice is that the cooling power goes down when having 3 and 4 Peltier modules but the power consumption goes down drastically. This is due to the restriction on the maximum temperature on the hot side. For 1 and 2 Peltier modules the power consumption is the limit and for 3 and 4 elements the temperature is the limitation.

Table 3.1 Table of calculations with water flow of 1 l/min

Cold side flow: 1 l/min				
Nr of Peltier modules	1	2	3	4
Thermal resistance (°C/W)(cold)	0.010	0.020	0.030	0.040
Thermal resistance (°C/W)(hot)	0.013	0.026	0.039	0.052
Cooling power (W)	181	260	225	188
Power consumption (W)	300	295	162	112
$T_{hot}(°C)$	40	50	50	50

Table 3.2 Table of calculations with water flow of 5 l/min

Cold side flow 5 l/min				
Nr of Peltier modules	1	2	3	4
Thermal resistance (°C/W)(cold)	0.004	0.008	0.012	0.016
Thermal resistance (°C/W)(hot)	0.013	0.026	0.039	0.052
Cooling power (W)	186	262	234	188
Power consumption (W)	300	288	159	108
$T_{hot}(°C)$	40	50	50	50

Peltier module water-air

This solution is almost the same as the previous but instead of having a cold plate on the hot side there is a heat sink. Due to the higher thermal resistance of the heat sink compared to a cold plate this solution has lower efficiency. Table 3.3 and 3.4 show the calculations on different setups.

The setups analysed here was with 1,2 and 4 Peltier modules, 1 cold plate and 1-2 heat sinks. One thing we can notice directly is that the temperature is a limitation in all setups. This is because the heat sink has much higher thermal resistance than the cold plate. One thing to notice is that the cooling power is highly dependent on the amount of heat sinks in the setup. When comparing 2 and 3 the cooling power is doubled when adding a heat sink.

Table 3.3 Table of calculations with water flow of 1 l/min

Cold side flow 1 l/min				
Nr of Peltier modules	1	2	2	4
Nr of heat sinks	1	1	2	2
Thermal resistance (°C/W)(cold)	0.010	0.020	0.030	0.040
Thermal resistance (°C/W)(hot)	0.045	0.09	0.045	0.09
Cooling power (W)	142	98	200	104
Power consumption (W)	236	70	135	64
$T_{hot}(°C)$	50	50	50	50

Table 3.4 Table of calculations with water flow of 5 l/min

Cold side flow 5 l/min				
Nr of Peltier modules	1	2	2	4
Nr of heat sinks	1	1	2	2
Thermal resistance (°C/W)(cold)	0.004	0.008	0.008	0.016
Thermal resistance (°C/W)(hot)	0.045	0.09	0.045	0.09
Cooling power (W)	145	100	207	106
Power consumption (W)	227	68	126	64
$T_{hot}(°C)$	50	50	50	50

3.6 Placement of cooling and heating

The placement of cooling was considered for both solutions but for heating only the Peltier module water-water solution was considered. This due to the fact that the Peltier module water-air solution dissipate the heat through the air and not through water.

7 possible solutions for the placement of the cooling and 2 placements for heating were identified. The possible placements can be seen at figure 3.7.

Cooling

Position 3 and 4 could be discarded directly since they are placed just before a drainage. This means that there will be some immediate losses and a better placement could be 5 and 7. Position 1 and 6 were discarded since both positions have a low and discontinuous flow. From theory we know that the cooling blocks have

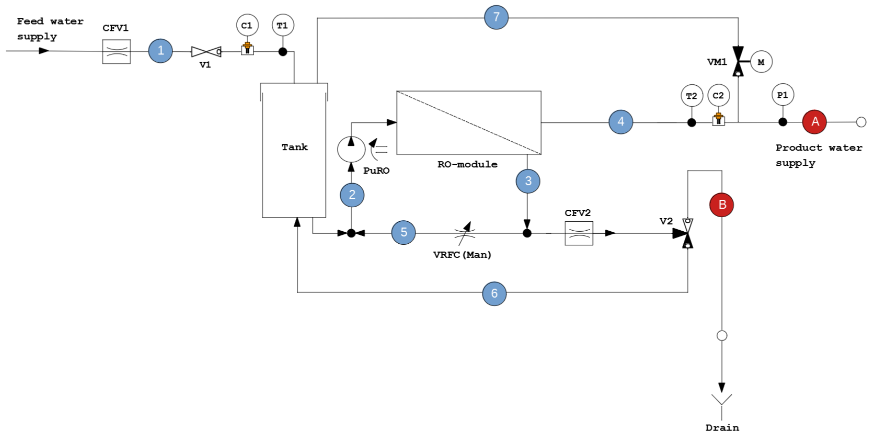

Figure 3.7 Placement of heating and cooling

higher efficiency when the flow of water is higher. The water flow is in order from highest to lowest 2, 5 and 7.

The drawbacks with a higher flow is the increase in pressure due to the cold plate. The increasing pressure could have been a problem for 2 and 5 since they were on the high pressure side of the system which position 7 isn't.

Heating

The water flow in these positions are similar with the difference that the flow is continuous in position A and discontinuous in B. Position A has a limitation on the maximum allowed temperature which is 37 degrees which position B don't have. Position A had the big advantage in the case that the heater used to warm up the product water could be removed completely.

3.7 Decision meeting

At the decision meeting it was decided which of the solutions to proceed with. Positions in the flowchart are found in figure 3.7

The solutions that were discussed was Peltier water-air and Peltier water-water. The meeting decided that the water-water solution was the preferred solution. The biggest main advantage of the water-water solution was that the heat dissipated through the water instead of the air. Since the water device is placed in a room with the patient, often their home, it's preferable to not dissipate the heat through the air and heat up the surrounding air. Some other advantages of the water-water solution was that the solution was much smaller and gave a better cooling power. The main advantage of the water-air solution was that the performance was not dependent on a second water flow.

The placement of the cooling and heating was also discussed. The placement of the cooling should be in a place where the flow of water is continuous due to the loss of efficiency with a lower flow. For the heating position A was the preferred position but it was decided to investigate both solutions. A big advantage of the preferred solution was that the heater may be disabled and the permeate water heats up by the hot side of the Peltier module solution. With this solution the water temperature is controlled at position A. For the other solution the temperature on the cold side is controlled since the temperature of the drain water doesn't have a restriction.

It's was highly desired to find an assembly of the solution rather than order separate parts. This was due to the difficulties of isolating and tightening the solution. The force on the Peltier module from the cold blocks is crucial and if not achieved the efficiency decreases drastically and could potentially be a time consuming moment in the process.

4

Implementation and testing

4.1 Peltier module system overview

In order to control the water temperature the following components were needed.

- Actuator
- Sensor
- Controller

In this project a Peltier assembly was the actuator. An Arduino was used as a controller and to measure the temperature an Arduino compatible temperature sensor was used. Figure 4.1 shows the control diagram over the system.

