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Abstract

The content of the project work performed by Larissa Franzke at NTNU contains the following:

The energy consumption of mankind is high and mostly expensive. The idea to use an ice storage system helps, to consume energy out of this system when there is low availability and to store energy in form of ice in high availability phases. This Cold Thermal Energy storage (CTES) is tested at NTNU. The ice bank consists out of three helical coils (heat exchanger) which are located inside a big water tank. The coils end up in a double pipe heat exchanger with glycol.
The glycol helps to pretend the usage inside the refrigerator in a supermarket. It should be kept at a constant level of 5 °C. The system is charged during the night (evaporator) with cold CO_2 as a refrigerant and discharged during the day (condenser). This report focuses on the glycol cycle and the newly fitted parts in the system. The new heater helps to get stable glycol temperatures and therefore constant working conditions which supports a stable flow of CO_2. The idea was to get a high heat input into the glycol (500 W) and still have low temperatures with a working thermosiphon. This could not be achieved totally but the improvements helped to get the required stable conditions.

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1 Introduction

There is a very high amount of energy which is used in everyday life, therefore the energy production is already very high level these days. To reduce it there has to be a way to get a higher efficiency for the already existing energy consumer. In case of cooling systems the idea of storing energy in ice is used when there is more energy produced then required. This can happen often during the night because people are sleeping and do not require a lot of energy comparing to day time. Another idea is to use the energy while a lot of renewable power is available but not fully used. In these cases the energy is cheaper so money can be saved. Another advantage could be, that it can be used in case of a blackout to keep the supermarket refrigerants running. This is very important because the food stored inside is worth plenty of money.
At the NTNU in Trondheim a prototype was build to check if this could be an idea to use in e.g. supermarkets. Supermarkets normally have plenty of space on top of the refrigerator so that could be a good place for the system. To keep low costs water ice could be used as an energy source on the high peek of the day.

2 Working Fluid and Cold Thermal Energy Storage

2.1 Working Fluid

There are discussions about the right refrigerants lately. A lot of refrigerants are getting very expensive and should not be used anymore to preserve the ozone layer. But there are natural refrigerants instead which can be used. These refrigerants are getting more important , for example the R744/CO_2. CO_2 has a lot of advantages. It has an ODP of zero and a very low GWP. Other advantages are that it is non flammable and not toxic, very cheap and has a low critical point and a low triple point.

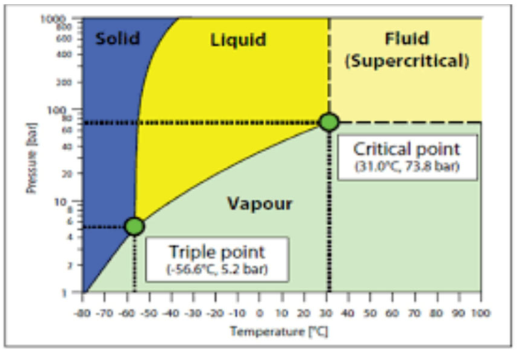
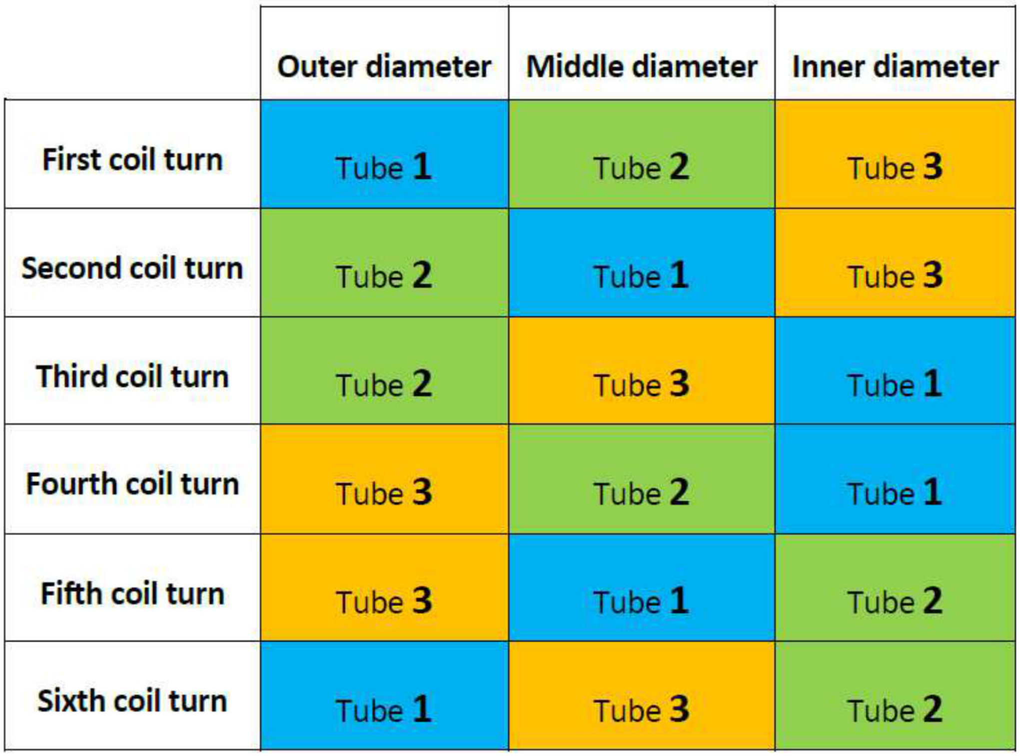


Fig. 1 Triple point and critical point of CO_2

The low triple point allows us to use this refrigerant at very low temperatures. Because the critical point is at a very low temperature of 31 °C the system should operate transcritical. This is important because in many countries it gets warmer than 31 °C commonly.

2.2 Set up of the CTES (Cold Thermal Energy Storage) Basic idea

The CTES consists out of different coils which are inside a water container and fixed to a frame because they were not able to hold their own weight. The coils are arranged in a spiral shaped way which gives it a bigger surface for heat exchanging and does not require a lot of space. To get even better heat exchanging the coils have different diameters this would also lead to different lengths of the tube and therefore to a different pressure drop. To get a similar pressure drop in each coil they are varying the diameter which shows the table below.



	Outer diameter	Middle diameter	Inner diameter
First coil turn	Tube 1	Tube 2	Tube 3
Second coil turn	Tube 2	Tube 1	Tube 3
Third coil turn	Tube 2	Tube 3	Tube 1
Fourth coil turn	Tube 3	Tube 2	Tube 1
Fifth coil turn	Tube 3	Tube 1	Tube 2
Sixth coil turn	Tube 1	Tube 3	Tube 2

Fig. 2 Different diameter with different turns

The CTES system is working with the help of CO_2 and the liquid inside the container is water. While running cold CO_2 through the coils the ice is going to be built around the tubes and with warm CO_2 the ice is melting again. The CO_2 is warmed up in the heat exchanger with the glycol side.

2.3 Basic idea

To get a basic idea how the system works the picture underneath shows a simple set up without any valves, just the circles.

