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SEMESTER PROJECT

Temperature stabilization inside a Herzan Cabinet to secure laser-light alignment

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Abstract

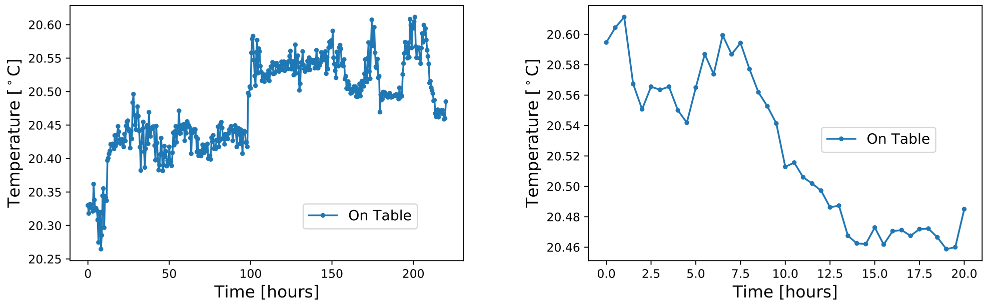
This semester project aimed to stabilize and cool down the temperature inside a laser cabinet to work with quantum states of ions. Perfectly aligned laser beams without distortion of temperature are required. The cabinet houses several lasers as well as optical instruments producing a heat load that causes the temperature to rise inside the well isolated cabinet. The project designed and realized a water cooled system established inside the cabinet that ~~allowed to stabilize~~ the temperature to $\pm 0.03°C$.

Contents

1 Introduction

To work on ions for quantum information, lasers are used to ~~produce~~ transitions between ~~coherent~~ states of the ions [1]. The laser light ~~needs to~~ be close to resonant frequency of the ion. It is therefore necessary that the experimental set-up secures an optimal alignment. A changing temperature ~~impairs~~ the laser and therefore complicates the intended ion-state manipulation.

The experimental set-ups are usually arranged on large optical tables where the temperature is held constant by a homogeneous airflow. Lasers and different optical instruments are used to manipulate the ions inside a vacuum ion trap. Despite the air cooling for optical tables, temperature varies, especially in longer term experiments (Figure 1). Since all optical instruments need to be precisely calibrated and perfectly aligned, the temperature change over longer time periods causes misalignments.



(a) Ten days measurement

(b) One day measurement

Figure 1: Temperature on optical tables

As an alternative, the set-up of the laser and optical instruments inside a cabinet was perceived to avoid temperature volatility and exogenous impact. A cabinet provides a well isolated environment that allows to keep temperature at a constant level. Indeed, the cabinet protects from vibrations as well as temperature and humidity changes of the surrounding. Additionally, cabinets save ~~a lot of place~~ inside the laboratory ~~and thereby offer advantageous working conditions~~. The hope for stable temperature, reduced humidity, less vibrations, and reduced noise was expected to allow an optimal alignment of the laser.

While a cabinet avoids exogenous temperature impact an internal control challenge arises. When using the apparatus of lasers and other powered optical instruments such as acousto-optical modulators (AOM's), ~~a~~ heat ~~load~~ is produced. Due to the isolation of the cabinet, this load causes a rise of the temperature inside the cabinet by several degrees. Hence, the internal heating jeopardizes an alignment of the laser. This semester project assessed different cooling approaches ~~as cooling options~~ to control and stabilize the temperature inside the cabinet. ~~Additional restrictions for an optimized design of cooling and control concept needed to be considered.~~ The cooling solution should avoid vibrations or airflow. The isolation of the cabinet should not be damaged. A solution ~~needed to~~ consume minimal shelf space. As a result of the experiment, according measuring, and realignment, a water cooling system ~~could be~~ designed and tested. The resulting system fulfils the objectives of temperature control, considering the restrictions of an optimal experimental design and working conditions.

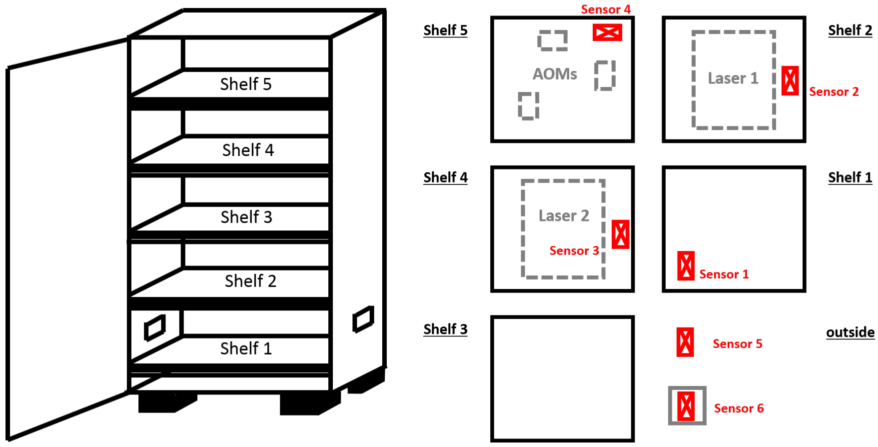
1.1 Experimental Set-up

The selected cabinet consisted of a customized 'Herzan Silencer Acoustic Enclosure'. This Herzan cabinet offers the advantages of reduced acoustic noise as well as EMI noise inside the enclosure. Alongside the isolation, space is minimized and working conditions are improved.

The cabinet set-up used is sketched in Figure 2.a. The cabinet is subdivided into five shelves. Small holes in the side walls can be opened and sealed to let cables enter the cabinet but still keeping the isolating of the system. These are used to connect instruments inside the cabinet to periphery devices, computers, or other measuring instruments.

Figure 2.b shows the individual compositions on the five shelves. The bottom shelf (shelf 1) did initially not contain experimental set-up and served for partial experiments and testing. One temperature sensor (sensor 1) was attached to this shelf. One laser (laser 1) was placed on the shelf above (shelf 2). Shelf 3 again was initially left empty to host eventual cooling devices, testing purposes or test instruments. A second laser (laser 2), identical to laser 1, was placed in shelf 4. Behind both lasers temperature sensors (sensor 2,3) were placed on the right-hand side. The top shelf (shelf 5) was equipped with AOM's as well as other optical instruments as mirrors or cavities and a further temperature sensor (sensor 4).

The whole enclosure was equipped with a system of temperature and humidity sensors. The sensors were 'Sensiron SHT31-D Temperature and Humidity Sensors'. The data was send to the 'Grafana' data platform for an evaluation in a project named 'Herzan Temperature Monitoring'. For further investigation, two additional sensors were placed outside the cabinet. One (sensor 5) measured the temperature outside the cabinet in the lab. The other one (sensor 6) was a portable sensor connected where needed in the course of the experiments.



(a) Cabinet (b) Shelves Equipment

Figure 2: Herzan Enclosure Layout

Although the cabinet offered the advantage that the isolation excluded external temperature influences, it suffered a heat influence within the set-up. The lasers and the AOMs are heat load producers and the isolation of the cabinet renders the heat to remain within the closed system with the result of a rising temperature.

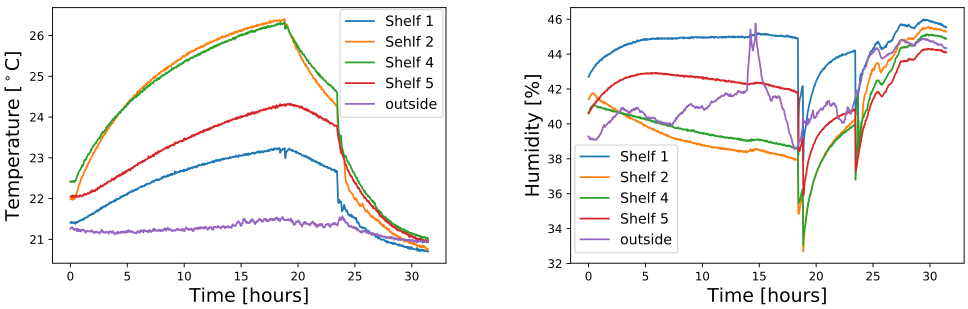
The lasers are prime reason for heat load, but also the AOMs contribute. Focus of this project however was the stabilization of the laser-equipped shelves to fight their temperature increase. The lasers were diode lasers in the low UV-light spectrum i.e. 'Toptica TA-FHG pro'. Laser components needed to be cooled to ~~allow an aligned laser light at the precise frequency.~~ The heat produced by the lasers was not caused by the laser light itself but ~~stemmed from inside the laser.~~ Indeed, the cooling placed inside the laser increased the temperature outside. This cooling system as well as the powered components inside the laser then produced heat that caused the temperature of the air outside the laser to rise.

Another heat producing element inside the cabinet was the acousto-optic modulator~~, short AOM.~~ This device is used for laser light manipulation like frequency or directional shifts. In an AOM sound waves were electrically generated inside a quartz crystal. It then was used to shift the wavelength of the laser light via diffraction into several orders. The power device of the AOM as well as the AOM's themselves produce some heat, but to a minor degree compared to the lasers. Due to the lower weight and higher flexibility their heat load was used for first cooling approaches without stressing the heavy and sensitive lasers.

1.2 Initial Experimental Situation

The heating problems with a resulting temperature impact is more relevant for extended time periods but also occurs for short term experiments. The cabinet system loses heat to the lab, which is held at a temperature of roughly $21°C$, due to a not perfectly isolated cabinet. Since the amount of lost heat is small as evaluated later in this section, this cooling effect is not strong enough to compensate the heat load produced by the lasers. Hence, the temperature rises when the lasers are operational. On the other hand, the temperature declines when the lasers are turned off again. While short experiments might suffer less from the distortion of the heat sources, long-term applications need to secure a consistent temperature control in the cabinet to receive reliable results.

In practice, the cabinet was used for experiments with both lasers working in a closed environment. As a result, they produce heat over a longer period of many hours. Figure 3 shows ~~exemplary~~ the temperature profiles of such an operation with 18 hours of laser activity of both lasers.



