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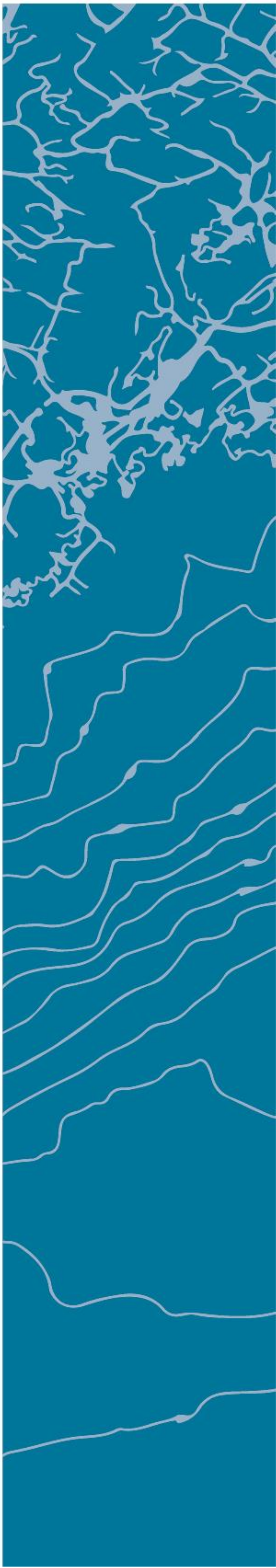

Design and Fabrication of Solar Water Distillation System for Developing Countries

IDA FLATVAL ULEBERG

SUPERVISOR
Associate Professor Souman Rudra

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Faculty of Engineering and Science
Department of Engineering Sciences

Abstract

The local population in Somalia is experiencing a shortage of fresh drinking water due to high salt content in the ground water. The humanitarian organization Yme is a big contributor for providing clean and safe drinking water for local communities. Yme is interested in building an effective water distillation system to improve the water quality and better the health situation in the country.

The main goal of this thesis was to contribute to improving water quality by building a solar water distillation system. As the system is meant for local communities in Somalia, the technology should be easy and without modern control system.

The project was highly limited by time. The parts for the prototype was therefore ordered from stock and not custom made for the project. It was also limited by location. Fabrication and testing were conducted in Norway, and not Somali conditions.

To design the prototype an optimization was performed in Matlab to find optimal system temperatures. A pinch analysis was performed based on the temperatures, and the size of key components were calculated. Prior to fabrication, a 3D model of the system was made in Solidworks in order to design the system.

Due to low temperatures during testing, the prototype was not able to evaporate the saline water. The main reason for the system’s inability to distillate water was the external conditions in the testing environment. Calculations indicates that the system should be able to evaporate the water in Somali conditions.

For future work, the system should be insulated and tested under various conditions to find the external conditions requirements for the distillation to take place.

Acknowledgements

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Author

Ida Flatval Uleberg

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1 Introduction

This report includes the work that has been done for the course ENE 500 – Master's Thesis Renewable Energy at the University of Agder. It is the final thesis for the Master of Science in renewable energy engineering. The work is based on the preliminary study "Solar Water Distillation System for Developing Countries".

1.1 Motivation

Somalia experiences a shortage of drinking water due to a high salt content in the ground water. The humanitarian organization Yme is a big contributor for providing clean and safe drinking water for local communities. Yme wants to build an effective water distillation system to improve the water quality and better the health situation in the country. Renewable energy in the form of solar energy is highly available in Somalia, and can be used as an energy source to clean the saline ground water.

1.2 Problem Statement

The main goal of this thesis is to contribute to improving water quality by designing a solar water distillations system. The system should be able to supply 20 litres of water per day, which, according to Yme, is approximately the demand for one household.

As the system is meant for local communities in Somalia, the technology should be easy and without modern control system. The system should also be robust, and require low maintenance.

1.3 Objectives

The general objective of the thesis is to design and build a prototype of the solar water distillation system and test that prototype for further improvement. The test should determine the system temperatures during production, the production rate and the quality of the distilled water.

The specific objectives are to optimize the system temperatures and determine the size of the different system parts. Further, to find the cost of the prototype, as well as an alternative budget for any future production. The last specific objective before building the prototype is to make a 3D model of the solar water distillation system.

1.4 Limitations

The most significant limitation for the project is the time limit. The parts for the prototype are therefore ordered based on delivery time rather than cost. All parts are purchased from Norwegian suppliers.

The prototype is built in Norway, and also tested in Norway. The results are therefore not from Somali conditions.

1.5 Method

The system temperatures are optimized in Matlab. A pinch analysis are conducted to find the optimal required heat in the system, and thereby the size of the evaporator, condenser and solar collector. Aspen plus is used to do a simple simulation on the streams in the system, to find the actual system temperatures. A 3D model of the system is made in Solidworks, to determine how to assemble the parts of the system.

The testing of the prototype is conducted in Norway. To simulate the Somali groundwater, salt is added to fresh water when testing the solar water distillation system.

1.6 Thesis Outline

Chapter 2 contains the theory behind the thesis. The main part of this chapter is an overview of the preliminary study conducted before the thesis. Chapter 3 contains the description of method. Matlab optimization, pinch analysis and Aspen plus simulation are described. Additionally, the modelling and testing approach are described. In Chapter 4 the results are presented. The chapter includes the result from the optimization in Matlab, the pinch analysis and the simulation in Aspen plus. Further, it includes the calculation of the evaporator, condenser and solar collector sizes, as well as the determination of the remaining system parts. The system design, system cost and result of the experiment on the prototype are also presented in Chapter 4. Chapter 5 and 6 are the discussion of the results and the conclusion of the thesis. The final Chapter 7 gives suggestions for future work.

2 Theory

This chapter includes the theory behind the thesis. First, an overview is given of the preliminary study the thesis is based on. Then the assumptions behind the calculations are given. Lastly, the requirements for good water quality are described.

2.1 Background

A preliminary study was conducted prior to the master thesis. This section contains an overview of the literature review and results from the preliminary study "Solar Water Distillation Systems for Developing Countries" [1].

2.1.1 Distillation System

There are several different methods for solar distillation, like basin distillation, indirect solar desalination and humidification-dehumidification desalination. The basin distillation is the simplest solar desalination technology. A basin with an inclined glass cover is partly filled with saline water. Solar irradiation evaporates the water in the basin, which rises and condenses as it meets the glass cover. As the glass cover is inclined, the condensed water will run down the glass and be collected as clean water in the bottom of the basin. An example of a basin type distillation system is displayed in Figure 2-1 [2].

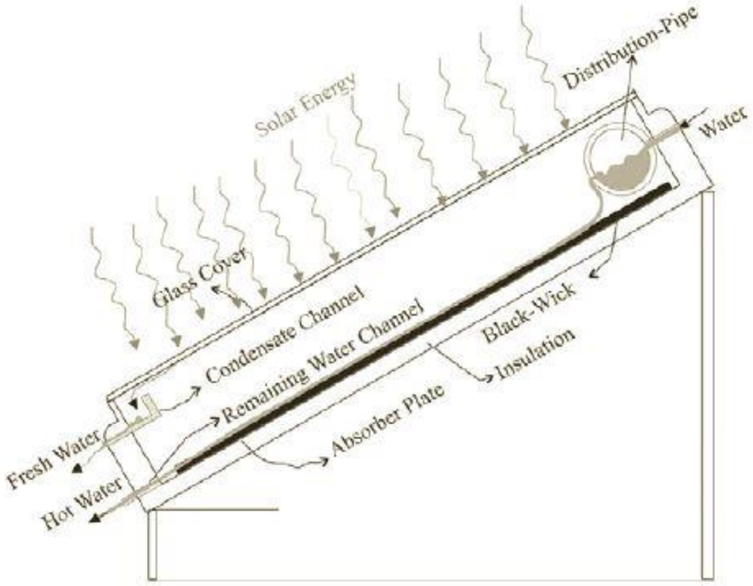


Figure 2-1: An example of a basin type distillation system [2].

Indirect solar desalination includes several methods for desalinating water. Common to them all are that they use a solar collector as the heating source for the saline water, rather than the water being heated directly by the solar irradiation.

Humidification-dehumidification desalination is an indirect solar desalination where dry air is used as working fluid. The dry air is humidified by the evaporated saline water. The humid air transport the clean water vapor to a condenser, where the water is condensed and can be collected as clean drinking water.

Indirect solar desalination is the method used in this project, where a solar collector with a heating fluid is used as the heat source. Additionally to the solar collector, the system consist of two heat exchangers, one that evaporate the saline water and one that condense the steam from the evaporator.

The saline water is stored in a water storage tank before it is preheated in the condenser tankside. The evaporator is connected to a solar collector that works as the heat source. A heating fluid flows in a loop through the solar collector and the evaporator tubeside, where it heats the saline water located in the evaporator tankside. To ensure the flow of the heating fluid, a small pump, supplied by a solar panel, is used. The evaporated water flows from the evaporator and through the tubes in the condenser where the steam condenses. Lastly, the distilled water flows through a remineralization filter before it is collected in a second storage tank. Figure 2-2, overleaf, shows an overview of the system. The figure is a modified version of the original drawing made by Yme.

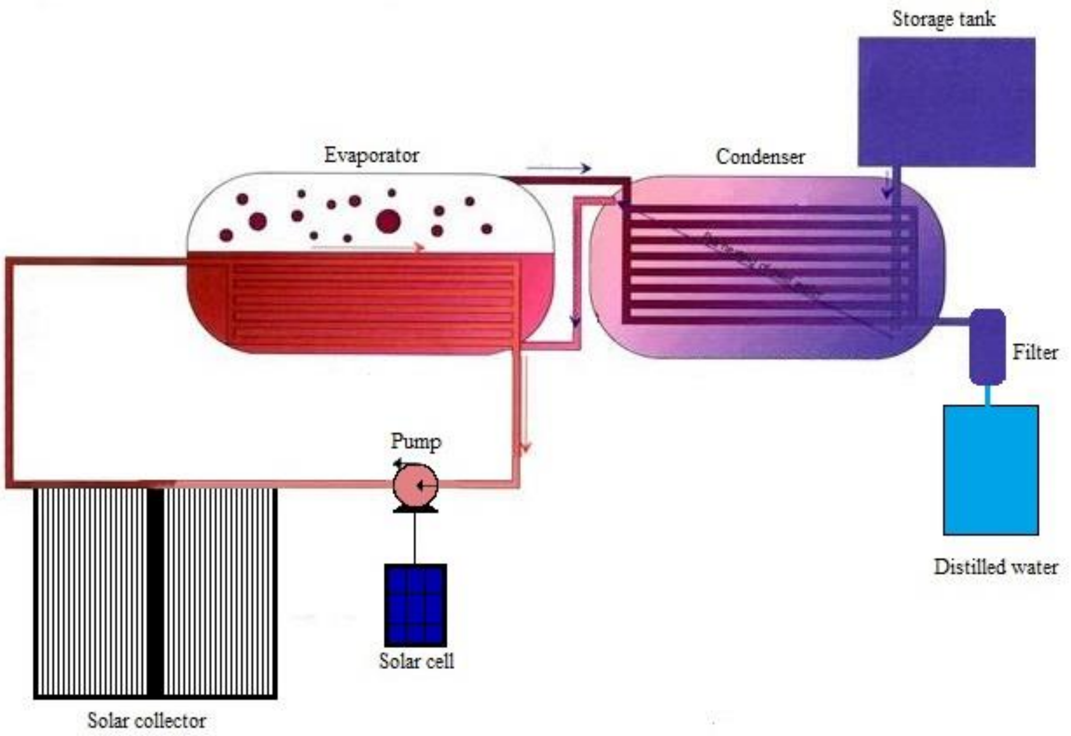


Figure 2-2: A simple overview of the system based on Yme's original design.

2.1.2 Solar Collector

The three main suitable solar collectors for distillation are flat plate, evacuated tube, and parabolic trough solar collector. The flat plate solar collector does not reach high enough temperatures to evaporate the saline water and is therefore not suitable for this project. After reviewing the collectors, the evacuated tube solar collector was considered the best option based on availability, price and temperature range.

2.1.3 Heat Exchangers

Both the evaporator and condenser should be counter-flow heat exchangers, as the counter-flow has a higher effectiveness than parallel-flow heat exchangers. Both will also be shell and tube heat exchangers, as it is the most common and versatile heat exchanger [3]. The condenser will be positioned, so the streams will flow by the force of gravity. The evaporated water will flow into the condenser due to steam pressure.

The heat transfer area was in the preliminary study calculated to be 0.292 m^2 and 0.14 m^2 for the evaporator and condenser, respectively. The size of the shell was calculated to approximately 13x17x132 cm for the evaporator and 13x14x68 cm for the condenser.

2.1.4 Heating fluid

A heating fluid will be used to heat the water in the evaporator tank. After comparing several heat transfer fluids, silicone was decided to be the best alternative as it is non-corrosive, long-lasting and has a high boiling point [1].

It was also decided that a pump will be used to ensure the flow of the heating fluid. To power the pump a small solar panel is to be used. A regular pump has 230 V rated voltage, and a small solar cell typically has a 12 V system voltage. An inverter will, therefore, be used to apply the rated voltage to the pump.

2.1.5 System Temperatures

For analysis and calculations, the temperatures in the system must be known. The temperature of the saline ground water is, according to Yme, 30°C. The steam temperature was set to be 100°C, as water evaporates at this temperature in atmospheric pressure [4]. The remaining temperatures were assumed in the preliminary study. Table 2-1 displays the assumed system temperatures. Where $T_{H,in}$ and $T_{H,out}$ is the temperature of the hot stream in and out of the two heat exchangers. $T_{C,in}$ and $T_{C,out}$ are the cold stream in and out of the two heat exchangers.

Table 2-1: The assumed temperatures in the system [1].

Temperature	**Evaporator**	**Condenser**
$\mathbf{T_{H,in}}$	150°C	100°C
$\mathbf{T_{H,out}}$	80°C	40°C
$\mathbf{T_{C,in}}$	50°C	30°C
$\mathbf{T_{C,out}}$	100°C	50°C

For the evaporator, the hot streams in and out are the heating fluid in and out of the evaporator. The cold streams in and out are the preheated water and the steam, respectively. For the condenser, the hot streams in and out are the steam and the distilled water, respectively. The cold streams in and out are the saline water and the preheated water, respectively.

2.1.6 Water Storage

There will be two storage tanks in the system. One for the saline water before it enters the condenser and one for the produced water after distillation. As the goal is to produce 20 litres of water per day, the storage tank for the distilled water will have to be a 20 litres tank. The storage tank for the saline water will have to be bigger, as the saline water is containing salt and minerals that will not be in the distilled water. The saline water storage tank was set to have 25 litres of volume in the preliminary study.

2.1.7 Water quality

Important aspects of the water quality are content of salt, metals and bacteria. As the water will be distilled, salt and metals will not leave the evaporator tank when the water evaporates. When water boils, all pathogens are killed. Salt, metals and bacteria in the water will therefore not be an issue [1].

The issue with distilled water is the low content of minerals and possible issues with taste and odour. The distilled water will, therefore, be filtered in a remineralization filter before entering the storage tank. The filter will add calcium to the water.

2.2 Assumptions

In the preliminary study, the calculations were based on four hours of operation per day, with average solar irradiation 915.75 W/m^2. The sun irradiates all day, and a longer production time is therefore possible. For the thesis, the production time is assumed eight hours per day. The irradiation is set to 756.67 W/m^2, which is the average irradiation in Somalia between 08.00 – 16.00. The irradiation is calculated from the average daily irradiation in December, as December is a month with medium solar irradiation in Somalia. The solar irradiation information was found in the online solar calculator PVGis [5].

A project funded by the European Union measured the groundwater quality in different areas of Somalia in 2012. They found salinity levels between 160 µS/cm and 11 000 µS/cm, or approximately between 96 mg/l and 6 600 mg/l [6, 7]. 6 600 mg/l will be assumed the salt content in this thesis, as the system should be able to handle the worst case scenario.

2.3 Water Quality Requirements

An important part of testing the system will be on the water quality. As mentioned in Section 2.1.7, the issues with distilled water are low mineral content and possible issues with taste and odour. Besides testing the taste and odour by drinking and smelling the water, the pH value will be tested, as it can affect the taste. The pH value should be between 6.5 and 8.5 [1].

Additionally, the calcium content of the water will be tested, as the remineralization filter will add calcium to the distillate. Due to uncertainties regarding mineral nutrition from drinking water, the World Health Organization does not make recommendations for the minimum content of calcium. Although, they give a taste threshold for the calcium between 100 and 300 mg/l [8]. The National Institute of Public Health in the Czech Republic states in a report that the minimum and optimal values for calcium content in drinking water are 20 mg/l and 40-80 mg/l, respectively [9].

Salt content is not an issue, required the system functions correctly. The water salinity should therefore be tested, to make sure saline water has not entered the condenser tubeside. Salinity is measured by the conductivity of the water. No Somali requirements for salt content in the drinking water were found. According to Norwegian regulations concerning water supply and drinking water, the conductivity of drinking water can not exceed 2500 μS/cm, or 1 500 mg/l [10].

3 Method

This chapter contains an explanation of the methods used to design the solar water distillation system. It includes the methods behind the optimization of the system, the modelling of the system, and finally the testing approach.