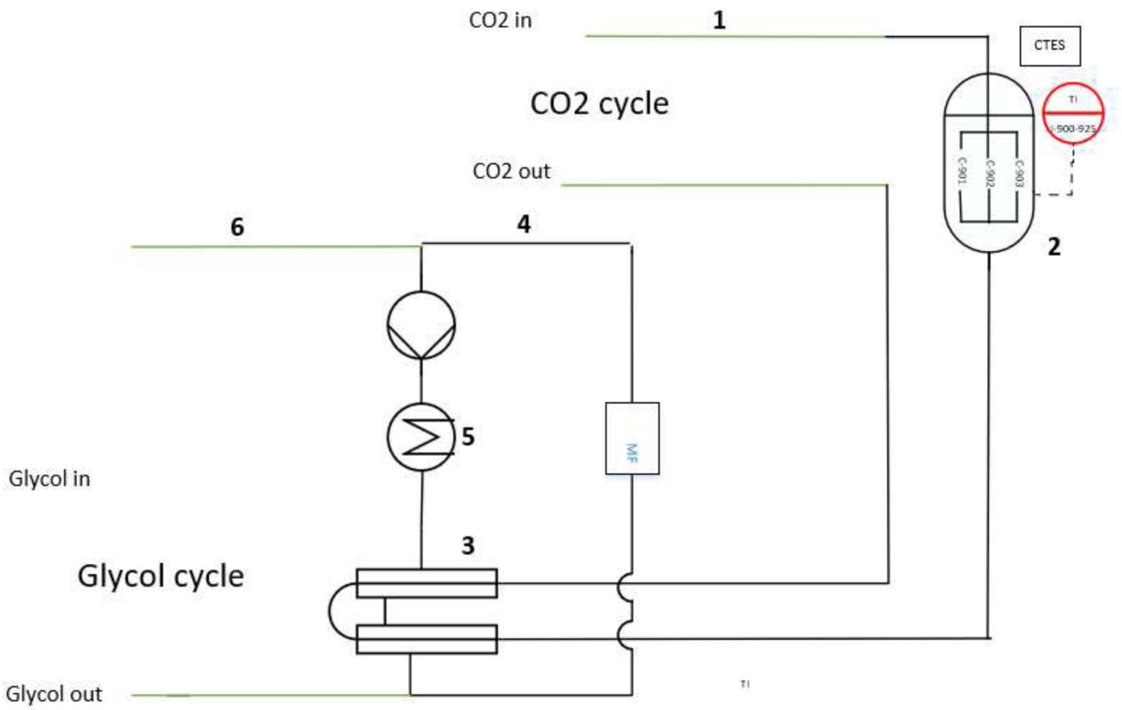


Fig. 3 Simplified flow chart of the test facility

The green lines marked with number 1 are for charging the cycle. The coils are opened to the tank during charging period over the night. For discharging the system is filled with CO_2 once and then it is disconnected from the tank. The CO_2 flows through the CTES, (number 2) after that. The focus is on the discharging part during this project. The CO_2 melts the ice coils in the CTES and cools itself during this procedure. After that it enters the heat exchanger, (number 3) where it gets heated up from the glycol side. The now warm CO_2 enters the CTES again and the cycle starts from the beginning. The glycol cycle is a closed loop (number 4) which gets heated up by a heater (number 5). It flows with the CO_2 through the heat exchanger and gets cooled down by it. The green lines at the glycol cycle show the connection to the tank (number 6) which is used as an expansion vessel. The main aspect of the tests were to get a stable working thermosiphon and a stable glycol temperature.

2.4 Original Setup

Fig. 4 shows the setup of the project. It consists out of two parts. One is the CO_2 cycle and the other one is the glycol cycle. Both are connected through a double pipe heat exchanger. The glycol cycle is connected to the tank and mixing glycol from the original loop and the tank together to get the required temperatures. The problems recognized are unstable temperatures in the tank that have a great influence to the results of the test. With the help of the CO_2 the ice around the coils is produced. While charging it very cold CO_2 enters and warm CO_2 goes out again. While discharging it is the other way round. The detailed process of charging and discharging is explained later

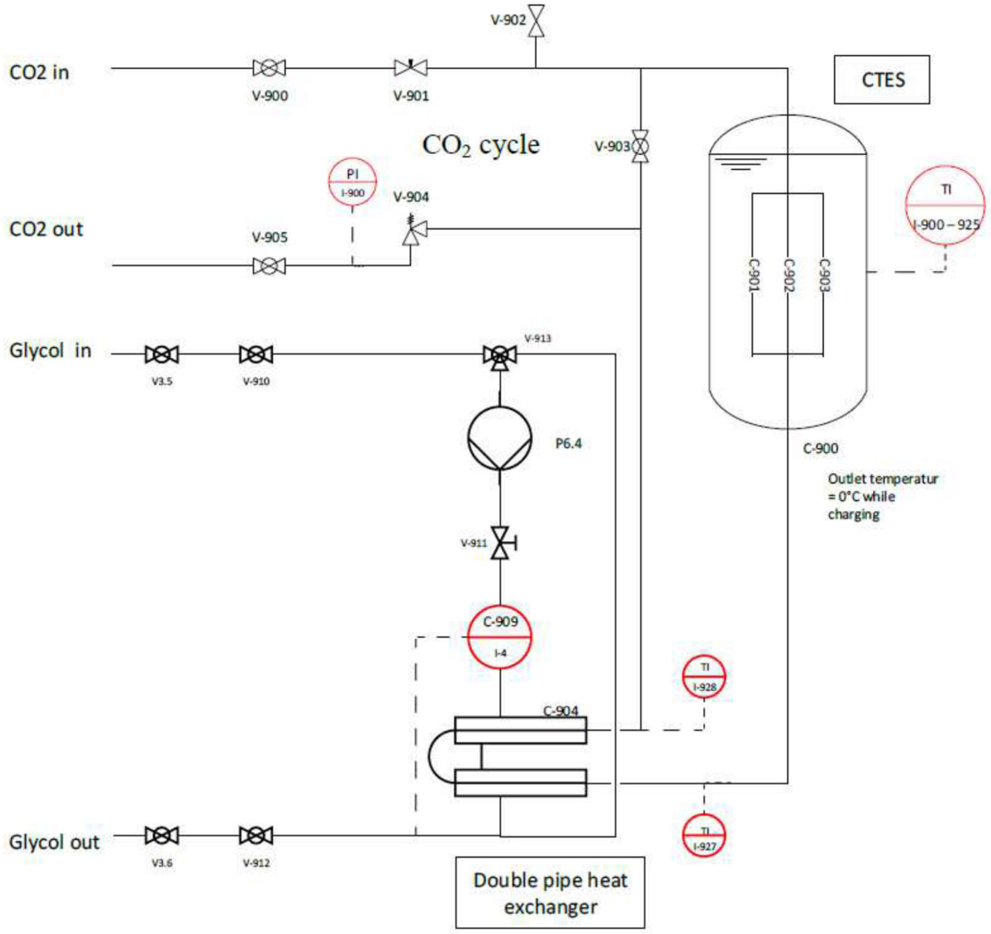


Fig. 4 Original setup of the test facility

2.5 Working Principle

The CO_2 inside the pipes is the refrigerant in the cooling system. With the help of the thermosiphon principle which is explained in the following chapter, the CO_2 runs through the system.
With the assumption that there would be a cooling capability required for a middle sized cabined of about 500 W the glycol cycle should be heated with 500 W but keeping the glycol temperatures still at a cold level(5 °C) at the same time.
It is important to check the different temperatures on all parts of the system. Therefore temperature sensors have been placed in the whole system. It is important to measure the inlet and outlet temperature of the heat exchanger on the glycol cycle and on the CO_2 cycle. Another important thing to be considered is, that the CO_2 temperature in the bottom and the top of the coil can be different because vapor and liquid CO_2 are existing at the same time. The liquid CO_2 which has a different temperature flows at the bottom of the coils and the vapor CO_2 is at the top. Therefore the temperature sensors are placed on the top and the bottom of the coil.
In the glycol cycle the temperature on the top and bottom of the coil should be the same because the glycol should be fluid the whole time because the heat difference between the inlet

and outlet should be 3 K. For this reason there is only one temperature sensor on each side required.