(a) Temperature Values (b) Humidity Values

Figure 3: Herzan cabinet temperature and humidity

The effects of the heating phase - the time where the Herzan cabinet is closed - compared to a situation with its doors open are visible. The temperature rises several degrees in the first 18 hours and after turning the lasers off drops back down to the normal room temperature. With the doors opened, the temperature drops faster. The system reacts immediately but slowly. Furthermore, the temperature effects depending on the position of the lasers in the cabinet were observable. The two shelves with the lasers (shelves 2 and 3) showed the highest change in temperature. Following in temperature effect were the shelves above (shelf 5) and underneath (shelf 1) the shelves with the lasers. Here, the effect was about half the temperature raise compared to the laser shelves. This is not surprising since the cabinet is isolated to the outside but not inside between the shelves. The shelves are only separated by the shelf material which has holes for optical instruments to be installed. Hence there is a heat exchange between the different shelves. As warmer air rises inside the cabinet, the non-laser shelf above one with a laser (shelf 5) has a higher temperature rise than the shelf underneath (shelf 1). For comparison, the laboratory temperature outside the cabinet is rather stable but shows the known higher fluctuation.

The humidity rose in the shelves without laser (shelves 1 and 5) and fell in the shelves where the heat is produced by the laser (shelves 2 and 4). A difference of about ±2% to the internal humidity was observed but remained quite stable. The large peaks 19 and 24 hours after the start of the experiments were caused by brief openings of the cabinet.

To examine the time depending temperature in a more quantitative way, data of laser 1 in shelf 2 will be analysed regarding heating as well as cooling.

The heating process can be quantified by the following formula:

$$T(t) = T_E + A(1 - e^{-\frac{t}{\tau}}) \tag{1}$$

The cooling process follows an exponential decay:

$$T(t) = T_E + Ae^{-\frac{t}{\tau}} \tag{2}$$

T_E represents the environment temperature at the beginning of an experiment. The constant A provides the maximum additional temperature the system reaches or loses. The variable τ gives the rate at which the system heats up or cools down. Larger values lead to lower cooling or heating gradients.

Figure 4 and the tabular below show the data of the graphs described by the functions before [**2**].

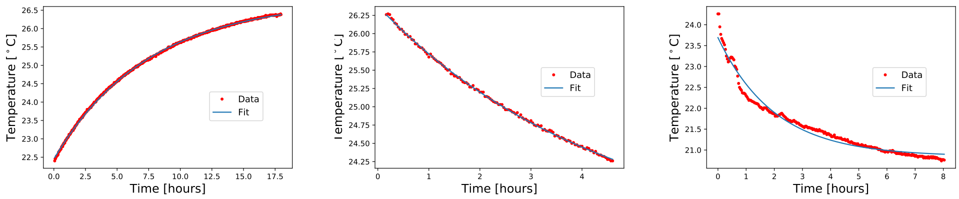
Phase	T_E [$^\circ C$]	A [$^\circ C$]	τ [hours]
Heating	22.5	4.3	7.47
Cooling (closed cabinet)	23.1	3.3	4.5
Cooling (opened cabinet)	20.9	2.8	2.0

The three fitted functions as shown in Figure 4 are:

$$\text{Heating}: T(t) = 22.5 + 4.3(1 - e^{-\frac{t}{7.47}})$$

$$\text{Cooling (Closed)}: T(t) = 23.1 + 3.3e^{-\frac{t}{4.5}}$$

$$\text{Cooling (Opened)}: T(t) = 20.9 + 2.8e^{-\frac{t}{2}}$$



(a) Heating (b) Cooling (closed) (c) Cooling (opened)

Figure 4: Data analysis of laser heating and cooling down

1.3 Experimental Approaches

Three optional cooling ~~solutions~~ need to be considered as potential solution to regulate temperature ~~conditions~~ in the laser environments:

- Thermoelectric cooling
- Air cooling
- Water cooling

Thermoelectric cooling exploits the Peltier effect [**4**]. A heat gradient between two sides of the Peltier element causes electric voltage. A current flowing through it then transfers heat from the cooled side to the warmer side diminishing the temperature on the cooler side. In order to apply thermoelectric cooling, a differential of a cold and a hot elementary side is needed. Inside the cabinet, the temperature is intended to remain constant. Hence the idea of a constant flow exploiting the Peltier effect with a cold reservoir to remove heat from the laser in the closed system did not represent a viable option. The Peltier effect could be realized by a transfer of the heat produced by the laser into the air or the other way round causing the laser to overheat, or the air inside the cabinet to heat up even more. Consequently, such a method is not useful for the air temperature stabilization.

Air cooling is applied for optical tables outside a cabinet [**5**]. Implementing such a cooling in a cabinet requires adequate space because the fans have to be placed in a useful position for air circulation. Additionally, an outlet for the warmer air to escape is needed. Hence, this cooling disregards the required restriction of minimal space consumption and a closed system with isolation. Additionally, the fans create an airflow with potential negative effect, due to vibration. ~~Not random collisions of the laser light with the atoms of the air on the experimental set up risk a misalignment of the laser.~~

As a result, the third cooling option based on a liquid cooling system (Figure 5) remains as the most promising solution. Basically, a liquid serves to absorb temperature. The heat load from inside the cabinet would be transferred to an outside heat exchanger. This heat exchanger can then be placed wherever a change in temperature is convenient. Testing water cooling system needed to show if they possess the power to cool air and not only elements in thermal contact. Having decided for this cooling approach, an optimal placement and design of the cooling system was needed. The following experiments and iterative conceptual adaptations resulted in an optimized cooling solution.

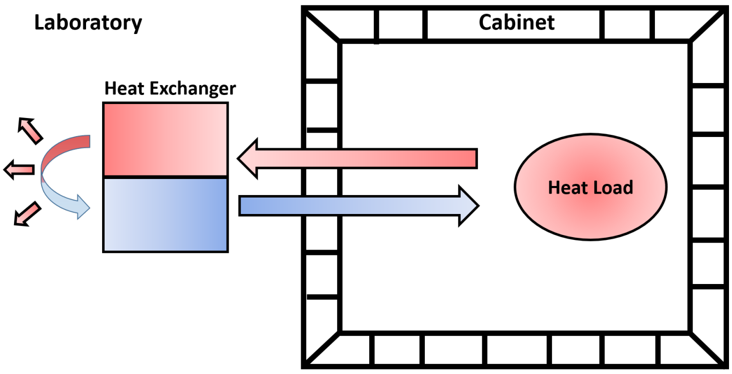


Figure 5: Schematic Liquid Cooling Configuration

2 Set-up Concept

To evaluate the concept, design, and suitability of a liquid cooling system different set-ups were tested. The principal component of the liquid cooling is a cooling plate placed within the cabinet. This plate is powered by an external chiller, acting as heat exchanger ~~the plate is connected to~~. In order to stabilize the temperature, a valve was tested in the circuit to control the liquid flow and thus the cooling power. For all tests, water was used as ~~suitable liquid~~. ~~Water represented a cost efficient and easily available resource not potentially harming the laser.~~

2.1 Temperature Measurement

Means to control the temperature as well as humidity were needed and installed in form of sensors. Generated data was send to the 'Grafana' platform where it could be accessed, plotted, ~~or~~ critical temperature limits be tracked. The sensors allowed to measure data at intervals of milliseconds but a measuring cycle of initially around every minute was ~~realized~~ for the experiments. For later experiments and extended times of experimental operation, measuring intervals of six minutes proved to be sufficient and reliable. These intervals further reflect that temperature and humidity in such closed environments are rather slow reactions. An additional sensor secured the tracking of the temperature of water in the tubing system. This sensor was evaluated via the 'Alphacool Heatmaster II' controller. Data could be tracked on a monitoring board with the corresponding software.

2.2 General Set-up

Core of the water cooling system in a cabinet and therefore the described experimental set-up built a cooling plate (no.1 in Figure 6), as shown in the whole set-up sketched in Figure 6. The cooling plate was placed inside the Herzan Cabinet individually on one of the two lowest shelves. The plate connected at the beginning with rotatable G1/4 fittings (no.2 in Figure 6) to 3/8" PVC tubes (no.3 in Figure 6). Initial trials identified a water leaking of these fittings. They were hence ~~removed~~ by straight ones that minimised the leaking probability as movement was restrained. The chiller (no.4 in Figure 6) was placed outside the cabinet trying different locations inside and outside the lab, connected to the tubing system with the corresponding connections (no.5 in Figure 6). It allowed to assess optimal positions to avoid noise and temperature impairment. The chiller worked as a heat exchanger and enabled to regulate the water temperature running through it. Additional quick-release fittings (no.6 in Figure 6) were added to allow access to different locations of the cooling circuit. These fittings were designed and implemented to be opened without water pouring out. Such a design enabled that the cooling plate could be removed from inside the cabinet without clearing the circuit. Subsequently, the circuit was upgraded by a magnetic valve (no.7 in Figure 6) and a water temperature sensor (no.8 in Figure 6) at two positions.

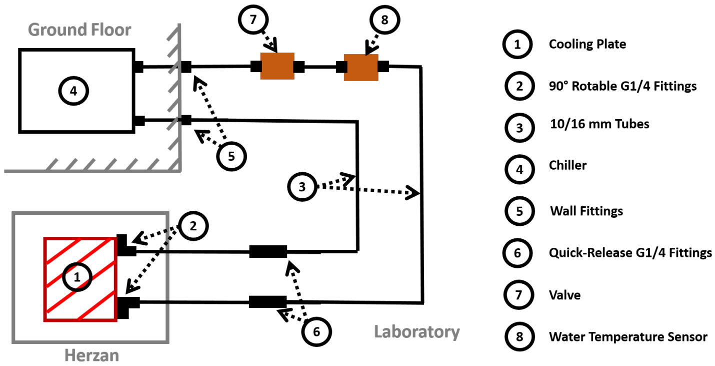


Figure 6: General Set-up

To reduce the risk of eventual damage caused by leaking water only the two ground shelves were used for the experimental installations. Especially the first set-up testings were executed outside the cabinet or in the ground shelf. Laser 1 in shelf 2 was appointed to be the relevant laser producing the heat that needs to be cooled. The set-ups therefore aimed to finally place the cooling plate inside the cabinet in a way that shelf 2 stabilizes its temperature.