3.1 Optimization

The system temperatures is first optimized in Matlab, then the optimized temperatures are used to conduct a pinch analysis. Lastly, a simulation is done on the system temperatures in Aspen plus.

3.1.1 Matlab Optimization

Matlab is a software that uses matrix-based language to express computational mathematics. It is used to analyse and design systems and products, and for solving science and engineering problems [11]. Matlab is used in this project to optimize the system temperatures.

To produce 20 litres of water, with density 1000kg/m^3, during the course of eight hours, the average flow rate of the produced water, the steam and the saline water from the storage tank should be approximately 1/1440 kg/s. The specific heat of water is 4800 J/kg*K. Clearco supplies a silicone heating fluid. It has specific weight 0.95 and specific heat 1.6 kJ/kg*K [12].

From the preliminary study, the volume of the heating fluid is approximately 1.04 litres [1]. Assuming the heating fluid circulates once every five minutes, the flow rate is 0.0012 kg/s.

The objective function is based on the thermal energy balance in the two heat exchangers. The heat transfer rate, or thermal energy per time, is calculated by Equation 1 [13].

$$\dot{Q} = \dot{m} * \Delta T * c_p \qquad \text{Equation 1}$$

Where:

- $\dot{Q}$ = Heat transfer rate [W]
- $\dot{m}$ = Mass flow [kg/s]
- ΔT = Temperature difference between inlet and outlet [K]
- c_p = Specific heat [J/kg*K]

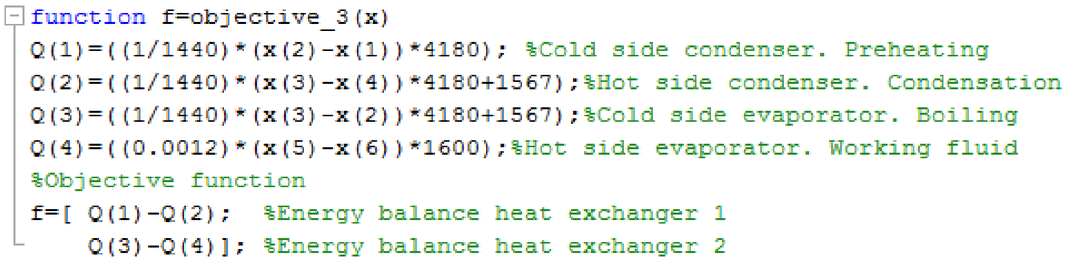
Additional to the thermal heat calculated by Equation 1, the system needs heat to change the phase of the water first from liquid to gas and then back to liquid, also called latent heat. The heat transfer rate of the latent heat can be calculated to 1567 W by Equation 2.

$$\dot{Q} = \dot{m} * L \qquad \text{Equation 2}$$

Where:

- $\dot{Q}$ is the heat transfer rate [W]
- $\dot{m}$ is the mass flow rate [kg/s]
- L is the specific latent heat [kJ/kg] (2257 kJ/kg for water [14])

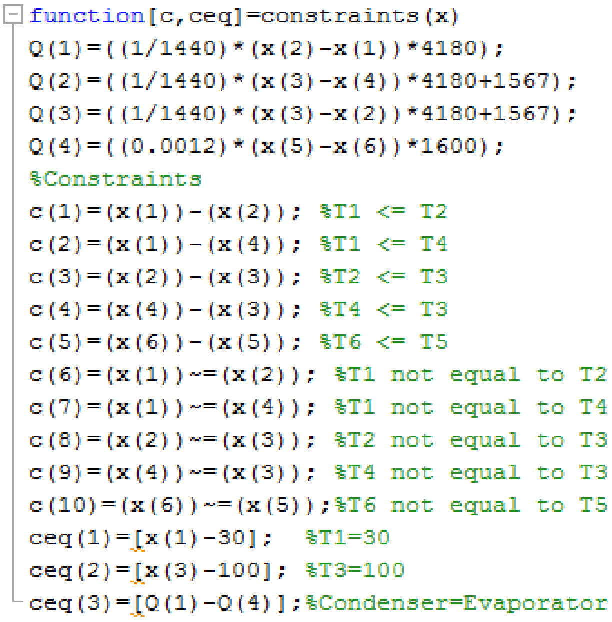
For the optimization, the system is assumed ideal and losses are not included. Figure 3-1 shows the Matlab code for the objective function.



```
function f=objective_3(x)
Q(1)=((1/1440)*(x(2)-x(1))*4180); %Cold side condenser. Preheating
Q(2)=((1/1440)*(x(3)-x(4))*4180+1567);%Hot side condenser. Condensation
Q(3)=((1/1440)*(x(3)-x(2))*4180+1567);%Cold side evaporator. Boiling
Q(4)=((0.0012)*(x(5)-x(6))*1600);%Hot side evaporator. Working fluid
%Objective function
f=[ Q(1)-Q(2);  %Energy balance heat exchanger 1
    Q(3)-Q(4)]; %Energy balance heat exchanger 2
```

Figure 3-1: Objective function for Matlab optimization.

Figure 3-2 shows the Matlab code for the temperature constraints. The different temperatures are described in the following Table 3-1, overleaf.



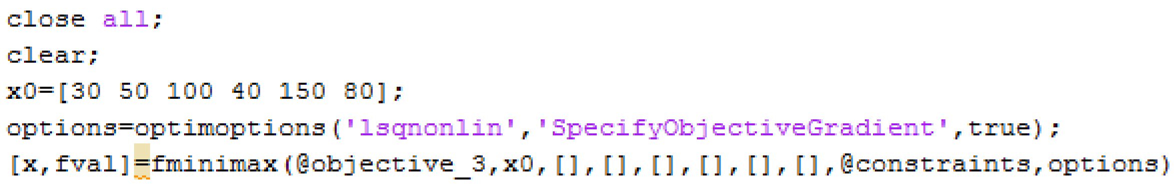
```
function[c,ceq]=constraints(x)
Q(1)=((1/1440)*(x(2)-x(1))*4180);
Q(2)=((1/1440)*(x(3)-x(4))*4180+1567);
Q(3)=((1/1440)*(x(3)-x(2))*4180+1567);
Q(4)=((0.0012)*(x(5)-x(6))*1600);
%Constraints
c(1)=(x(1))-(x(2)); %T1 <= T2
c(2)=(x(1))-(x(4)); %T1 <= T4
c(3)=(x(2))-(x(3)); %T2 <= T3
c(4)=(x(4))-(x(3)); %T4 <= T3
c(5)=(x(6))-(x(5)); %T6 <= T5
c(6)=(x(1))~=(x(2)); %T1 not equal to T2
c(7)=(x(1))~=(x(4)); %T1 not equal to T4
c(8)=(x(2))~=(x(3)); %T2 not equal to T3
c(9)=(x(4))~=(x(3)); %T4 not equal to T3
c(10)=(x(6))~=(x(5));%T6 not equal to T5
ceq(1)=[x(1)-30];  %T1=30
ceq(2)=[x(3)-100]; %T3=100
ceq(3)=[Q(1)-Q(4)];%Condenser=Evaporator
```

Figure 3-2: Constraints for Matlab optimization.

Table 3-1: Description of the temperatures in the optimization.

	Heat exchanger	**Stream**	**Name**
T1	Condenser	Cold in	Raw water
T2	Condenser / Evaporator	Cold out/Cold in	Preheated raw water
T3	Evaporator/Condenser	Cold out/Hot in	Steam
T4	Condenser	Hot out	Distilled water
T5	Evaporator	Hot in	Heating fluid
T6	Evaporator	Hot out	Heating fluid

Figure 3-3 shows the Matlab optimization code. The initial guess of the temperatures are set to the temperature assumptions made in the preliminary study, listed in Table 2.1 in Section 2.1.5.



```
close all;
clear;
x0=[30 50 100 40 150 80];
options=optimoptions('lsqnonlin','SpecifyObjectiveGradient',true);
[x,fval]=fminimax(@objective_3,x0,[],[],[],[],[],[],@constraints,options)
```

Figure 3-3: Matlab optimization code, made by first year master students.

3.1.2 Pinch Analysis

From the optimized temperatures, a pinch analysis is performed to calculate the correct size of the two heat exchangers and the solar collector.

To conduct a pinch analysis, the enthalpy change must be known. The enthalpy change is found as the heat transfer rate calculated by Equation 1 and Equation 2 for thermal and latent heat, shown in Section 3.1.1.

The pinch analysis is conducted in an online tool written by Jeffrey S. Umbach [15]. The analysis is conducted for each the evaporator and condenser to determine the optimal heating area needed in each. It is also conducted for the two heat exchangers combined, to find the minimum heat requirement for the total system. For shell and tube heat exchangers the minimum temperature difference between hot and cold stream is often set between 3-5°C [13]. The minimum temperature difference is, for the thesis, set to 5°C for the three analyses.

From the minimum required heating the heat transfer area of the evaporator and condenser is calculated by Equation 3 [13].

$$A = \frac{\dot{Q}}{U * \Delta Tlm} \qquad \text{Equation 3}$$

Where:

- A is the required heat transfer area [m^2]
- $\dot{Q}$ is the ideal minimum required heating [W]
- U is the overall heat transfer coefficient [W/m^2K]
- ΔT_{lm} is the logarithmic mean temperature difference [K]

The area of the solar collector is calculated by Equation 4.

$$A = \frac{\dot{Q}}{I * \eta} \qquad \text{Equation 4}$$

Where:

- A is the solar collector area [m^2]
- $\dot{Q}$ is the heat transfer rate in the system [W]
- I is the solar irradiation [W/m^2]
- η is the efficiency of the solar collector [-]

3.1.3 Aspen Plus Simulation

A simple model was made in Aspen plus. Aspen plus is a software for design, operation and optimization of chemical processes [16]. The software is used in the thesis to simulate the operation of the solar water distillation system.

The Aspen plus model consists of the two heat exchangers and the streams in the system. In the software, the heat exchangers were designed by the shortcut method, which is a simplified model of a heat exchanger.

The process diagram of the system in Aspen plus is shown in Figure 3-4, overleaf. EVA and COND are the evaporator and condenser, respectively. HINEVA, HOUTEVA, CINEVA and COUTEVA are the hot streams in and out of the evaporator and the cold streams in and out of the evaporator, respectively. Lastly, the CINCOND and COUTCOND are the cold streams in and out of the condenser.

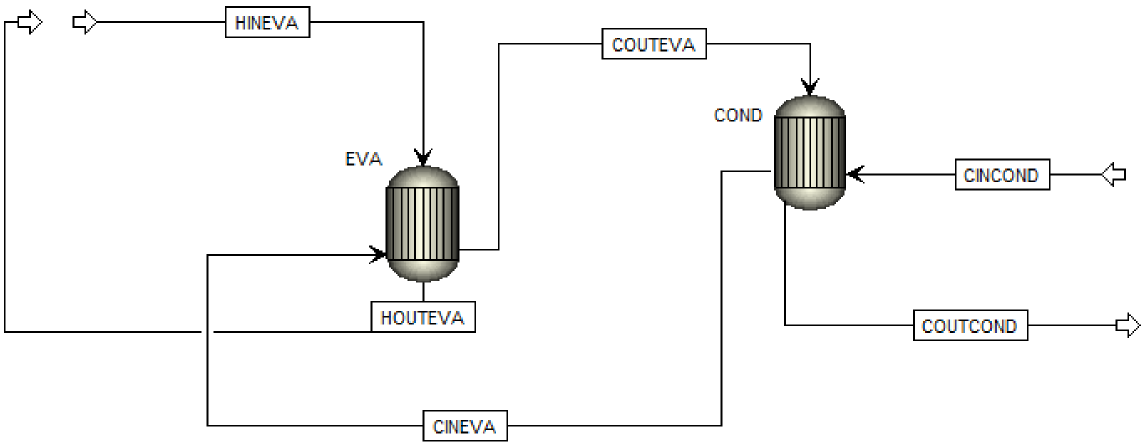


Figure 3-4: The Aspen plus model of the streams in the system.

3.2 Modeling

The prototype is designed as a 3D model before it is fabricated. The design is made in the designing software Solidworks. Additional to the assembling of the parts of the solar water distillation system, salt cleaning and water lever control are important aspects of the design.

3.2.1 Design

The prototype of the solar water distillation system is designed in Solidworks. Solidworks is a complete 3D software tool. It can be used to design, simulate, publish and manage data [17]. For the thesis, the software is used to design the prototype, and determine how to assemble the parts.

The parts in the system is first made separately. The sizes of the parts are determined by the information given by suppliers. All the parts are then assembled, and a rig is designed based on the assembly.

3.2.2 Salt Cleaning

When desalinating water, heat exchanger fouling needs to be considered. Fouling occurs because of unwanted deposits on the heat exchanger surfaces [18]. In this project, the build-up of salt in the evaporator tank is the main reason for fouling.

There are several methods for cleaning heat exchangers. They are divided into two main groups; on-line and off-line cleaning. The groups indicate whether or not the heat exchanger is connected to the stream during cleaning. On-line techniques often use chemicals or mechanical mechanisms, and are therefore not optimal for the prototype, as it should be easy to maintain. The on-line techniques generally need additional equipment that is included in the design [18]. As the heat exchangers in this project will not be custom made, additional equipment will not be implemented in the design.

Off-line cleaning methods can be chemical or mechanical as well, but the group also includes manual cleaning and steam- or hydro-blasting [18, 19]. Blasting means the inside of the heat exchanger is cleaned with pressurized steam or water.

The evaporator used for the prototype is small enough to be disconnected from the system so the salt could be manually poured out. Disconnecting the evaporator would cause the heating fluid to leak out, and should therefore be avoided. Hydro-blasting is a better option for the prototype. The evaporator then only needs to be disconnected from the condenser, and the salt can be flushed out by pressurized water.

3.2.3 Water Level Control

For the distilled water to be clean, it cannot mix with the saline water. It is important to control the water level, and avoid the saline water to rise in the evaporator tankside and mix with the distilled water in the condenser tubeside.

A floating valve is a good option for controlling the water level. The valve would be placed in the evaporator tank inlet, and it would close when the water level is close to the outlet. Figure 3-5 shows a typical floating valve. The valve closes when the ball floats up with the increase in water level.

Figure 3-5: A typical floating valve [20].

Unfortunately, a floating valve is too big to fit in the evaporator tank, due to the tubes inside. In a custom-made evaporator, there could be made room for a floating valve. In the prototype, the water level will be controlled manually by opening and closing a spout on the storage tank with the saline water. The manual control will be approximate, as the water level can not be seen from the outside of the evaporator tank.

3.3 Testing approach

To test the system, it must be fed with saline water. As mentioned in Section 2.2, the Somalian groundwater has a salt content up to 6 600 mg/l. To achieve the correct salinity, salt will be added to freshwater. Approximately 0.13 kg of salt is added to 20 litres of water to obtain 6 600 mg/l salt content.

The testing will be conducted outside in Norwegian conditions. It will be conducted in Birkeland in the beginning of May. The test lasts for eight hours, between the hours of 09.00 and 17.00. As the testing is conducted outside and not in a lab, external conditions are not controlled and are, therefore, registered. External conditions include the solar irradiation, cloudiness and ambient temperature.

The amount of produced water and the water quality will be tested. PH value and calcium content will be measured to find the quality of the water. Salt content will be measured to determine if any saline water has entered the condenser tubeside.

The pH value will be measured by a digital meter from 24shop.no. The pH meter measures pH from 0.0 – 14.0, with 0.1 pH uncertainty [21]. The pH meter is displayed in Figure 3-6.

Figure 3-6: A picture of the pH meter [21].

Test paper strips will measure salt content. The strips measure salt content from 400 ppm to 7000 ppm, or 400 mg/l to 7 000 mg/l [22]. The calcium content will be measured by a titration test, where a reagent is dripped into a sample of the produced water until the colour of the sample changes. The calcium content is found by counting the number of drops needed to change the colour. Each drop translates to 20 mg/l [23].

Further, system temperatures will be measured. The temperature of the hot stream in and out of the evaporator and the cold stream into the evaporator will be measured. The streams contain the preheated water from the condenser, the steam flow, and the heating fluid into the evaporator, respectively.

4 Results

This chapter contains the results of the thesis. The results from the optimization, design and testing are included. The economics of the solar water distillation system are also included in this chapter. Finally, the results from the experiment are presented.

4.1 Optimization

As described in Section 3.1.1, the system temperatures are optimized in Matlab. The result of the optimization is then used in a pinch analysis to find minimum heating and cooling in the system. From the pinch analysis, the sizes of the evaporator, condenser and solar collector are calculated. Finally, a simulation is conducted in Aspen plus to find the actual system temperatures.

4.1.1 Matlab Optimization

In the Matlab optimization, the objective function is based on the thermal energy balance of the two heat exchangers. In the constraints the temperature of the saline water is set to be 30°C, and the temperature of the steam flow is set to be 100°C. Table 4-1 shows the results of the Matlab optimization.

Table 4-1: Results of the Matlab optimization.

	Temperature [°C]
T1	30.00
T2	64.02
T3	100.00
T4	40.00
T5	140.73
T6	89.27

The temperature of the saline water and the steam are 30°C and 100°C, respectively, as set in the constraints. Further, the temperatures of the preheated water, the produced water and the heating fluid in and out of the evaporator have optimized values 64.02°, 40°C, 140.73°C and 89.27°C, respectively.

