ENVRIplus DELIVERABLE

D3.4
Report on improved robustness in extreme conditions

WORK PACKAGE 3 - Improving measurement networks: common technology solutions

LEADING BENEFICIARY: **Italian National Research Council (CNR)**

Author(s):	Beneficiary/Institution
Vito Vitale	Consiglio Nazionale delle Ricerche (CNR)
Federico Zardi	Consiglio Nazionale delle Ricerche (CNR)
Mauro Mazzola	Consiglio Nazionale delle Ricerche (CNR)
Angelo Lupi	Consiglio Nazionale delle Ricerche (CNR)

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ABSTRACT

The results of a questionnaire on *energy, operations and data transmission in extreme conditions.*, aiming to identify needs of Research Infrastructures (RI) remote stations with respect to extreme conditions, clearly indicate that the main problem/need for RIs operating in extreme conditions is in relation to temperature to which instruments/sensors operate and data are collected. Internal humidity conditions are also environmental conditions of relevance for RIs that are operating in extreme environments. Based on these findings, work on task 3.2 reported in this deliverable concentrates on developing an electronic board and related firmware able to pilot selected technical solutions for regulating/controlling Temperature and Relative Humidity at which instruments operate in extreme environmental conditions.
Existing technologies to regulate T and RH have been extensively reviewed and the most suitable to support RIs operations/activities in remote and extreme environments have been selected. For them we developed a PCL-based control unit/tool, based on two electronic boards (we separated power operations from the more delicate signals/commands handling and generation as well as data acquisition) and dedicated firmware providing the intelligence to drive each of the three selected technologies to regulate/control the temperature at which instruments should operate. The system is able to control non only the target temperature but also as much as possible thermal gradients internal to the heated box.
To extensively test the efficiency of the developed hardware and software in real conditions (i) thermoregulated systems (proofs of concept) have been designed and then in large part realized, and (ii) a test plans has been prepared and in large part implemented. Results Analysis clearly demonstrate capability of our control unit and associated algorithms to control temperature in a very extended range of environmental conditions. Developed control unit, joint to recommendations and information provided in this deliverable should able ENVRI RIs to address in the right way issue related to operational temperature control in the largest part of cases.

Project internal reviewer(s):

Project internal reviewer(s):	**Beneficiary/Institution**
Carole Philippon	Commissariat à l'énergie atomique et aux énergies alternatives (CEA)
Philipp Kozin	Commissariat à l'énergie atomique et aux énergies alternatives (CEA), Laboratoire des Sciences du Climat et de l'Environnement

Project external reviewer(s):

Project internal reviewer(s):	**Beneficiary/Institution**
Laurent Delauney	Institut français de recherche pour l'exploitation de la mer (Ifremer)

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Amendments, comments and suggestions should be sent to lead Authors Vito Vitale, v.vitale@isac.cnr.it and Federico Zardi, f.zardi@isac.cnr.it

TERMINOLOGY

A complete project glossary is provided online here:
envriplus.manageprojects.com/s/textdocuments/nLFCMXHHCwS5hh

PROJECT SUMMARY

ENVRIplus is a Horizon 2020 project bringing together Environmental and Earth System Research Infrastructures, projects and networks together with technical specialist partners to create a coherent, interdisciplinary and interoperable cluster of Environmental Research Infrastructures across Europe. It is driven by three overarching goals: 1) promoting cross-fertilization between RIs, 2) implementing innovative concepts and devices across RIs, and 3) facilitating research and innovation in the field of environmental understanding and decision-making for an increasing number of users outside the RIs.

ENVRIplus aligns its activities to a core strategic plan where sharing multi-disciplinary expertise will be most effective. The project aims to improve Earth observation monitoring systems and strategies, including actions to improve harmonization and innovation, and generate common solutions to many shared information technology and data related challenges. It also seeks to harmonize policies for access and provide strategies for knowledge transfer amongst RIs.

ENVRIplus develops guidelines to enhance trans-disciplinary use of data and data-products supported by applied use-cases involving RIs from different domains. The project coordinates actions to improve communication and cooperation, addressing Environmental RIs at all levels, from management to end-users, implementing RI-staff exchange programs, generating material for RI personnel, and proposing common strategic developments and actions for enhancing services to users and evaluating the socio-economic impacts. ENVRIplus is expected to facilitate structuration and improve quality of services offered both within single RIs and at the inter-RI (European and Global) level. It promotes efficient and multidisciplinary research offering new opportunities to users, new tools to RI managers and new communication strategies for environmental RI communities. The resulting solutions, services and other project outcomes are made available to all environmental RI initiatives, thus contributing to the development of a coherent European RI ecosystem.

TABLE OF CONTENTS

1 - INTRODUCTION

Distributed RIs infrastructures, with cascading networks of in situ observatories from large-scale networks of platforms or sites to local networks of various sensors, face specific technological problems when they need to operate in remote areas or extreme conditions. Moreover, such burdens usually increase with the remoteness of the station, and remoteness and extreme conditions are often inter-linked with each other. It must be also noted that extreme conditions cover a very large spectrum of operational cases. They are not limited to cold conditions and polar regions, but can include hot seasons and areas (like deserts or volcanoes), deep sea, and (out of the domain of ENVRIplus partners) vacuum and space. Conditions can be extreme with respect to only one parameter (i.e. temperature) or arise by several of them combined, such as many environmental conditions, as well as operational constraints, including power supply, data storage/transmission, access, etc.

RIs are operating in polar (SIOS), high mountains (ACTRIS, ICOS), deep sea (EMSO) conditions and on-board floating infrastructures (EURO-ARGO) and planes (IAGOS). Therefore, existing RIs have developed ad-hoc solutions to overcome specific problems and we expect that common activities toward network integration could contribute to generate important cross fertilization across the infrastructures. Robust inter-connection within and across these networks is still at an infancy level, while various innovative technologies are becoming available and their evolution is offering new technical solutions at fast speed. Role and scope of ENVRIplus is to foster sharing of experiences and common practices as well as to mobilize competencies to profit from technological innovation to find and develop up-to-date joint solutions for field installations. Aspects related to (i) existing technologies addressing energy production at remote sites, (ii) improved data transmission and communication (with particular attention to NRT problem) and (iii) standard test methods to qualify single instruments as well as complex observing platforms to operate for long durations in all kinds of environments with reliable accuracy, are illustrated and discussed in other deliverables of WP3. Scope of this deliverable is to discuss aspects related to operations in extreme environmental conditions, and present the work made in ENVRIplus to develop innovative solutions addressing this specific issue.

Being, as remarked above, extreme conditions a very broad field, perceived very differently depending on the needs of the user, the results of the WP3 questionnaire on *energy, operations and data transmission in extreme conditions.*
(https://docs.google.com/forms/d/1-xlA675xoPn- bwnUdO8Mm7nzARvdnVjzIRVoHBu8qsI/viewform), aiming to provide technical information on European Public Research Infrastructures (RI) remote stations with respect to:
-> ENERGY (production and storage) (WP3 task 1)
-> EXTREME CONDITIONS (technical solutions/standards) (WP3 task 2)
-> DATA TRANSMISSION (WP3 task 3)
collected up to now clearly indicate that the main problem/need for RIs operating in extreme conditions is in relation to temperature to which instruments/sensors operate and data are collected.
Internal humidity conditions and water resistance/corrosion are also environmental conditions of relevance for RIs that are operating in extreme environments.

Based on these findings, work on task 3.2 reported in this deliverable concentrates on developing an electronic board and related firmware able to pilot selected technical solutions for regulating/controlling Temperature and Relative Humidity at which instruments operate in extreme environmental conditions. Existing technologies to regulate T and RH have been extensively reviewed and the most suitable to support RIs operations/activities in remote and extreme environments have been selected. For Temperature, in addition to classical and obvious heating systems based on thermo-regulated resistors, we have selected also Peltier and heat pipe technologies, considering both possible limitation in available power supply and efficiency. For relative humidity we have at the end considered just one technical solution.

On the basis of these choices, we developed a control unit/tool, based on two electronic boards (we separated power operations from the more delicate signals/commands handling and generation as well as data acquisition) and dedicated firmware providing the intelligence to drive each of the three selected technologies to regulate/control the temperature at which instruments should operate. The system is able to control not only the target temperature but also as much as possible thermal gradients internal to the heated box. Considering the possible need of an inspection inside the box containing instruments, we have included the capability to connect, if necessary, a door sensor, through which we can know if there are heat dispersions caused by box opening or malfunction. Thanks to this sensor, if the door opens, the system automatically switches off the fans and the heating/cooling device to save energy.

To extensively test the efficiency of the developed hardware and software in real conditions for selected technologies/solutions indicated above, we designed and then in large part realized systems for each of the three technical solution for temperature control (proof of concept). For Peltier and heat pipes, selection of commercial devices to utilise was based on a careful analysis of the market. In the developed proof of concept, control of temperature and gradients are performed thanks to several sensors. To drive the heating power if the temperature is below the set target, ambient temperature and humidity conditions are measured outside the box and continuously compared with corresponding sensors placed inside the box in a central position of the box volume. Other sensors are also placed inside the box, in different positions, with the scope to monitor how the heat distributes within it and the temperature gradients, activating/regulating if necessary fan(s) to homogenize the temperature. This is necessary, since in extreme conditions, without forced circulation, we can have very strong and persistent temperature gradients even in few centimetres even inside a heated box. A test plan was developed and is under implementation to proof/verify the capability of our system to correctly control technical solutions in the very extended range of environmental conditions that typically RIs can encounter in atmospheric as well as other domains.

The following sections present in detail the work briefly summarized above: technology analysis and selection, technical features of developed boards, dedicated firmware and proof of concept, results of first tests.

2 – TEMPERATURE AND HUMIDITY CONTROL IN ENVIRONMENTAL MEASURES

Measuring instruments characteristics and performances are strictly connected to the environmental conditions in which they operate, and in particular to temperature. This sensitivity is a direct consequence of the fact that (i) the *sensor* of the instrument is a device that produces a proportional output signal (electrical, mechanical, magnetic, etc.) as response to a physical phenomenon (temperature, displacement, force, etc.), and (ii) the properties of other instrumental components (e.g. interference filters) vary with environmental conditions like temperature and humidity. User manuals and instrumental characteristics provided by manufactures refer to environmental conditions they consider typical for applications for which instruments were developed.

In addition, electronic components generally need to work at temperatures above zero, while operation at very high temperatures tend to degrade components and increase the risk of breakages. In addition, they need to operate in an ambient where humidity is far both from 0% and 100%. While the second is quite obvious the first is less considered in general by users, since people tend to underrate the role air humidity play in redistributing electrostatic charges and maintain equipotential conditions among electronic components of a board.

As a consequence of the above remarks, for activities in remote sites and/or extreme conditions, in order to assure realistic and accurate measurements, it is generally very important to control and regulate most important environmental parameters to which the instrument will work. This can be a non-trivial job for outdoor instrumentation. In this chapter, the general problem of controlling temperature and humidity will be posed and treated from the point of view of measurements important to Environmental RIs.

2.1 – <u>Temperature control</u>

Controlling the temperature in extreme environments implies a series of a priori considerations in order to select the more suitable technology and methodology to use for each specific case. They are connected with the environmental conditions in which we will operate, as well as with aspects related to operational conditions, e.g. available power supply.

The first question to address refers to the temperature range: at what extremes will we operate? In very hot or very cold environment? How far will we be from the temperature for which the manufacturer provides instrumental characteristics and constants? Usually, the reference temperature for reporting the working characteristics is 25 °C. This temperature, representing the most common operational environmental conditions, was selected by industry and manufacturers to calibrate components and evaluate functioning of the electronic and optical components. Response curves provided by manufactures are usually centred around this value.

Another important question refers to the power supply we have available and hence the energy available for thermo-regulating the instrumentation. Very often extreme environments operation of RIs also imply a long distance from easy sources of electric power. So, considering our range of applications, for the rest of the document we will consider that energy available is always, to some extent, limited. That said, we will continue to have a wide spread of conditions ranging from few watts up to few hundred watts for the thermo-regulating system.

Limitation of power supply is strictly connected with a third question we need to address when we are designing a thermostatic system: which parts of the instrument need to be protected against extreme conditions in order to assure the operation and characteristics of the instrument and the quality of the measurements. Sometimes, it is possible to limit protection only to part of the instrumentation, thus reducing energy needs. Many other times, this is impossible, so that users are forced to design large enclosures and boxes for the whole instrument, and to use materials with very low thermal conductivity in order to increase thermal efficiency and reduce current consumption. Table 1 lists the most common materials used for thermal insulation, with the corresponding thermal conductivity.

Table 1 List of common materials adopted for thermal insulation, together with their conductivity coefficients.

Material	λ [W/m K]
Polyurethane foam	0.032 – 0.034
Polyethylene	0.33
Polystyrene	0.035
Cork	0.052
Wood	0.10 – 0.12
Silica airgel in panels	0.013
Micronal in panels	0.018

The distribution of heat within a space is another point to consider in the design of a thermo-regulated system. Usually the medium through which heat flows is air, so we need to move it through use of fans. They should be dimensioned according to the volume of the box/container/envelope that we need to thermostat, in such a way as to make the temperature inside that as uniform as possible. Usually, fans are installed on/near the heat sinks.
Heat sinks shape, dimension and position are the last elements that we need to consider when we need to take into account and define when designing a system to regulate and control operation temperature and identify the best technology and components for it.
The choice of the materials, as well as the technology to be used for the construction of a thermostatic system for extreme environments, should take into account also the aspects of object transportability, weight and size being a limiting factor when these objects need to be transported and installed in remote and extreme places.
On the basis of the above remarks, for scope and operations of interest of Environmental Research Infrastructure, we have selected three thermostatic technologies among all the different ones available: heating resistors; Peltier cells; heat pumps and heat pipes. Below, these three technologies as well as devices/component offered by the market for each of them are described.

2.1.1 - Heating resistors

Heating resistors are electrical devices made of conductive materials, which undergo a heating effect proportional to the current flowing through them, via the Joule effect. The produced heat varies according to the resistance value, which is dependent on the construction material, the length and the cross-section of the element according to the following formula.

$$R = \rho * \frac{l}{s}$$

ρ = electrical resistivity [Ω*m]

l = conductor length [m]
s = conductor section [m^2]

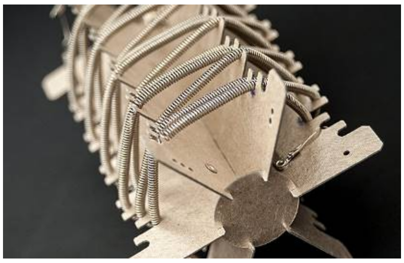
The produced heat is proportional to the square of the current and to the resistance.

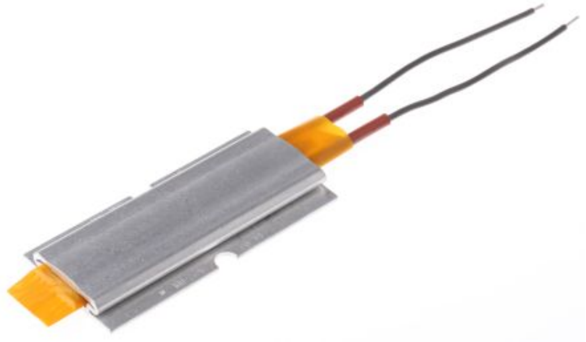
$$Q = R * i^2$$

This technology has low cost and simply mechanical installation. The electricity used turns completely into heat, so the efficiency of the technology is maximum. These characteristics make this technology suitable for extremely cold environments.

Depending on the type of application, various types of resistive heaters are available. Some of theme are described in Table 2 below.

Table 2 Different types of resistive heaters.

	Cartridge heater: its uses are the most varied. This rectifier allows very high power densities (up to 50 W/cm^2 on the surface of the sheath) to be obtained.
	Heating wire: easily positioned and with excellent heat distribution in any application.
	Suspended wire heater: its classic application is the hairdryer. This device permits an excellent heat exchange with the air passing through it. Air should be force to flows trough this element.
	Kapton heater: its advantage is flexibility and the possibility to be glued with a sticker to any surface, with a very small footprint. If installed correctly, it guarantees a very homogeneous distribution of heat.
	Heater for liquids: is used for heating water in washing machines, dishwashers and electric radiators, etc. Its shape permits to transfer the maximum of the energy produced.

	PTC Thermistor: All resistors have some dependency on temperature, but in general temperature coefficient is minimized. In the case of thermistors at high temperature a high coefficient is achieved. In the case of PTC thermistor they have a Positive Temperature coefficient (PTC). As a consequence, they are able to self-regulate the maximum temperature, thanks to the variation of resistance with temperature.

The last category in Table 2, PTC thermistor, certainly deserves a closer look for its great utility and flexibility for particularly cold environments such as the polar regions. PTC thermistors are used when a sudden change in resistance at a certain temperature is required **(1)**. They exhibit a sudden increase in resistance above a defined temperature, called the switch, transition of “Curie” temperature. The most common switching temperatures are in the range of 60°C to 120°C. Among PTC thermistors, the switching types are most relevant for our applications, since they are characterized by a highly nonlinear resistance-temperature curve. Switching PTC thermistors have a slightly negative temperature coefficient up to the point of minimum resistance. Above this point, they experience a slightly positive coefficient up to its transition temperature TC. This temperature is called the switch, transition or Curie temperature. The switch temperature is the temperature at which the resistance of switching type PTC thermistors starts to increase dramatically **(2)**.
Thanks to these nonlinear characteristics switching PTC thermistor are suitable to realize self-regulating heaters. If there is a current running through a switching PTC thermistor, it will auto-stabilize at a certain temperature not far from TC. In fact, if the temperature is decreased, the resistance will decrease as well, allowing more current to flow and thus heating the device. Similarly, if the temperature is increased, the resistance is increased as well (dramatically just after passing TC), limiting the current passing through the device, thus cooling it down.
These PTC thermistors are often made of ceramics in various shapes and sizes, and, because of their design flexibility, PTC ceramic heaters are a great choice for providing controlled electrical heat. For temperature regulation, the ceramic heating elements need to be mounted on aluminium heat sinks or grids in order to increase heat transfer and therefore efficiency. Combination with fans is also important to avoid strong gradients throughout the heated volume.

2.1.2 – Peltier cells

This technology is based on a thermoelectric effect discovered in 1834 by the French physicist Jean-Charles-Athanase Peltier (from which the name) **(3)**. The Peltier effect consists in the fact that if electric current is passed in a bimetallic circuit, one of the junctions is heated (giving heat to the environment) and the other is cooled (absorbing heat from the environment); if the direction of the current is inverted, the junction that was previously heating up cools, and vice versa. The quantity of heat dQ exchanged by an external junction in a time interval dt is proportional to the intensity of the current and to a coefficient called Peltier coefficient or Peltier electromotive force. It is important to note that the Peltier effect is a reversible effect, in the sense that the quantity of heat exchanged in the process is either emitted or absorbed by the joint according to the direction of the current. It is also important to note that the Peltier effect is always combined with the Joule effect, since we are dealing with the passage of current into a resistive circuit. This last consideration takes on great importance in the development of an optimal algorithm for piloting any device based on this effect.

Peltier cell devices are basically a solid-state heat pump with the appearance of a thin plate. Thanks to application of the Peltier effect above described, one of the two surfaces absorbs heat while the other emits it. while the direction in which the heat is transferred depends on the direction of the direct current applied to the ends of the plate itself. A common Peltier cell is made of an N-type and a P-type doped semiconductor material, connected to each other by a copper lamella. If a positive voltage is applied to the N type and a negative voltage to the P type, the upper lamella cools while the lower one becomes hot. By inverting the voltage, the thermal energy displacement reverses. On the market there are insulated Peltier cells and non-insulated Peltier cells: the first ones are coated with ceramic material and guarantee higher yields than the second ones.

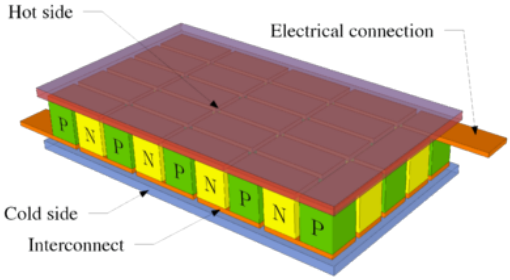


Figure 1 Graphic representation of a Peltier cell.

The common use of the cell is the subtraction of heat by adhesion of the cold side to the body to be cooled; the subtraction of heat is favoured by the creation of appropriate thermal bridges (thermo-conductive adhesives or, for a better thermal transfer, graphite sheets with a thickness of a few tenths of a millimetre) that allow the best conduction. The subtracted heat is transferred to the hot side, together with the operating heat (which is the majority); on the hot side the heat must be transferred to the external environment.
The main problem related to the use of Peltier cells is the control of the current intensity o to which corresponds the intended subtraction of heat. Using temperature sensors on both side of the element, and through a suitable feedback circuit, the intensity of current supplied to the cell can be dinamically adjusted. If this is not correctly implemented, two major effects can occur:

I. The chilled thermal source decreases the production of heat or ceases to produce it: in this case, the heat subtraction of the cell, if not controlled, can lower the temperature below the freezing point in a few seconds. In the event that the cooled part is, for example, the CPU of a computer, this means that the Peltier CPU-plate assembly can freeze and, if exposed to the atmosphere, condense atmospheric moisture into ice.
II. The thermal source increases the production of heat: in this case, if the cell doesn’t increase the subtraction of heat, its hot side can also heat up and if its temperature exceeds the maximum allowed value, the cell can "cook", i.e. be irreparably damaged and stop working. Moreover, the damage interrupts the subtraction of heat, with potential catastrophic consequences on the whole device.

In summary, subtraction of the variable heat needs to be carried out carefully, governing the current that is driving the cell and checking that the removed heat is transferred to the environment. Harmful temperatures for the cell are usually around 75 ° C and it’s necessary to remove the heat generated by means of heat sinks, radiators or heat pipes, which generally have dimensions and weights of several orders of magnitude greater than the cells themselves. This means that the dimensions of a Peltier-based thermal system depend mainly on the cooling system of the same.
The main limit on the use of Peltier cells remains their very low efficiency, and this penalizes their use. Indeed, the amount of heat dissipated by the cell is much greater than that which can be removed from the cold side. This constraint limits the use of the Peltier cells to applications in which the powers to be used are relatively modest, but above all limits the temperature gradient that can be generated. The first limitation is not a problem for the typical applications and uses of Environmental Research Infrastructures. The second, instead, has a stronger impact, limiting the usefulness of this technology

in case of very cold or very hot environmental conditions. On the other hand, in case the environmental temperature during the year range above and below the operational temperature at which we need to maintain the instrumentation, this technology can offer the great advantage to be always suitable just reversing the direction of the direct current in the circuit.
There are different systems of Peltier cells. The easiest to find are the single Peltier cells, with a great variety of available dimensions, powers and supply voltages. For systems that need more hear transfer, multi-stage cell systems exist. Beyond single or stacked cells, we can find various compact systems with heat sink and fans mounted on the Peltier cells, with different configurations suitable for cooling air, liquids or solid parts. Examples of what market is offering are presented in Table 3.

Table 3 Different types of Peltier cell systems.

Classic Peltier cell	**Stacked Peltier cells**
	
Peltier air-air system	**Peltier air-liquid system**
	

In the last few years this technology progressed greatly: features of Peltier cells on the market are now much better than 10-15 years ago, and mainly the gradient achievable between the two surfaces is much improved. However, we need to consider that the gradient we can obtain between the internal volume of the box and the external environment is in general much lower, and it strongly depends on the running algorithm as well as other elements such as insulation, heat sinks and fans associated with Peltier cells. Advancement of technology also brought a large number of producers onto the market. The very partial list of producers and distributors of Peltier cells and complete cooling Peltier systems that we provide below is a clear demonstration of this statement.