2.3 Set-up Variations

To develop a sufficient cooling set-up, different variations of arranging the components inside the cabinet were tested. Two different cooling plates were verified to explore whether they are capable to cool a shelf without or with heat load. The resulting variations led to multiple measurements, partly executed successively with both plates. At the end, successful concepts showed promising results to then change the system set-up. Others failed in their test but opened new ideas or examined the efficiency of the cooling plates. ~~As a result, the design of the optimal cooling system developed evolutionary.~~

2.3.1 Alphacool Copper / Acetal Cooler

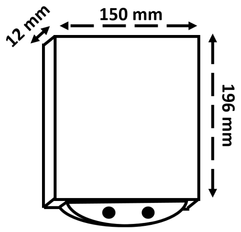
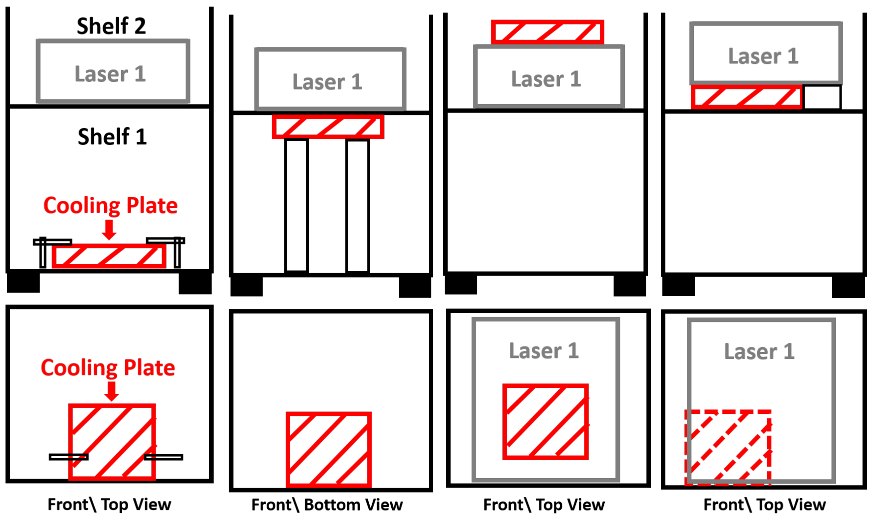


Figure 7: Dimensions Alphacool plate

The first cooling plate was a 'Alphacool Copper/Acetal Cooler' plate, originally ~~made~~ for power-supply cooling. Due to the copper surface the thermal conductivity is very high. A water cooling system relying on a small cooling plate, measuring 20 to 15 cm, could easily be placed inside the cabinet (Figure 7). Due to its original usage of cooling power-supplies with thermal contact, it was eligible to have the copper side of the plate in thermal contact with the cooled element. This device allowed to be placed in different ways inside the cabinet opening the possibility to create diverse configurations to evaluate different properties of the cooling plate. The different set-up options tested are shown in Figure 8 (upper drawings providing a perspective from inside the Herzan cabinet when opening the door and the lower drawings illustrate the set-ups by a helicopter view). Four different lay-outs were realized as shown in Figure 8.a -d:

- **Set-up 1.a:** The plate is mounted in thermal contact with the ground shelf (shelf 1).
- **Set-up 1.b:** The plate is placed in shelf 1, fixed underneath shelf 2 using plastics to push it in thermal contact against this shelf.
- **Set-up 1.c:** The plate is placed on top of laser 1 in shelf 2.
- **Set-up 1.d:** The plate is fixed on one side underneath laser 1. Respectively, the laser is placed on top of the cooling plate and held on the other side by PVC plates with the same height as the cooling plate.



(a) Set-up 1.a (b) Set-up 1.b (c) Set-up 1.c (d) Set-up 1.d

Figure 8: Set-ups Alphacool plate

2.3.2 ThorLabs Water-Cooled Breadboard

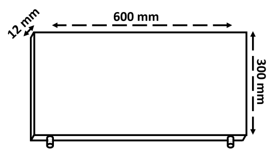
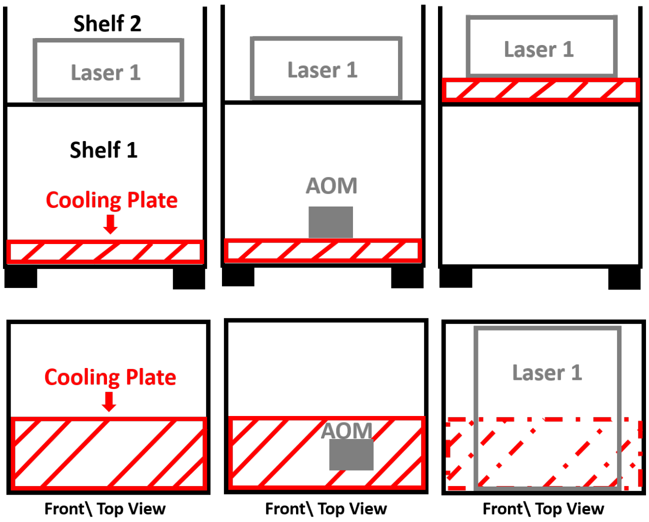


Figure 9: Dimensions ThorLabs plate

An alternative set-up surrounding was introduced based on a different cooling plate. ThorLabs designed a cooling plate serving as a breadboard (Figure 9) that allowed for eas fixation of optical instruments. Thereby this device fitted perfectly in the Herzan Cabinet. This lay-out further profited of smaller tubing connections. Still, special fittings to the 10/16 mm PVC tubes needed to be installed. The placing of the cooling plate was in accordance to the first plates set-up and is sketched in Figure 10.

- **Set-up 2.a:** The plate is mounted in thermal contact with the ground shelf (shelf 1).
- **Set-up 2.b:** The plate is mounted in thermal contact with the ground shelf (shelf 1) and an AOM placed on top.
- **Set-up 2.c:** The plate is fixed underneath laser 1 (shelf 2).



(a) Set-up 2.a (b) Set-up 2.b (c) Set-up 2.c

Figure 10: Set-ups ThorLabs plate

2.3.3 Chiller exchange

The first chiller used was a 'HRS-W Thermo Chiller' from 'SMC'. After initial trials an alternative chiller was tested. A preceding version of the 'KTC Chiller' from 'Applied Thermal Control' replaced the HRS chiller that initially was standing outside the laboratory. The new configuration allowed to position inside the lab and accessible right next to the enclosure.

Experiments concerning the temperature stabilization were risky at the beginning since some trial were based on unproven assumptions. Thus, for a few testing series the cooling plate was mounted outside the cabinet right next to the chiller to avoid that leaking water pours inside the cabinet. A potential problem with the KTC chiller was seen in the fluctuating water temperatures. But the experiments and according analysis showed that the fluctuations were limited and corresponded to the ones of the water stemmed from the lab. Overall, the chiller proved suitable for plate cooling purposes.

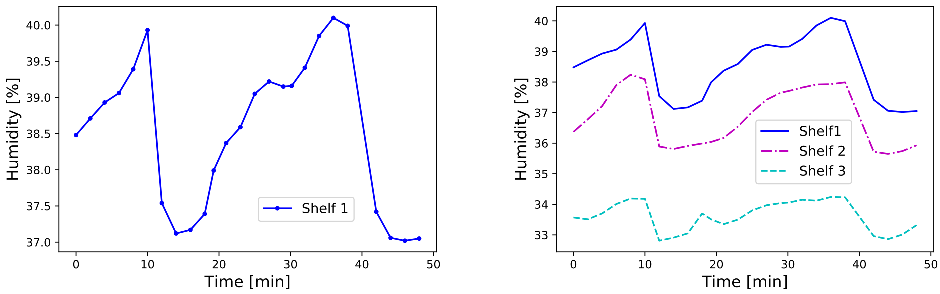
3 Experimental Results

~~Realization~~ and optimization of a cooling system requires information about the system ~~as well as about the different~~ components. Therefore, different test environments and runs were needed to determine the suitability of the component properties in different set-ups. An iterative testing allowed to step-by-step realize a ~~reliably working~~ cooling system with stabilization of the temperature. The set-ups were explained in the previous section as alternative designs ~~and~~ will be referred to in this section. The different tests were evaluated and the results are described in this section in ~~predominantly~~ chronological order. In appendix A all experiments and trials are listed in detail with the corresponding data and measured outcomes.

3.1 Humidity Control

~~To react in case~~ of water pouring out of a tube or connection and to control humidity in the cabinet, ~~a sensor system with adequate code reflection of the humidity gradients was established.~~ In case of exceeding humidity levels this approach allowed to intervene in the system and react accordingly e.g. closing the valve.

In order to measure the effect of additional water changing the humidity level, a 100x50 mm bowl filled with water was placed on shelf 1 in the cabinet. The bowl was inserted twice with two different water amounts. Firstly the water reached a level of about 1 cm to the bowl bottom, for the first test. Secondly water just covered the ground of the bowl in a second attempt, the countering test.



(a) Shelf 1 with water (b) Influences of water on shelves 1-3

Figure 11: Humidity evaluation

Figure 11 shows the humidity values received by retrieving the two different water probes: detailed inside shelf 1 showing hence data of sensor 1

(Figure 11.a) but also covering the effect in the shelves above (Figure 11.b).

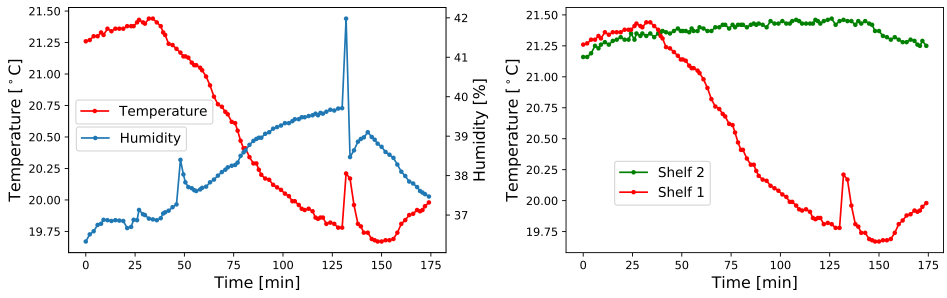
Both samples cause the humidity to rise a few percent. The effect was still visible the shelves above. Hence, possible leaking could be detected by evaluating the humidity gradients of the air even if there is no water in direct contact with the sensor. Acknowledging the humidity impact the aim was to implement a function that constantly checked the humidity gradient and allowed to discontinue the water circuit if necessary. As the standard process naturally caused humidity, critical values for water humidity needed to be ~~fine tuned~~ to avoid a shut-down of the cooling system through normal operations. A reasonable setting for the experiments was defined at: 0.8% over a time range of about 5 to 6 minutes or 0.2% for 30 seconds to one minute.

3.2 Alphacool Plate

As described, the first approaches with the Alphacool cooling plate based on different set-ups inside the Herzan cabinet. The key ambition was to produce maximum cooling power with the plates. This cooling power was then adapted so that the cooling power controlled a stable temperature inside the shelf. The experiments started out evaluating the cooling power and temperature impact of the plates on the empty shelf. As a next step, new set-ups and cooling in closer contact to the laser were run. For all experiments the guiding constraint was to stress the laser the least possible. A replacement of the laser was therefore not an option.