Fig. 5 Temperature sensors at the heat exchanger (evaporator)

The rest of the temperature sensors are placed inside the tank. Most of them on different parts of the coils, the others on the frame and on the sides of the tank to get information about the temperature inside the tank. The picture below shows the assembly of the different coils on the left and on the right the different temperature sensors can be seen.

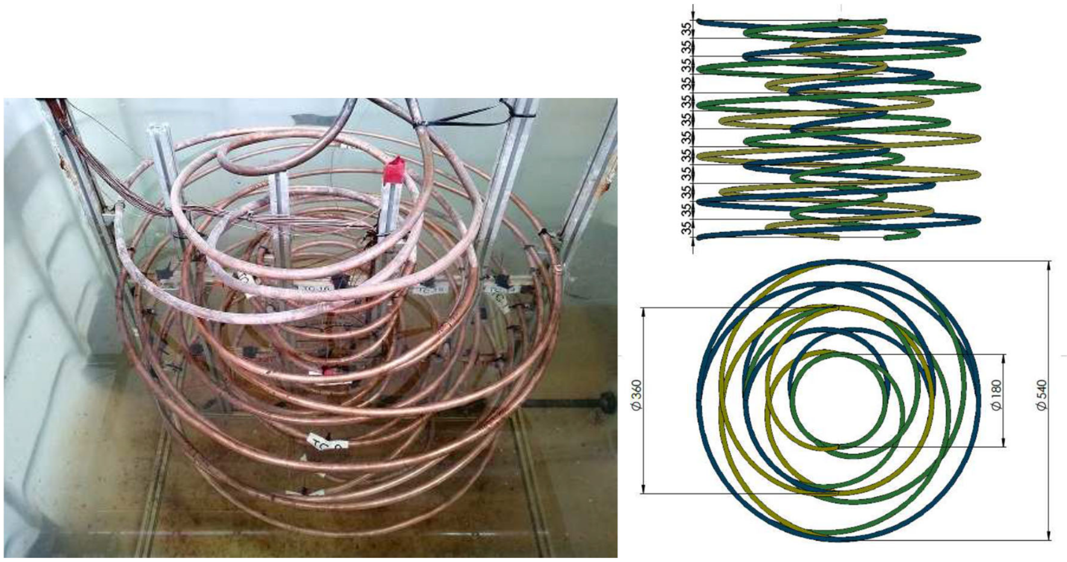


Fig. 6 Temperature sensors on the coils

2.5.1 Thermosiphon Principle

This principle is used for getting a working CO_2 flow. It based on a heat exchanger with the help of natural convention because of density and phases change. The glycol is heated up and transfers the heat to the CO_2. There has to be enough heat that the CO_2 vaporizes. After continuing going through the loop it comes to the condenser where it gets liquid again and a natural cycle starts. It would also work with only vapor too, but it is not as efficient as utilizing the phase changes of the CO_2.

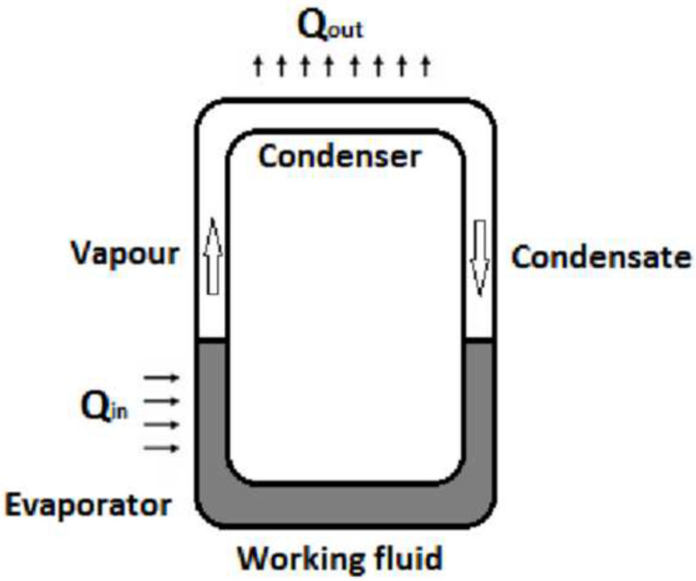


Fig. 7 Thermosiphon principle

2.5.2 Charging and Discharging

The charging and discharging process can be complex. For discharging there are different ways. For example there can be an external melt ice on coil process or an internal melt ice on coil. The CTES system at the NTNU uses the internal melt ice on coil strategy explained underneath. The charging process takes place over the night from 4:00 pm - 8:00 am. After that the discharging is started for the working day. Therefore the charging period is 16 hours.

Through the cold CO_2 which flows through the pipes, the pipes are cooling down and the water in the tank around the coils is cooling down as well. This whole procedure of charging can be separated in 4 steps. The first one is the cooling down of the water. After that, it slowly starts to get small ice cylinders grow around the coils (a). After some time stage three starts: The ice cylinders get bigger until they touch each other (b). If this is going on for a longer time, all water will be turned into ice (c). In our experiment this does not happen, because the CO_2 flow is not high enough and the tank where the coils are placed inside is square shaped. While charging the tank is used as an evaporator. In the picture below the different stages are shown.