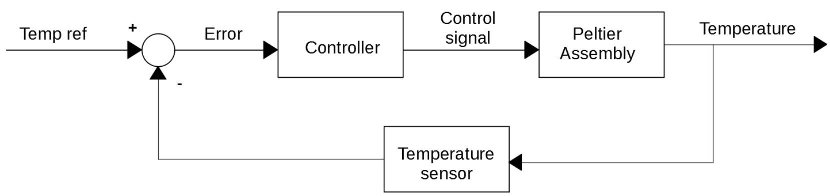

Figure 4.1 Control diagram

Peltier assembly

A Peltier assembly was found that performed similar to the ones calculated. There was no data on the efficiency at different flow rates and the cooling power was somewhat lower than the suggested solution. Since information about the flow rate was missing a rough estimate was made that the solution would have a cooling power of 170 W according to the manufactures website. The power requirements for the Peltier assembly was 200 W which would be a bit under the 300 W limit. Figure 4.2 shows the Peltier module assembly.

Figure 4.2 Peltier assembly [10]

The chosen Peltier assembly had a nominal voltage of 24 V. In order to control the cooling power from the Peltier assembly the voltage over the Peltier assembly needed to be adjustable in some way.

This was solved using a PWM signal. If switching the power supply using a PWM signal the voltage to the Peltier assembly could be controlled and set to the desired value. A high power MOSFET was used to achieve this. Figure 4.3 shows a circuit diagram of the solution. The PWM signal from the Arduino was connected to the gate and the Peltier assembly(PA) was connected to the source. Since the voltage on the gate could be 5 V an Arduino could be used to output a PWM signal. The 10k resistor in the circuit was used as a pull up resistor.

Controller

The controlling unit needed to solve three tasks. Reading an analog signal from the temperature sensor, computing the control signal and to output a PWM signal. Since an Arduino is capable of doing all these tasks it was selected to work as the controlling unit. Due to some previous experience of using Arduino it was also a favourable pick.

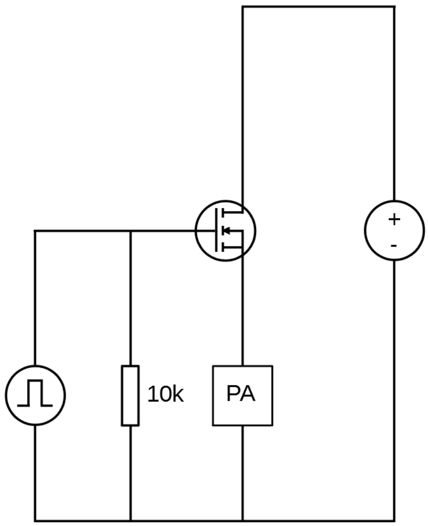

Figure 4.3 Circuit diagram

Temperature sensor

The temperature sensor used was a "Gravity: Analog High Temperature Sensor". This was available at the company and was almost plug and play with the Arduino. In order to work an Arduino library was downloaded from the website. Since the sensor together with the library outputs integers the resolution was a bit low. To solve this problem the sensor values was averaged over time. The result is shown in figure 4.4. During the test the sensor was moved from cold to hot water. As can be seen the resolution is much better when averaging is applied. The sensor was then compared to a calibrated sensor to measure the performance. The sensor was off by ± 0.3°C in average which was acceptable for this project.

The results show some weird behaviour at 120 seconds. The average value is at this point higher than the sampled data. The cause to this behaviour is that the data is sampled. If the data would have been sampled with a higher frequency the weird behaviour would disappear.

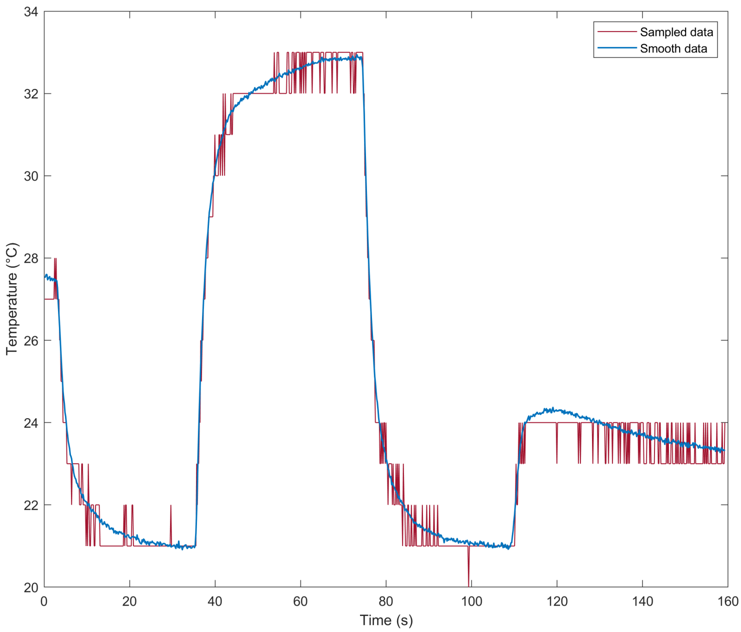

Figure 4.4 Sampled and smooth data

4.2 Building the rig

The rig was built in the water lab at Baxter. An overview of the rig can be seen in figure 4.5. The heart of the rig was a water device used in a current R&D project. The water device was modified with the Peltier assembly. A computer was used to communicate with the water device. In order to have a stable and controllable temperature of the water entering the water device a water circulator rig was used which can bee seen at the left side of the figure. Water was filled in a tank that acted as water source. The water from the tank was pumped through a heat exchanger and into the water device. The other channel of the plate heat exchanger was connected to the water circulator. By changing the temperature of the water inside the water circulator the temperature of the water entering the water device could be controlled. The water circulator and the water tank can be seen in figure 4.8. The modified water device can be seen in figure 4.7. In figure 4.9 the Arduino, power supply, temperature sensor and the circuit controlling the power supply can be seen. The MOSFET needed two heat sinks in order to not be overheated. This can be seen in figure 4.10.