- Adaptive Thermal Management
- Applied Thermoelectric Solutions LLC

- Acal BFI
- Adcol Electronic
- ADV Engineering
- Alflex Technologies
- Alphabet Energy, Inc.
- Align Sourcing
- Ambient Micro
- AMS Technologies
- Analog Technologies
- Asia Inno
- Beijing Huimao Cooling Co., Ltd.
- Bentek Systems
- BTS Europe
- Cidete Ingenieros SL
- CUI
- Custom Thermoelectric Inc.
- Crystal LTD.
- European Thermodynamics
- Everredtronics Ltd.
- Ferrotec Corporation
- Gentherm
- Gentherm Global Power
- Green TEG AG
- Griot Group
- Guang Dong Fuxin Electronic
- Hangzhou Aurin Cooling
- Hebei IT
- Hicooltec Electronic
- Hi-Z Technology, Inc
- Hui mao
- Interm
- Kelk Ltd.
- Kryotherm
- II-VI Marlow
- INB Thermoelectric
- ISA Impex
- Innoveco
- Merit Technology Group
- Micropelt GmbH
- Newmark International
- OTE International
- P&N Tech
- Perpetua Power
- Phononic
- Qinhuangdao Fulianjing
- Quick Cool
- RFI Corp.
- RMT LTD
- Sheetak
- S&PF Modul
- Taicang TE Cooler
- TE Technology, Inc.
- TEC Microsystems
- TECTEG
- TEGEOS
- TEGPRO Thermoelectric Generator
- Tellurex corporation
- Termo-Gen AB
- Thermal Electronics
- Thermalforce
- Thermion Company
- Thermix
- Thermonamic Electronics
- Tybang Electronics
- UWE Electronic
- Wellen Tech
- WeTEC
- Z-max

2.1.3 – Heat pumps & Heat pipes

A heat pump is a device that transfers energy from a heat source to a destination called a "heat sink". Heat pumps are designed to transfer heat in the opposite direction of spontaneous direction by absorbing heat from a cold space and releasing it to a warmer one. A heat pump uses a small amount of external power to perform the work of transferring energy from the heat source to the heat sink **(5)**. While air conditioners and freezers are familiar examples of heat pumps, the term "heat pump" is more general and applies to many HVAC devices (heating, ventilation and air conditioning) used for space heating or space cooling. When a heat pump is used for heating, it uses the same basic refrigeration cycle used by an air conditioner or a refrigerator, but in the opposite direction, releasing the heat into the conditioned space rather than the surrounding environment. In heating mode, heat pumps are three to four times more effective at heating than simple electric resistance heaters using the same amount of electricity. On the other hand, the typical cost for a heat pump is about 20 times greater than the resistance heaters. In heat pumps with electric power the heat transferred can be three or four times larger than the electricity consumed, giving the system a coefficient of performance (COP) of 3 or 4, unlike a COP of 1 for an electrical resistance conventional heater. This is because heat pumps move heat rather than generate heat **(6).**

Heat pumps use refrigerant as an intermediate fluid: it absorbs the heat when it vaporises, in the evaporator, and then releases the heat when it condenses in the condenser. The refrigerant flows through insulated tubes between the evaporator and the condenser, allowing an efficient transfer of thermal energy over relatively long distances.
In the last 30-40 years this technology has greatly grown and improved also thanks to the Technology Collaboration Program on Heat Pumping Technology (HPT TCP) of the International Energy Association (IEA) **(7)**. Their web site is a precious source of information to know the actual status of technology and market.

2.1.3.1 - Refrigeration cycle

A refrigeration cycle is a thermodynamic cycle capable of transferring heat from a low temperature environment to a higher temperature one. The machine that performs a refrigeration cycle can be interpreted, and used:

• as a refrigerating machine, with the purpose of subtracting heat from a cold environment by transferring it to a warm one, cooling it, with respect to its natural conditions (this effect is therefore used in refrigerators and air conditioners).

• as a heat pump whose purpose is to provide heat to a warm environment, taking it from a colder environment.

In both uses, it is necessary to dispense a work to make the cycle work, to subtract heat from the hot point of the cycle and absorb heat from the coldest point (useful effect of the machine functioning as a refrigerator).

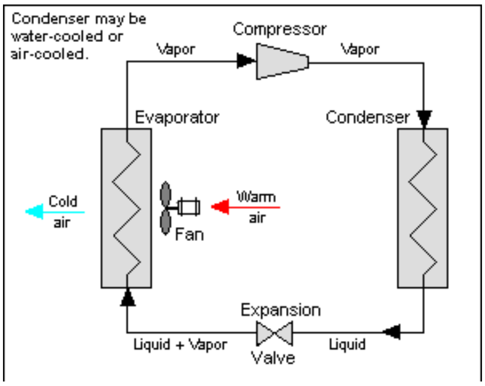


Figure 2 Typical single-stage vapour compression refrigerator.

Kelvin devised a thermodynamic cycle in which compression work was applied to change a fluid from the gaseous state to the liquid state; compression and change of state produce heat, which is extracted from the cycle; subsequently the liquid is expanded and evaporated, subtracting heat in the inverse state change; the liquid in evaporation (and expansion) therefore produces the desired cooling effect.
In the compression refrigerating cycle, it is therefore essential to use a cycle fluid that is capable of condensing and evaporating cyclically: it is therefore important to choose a fluid that does that within the range of temperatures of the cold body and the hot source. Among the first cycle fluids was ammonia, which has the advantage of having particularly high latent heat, but is corrosive and toxic; since 1931 and for many years afterward some alkyl halides have been used, called commercially Freon, then recently (1990) prohibited by the Montreal Protocol. Today we try to use less polluting fluids like HFC, and HFE.

2.1.3.2 - Reversible heat pumps

Reversible heat pumps operate in both directions to provide heating or cooling to the interior space. They use an inversion valve to reverse the flow of refrigerant from the compressor through the condenser and the evaporation coils. In heating mode, the external coil is an evaporator, while the inside is a condenser. The refrigerant flowing from the evaporator (external coil) carries the thermal

energy from the outside (or ground) air inside. The temperature of the steam is increased inside the compression pump. The internal coil then transfers the thermal energy (including energy from compression) to the indoor air, which is then moved into the building by an air handler. Alternatively, thermal energy is transferred into water, which is then used to heat the building via radiators or underfloor heating. The heated water can also be used for the consumption of domestic hot water. The refrigerant is then allowed to expand, cool and absorb the heat from the outside temperature in the external evaporator and the cycle repeats. This is a standard refrigeration cycle, except that the "cold" side of the refrigerator (the evaporator coil) is positioned so that it is outdoors where the environment is colder.
The mechanical heat pumps exploit the physical properties of an evaporative and condensing fluid known as refrigerant. The heat pump compresses the refrigerant to make it warmer on the side to be heated and releases the pressure on the side where the heat is absorbed.

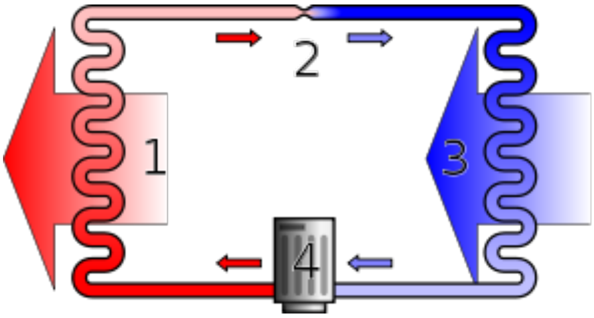


Figure 3 A simple stylized diagram of a steam compression refrigeration cycle of a heat pump: 1) condenser, 2) expansion valve, 3) evaporator, 4) compressor.

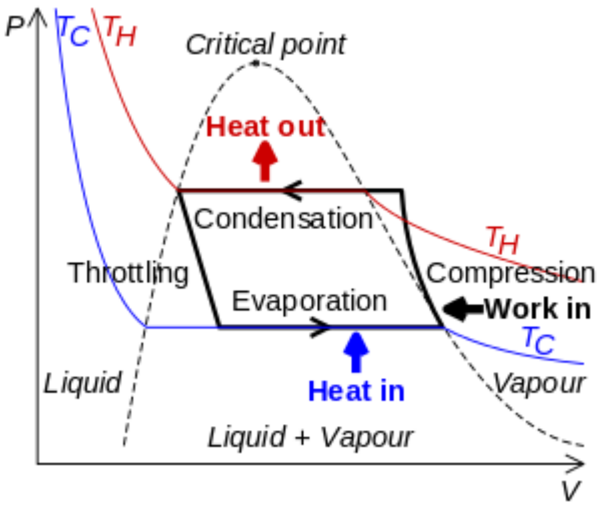


Figure 4 A dummy volume-pressure diagram for a typical refrigeration cycle.

The working fluid, in its gaseous state, is pressurized and circulated through the system by a compressor. On the discharge side of the compressor the now hot and highly pressurized steam is cooled in a heat exchanger, called the condenser, until it condenses in a liquid at moderate temperature and at high pressure. The condensed refrigerant then passes through a pressure-lowering device also called a measuring device. This can be an expansion valve, a capillary tube, or perhaps a work extraction device like a turbine. The low-pressure liquid refrigerant then enters another heat exchanger, the evaporator, in which the fluid absorbs heat and ignites. The refrigerant then returns to the compressor and the cycle is repeated.

2.1.3.3 - Heat pipes

A typical heat pipe is a hollow tube (hollow cylinder) of heat-conducting metal, for example copper or aluminium, closed, containing a small amount of cooling fluid such as water, ethanol or mercury; the rest of the tube is filled with the vapour of the liquid, so that no other gases are present.
A heat pipe serves to transfer heat from one end (heat) to the other (cold) of the duct, by means of evaporation and condensation of the refrigerant. The hot end, in contact with a heat source, releases heat to the cooling liquid, which vaporises and therefore increases the pressure of the steam in the tube. Furthermore, the latent heat of vaporization absorbed by the liquid decreases the temperature at the hot end of the cylinder. The vapour pressure near the hot end is higher than the equilibrium pressure at the cold end, so this pressure difference means that there is a very fast transfer of steam to the cold end, where the steam is in excess compared to the condensation equilibrium, giving heat to the cold end. The cooling liquid then flows back to the extreme heat of the pipe.

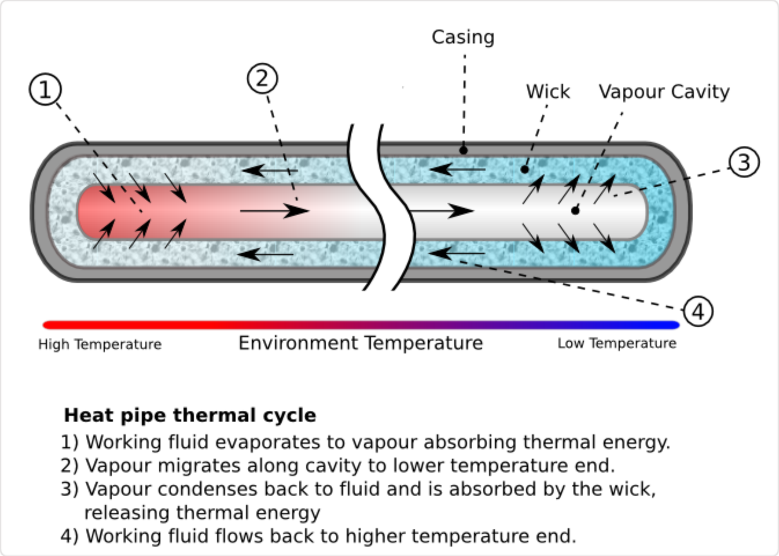


Figure 5 Heat-pipe thermal cycle.

A notable property of a heat pipe is the operating temperature (i.e. the boiling temperature of the fluid, the temperature around which the heat pipe is efficient). In a conduit where the vacuum has been created and then a very small amount of water has been inserted, the boiling temperature approaches 0 ° C, while if the water is put under pressure in the tube to a hundred atmospheres, the boiling temperature can rise above 300 ° C.
The main reason for the efficiency of heat pipes depends on the evaporation and condensation of the contained liquid, which requires or releases much more energy than that required for simple temperature change. Almost all energy is rapidly transferred to the cold end when the fluid condenses. The heat pipe is very efficient in transferring heat, much more than a full copper conduit with the same section. Thermal fluxes greater than 230 MW/m^2 have been recorded.
Heat pipes do not contain moving parts and therefore do not require maintenance, even if heat pipes in which the refrigerant is a gas without condensation can lose gas by diffusion through the walls of the pipe and in the long run lose effectiveness.
Refrigerants range from liquid helium for extremely low temperature applications, to mercury for high temperature applications. However, most thermal conduits use ammonia or water as an operating fluid.

The basic heat-pipe device is a tube made of copper. This solution is not easy to use directly in a dissipation system, while it is versatile if we need to create a custom heat-dissipation path, because it is possible to fold it.

Figure 6 A sealed copper tube is the base for a heat-pipe system.

This device can have different diameters and lengths, as well as different working temperature ranges, depending on the specific substance used inside the tube.

In addition to individual tubes, is possible to find heat sink systems where the heat-pipe tubes are immersed inside the heat sink body (Figure 7), to increase the thermal conductibility. The best characteristic of heat-pipe systems is their capability to remove the heat from small areas, with applications to the electronics chips cooling, like for micro-controllers or micro-processors.

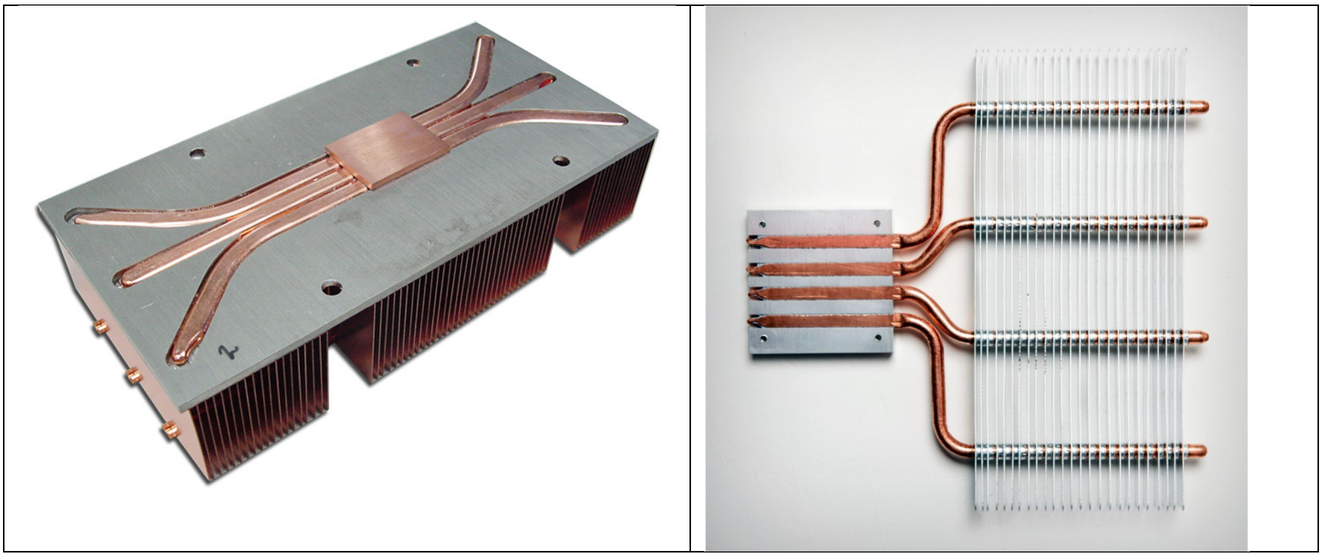


Figure 7 Heat-pipe systems integrated in heatsink bodies.

Figure 8 shows an air-to-air heat pipe device. This a very efficient system, as the only active and power demanding devices are the fans.

Figure 8 An air-to-air heat-pipe system.

Some producers and distributors of heat-pipe and heat-pipe systems are:

- Aavid Thermalloy
- Boyd Corporation
- CIAT
- CRS Engineering
- European Thermodynamics Ltd.
- THERMACORE

As reported above a precious source of information with respect the status of heat pumping technologies and market are the web site as well as reports of the IAE's HPT TCP **(7)**

2.2 – <u>Humidity control</u>

Humidity is a complex parameter to control accurately. Fortunately, for environmental applications and for scopes related to the environmental measurements of RIs, it is sufficient to regulate this parameter in such a way as to avoid "wet conditions". At the beginning of the chapter we also indicated the necessity to keep relative humidity RH far from very dry conditions. Fortunately, this situation only pertains to peculiar extreme cold environments. On our planet the only geographical areas presenting so highly dry conditions are the Antarctic Plateau and very high mountain ranges. Therefore, we can limit our analysis to the first condition, with the only recommendation not to forget this point if we are engaged with operation in those areas. Obviously, operations at high altitude in the atmosphere can also present very dry conditions. However, two conditions reduce the need to deal with low humidity in that case: (i) measuring instruments, for example in an aircraft, are well insulated from the external environment and operate in a pressurized atmosphere with relative humidity conditions typical of much lower elevations; (ii) many applications make use of very low power, so that electrostatic charges are not a problem. For the installation of instrumentation in extreme environments, we do not need then to accurately control the humidity present inside the system, but more simply keep it low, avoiding the formation of condensation on the devices, which could damage them or affect their durability and stability. Acquisition systems are electronic and optical devices, which are negatively sensitive to the presence of moisture, which is conductive and ruinous for electronic systems, instead interfering with optical systems. This is a much easier technological scope for which is possible to use various systems. Among them, for our scope we can consider three simple methods to keep the moisture concentration low. They are in one way or another commonly used for environmental applications.

2.2.1 – Humidity control with hydrophilic materials

Use of hydrophilic materials is based on the physical ability of some materials to bind with water. One of the most commonly used materials for keeping the humidity level low inside packs is silica gel, a silicon dioxide polymer, exploited for its dehydrating and extremely adsorbing properties.
This solution is extremely simple and inexpensive, applicable to any type of box. It is a solution that involves maintenance, because once the silica gel molecules are saturated with water, they must be replaced in order to continue to perform their work by holding the humidity and not dispersing it in the surrounding air to the instrumentation.

Figure 9 Typical bag containing silica gel.

2.2.2 – Humidity control with overpressure and dry air

Another way to keep moisture away from the instrument container is by means of a small overpressure created with an inert gas, such as Argon or Nitrogen. This solution implies a mechanical construction of the container that ensures its sealing, as much as possible. Internal overpressure can be assured by inserting the inert gas during the final assembling of the device and providing that this is done after every maintenance that requires opening it. Alternatively, the device can be equipped with a gas cylinder containing the inert gas and with a control valve that can dynamically adjust the pressure in order to maintain it above the external one. This requires only that the bottle be refilled from time to time.

2.2.3 – Humidity control with condensation

Removal of internal humidity is possible also by making it condense and collecting it, taking it out of the box. The humidity present in the air inside the box is condensed on a surface cooled by some degrees below the temperature of the air. The water in the gaseous state liquefies on the cold surface, is collected and flows out through a pipe. This technical solution can be implemented in such a way as to work for unlimited time without any maintenance, since it does not imply in principle the consumption of any material like the previous two methods.

2.3 - Advantages and disadvantages of various technical solutions

In sections 2.1 and 2.2 we have briefly described technologies to control and regulate temperature and relative humidity that are suitable for operation of Environmental Research Infrastructures in extreme environments or conditions. We have sometimes in the text reported comments on efficiency as well as advantages and disadvantages. In this section we aim to come back more systematically on this topic with the aim to provide elements that could guide users to select the most appropriate and efficient technology for the specific application.

2.3.1 Temperature control

Resistance heaters are the most common heating systems in cold environments, being available in different shapes and powers, at a very low costs. Their performance is very high, because almost all of

the electrical energy supplied is transformed into heat, but the efficiency of the "complete" system depends on how the heat is taken from the heating element to the surrounding air. A good heat sink and a fan with flows suitable to the volume to be heated is essential to transfer the heat from the surface of the heater to the surrounding environment. Simplicity of use can be an advantage but also be a limitation: since in practice we can use them only as an on/off heating device, in order to design a correct thermo-regulating system for our application, we need to answer accurately all a priori questions listed at beginning of section 2.1. We need to fix in advance the target temperature to which we wish to maintain the volume containing the instrument or its sensible parts as well as the allowed variability. We need, moreover, to estimate with good accuracy the environmental conditions that the system will experience during operations. This is not very easy if our ambient is air, because for thermoregulation it is important the combination of air temperature and wind speed. Based on this choices, we need to dimension in a proper way all components of the system: heating device, heat sinks and fans.
If we are not interested in maintaining with great or good accuracy a fixed temperature, but only interested in avoiding that the operational temperature of the instrument drops below zero (without reaching values too high) self-regulating resistors (PTC thermistors) can represent a very practical and effective solution, that does not require any electronic control. This solution can be conveniently combined with a very good insulation to assure, with a low power consumption, operations both in extreme cold conditions occurring in polar night, as well as during much less extreme conditions during summer. The only important thing is to avoid selecting a heating device too strong or with an equilibrium (critical/Curie) temperature too high. If it is necessary, insulation can be increased to help the system to keep above zero temperature and/or to reduce power consumption. In chapter 5, the use of this technical solution at the Antarctic Plateau station Concordia will be presented.

Peltier cells have the great advantage, with respect to resistor heaters, to be a reversible system: they have the possibility of both heating and cooling, even if with different efficiencies. The heating efficiency is similar to the resistance heater, while when used in cooling mode, the efficiency if about 60%, this value depending on the specific cell type. As a consequence of this reversible capability, this technology is particular useful when we operate in environmental conditions that, in the course of the operational period (e.g. the whole year) can see temperatures both above and below the operational instrument temperature. As indicated in section 2.2, the maximum gradient we can achieve between instrument/internal temperature and external ambient temperature with a single stage Peltier cell system range around 20-25 °C. Compared to the heating resistors, Peltier cells technology is more suitable when we need to control accurately a target temperature. If allowed by the instrument characteristics, changing opportunely the target temperature of a few degrees, we can cover a temperature range of more than 50-60°C. If we need to cover a wider environmental temperature range, we can realize or purchase a system based on a double stage of Peltier cells. On the market we can nowadays found very compact devices including the Peltier cells, the two heat sinks and the fans to facilitate heat exchange.
The flexibility and accuracy of this technology are offset by the relative complexity of driving; this complexity increases greatly if we move from a single stage to a double stage. Another consequence is the larger need of power. Peltier systems are for sure not suitable for remote stations with very limited power supply, while they can be a very efficient solution if we can have from a few tens of watts up to 1-2 hundred watts for large volumes.

The heat-pipes are very efficient at transporting the heat very quickly and at extracting heat without consuming too much energy. Their high heat conductivity makes it possible to remove big quantity of heat from small surfaces, for example in the heat-pipes that are used inside the electronic devices of computers to cool the microprocessors. Being them passive systems, they don’t need high power to work, except for the fans helping the heat exchange with air flow. These characteristics clearly indicate that this system can be very efficient and effective when we are experiencing very high temperature conditions. Like in the case of heating resistors, it is easier to use this technology to maintain the system within a small range of temperatures rather than to control a target value.

2.3.2 Humidity control

If maintenance is not a problem, keeping humidity at low level using hydrophilic materials is for sure the easiest and simplest solution. However, availability of personnel on the field is not the only element that we need to consider. In extreme conditions, to replace this material when necessary can be not an easy operation. Even if manufacturers normally provide this solution for their instruments when they are sensitive to high humidity conditions (e.g. when they have optical parts), not very often they consider the need to operate in very cold or very hot environmental conditions without removing the instruments and bringing them in a laboratory or closed space. More than this, they normally do not consider extremely humid environmental conditions like we can have over the sea or in sub-polar areas with strong snowing regime, so they tend to consider necessary to make this operation not very often. As a consequence, several times the technical solutions provided by manufactures are not effective and/or not satisfactory.

If maintenance is a problem or solutions based on hydrophilic materials included by manufacturers are not satisfactory for the specific case/application, the technical solution proposed in section 2.2.3 (humidity removal by condensation) can be an alternative insuring good operation in all conditions and without limitations related to environmental conditions. If we consider that, most of the time, humidity control comes together with the need to implement also temperature control, this technical solution can easily be implemented as an additional functionality of a thermo-regulating system. This technical solution adapts to any environment, polar as well as marine areas, any temperature and altitude. This is the reason why in developing our control and regulation tool, for humidity control we have selected only this technique, while for temperature control we will develop a board and associated firmware able to drive and manage each of the three technologies presented.