3.2.1 Test 1.1 - Cooling Reliability

To assess the cooling effect of the plate in an isolated surrounding and the resulting impact on the temperature as well as air humidity, the plate was mounted without any contact to the laser shelf using set-up 1.a.



(a) Cooled Shelf 1　　(b) Effect on other shelves

Figure 12: Cooling Reliability

A substantial cooling effect could be achieved. The starting temperature above $21°C$ was cooled down to less than $20°C$ in about two hours. Simultaneously the humidity in the air rose to about the same extend as the temperature fell - a plus of around 5% of the initial values. The cooling plate only affected the shelf of placement. Shelf 2 above, where the laser but not the cooling plate was positioned, apparently did not profit ~~of~~ the cooling effect in the course of the observed time span. The cooling plate was able to cool the shelf of its placement but the system was not powerful enough to cool the more distant and detached laser shelf.

3.2.2 Test 1.2 - First Approaches Laser Cooling

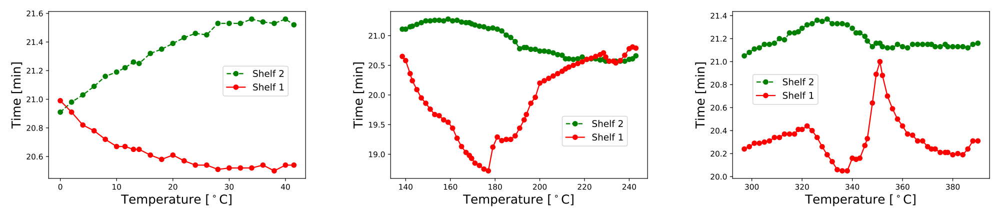
The shelves with lasers offer restricted capacity for a cooling system, as the lasers ~~require space~~. A preferable way to save room and secure the laser ~~was therefore the placement of~~ the cooling plate on the underneath of the laser ~~installations~~. The plate consequently needed sufficient power to cool through the shelf board that is seven centimetres thick. The according test design required thermal contact with the bottom of the laser shelf above (set-up 1.b). The first approaches can be split up into three different sections of the experiment:

Test 1.2a: For the first half hour, the operational laser 1 emitted heat and the cooling system was adjusted to a water temperature of $18.0°C$. The measured results (Figure 12.a) illustrate that the cooling power was not strong enough to cool the shelf above (shelf 2) beyond simply cooling the air. Despite that the plate was fixed underneath the second shelf, in thermal contact, the cooling system could not cool the laser environment.

Test 1.2b: After two hours, another run was started, keeping the cooling system but a non-operational laser. This time, the cooling was tuned down to very low water temperature of $5.0°C$ to see whether this provides sufficient cooling effect. This set-up resulted (Figure 12.b) in strong cooling again in shelf 1 but shelf 2 was cooled down,but with less impact. Only one third of the cooling effect could be achieved compared to the shelf where the cooling system was placed. Still, comparing this test to the previous one showed the possible impact of very low water temperatures. The problem occurring though was that the low water temperature led to condensation on the plate. The cabinet slowly soaked. As a result, a temperature regulation only based on minimizing the temperature of the water in the cooling circuit was not a viable solution.

Test 1.2c: To test a system with minimal distance and no barriers to the heat source the cooling plate was then placed inside the cabinet of the laser (set-up 1.c). Five hours after the experiment started, the laser was turned on. The water temperature was adjusted at $18.0°C$. As in the first part of this test, the cooling power proved not to be sufficient (Figure 12.c) to cool its shelf 2. The apparent challenge with this set-up was that the copper surface of the cooling plate had no thermal contact with the laser. Additionally, the electronics inside the laser are mounted on the bottom and not on the top where the cooling plate is placed.

This test session illustrated that turning the cooling on just in operational mode of the lasers is not sufficient to cool the shelf with the laser. This can neither be achieved from underneath nor from above the laser. Hence, an examination whether the cooling effect is larger when the whole shelf is already cooled prior to operational settings or if positioning the cooling plate in thermal contact with the laser bottom was realized.



(a) Test 1.2a (b) Test 1.2b (c) Test 1.2c

Figure 13: Data Test 1.2

3.2.3 Test 1.3 - Long term cooling

The test 1.2 showed that the cooling power of the plate wasn't strong enough. For an extended testing, the cabinet aimed to firstly be cooled by a water temperature of $18.0°C$. Then, laser 1 was turned on to assess whether the heat load impacts the shelf or if the cooling just needed sufficient time to be strong enough. This is tested with set-up 1.b

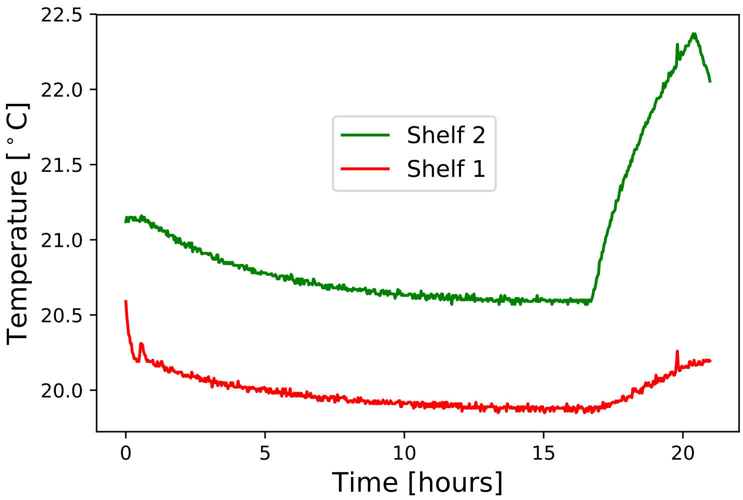


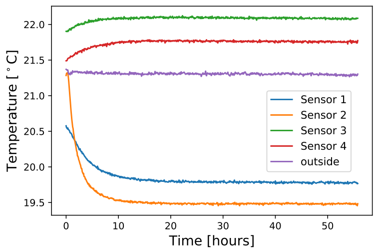
Figure 14: Long term cooling

The system resulted in a cooling effect, also in the neighbouring shelf. With an operational laser after 16.5 hours the cooling did not ~~proof~~ to be strong since the temperature rose directly, although the cabinet was cooled throughout the entire experiment. Apparently a long term cooling does not ~~stable~~ the working environment.

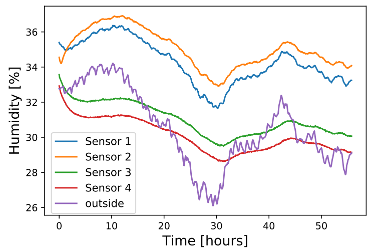
3.2.4 Test 1.4 - Laser cooling with thermal contact

Another trial with the cooling plate mounted directly underneath the laser was realized (set-up 1.d). This set-up was expected to be promising since the heat producing parts were fixed to the laser bottom and hopefully the laser itself would allow a thermal conductivity of the plate and the laser.

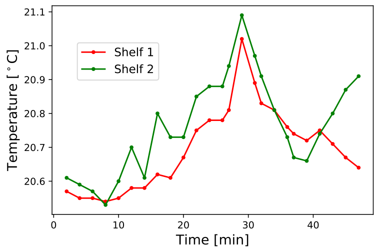
Based on the Set-up 1.d the cooling water temperature was set at $18°C$ and laser 1 was turned on (Figure 15.c). Secondly, an extended period of cooling with the laser turned off, was introduced (Figure 15.a and 15.b).



(a) Temperature



(b) Humidity



(c) Cooling Laser

Figure 15: Cooling over weekend

The cooling phase profited of a cooling of the laser, so that the temperature inside the cabinet was prevented from further rise. Mounting the plate in this position, underneath the laser but in thermal contact, had a positive cooling effect. A running cooling system for an extended period still resembled the results of the prior test, with primary cooling effect on the shelf with the plate and directly associated shelves. The humidity was in line with the humidity outside the cabinet but showed less fluctuation.

3.3 ThorLabs Plate

The identified temperature and humidity effects of the Alphacool plate with the uncovered reliable cooling effects were now tested with an alternative plate. The cooling plate from ThorLabs is about six times the size of the power-supply cooling plate Alphacool. Accordingly, with this larger cooling area the amount of water going through the plate at once is higher and therefore should allow to absorb more heat from the cabinet. The Alphacool plate ~~was~~ made ~~out~~ of copper which has high thermal conductivity. The ThorLabs Plate is ~~basically~~ made ~~out~~ of aluminium with different thermal characteristics.

$$\dot{Q} = \lambda A \frac{T_{water} - T_{air}}{d}$$

As shown in the formula the heat transfer $\dot{Q}$ between two materials, in this case water and air, with different temperatures and with A being the area between the two materials with gap d and the thermal conductivity λ [**5**] is dependent on the two factors in which the cooling plates differ. Values for the thermal conductivity are : $\lambda_{Alumnium} = 239\frac{W}{m*K}$ and $\lambda_{Copper} = 390\frac{W}{m*K}$ [**5**]. Assuming an identical distance d between the two materials as well as same temperature distance the relative cooling power of the ThorLabs plate can be calculated using the area of the cooling plates. The larger aluminium plate has therefore a larger heat exchange with the air than the smaller copper plate: $\dot{Q}_{Aluminium} = 3.7\dot{Q}_{Copper}$. This absorption capacity was expected to result in better cooling power of the ThorLabs Plate since more heat can be removed. The question was whether the larger area really compensates the lower thermal conductivity of the aluminium in comparison to the Alphacool copper plate.

3.3.1 Test 2.1 - Cooling Reliability

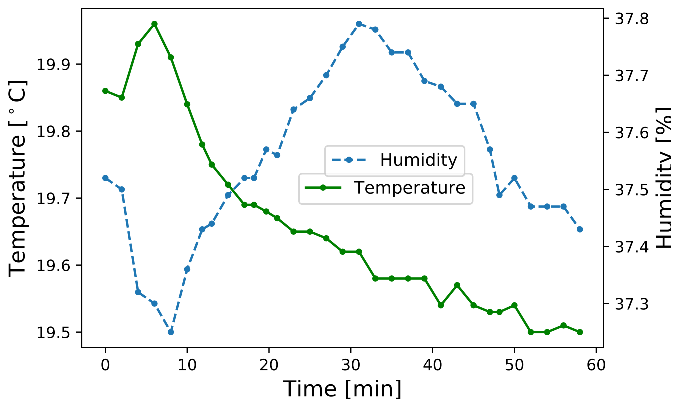


Figure 16: Cooling Reliability

Corresponding to the test with the Alphacool plate, the first set-up (Set-up 2.a) with the ThorLabs plate explored the influence of the cooling plate in an isolated surrounding without any heat load. The water was held at a constant temperature of $18.0°C$ to prevent condensation, as experienced in the test with low water temperature (Chapter 3.2.2.)