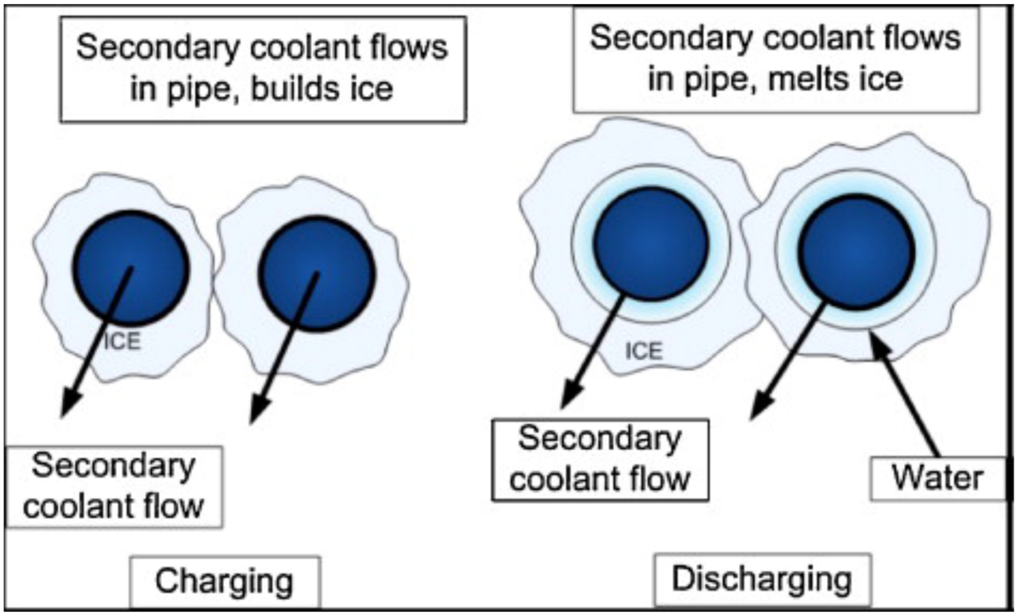


Fig 8. Charging and discharging process

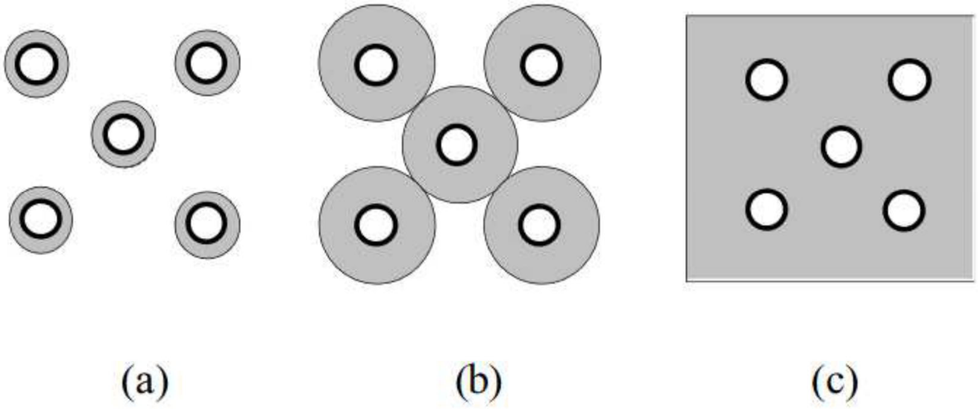


Fig 9. Different stages of the charging process

In discharging mode the tank is working as a condenser. In case that the liquid CO2 inside the tube is warmer than the freezing point because the glycol in the heat exchanger transfers the warmth to the CO2, the ice next to the tube start melting in a cylindrical shape(a). Because of the different density of water and ice, the ice block will not stay symmetrical around the coils. The ice coils float up which lets to a thinner ice coil on the bottom (b). When the finest part is broken they will leave the coil and float up until they contact the tube above(c). After the top part of the ice coil is melted, the rest of the ice coil breaks into small pieces (d). In our case the expected floating state never happened. The assumption is that the ice is frozen at the frame as well and this is not heated up through warm CO2 which makes the ice coils stay around the tubes. Another part to be considered is, that the ice at the bottom of the tank melted earlier than on the top. The first assumption would be the other way round because the CO2 enters the coils at the top is warmer than the one which leaves at the bottom. But because of a phase change the CO2 at the bottom the CO2 transfers more energy, which melts the ice faster.

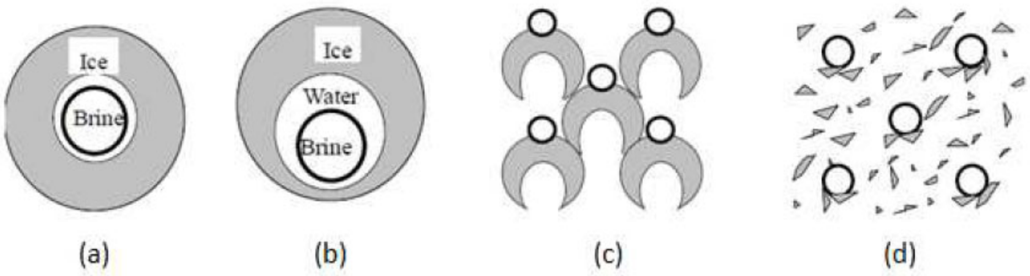


Fig 10. Different stages of the discharging process

2.6 Changes for improvement

To improve the tests, some changes in the cycles had to be made:

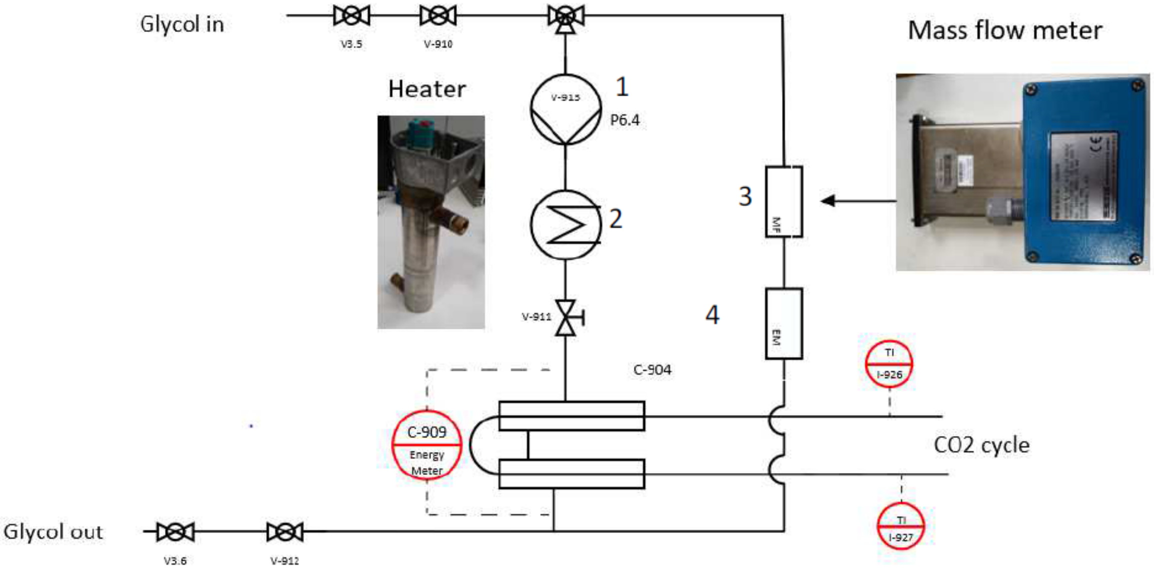


Fig. 11 Changes for improvement

In the glycol cycle the glycol is moved by a pump (1 in figure 11). There are some temperature differences in the cycle because of the connection to the tank, where the temperatures vary during the day. To reduce

the influence of these variations, the glycol loop is disconnected from the tank and a heater (2 in figure 11) is included. To regulate the heat input correctly there is a wattmeter connected to the heater. This enables to put only as much power inside as required. There still has to be a connection to the tank to use it as an expansion vessel. Another improvement is, to include a mass flow meter (3 in figure 11). It will be next to the energy meter (4 in figure 11) to get more accurate measurements. Additional added is a service valve (not shown in this picture) to tap oil. Here it is important that it is at the lowest point so the oil can be dumped easily.
The glycol already has a volumetric flow meter inside but it seems to be inaccurate. The reason could be, that it is not designed for glycol. To see, which difference there is between the new coriolis mass flow meter which measures very exact and the volumetric flow meter the difference has been calculated.
The mass flow meter shows: 4,93 kg/min
The volumetric flow meter shows: 0,243 m^3/h_
With the help of the density of glycol $\delta_{glycol} = 1057\ kg/m^3$ the volumetric flow can be converted to the same units. So the mass flow rate recalculated from the volumetric flow rate is 4,28 kg/min.

This shows that the value from the mass flow meter is 1,15 times higher than the other one.
This approves the suspicion that the volumetric flow rate does not work accurately. The accurate mass flow is important because there has to be a calculated mass flow of 2,7 kg/min to get a 3 K difference between the inlet and outlet temperature with a heat load of 500 W.

Fig 12 CO_2 cycle mass flow meter.

The only change at the CO_2 cycle is to add a mass flow meter. The mass flow meter should be on a place with few loses, that means in the liquid part of the cycle. The mass flow meter is placed near the inlet of the heat exchanger. The pipe after the mass flow meter is rising to get the liquid trapped, that it delivers the correct measurements on the mass flow. The new mass flow meter helps to sense if the thermosiphon works. As long as there is a mass flow it can be assumed, that the principle is working. This also helps to get the correct amount of CO_2 inside the system.