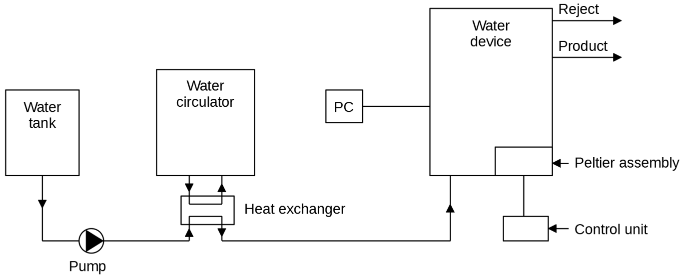

Figure 4.5 System overview

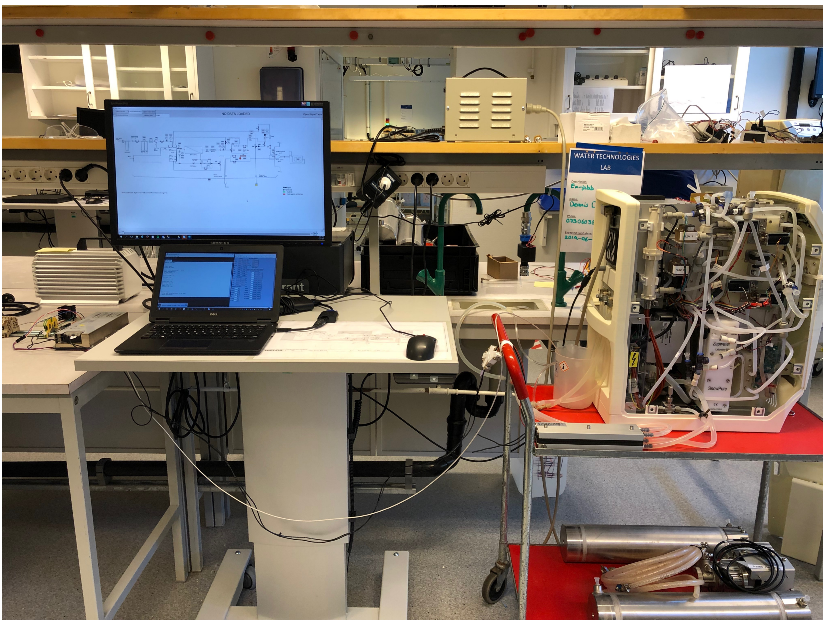

Figure 4.6 Computer and water device

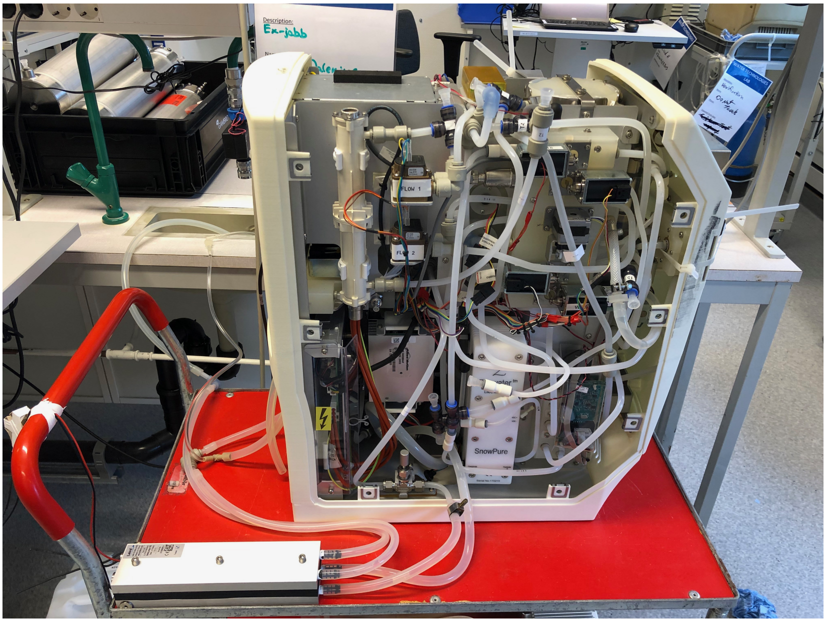

Figure 4.7 Side view of modified water device

Figure 4.8 Water circulator and water tank

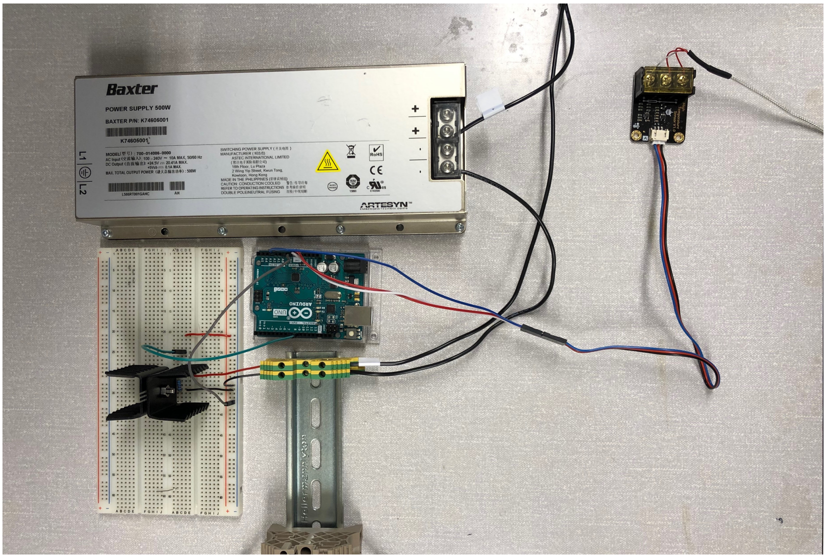

Figure 4.9 Power supply, Arduino, temperature sensor and PWM circuit.

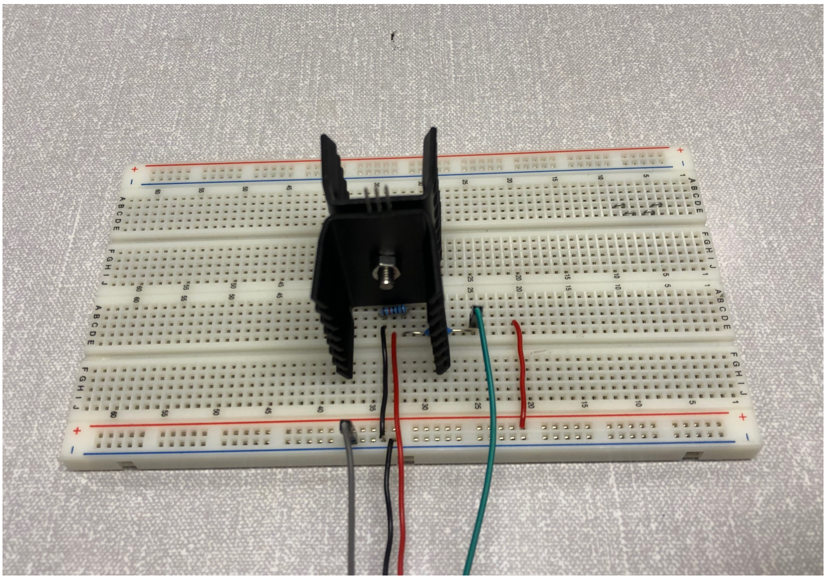

Figure 4.10 PWM circuit

4.3 Measurements on the physical system

All the tests were performed with the lid open on the water device. This due to limitations on the project and the challenges of fitting the solution inside the water device. The drawback of this was that the ambient temperature was at room temperature. During normal operation the temperature inside the water device is higher than room temperature and a lower temperature of the Peltier assembly results in better cooling. The results of this was that the tests show better results compared to if the solution would have been placed inside the water device with the lid sealed.

Before any measurements were made on the solutions a measurement on the theoretic conductivity decrease was made. Figure 4.11 shows measurements from the testing where the temperature was decreased from 30 to 20 °C. The results shows that the relative conductivity decrease for the simulated system is a bit higher compared to the physical system.