A cooling could be achieved (Figure 16) but the humidity rose. The cooling effect was stronger than with the alternative plate supporting that the large area of the used plate increases the cooling power beyond calculated effects.

The water temperature of 18.0° provided good results. Air could be cooled underneath 21°C, in line with the outside temperature of the laboratory. Additionally, such a set-up did not require an additional cooling of the water circuit, since that was the constant water temperature provided by the external water supply in the laboratory. Additional costs for a chiller could therefore be avoided. As a result, this cooling system environment provides an optimal situation for the lab.

3.3.2 Test 2.2 - AOM Cooling with thermal contact

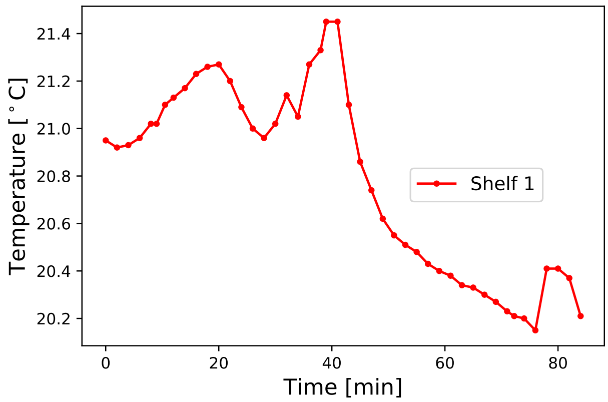


Figure 17: Cooling AOM

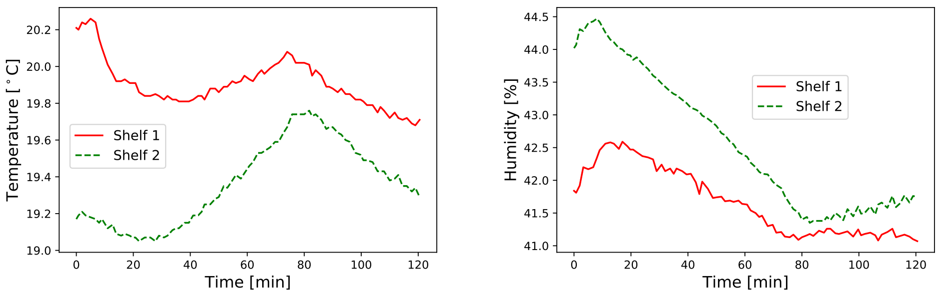
In line with the prior testing of the plates cooling power with thermal contact, an AOM was placed on the ThorLabs plate (set-up 2.b). At the beginning, this was just attached to the power supply. Then, in a second testing, the AOM was simulated to work with laser light.

Figure 17 shows the temperature of shelf 1. When the temperature reached the two visible peaks the cooling was turned on, while the powered AOM were kept operational. The prior temperature increase was due to the fact that the door of the cabinet was opened to place the AOM. A lab temperature of around 21.5° hence increased the temperature in the cabinet.

The plate cooled the heat load produced by the AOM immediately. Since the AOM produces a much smaller heat load compared to the lasers, the next step required to test the second plate in regards to cooling the laser as primary heat load.

3.3.3 Test 2.3 - Laser cooling with thermal contact

As the AOM heat load was apparently successfully suppressed by the cooling plate an according cooling effect on the laser was hoped for. Profiting from the results of the prior tests, the cooling plate was fixed underneath the laser to minimize distance and therefore enable maximum cooling power. Based on set-up 2.c a test with a water temperature of $18.0°C$ was realized (Figure 19). The experiment started with a first cooling period of 20 minutes. Then turning laser 1 on, a second cooling began 60 minutes later to verify the impact of the cooling system with an operational laser.



(a) Temperature (b) Humidity

Figure 18: Laser cooling with thermal contact

An immediate cooling effect was realized in both shelves. Shelf 2, with the operational laser, was cooled by $0.2°C$. The shelf below could be cooled by half a degree Celsius. The ~~pleasant~~ stronger cooling power of the ThorLabs plate due to its larger surface went alongside with increased humidity gradients. The opposing effects of temperature and humidity demanded further investigation in order to design a reliant, stable cooling system.

3.4 Stabilization Experiments

The results so far allowed for an optimal design of components, placements, and system conditions. In order to increase the stability and therefore optimize the transition effect on the ions, a valve system supported by a steering and controlling algorithm enlarged the project scope. Besides the physical introduction of the valves, a program controlling the valves to regulate the temperature needed to be created.

A magnetic valve was placed inside the circuit. The amount of water running through the plate can thereby be controlled and the cooling power can be regulated. Recalling that a stable temperature was the main target of the project, a regulation of the water flow was essential. The chiller, taking a lot of room inside the lab, had to be placed outside in distance and thus was not immediately accessible. A fine-tuned regulation in the initial set-up of the lab and the cabinet was therefore not possible. Introducing a magnetic valve served as a potential media to control liquid flow. A relay placed inside a box and coupled with the temperature and humidity values from the portable sensor (sensor 6) was introduced to control the valve via an Arduino. The resulting data of the experiment were transmitted to the Grafana platform. In parallel, a code containing a PID control to calculate opening and closing ratios for the valve was programmed. The code is delivered in detail (Chapter 4).

3.4.1 Test 3.1 - Large Interval Cooling

The valve was enclosed into the cooling circuit. An initial setting consisted of 5 minutes intervals alternating a closed or opened valve for 2.5 minutes. Such an initial setting allowed to seize the impact of an operational valve and then to fine-tune the PID controlling. Based on the set-up 2.c (plate underneath the laser).

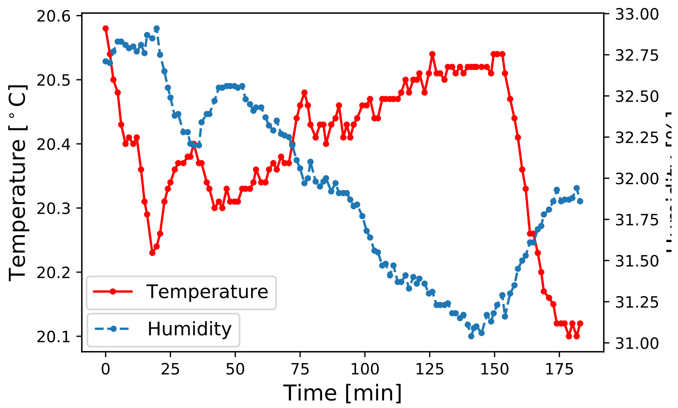


Figure 19: Cooling down to 20 degrees

In line with expectations, the cooling worked well with an opened valve (Figure 19). When activating the valve, the chosen interval with rather extensive phases of an open or closed valve resulted in an overheating of the chiller. As visible in the experiment e.g. in the ongoing experiment looking at minutes 40 to 70 - the chiller was expected to cool down since the valve was opened for around 2.5 minutes each. Against the expected stable temperature it has risen with strong fluctuations. The cabinet apparently heated up although neither the laser nor other internal heat loads were turned on. The closed valve prevented the water to circulate for a longer time. Unfortunately, a backflow was created. As a consequence, the chiller was overstressed. It heated up and so did the water inside. Instead of cooling the system it generated higher temperature. An alarm of the chiller signalized the overheating.

Acknowledging this problem two possible solutions were tested. The first consisted of an introduction of a branching inside the circuit (Figure 20). Water was allowed to flow back into the chiller in a smaller circuit when the valve was closed. In the experiments, the chiller was turned on again 160 minutes after the test started. A strong cooling resulted. Hence, the chiller was strong enough to push water through the cooling plate as well as the branching with the valve opened.

The second tested solution consisted of a reduced valve operational interval. The initial interval of 5 minutes interval was reduced to 30 seconds. This minimizes the risk of overheating due to shorter closing intervals.

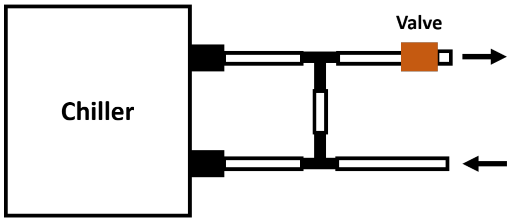


Figure 20: Branching

3.4.2 Test 3.2 - New Chiller

With the branching implemented, the HRS chiller produced a noticeable cooling effect. As described in the set-up concept, the HRS chiller had to be exchanged against a KTC chiller. The pump inside the KTC chiller was not strong enough to let water circulate through the entire circuit, it only pumped through the branching. As a result, the prior solution based on a branching was not compatible with the new chiller. Indeed, the set-up did not achieve a cooling effect, just randomly fluctuating temperature values (Figure 21).

Additionally the chillers water temperature seems to fluctuate as well. To make sure that this fluctuation was not an effect of inaccurate components or data quality, a few data sets were taken for evaluation. The water temperature was set to $16.0°C$. To assess whether the fluctuating temperature was due to the long cooling circuit, it was compared to a second short circuit data series.