4.1.2 Pinch Analysis

Table 4-2 and Table 4-3 displays the calculations of the enthalpy change used in the pinch analysis for, respectively, the hot and cold streams of the system. Where H1 and H2 are the heating fluid and the produced water, respectively. C1 and C2 are the saline water from the storage tank and the water in the evaporator, respectively.

Table 4-2: Calculations of enthalpy change for the hot streams in the system.

Hot streams	**Flow rate * Specific heat**	**Supply temperature**	**Target temperature**	**Enthalpy change**
H1	0.0012 kg/s * 1.6 kJ/kg*K	140.73 °C	89.27 °C	98.8 W
H2	1/1440 kg/s * 4.18 kJ/kg*K	100 °C	40 °C	174.2 W
Condensation	1/1440 kg/s * 2257 kJ/kg*	-	-	1567 W

Table 4-3: Calculations of enthalpy change for the cold streams in the system,

Cold streams	**Flow rate * Specific heat**	**Supply temperature**	**Target temperature**	**Enthalpy change**
C1	1/1440 kg/s * 4.18 kJ/kg*K	30 °C	64.02 °C	98.8 W
C2	1/1440 kg/s * 4.18 kJ/kg*K	64.02 °C	100 °C	104.4 W
Evaporation	1/1440 kg/s * 2257 kJ/kg	-	-	1567 W

The evaporator is analysed by inserting stream H1, C2 and evaporation, from Table 4-2 and 4-3, into the online pinch analysis tool. The pinch temperature is 69.02°C, the ideal minimum heating required is 1572.6 W and there is no minimal cooling required. Figure 4-1 and Figure 4-2, overleaf, from the online pinch analysis tool, displays the combined composite curve and the grand composite curve, respectively.

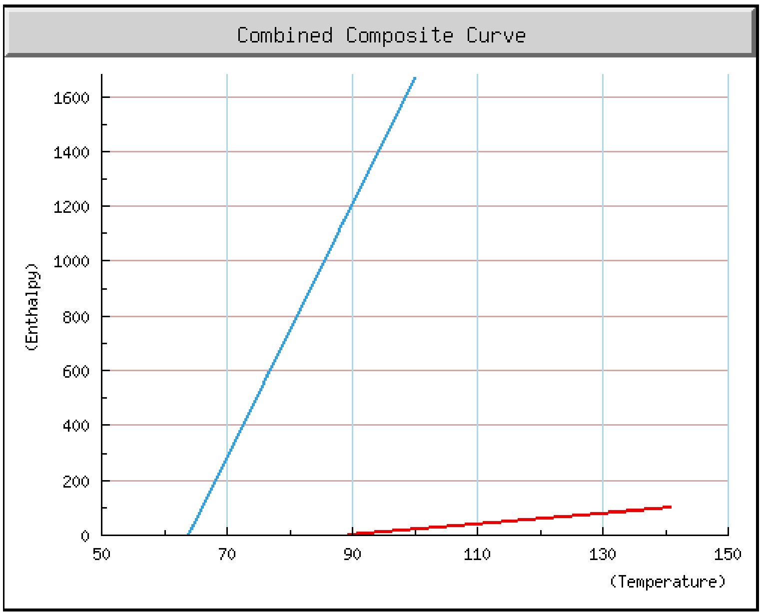


Figure 4-1: The combine composite curve for the evaporator.

The cold stream, blue line, reaches a temperature higher than the pinch temperature, showing that the system requires heating. The hot stream, red line, has an initial temperature higher than the pinch temperature, showing that the system requires no cooling.

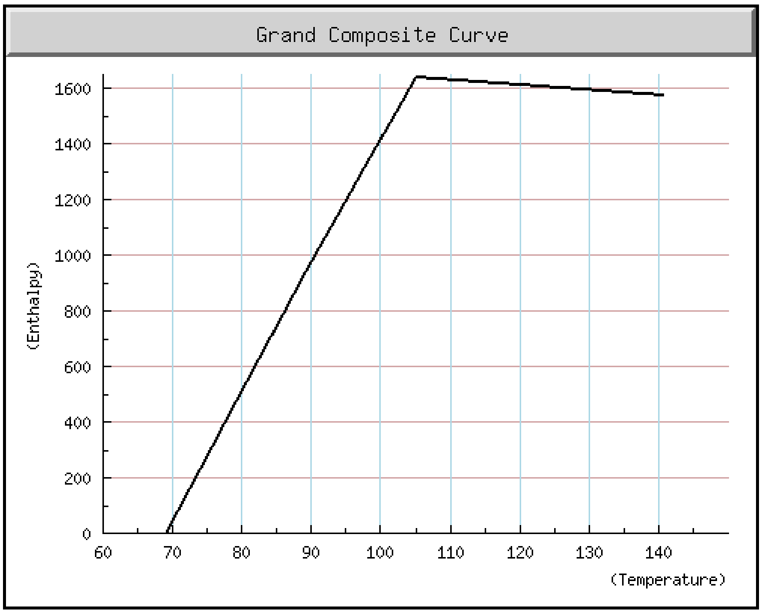


Figure 4-2: Grand composite curve for the evaporator.

The ideal minimum heating of 1572.6 W, is seen in Figure 4-2 as the end point at the highest temperature.

The condenser is analysed by inserting stream H2, C1 and condensation, from Table 4-2 and 4-3, into the online tool. The pinch temperature is 100°C, the ideal minimum cooling required is 1642.4 W and there is no minimal heating required. Figure 4-3 and Figure 4-4 display the combined composite curve and the grand composite curve, respectively.

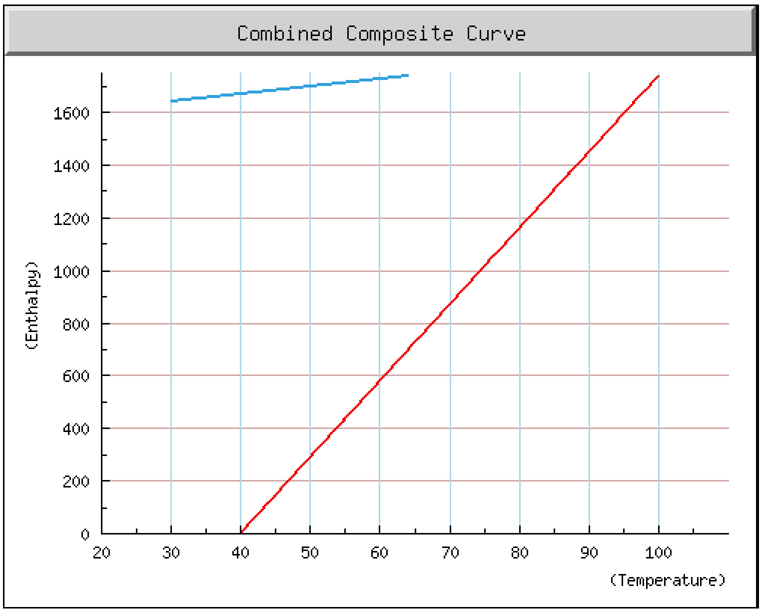


Figure 4-3: Combined composite curve for the condenser.

The cold stream, blue line, increases to a temperature lower than the pinch temperature, showing that the system requires no heating. The hot stream, red line, has an initial temperature lower than the pinch temperature, showing that the system requires cooling.

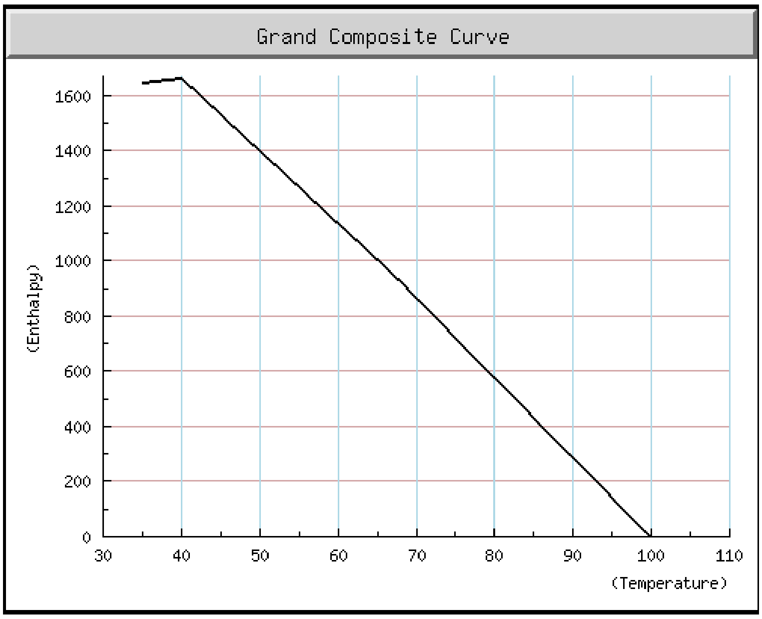


Figure 4-4: Grand composite curve for the condenser.

The ideal minimum cooling of 1642.4 W, is seen in Figure 4-2 as the start point at the lowest temperature.

For the analysis of the system all the streams from Table 4-2 and 4-3 are inserted in the online tool. The analysis gives 69.02°C pinch temperature, 743.36 W ideal minimum cooling and 673.56 W ideal minimum heating. Figure 4-5 and Figure 4-6, overleaf, displays the combined composite curve and the grand composite curve, respectively.

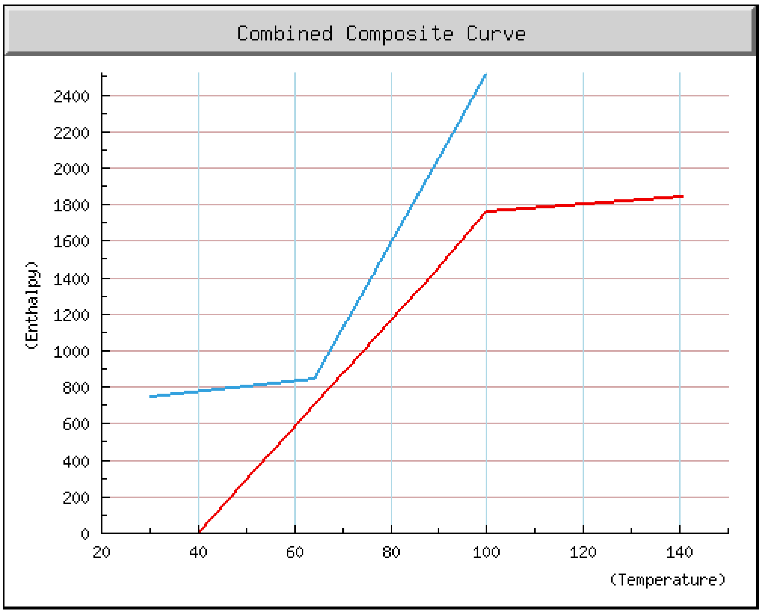


Figure 4-5: Combined composite curve for the system.

The cold stream, blue line, reaches a temperature higher than the pinch temperature, showing that the system requires heating. The hot stream, red line, has an initial temperature lower than the pinch temperature, showing that the system requires cooling.

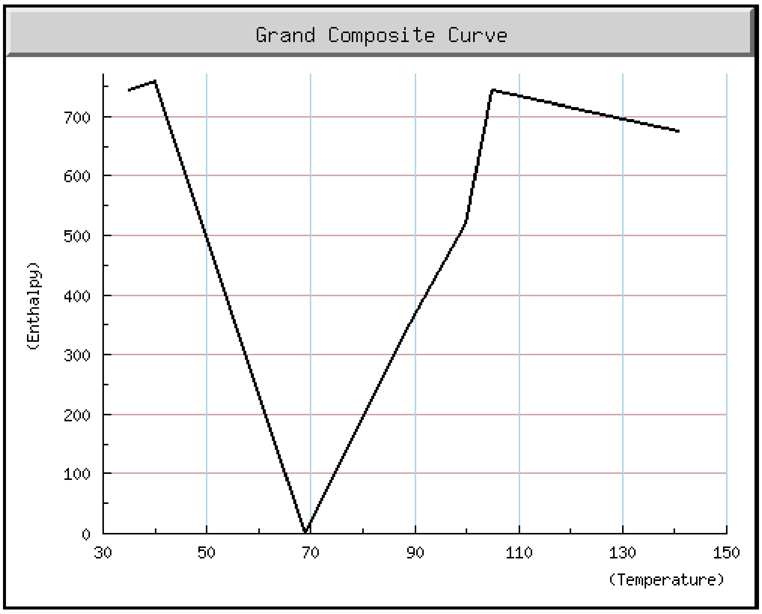


Figure 4-6: Grand composite curve for the system.

The ideal minimum cooling of 743.36 W is shown as the start point at the lowest temperature. The ideal minimum heating of 673.56 W is shown as the end point at the highest temperature.

The required heat transfer for the system was found by adding the minimum heating and cooling found in the pinch analysis, giving a total required heat transfer rate of 1 416.92 W.

4.1.3 Aspen Plus Simulation

The Aspen plus model was used to simulate the temperatures of the system. By inserting the optimized temperatures found in Section 4.1.1, the solution would not converge. The temperature of the hot stream out of the evaporator was changed until a solution converged. It was found that for the model to have a solution, the temperature of the hot stream out of the evaporator had to be 90°C.

The simulation gave a high temperature for the hot stream out of the condenser, which is the distilled water. This temperature was then set to 40°C, which was found in the optimization. The result of this was an increase in temperature for the cold stream into the evaporator, which is the preheated water. The simulation showed the temperature of the preheated water had to be 80°C.

Also, the cold side of the heating fluid increased its temperature. By setting 140°C, as found in the Matlab optimization, as the hot stream into the evaporator, the hot stream out had a temperature of 121°C.

Figure 4-7 shows the result of the Aspen plus simulation, with the system temperatures displayed.

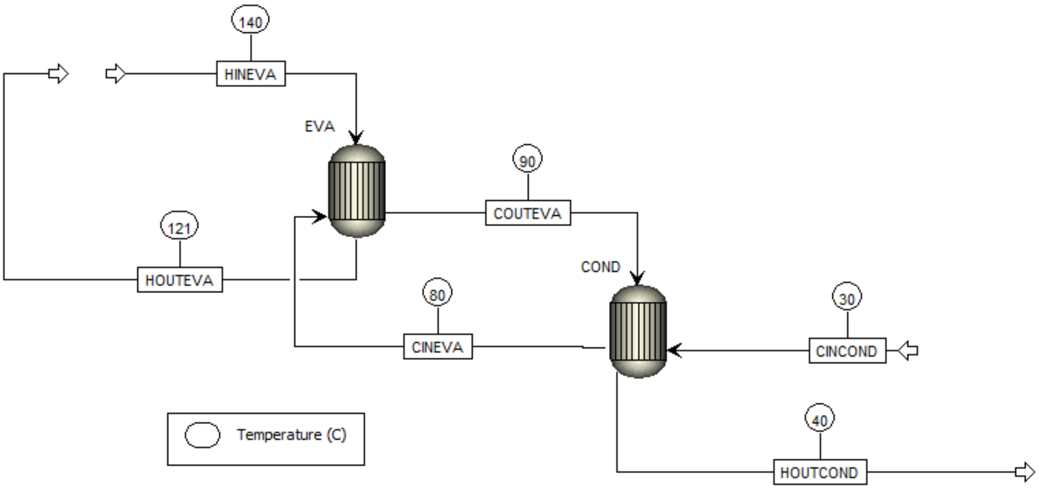


Figure 4-7: The Aspen plus model, with the temperatures of the streams displayed.

4.2 Design

First in the design process, the size of the evaporator, condenser and solar collector are calculated. The specifications of the remaining parts of the system are then determined. Finally, before the building of the prototype, the system is designed by making 3D models of the parts and determine their assembly.

4.2.1 Evaporator and Condenser

Based on assumptions in the preliminary study, the overall heat transfer coefficient of the evaporator is 300 W/m^{2}K and the logarithmic mean temperature difference is 39.15°C [1]. From the pinch analysis on the evaporator and by Equation 3, this gives a heat transfer area for the evaporator of 0.13 m^2, approximately what was calculated for the condenser in the preliminary study.

VidaXL supplies heat exchangers with diameter 13.4 cm and various lengths [24]. Assuming there is a correspondence between heat transfer area and volume, the length would have to be 87.8 cm to have the same volume calculated for the condenser in the preliminary study. The largest heat exchanger from vidaXL is 61.3 cm. As the evaporator was found to be smaller than what was calculated for the condenser in the preliminary study, the 61.3 cm long heat exchanger will be used as the evaporator.

From the minimum required cooling in the pinch analysis on the condenser, Equation 3 is used to calculate the required heat transfer area of the condenser. Based on the assumptions in the preliminary study that the overall heat transfer coefficient is 1000 W/m^{2}K and the logarithmic mean temperature difference is 24.85°C, the required heat transfer area is 0.066 m^2 for the condenser [1]. The area is around half the size of the evaporator. The heat exchanger from vidaXL with length 35.5 cm will be used as the condenser.