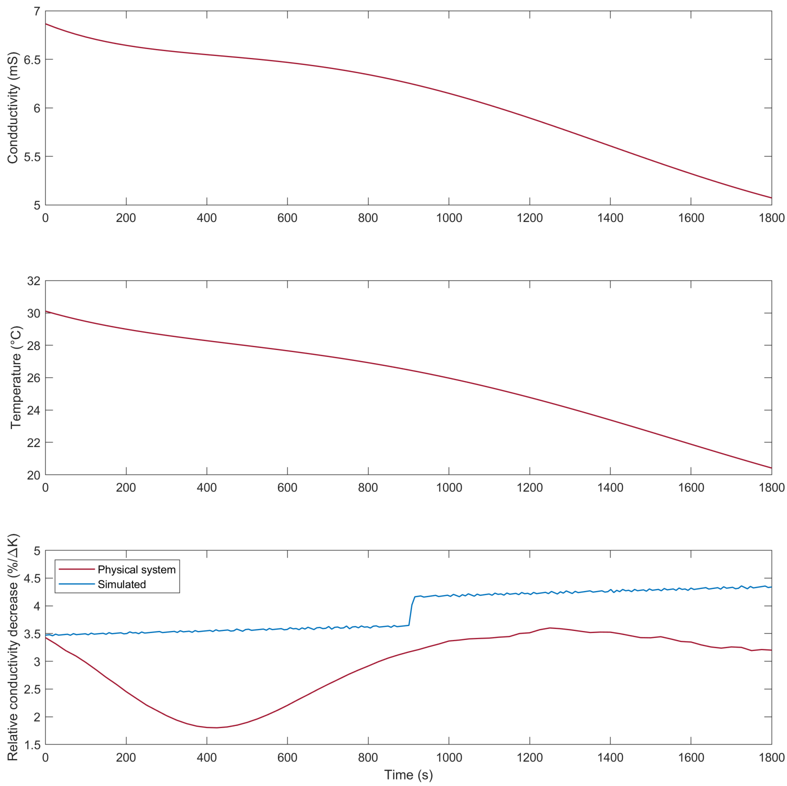

Figure 4.11 Conductivity and temperature decrease

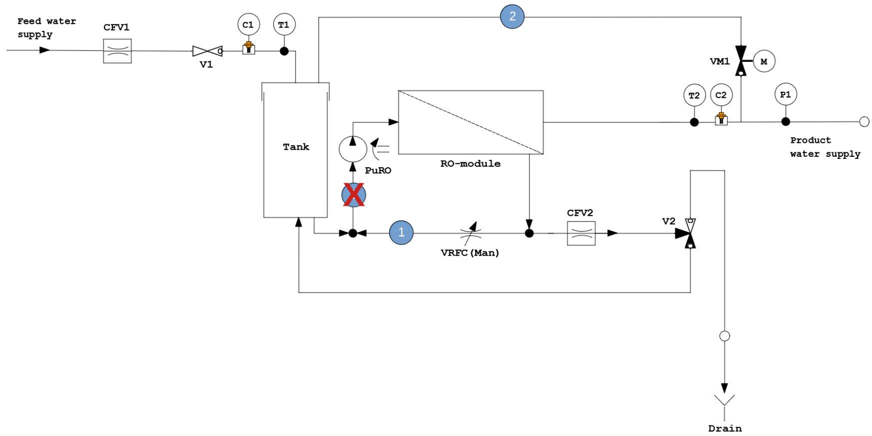

Figure 4.12 Position of the cooling in the flowchart

Comparison of the placement of cooling

We know from section 3.6 that there were several possible placements for both the cooling and the heating which needed to be compared against each other. To test which of the solutions that performed best the comparison was split into two parts, one comparison for the cooling and one for the heating.

The first test was to compare where the cooling should take place. The highest and the lowest flow of the positions were here considered. Due to difficulties in installing the cooling right before the pump there was only two positions left to compare. The positions can be seen in figure 4.12. The two positions differ in the flow rate where position 1 has a flow of approximately 6 l/min and position 2 has a flow rate of 1 l/min.

The test was made with a supply water temperature of 23 °C. Before the Peltier assembly was powered on, the water device produced water until the temperature of the water inside the water device reached a steady state. Then the Peltier assembly was used with maximum power during 14 minutes. During the test the temperature at T2 was measured. Figure 4.13 shows the results of the test. After 14 minutes the water temperature with cooling at position 1 had a water temperature which was 0.6 °C lower than when cooling at position 2.

Due to the results position 1 was used for the cooling at all the remaining tests.

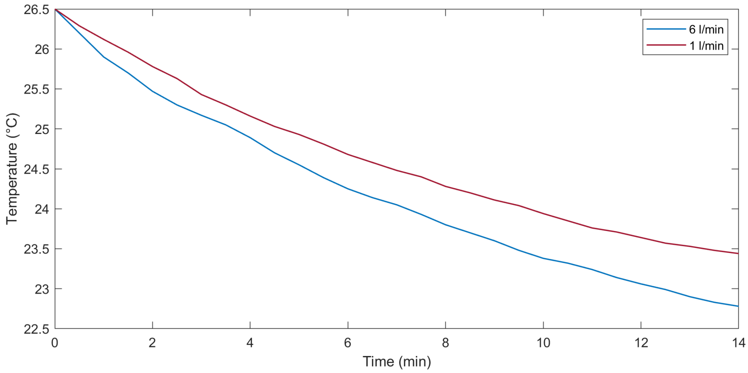

Figure 4.13 Cooling comparison between two positions

Comparison of the placement of heating

From section 3.6 we know the heating of the water could take place at two positions which can be seen in figure 4.14. One could here do a similar test as for the cooling and compare the two positions by running the systems with full power on the Peltier assembly. But since there was some differences between the two solutions such tests would be unnecessary. The first solution, where the heating takes place at position 1, controls the water temperature in the main loop e.g at T2. The second solution controls the water temperature after the heating at position 2. Due to the restrictions this temperature cannot be too hot.

The first solution is a slow process compared to the seconds solution and in order to compare the two solutions control parameters for each solution first needed to be calculated.

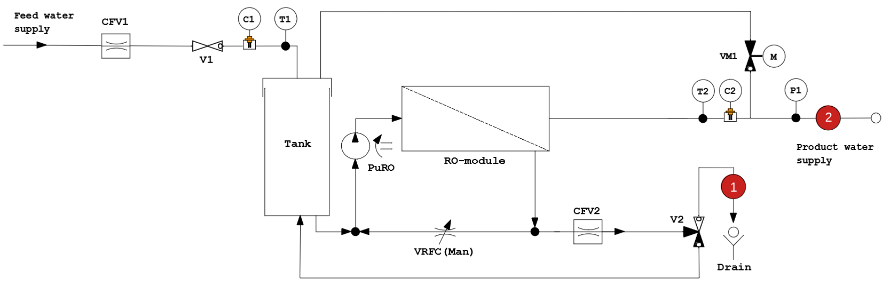

Figure 4.14 Position of the heating

Lambda method

The lambda method was used to calculate the control parameters for both solutions. The method is a step response method and is a common method to experimentally tune the control parameters for PI controllers. From the theory we know how to calculate the control parameters when using the lambda method where u is the control signal and y is the reference signal. Equations 2.2-2.4 from section 2.13 were used to calculate the control parameters.

$$K_p = \frac{\Delta y}{\Delta u}$$
$$K = \frac{1}{K_p} \frac{T}{L+\lambda}$$
$$T_i = T$$

Solution 1 For this solution the test was made with a step change of 255. Figure 4.15 shows the test. From the test we get that $L = 29.3$, $T = 400.7$ and $\Delta y = 2.36$. λ is set to T. Using the equations we get $K = 400.7/(0.0093(29.3+400.7)) = 100$ and $T_i = 400$