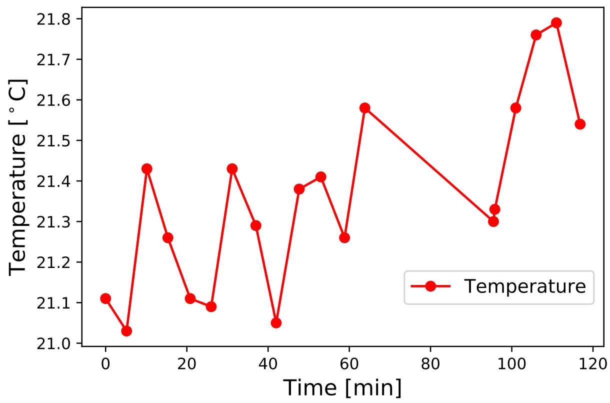


Figure 21: Shelf 2

This is the data with the cooling circuit used:

t [s]	0	30	60	90	120	150	180	210	240	270	300	330
T [$\circ C$]	16.0	16.0	16.5	17.3	17.8	17.9	17.6	16.7	16.0	16.0	16.0	17.1

This is the data with the shortened circuit used:

t [s]	0	10	20	30	40	50	60	70	80	90	100	110
T [$\circ C$]	16.0	16.3	16.6	16.7	16.8	16.9	16.9	16.9	16.9	16.9	16.8	16.8
t [s]	120	130	140	150	160	170	180	190	200	210	220	230
T [$\circ C$]	16.7	16.7	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.0	16.0
t [s]	240	250	260	270	280	290	300					
T [$\circ C$]	16.0	16.0	16.0	16.0	16.0	16.2	16.7					

According to the display the variation of the temperature was 1.5 e.g. $0.7°C$. The stated temperature on the chiller corresponded was compared to the actual temperature of the water by a sensor. Indeed, the water temperature suffered volatility. Whereas the chiller signalized a difference of around $0.8°C$, the sensor measured $0.5°C$. The variation turned out to be smaller than informed by the chiller device, but it was existent. To react to this the temperature ~~set~~ on the chiller was readjusted to $17.5°C$. This corresponded to the actual temperature of the water taking its fluctuations into consideration. This setting of the chiller was used for the following experiments as well.

3.4.3 Test 3.3 - Plate Temperature Stabilization

A testing of the cooling plate outside of the cabinet allowed to assess the temperature impact of the plate surface using the valve mechanism. After having changed the open and closing interval down to 30 seconds, it was necessary to test whether this still could achieve a sufficient cooling to a stable temperature.

Heat loads, using a heat gun, were applied observing the change in temperature. To measure the plate temperature correctly and not the air temperature, the sensor was mounted with thermal contact to the cooling plate. The heat loads affected the plate directly next to the sensor. The heat loads were applied only over a short time range to prevent overheating and damaging the cooling plate. To profit of the utmost cooling power of the plate, two experimental effects were introduced. For the one part, the cooling was turned on as usual but with the valve mechanism being opened 30 percent of the 30 seconds i.e. about 10 seconds opened and then 20 seconds closed. In the other setting the cooling was turned off to determine the cooling effect due to the air temperature of the lab.

The cooling effect does not differ by much (Figure 22). With Formula (2): $T(t) = T_E + Ae^{-\frac{t}{\tau}}$ from chapter 1.2 the resulting values for τ from the data fit were:

τ(cooling off)= 63.8 s

τ(cooling on)= 72.3 s

As the resulting values differ by less than 5%, the direct effect of the cooling plate is rather negligible in the experiment with the plate outside the cabinet. To realize the effect of the shorter intervals for temperature stabilization, the plate needs to be placed inside the cabinet.

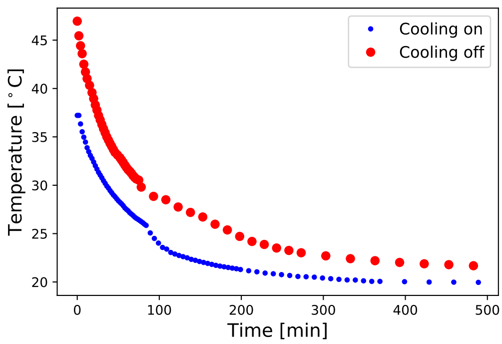
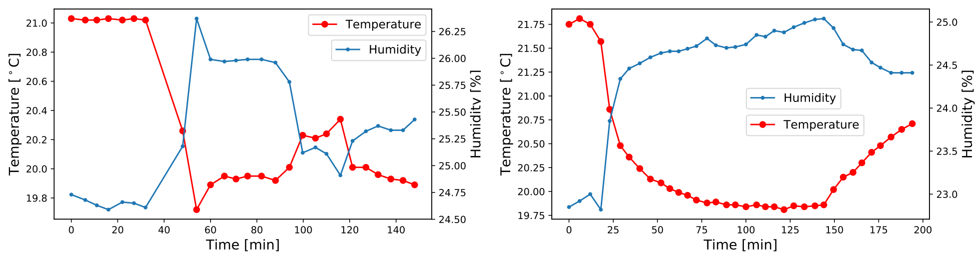


Figure 22: Heat Load

3.4.4 Test 3.4 - Shelf Temperature Stabilization

For temperature stabilization inside the cabinet, tests with alternative values for opening and closing the valve within the chosen interval and a water temperature of $17.5°C$ were realized.

Applying et-up 2.a and according tuning of the PID control allowed to stabilize the air temperature of the empty shelf. The shelf was cooled with minor deviation from the targeted temperature of $20.0°C$, resulting in around $19.85°C$ (Figure 23.a). The shortened intervals hence led to a good temperature stabilization. The cooling started quickly after the water was turned on, visible from minute 40. A second cooling period fixed the overshoot of the temperature that has been experienced in the prior experiment (see minute 111 onwards).



(a) Set-up 2.a (b) Set-up 2.c

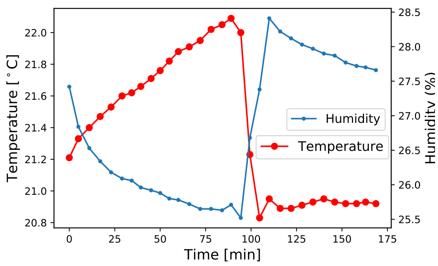
Figure 23: Cooling down to $20°C$

For set-up 2.c the cooling was turned on until a stable temperature was reached before turning the laser on. The temperature could be stabilized (Figure 23.b) at a value similar as in the prior experiments (e.g. see minute 80 and onwards). Thus, the cooling power exceeded the heat load of the laser and allowed to create a stabilized environment. When the cooling system was turned off (see minute 140), the laser caused the temperature to rise again immediately.

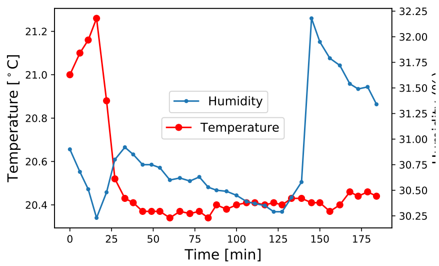
Both build ups show that humidity rises in the same manner as the temperature falls, with a strong gradient (Figure 23 a and b). Overall, a decent stabilization of temperature as well as humidity could be reached respecting the important requirements for the laser alignment.

To tune the valve 'open/closed' ratio at different set-temperatures, the cooling was changed to a temperature of $20.5°C$ (Figure 24.b) and alternatively to $21.0°C$ (Figure 24.a). Again, a good result was achieved with a temperature level slightly below the targeted one.

The last testing consisted of a set temperature of 20.5°C (Figure 24.b). Tuning the PID control in several steps got even better stabilization results. Overall, the testing has proven the ability to manage the cooling and secure laser-light alignment in the required regime between 20 and 21°C.



(a) 21.0°C set temp



(b) 20.5°C set temp

Figure 24: Control tuning

4 Valve Control Program

4.1 Control Build-up

To ensure temperature stability the valve mechanism needs to react to changes in the environmental conditions as well as to report to the user the need for action. The valve as well as the sensors are controlled via an 'Arduino Uno'. The communication between the Arduino and the data base ~~'InuxDb'~~ is executed by a Python program. The corresponding codes are presented in Appendix B.

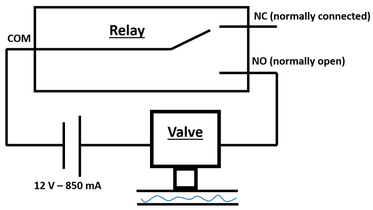


Figure 25: Relay circuit

To access all devices, the Arduino is placed inside a box, named Bart. Figure 26 shows the composition of the box. Once connected to a power supply via USB-B, Bart can connect to the temperature and humidity sensors using Ethernet cables. With 12V and 850mA applied to the 'Power' BNC-port the valve can be controlled when connected to the 'Valve' BNC-port. Therefore, a relay was placed between the Arduino and the valve. To work with the electromagnetic valve, powered by 12V and 850mA, the relay 'Adafruit Power Relay FeatherWing' has been chosen. The Arduino sends a signal to a digital pin and activates a switch inside the relay to let the current run through the valve and open it. The power circuit of the relay is shown in Figure 25.

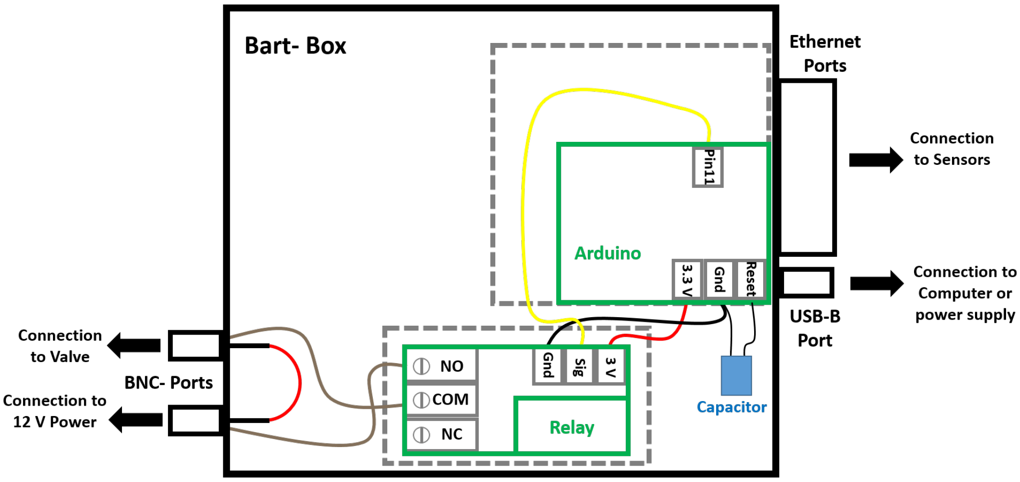


Figure 26: Bart-Box composition

4.2 Control Code

To control the devices, the Arduino executes a main loop consisting out of four parts as seen in Figure 27:

First, temperature and humidity values are received from the sensor. Then, to check for water leakage, a safety function secures that the valve must not be closed immediately. Following, the serial function opens a connection, receives instruction and returns information. At the end of the loop, the PID control inside the function valve regulates the valve.