4.2.2 Solar Collector

Agder Solenergi supplies solar collectors [25]. From their solar collector data sheet in Appendix A, the efficiency of the collector is found to be 74.4 % for all the collector sizes. As mentioned in Section 2.2, the average irradiation is set to 756.67 W/m^2. The needed solar collector area is then calculated by Equation 4 to be 2.5 m^2. As the tubes in the collector are 1.7 m long and have a diameter of 58 mm, the number of tubes needed is 25.

4.2.3 Pump and Solar Panel

As mentioned in Section 2.1.4, a pump will be used to ensure the flow of the heating fluid. The pump will be connected to the closed loop between the solar collector and the evaporator. As mentioned, the evacuated tubes of the solar collector are 1.7 m long. The maximum height of the solar collector is then 1.7m. By taking into account some additional height for the rig the collector is mounted to, the pump should have a head of at least two metres. The pump will be placed on the outlet side of the evaporator, and should be able to withstand liquid with a temperature of around 120 °C , as found in the Aspen plus simulation for the hot stream out of the evaporator. Grundfos Alpha 2 is a small circulation pump with four meters maximum head, and maximum liquid temperature of 110 °C [26]. This pump is suitable for the prototype. Further pump specifications are listed in Appendix C.

To power the pump, a small solar panel will be used. The pump has 230 V rated voltage, and a maximum current consumption of 0.18 A. The solar panel should, therefore, be able to supply at least 40 W of power. A 55 W solar cell from sparelys.no is chosen for the prototype [27]. The specifications of the solar cell are listed in Appendix D.

The system voltage of the solar cell is 12 V, while the rated voltage of the pump is 230 V. An inverter is needed to operate the pump. To supply the needed power to the pump, the inverter should also be able to supply at least 40 W. Elfadistrelec.no supplies a variety of electrical components. Their smallest inverter for conversion from 12 VDC to 230 VAC has a maximum output power of 110 W, which is sufficient to run the pump [28]. The technical specifications for the inverter are listed in Appendix E.

4.2.4 Heating Fluid, Water Storage and Filter

Additional to the parts described in Section 4.2.1 through Section 4.2.3, the prototype needs heating fluid, water storage tanks and filter. Silicone was preferred as the heating fluid, as it is long-lasting and has a high boiling point [1]. Instead, a glycol heating fluid is purchased, due to it being the only heating fluid available from Norwegian suppliers. Varmeshop.no delivers the glycol based heating fluid Fernox Solar S1 [29]. The specifications of the heating fluid are listed in Appendix F.

Two storage tanks with a volume of 20 litres is purchased. The size is decided based on availability. They are supplied by Biltema, and they are the largest supplied tanks that are suitable for drinking water. The water tanks each have a cap that can be removed to fill water, and a spout with a closing mechanism.

Klart vann AS is a Norwegian supplier of different filter medias. They have a marble called “Juraperle marmor” which is suitable for remineralization of distilled water [30]. It raises the pH of the water and adds calcium. The datasheets for the filter house and the marble, obtained from an e-mail from Klart Vann AS, are listed in Appendix G.

4.2.5 System Design

A 3D model of the system was made in Solidworks. The model was made to determine how to assemble the parts when building the prototype. The solar panel and inverter are not included in the model, as they are not fixed parts, but only needs to be connected to the pump through electrical wires.

The parts were made separately in Solidworks, based on information from the suppliers. The information can be found in Appendices A-G. They were then assembled and connected by pipes. A 2D sketch of the model with dimensions is shown in Appendix H.

Figure 4-8 and 4-9, overleaf, displays the 3D model of the system in two different views. In the first figure, descriptions of the parts are included. The figures display where the components will be placed on the rig, but the mounting is not shown.

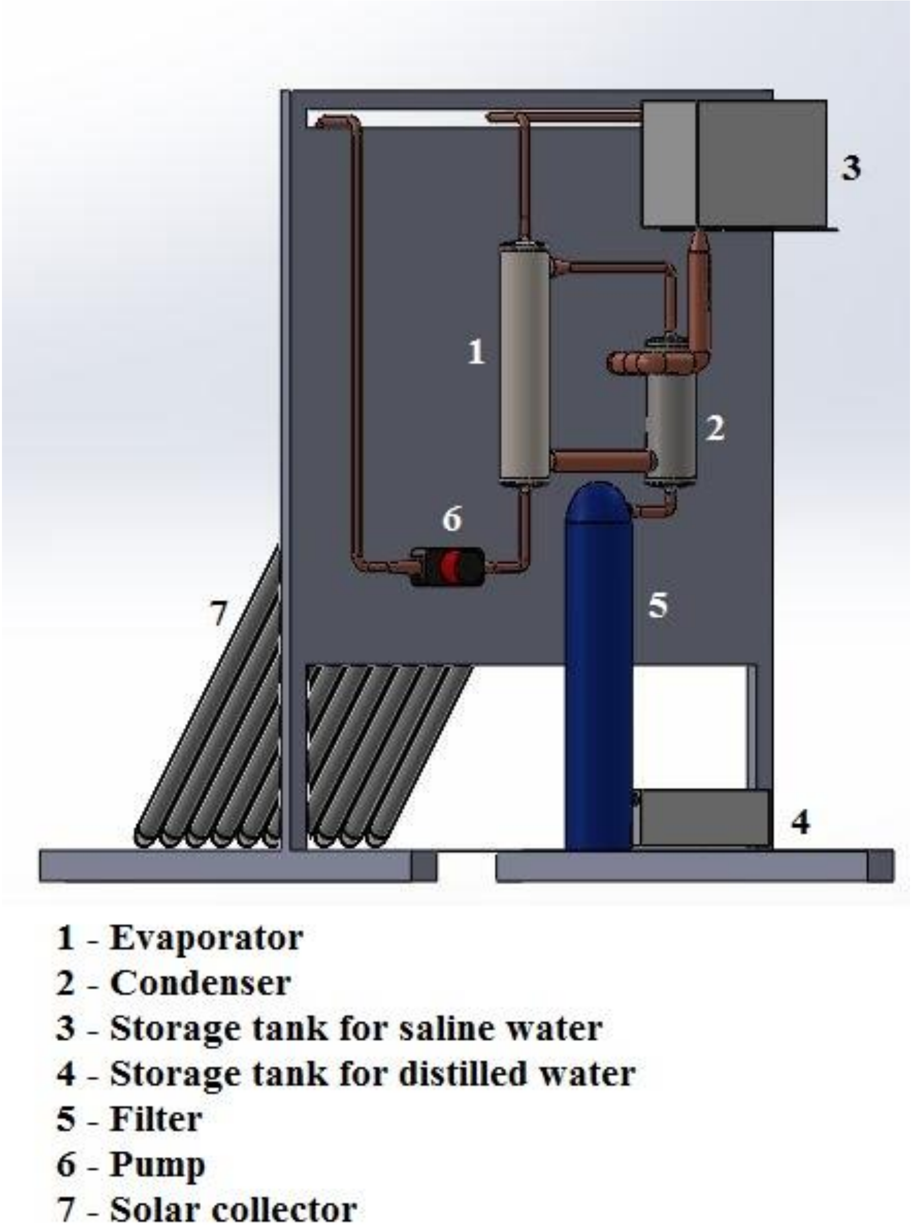


Figure 4-8: 3D model of the system, including descriptions of the parts.

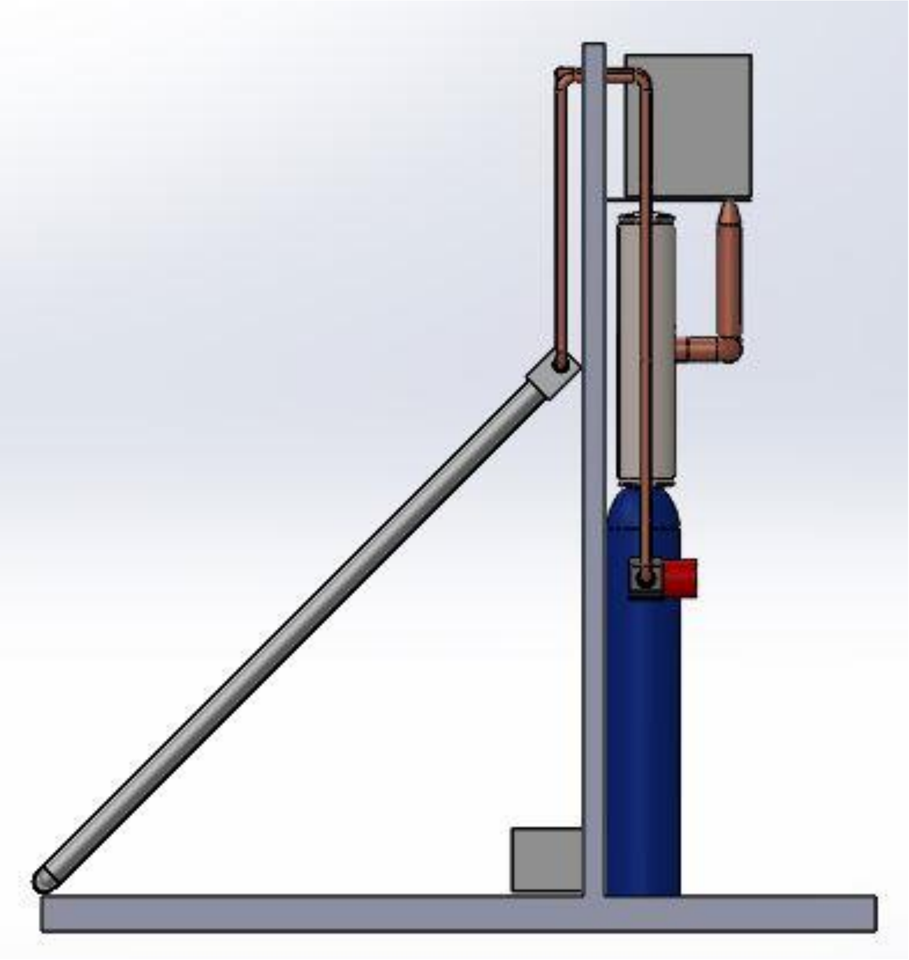


Figure 4-9: 3D model of the system, seen from the side.

As can be seen in the previous figures, the two heat exchangers are vertical. This is so gravity can pull the water down, instead if needing to use pumps. The condenser will have to be parallel flow, to be able to take advantage of the gravitational force.

Figure 4-10 shows the rig with the main dimensions in millimetre. The dimensions of the rig were based on the size of the system after assembly.

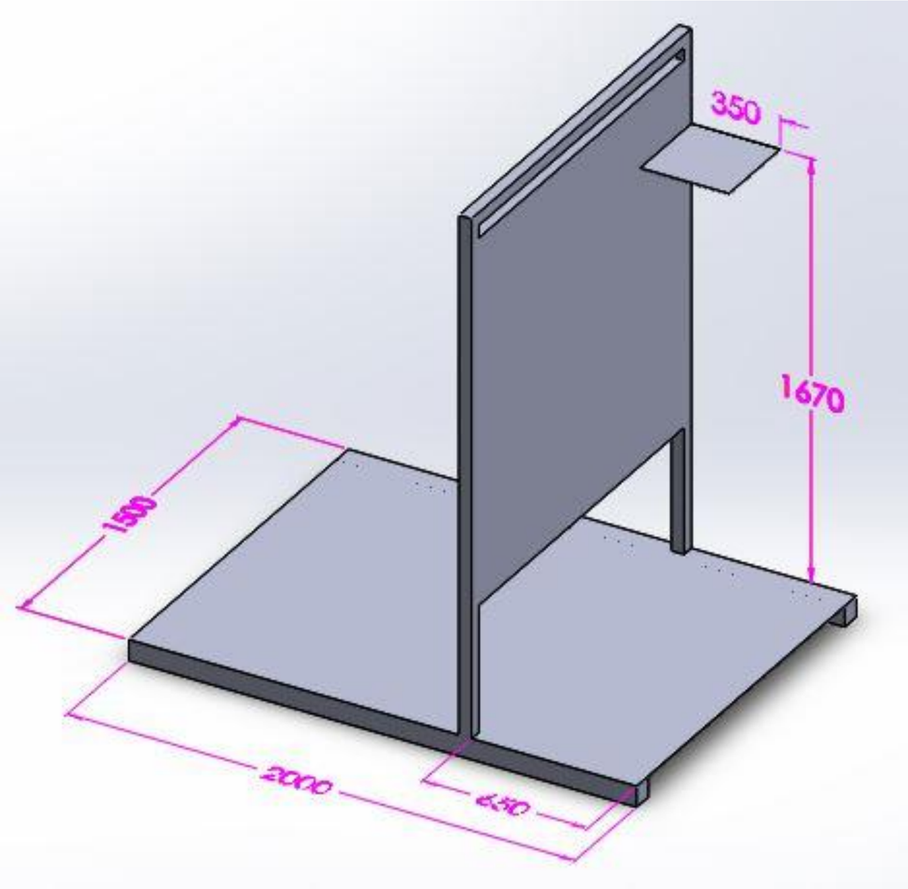


Figure 4-10: 3D model of the rig. With the main dimensions in millimetre.

The design for the two heat exchangers consists of an assembly of three parts, tube bundle, shell and an end piece in each end. The heat exchanger parts are displayed in Figure 4-11, where the tube bundle is on the left, the shell is in the middle and the end piece is on the right side of the figure.

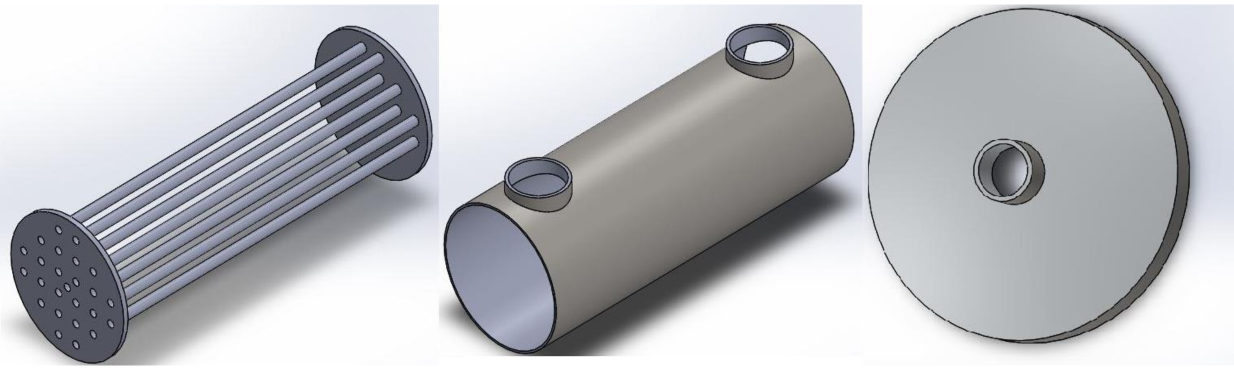


Figure 4-11: The parts of the heat exchanger. Tube bundle on the left, shell in the middle and end piece on the right.

Figure 4-12 shows the evaporator. A cut is made in the figure to display the inside of the evaporator. The condenser is similar, only shorter.

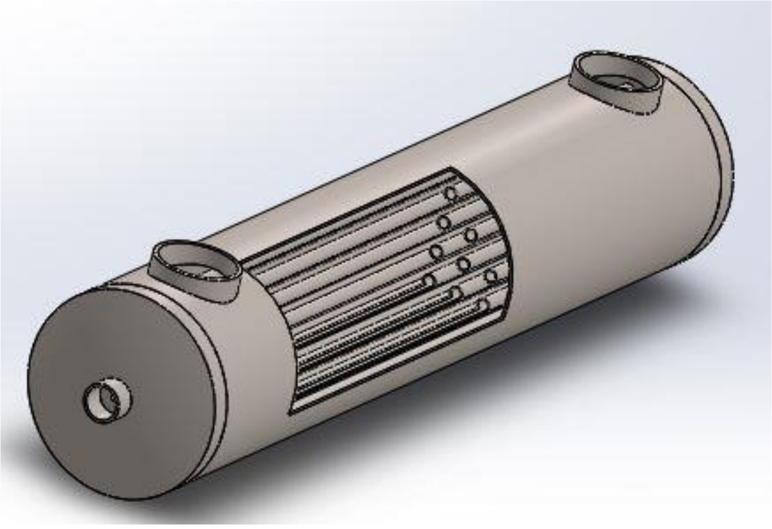


Figure 4-12: 3D model of the evaporator.

The solar collector consists of several evacuated tubes. Figure 4-13 displays the solar collector on the left, and one evacuated tube on the right. The heat pipe is shown sticking out of the top of the tube.