The only case in which the technical solution based on a control with condensation is not suitable is when humidity conditions change very fast. This is the case of an instrument mounted on an airplane that rapidly ascends or descends the atmospheric column to carry out a vertical profile of a physical parameters. In this case the most suitable technical solution is for sure the overpressure obtained thanks to a control system that operates to keep constant the difference between internal and external pressure. Being aircraft operations limited in time, the limitation arising from the consumption of inert gas is not a real problem.

3 – CONTROL UNIT: HARDWARE AND FIRMWARE DEVELOPMENT

The analysis of the general problem of controlling operational temperature of measurement instruments in extreme environments, clearly indicates that, given the conditions Research infrastructures (RIs) pertaining to different Environmental domains can experience, a unique optimal technical solution does not exist. Each of the techniques illustrated in chapter 2 has a specific range of application. Vice versa, for humidity control, for relatively smooth changes of relative humidity RH, we can satisfactorily use the condensation technique. This technique requires temperature control of a device and is, therefore, very convenient if combined with a temperature control system.

Based on these remarks, we developed a unique system able to manage all the aforementioned technologies with a single set of electronics, simply by setting the firmware/software. This was possible because each of the three methods of thermoregulation, as well as the method for humidity control, need common elements, such as sensors for temperature and relative humidity, fans to create the air flows, and require modulation of the current through heating resistors or Peltier cells.

The Control Unit (CU) was designed and developed in such a way to be able, in addition to controlling temperature and humidity, also to evaluate the efficiency of the implemented hardware solution. In this way, it is possible to compare different types of insulation, or the performance of each technical solution in a specific case. Any application can become a learning exercise if/when necessary, increasing our overall knowledge and expertise. In this chapter all information on hardware and firmware of the designed and developed CU are provided, together with basic elements to connect it to thermo-regulating systems and basic notions to start using it in a generic application.

3.1 – Hardware

The system we developed is able to receive and read the signals from 6 temperature sensors, 2 relative humidity sensors and a sensor that indicates the opening of the box. The currents absorbed by the H bridge channel, the heater and the condenser are continuously monitored in order to measure the actual consumption of the control devices. Furthermore, two channels are at disposal to drive fans, regulating their speed on the base of firmware choices. A solid-state switch that drives a solenoid valve and one relay can be used to turn on/off the instrumentation.

The electronic is designed to operate at 24 V and can handle power up to 1000 W. This power can be used to provide energy both to instrumentation and regulating devices. The H bridge can deliver a maximum power of 480 W and reverse the voltage at its ends, thus permitting to drive the Peltier cells both as cooling and heating devices, reversing the direction of the flow of the current that passes through them. The heater output, designed to connect a heating resistor, can supply 120 W, regulated with a Pulse Width Modulation (PWM) system. The condenser output is designed to drive a Peltier cell in cooling mode for moisture condensation. Each fan output channel can drive up to 50 W, and can be modulated using a PWM system. Each channel has a circuit that allows reading current and voltage, to monitor power consumption.

The board has a micro controller with a 12 bits analogue to digital converter (ADC). This is used to read the analogue signals from the environmental (temperature and humidity) and power (voltage and current) sensors. These raw signals are adapted to the ADC readings by different analogue circuits, described in the following schematics.

The temperature sensors are manufactured by Analog Devices (model AD22100), with temperature range from -50 to 150 °C. The humidity sensors are manufactured by Honeywell (model HIH-4000-004) and measure relative humidity with a 3.5% accuracy. The power sensors are made with an electronic circuit composed by one shunt resistance, reading the voltage drop at its ends.

On the board, there is a card reader where it is possible to insert a common micro SD card, where all collected data and the board configuration are stored

The system has three communication standards on board: Ethernet, USB and RS232 serial port. Using the Ethernet link it is possible to login to the internal web server and modify the configuration, give commands, view runtime data and download all collected data.

About possibility to expand the system, adapting them to specific more demanding requests: (i) if we need to drive and regulate more than two fans, we can place them in parallel with those installed yet, with the only limitation that overall power at disposal of each channel is 50 W; (ii) if we need to add a fan operating continuously at the same speed we can connect them directly to the power supply circuit; (iii) if we like to add other channels to drive more sensors and/or read more parameters we can use the RS232 port to connect another board. Only in this latter case we need to made modification to firmware in order to introducer these new variables and parameters in the algorithm.
Follow the electrical schematics of the two boards that compose the system, PowerDrivers and MainBoard, including details of their components.

The **PowerDrivers** board (Figure 10) hosts the power components that regulate the current on each channel.

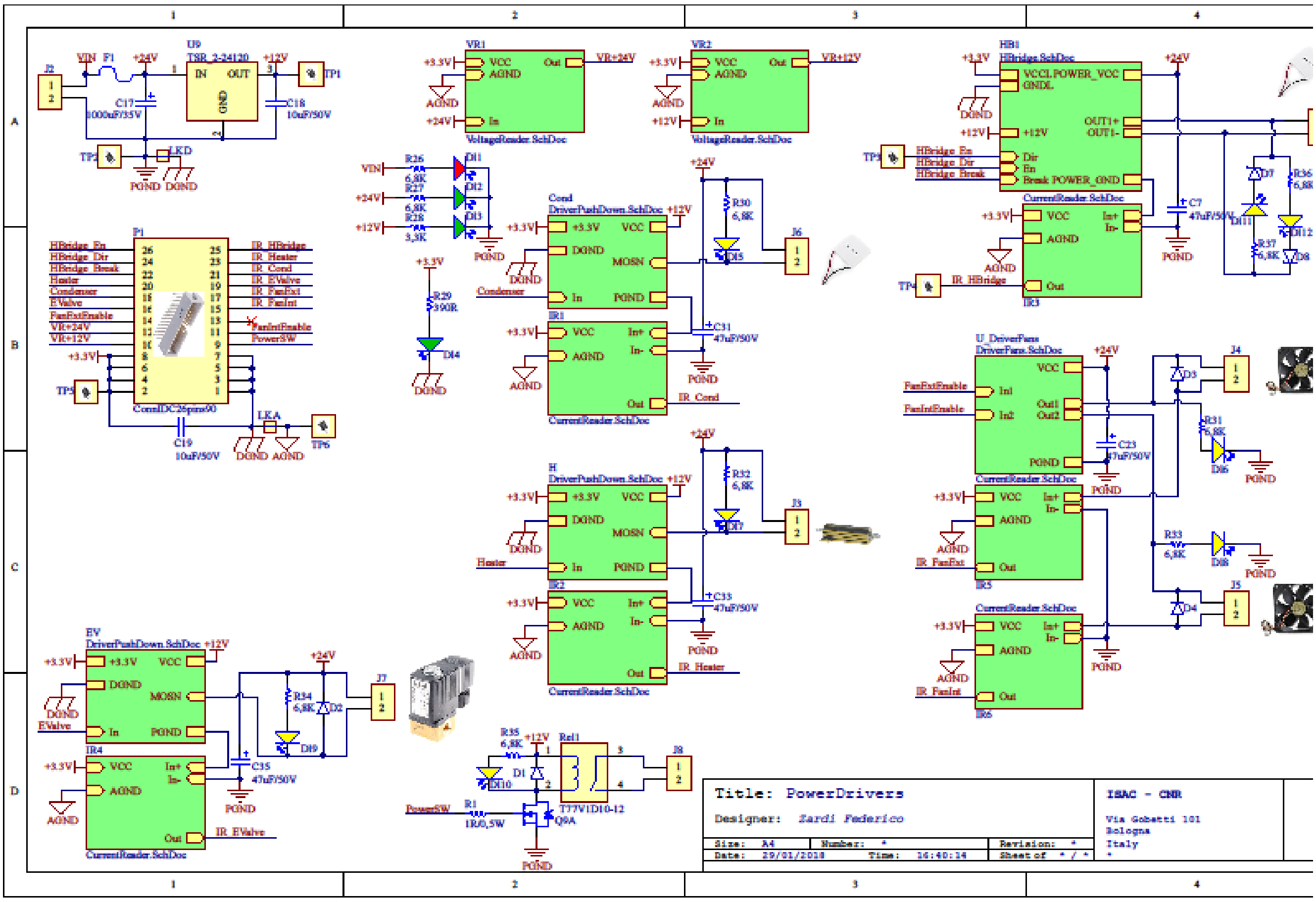


Figure 10 Schematic of the PowerDrivers board.

The H bridge (Figure 11) manages and gives power to the Peltier cells. It can also reverse the current flow in output.

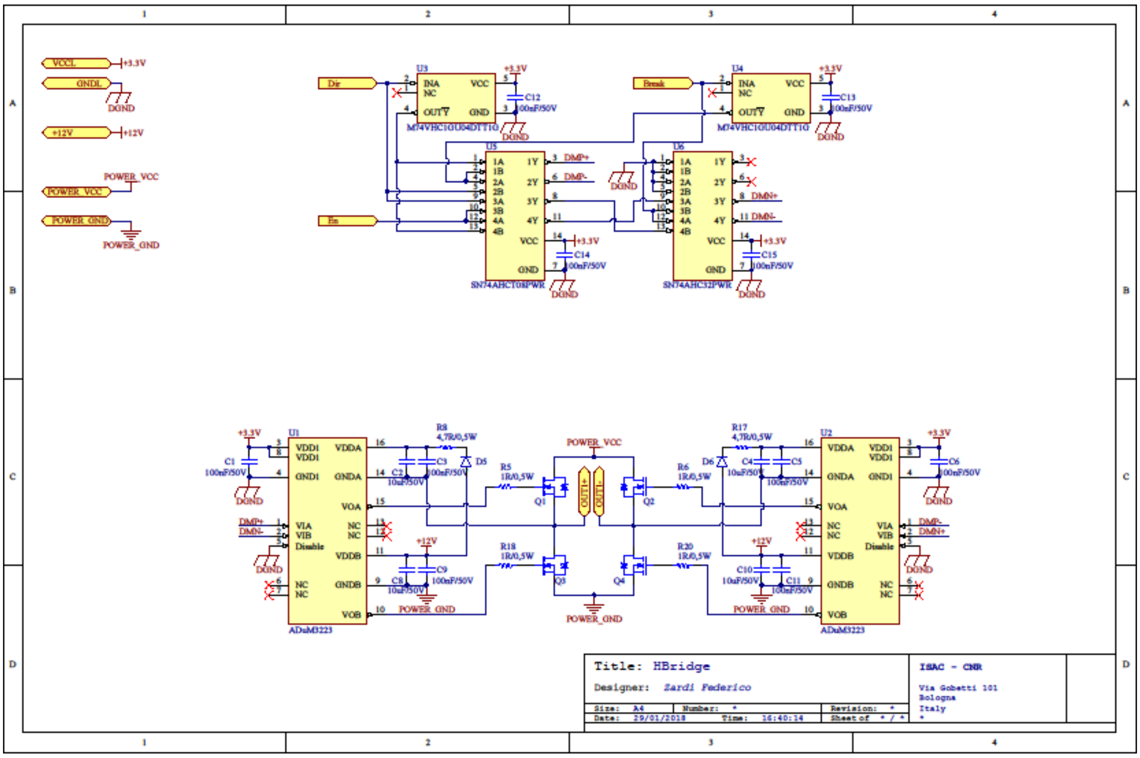


Figure 11 Schematic of the HBridge circuit.

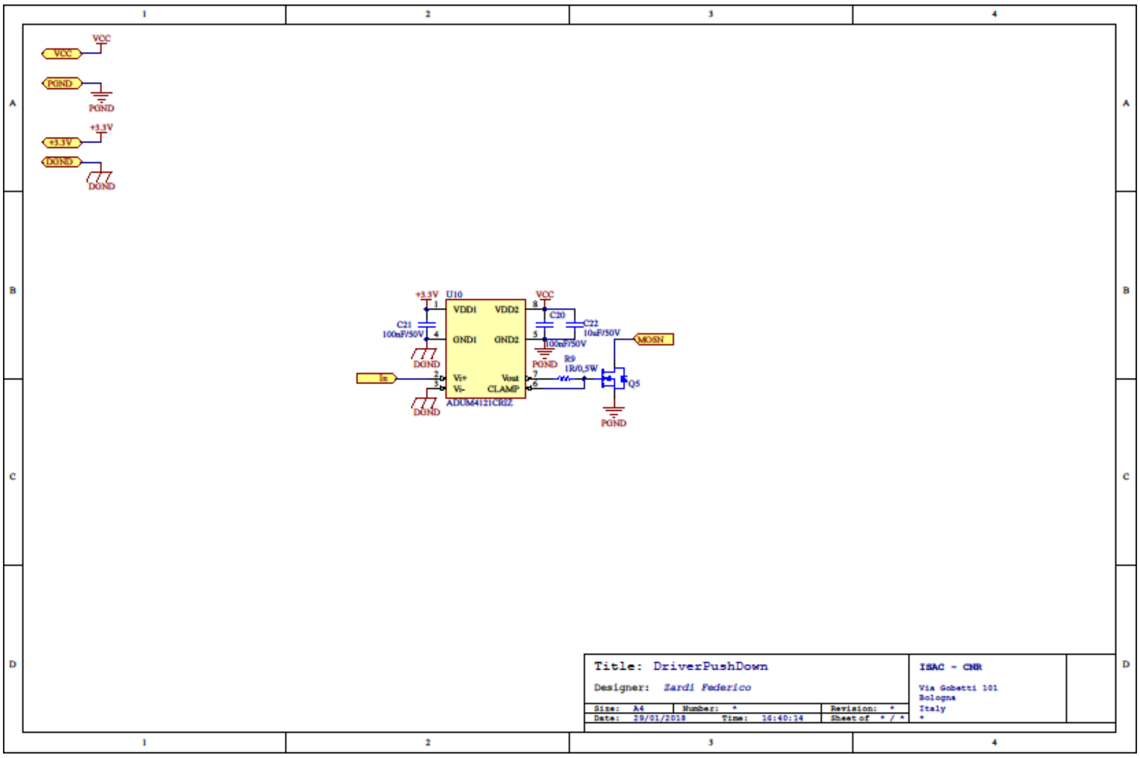


Figure 12 Schematic of the DriverPushDown circuit.

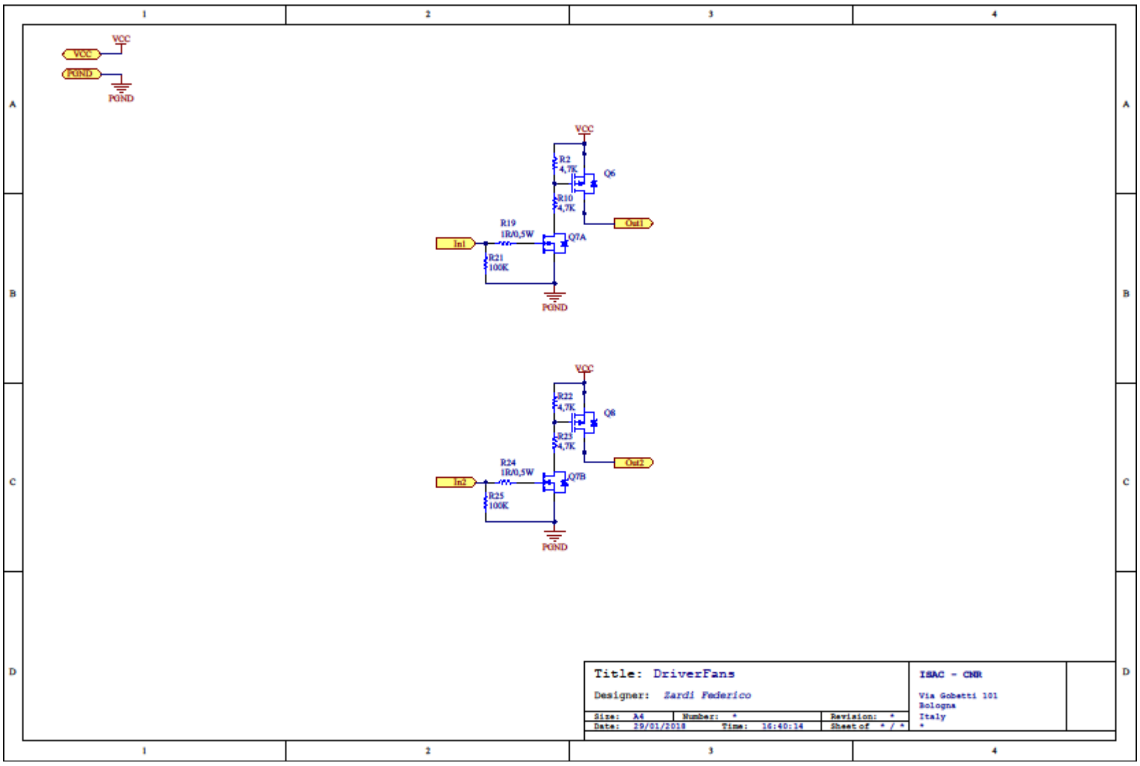


Figure 13 Schematic of the DriverFans circuits.

Figure 14 and Figure 15 show the power reader circuits, with the shunt resistance and one operational amplifier to read and amplify the drop voltage. The second amplifier with RC filter is used to filter the signal and give the average current read.

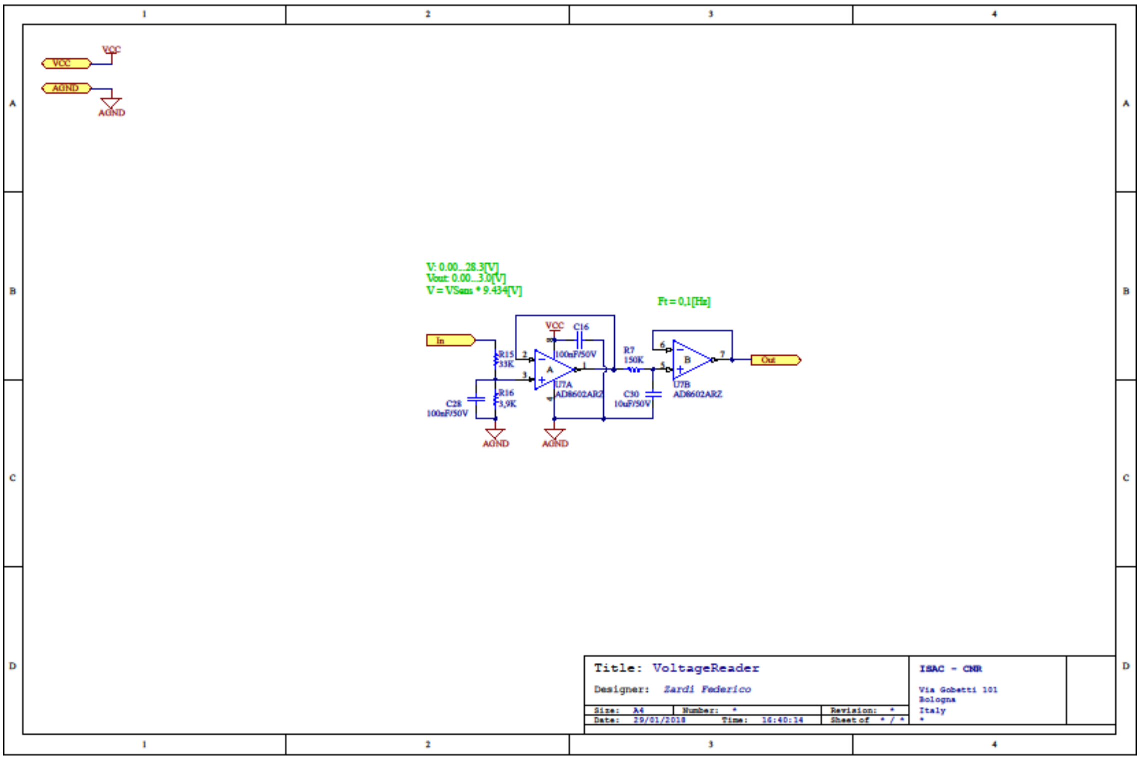


Figure 14 Schematic of the VoltageReader circuit.

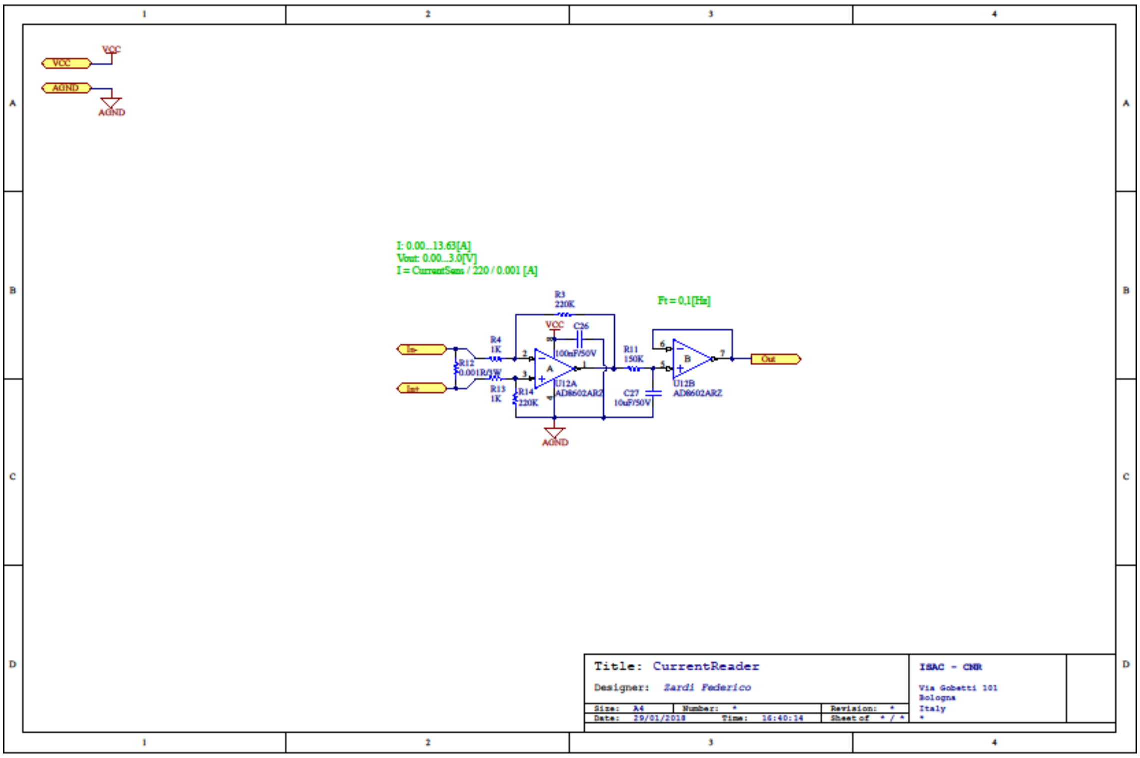


Figure 15 Schematic of the CurrentReader circuit.