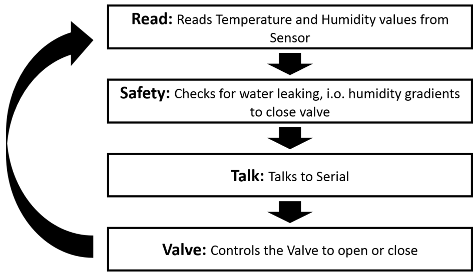


Figure 27: Main Loop Control Program

4.2.1 Global Variables

To increase security, ~~bool~~ variables were introduced to prevent a malfunctioning of the valve.

- The variable safe supervises the valve. The valve therefore only opens when safe = 1. If that is not the case, the valve was closed.
- The variable state controls the sate of the valve. When state = 1 ~~teh~~ valve is opened and for state = 0 the valve is closed. When the digital pin connected to the relay is changed, so will the variable state.
- The variable flip secures that the valve only opens and closes once in a period. If the variable is 1 the valve has already changed. After one period this variable automatically resets back to 0.

4.2.2 Read Function

To control the valve, the current values of humidity as well as temperature need to be used. With sensors attached, the implemented void-function reader does this.

The values from the SHT-sensors can be obtained using the following libraries.

```
#include <Wire.h>
#include <Adafruit_SHT31.h>
Adafruit_SHT31 s = Adafruit_SHT31()
```

To get the present values, the functions from to libraries above can be used.

```
temp = s.readTemperature();
hum= s.readHumidity();
```

These values are then stored in variables as well as arrays containing 10 values each. These values lie 30 seconds or one complete valve period behind.

4.2.3 Serial Talk Function

This function opens a serial connection if possible. The received data is then executed. The commands implemented inside the python communication code are those receiving the temperature and humidity values. The Arduino function does also contain other possibilities:

T: returns temperature value

H: returns humidity value

R: resets safe value to 1 - Reset function

A: sets safe value to 0 - Alarm function

C: returns control variable bool values: state and safe

W: returns response string containing error messages.

4.2.4 Valve Control Function

The valve could be coordinated via the relay to be opened or closed by the Arduino board. The valve was opened and closed each only once a period. The period set was 30 seconds which does not cause an overheating of the chiller and does not overheat the relay due to a too high activity.

The function valve() that is executed in the main loop first checks whether the time is still inside the period or exceeds it, to restart a new period. The value control represents the 'open to closed ratio' of the valve. Data was tracked every time the function was executed by the PID controller. It therefore can be measured in the percentage the valve is opened or closed and measured by a value between 0 and 1. For 1, the valve does not close at all. To open the valve, the digital pin (pin 11) connected to the relay needs to be activated.

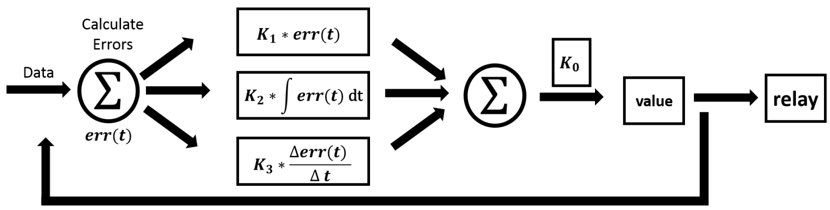


Figure 28: PID-Controller

The valve controlled via a Proportional Integral Derivative (PID) controller (Figure 28). This controller calculates a value between 0 and 1 and transmits it into opened to closed ratio. The general form of this value is obtained by :

$$value = K_0 + K_1 * err + K_2 * int_{err} + K_3 * der_{err}$$

This value should be between 1 and 0 . The values $err, int_{err}, der_{err}$ state the current error, a value obtained via integration over the last error values as well as the derivative of the last error values [**3**]. The four constants specify the weight of the three controlling rates and K_0 the value regulating the valve when the deviation to the set temperature is 0.

As a starting point the control is only subject to a proportional constant and therefore K_2 and K_3 equal 0. With the experiments from section 3.2 The experiments with different temperatures and variable values had the following results:

temperature	set temperature	err(T)	K_0	K_1	value
20.35	20.5	-0.15	0.25	0.75	0.175
20.40	20.5	-0.1	0.23	0.75	0.155
20.45	20.5	-0.05	0.19	0.75	0.1525
20.93	21.0	-0.07	0.2	1	0.13
19.85	20.0	-0.15	0.3	0.4	0.294

With the following function that converts a given temperature into the corresponding value K_0. Using the data above K_0 values for the set temperatures can were calculated using following formula: $value = K_0 + err(T) * K_1$ Expanding linearly, this gives an approximation of appropriate K_0 values for stable temperatures:

temperature	K_0
20.0	0.23
20.5	0.15
21.0	0.127

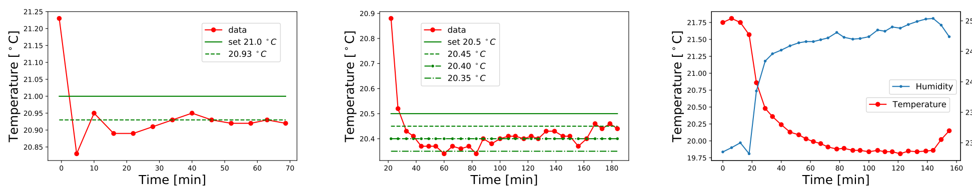
4.2.5 Safety Function

To safeguard the expensive equipment, especially to prevent the costly lasers and optical instruments from being damaged, the safety() void-function looks after malfunction of the sensors as well as for large humidity gradients. The program constantly verifies three potentially problematic areas. First, it checks whether the sensors return values. Second, the humidity values are scanned checking for strong gradients. From the testing in Chapter 3.1 it is known, that the humidity gradient rises when free water pours out within the systems. To allow fruitful response, two control functions were implemented: one reacts to recent changes in the last two humidity values and one in case of potential need for action evaluates the values of the last 5 minutes. The critical gradients determined from the data were set at 0.2% for recent gradients as well as 0.8% for a larger time scale. With gradients exceeding this limit the valve is closed and the safety switch turns to 0.

5 Conclusions and final set-up

A cooling plate as solution to heating inside a cabinet allows to reduce and stabilize the temperature. Larger as well as smaller heat loads are detected and the temperature gradient due to heating can be reversed by cooling in short time range. To regulate the temperature, an Arduino was programmed using a PID controller to evaluate data. It has proven to enable the management and control of the valve and the cooling system. The cabinet temperature was successfully influenced and the experimental conditions safeguarded.

The final set-up for the fluid-based cooling system relied on a plate from ThorLabs which proved to be stronger and more useful for temperature stabilization. This plate should ideally be mounted underneath the laser to save place and be effective in regards to the cooling ambitions. The designed circuit consisted of a connection to a chiller with a water temperature of about $18.0°C$. This chiller was connected to the plate by tubes separated by quick-release connections to make the plate accessible. Inside the circuit, a magnetic valve controlled the water as key for temperature control. As a result, the temperature in the laser cabinet can be stabilized to a regime of about $0.03°C$ at a large range of possible equilibrium temperature values (Figure 29.a). Additionally, the fluctuation of temperature still was significantly reduced. Further offset can be regulated by adjusting via control code (Figure 29.b). The PID control with an according program allow to stepwise adjust to the target temperature. Not only could the initial ambition of the project be fulfilled. The proposed and iteratively designed set-up also allows to manage humidity. In the course of the experiments, possible temperature steering solutions turned out to result in unacceptable humidity as the humidity rises when the cooling water is used for cooling (Figure 29.c). The final set up allowed to control temperature without jeopardizing experiments due to unstable humidity. The programmed code built in automated reactions to support monitored and properly managed experiments.



(a) $21°C$ set (b) Adjustment (c) Humidity

Figure 29: Stabilization Precision

A Tables of Experimental Procedures

To examine the detailed experimental line of action the tables explain the operations made in the experiments. The corresponding time can be used to look for the experimental data in detail on Grafana. The set-ups and laser numbering correspond to the Concept from chapter 2. Regarding the stated temperature values for the water coming out of the chiller (T_w) the first temperature corresponds to the set temperature and the one inside the bracket to the, using the water temperature sensor , measured actual water temperature.

Initial Experimental Situation

Date	time [hours]	Operations
23.10.2017 - 18:48	0	Cabinet closed
23.10.2017 - 19:12	0.6	Laser 1 and Laser 2 turned on
24.11.2017 - 13:32	18.7	Laser 1 and Laser 2 turned off
24.11.2017 - 13:41	18.9	Cabinet shortly opened and closed again
24.11.2017 - 18:16	23.5	Cabinet opened

Humidity control

Date	time [min]	Operations
22.11.2017 - 14:00	0	First water probe added and cabinet closed
22.11.2017 - 14:10	10	Open cabinet and second water probe added
22.11.2017 - 14:18	18	Closed cabinet

Test 1.1

Date	time [min]	Operations
10.11.2017 - 15:54	0	Set-up 1.a: Cooling water on at $T_w = 23.0°C[21.7]$ with cabinet opened to look for water leaking
10.11.2017 - 16:25	29	$T_w = 20.0°C[19.2]$ and cabinet closed
10.11.2017 - 16:54	58	$T_w = 18.0°C[17.6]$
10.11.2017 - 18:20	144	Cooling water off and cabinet still closed

Test 1.2:

Date	time [min]	Operations
15.11.2017 - 11:34	0	Set-up 1.b: Cabinet closed and Laser 1 and Laser 2 turned on. Cooling water on at $T_w = 18.0°C[17.5]$
15.11.2017 - 11:55	21	Laser 2 turned off
15.11.2017 - 12:00	26	Laser 1 turned off
15.11.2017 - 13:55	156	$T_w = 10.0°C[10.5]$
15.11.2017 - 14:11	173	$T_w = 5.0°C[6.4]$
15.11.2017 - 14:29	191	Cooling water off and cabinet opened. Set-up changed to Set-up 1.c
15.11.2017 - 15:38	260	Set-up 1.c: Cabinet closed with cooling water on at $T_w = 18.0°C[17.5]$
15.11.2017 - 15:57	279	Laser 1 turned on
15.11.2017 - 16:27	309	Cooling water off
15.11.2017 - 16:54	336	Cooling water on at $T_w = 14.0°C$

Test 1.3

Date	time [hours]	Operations
15.11.2017 - 17:30	0	Set-up 1.b: Cabinet closed and cooling water on at $T_w = 18.0°C[17.6]$
15.11.2017 - 18:00	0.5	Cabinet opened to check tubes and fittings for overnight run.
15.11.2017 - 18:15	0.5	Cabinet closed.
16.11.2017 - 10:00	16.5	Laser 1 turned on
16.11.2017 - 14:00	20.5	Laser 1 turned off and cooling water off.