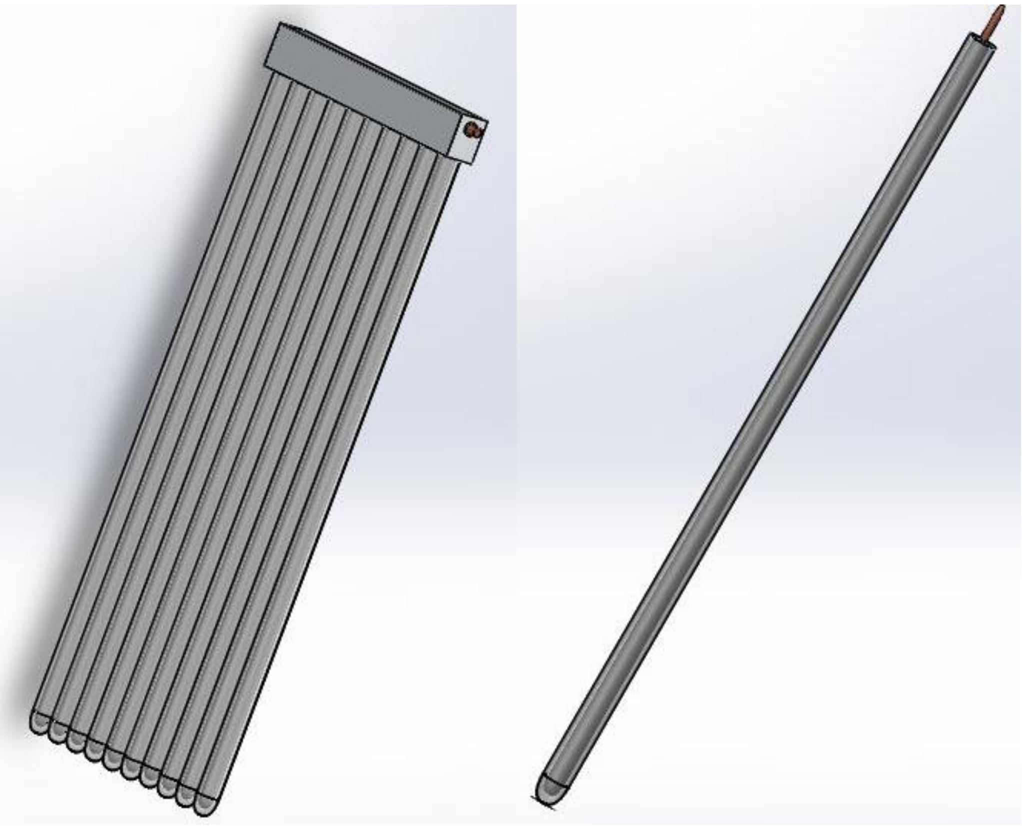


Figure 4-13: The solar collector on the left and a single evacuated tube on the right.

The remaining system parts, the storage tanks, pump and filter, are displayed separately in Appendix I.

4.2.6 Building Process

The rig for the system, described in the previous section, was built by Tratec Koab AS. They based the construction on the sketch in Figure 4-10, and were allowed to make modifications if needed, as they have good knowledge about steel constructions. The modifications they made were adding support beams underneath the rig to make it more stable for transportation. The finished rig is displayed in Figure 4-14.

Figure 4-14: The rig, built by Tratec Koab AS.

Tratec Koab AS also mounted the system components to the rig. After the parts were mounted to the rig, a plumber finished the piping to connect the parts. Figure 4-15 and 4-16 displays the finished system from two sides, ready for testing.

Figure 4-15: The finished system seen from the solar collector side.

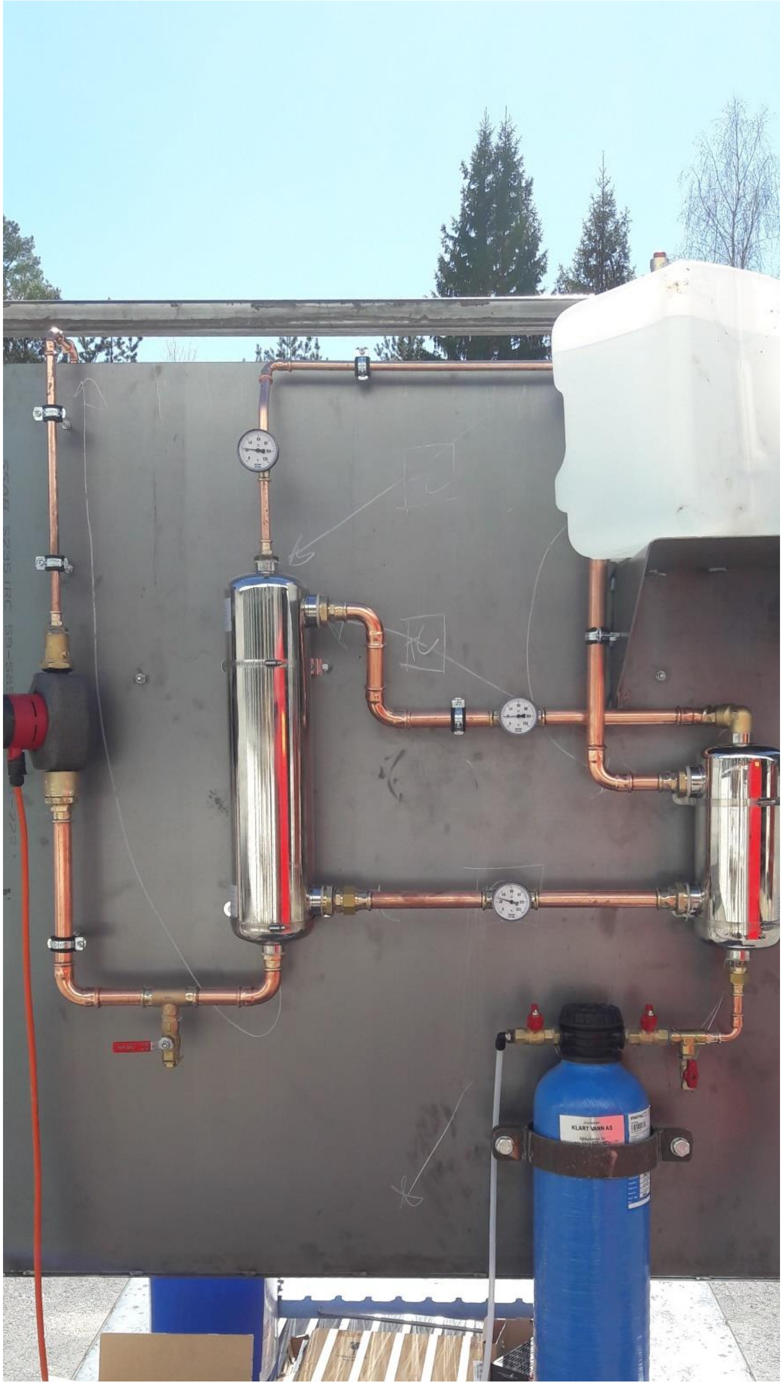


Figure 4-16: The finished system seen from the heat exchanger side.

4.3 Economics

This section includes an overview of the cost of the prototype and an alternative budget for future production.

4.3.1 System Cost

Due to the projects time limitation, the choosing of parts was based mainly on delivery time. Therefore, the size of the parts depend on what is available. They were be purchased with similar properties as calculated but were not custom made to the optimal values. All parts were purchased from Norwegian suppliers, to avoid having the parts held up at customs.

The purchased parts are described in Section 4.2. The purchased solar collector has 10 pipes and not the 25 pipes calculated in Section 4.2.2. This is due to a miscalculation that was not corrected before the tubes were purchased. Additional to the purchased parts, the system includes a rig and piping to connect the parts, as mentioned in Section 4.2.6.

Table 4-4 shows the real cost for the prototype, including the different parts of the system and the supplier of each part.

Table 4-4: Cost of the prototype.

Item	**Supplier**	**Cost**	**Shipping**
Evaporator + Condenser	vidaxl.no [24]	3 390 NOK	-
Solar collector	Agder Solenergi [25]	2 900 NOK	-
Filter	Klart vann AS [30]	5 662 NOK	
Pump	BilligVVS.no [26]	1 899 NOK	149 NOK
Solar cell	Sparelys.no [27]	995 NOK	169 NOK
Inverter	Elfa Distrelec [28]	2 147.5 NOK	-
Heating fluid	Varmeshop.no [29]	995 NOK	210 NOK
Storage tanks	Biltema	298 NOK	-
Piping and plumbing	Rørlegger Roald Lien	14 786 NOK	-
Rig and mounting	Tratec Koab AS	17 500 NOK	-
SUM		**50 572.5 NOK**	

As Table 4-4 shows, the cost of the system parts sums up to 33 072.5 NOK, and the total cost of the system is 50 572.5 NOK.

4.3.2 Alternative Budget

An alternative budget was made for the system parts. In this budget the focus was on the cost of the various parts, as the system cost is an important aspect of any production of the system. The delivery and customs cost is not included in the alternative budget, as the cost is not known for larger orders of several parts.

Table 4-5 displays the alternative budget, to make the system cheaper when time is less of a limit. The parts have similar properties and dimensions as the parts used in the prototype. The price of the piping is based on the amount of piping in the 3D model in Section 4.2.5. The prices were stated in American dollars or British pounds. For easier comparison of the two budgets, the cost is converted to Norwegian kroner. The conversion is made based on the exchange rate given by DNB at 20.04.2017 [31].

Table 4-5: Alternative budget for the production of the system.

Item	**Supplier**	**Cost**
Evaporator + Condenser	Baode heat exchanger www.made-in-china.com	1034 NOK
Solar collector	DIMAN overseas www.dimanoverseas.net	2 016 NOK
Filter	Vitev www.vitev.com	1 284 NOK
Pump	Screwfix www.screwfix.com	1 327 NOK
Solar cell	Hurricane wind power www.hurricanewindpower.com	603 NOK
Inverter	AIMS power www.aimscorp.net	939 NOK
Heating fluid	Clearco www.clearcoproducts.com	733 NOK
Storage tanks	Plastic-mart www.plastic-mart.com	827 NOK
Piping	The home depot www.homedepot.com	832 NOK
SUM		**9 595 NOK**

The alternative budget in Table 4-5 is just a rough estimate, and does not take into account shipping or customs cost. Possible deals regarding large orders for lower price or cost of labour are also not taken into account, neither are materials for and building of the rig, as the cost will vary a lot depending on labour cost. The cost of the prototype sum up to 9 595 NOK in the alternative budget.

The heating fluid is more expensive in the alternative budget than in the budget for the prototype. The reason for this is that in the alternative budget the heating fluid is a silicone fluid, as was decided the best option in the preliminary study [1].

4.4 Experiment

The prototype was taken out of a storage in the morning to test it outside. The ambient temperature in the storage was 11°C. During the testing, the pump was connected to a 230 V power outlet instead of the solar panel. This was to test the functionality of the system, regardless of the solar panels ability to supply the pump. The pump automatically ensured a flow of 1.0 m^3/h for the heating fluid.

4.4.1 External Conditions

As the testing was conducted outside, and not in a lab, external conditions were registered. The cloudiness, ambient temperature, and irradiation are the main external factors that can affect the test results. The irradiation at Birkeland was found in PVGis. Based on the average daily irradiation in the month of May, the average irradiation for the eight hours of testing was 543 W/m^2 [5]. Table 4-6, overleaf, shows the external conditions during the test. The measurements were obtained hourly.

Table 4-6: The external conditions during the test.

	Cloudiness	**Ambient Temperature [°C]**
09:00	Clear sky	7.9
10:00	Clear sky	9.2
11:00	Clear sky	10.5
12:00	Clear sky	11.4
13:00	Partly cloudy	10.4
14:00	Cloudy	10.1
15:00	Cloudy	10.1
16:00	Cloudy	9.7
17:00	Cloudy	9.6

The ambient temperature was at its highest at noon, before it decreased as the sky became cloudy, as shown in Table 4-6.

4.4.2 System Temperatures

The temperature was measured at three points in the system. It was measured at the cold stream in and out of the evaporator and the hot stream into the evaporator. Meaning the pipe with the preheated water from the condenser to the evaporator, the steam outlet of the evaporator and the inlet of the evaporator where the heating fluid enters were the measured streams. Figure 4-17 displays the thermometer measuring the temperature of the heating fluid as it enters the evaporator.

Figure 4-17: The thermometer measuring the temperature of the heating fluid.

The temperature was measured once every 20 minutes during testing. Table 4-7, overleaf, shows the temperature measured at the different points in the system.

Table 4-7: The measurements of the system temperatures.

	Preheated flow [°C]	**Steam flow [°C]**	**Heating fluid [°C]**
09:00	11	11	11
09:20	12	11	12
09:40	12	11	13
10:00	18	12	30
10:20	24	12	40
10:40	32	13.5	48.5
11:00	37	15	52.5
11:20	42	16	56
11:40	45	16.5	59
12:00	48	17	59.5
12:20	49.5	18	62
12:40	51	18.5	64
13:00	52	19	64
13:20	53	20	65
13:40	54	20	67
14:00	52	17	64
14:20	54	18	66
14:40	55	18	67.5
15:00	55	17.5	66
15:20	52	16	62
15:40	49	15	57
16:00	44	13	50
16:20	37	11	40
16:40	30	10.5	34
17:00	30	10	32

Table 4-7 shows that the all measured system temperatures were equal to the ambient temperature of the storage space, at the beginning of testing. The highest temperature of the three measurement point was 55°C, 20°C and 67.5°C for the preheated water flow, steam flow and heating fluid, respectively. All three temperatures were lower than what was found in the simulation in Section 4.1.3. The temperature measurements are shown graphically in Figure 4-18.

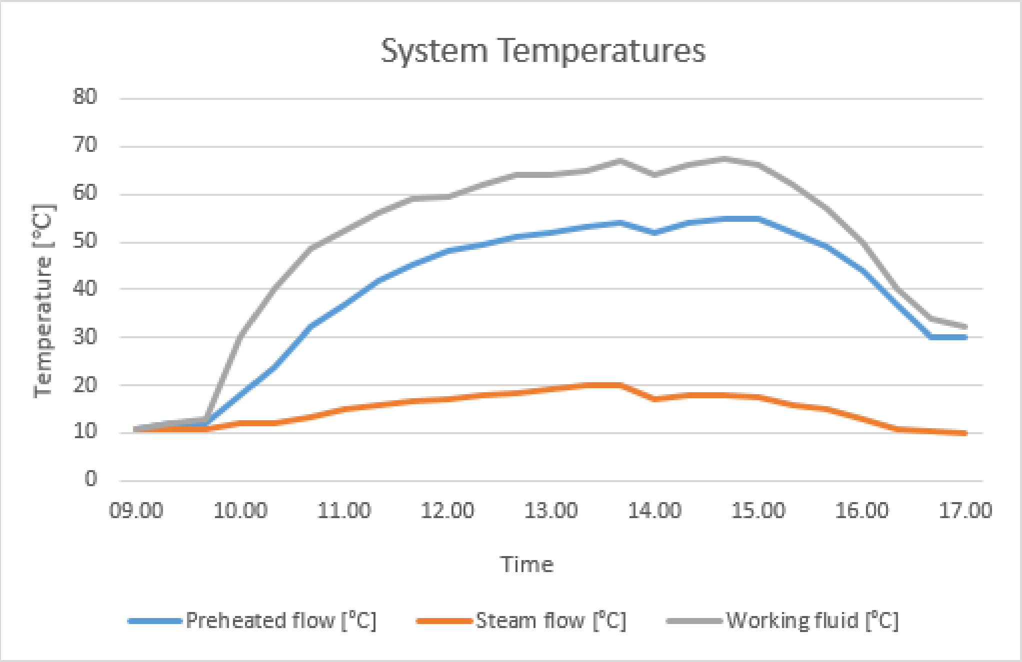


Figure 4-18: The system temperatures displayed graphically.

As shown in Figure 4-18, the temperatures rapidly increased from the start of the testing until noon. The temperature increase was slower after noon until 15:00 when the temperature started to decrease rapidly.

4.4.3 Heat Transfer

As mentioned in Section 2.2, the solar irradiation in Somalia and Norway is 756.67 W/m^2 and 543.0 W/m^2, respectively. Meaning the irradiation is 1.39 times higher in Somalia in December than in Norway in May when the testing was conducted.

Equation 1, from Section 3.1, calculates the heat transfer from the solar collector to the heating fluid. From the heating fluid data sheet in Appendix F, the density and specific heat capacity of the fluid is 1.035 kg/l and 3.65 kJ/kg*K, respectively. As mentioned the pump ensured a flow of 1 m^3/h, meaning the mass flow of the heating fluid was 0.29 kg/s.

By not taking into account the time with a decrease in temperature, the thermal heat transfer rate while heating the heating fluid from 11°C to 66°C was 58.21 kW. As the irradiation is 1.39 times higher in Somalia, the heat transfer for the same amount of time should be 1.39 times higher. The heat transfer rate in Somali conditions is therefore assumed to be 80.76 kW.

By rearranging Equation 1, the increase in temperature is calculated to be 76.3°C in Somali conditions.

The ambient temperature in Somalia is higher than in Norway. It can, therefore, be assumed the initial temperature of the heating fluid would be higher in Somali conditions. In the month of December, the average minimum temperature is 23°C in the south of Somalia [32]. Assuming the initial temperature of the heating fluid is equal to the ambient temperature, the fluid should reach a temperature of 99.3°C. Which may be sufficient for the evaporation to start in the evaporator.

5 Discussion

The main goal of the thesis was to design and fabricate a solar water distillation system to help better the health situation in Somalia, where they have a shortage of clean drinking water. The system was tested at Birkeland in Norway in the beginning of May. Only one test was conducted. The results from the experiment showed that the system was not able to produce any distilled water.