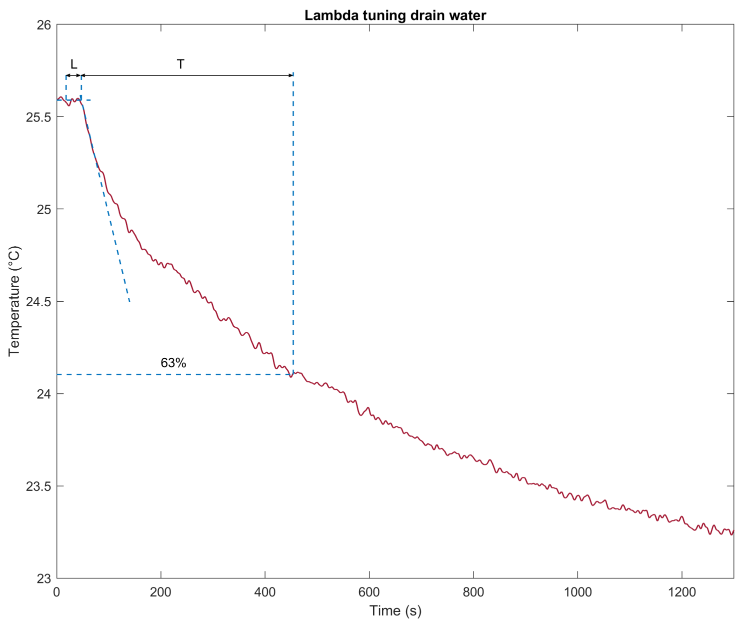

Figure 4.15 Lambda tuning step response

Solution 2 For this solution a step change of 150 was made. Figure 4.16 shows the test. From the test we get that $L = 7.7$, $T = 34.9$ and $\Delta y = 12.2$. λ is set to T. By using the equations to calculate the control parameters we get $K = 34.9/(0.08(7.7+34.9)) = 10.06$ and $T_i = 34.4$.

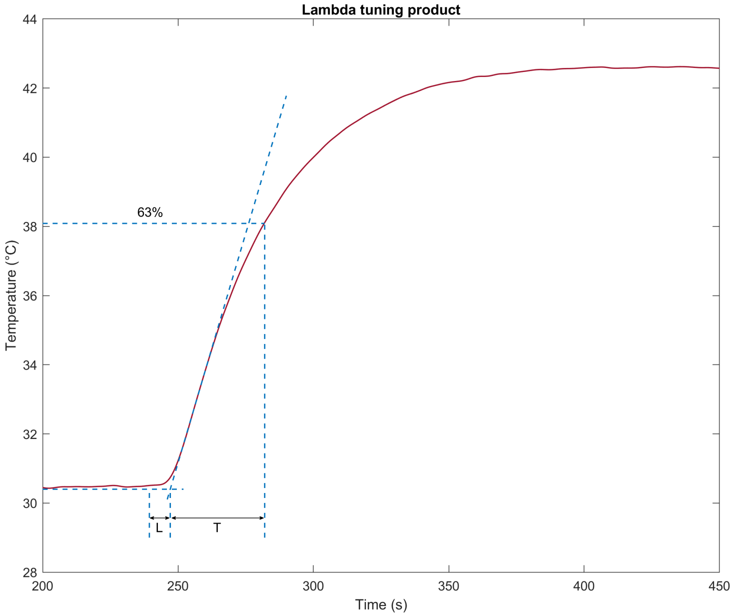

Figure 4.16 Lambda tuning step response

Lambda method calculation performance and tune

To test the performance of the calculated parameters a standard water production was performed. When the temperature had reached a steady state the controller was turned on and a step change in the set point was made.

Solution 1 With the calculated parameters the system was way too slow and $K = 500$ was found to give an acceptable performance. Figure 4.17 shows a step response with the new parameters. One can see some slight offset and oscillations around the set point but due to the small amplitude of the two the performance of the control was seen to be acceptable.

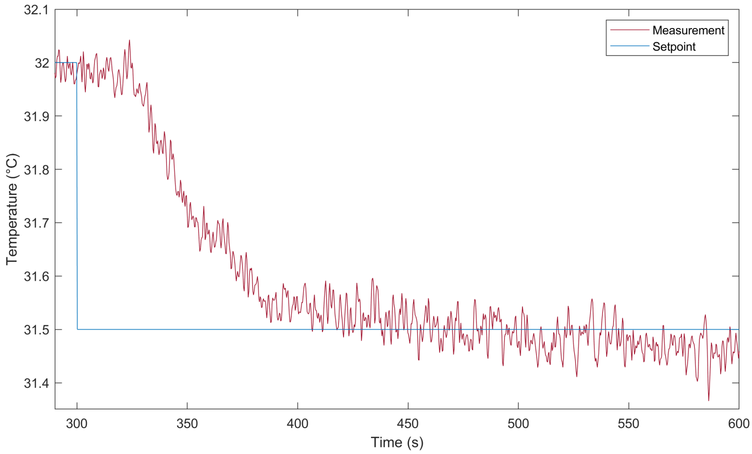

Figure 4.17 Step response with calculated control parameters

Solution 2 The performance of the parameters was tested by setting the set point to 37 °C at 100 seconds. Figure 4.18 shows a step response with the calculated parameters. One can see that there was an overshoot with the calculated parameters. The largest distance from the set point was 1.4 °C. The parameters were tuned to find a better control.

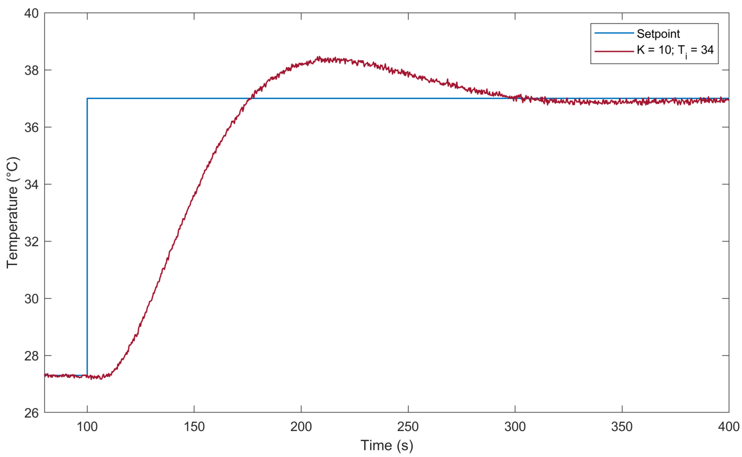

Figure 4.18 Step response with calculated control parameters

A more aggressive controller was tested with a higher K value and with higher value of T_i. The final result can be seen in figure 4.19. We can still see an overshoot but this time much lower. The biggest difference between the set point and the measurement signal was 0.7 °C. We can also see that the system is showing a smaller oscillatory behaviour. Since the system with tuned parameters had less offset from the set point it was selected to be the final system.