Test 1.4

Date	time [min]	Operations
17.11.2017 - 13:50	0	Set-up 1.d: Laser 1 turned on and cooling water on at $T_w = 10.0°C[10.5]$
17.11.2017 - 13:55	5	Cabinet closed
17.11.2017 - 14:11	21	$T_w = 5.0°C[6.4]$
17.11.2017 - 14:29	39	Laser 1 turned off and cooling water off

Date	time [min]	Operations
17.11.2017 - 15:39	0	Set-up 1.d: Cooling water on at $T_w = 18.0°C[17.8]$
17.11.2017 - 15:57	18	Laser 1 turned on
17.11.2017 - 16:30	51	Laser 1 turned off and cooling water off

Test 2.1:

Date	time [min]	Operations
22.11.2017 - 13:00	0	Set-up 2.a: Cabinet closed
22.11.2017 - 13:05	5	Cooling water on at $T_w = 18.0°C$
22.11.2017 - 13:57	57	Cooling water off and cabinet opened

Test 2.2

Date	time [min]	Operations
22.11.2017 - 16:08	0	Set-up 2.b: Cabinet closed and AOM power on
22.11.2017 - 16:25	17	Cooling water on at $T_w = 18.0°C$
22.11.2017 - 16:35	27	Cooling water off and cabinet opened to adjust AOM.
22.11.2017 - 16:51	43	Cabinet closed and AOM in use.
22.11.2017 - 17:24	77	Cooling water off and AOM tuned off

Test 2.3

Date	time [min]	Operations
24.11.2017 - 13:30	-150	Reset temperature measurement system
24.11.2017 - 15:54	0	Set-up 2.c: Cabinet closed
24.11.2017 - 16:00	6	Cooling water on at $T_w = 18.0°C[17.6]$
24.11.2017 - 16:15	21	Laser 1 turned on
24.11.2017 - 16:31	37	Cooling water off
24.11.2017 - 17:05	77	Cooling water on at $T_w = 18.0°C$
24.11.2017 - 17:53	130	Cooling water off
24.11.2017 - 17:55	132	Laser 1 turned off

Test 3.1

Date	time [min]	Operations
29.11.2017 - 16:12	0	Set-up 2.c: Cabinet closed with valve opening and closing in 5 minutes intervals. Cooling water on at $T_w = 20.0°C$
29.11.2017 - 16:30	18	Cabinet opened to control setup
29.11.2017 - 16:48	36	Cabinet closed
29.11.2017 - 17:22	70	Chiller gives alarm and cooling water off
29.11.2017 - 18:42	150	Branching added and cooling water on at $T_w = 16.0°C$
29.11.2017 - 18:55	163	$T_w = 18.0°C$
29.11.2017 - 19:05	173	Cooling water off

Test 3.2
Note: The data taken in this experiment is shown in the corresponding chapter 3.4.2.

Test 3.3
Note: The data taken in this experiment is shown in the corresponding chapter 3.4.3.
Note: Other heat load procedures were held in the same manner as the one explained above. The data was taken using Grafana. Since values only were send every 6 minutes, the effect is more ore less not visible. The last two sets then used data outputted manually via a serial connection.

Test 3.4a:

Date	time [min]	Operations
14.02.2018 - 12:42	0	Set-up 2.a: Cabinet closed to get a stable temperature
14.02.2018 - 13:21	39	Cooling water on at $T_w = 17.5°C$ with set-temp = 20.5, $K_1 = 0.1$ and $K_0 = 0.3$
14.02.2018 - 14:10	88	Cooling water off
14.02.2018 - 14:16	94	Cabinet opened
14.02.2018 - 14:33	111	Cabinet closed and cooling water on at $T_w = 17.5°C$ with $K_1 = 0.4$
14.02.2018 - 15:16	154	Cooling water off and cabinet opened

Test 3.4.b:

Date	time [min]	Operations
14.02.2018 - 16:00	0	Set-up 2.c: Cabinet closed to get a stable temperature inside the cabinet
14.02.2018 - 16:13	13	Cooling water on at $T_w = 17.5°C$ with set-temp = 20.0, $K_0 = 0.3$ and $K_1 = 0.4$
14.02.2018 - 17:26	86	Laser 1 turned on
14.02.2018 - 18:20	240	Cooling water off
14.02.2018 - 19:15	295	Laser 1 turned off

Test 3.4.c:

Date	time [min]	Operations
15.02.2018 - 09:47	0	Set-up 2.c: Cabinet closed and Laser 1 turned on
15.02.2018 - 11:21	94	Cooling water on at $T_w = 17.5°C$ with set-temp = 21.0, $K_0 = 0.2$ and $K_1 = 1.0$
15.02.2018 - 12:40	94	Cooling water off and Laser 1 turned off

Test 3.4.d:

Date	time [min]	Operations
15.02.2018 - 15:21	0	Set-up 2.c: Cabinet closed and Laser 1 turned on
15.02.2018 - 15:36	15	Cooling water on at $T_w = 17.5°C$ with set-temp = 20.5, $K_0 = 0.25$ and $K_1 = 0.75$
15.02.2018 - 16:46	85	$K_0 = 0.23$
15.02.2018 - 18:02	161	$K_0 = 0.19$
15.02.2018 - 18:30	199	Cooling water off and Laser 1 turned off

B Programs

The completed controlling programs are displayed in this section.

B.1 Arduino Program

The Program controlling the valve as well as the connection with the sensors is an Arduino Program written in C:

```
#include <Wire.h>
#include <Adafruit_SHT31.h>

Adafruit_SHT31 s = Adafruit_SHT31();

int D0 = 4;
int D1 = 3;
int D2 = 2;
int V0 = 11;
bool safe = 1;
bool state = 0;
float control = 0;
bool flip = 0;
float temp= 0;
float hum = 0;
float temparray [10];
float humarray [10];
float errarray [5];
char port= 48;
float t1;
float period = 30000; // 30 s
float settemp = 20.5;
float K0 = 0.15;
float K1 = 0.75;
String response = "";

void setup() {
  Serial.begin(115200);
  pinMode(V0, OUTPUT);
  pinMode(D0, OUTPUT);
  pinMode(D1, OUTPUT);
  pinMode(D2, OUTPUT);
```

```
  digitalWrite(D0, LOW);
  digitalWrite(D2, LOW);
  digitalWrite(D1, LOW);
  s.begin(0x44);
}
float t0 = millis();

void loop() {

    reader();
    safety();
    talk();
    valve();
  }

void valve(){
    t1= millis();
    if (t1-t0 > period){
      t0= millis();
      flip = 0;
    }
    control = pid();
    if ((t1-t0)/period > control and flip == 0){
      digitalWrite(V0, LOW);
      state = 0;
      flip= 1;
      }
    else if(safe == 1 and flip == 0){
       digitalWrite(V0, HIGH);
       state = 1;
     }
}

float pid(){
  float value = 0;
  float err= temp-settemp;
  value = K0 + Kp*err;
  if (value <0){
    value = 0;
  }
  return value;
```

```
  if (value >1){
    value = 1;
  }
}

void reader ()
  temp = s.readTemperature();
  hum= s.readHumidity();
  if (t1-t0 > period){
    for (int i = 0; i < 9; i++){
      temparray[i+1]=temparray[i];
      }
    temparray[0] = temp;
    for (int i = 0; i < 9; i++){
      humarray[i+1]=humarray[i];
      }
    humarray[0] = hum;
  }
}

void talk(){
  while (Serial.available() > 0) {
    int input = Serial.read();
    switch(input){
      case 'T':
        Serial.println(temp);
        break;
      case 'H':
        Serial.println(hum);
        break;
      case 'R':
        safe = 1;
        break;
      case 'C' :
        if (state ==1 and safe ==1){
          Serial.println("11");}
        if (state ==0 and safe ==1){
          Serial.println("01");}
        if (state ==0 and safe ==0){
          Serial.println("00");}
        if (state ==1 and safe ==0){
```

```
          digitalWrite(D0, LOW);
          Serial.println("10");}
        break;
      case 'W' :
         Serial.println(response);
         response = "";
         break;

     }
   }
 }

void safety(){
  if (!safe){
   digitalWrite(V0, LOW);
   state= 0;
  }
  if (isnan(temp) or isnan(hum)){
    safe = 0;
    response = response + " Sensor Error;";
    }
  float gradient= humarray[0]-humarray[9];
  if(gradient>3 and humarray[0]!= 0 and humarray[9]!= 0){
    digitalWrite(V0, LOW);
    state= 0;
    safe = 0;
    response= response + " Water ALARM - period; ";
  }
  if( humarray[0]-humarray[1]> 0.5 and humarray[0]!=0 and humarray[1]!=0){
    digitalWrite(V0, LOW);
    state= 0;
    safe = 0;
    response= response + " Water ALARM - recent; ";
  }
}
```

B.2 Python Program

The Program building up a connection between computer and Arduino is written in python:

```
import serial
import time
import influxdb
import argparse

#talk to Arduino:
def get_packet(port='COM3'):
    with serial.Serial(port=port, baudrate=115200, timeout= 10) as s:
        s.write('T'.encode())
        temperature = float(s.readline())
        s.write('H'.encode())
        humidity = float(s.readline())
        data = {'temperature': temperature,'humidity': humidity}
    return data
def output(data):
    print(data)

#Talk to InfluxDb:
def send_influx(data):
    json_body = [
    {
        'measurement': 'herzan',
        'fields': data
    }
    ]
    client = influxdb.InfluxDBClient('opticaltrap.ethz.ch', 8086, 'otuser', '25M
    client.write_points(json_body)
    output(data)
    print('data written to influxDB')

#Main Loop:
if __name__ == '__main__':
    parser = argparse.ArgumentParser(description='Connects to Herzan Data and ob
    parser.add_argument('-r', dest='read', action='store_const', const=output, d
    args = parser.parse_args()
    for attempt in range(10):
        try:
```

```
        args.read(get_packet('COM3'))
        break

    except Exception as e:
        print(e)
        print('try %d, error reading from serial port' % attempt)
        pass
```

C Abbreviations

Abbreviation	Meaning
AOM	Acousto-Optical Modulator
EMI	Electromagnetic Interference
PID Controller	Proportional Integral Derivative Controller

List of Figures

References

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