The **Mainboard** (Figure 16) hosts the unit to read all sensors and to drive the systems that warm or cool the box. Furthermore, on this board we have the connection systems (RS232, USB and Ethernet). On the board is present a temperature sensor to monitor the electronic temperature.
The green LEDs indicate if all power supplies are present, the yellow LEDs indicate an operation in act, for example writing on SD card or USB data transfer. Two other LEDs, one green and one red, give the state of system: the green LED blinks when everything works fine and the red LED blinks when errors occur (the number of blinking indicating the error code)

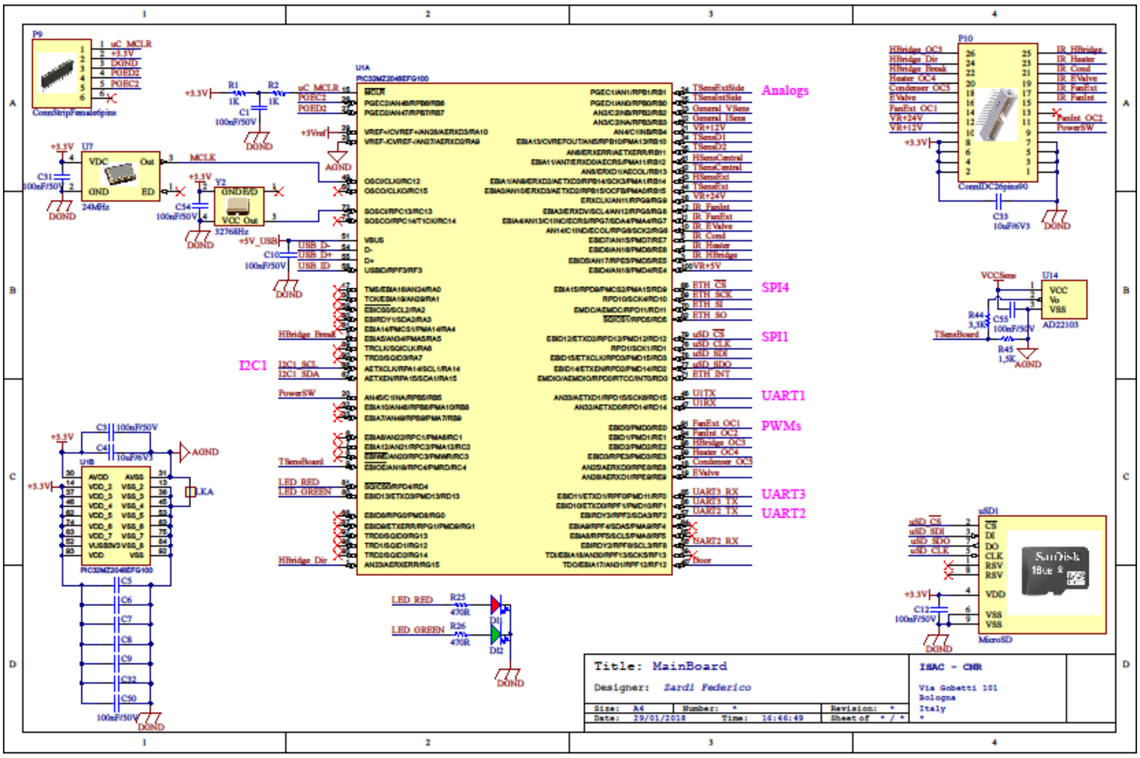


Figure 16 Schematic of the MainBoard circuits.

Figure 17 shows the power supply circuit, that generates all voltage supplies for the system. There is also the control circuit that monitors the voltage and the current used by the unit board, in order to estimate the power consumption.

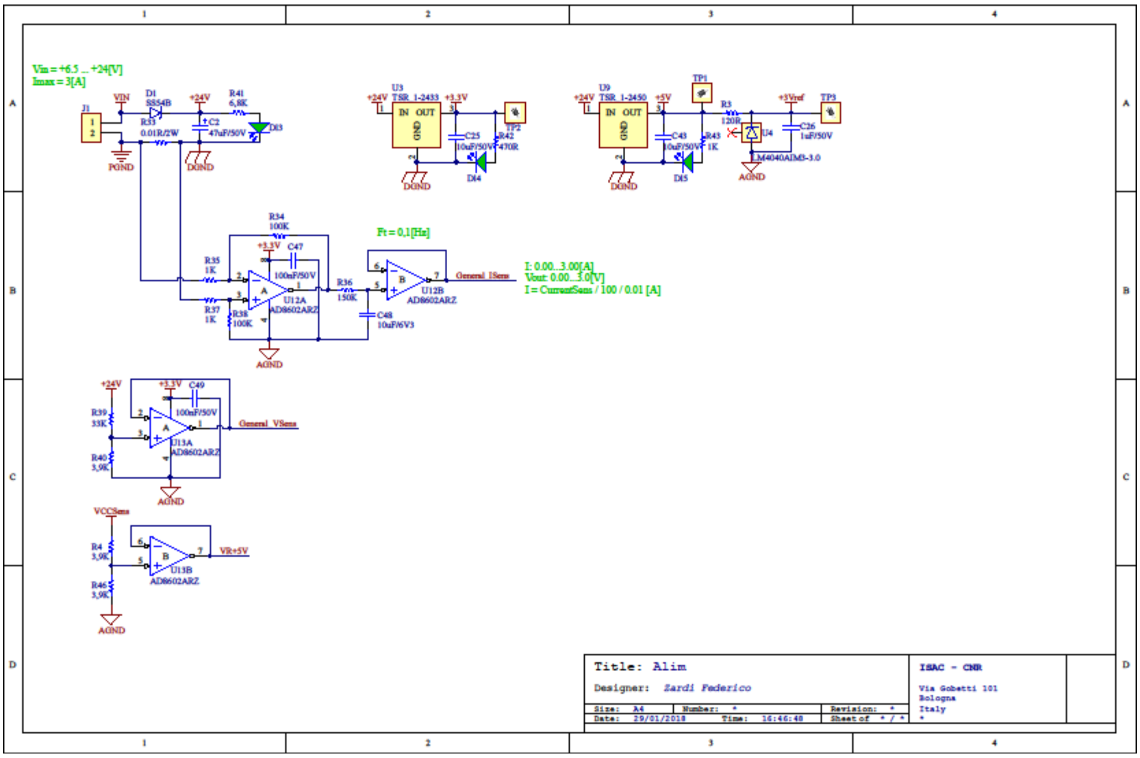


Figure 17 Schematic of the power supply circuit.

Figure 18 shows the analogue circuits to adapt the analogue signals coming from the sensors to the ADC converter inputs. The sensor supplies are filtered by an LC circuit, in order to reduce the noise on the measure.

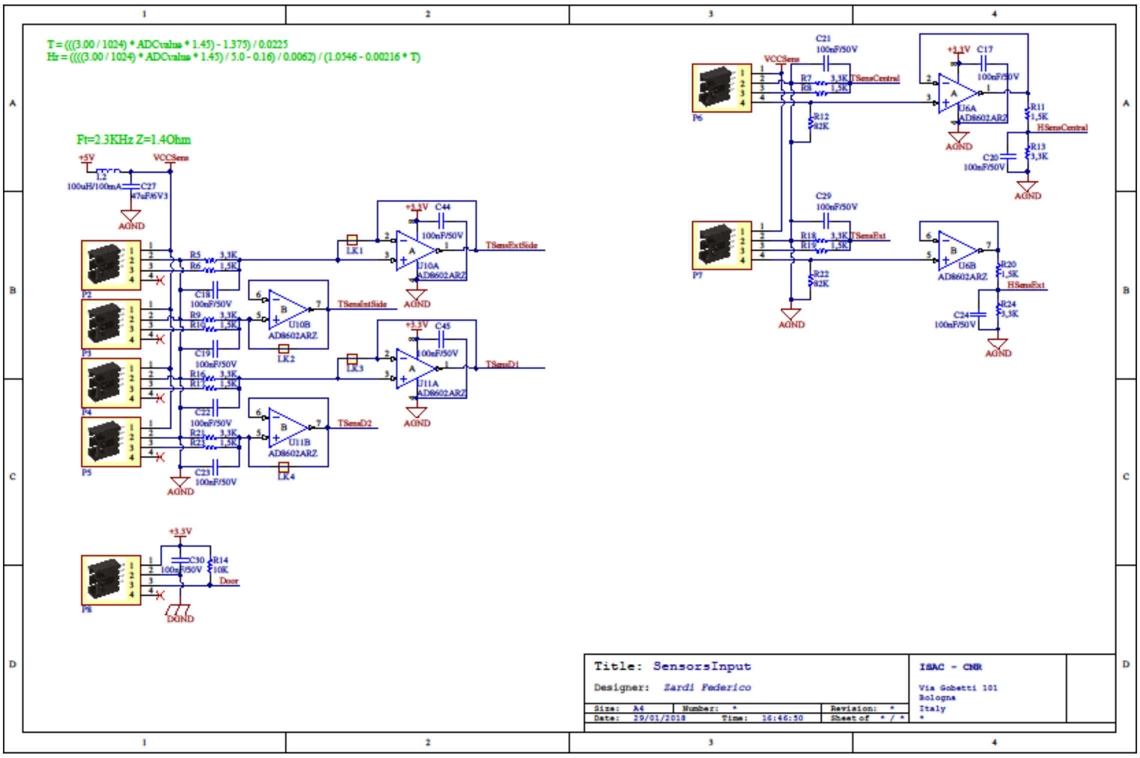


Figure 18 Schematic for the SensorsInput circuits.

Finally, Figure 19 shows the interfaces circuits of the physical layer of Ethernet standard, with its connector. A MAX3232 is provided to adapt the serial signal to the RS232 standard. The micro controller mounted on this board has the logic to decode the signals of USB standard. Moreover, there are three other connectors: two UART interfaces and one I2C for future application.

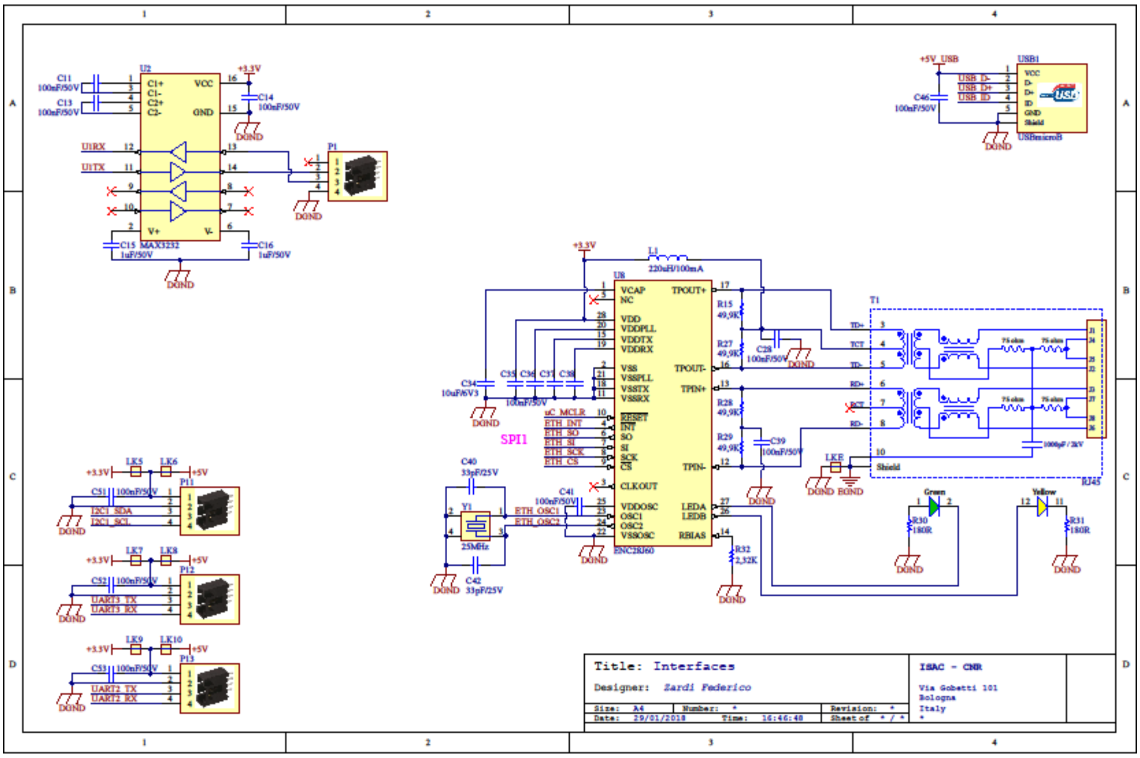


Figure 19 Schematic of the Interfaces circuits.

Figure 20 and Figure 21 show the rendering of the PCB of PowerDrivers board, with the connectors for the devices: HBridge, fans, heater, solenoid valve, condenser. The HBridge is meant to connect Peltier cells, so it's possible to reverse the current and use the cell both to warm and to cool. On the left of the board there is the power switch connector, where we can connect the instrumentation and switch it off to save that in case of danger.

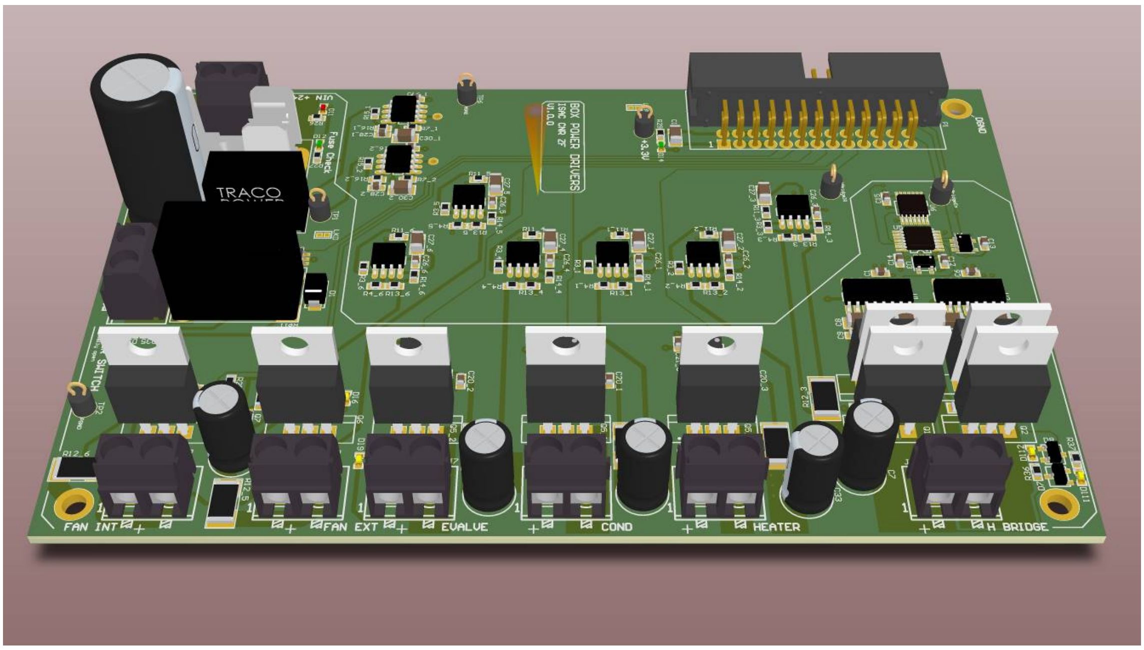


Figure 20 Rendering of the PowerDrivers board.

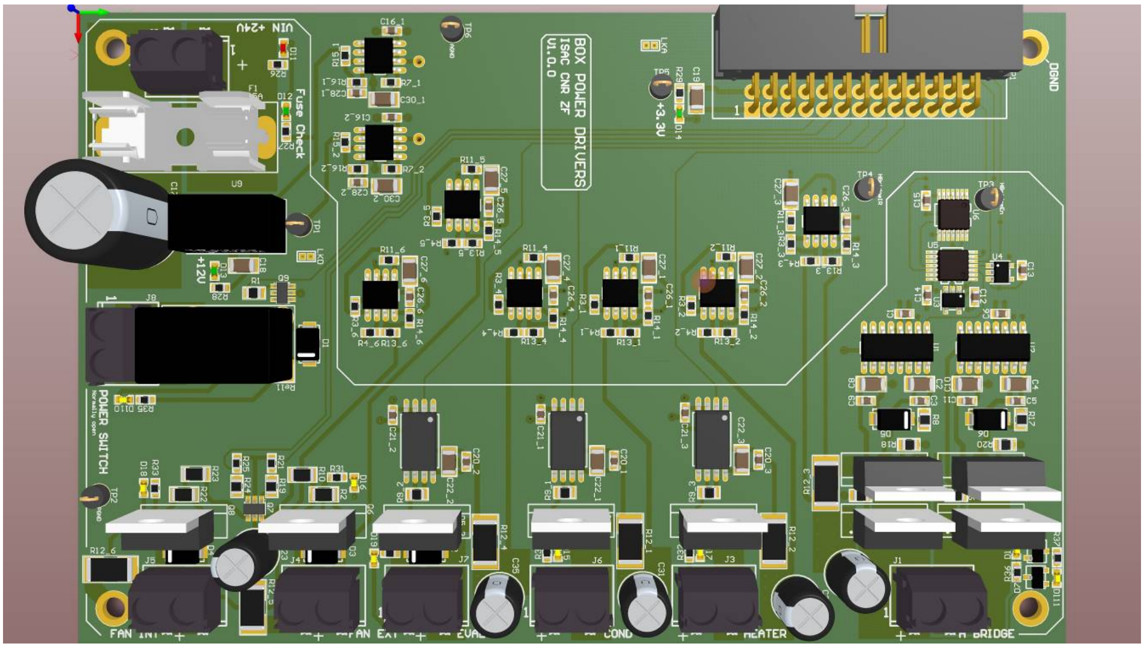


Figure 21 Another view of the rendering of the PowerDrivers board.

Figure 22 and Figure 23 show the rendering of the PCB of the Mainboard, with the connectors for the sensors: temperature, humidity and door. On the upper part of Figure the microSD support is visible, together with three connectors to expand the functionalities of the board. On the left side, the connector for the communication with the PowerDrivers board. Figure shows the connections to link the system to a computer or directly connect to the network.

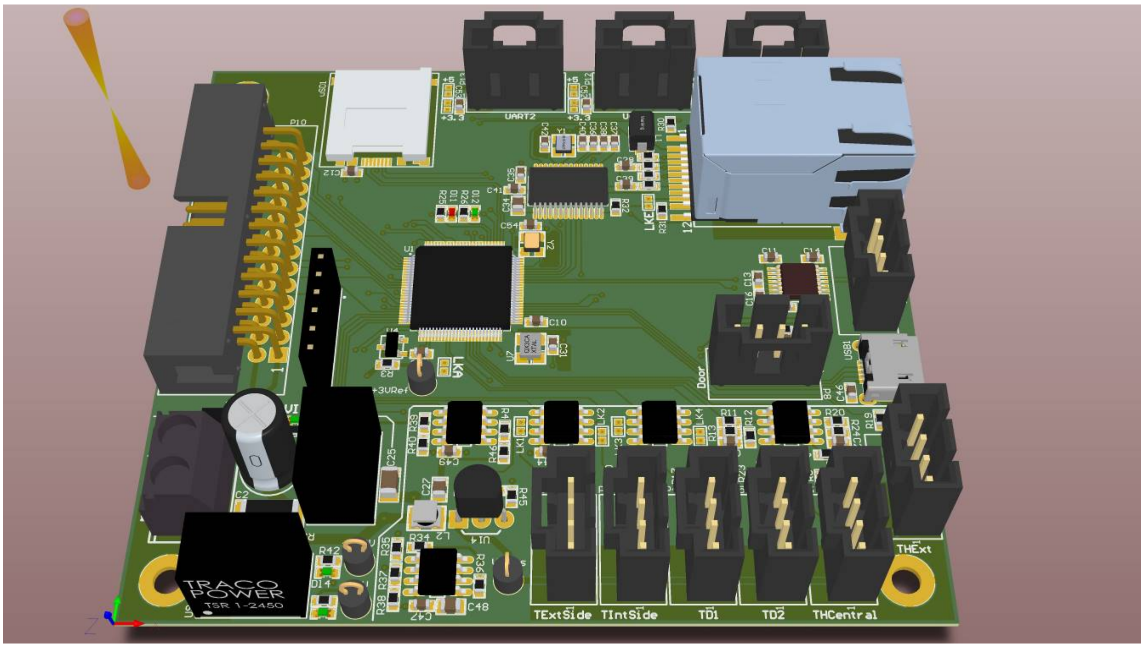


Figure 22 Rendering of the PCB of the Mainboard.

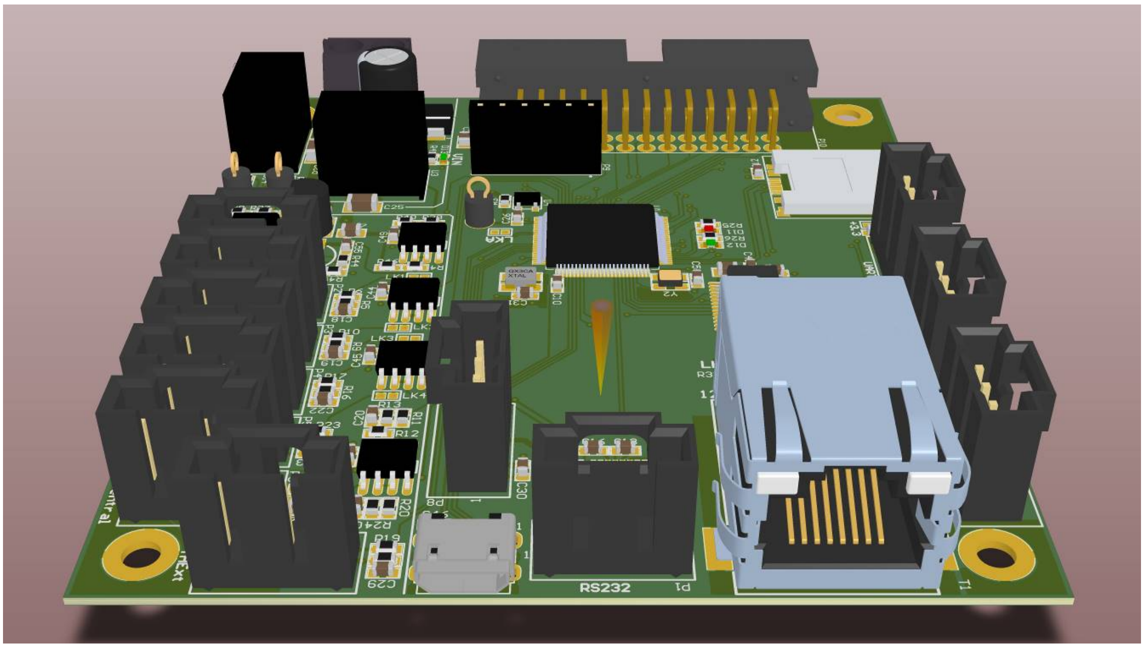


Figure 23 Rendering of the PCB of the Mainboard. In front the communication connections are visible.

The two electronic boards are mounted in a small box, stacked and connected with a flat cable (Figure 24, Figure 25, Figure 26). The electronic box need to be installed inside the thermo-regulating box, since it is not designed to resist to adverse environmental conditions.

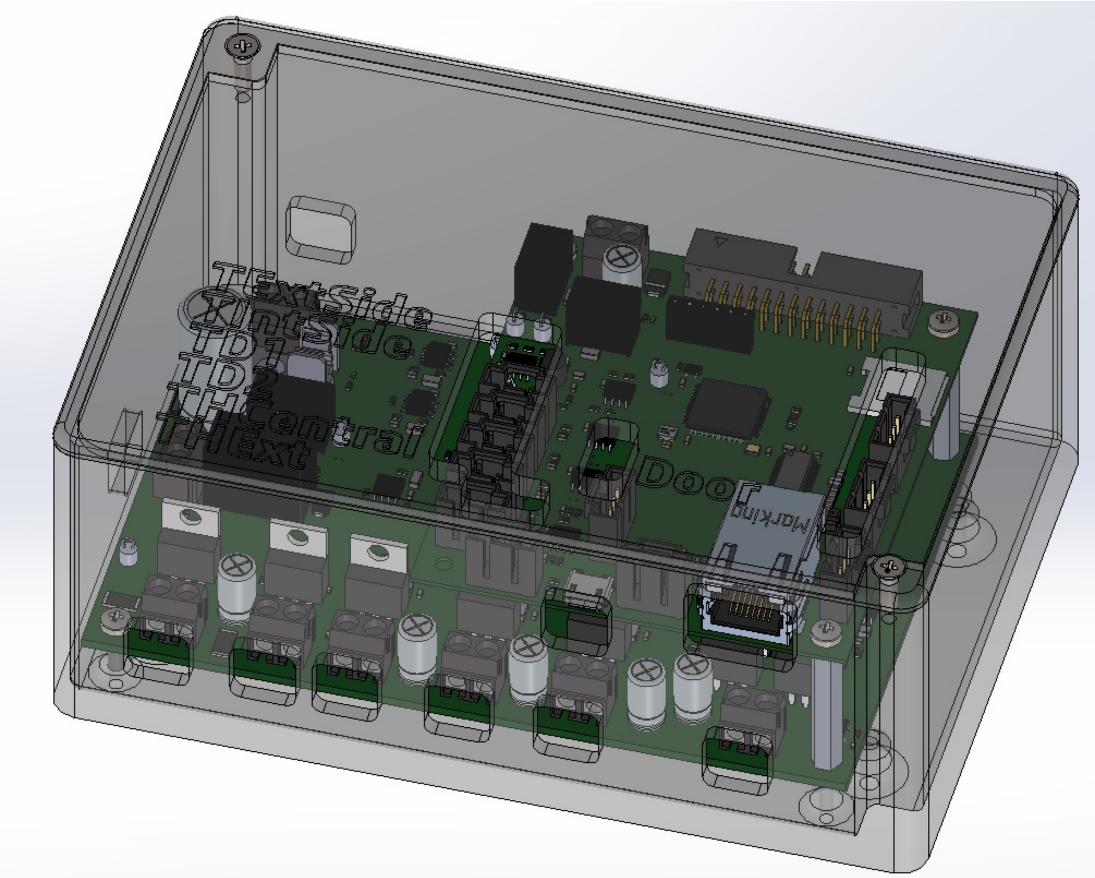


Figure 24 Rendering of the box containing the electronic boards (front view).