The heating fluid reached 67.5 °C as the highest temperature before it started decreasing. This temperature was not high enough to evaporate the saline water in the evaporator tank. The system was, therefore, not able to produce any distilled water, and no test on water quality was conducted.

5.1 Optimization

Some of the temperatures in the Aspen plus simulation were different from what was found in the Matlab optimization. The simulations mainly show that the temperature of the steam will start to decrease in the pipe between the evaporator and condenser, and that the preheated water needed to have a higher temperature than found in the optimization.

5.2 Design

As the parts of the system were not custom made, salt cleaning and water level control were not implemented in the system. This did not pose problems during testing, as the system did not manage to distillate the water. As described in Section 3.2.2, the salt cleaning could be done manually by hydro-blasting. This was not tested in the system, as there was no need to clean the salt when there was no evaporation.

The system was designed with the two heat exchanger in vertical position, for the water flow to take advantage of the gravitational force. The vertical position of the evaporator could affect the heat transfer from the heating fluid. As the water level in the evaporator had to be controlled to avoid the saline water flowing into the condenser tubeside, part of the evaporator tubes with the heating fluid was not in contact with the saline water.

As mentioned in Section 4.3, a solar collector with fewer tubes was purchased, than the number of tubes found in the optimization in Section 3.2.3. This could contribute to the low temperature of the heating fluid, by not absorbing enough heat from the solar irradiation.

5.3 Experiment

The heating fluid reached a temperature of 67.5°C, which is less than half of the optimized temperature found in the Matlab optimization and the Aspen plus simulation. The preheated water had an optimized temperature of 64.02°C. The temperature in the Aspen plus simulation was 80°C for the preheated water. In the testing, the preheated water only reached 55°C. As there was no evaporation, the raw water was preheated by the heating fluid, and not the condensing steam. The heat was transferred by the heating fluid, to the saline water in the evaporator tank and back through the pipe to the condenser tank.

The temperature of the cold stream out of the evaporator reached much lower temperatures than the other measured temperatures, with 20°C as the highest temperature. The temperature also started decreasing earlier than the two other temperatures. As the system did not evaporate the saline water, the stream did not contain steam. The system was standing outside in the sun, and the increase in temperature could due to air in the pipe being heated by the surroundings. As the temperature in the pipe was higher than the ambient temperature, the increase could also be due to heat radiation from the saline water in the evaporator tank.

The external conditions seem to have a great impact on the performance of the system. The temperature increased until the sky was clouded, the temperatures than decreased. The ambient temperature during testing was low compared to the temperature of the heating fluid. The lack of insulation around the pipes and heat exchangers may have contributed to a large heat loss to the surroundings, leading to the system not being able to reach the temperature for evaporation.

Also, the low initial temperature of the heating fluid could have contributed to the system not being able to distillate the saline water. The system was not able to heat the fluid enough before the sky was clouded, it might have been able to with a higher initial temperature.

Some challenges occurred during the project that could have had an impact on the results. The fabrication of the system took longer than expected and contributed to allowing less time for testing, and not allowing time for modifications. With only one testing day, it was not conducted tests with various external conditions. Higher ambient temperature and less clouds could have given a different result.

As shown by the calculations in Section 5.3, the system might reach high enough temperatures to distillate the water with the Somali irradiation, compared to the irradiation in Norway. The system might also reach high enough temperatures in the Norwegian irradiation, with different weather conditions, as mentioned.

6 Conclusion

Somalia is experiencing a shortage of potable drinking water due to a high salt content in the country's ground water. The humanitarian organization Yme wanted to build an effective water distillation system to improve the water quality and better the health situation in Somalia. Yme is a big contributor for providing clean and safe drinking water for local communities.

The goal of this thesis was to design and fabricate a prototype of a solar water distillation system. The system should consist of simple technology and require low maintenance. Renewable energy in the form of solar energy is highly available in Somalia, the distilling system, therefore, used solar energy as heat source.

The prototype was tested at Birkeland in Norway in the beginning of May. System temperatures were measured, and the external conditions were registered. The measured temperatures were of the cold stream in and out of the evaporator and the hot stream into the evaporator, meaning the preheated water, steam flow and heating fluid. The external conditions registered was solar irradiation, cloudiness and ambient temperature.

The temperatures in the system increased during testing, but the prototype did not produce any distilled water. The system did not reach high enough temperatures to evaporate the saline water, it was, therefore, no production of water.

There are several possible reasons for the systems inability to distillate the saline water, as discussed in Chapter 9. The external conditions seems to have the greatest impact, especially the cloudiness. Further testing needs to be conducted on the prototype to determine its ability to distillate saline water. By modifying it, better results can be obtained in the future.

With some modifications and more testing in more suitable conditions, the implications of this thesis could be a better health situation for areas struggling with a shortage of clean drinking water. This system could potentially be used all over the world in areas with high solar irradiation.

7 Future Work

Future work should include modification of the system, then further testing. The system should be tested in various external conditions to determine the required conditions for the water production to start. It should also be tested to find the amount of produced water for different conditions. Suggestions for modifications are listed below.

- Increase the number of solar collector tubes.
- Insulating the piping and heat exchangers.
- Perform tests in conditions more similar to the climate in Somalia.

Further testing should also be conducted on the system with the pump connected to the solar panel, to find the panels ability to supply the needed power to the pump.

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Appendices

Appendix A – Heat exchangers

Evaporator details

Detaljer

- Materiale: SS304 rustfritt stål
- Størrelse:355 x 134 mm(L x Φ)
- Effekt: 40 kW
- Basseng tilkoblingsdiameter: G1 1/2 " (1.27cm)
- Varmeren tilkoblingsdiameter: G1 " (2.54cm)
- Antall rør: 25
- Tilkobling på samme side
- Merk: vidaXL
- SKU: 90868
- EAN: 8718475918240

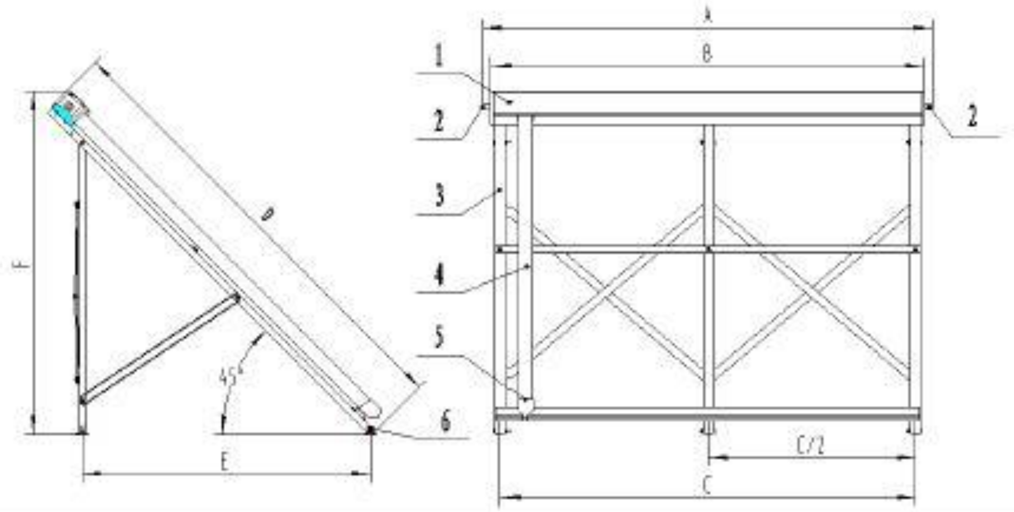
Condenser details:

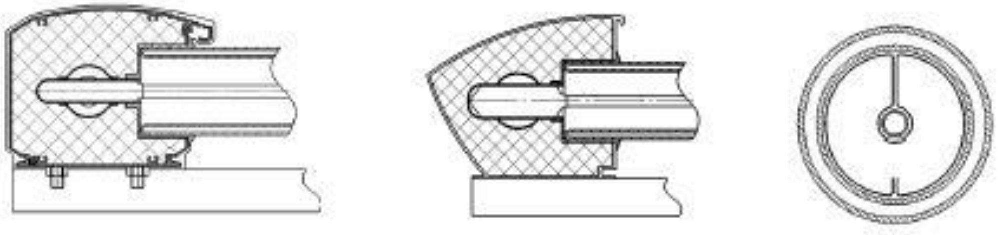
Detaljer

- Materiale: SS304 rustfritt stål
- Størrelse:613 x 134 mm(L x Φ)
- Effekt: 75 kW
- Basseng tilkoblingsdiameter: G1 1/2 " (1.27cm)
- Varmeren tilkoblingsdiameter: G1 " (2.54cm)
- Antall rør: 25
- Tilkobling på samme side
- Merk: vidaXL
- SKU: 90870
- EAN: 8718475918264

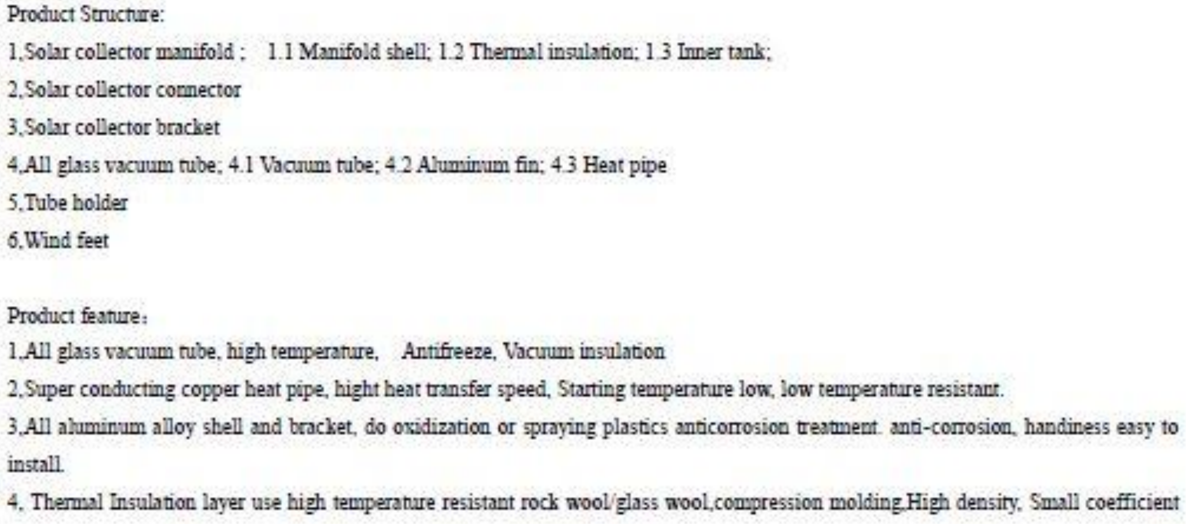
Appendix B – Solar collector

SC-H-10~30




SC-H-10~30

SC-H1-10~30


Product Structure:

1,Solar collector manifold ; 1.1 Manifold shell; 1.2 Thermal insulation; 1.3 Inner tank;

2,Solar collector connector

3,Solar collector bracket

4,All glass vacuum tube; 4.1 Vacuum tube; 4.2 Aluminum fin; 4.3 Heat pipe

5,Tube holder

6,Wind feet

Product feature：

1,All glass vacuum tube, high temperature, Antifreeze, Vacuum insulation

2,Super conducting copper heat pipe, hight heat transfer speed, Starting temperature low, low temperature resistant.

3,All aluminum alloy shell and bracket, do oxidization or spraying plastics anticorrosion treatment. anti-corrosion, handiness easy to install.

4, Thermal Insulation layer use high temperature resistant rock wool/glass wool,compression molding,High density, Small coefficient of thermal conductivity

5,Inner tank use Proof Pressure, anticorrosive ,High purity high quality brass processed, Can withstand pressure 1 Mpa

6,The gravity heat pipe one-way heat transfer, collector efficiency high, Small heat loss

7, Through Europe's authoritative testing institutions test, and get SOLARKEYMARK SOLARKEYMARK

8,All kinds of collectors, Can design to meet customer demand, integrated structure , Flat roof and pitched roof all can be installed, transportation, easy installation

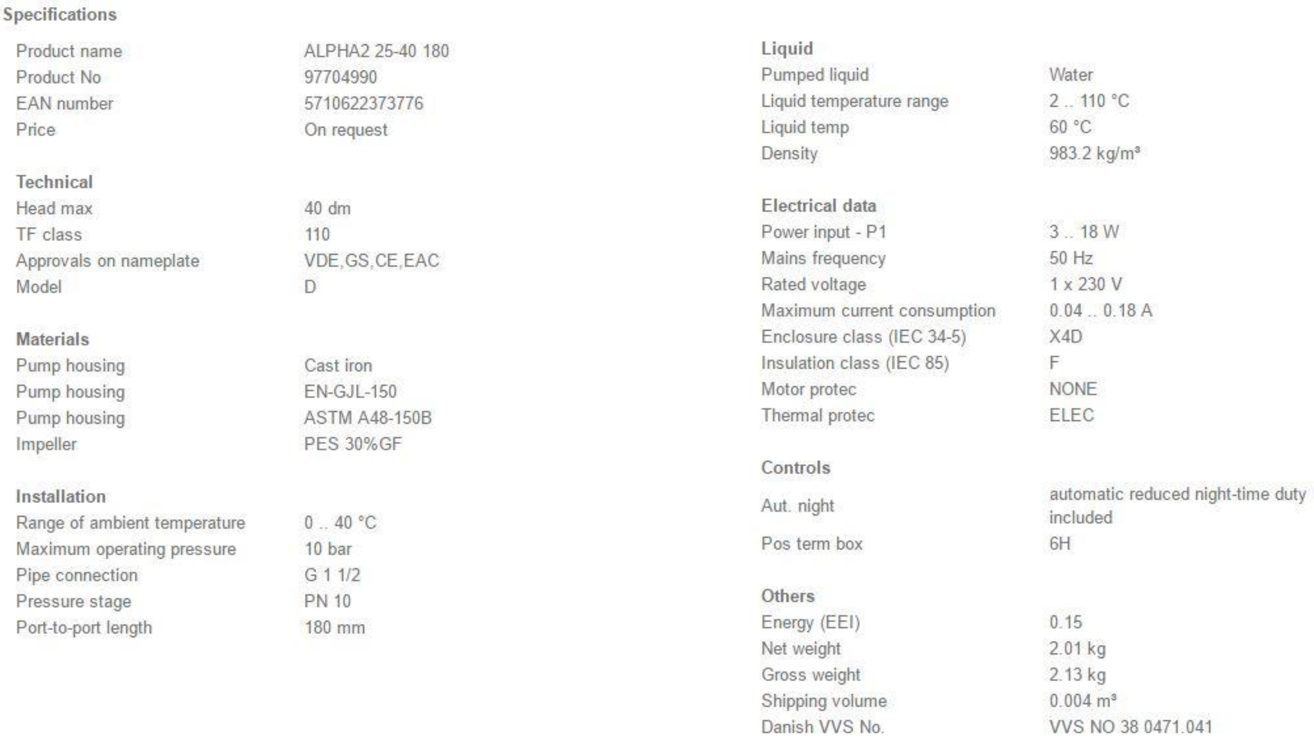
Product's Technical Parameters ：

Model	SC-H-10	SC-H-15	SC-H-18	SC-H-20	SC-H-24	SC-H-25	SC-H-30
Vacuum tube quantity(pcs)	10	15	18	20	24	25	30
Tube spacing （mm）	75	75	75	75	75	75	75
Vacuum tube diameter/length （mm）	φ58/1700	φ58/1700	φ58/1700	φ58/1700	φ58/1700	φ58/1700	φ58/1700
Vacuum tube material	high borosilicate glass 3.3	high borosilicate glass 3.3	high borosilicate glass 3.3	high borosilicate glass 3.3	high borosilicate glass 3.3	high borosilicate glass 3.3	high borosilicate glass 3.3
Vacuum tube inner/outer pipe wall thickness （mm）	1.6/1.8	1.6/1.8	1.6/1.8	1.6/1.8	1.6/1.8	1.6/1.8	1.6/1.8
Heat pipe condensing end diameter/length （mm）	φ14/1750	φ14/1750	φ14/1750	φ14/1750	φ14/1750	φ14/1750	φ14/1750
heat pipe material/wall thickness （mm）	Copper tp2/0.6	Copper tp2/0.6	Copper tp2/0.6	Copper tp2/0.6	Copper tp2/0.6	Copper tp2/0.6	Copper tp2/0.6
inner tank diameter/wall thickness （mm）	φ35/1.0	φ35/1.0	φ35/1.0	φ35/1.0	φ35/1.0	φ35/1.0	φ35/1.0
connector size	φ22 or 3/4"	φ22or 3/4"	φ22or 3/4"	φ22or 3/4"	φ22or 3/4"	φ22or 3/4"	φ22or 3/4"
collector insulation material/thickness （mm）	Rock wool/40	Rock wool/40	Rock wool/40	Rock wool/40	Rock wool/40	Rock wool/40	Rock wool/40
solar collector rated pressure （MPa）	0.6	0.6	0.6	0.6	0.6	0.6	0.6
collector operating temperature ℃	＜100	＜100	＜100	＜100	＜100	＜100	＜100
collector volume （L）	0.69	0.98	1.15	1.27	1.50	1.56	1.85
collector aperture area （㎡）	1.0	1.5	1.8	2.0	2.4	2.5	3.0
collector total area （㎡）	1.56	2.30	2.74	3.04	3.63	3.77	4.51
referral traffic （L/min）	0.75	1.13	1.35	1.50	1.81	1.88	2.26
intensity pressure （Pa）	23.2	59.2	90.6	116.7	181.7	200.2	314.0
intercept efficient η0	0.744	0.744	0.744	0.744	0.744	0.744	0.744
heat loss coefficient a	2.09	2.09	2.09	2.09	2.09	2.09	2.09
collector power （W） 1000W/㎡ irradiation	620	870	1047	1165	1401	1457	1748

a (mm)	895	1270	1495	1645	1945	2020	1395
b (mm)	800	1175	1400	1550	1850	1925	2300
c (mm)	725	1100	1325	1475	1775	1850	2225

c/2 (mm)	——	——	——	——	887.5	925	1112.5
d (mm)	1980	1980	1980	1980	1980	1980	1980
e (mm)	1240	1240	1240	1240	1240	1240	1240
f (mm)	1470	1470	1470	1470	1470	1470	1470
packing size （mm）							