2.7 Heat transfer to the environment

By adding a known heat load into the glycol loop of the heat exchanger, the heat loss to the ambient was measured. The electrical input power was 76 W.

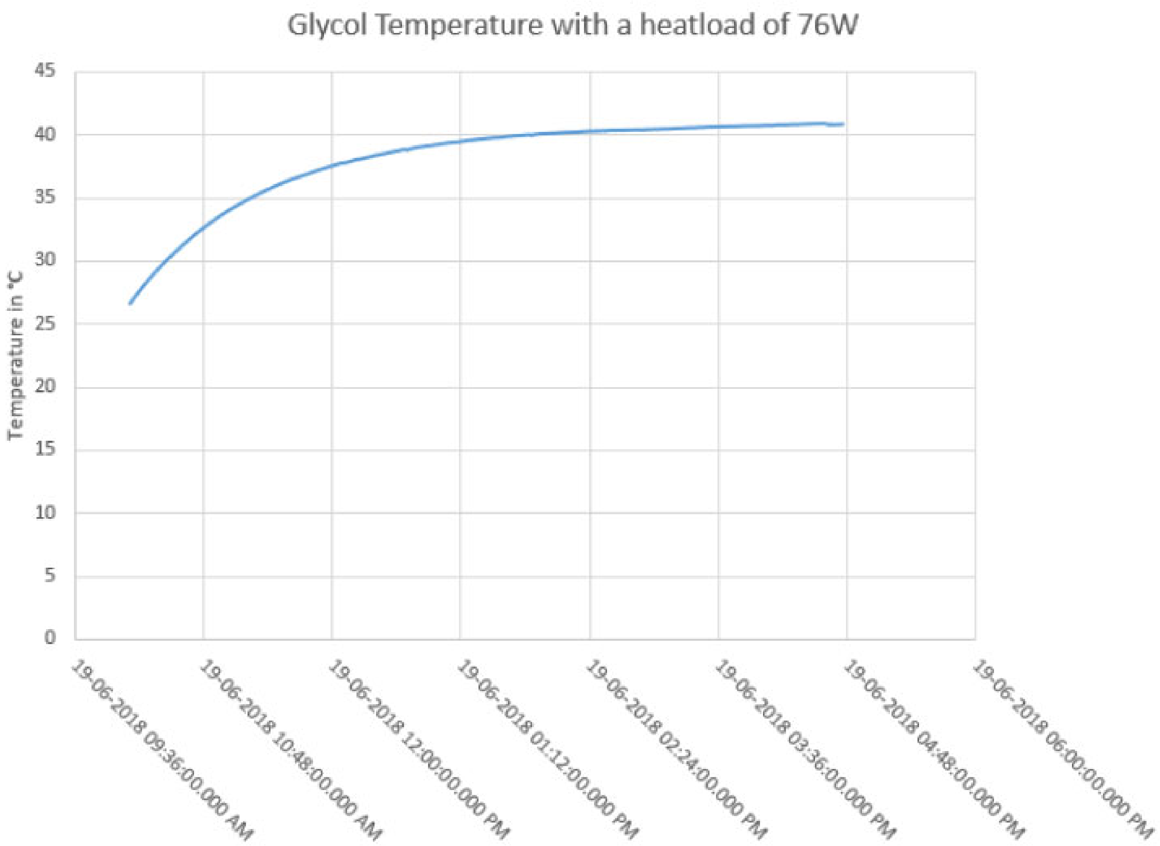


Fig 13 Measurement of heat loss from evaporator loop.

As shown in Fig. 13, the final glycol temperature approached 41°C while heating the circuit continually with 76 W electrical power.

The room temperature was 22 °C, therefor the k value can be calculated:

$k = Q/\Delta T = 4$ W/K

2.8 Velocity and Reynolds number in the Glycol cycle (heat exchanger)

To get an idea of the glycol flow inside the heat exchanger, the velocity and the Reynolds number is calculated. For the needed surface the different tube diameters have to be considered.

outer diameter glycol tube	d_{glycol}		22	mm
wall thickness	t		1	mm
outer diameter of inner tube of heat exchanger	d_{inHX}		10	mm
Volumetric Flow	V		0,156	m^3/h

In the table above the given information of the glycol cycle can be seen. The velocity inside can be calculated by the formula below. It is calculated by the help of the volumetric flow and the surface.
$C=V/A = 0.18$ m/s
The velocity inside the glycol cycle helps to calculate the Reynolds number. The Reynolds

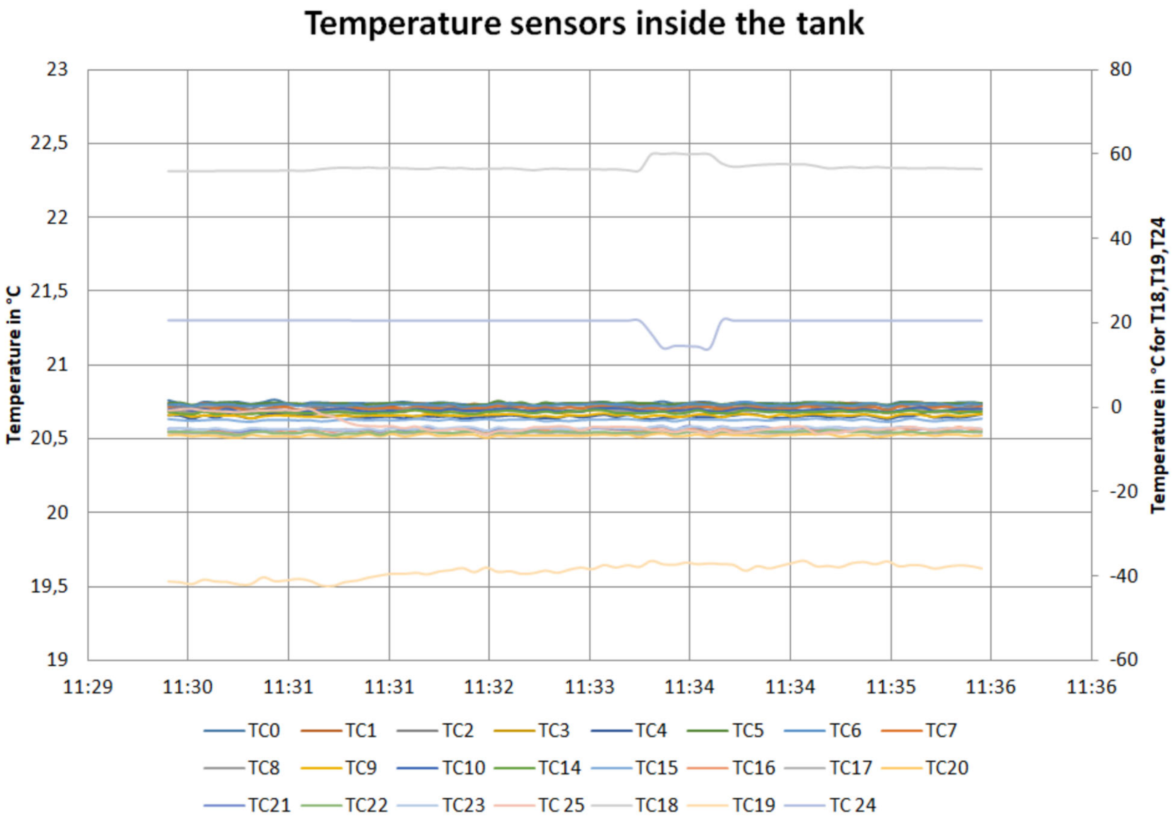
number is calculated by the velocity the hydraulic diameter and the viscosity.