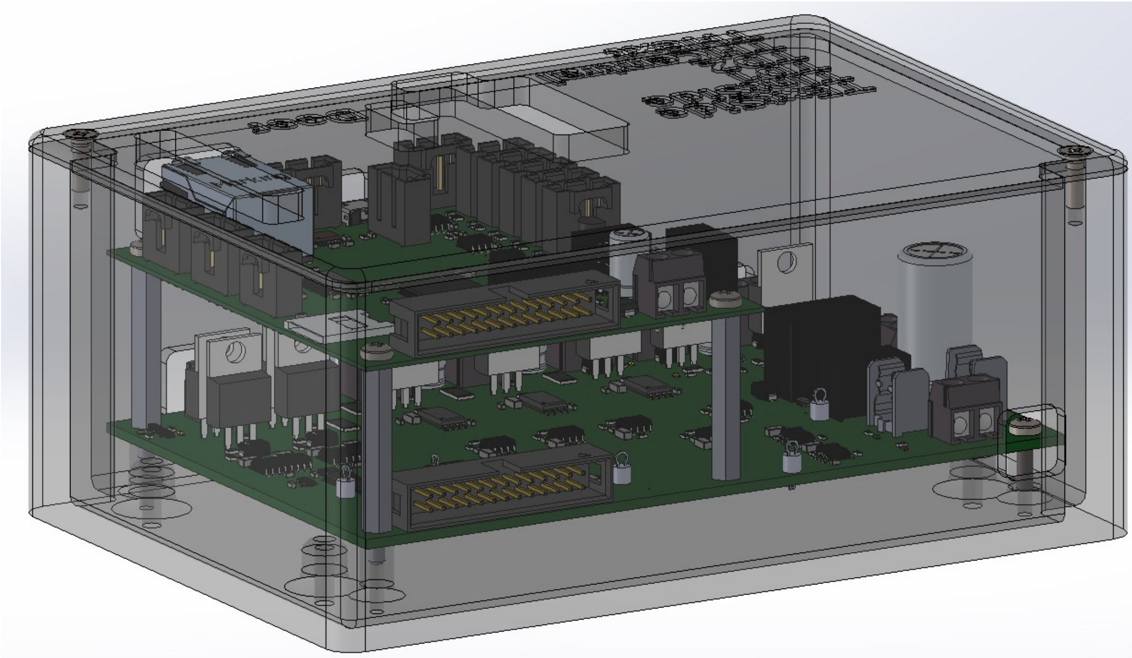


Figure 25 Rendering of the box containing the electronic boards (rear view).

Figure 26 Rendering of the box containing the electronic boards (top view).

3.1.1 – Heating resistors configuration

This configuration is the simplest example: we need to keep a certain temperature inside an instrumental box. A heating element is connected to the “Heating” port of the system. On the heating element a temperature sensor is installed and connected to the “TSensHotSide” port, as the system needs to know the element temperature to control it. Another important part for a heating air system is the fan, so this component has to be connected to the “FanInt” output, through which the system will adjust the fan speed.
The most important sensor to make the system work is the temperature sensor inside the box called “TSensCentral”. Based on its readings, the algorithm regulates the output power on the “heater” output to maintain the preset temperature.
In this configuration, the other sensors are optional. Connecting the instrumentation to the PowerSwitch output, the system can activate it only when the temperature is above the preset value.

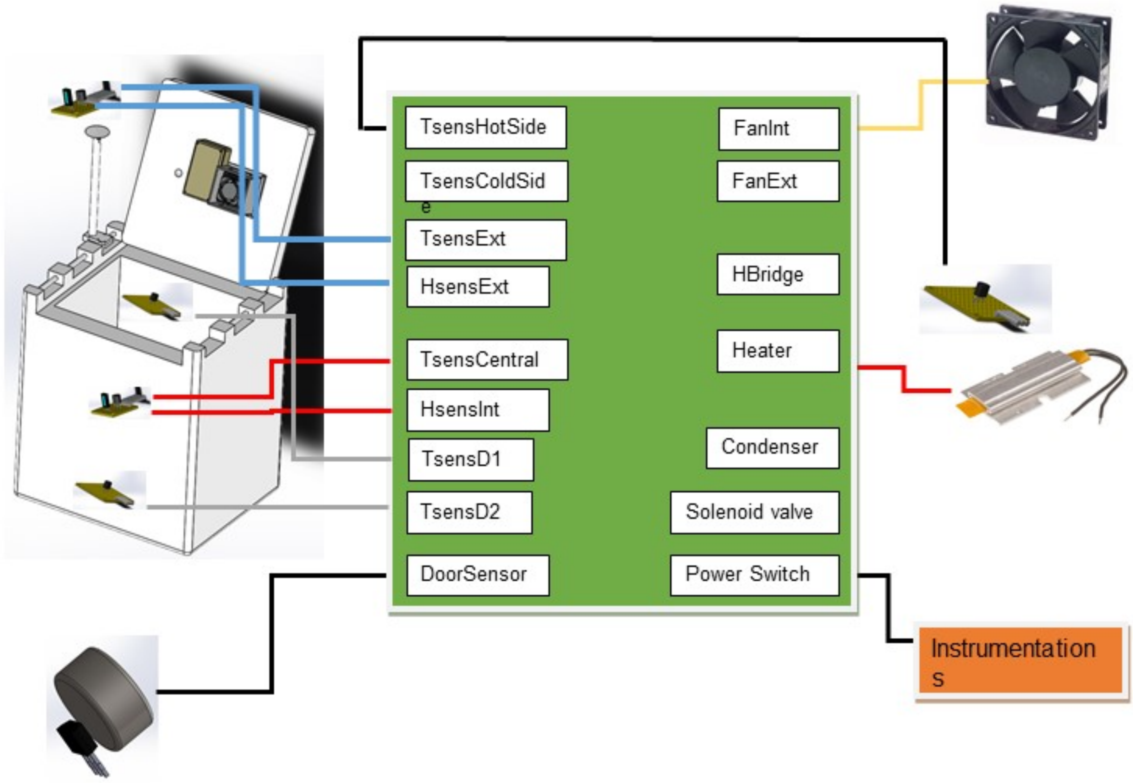


Figure 27 Logical scheme for the connections in the heating resistors configuration.

3.1.2 – Peltier cells configuration

This configuration is used to heat/cool the instrumental box, so we need a Peltier heating/cooling system that we connect to the “HBridge” port of the system. On the Peltier system we have to install two temperature sensors, one on the hot side connected at “TSensHotSide” input and one on the cold side, connected to the “TSensColdSide”, as the system needs to know these temperatures to control and manage the Peltier cells at their best.
If we have a heating/cooling Peltier air-air system, we have two fans to manage and connect these to the respective outputs: “FanExt” and “FanInt”.
The most important sensors to make the system work are the temperature sensor inside the box called “TSensCentral” and the temperature sensor outside the box to measure the environmental

temperature. Based on the inputs from these sensors, the algorithm regulates power and current direction on the "HBridge" output to maintain the preset temperature.
Like in the previous configurations, the power on the instrumentation can be controlled by the system based on the internal temperature.

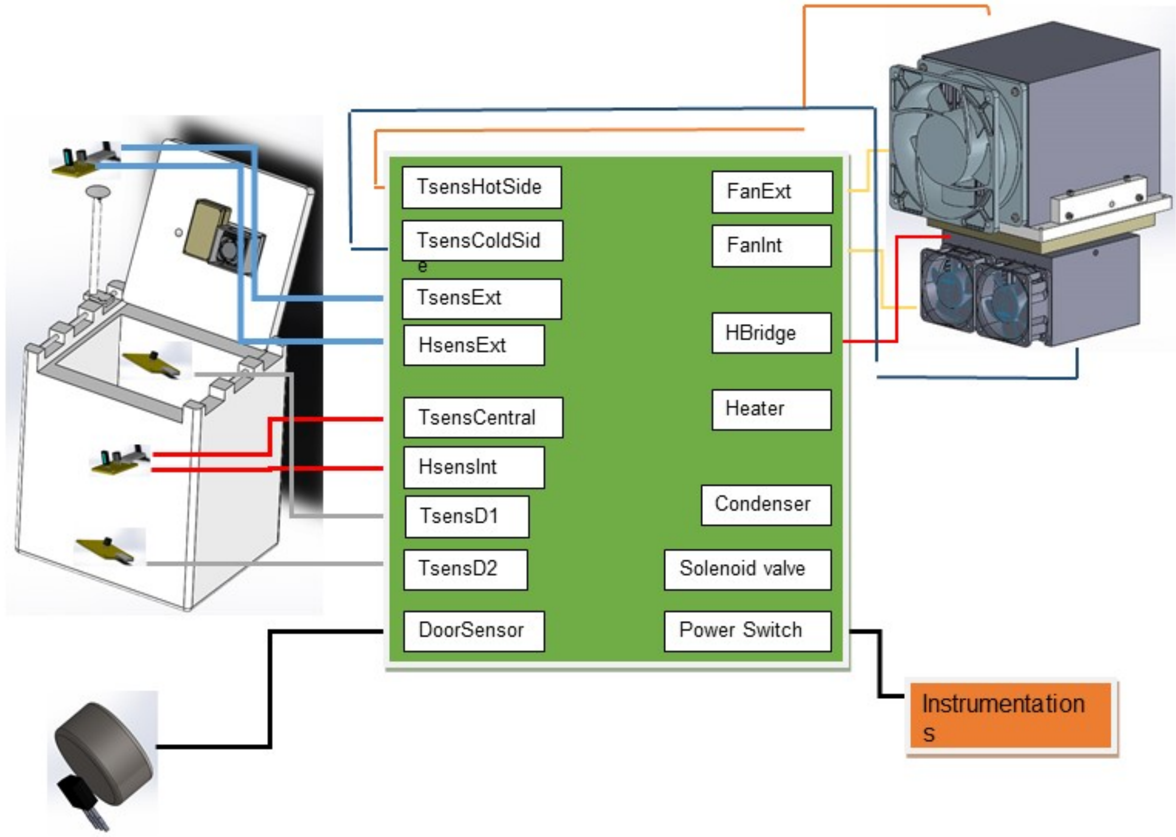


Figure 28 Logical scheme for the connections in the Peltier cells configuration.

3.1.3 – Heat-pipes configuration

This configuration is a hybrid example, with heat-pipe and heater devices, suitable in the presence of a very well insulated container and when the instrumentation produces the heat necessary to maintain the preset temperature. The system provides only the exchange of small amounts of heat with the outside environment, cooling the air inside the box with the least energy consumption.
The heater is used only at the start-up of the system, to reach the preset temperature before starting the instrumentation. Later, the heater will be turned off and the smart unit will control the fans to manage the inside temperature. On this hybrid system, two temperature sensors are needed, one on the external side connected at "TSensHotSide" input and one on the internal side connected at "TSensColdSide", as the system needs to know these temperatures to control and manage the fans.
Furthermore, two fans need to be connected to the respective outputs: "FanExt" and "FanInt".
The most important sensors to make the system work are the temperature sensor inside the box called "TSensCentral" and the temperature sensor outside the box, to measure the environmental temperature. On these readings, the algorithm regulates the fans that remove the heat from the two extremes of the heat-pipe, in order to maintain the preset temperature.

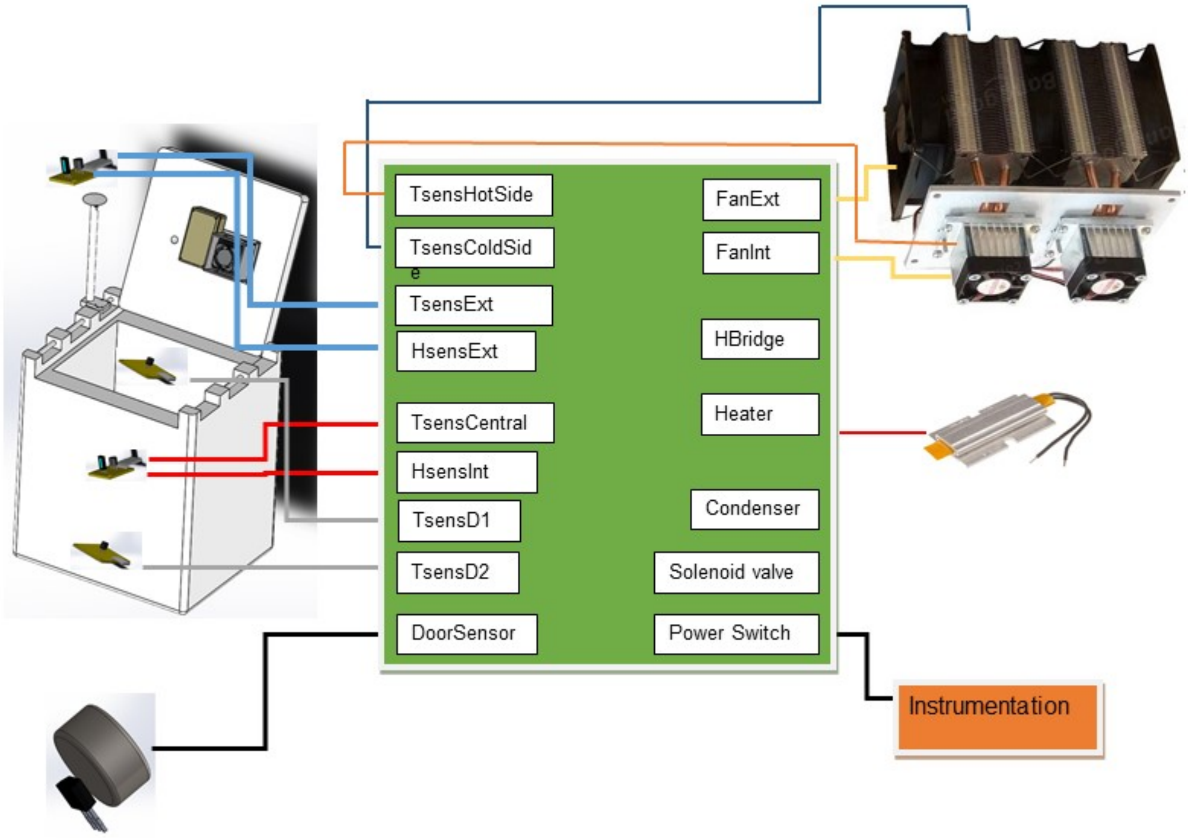


Figure 29 Logical scheme for the connections in the Heat-Pipes configuration.

3.2 – Firmware & Software

The TemperatureHumidityManager board mounts a microcontroller that regulates the power outputs through PWM peripherals, reads the sensors' values and executes the algorithm to control temperature and humidity.

Furthermore, this controller manages the communication with the external world through the Ethernet protocol. The firmware is able to manage a web server. This gives us the possibility to see all the information about the system trough a browser, and use this browser to control and configure the system itself. A microSD memory reader is installed on the board, where all sample data can be collected with 1 second resolution. On the web page, it is possible to see the list of all data files present in the memory and download them as text files.

Figure 30 shows the Control Unit and the functional blocks implemented. The firmware manages these functional blocks and makes them communicate, so every second the control unit reads all analogue inputs, filters every signal, calculates the real values, checks the signal integrity and stores it inside a variable

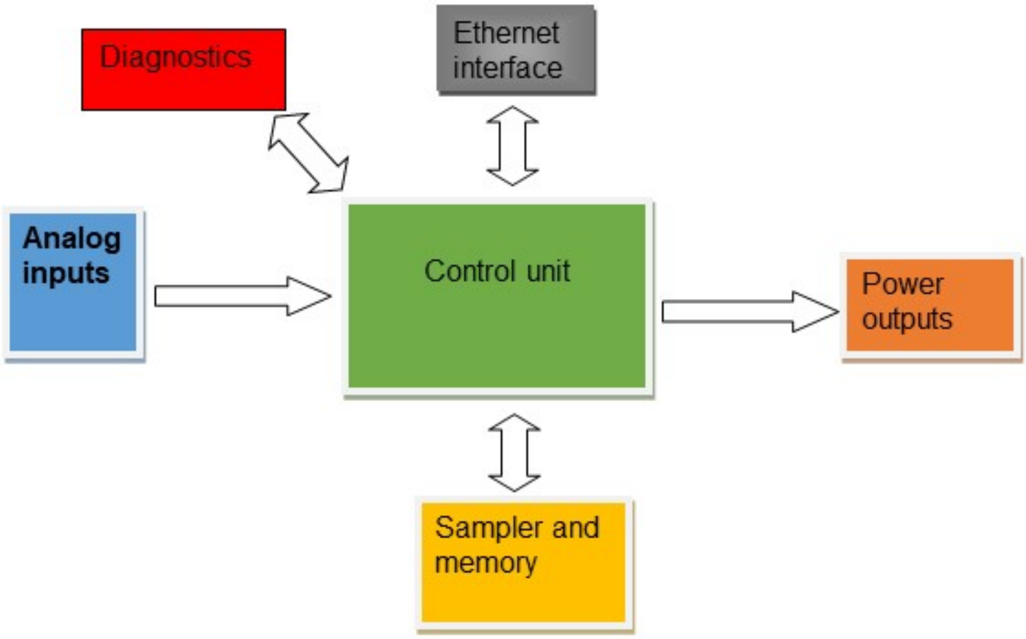


Figure 30 Functional blocks of the system.

The first control to do after reading the analogue signals is to check the voltages and the currents used by the system and verify if these values are within the allowable ranges and consistent with the active commands. For example: check the current absorbed by the "heating" output and verify if the value is corresponding to the status being on or off. If any parameter is outside the allowed range or not consistent, the control unit goes into error state to protect itself, while the diagnostics system reports the error through the Ethernet and LEDs interface.
The reset and restart of the system after checking and repairing the problem is made trough the web page ("Diagnostics reset" button in the configuration menu).
Another function that is managed by the control unit is the sampling of all the data reads (environment sensors, power used on all outputs, etc...). Data sampling can be started by the web page menu "Sampling page", the system storing the data every second inside the microSD memory card in a text file. The text file is named with the current date, with a further progressive number if the system is restarted on the same day.
The most important part of the firmware is the control of temperature and humidity with the various technologies at disposal.
In **all modes** there are some common functionalities, such as the internal fan output is activated and deactivated checking the homogeneity of the internal temperatures (D1, D2, and central sensor). However, the installation of the D1, D2 sensors is not mandatory. Also the voltage and current controls are always running.
In **heater mode**, beside the diagnostic controls for the correct working of the system, it drives the current to the heater output and controls the internal fan in order to dissipate and spread the heat inside the container. When the "Temperature central" is near the target temperature, the system switches off the current at the heater output and lets the internal fan extract all the heat still on the heater device. The right connection for this technology is shown in Figure 27. In order to avoid temperature overshooting and waste of energy, the power regulation is done with a PI (Proportional Integrative) algorithm that reduces power when the temperature approaches the target.
In **Peltier mode,** the control algorithm is more complex as this need some shrewdness to work at the maximum efficiency. The first thing is checking the working range of the Peltier cells and setting these values in the configuration page, in order to avoid damaging them or reducing their efficiency.

The algorithm gives current to the cells with the suitable polarity based on the temperature target with respect to the “central” temperature sensor. The power is regulated by the PWM control through the “HBridge” output. At start, the PWM duty cycle is set to 50%, then the temperature of the hot and cold side of the Peltier system are read and the algorithm regulates the power, checking for example if the hot side, during the cooling phase, manages to dissipate the heat extracted from the cold side. Figure 28 shows the connections for the Peltier technology. If the hot side temperature is considered acceptable compared to the ambient temperature in which the heat sink is immersed, the system increases the duty cycle by providing more energy to the cells, going to further cool the cold side. When the maximum possible temperature difference between cold and hot side (determined by the ability to dissipate heat on the hot side and the limits of the Peltier cell) is reached, the current is limited, and the temperature difference is held constant until the target temperature is reached.
When the target temperature is reached, the Peltier output is turned off, but cooling the external heat-sink is still needed, in order to not return the heat to the cold side. To do this, the algorithm switches to the “shutdown cells” mode, where it gives a bit of power to the cells and starts the external fan at the maximum power to cool the external heat sink, till the external side temperature is around the environmental temperature, at which point the system switches off the fan and stops the current to the Peltier cells.
In **heatpipe** mode the system can move the heat from one side to the other only by adjusting the fans' speeds. This mode can be useful to remove the heat generated by instrument installed in a well insulated box placed in a cold environment. The devices installed inside the box warm the internal environment, so that, when the temperature goes over the target temperature, the control unit switches on the fans to bring out the heat through the heat pipes and to evenly distribute the internal heat. Furthermore, this configuration can be used to heat-up the system's internal environment before switching on the electronics devices that have to work at a given working temperature range. The connection for this kind of technology is shown in Figure 29.

The **Humidity control** is carried out by means of a Peltier cell used to condense the water vapour in the air, collecting it in a container and then expelling it by opening a solenoid valve towards the outside of the system. The system reads the external and internal relative humidity through the corresponding sensors and tries to maintain the humidity under a preset target, adjusting the humidity condenser with periodic cycles and expelling the collected liquid water from time to time.

Following, there is the description of the **user interface,** where it is possible to configure each parameter of the system and check all data taken from the sensors and elaborated by the control unit.
Figure 31 shows the **home page** of the user interface. In this page, all the parameters useful to evaluate the status of the system and working conditions are shown. Specifically, they are all the environmental values, the power consumption of the various devices (fans, heater, condenser), the power used for the control unit and the diagnostic parameters.

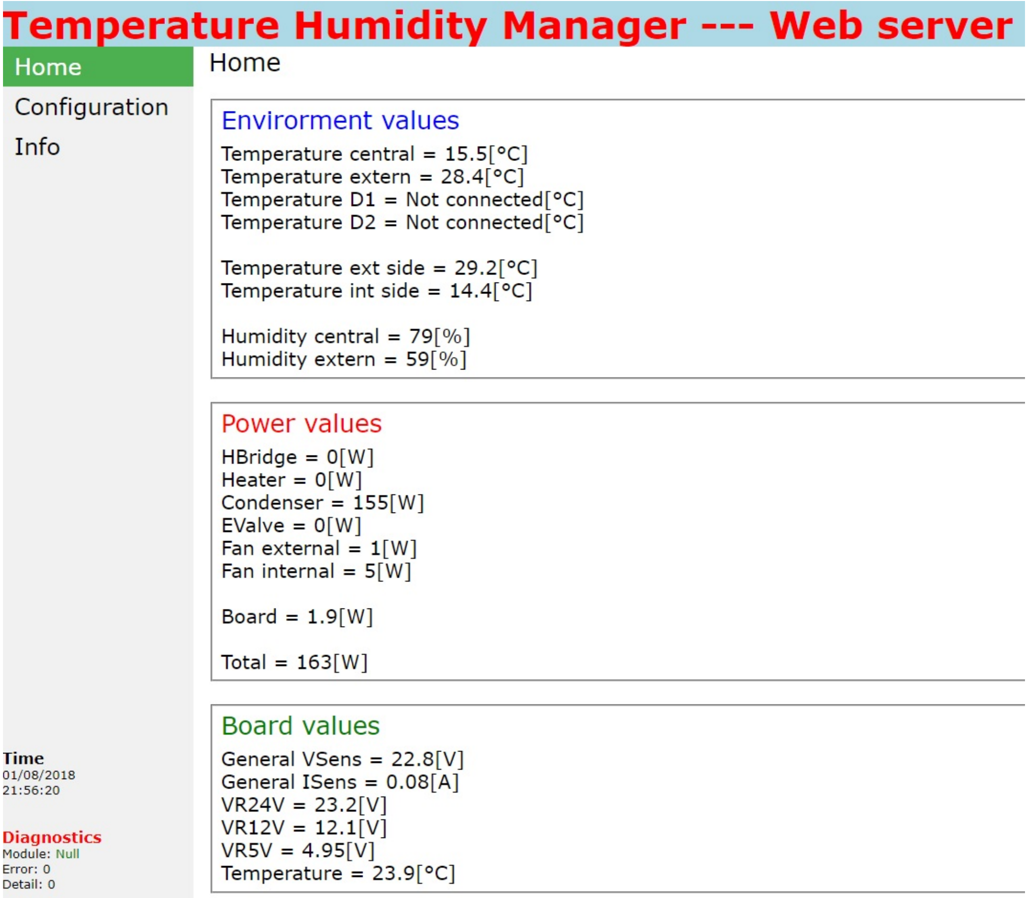


Figure 31 Homepage of the TemperatureHumidityManager.