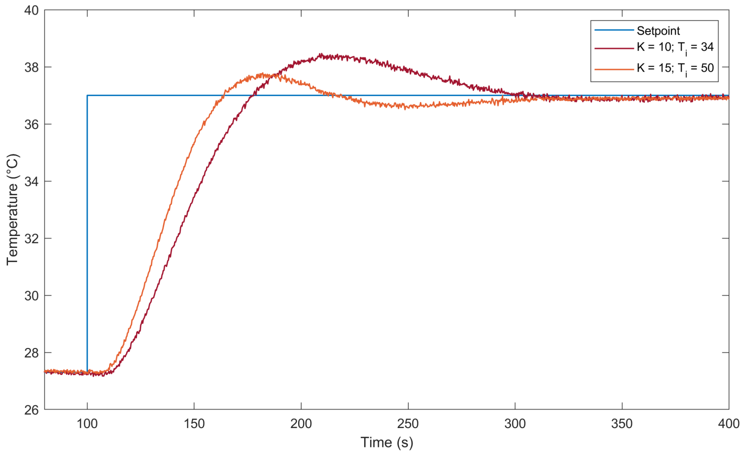

Figure 4.19 Comparing the performance with $K = 10$ and $K = 15$

4.4 The final testing

The final testing of the two solutions was performed when the water device was producing water with the standard program. The Peltier assembly was turned on when the water temperature had reached a steady state, approximately 6-8 minutes after startup. When the Peltier assembly was turned on it ran for 10 minutes with the controlling unit turned on. The tests were performed with two different temperatures on the feed water, 30 and 23 °C.

Solution 1

When the performance of this solution was tested the set point was set to 5 °C below the starting temperature. Figure 4.20 and 4.21 show the results of the test. The water temperature never reached the set point for both tests. During both runs the control signal was at its maximum value all the time. The drain water which was heated by the Peltier module increased it's temperature by 28 °C which means the temperature of the drain water was around 53-58 °C. This was a bit over the 50 °C specification set in the beginning of the project. The decrease in temperature during the run of 15 minutes was 2 °C when the in water temperature was 30 °C and 3 °C when the temperature was 23 °C which both is less than the initial goal of a temperature decrease of 5 °C.

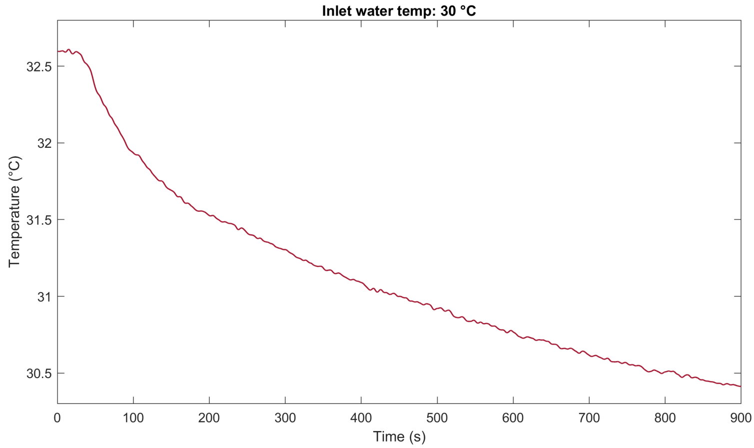

Figure 4.20 Performance with feed water temperature of 30 °C

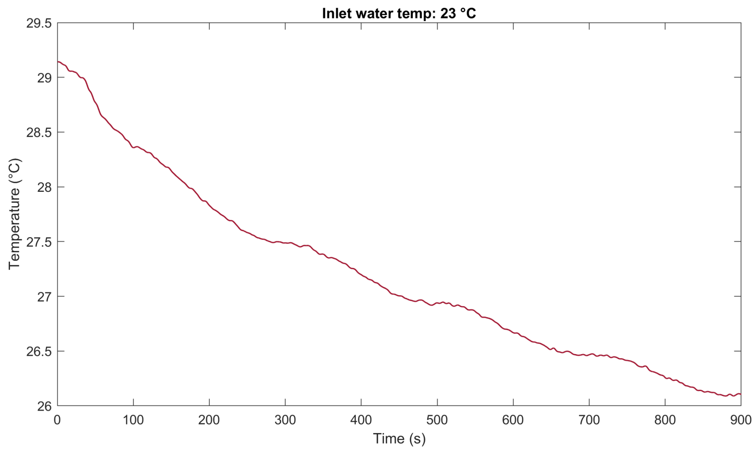

Figure 4.21 Performance with feed water temperature of 23 °C

Solution 2

During these two tests the set point was set to 37 °C. Figure 4.22 and 4.23 show the results of the test runs. The system settled at a steady state after 300 seconds for both tests. The big difference between the two is the temperature decrease and PWM signal at steady state. When the in water temperature was 30 °C the duty cycle was 20 % and a temperature decreased by 0.8 °C. When the feed water temperature was 23 °C the duty cycle was 40% and the temperature decreased by 1.5 °C.