Appendix C - Pump



Specifications

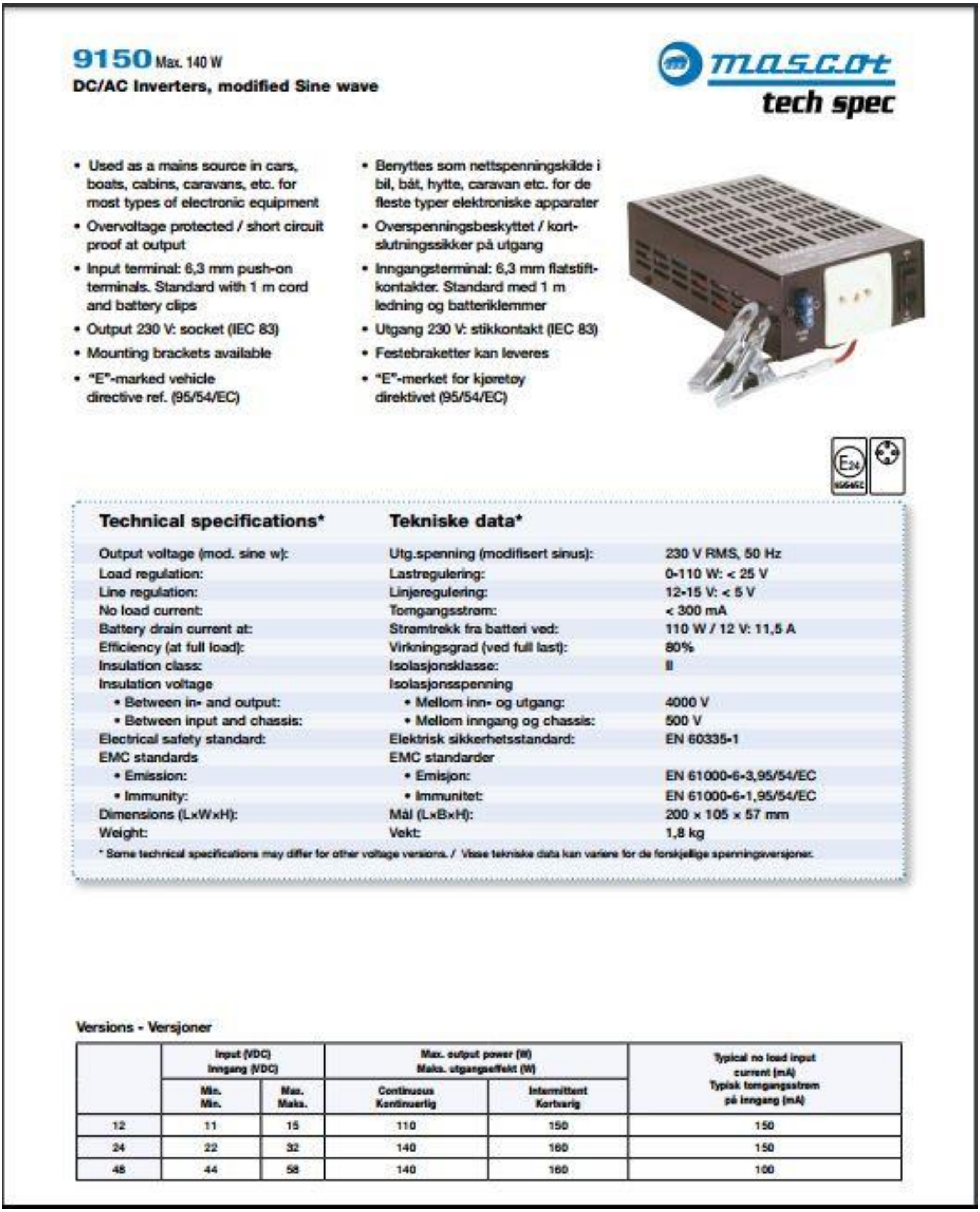
Product name	ALPHA2 25-40 180
Product No	97704990
EAN number	5710622373776
Price	On request
Technical	
Head max	40 dm
TF class	110
Approvals on nameplate	VDE,GS,CE,EAC
Model	D
Materials	
Pump housing	Cast iron
Pump housing	EN-GJL-150
Pump housing	ASTM A48-150B
Impeller	PES 30%GF
Installation	
Range of ambient temperature	0 .. 40 °C
Maximum operating pressure	10 bar
Pipe connection	G 1 1/2
Pressure stage	PN 10
Port-to-port length	180 mm

Liquid	
Pumped liquid	Water
Liquid temperature range	2 .. 110 °C
Liquid temp	60 °C
Density	983.2 kg/m^3
Electrical data	
Power input - P1	3 .. 18 W
Mains frequency	50 Hz
Rated voltage	1 x 230 V
Maximum current consumption	0.04 .. 0.18 A
Enclosure class (IEC 34-5)	X4D
Insulation class (IEC 85)	F
Motor protec	NONE
Thermal protec	ELEC
Controls	
Aut. night	automatic reduced night-time duty included
Pos term box	6H
Others	
Energy (EEI)	0.15
Net weight	2.01 kg
Gross weight	2.13 kg
Shipping volume	0.004 m^3
Danish VVS No.	VVS NO 38 0471.041

Appendix D – Solar Panel

- Nominell effekt: 55 Watt
- Effekttolleranse: +/- 3%
- Systemspenning: 12 Volt
- Maks ladestrøm: ca 2,9 A
- Kortsluttningsstrøm: ca 3,2 A
- Spenning ved åpen krets: ca 22,5 Volt
- Spenning ved maks effet: ca 19,0 Volt
- Lengde: ca 67,0 cm
- Bredde: ca 54,0 cm
- Tykkelse: ca 3,5 cm
- Vekt: ca 5,0 kg

Appendix E – Inverter



9150 Max. 140 W

DC/AC Inverters, modified Sine wave

- Used as a mains source in cars, boats, cabins, caravans, etc. for most types of electronic equipment
- Overvoltage protected / short circuit proof at output
- Input terminal: 6,3 mm push-on terminals. Standard with 1 m cord and battery clips
- Output 230 V: socket (IEC 83)
- Mounting brackets available
- "E"-marked vehicle directive ref. (95/54/EC)

- Benyttes som nettspenningskilde i bil, båt, hytte, caravan etc. for de fleste typer elektroniske apparater
- Overspenningsbeskyttet / kortslutningssikker på utgang
- Inngangsterminal: 6,3 mm flatstiftkontakter. Standard med 1 m ledning og batteriklemmer
- Utgang 230 V: stikkontakt (IEC 83)
- Festebraketter kan leveres
- "E"-merket for kjøretøy direktivet (95/54/EC)

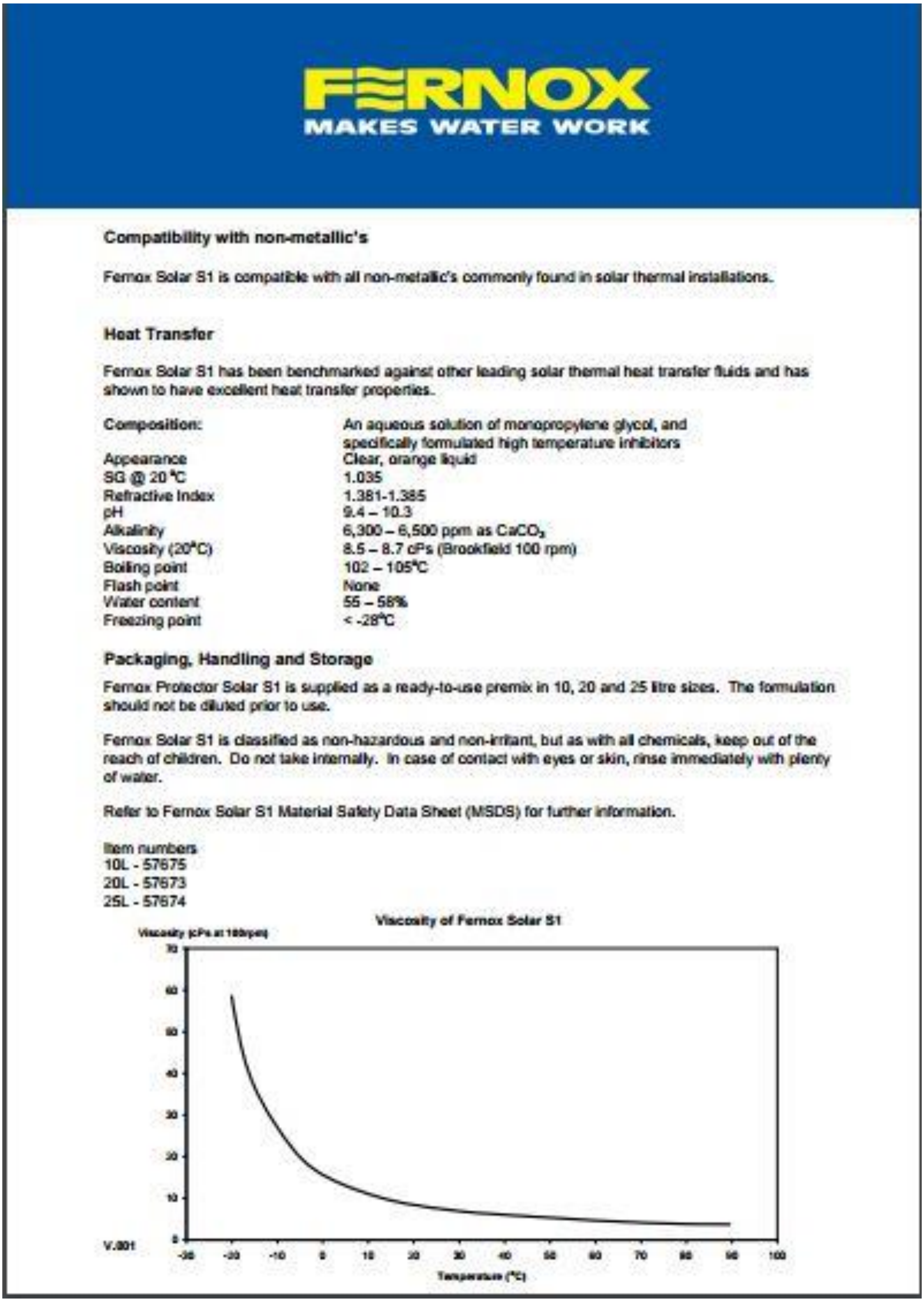
Technical specifications*	**Tekniske data***	
Output voltage (mod. sine w):	Utg.spenning (modifisert sinus):	230 V RMS, 50 Hz
Load regulation:	Lastregulering:	0-110 W: < 25 V
Line regulation:	Linjeregulering:	12-15 V: < 5 V
No load current:	Tomgangsstrøm:	< 300 mA
Battery drain current at:	Strømtrekk fra batteri ved:	110 W / 12 V: 11,5 A
Efficiency (at full load):	Virkningsgrad (ved full last):	80%
Insulation class:	Isolasjonsklasse:	II
Insulation voltage	Isolasjonsspenning	
• Between in- and output:	• Mellom inn- og utgang:	4000 V
• Between input and chassis:	• Mellom inngang og chassis:	500 V
Electrical safety standard:	Elektrisk sikkerhetsstandard:	EN 60335-1
EMC standards	EMC standarder	
• Emission:	• Emisjon:	EN 61000-6-3,95/54/EC
• Immunity:	• Immunitet:	EN 61000-6-1,95/54/EC
Dimensions (L×W×H):	Mål (L×B×H):	200 × 105 × 57 mm
Weight:	Vekt:	1,8 kg

* Some technical specifications may differ for other voltage versions. / Visse tekniske data kan variere for de forskjellige spenningsversjoner.

Versions - Versjoner

	Input (VDC) Inngang (VDC)		Max. output power (W) Maks. utgangseffekt (W)		Typical no load input current (mA) Typisk tomgangsstrøm på inngang (mA)
	Min. Min.	Max. Maks.	Continuous Kontinuerlig	Intermittent Kortvarig	
12	11	15	110	150	150
24	22	32	140	160	150
48	44	58	140	160	100

Appendix F – Heating fluid



FERNOX
MAKES WATER WORK

Compatibility with non-metallic's

Fernox Solar S1 is compatible with all non-metallic's commonly found in solar thermal installations.

Heat Transfer

Fernox Solar S1 has been benchmarked against other leading solar thermal heat transfer fluids and has shown to have excellent heat transfer properties.

Composition:	An aqueous solution of monopropylene glycol, and specifically formulated high temperature inhibitors
Appearance	Clear, orange liquid
SG @ 20 °C	1.035
Refractive Index	1.381-1.385
pH	9.4 – 10.3
Alkalinity	6,300 – 6,500 ppm as $CaCO_3$
Viscosity (20°C)	8.5 – 8.7 cPs (Brookfield 100 rpm)
Boiling point	102 – 105°C
Flash point	None
Water content	55 – 58%
Freezing point	< -28°C

Packaging, Handling and Storage

Fernox Protector Solar S1 is supplied as a ready-to-use premix in 10, 20 and 25 litre sizes. The formulation should not be diluted prior to use.

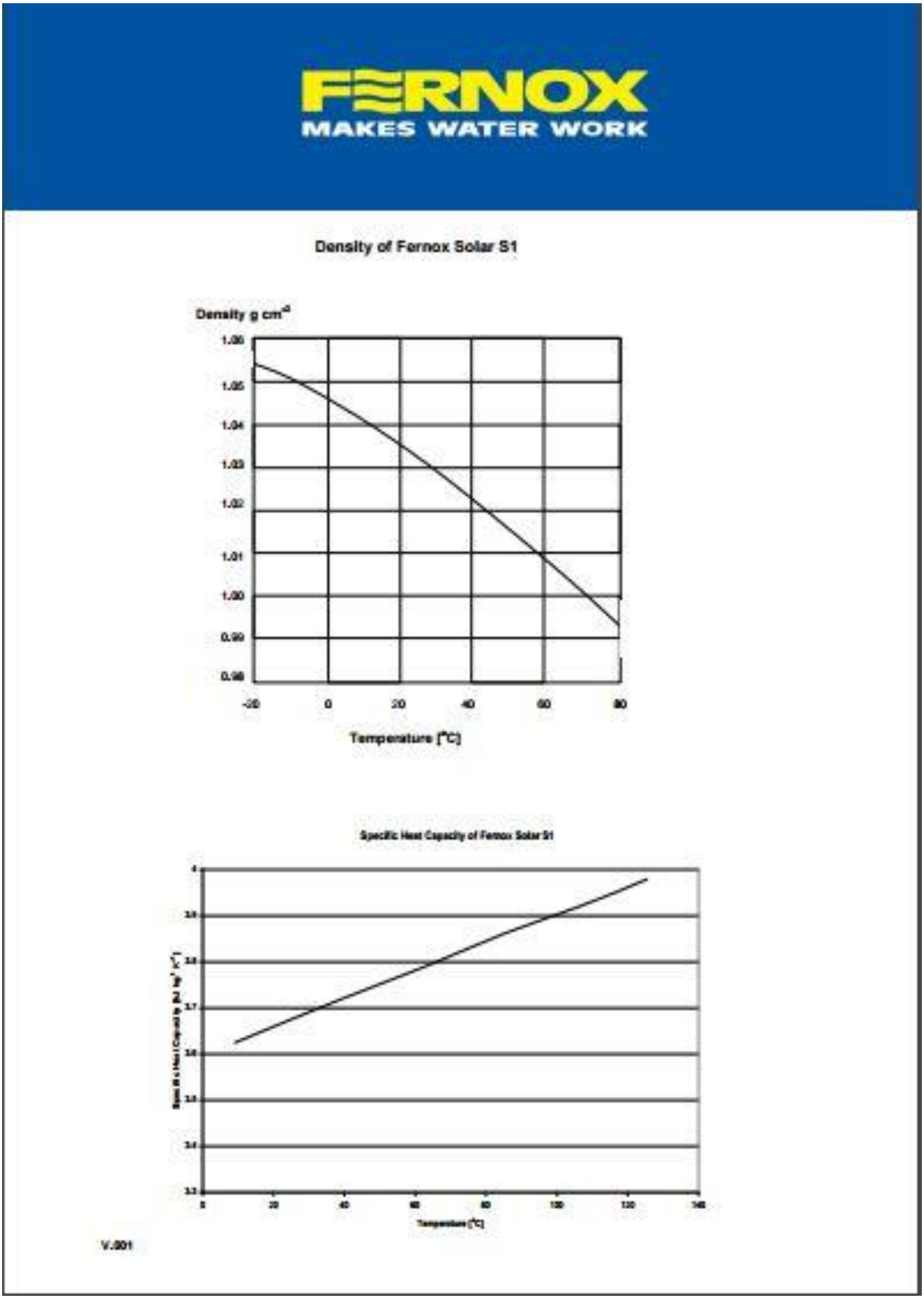
Fernox Solar S1 is classified as non-hazardous and non-irritant, but as with all chemicals, keep out of the reach of children. Do not take internally. In case of contact with eyes or skin, rinse immediately with plenty of water.