Clicking on the "Configuration" button in the left side menu, the system ask for user authentication (Figure 32).

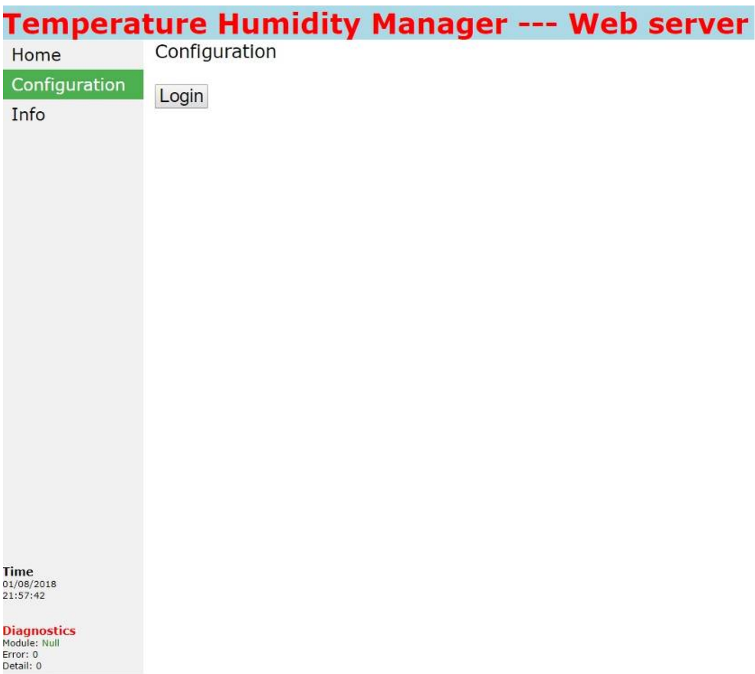


Figure 32 The configuration page need the user to login.

Figure 33 show the configuration page after login. Clicking on the "**Configuration**" button it's possible choose the function Mode: Heater, Peltier or heat pipes (Figure 34).

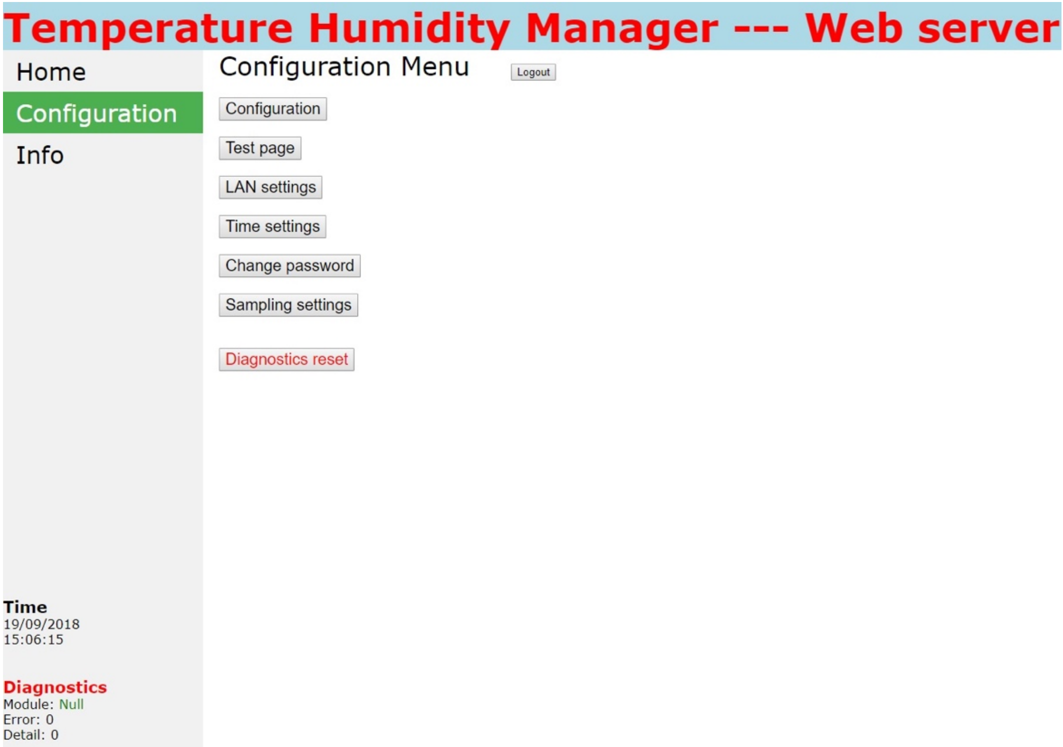


Figure 33 The configuration menu after login.

In the same page, it is possible to change the "Temperature set", the parameter defining the target temperature to maintain inside the box, and the "Hysteresis set", that defines maximum deviance from the target temperature.
Two others important parameters to set for the safety of the heating or cooling elements are the "Element temperature min set" and "Element temperature max set", these values defining the absolute working limits of temperature of the device, in order to avoid damages.
The three parameters pertaining to the proportional–integral–derivative algorithm (PID, see https://en.wikipedia.org/wiki/PID_controller for details) used to control the temperature are KP, KI, KD. They can be adjusted according to the box dimensions and the power of the heating or cooling elements.
When in Peltier mode, at the bottom of the page, other three parameters can be configured. The parameter "Int heatsink cooling DT max" sets the maximum temperature difference between the internal heatsink and the "temperature central" (the air temperature inside the box). If this difference goes over this value, the system drives the element to cool the heat sink in order to send out the heat. The "Heatsink balance cooling power KP" parameter is the proportional constant to be applied to the temperature difference DT, in order to determine the power to be sent to the heat sink. This parameter needs to be set according to the system power and the heat sink thermal inertia.
The last parameter in this page is "Ext heatsink cooling DT max", i.e. the maximum temperature difference between the external heat sink and the external air temperature. If the heat sink temperature is greater than the sum of the external temperature and this parameter, the control activates the external fan to bring the heat sink temperature as close as possible to external air temperature.

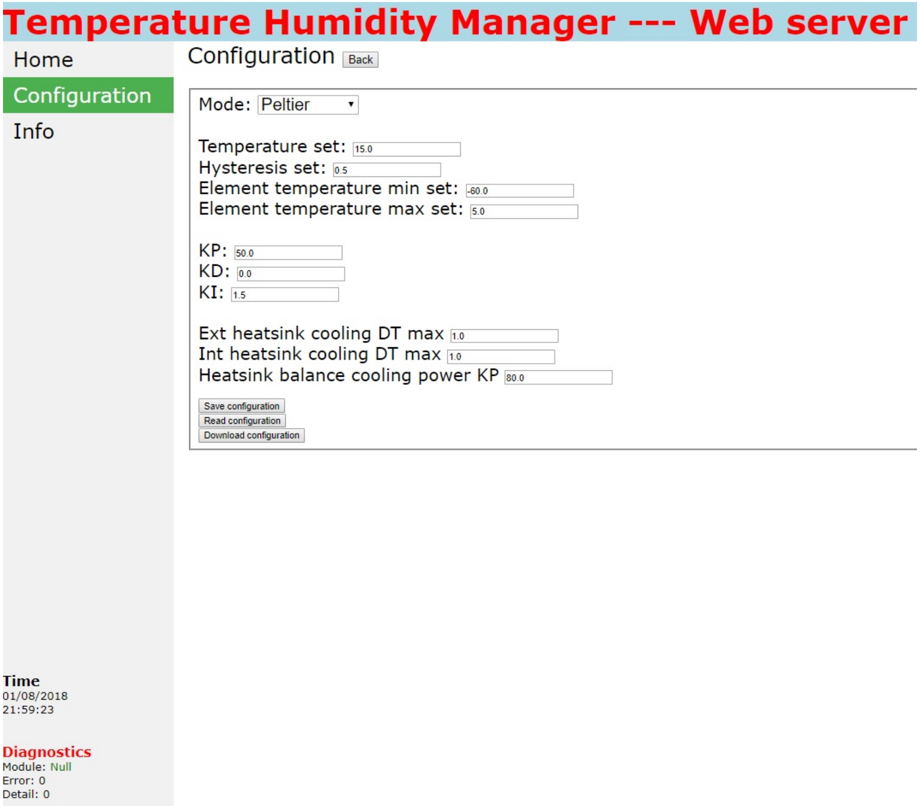


Figure 34 Changing the parameters in the configuration menu.

From the configuration page is also possible to access to the **LAN settings**, where is possible to set the IP address, Subnet mask, Gateway, and two DNS servers (Figure 35), and to the **TIME settings,** for setting the date, time and activate the internet time synchronization through SNTP server (Figure 36).

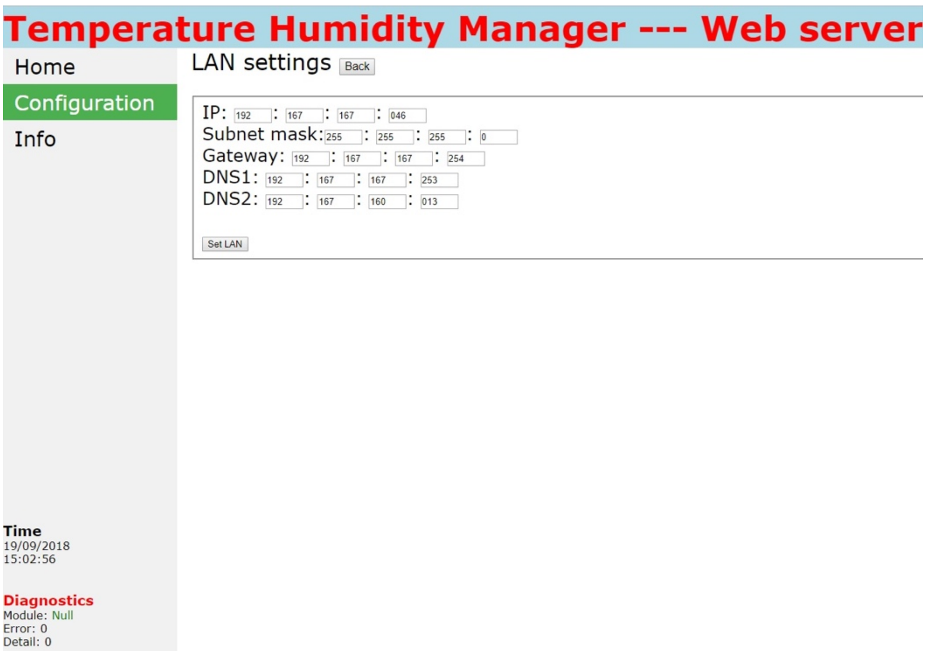


Figure 35 Changing the network configuration.

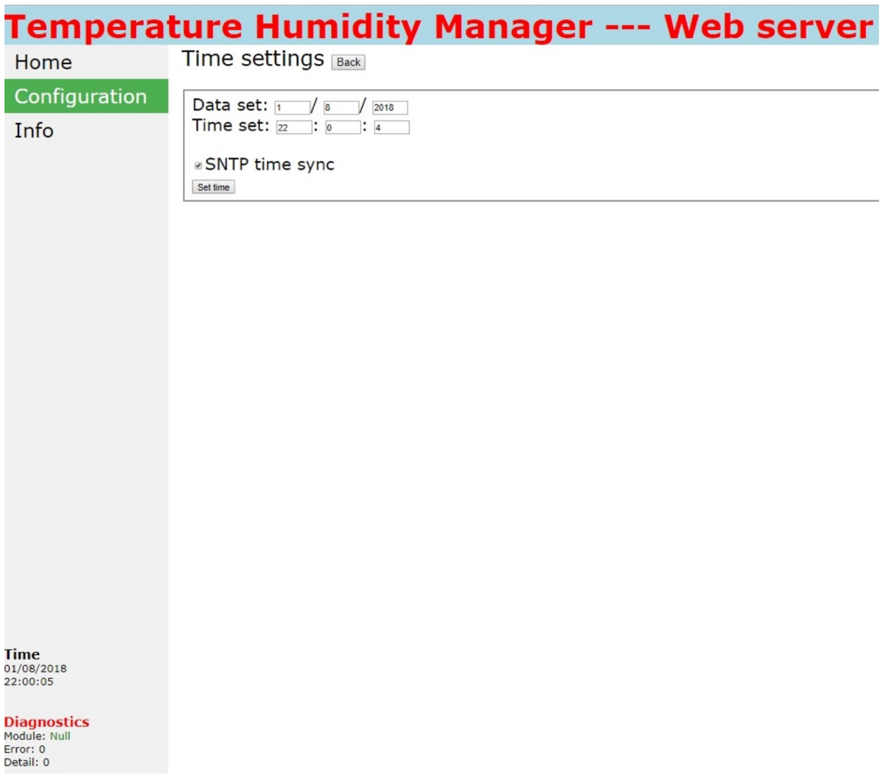


Figure 36 Setting the time.

In the configuration page, it is also possible to change the credentials to login into the configuration page trough the "**Change password**" button (Figure 37).

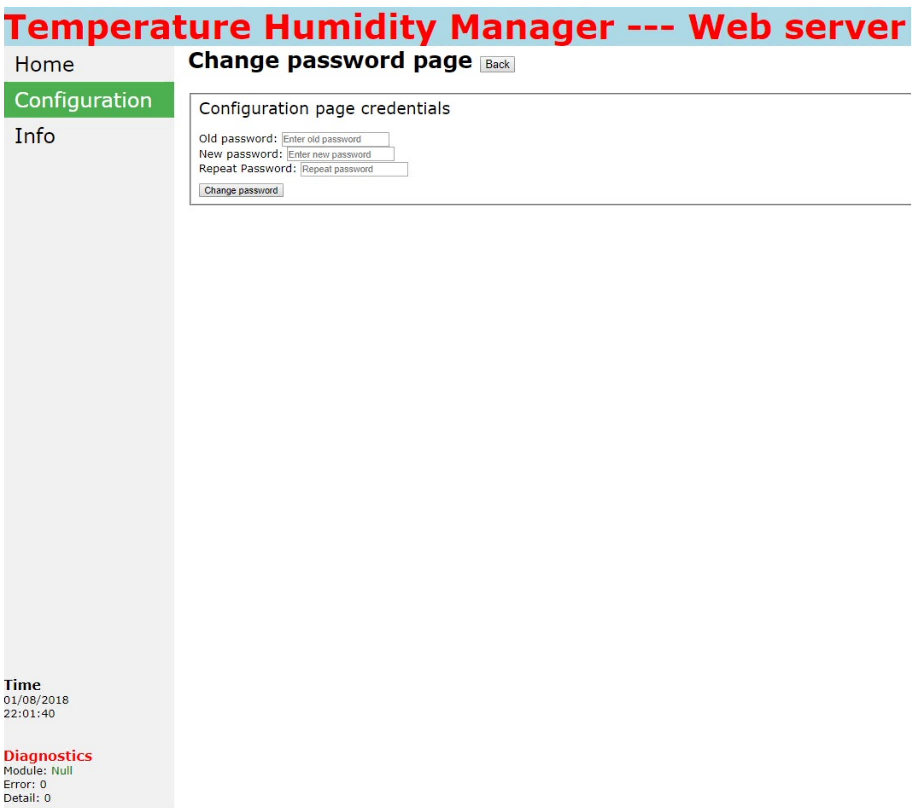


Figure 37 Setting the password for login.

The submenu “**Sampling page**” brings to a page to start/stop the sampling and get a list of the sample files present in the memory card (Figure 38). The single file can be downloaded by mouse right-click and deleted by left-click.

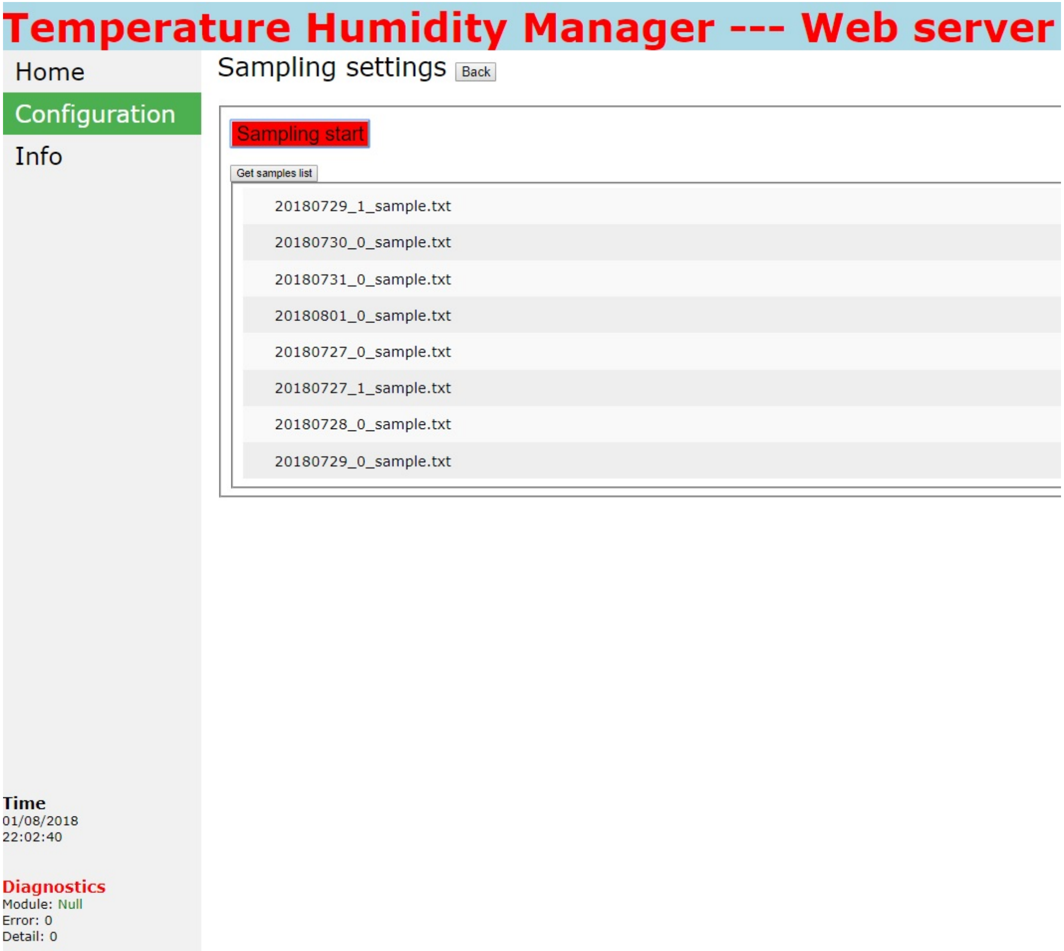


Figure 38 Starting/stopping the sampling and file list.

4 - PROOFS OF CONCEPT DEVELOPED FOR TEST CASES

In the previous sections, we have briefly analysed the general topic of temperature and humidity control for instrumentation and activities of interest for Environmental Research Infrastructures (RIs). A much broader and comprehensive view of the temperature measurements and control strategies, temperature control requirements for various types of equipment and control systems to meet specific objectives can be found in publications realized by the International Society of Automation (ISA - www.isa.org) **(8)**. In chapter 2, we have discussed the problems and identified the most suitable technologies, while in chapter 3 we have described in details characteristics and functionalities of a electronic board and a firmware developed with the aim to provide a tool for ENVRI RIs applications suitable to control and use all identified technologies. What we developed is a PLC-based control **(9,10)** system with advanced functionalities mainly with respect to communication, to take advantage of all remote control potentialities offered by an implemented browser environment. With respect to typical systems we can find on the market, firmware is developed to take decisions starting from measurements supplied by several different sensors (to maintain homogenous temperature also in large volumes) and drive and control not only heating resistances but also technologies that are very different from the control point of view, like Peltier cells and heat pipes. We will come back to this point more extensively in section 4.2.
In order to evaluate performance in real conditions (and not, as done many times, only through simulations with simulators developed for example using the MATHLAB© environment), we also developed and realized complete systems able to host instrumentation and to be installed in the field. In section 4.1, we will briefly present what we can consider "*proofs of concept*" allowing us to test performances of hardware and firmware developed in real conditions. Results of test cases are then presented and discussed in the next chapter.
In section 4.2 we compare our "proofs of concept" with what the market could offer as alternative. This was done to state clearly what can be the advantages and new possibilities for ENVRI RIs arising from the new tool we developed.

4.1 – Proofs of concept

We realized three different systems, all of them based on our temperature and humidity control board and firmware, thanks to which it is possible to drive for each system the technology selected from the three indicated in chapter 1 for temperature and the solution for humidity control.
Each system has multiple sensors: two sensors to measure the ambient temperature and humidity; another two sensors placed inside the box in a central position of the area, with the aim to provide the main input to the algorithm that regulates the heating device (heating resistor, Peltier cell or heat pipe); the last two sensors placed in a different position inside the box, with the scope to provide information to the PLC-based unit about the temperature gradient behaviour, so as to enable control board and software to activate and regulate in the right way components (fans in our proofs) introduced to assure that heat it is evenly distributed in the volume we aim to thermo-regulate.
The electronics board has another two inputs for two temperature sensors called, TsensHotSide and TsensColdSide, these inputs are used to read the temperature of the heating/cooling devices. It's important to know and control the temperature of the heating devices in order to monitor its functioning status and keep it within the breaking temperature limits. For Peltier cells, these readings represent also very important inputs for the algorithm that drives the cells in order to always maintain the maximum efficiency and response speed of the thermoregulation system.
A door sensor was added to all systems, so that the control unit can be informed when the box is opened and a large heat dispersion exists. In such case the control unit switches off the fans and the heating/cooling device to save energy.

The systems were realized and cabled following schemes illustrate in chapter 3 (cfr. Figures 27-29). Figure 39 shows the two boards, "PowerDrivers" and "MainBoard" mounted in their box. The photo shows the compact design and engineering of the two boards, that are connected through a flat cable for signals.