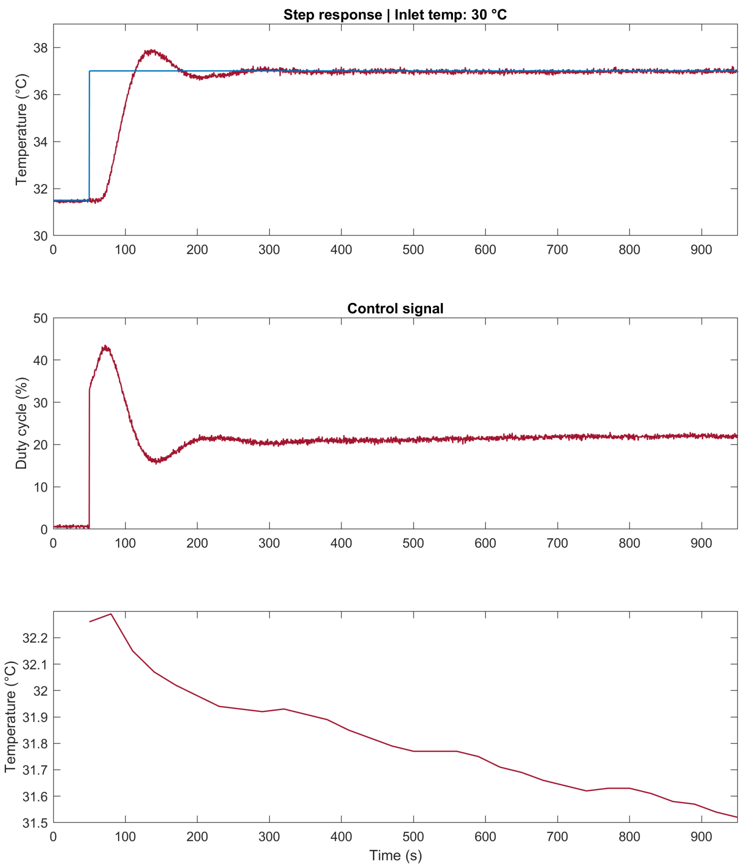

Figure 4.22 Performance with in water temperature of 30 °C

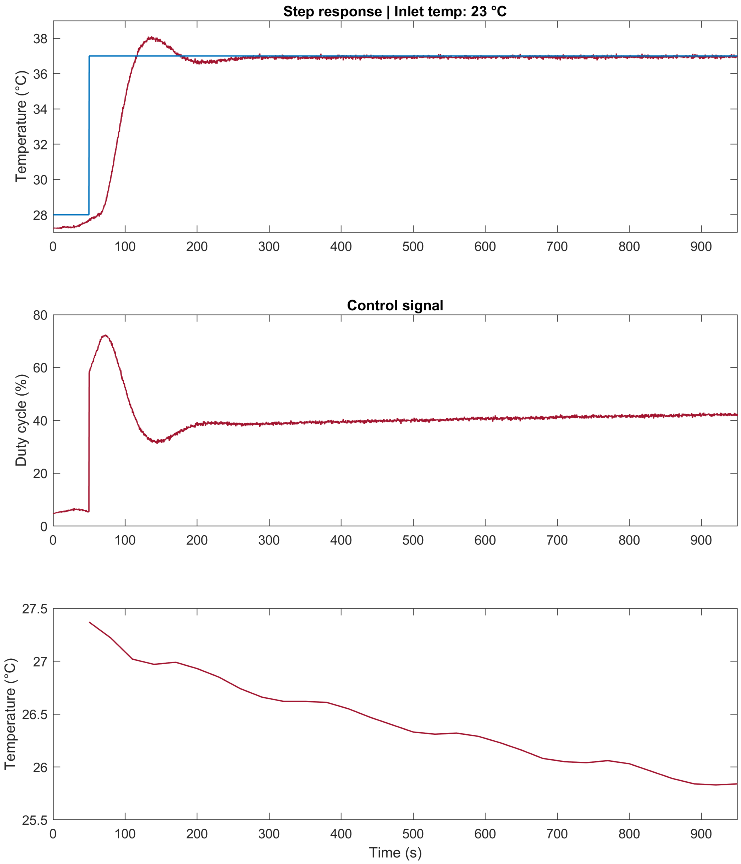

Figure 4.23 Performance with in water temperature of 23 °C

4.5 Testing without limitations

The earlier tests that had been done were all restricted in some way. For solution 1 the flow where the water was heated was periodic and was limited to 100 ml/min during normal operation. Solution 2 had a restriction on the maximum temperature at the heated water flow. Following test will show what happened when the flow was increased and when there was no limitation on the maximum temperature.

Figure 4.24 shows a run without limitation on the temperature. The temperature decrease during almost 700 seconds was 3 °C. This was a clear improvement from the tests when the set point was set to 37 °C. As expected the temperature after the heating was high. For this test the temperature increased by 20 °C.

The next step was to see how high the flow needed to be to still have an acceptable temperature after the heating and still run the Peltier assembly on high duty cycle. In order to make this test possible the hot side of the Peltier assembly was disconnected from the water device and was replaced by a separate tank and pump. This was made since the water device had a constant flow of 200 ml/min at the product water. With a separate tank and pump the flow could be adjusted to the desired value. The cold side was still connected to the water device in order to apply the cooling effect. The water temperature in the tank was held at the same temperature as the temperature of the water inside the water device. With a flow of 500 ml/min the temperature increase of the water running through the heater was 10 °C. Figure 4.25 shows the temperature decrease of the water inside the water device. During 700 seconds the temperature decreased by 4 °C.

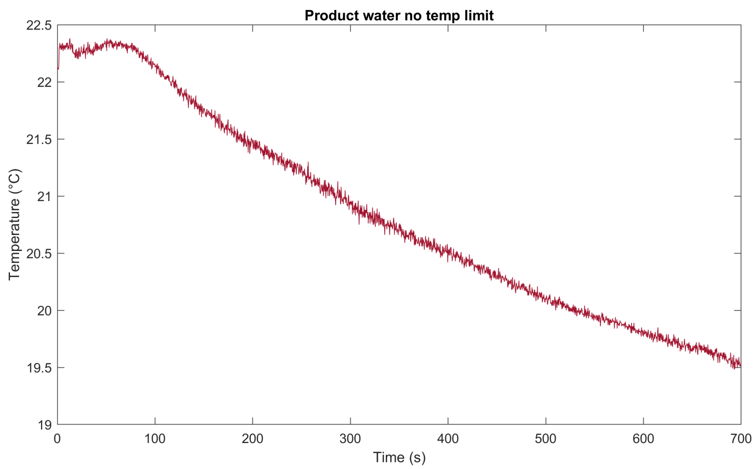

Figure 4.24 Solution 2 with no limit on temperature

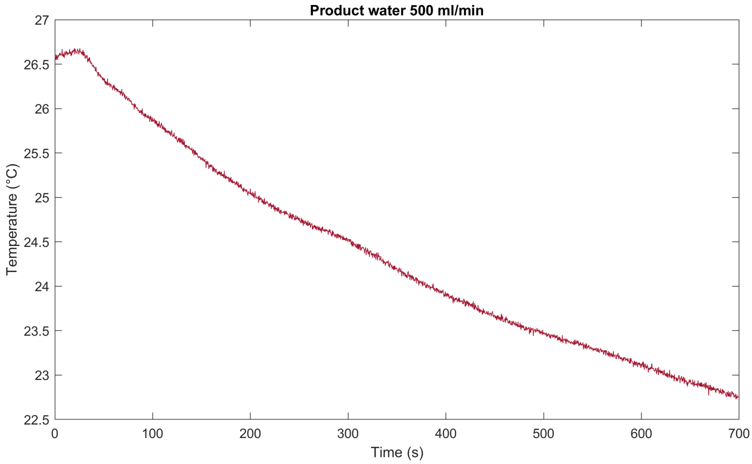

Figure 4.25 500 ml/min water flow through hot side of Peltier element

4.6 Dead time

When the lambda method was used we saw that both solution had a significant dead time. Solution 1 had a dead time of 30 seconds and solution 2 had a dead time of roughly 8 seconds. Some of that dead time was caused by the placement of the temperature sensor.

For solution 1 the temperature sensor was placed at position 2. Since the cooling of the water occurs at position 1 there is some slight delay. Figure 4.26 show the positions.

For solution 2 the temperature sensor was placed 60 cm after the heating. The inner diameter of the tube was 0.4 cm. We also know that the flow here was 200 ml/min. The velocity of the water is calculated by dividing the flow by the inner area of the tube. This gives a velocity of 26.5 cm/s. Given this velocity of the water the dead time caused by the placement of the sensor was $60/26.5 = 2.26$.

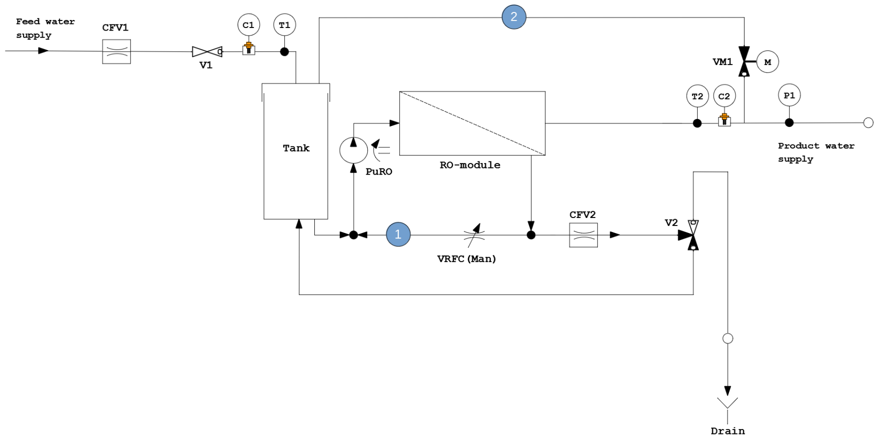

Figure 4.26 Position of cooler and temperature sensor

5

Discussion

5.1 Peltier assembly

From the tests we saw that the flow of the water affected the efficiency of the Peltier assembly drastically. Some other factors also affect the efficiency but the flow was the biggest contributor to the reduced efficiency.