Re = c*d/v = 343

This indicates that there is laminar flow inside the glycol heat exchanger.

3 Test results

The new test campaign is conducted under different conditions. Most important is, to see if the changes are helping to get stable glycol temperatures and to be sure that the thermosiphon works. This is operated under different pressures and temperature conditions. In the tests which were done earlier, some temperature sensors were showing strange values so it had to be checked, if all of them measure correct. That was done with the help of a stirrer, placed inside the water while the system was not running to move the water.



The graph above shows, that all temperature sensors work correctly, except T18, T19 and T24. Those sensors are all either placed on the frame or on the wall of the tank so it was decided that the other sensors are enough and the wrong ones do not have to be changed.

3.1 Test 1: 0 °C on the ice, 5 °C at the CO2, 10 °C at the glycol

The first test was conducted to get a stable temperature of 0 °C at the ice, 5 °C at the CO_2 and 10 °C on the glycol. It was not possible to get stable conditions because it took about 2 . hours to reach 40 bar inside the pipes and while that the ice around the coils already melted so the temperature increased. Another problem occurred: The heater had to be turned up very high to get 40 bar inside but as a result, the glycol temperature raised.
As a conclusion of this experiment it could be checked that everything is working, there is a heat flow of CO_2 and there is a flow of glycol which makes the thermosiphon principle work.

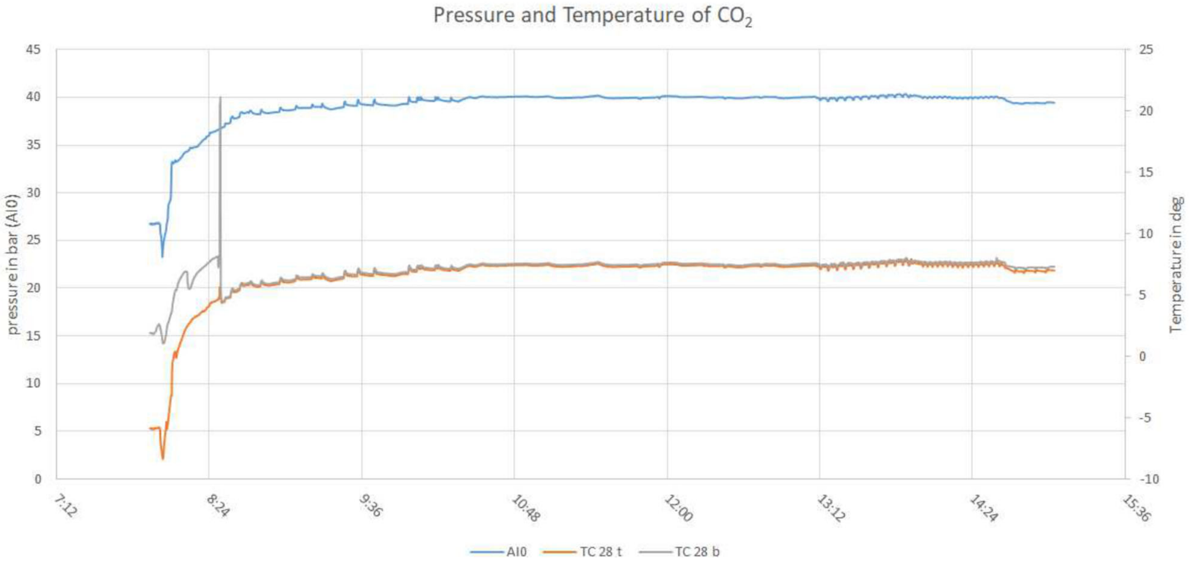


Fig. 15 Pressure and temperature difference of the CO_2

This graph above shows the relation between the temperature sensors at the inlet of the heat exchanger and the pressure. AI0 is the pressure and the T28 are the temperature sensors which are located on the top and at the bottom of the tube. In the test it was expected to get 40 bars and 5°C. The measurements show, that as soon as there is a pressure of about 40 bars, the temperature is stable at 7.5°C. One reason for this could be, that the manometer is placed about 4 m above the CO_2 inlet. This could cause for a higher pressure at the temperature sensors and therefore to a higher temperature. Another aspect to be considered is, that the temperature sensors are placed outside on the tube so there could be some differences between the measured temperature and the real temperature inside.
With the help of the height difference of h = 4.34m the pressure at the heat exchanger and at the temperature sensors can be calculated:
$p_{heatexchanger} = p_{top} + g * h * \varrho_{CO2,\ liquid}$

The CO_2 will enter the heat exchanger fluid, so the density of fluid CO_2 $\delta = 466\ kg/m^3$ has to be taken.
$p_{heatexchanger} = 40.198$ bar

This gives out a pressure of 40.198bar. This is not a big difference to the measured pressure on the top of the system.
Another aspect is to check, if the absolute or the gage pressure is measured. The pressure sensor included in the CO_2 cycle is measuring the absolute pressure which means, it uses the vacuum as a reference.
This indicates, that the temperature sensors are either measuring a bit vague, or that the difference between the outside and the inside of the tube is bigger than originally expected.

For getting an idea in which states the CO_2 enters or leaves the heat exchanger, the enthalpy is calculated. This can be done with the help of our collected data.

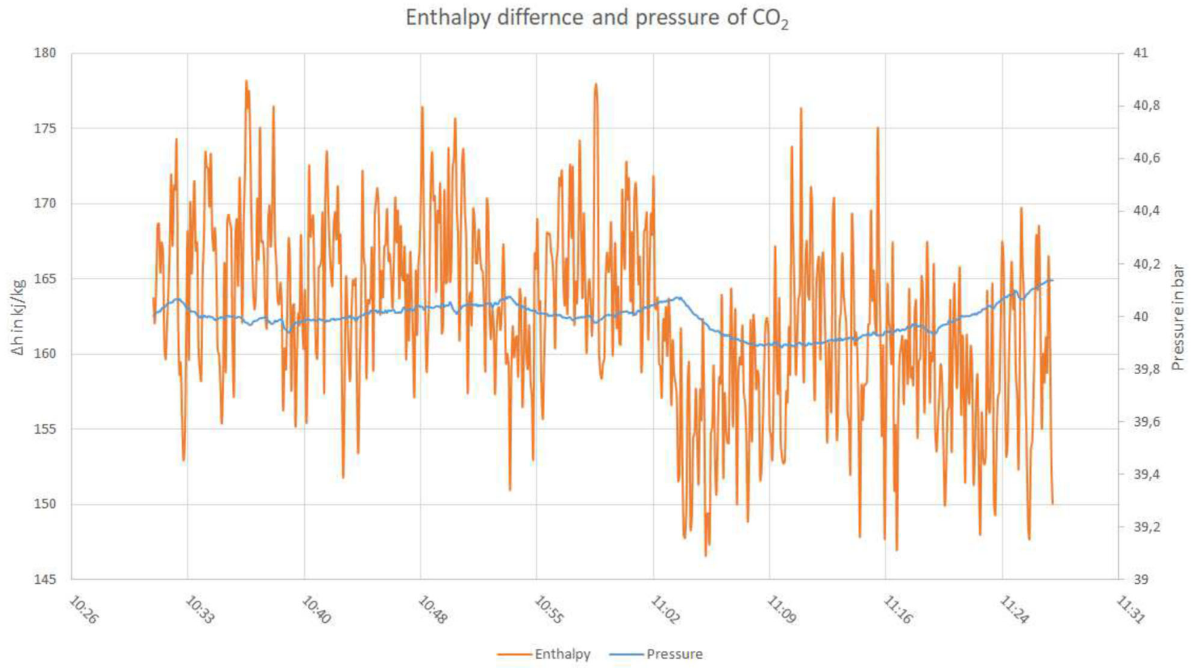


Fig 16. Enthalpy difference

This graph shows that the enthalpy is not stable. A lot of aspects influence the enthalpy. In the calculation below can be seen how many aspects that are. In the graph above, the influence of the pressure gets clear. Higher pressure leads to a lower enthalpy and the other way round. The enthalpy is calculated with the help of the different heat loads.