Refer to Fernox Solar S1 Material Safety Data Sheet (MSDS) for further information.

Item numbers
10L - 57675
20L - 57673
25L - 57674

Viscosity of Fernox Solar S1

V.001



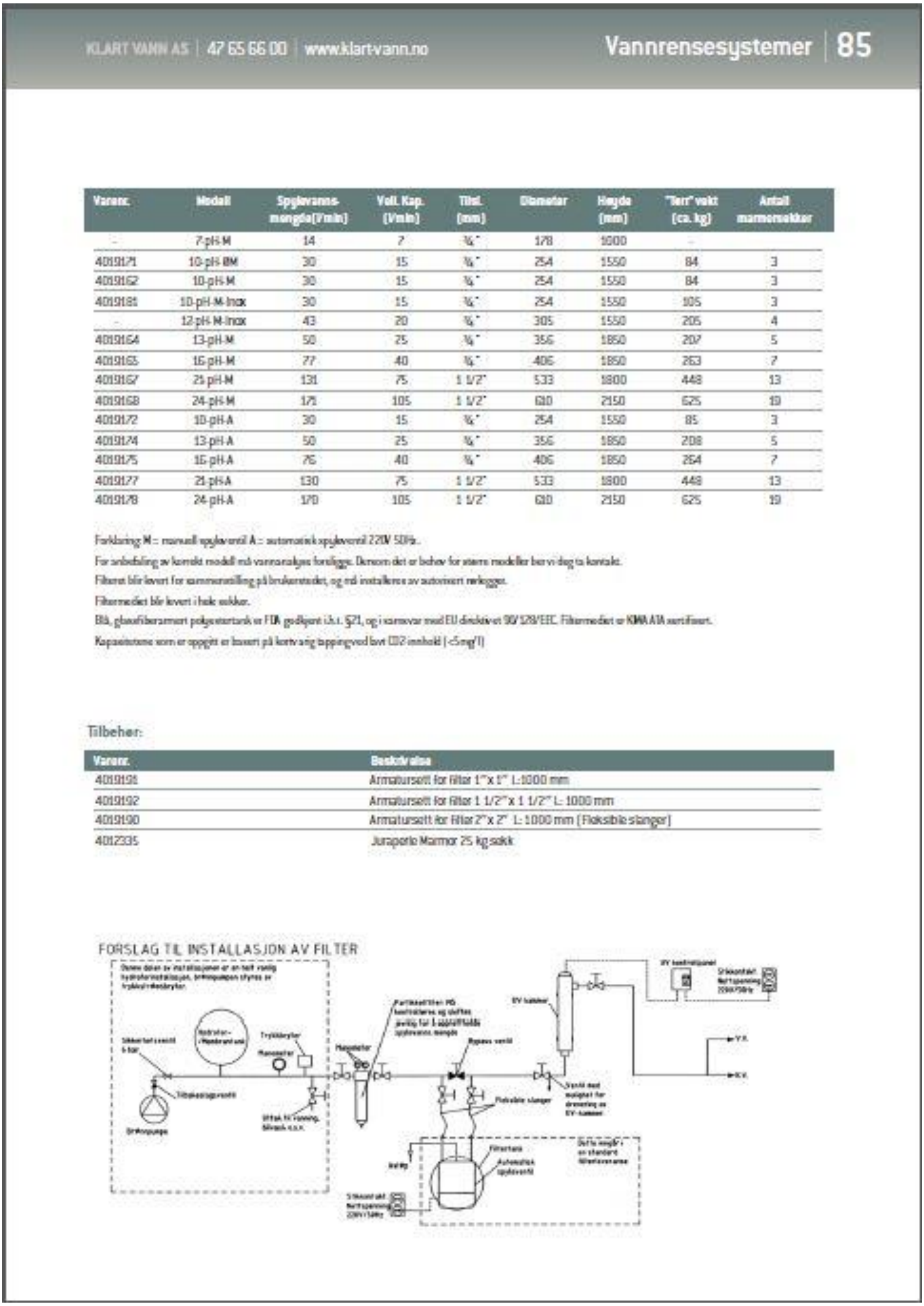
FERNOX
MAKES WATER WORK

Density of Fernox Solar S1

Specific Heat Capacity of Fernox Solar S1

V.001

Appendix G – Filter and Marble



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Vannrensesystemer | 85

Varenr.	Modell	Spylevanns-mengde(l/min)	Vell. Kap. (l/min)	Tilsl. (mm)	Diameter	Høyde (mm)	"Terr" vekt (ca. kg)	Antall marmorsekker
-	7-pH-M	14	7	¾"	178	1000	-	
4019171	10-pH-ØM	30	15	¾"	254	1550	84	3
4019162	10-pH-M	30	15	¾"	254	1550	84	3
4019181	10-pH-M-Inox	30	15	¾"	254	1550	105	3
-	12-pH-M-Inox	43	20	¾"	305	1550	205	4
4019164	13-pH-M	50	25	¾"	356	1850	207	5
4019165	16-pH-M	77	40	¾"	406	1850	263	7
4019167	21-pH-M	131	75	1 1/2"	533	1800	448	13
4019168	24-pH-M	171	105	1 1/2"	610	2150	625	19
4019172	10-pH-A	30	15	¾"	254	1550	85	3
4019174	13-pH-A	50	25	¾"	356	1850	208	5
4019175	16-pH-A	76	40	¾"	406	1850	264	7
4019177	21-pH-A	130	75	1 1/2"	533	1800	448	13
4019178	24-pH-A	170	105	1 1/2"	610	2150	625	19

Forklaring: M = manuell spyleventil A = automatisk spyleventil 220V 50Hz.

For anbefaling av korrekt modell må vannanalyse foreligge. Dersom det er behov for større modeller ber vi deg ta kontakt.

Filteret blir levert for sammenstilling på brukerstedet, og må installeres av autorisert rørlegger.

Filtermediet blir levert i hele sekker.

Blå, glassfiberarmert polyestertank er FDA godkjent i.h.t. §21, og i samsvar med EU direktivet 90/128/EEC. Filtermediet er KIWA ATA sertifisert.

Kapasitetene som er oppgitt er basert på kortvarig tapping ved lavt CO2 innhold (<5mg/l)

Tilbehør:

Varenr.	Beskrivelse
4019191	Armatursett for filter 1"x 1" L:1000 mm
4019192	Armatursett for filter 1 1/2"x 1 1/2" L: 1000 mm
4019190	Armatursett for filter 2"x 2" L: 1000 mm (Fleksible slanger)
4012335	Juraperle Marmor 25 kg sekk

FORSLAG TIL INSTALLASJON AV FILTER

JURAPERLE MARMOR

Juraperle har en renhet på mer enn 99 % kalsiumkarbonat, og en spesiell struktur som gjør den til et absolutt topprodukt for CO_2-fjerning, økt pH og kalsium. I praksis viser det seg at Juraperle marmor også kan behandle virkelig store konsentrasjoner av Fe (jern) og Mn (mangan), og alt dette kan i mange tilfeller oppnås i bare ett behandlingstrinn.

Fordeler/egenskaper

På grunn av sin mikrokrystalliske struktur er den overlegen sammenlignet med ordinær kalkstein (marmor). Siden Juraperle er et enkelt produkt å bruke og lett å ha med å gjøre, er det ikke bare store vannverk som benytter den i stor skala.

Også gårdsbruk, campingplasser, husholdninger etc. benytter seg av dette effektive filtermediet. Legg merke til at det ikke forekommer tilstopping, gjengroing eller sementering av filterkornene som i andre system.

Bruksområder:

- CO_2-reduksjon og karbonatisering (remineralisering) av bløtt vann
- Remineralisering av destillat og/eller omvendt osmosevann (membranfiltrering)
- Fjerning av jern, mangan og aluminium

Varenummer	Produkt	Beskrivelse
4052335	Aqua-Juraperle marmor 25 kg sekk	1,2 – 1,8 mm

Teknisk informasjon:

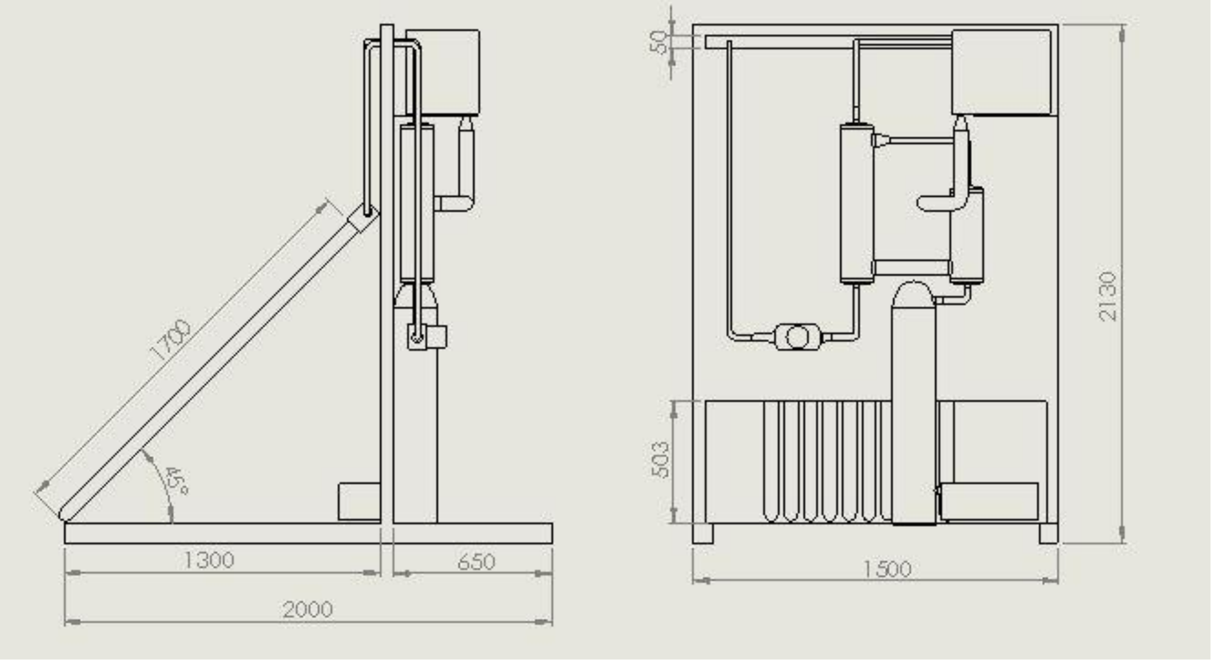
	Gjennomsnittlige verdier	EN 1018, Type 1
Tetthet	2,7 g/cm^3	2,71 g/cm^3
Romvekt	1500 kg/m^3	1000 - 1500 kg/m^3
Form	Splintret, uregelmessig	Splintret, uregelmessig
$CaCO_3$ (pr. masse)	99,1 %	> 98 %
$SiO_2 + Al_2O_3$ (pr. masse)	0,34 %	–
Fe_2O_3 (pr. masse)	0,04 %	–
Arsenikk (As)	0,25 mg/kg	< 3 mg/kg
Kadmium (Cd)	< 0,25 mg/kg	< 2 mg/kg
Krom (Cr)	< 2 mg/kg	< 10 mg/kg
Kvikksølv (Hg)	<0,02 mg/kg	< 0,5 mg/kg
Bly (Pb)	0,25 mg/kg	< 10 mg/kg
Selen (Se)	0,9 mg/kg	< 3 mg/kg

Godkjent for bruk i offshore-sammenheng, KIWA-sertifisert.

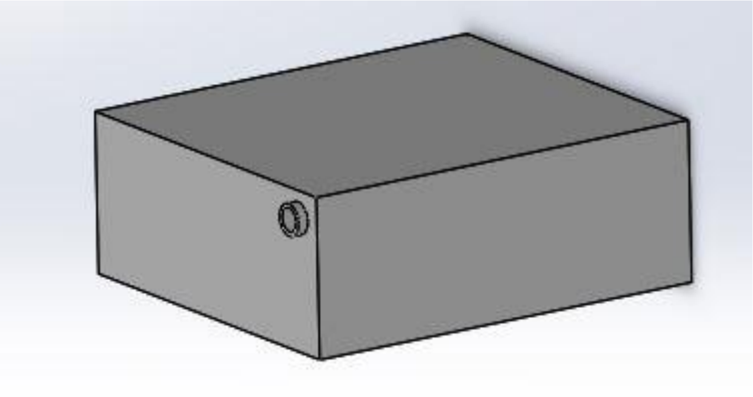
Filterhastighet:	Åpne filter, 5-15 m/t
Trykktank, maksimum 30 m/t	
Filterdybde:	Minimum 1500 mm (unntak kan diskuteres)
Hardhetsøkning:	Pr. 10 mg/l forbrukt CO_2 øker hardheten med henholdsvis 1.3°dH (tyske hardhetsgrader) = 2.3 °F (fransk hardhetsgrad) = 9.3 mg Ca/l.
Forbruk:	Ca. 2.5 gram Juraperle forbrukes pr. gram forbrukt CO_2.
Påfylling:	Etter å ha forbrukt 10 % av opprinnelig volum.

Appendix H – 2D sketch of system

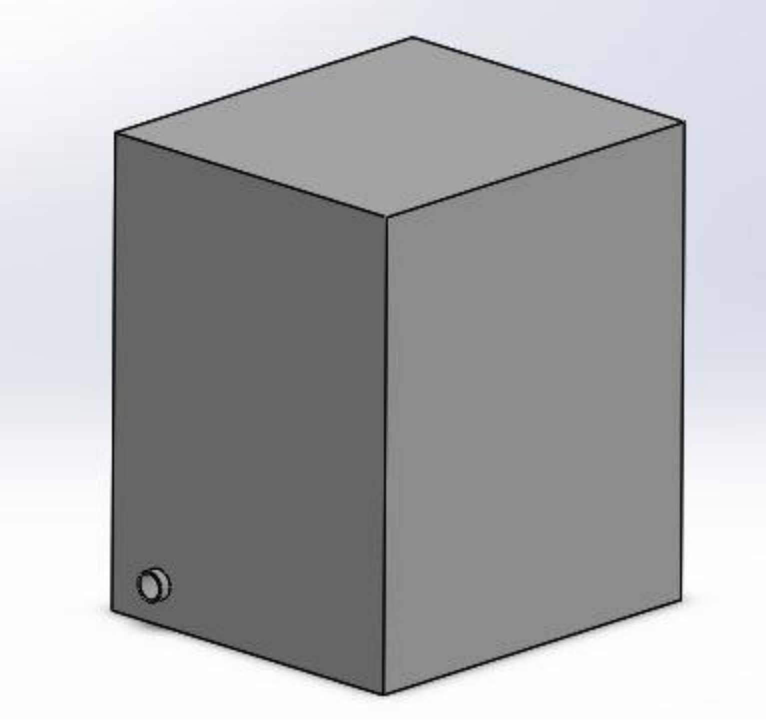
Dimensions are in millimetres.



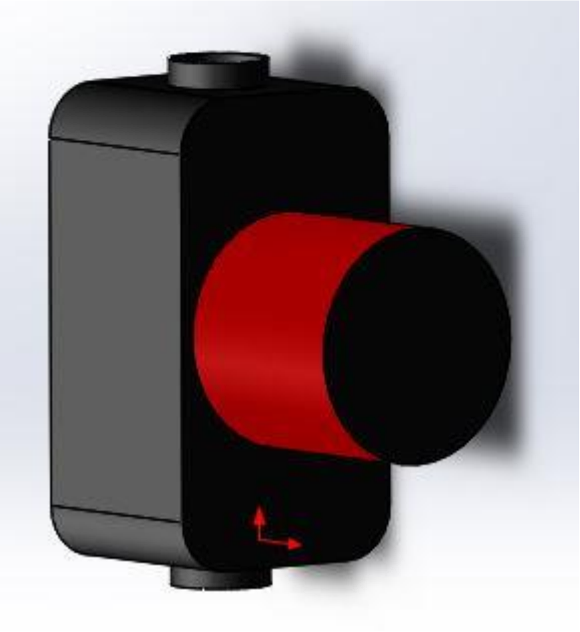
Appendix I



Storage tank for distilled water.



Storage tank for saline water.



Pump.

Filter.