Solution 1

The problem with this solution was that there was no continuous water flow at the hot side of the Peltier assembly, in this case at the drain, which resulted in a low average water flow. The flow of water was periodic and depended on the quality of the inlet water. During the tests the water quality was high. If the water quality is low the average flow of water at the drain is increased. An initial thought could be that the efficiency is increased when the quality is low, but since the duty cycle of the pump is increased with a lower quality of the water the effect of this cannot be answered without further testing. A higher duty cycle of the pump increases the heat from the pump to the water.

A big problem with this solution could be that the water heats up quickly when there is no water flow. A possible solution could be to turn off the Peltier assembly when there is no flow and turning it on when there is flow of water. Since no experiments were performed with this solution there is no data that confirms the effects. If such a solution is applied the dead time of the Peltier assembly could be a vital parameter to account for.

Solution 2

The problem with this solution was also the low flow of water through the hot side of the Peltier assembly. We know from before that the product water had a constraint on the maximum temperature allowed. Due to this fact the Peltier assembly could not run on maximum power. The test showed that the duty cycle of the Peltier assembly was 40 % when the inlet temperature was 23 °C and 20 % when the temperature was 30 °C. This resulted in a temperature decrease two times higher when the inlet temperature was 23 °C compared to 30 °C. If the difference between the maximum allowed temperature and the temperature of the water before the heating is small the cooling power of the Peltier assembly will be small.

A higher water flow of the product water would result in a lower temperature increase of the product water and would allow the Peltier assembly to run at a higher duty cycle. Section 4.5 showed what difference a higher flow could do. When the flow was increased to 500 ml/min the temperature increase of the product water was 10 °C instead of 20 °C.

The big bottleneck was the flow through the Peltier assembly on the hot side. The most obvious solution would be too increase the flow through the Peltier assembly. Without modifying the flow path and flows in the system a possible solution could be to combine the flow of the drain water. Since the product water and the drain water cannot be mixed the Peltier assembly would need some modification. A second cold plate could be mounted on top of the cold plate on the hot side of the Peltier assembly and then be connected to either drain or the product water. Another solution could be to use two separate Peltier assemblies, one for the product solution and one for the drain solution.

Comparison between the solutions

When comparing the performance of these two solutions solution 1 is the clear winner in the case of highest temperature decrease. The temperature decrease for solution 1 was two times higher than for solution 2. None of the solutions reached the goal of lowering the temperature 5 °C during 6 minutes.

Additional Peltier assembly

The Peltier assembly that was used in this project had a power consumption of 200 W. This was 100 W lower than the maximum power limit and could have been used to power an additional Peltier assembly. But this wouldn't give more cooling power to the system. Since there was requirements on the maximum temperature of the product water and the drain water, which was already a problem with one Peltier assembly, an additional Peltier assembly wouldn't give more cooling power.

5.2 Test environment

In section 4.3 it was explained that all the tests were performed with the lid open and that this would affect the test results. Since the temperature inside the water device is higher than the room temperature the Peltier assembly would be hotter with the lid closed compared to when the lid is open.

A solution to this problem could be to enclose the space where the Peltier assembly is placed and to ventilate the space with the surrounding air in the room. A problem with this solution is that this would transfer heat from the Peltier assembly to the room.

5.3 PWM-control circuit

The efficiency of the Peltier assembly decreased a bit due to the transistor used in the circuit. The ideal case of this circuit would be to have a V_{DS} of 0 V. This would mean that the Peltier assembly could use all the power from the power supply. But since the transistor used had a $R_{ON} = 0.1\Omega$, V_{DS} was roughly 1 V. When the Peltier assembly was maxed the voltage over the Peltier assembly was 23.5 V. With the use of a transistor with a smaller R_{ON}, V_{DS} would have been lower which would have resulted in a higher voltage over the Peltier assembly.

5.4 Control

Dead time

From section we know that some of the dead time in both solutions could be reduced by placing the temperature sensor closer to the actuator. For solution 2 the dead time was 7.7 seconds and could be reduced to 5.3 seconds, a decrease by 30 %. This reduction could simplify the control of the system.

Tuning

The lambda method was selected since it's a common method of choice in industry. In both solutions the parameters needed some tuning to perform acceptable. Solution 1 performed good with some minor oscillation around the set point. But due to the small amplitude of those oscillations the control was seen acceptable. Solution 2 had some small overshoot which is an unwanted feature. Since the water temperature inside the water device doesn't change that quickly its unlikely that this overshoot would be a problem. A method to dampen the overshoot could be to implement set point weighting on the proportional part. In equation 5.1 β is the set point weighting and is set to a value between 0 and 1. A low value of beta would dampen the proportional part and make the integral part more dominant. Using set point weighting is a common way to improve the performance of PID controllers.

$$P = K(\beta r - y) \tag{5.1}$$

5.5 Future work

We know that the solution didn't meet the requirements and some possible improvements have been discussed. Other than improving the solution some further testing of the solution could be performed.

In section 5.2 it was explained that the testings was performed with the lid open to the water device and that this would have some effect on the measurements. To know the actual performance of the solution the testings must be performed with the lid closed and the solution placed inside the water device.

One test that could be interesting to perform is a test which compare the performance during a water production with and without the cooling. All of the tests that was performed in this project were performed when the water temperature inside the water device had reached a steady state. During this test the solution would be activated when the water production starts and continued during a specific time. This test would then be compared to a standard water production without the cooling activated. This would give a good result on the actual performance of the solution.

It's hard to say if this solution is a solution worth implementing to the system but with these two test the decision would be easier.

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Title and subtitle
Reverse osmosis temperature control

Abstract
Baxter develops medical devices that take advantage of reverse osmosis to purify water that's being used in dialysis fluids. Reverse osmosis is a commonly used water purification process that removes unwanted particles from the water.

The membrane that is used to purify the water has a temperature dependency that changes the performance of the membrane when the temperature is changed. When lowering the temperature of the water the purification of the water is increased. In this thesis the possibilities of lowering and controlling the temperature of the water was investigated. The goal was to implement a solution on a physical water device and to analyse the performance.

Several solutions for the problem was presented where one of the solutions was selected for implementation on the real system. The final solution was a Peltier assembly which transfer heat from a flow of water and dissipating the heat through a second flow of water. The heart of the solution was a Peltier module which is a solid state heat pump that has no moving parts.

A test rig was set up in a lab at Baxter with the water device and other components. In order to control the temperature of the water a controller was implemented and tuned. To analyse the performance several tests were performed.

The results showed that the temperature could be lowered but not as much as the initial goal. A major issue was the low flow of the dissipating water. The effect of the low water flow was that the efficiency of the Peltier assembly was decreased.

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