It can be assumed that:

$$\dot{Q}_{CO2}=\dot{Q}_{glycol}=\dot{Q}_{environment}+\dot{Q}_{heater}$$

The glycol and the CO_2 get the heat mainly from the heater but because the isolation is not perfect and the glycol is colder than the environment there may be a small heat flow too. The whole heat of the glycol should be transferred to the CO_2 cycle. Therefore these two numbers should be equal. The glycol heat load can be calculated by this formula:

$$\dot{Q}_{glycol}=\dot{m}_{glycol}*cp_{glycol}*\Delta T_{glycol}$$

$Q_{environment}$ can be calculated with the factor which was found earlier. Therefore the difference between the temperature of the environment and the glycol is taken. Because the glycol has a big temperature difference between the outlet and inlet the average is taken.

$\dot{Q}_{\text{environment}}$=k*ΔT

Because of some measuring differences or measuring mistakes $\dot{Q}_{\text{glycol}}$ and $\dot{Q}_{\text{heater}}+\dot{Q}_{\text{environment}}$ do not equal each other as they should. Therefore the average of those is taken for the CO_2.

With the help of the formula

$\dot{Q}_{\text{CO2}}=\dot{m}_{\text{CO2}}*\Delta h$

and therefore

$\Delta h=\frac{\dot{Q}_{CO2}}{\dot{m}_{CO2}}$

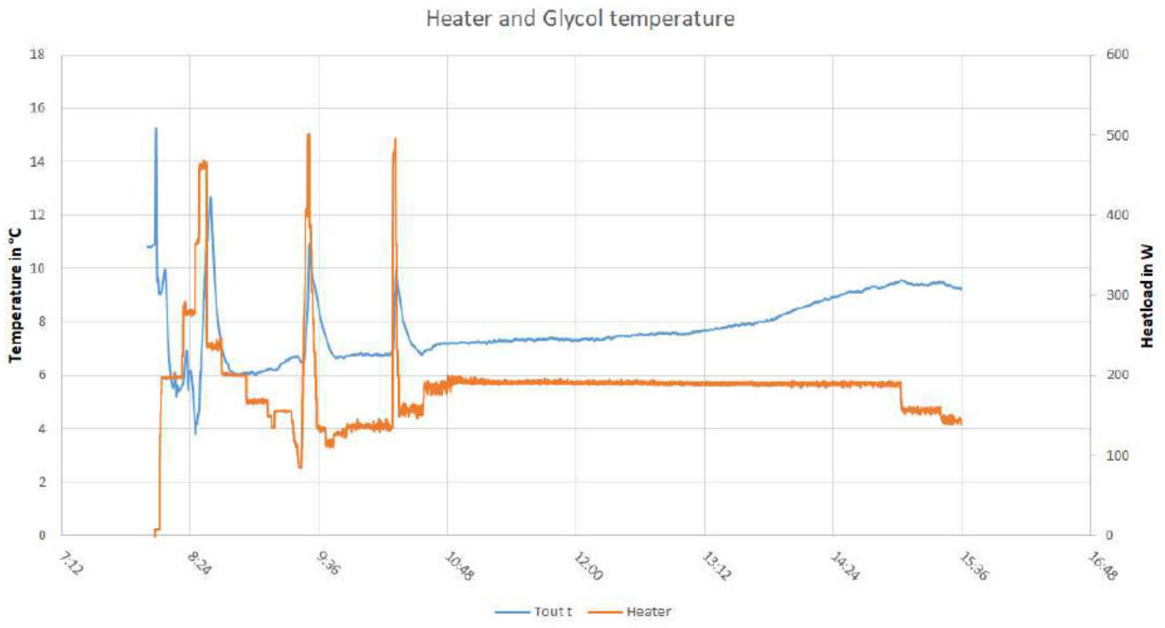
the average of the enthalpy is calculated $\Delta h= 165\,\frac{kj}{kg}$.

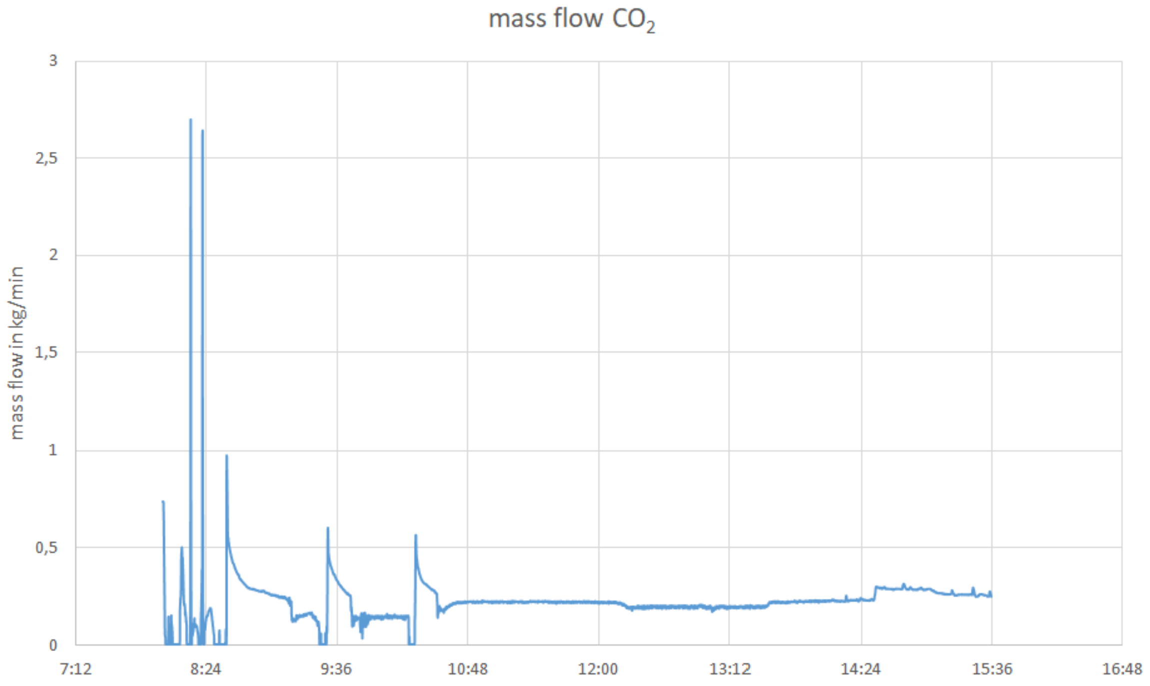
The enthalpy difference has to be compared to the total enthalpy of CO_2 between liquid and vapor $\Delta h=213.9\frac{kj}{kg}$ at 40 bars.

The temperature and the pressure leads to the result, that the CO_2 enters the heat exchanger liquid or even a little supercooled. With the calculated enthalpy it can be estimated, that the CO_2 which comes out of the double pipe heat exchanger is a mixture between gas and fluid.