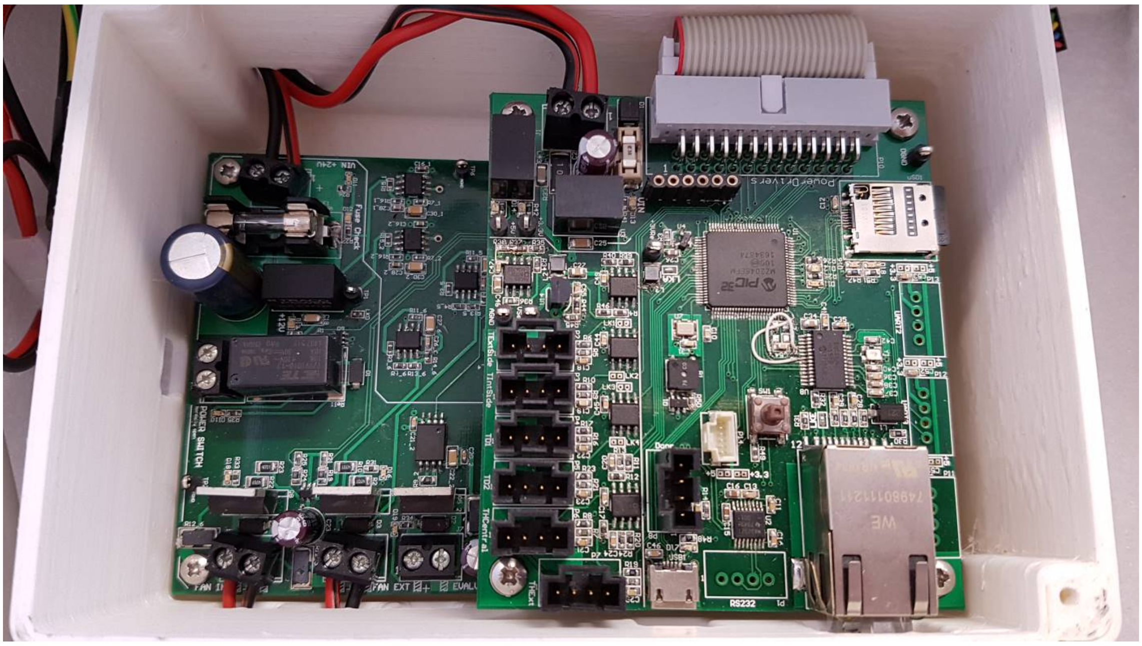


Figure 39 PowerDrivers and Mainboard.

Photo in Figure 40 shows the electronics box realized with a 3D printer.

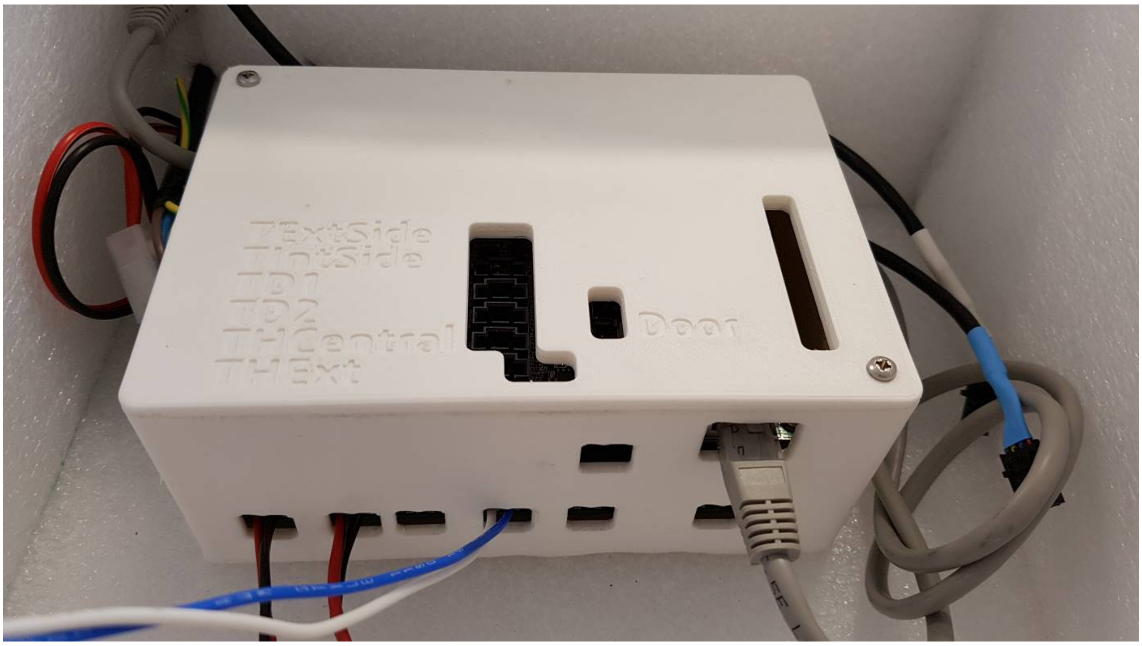


Figure 40 Box containing the two boards, printed with 3D printing technology.

Photo in Figure 41 shows the system realized to test performance of our PLC control unit when Peltier cells are used as thermo-regulating devices. The aluminium box has been internally insulated. A Peltier system has been installed on the roof of the box and not on the side walls since we consider this setup to provide more flexibility in an extreme environment (where snow can cover the box). Being Peltier cells a reversible device, our tests will be a little bit harder if the system is working as a heater, and simpler if the device is working as a cooler. The external side of the Peltier cell was protected against water and snow precipitation. The tube on the right side sustains the external sensors to monitor ambient temperature and humidity.

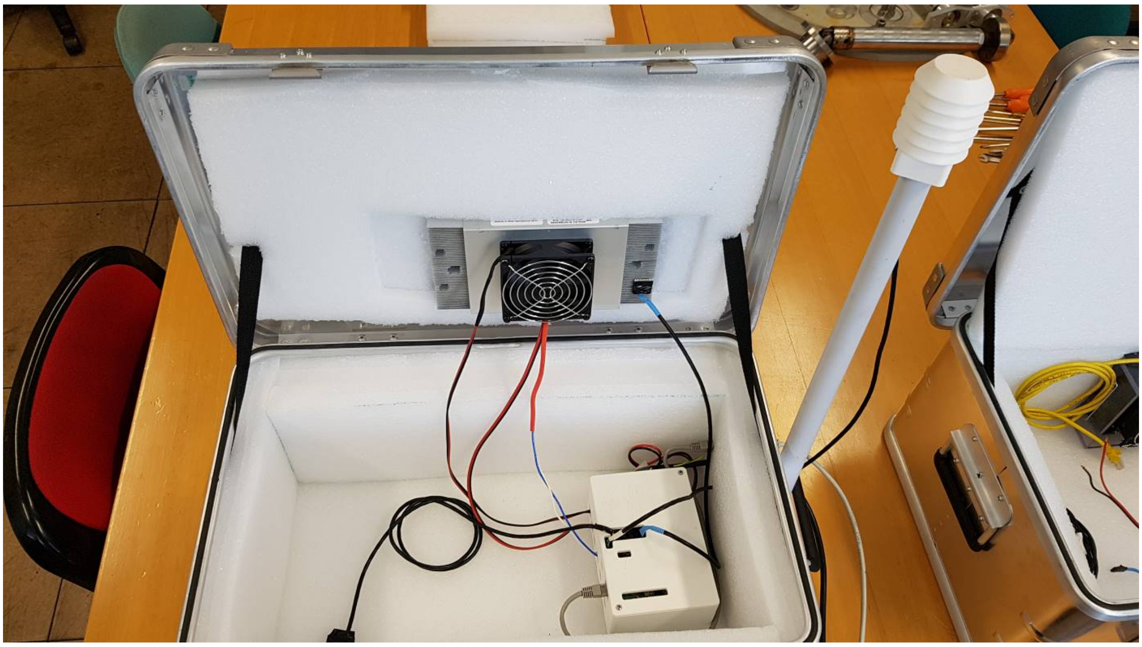


Figure 41 Aluminium box adapted to host a Peltier cell system.

Together with the proof of concept for Peltier technology, we realized two systems to test performance of our control unit when we use the simpler heating resistors technology.

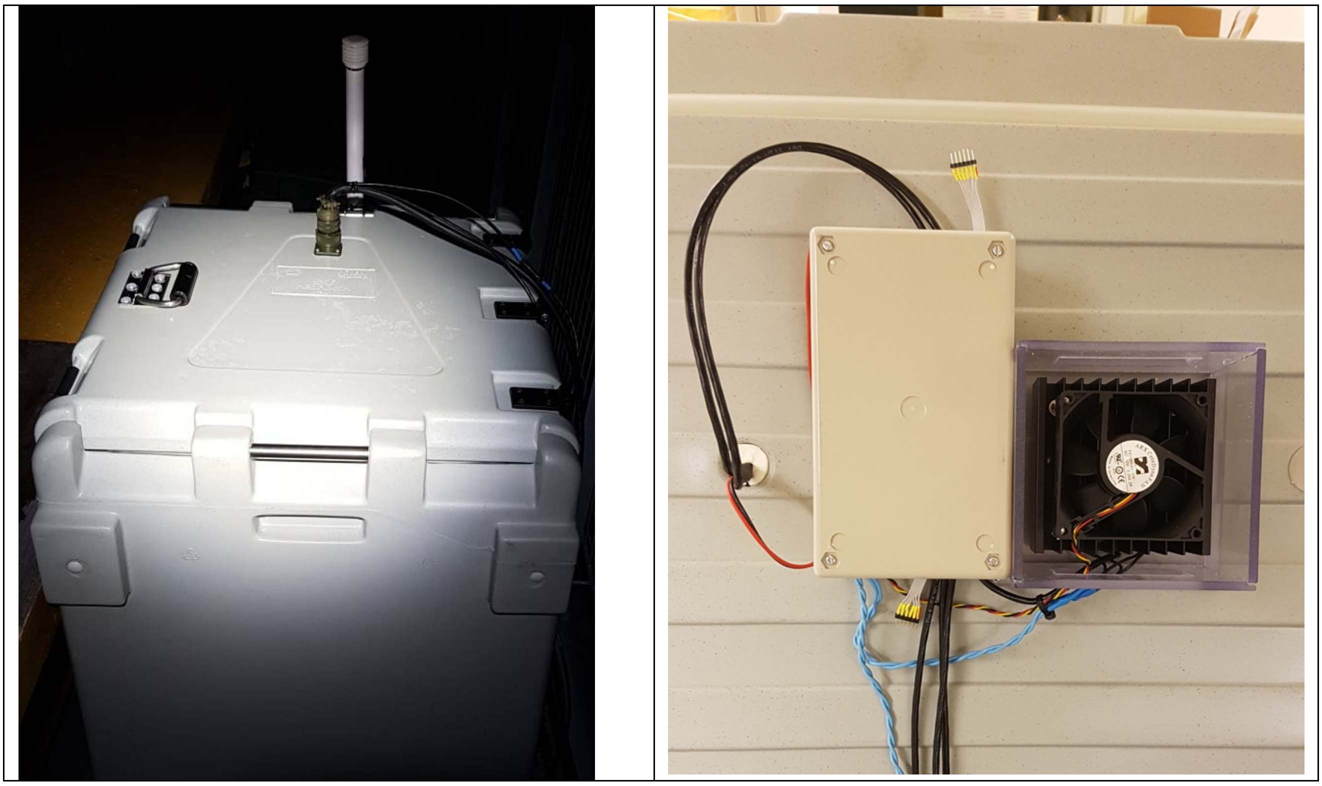


Figure 42 The commercial box manufactured by Melform (AF150V) with heating resistors

The first one was realized using a commercial box manufactured by Melform. These isothermal boxes are typically employed to transport food. They are insulated with CFC- and HCFC-free polyurethane foam **(11).** The specific model, AF150V has an internal volume of 148 l, a weight of 24 kg and 1 opening side. Figure 42 shows the box in the dark of polar winter in Ny-Ålesund (Svalbard Archipelago) and a detail of cabling. Both electronics and heating resistor coupled with a heat sink and a fan were installed in the lid. At that time the 3D-printed box was not yet realized.
The second system based on heating resistors was realized with an Aluminium box similar to that made for the Peltier cells. The two systems are shown together in Figure 43.
For the two systems in figure 43, isothermal characteristics can be easily changed just changing thermal characteristics and efficiency of the insulated material.
In all the three systems realized we simulate thermal effect of a working instrumentation inside the box with a resistance placed at the centre of the box and powered/controlled by our boards to dissipate 10-30 W of electric energy.

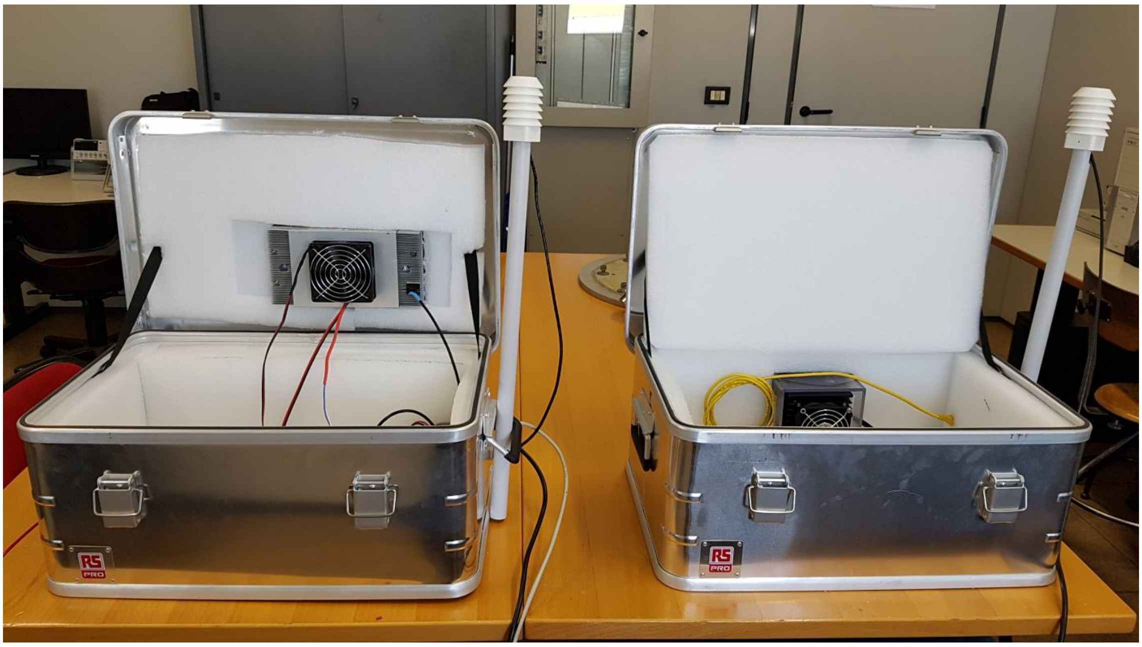


Figure 43 Two aluminium boxes with Peltier cell (left) and with heater (right).

Table 4 presents a complete list of test cases necessary to assess the performances of the developed PLC-based control unit for a truly wide range of environment temperatures. For each range, in the second column are indicated what we consider to be the most suitable technology and setup for thermo-regulating systems. We have realized only in part this plan and results of our test cases are presented and analysed in chapter 5. We aim to continue the work and carry out more tests until the end of the project and beyond.

Table 4 List of test cases to completely assess performances of our PLC control unit (both hardware and firmware).

Temperature range	**Systems**
Low temperature from -60 to 0[°C]	Heating resistors
	Heat pipes
	Hybrid Heat pipes + Heating resistors
Medium temperature from -10 to 40[°C]	Peltier cells
	Heat pipes
High temperature from 30 to 60[°C]	Peltier cells

	Heat pipes + Peltier cells

4.2 – Commercial systems and solutions

Unfortunately, applications for which exist a market sufficiently large to rise to manufacturer's attention are in large part very far from scientific applications and needs of ENVRI RIs. Thermal control solutions are developed mainly for industrial process control and automation and for transport and management of perishable products.
A large amount of industrial processes needs a very accurate, stable and fast control of the temperature. The ranges are, in any case, far from both environmental standard and extreme conditions, being very often related to phase transition of materials or other physics-chemical processes. A great number of commercial devices for temperature control can be found, from single loop on/off systems up to very sophisticated PLC control units. PID algorithms are the most used. These applications are always very well defined as to the environmental conditions in which they need to operate, so that when a production system is realized together with control unit, sufficient time can be spent to determine all parameters necessary for the algorithm to work as efficiently as possible. As an example of how far these systems are from the needs of environmental research and measurements in extreme environments we can give a look to the web pages
https://www.omega.com/section/temperature-process-controllers.html and
https://www.omega.com/prodinfo/temperaturecontrollers.html
of a global leader in the technical marketplace, offering more than 100,000 state-of-the-art products for measurement and control of temperature, humidity, pressure, strain, force, flow, level, pH and conductivity. A brief introduction brochure provided by the same company can be also very useful to understand the main characteristics of systems on the market **(12)**.

The second application, transport of food, medicine or other perishable products
(i) is rarely interested in maintaining a fixed temperature in the specific volume;
(ii) is in general interested in a temperature range relatively narrow between - 18 °C and 4-5 °C, with a clear preference for low temperatures, so as to assure proper heat retention, limiting the risk of bacterial proliferation whilst preserving food quality and organoleptic characteristics;
(iii) is many times interested in limited time periods so that, when possible, tends to use passive (insulation) solutions. When longer time is necessary, refrigeration technologies are employed, usually to big volumes (ISO10 or ISO20 containers) More recently, solutions based on thermochemical substances started to be commercially used. Examples are the Alcatherm containers of the COLDWAY company, able to generate cold entirely autonomously (from 12h to 48h), without the aid of any electrical supply **(13)**. The above remarks clearly indicate that even if we have used an isothermal box realized by MELFORM, we can't obtain from the market and commercial offers related to this application, systems suitable for ENVRI RIs activities.

Biology and medicine laboratories, whether they are for research or to carry out analytical work, have a great need of controlled temperature devices both to store and to treat biological and organic samples. Maintaining a constant temperature is vital in many processes to ensure consistency and safety, however this can be difficult in a working environment. Cooling systems might be used to keep a reaction or piece of equipment below room temperature, but they are also employed to remove excess heat generated by the system to give a constant temperature which might be at, or even above, the room temperature. Chilling circulators are one of the most versatile cooling systems **(14, 15)**. They comprise of a chilling bath (which actively cools the bath liquid by refrigerants) and a thermostat circulator (which controls the temperature and circulates the liquid). The bath liquid can then be circulated through insulated tubing to cool external systems, or smaller vessels like flasks or test tubes can be placed straight into the bath liquid. Many times in laboratories as well as industry, it is necessary to store materials and/or to carry out tests at controlled conditions. On the market, it is possible to find a lot of temperature- and humidity-controlled cabinets or climatic chambers **(16, 17)**. Most of the time, manufacturers just present their capability to realize systems and provide a range of prices, being ready to realize the system on the basis of custom requests. On the market, it is possible

to find commercial solutions operating in a very wide range, from -100 °C up to 250 °C **(18)**. Last typical application in laboratories is related to confined controlled ambient suitable for human manipulations of samples and chemical and medical substances. Compact Glove Boxes with full humidity control and full temperature control can be found without problems in the market **(19,20)**. Since this system involves human operations, the temperature range is narrow, typically from 10-20°C below zero up to 40-50 °C above zero at most.
Of course, all these devices are suitable for indoor operation and therefore not useful for application in extreme environments. However, we spent a few words on them because these devices are relevant for terrestrial domain RIs that also include laboratory activities in their perimeter of interest

The last commercial application we need to consider is related to green/renewable energy. This is the field closest to typical needs of ENVRI RIs for measurements in extreme environments. Fuel cells is a technology that can be very useful for providing electrical power in many conditions. A fuel cell is a device that generates electricity by a chemical reaction. Every fuel cell has two electrodes called, respectively, anode and cathode. The reactions that produce electricity take place at the electrodes. The Smithsonian Institution has realized a very nice web site providing all information on this technology **(21)**. Typical fuel cells produce very low pollution, being the exhaust by-product just water, therefore they combine the appeal to be a source of green energy with the advantage to be always available until the fuel they use lasts. Being the functioning of fuel cells related to a chemical reaction, it is not surprising that the efficiency of this technology is strongly related to operational conditions. Fuel cells devices are realized for indoor operation, and their efficiency decrease dramatically at temperature below zero. To assure the amount of energy needed at any weather conditions in outdoor applications, it would be necessary to place fuel cells in a temperature controlled box. Unfortunately, outdoor applications of fuel cells apparently are not much considered by users, so the market offers very few commercial products of this type. One of them is the ProEnergyBox realized by the EFOY **(22)**. From the web page of manufactures, we can read

> *The EFOY ProEnergyBox has been especially developed for extreme cold weather conditions. Effective temperature regulation means that the waste heat from the EFOY Pro fuel cell can be used when the temperature is below zero to keep the energy solution warm and to prevent the battery and electronics from freezing. For high ambient temperatures, an effective heat conduction system has been implemented to protect the components in the EnergyBox from heat.*

The box realized by EFOY is indicated as suitable to operate from -40°C up to 50 °C. However, the only function of the box is to maintain internal temperature above zero and avoid that insulation and internal heating could rise it to dangerous values for electronics and other component.

We can't conclude this analysis without underlining that the large amount of technologies and single component and devices for temperature and humidity control at disposal on the market, and the great specific knowledge and competencies arising from development of solutions for the applications above indicated, provide a lot of possibilities for access to custom product services from a large amount of manufacturers. This is in large part also the consequence of the large differences that usually exist from one specific case and another: the efficiency of a temperature and humidity control systems depends on so many factors that it is difficult that a single system can represent the best solution for two different cases. The possibility to have access to custom services can be strongly limited by the minimum number of pieces requested by a manufacturer to take an order **(23)**, or, most of the time, by high costs. Our PLC-based control unit can represent the core element of a custom system realized on the basis of specific needs of RIs. This tool still leaves the possibility to make a choice between the suitable technologies selected after the analysis of the general question in chapter 2, and firmware was developed considering typical measurement operations. Hardware and software are both completely documented and open to potential users. That means it will be possible to ameliorate or adapt to more specific needs not considered up to now.

5 - The activities in the field and the results obtained

This chapter is devoted to presenting and discussing the results of test cases performed with the proofs of concept we realized and that are described in the previous chapter. Since a large experience was acquired by the authors in the past as a consequence of the long activity in polar regions and in particular in the very peculiar and extreme site of Dome C above the East Antarctic Plateau, the main elements of these experiences are presented in the first section. This is because they represent the knowledge base on which our PCL control unit was then designed and implemented.

5.1 - Previous activities

The CNR-ISAC group in Bologna has gained experience on thermoregulating f instrumentation during several years, working mainly in Antarctica. Back in the 80s, different models of photometers and radiometers were designed and realized within the institute. These instruments needed thermoregulating both for facing the very low temperatures of the location where they were installed, and for ensuring the stability of the sensible internal components, mainly thermopiles and photodiodes. At the end of 90's, the activities of the group bring it to deal with the use of Peltier cells. The first application was for the temperature control of a custom UV radiometer, UV-RAD **(24)** that was built to operate at medium latitudes like Bologna and also in Antarctica. The second application was to realize an automatic dehumidifier for CO2 measurements. In this latter case, the need to reach -60°C and then create a gradient up to 80 °C obliged to employ Peltier cells in a double stage configuration.
Since 2005 the group started to operate at the Italian-French station Concordia over the East Antarctic Plateau, implementing and managing there a BSRN (Baseline Surface Radiation Network) station. The requirements of this network call for radiometric measurements not only very accurate but also carried out with a 360° horizon as free as possible. So, radiometric sensors and trackers need to be installed at a suitable distance and height with respect to the main station and shelters. As a consequence, we were faced with several problems connected with the necessity to keep operational along the whole year in a very extreme environment for data acquisition systems and moving devices as a solar tracker.
The Antarctic Plateau represents the hardest environment for mechanical as well as electronic and radiometric instrumentation. In a site like Dome C, where the Italian-French station Concordia was open as a permanent station in January 2004, during polar night, temperatures range normally between –70°C and –80°C, 30°C lower than the lowest operational limit given by the Kipp & Zonen for their 2AP-GD tracker. Even during summer, maximum temperatures are around –20°C, so that there is no period during the whole year in which maintenance can be performed without problems arising from temperatures below 0°C. At the same time, the difference between summer and winter conditions is very large, so that the temperature control needs to be able to manage in a proper way an environmental temperature change of more than 60°C: more insulation or more heating can't be the only solutions.
In order to maintain the power supply and acquisition systems installed on field at above-zero temperatures we found very suitable PTC Thermistors. Selecting in the proper way their power and the temperature at which they stop in practice to work, reducing at zero the current flow mostly by increasing resistance, and opportunely dimensioning the box insulation, heat sinks and fans, we were and continue to be able to realize temperature control boxes in which temperature is above zero during polar night and during summer normally do not rise above 20-30°C.
More challenging has been, instead, the work to allow continue operation of the 2AP-GD Kipp & Zonen solar tracker that we installed in 2006, ensuring its survival to the polar night. The most part of changes/improvements were performed during the austral 2007 campaign to recover a first failure of the tracker.
The 2AP-GD tracker is a system realized by Kipp & Zonen to operate in extreme environments. So it is equipped with an active internal on/off heating system. Heaters are switched by an internal air

temperature sensor: on when temperature is below 7°C; off when temperature reaches 13°C. These numbers have an accuracy of +/- 3 degrees Celsius. The tracker firmware measures air temperature with a sensor mounted on the controller board. In case temperature drops below -10°Celsius, the firmware will not drive the motors to avoid mechanical damage. The controller board itself keeps communicating, so that the status can be detected remotely by reading the instrument status. In addition to the active heating system, the manufactures provide for extreme cold conditions also an external insulation to mount on the tracker. With both systems mounted, tracker operations are considered possible until external temperatures drop to -50°C.
As quite obvious, the critical parts that need to be protected from excessive cold are electronics and engines. From this point of view, the tracker presents a couple of characteristic that can be critical in polar sites:
(1) – The position of the heaters and the absence of ventilation tend to produce in cold regimes a strong stratification of the temperature inside the 2AP-GD. Location of step motor drivers at the base and the use of the tracker bottom as a heat dissipation element, can produce strong thermal stress on the more sensible electronic component.
(2) – The impossibility to separate electronic board and heating system functioning and to have a pre-heating of the tracker, can produce many problems if maintenance is necessary when air temperature is below zero and/or station suffers even a short black out.
In Concordia, for sure the biggest challenge is represented by the strong temperature gradient that without modifications tend to create inside the instrument: between the bottom and the top of the tracker temperature difference can reach several tens of degree.
Confirming what has just been said, our group as well as others experienced failures that can be connected to (i) damage to the slo-syn step-motor drives, being they the most sensitive electronic components or (ii) a too strong mechanical coupling generated by the deformations of materials under the action of extreme cold. The two conditions produce the same failure message, so they are impossible to discriminate before dismounting and repairing the tracker.