3.1.1 Test 2: 0 °C on the ice, 2 °C at the CO2, 4 °C at the glycol

The second test was conducted to get 0 °C, 2 °C, 4 °C. Another interesting thing to know is, how much CO_2 is filled inside. Do get an idea the time while the valve is open was measured. In case it did not work the whole system was emptied again and then refilled. Here another important thing has to be considered. It is not known, if always CO_2 flows inside during the time while the valve is open. The reason can be the pressure difference. To charge there has to be a higher pressure in the tank, so the charging process is possible by the pressure difference. The pressure inside the tank has to be bigger so the CO_2 flows to the system where there is lower pressure until the pressures are equal or until the system is disconnected. In case this pressure drops which could happen because it depends on a different machine, it could happen to pull CO_2 out of our system into the tank. So the time just helps to get an idea of how long it takes.
After finishing the charging process happening over night, the discharging could start. For that the CO_2 was filled to see if it is possible to get 2 °C at the CO_2 and 4 °C at the glycol. The most important part was, to get stable conditions at the glycol side. It was tried to get the temperature up to the required 4°C with the support of the heater. There was not a chance to get the thermosiphon work at that low temperatures. (temperature rise at 8:24, Figure 17) For that it was tried to get stable glycol conditions. For this the valve was opened for 4 minutes and 30 seconds to get a good flow of CO_2.



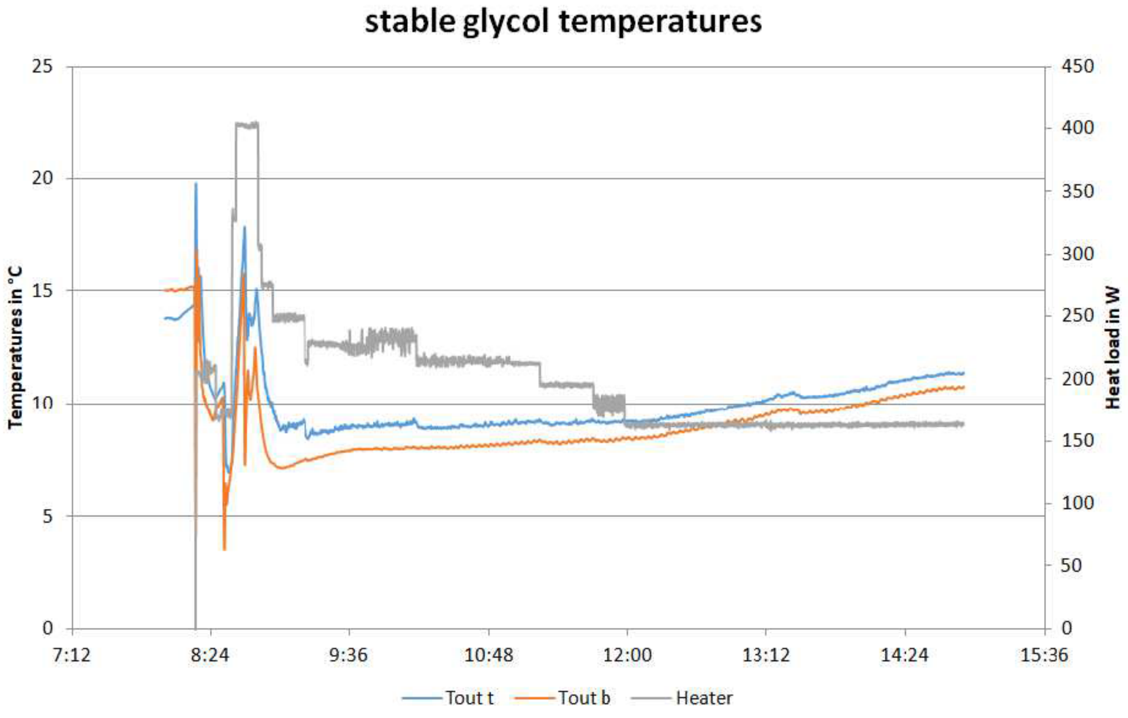


Shown in the graph 17, the glycol temperature was getting stable at 6°C while the thermosiphon worked. After sometime the heater was turned down to be sure, that the temperature stays stable. The thermosiphon stopped working and as a consequence the glycol temperature rose. In graph 18 can be seen, that it was noticed by the help of the mass flow. As soon as the mass flow was down to zero, the heater was turned up to get the Thermosiphon running again 25

and then down in small steps. That reduced the glycol temperature to 6.8 °C. Where it became stable for some time before the same happened again.
From this experiment the importance of the heater can be proven. It gives the option to change the power input very fast and also the following reaction. The graph shows that the heater is turned up nearly at the same time as the glycol temperature rises. The reason for that is, that the mass flow was checked continually and as soon as that stayed at 0 for some time, the heater was turned on. The heater gives the option to let the system run with less CO_2 and a working thermosiphon. But still there have not been the stable glycol temperatures in this test so it is probably better, to get temperatures which are a little higher but therefore constant. That was tried out in the third test.

3.1.2 Test 3: stable glycol temperatures

This test was performed for getting stable glycol temperatures while the thermosiphon works the whole time. That made some problems at the beginning because the thermosiphon did not start working although there was plenty of CO_2 inside and the heater was turned up to a high level. For that reason the system was totally emptied again and refilled. After the second time the system started working. This time it was filled for 3 minutes and 50 seconds. The required pressure at the beginning of the test inside the system was 39 bars.



With the help of the heater it was possible to get constant glycol temperatures of about 9 °C. Tout t shows the inlet temperature and Tout b the outlet temperature of the heat exchanger.

An advantage to most of the other tests was, that the heater was giving power of over 200 W for a long time. The stable glycol temperature provides a basis to work on. This is the most important aspect because otherwise the system cannot be used in the supermarkets.

4 Summary

The new improvements helped a lot, to get stable temperature inside the glycol cycle. This made the whole discharging process more reliable without putting enormous amounts of CO_2 inside the system. The stable glycol temperatures are important to pretend the real situation in the supermarket. With the help of the heater, there was nearly a constant mass flow of CO_2 so the thermosiphon was working perfectly. The mass flow meter inside the CO_2 system helped to verify the operating thermosiphon and to react fast so there was no to big temperature rising inside the glycol cycle. The temperatures could not been hold as cold as required. The lowest stable temperature has been 9 °C also when the temperature which is needed is 5 °C.

4.1 Further work

The latest changes on the glycol system made the system work constant. The thermosiphon works the whole time and the glycol temperatures can be kept stable with the help of the included heater. The next step would be, to get the heat input of the heater higher. Like mentioned in the test before, the required amount of heat input is 500 W and the test made by now are much lower. A reason for that could be, that the heat exchanger is too small.
Another point is the difference between the pressure and the temperature sensors. To make sure that the results are correct it could be thought about to but the temperature sensors inside the tubes so the correct temperature is measured.
Another change that could be made is the charging process. In this stage of the system, the CO_2 is charged inside the system manually. The CO_2 will be let inside without knowing how much is required. To get this charging procedure automatically the simplest way is to include a new sensor in the glycol cycle. The correct amount of CO_2 is inside as soon as the thermosiphon is working while the heater is running at the wanted level. This can be recognized by the temperature of the glycol. If the of the glycol is rising the thermosiphon does not work anymore. As soon as this happens, the sensor should sent a signal to the opening valve to let another amount of CO_2 inside the system. This procedure can be repeated until the thermosiphon is working constant again.