The second custom system to control internal temperature we realized aims to reduce the two critical issues mentioned above, allowing heating also when instrument is powered off, a much better homogeneity of internal temperature, and a more suitable location of heating elements and the control sensor.

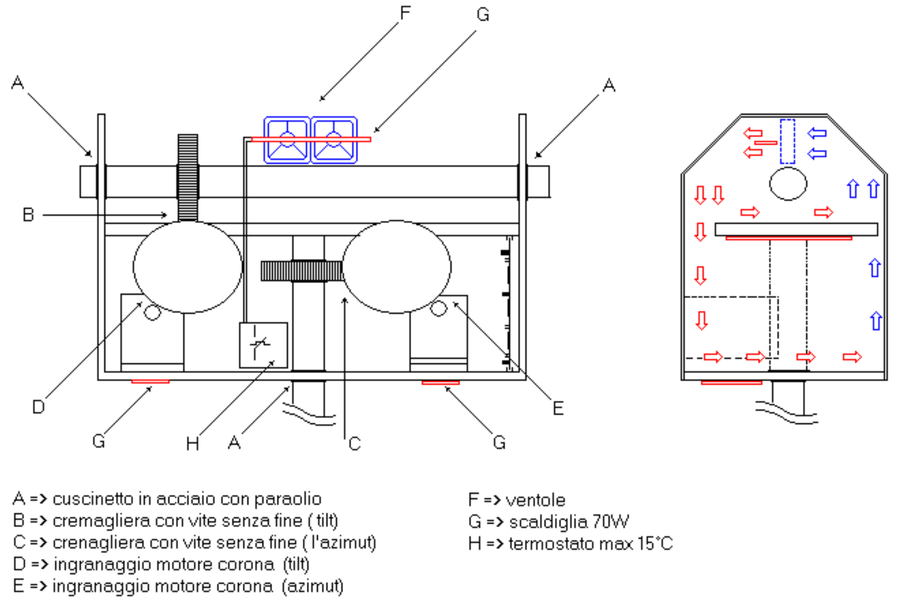


Figure 44 Schematic of 2AP Kipp & Zonen sun tracker and solutions adopted in 2007 to increase its operational capability in Dome C. Added elements, F-G-H, are in colour.

A heating thermo-regulating element of 50 W (G) was installed on the upper part, while two fans (F) force air flow inside the tracker. In addition, on the external side of the case bottom, two heating elements of 70W/220V (G) were installed in order to reduce as much as possible the risk of low temperature for the drivers and to reduce internal stratification of the temperature. Our independent heating system is regulated through a thermostat (H) aiming for a temperature of around 10-15 °C and located near the sensible step motor drivers. The supplemental internal heating element and fans are independently powered at 12V DC, while the two external AC heating system are powered through the 2AP power cable. In addition to this active systems, we also improved insulation of the stepping motor drivers with respect to the case bottom through a sheet of Kapton.
With these improvements, we were able to operate the tracker since 2007 up to now without failures connected with temperature issues. This example clearly shows that in extreme environments, for each specific case, the first step is to clearly understand the critical issues arising from extreme environmental conditions. This analysis need to be performed considering that extreme conditions can create unbelievable conditions (e.g. 20-30 °C gradient in 30-40 cm). A clear and correct analysis normally allows to immediately identify the effective solutions. The second learned lesson is to keep these solutions as simple as possible in order to increase their robustness.

5.2 – Activities performed during ENVRIplus

Testing of a box with heating resistors in Ny-Ålesund, Svalbard Islands, during winter.

Figure 45 The box installed on the roof of Sverdrup Station in Ny-Ålesund.

The heating box in Figure 45 is based on a Melform AF150V commercial box, with external dimensions equal to 69x57xh79 cm, while the internal are 53x43xh65 cm for a total capacity of 148 litres. The heat transmission coefficient U=0.42 W/m^2K defines which is the power exchanged with the external environment for each square meter and each degree difference. The total area of the walls is about 1.7 m^2. With the aforementioned overall heat transmission coefficient, the heat Qt nominally dissipated by this box is about 0.715 W for each degree of difference between inside and outside temperatures.
Considering an average environmental temperature equal to -10 °C during winter, in order to assure 20 °C inside the box (DT = 30°C), we need Qt * DT = 0.715 W/K * 30 K = 21.5 W. It should be noted that this is the nominal thermal power needed, that is different (lower than) from the electrical power, due to the efficiency of the heating system. Furthermore, it's important to keep in mind that this estimate don't consider the heat losses caused by various elements that may be present in the box (e.g. connectors) which can create thermal bridges with the external environment, each of them with different thermal conductivity.

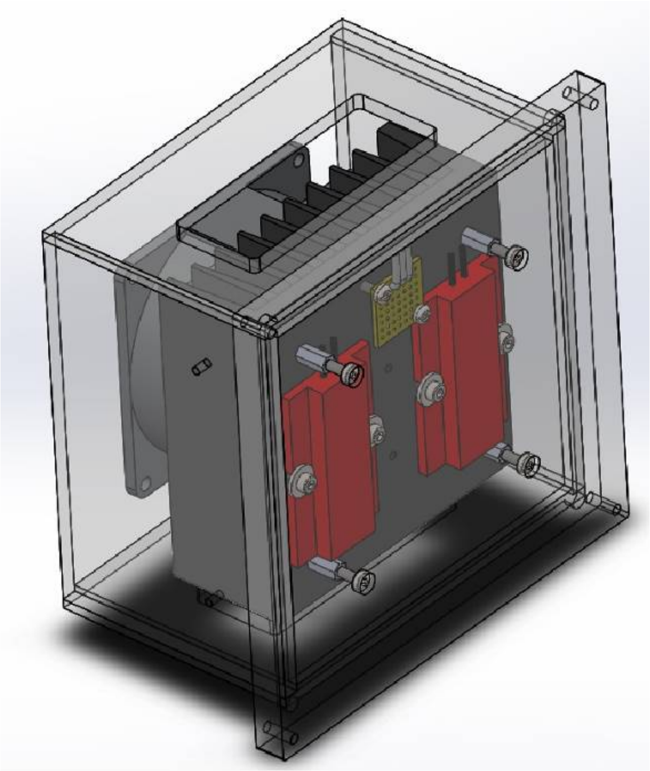


Figure 46 Drawing of the heating device designed for the system based on Melform box.

The heating device (Figure 46), we realized for this test case system (proof of concept), is composed by two heating resistor with 60 W of total power installed on a heat sink with 1 W/K of thermal conductivity. On the heat sink is installed a fan to facilitate the dissipation of the heat. The whole system is encapsulated in a container that channels the air into the heat sink and than redirects it to the box through the fan. On the heat sink is installed a temperature sensor to monitor and control the temperature.

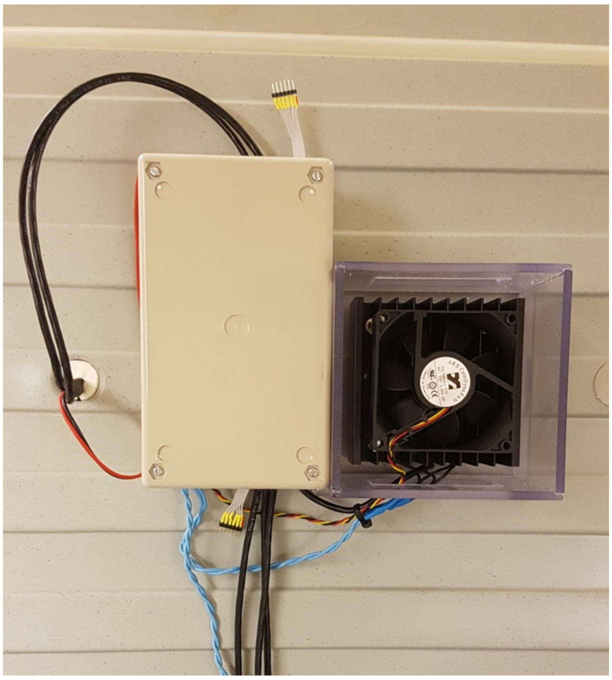


Figure 47 The electronic box and the heat sink box.

The dataset of this test is divided in two periods: from 13-12-2016 to 16-01-2017 (winter) and from 01-07-2017 to 01-08-2017 (summer). Figure 48 and Figure 49 show the internal and external temperatures, as well as the power consumption, during the two periods. We are interested to electric power employed to control temperature. Since in this test case, dissipation of scientific instruments help to reach/maintain our result, we powered the resistance simulating their thermal effect only for short periods, making harder our test (cfr. InstrHeat curve).

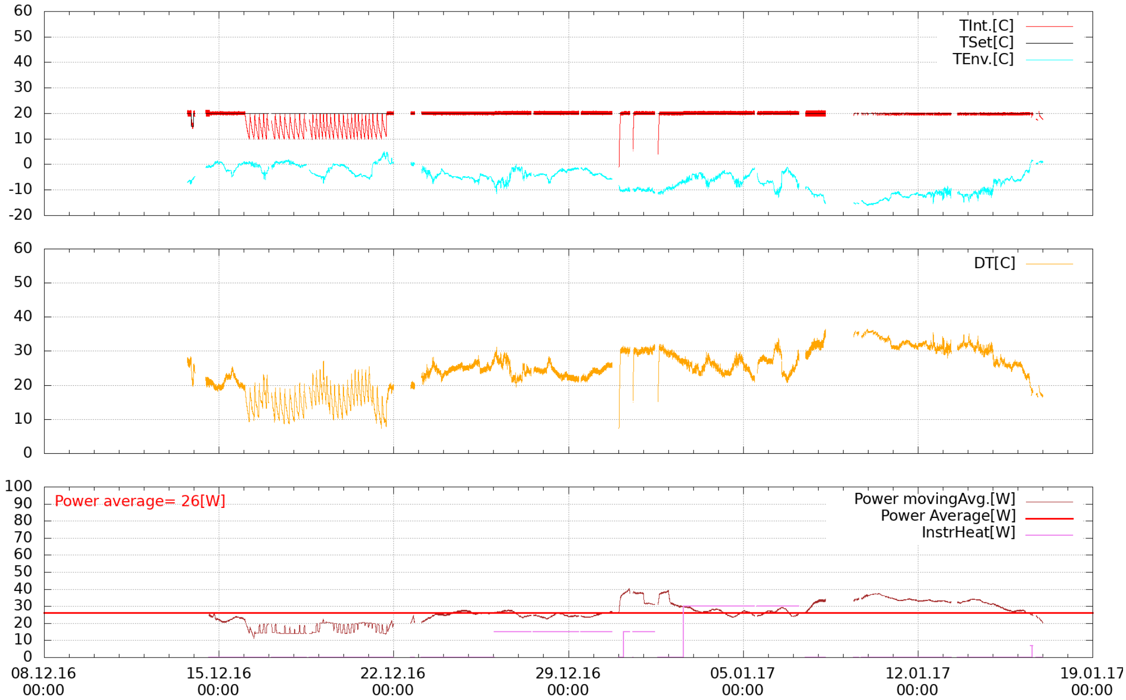


Figure 48 Environmental and electric parameters obtained during the first test period.

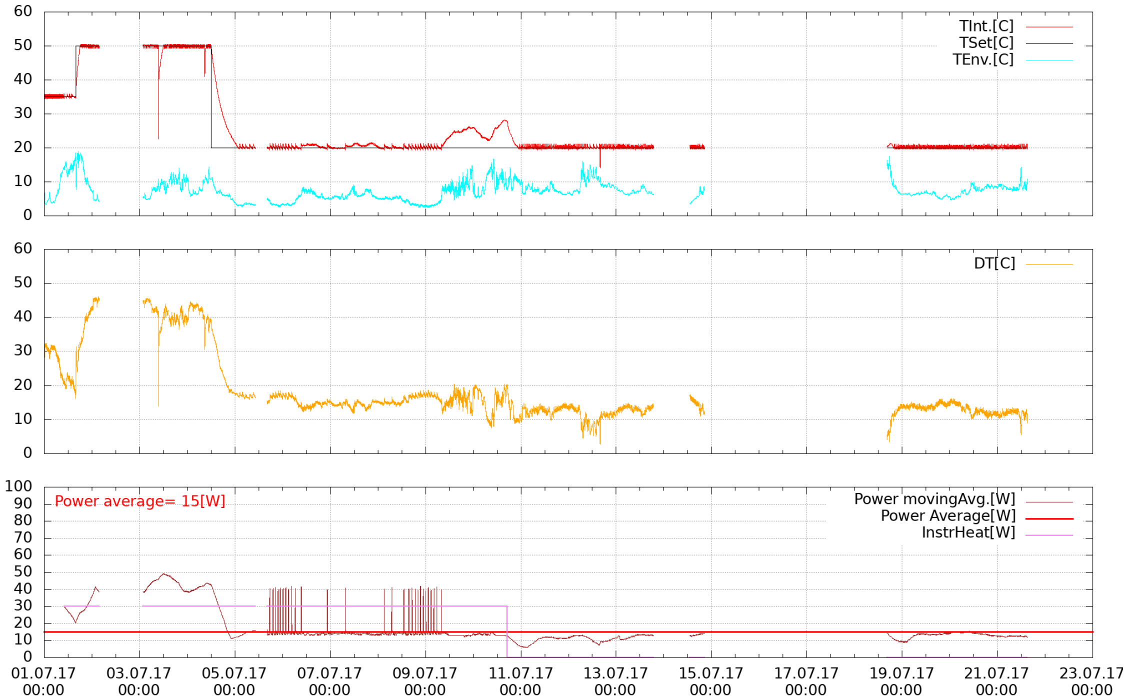


Figure 49 Environmental and electric parameters obtained during the second test period.

Within these two periods, different tests have been conducted, with different modalities.
During the first part of the winter period, from December 17 to 22, the system controlled the temperature in a preset range from 10 to 20 °C (Figure 50). As stated above, the power to the heating element is controlled by a "PI" (Proportional Integral) algorithm that avoid temperature overshoots and the useless consumption. The proportional and the integral constants should be changed according to the box characteristics, in order to make the system work at best. The system used about 17 W on average, with and external temperature oscillating around zero degrees Celsius.

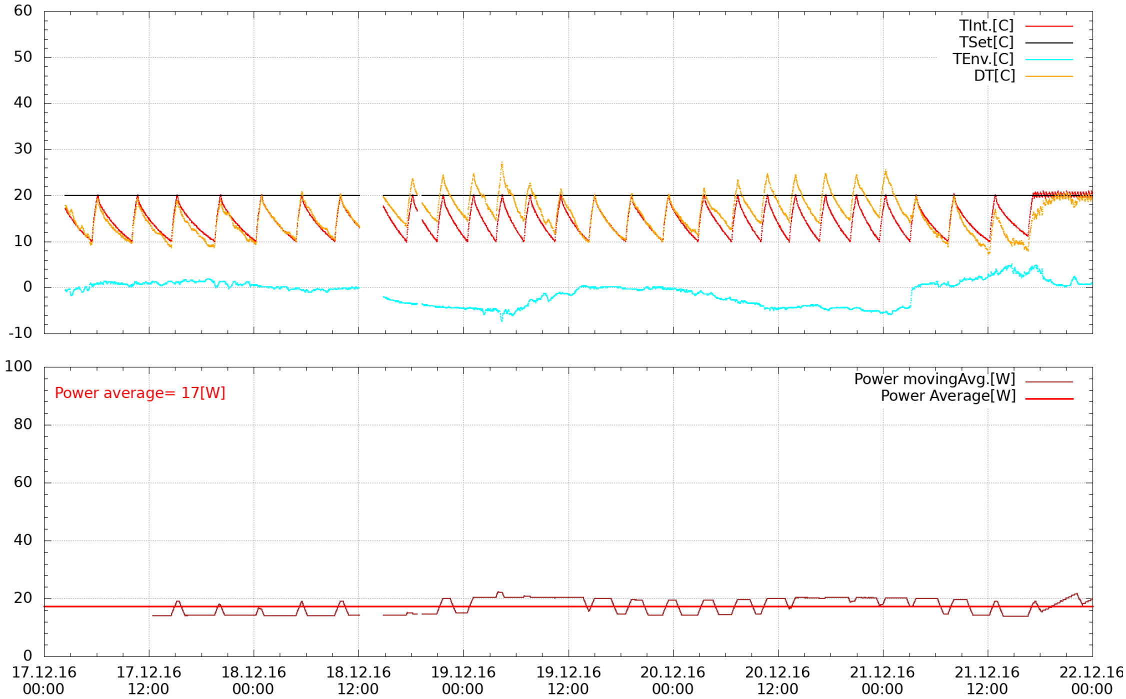


Figure 50 Test period with a 10 °C temperature range.

Figure 51 shows the results from another system configuration. In this case a single temperature value, in this case 20 °C is maintained in the box with a hysteresis of 0.5 °C. The test period was January 11 and 12, with and external temperature slightly below -10 °C. The average power necessary to maintain the internal temperature was 33 W.

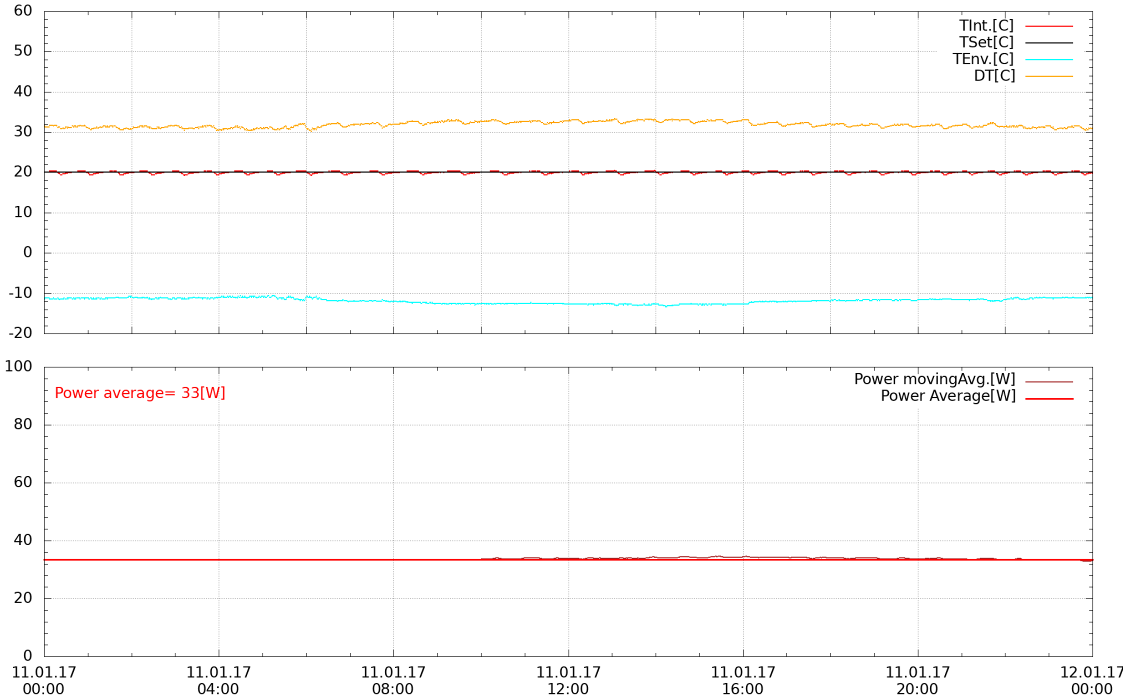


Figure 51 Test period with a fixed temperature target.

In the period from January 10 to 17, the external temperature varied between -15 °C to about 0 °C. In order to maintain a temperature of 20 °C inside the box, the power requirement varied between about 40 W to about 20 W (Figure 52).

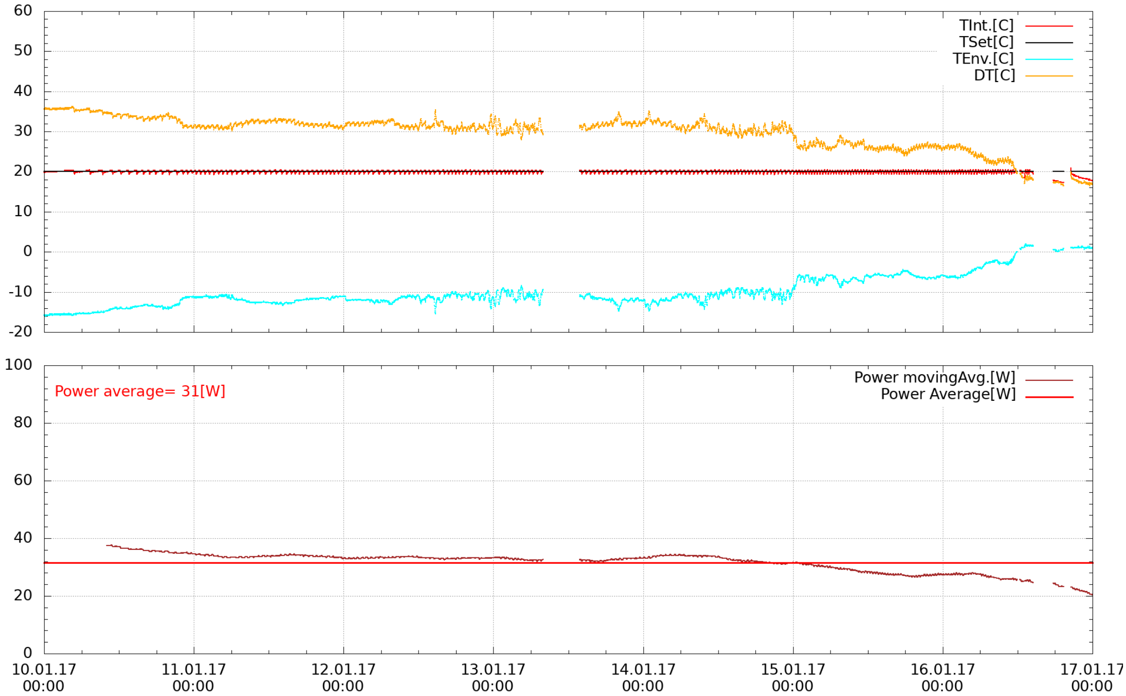


Figure 52 Test period with a very large environmental temperature variation.

In order to verify how the heat spreads inside the box, three temperature sensors are installed in different position with different distance from the bottom (Figure 53).

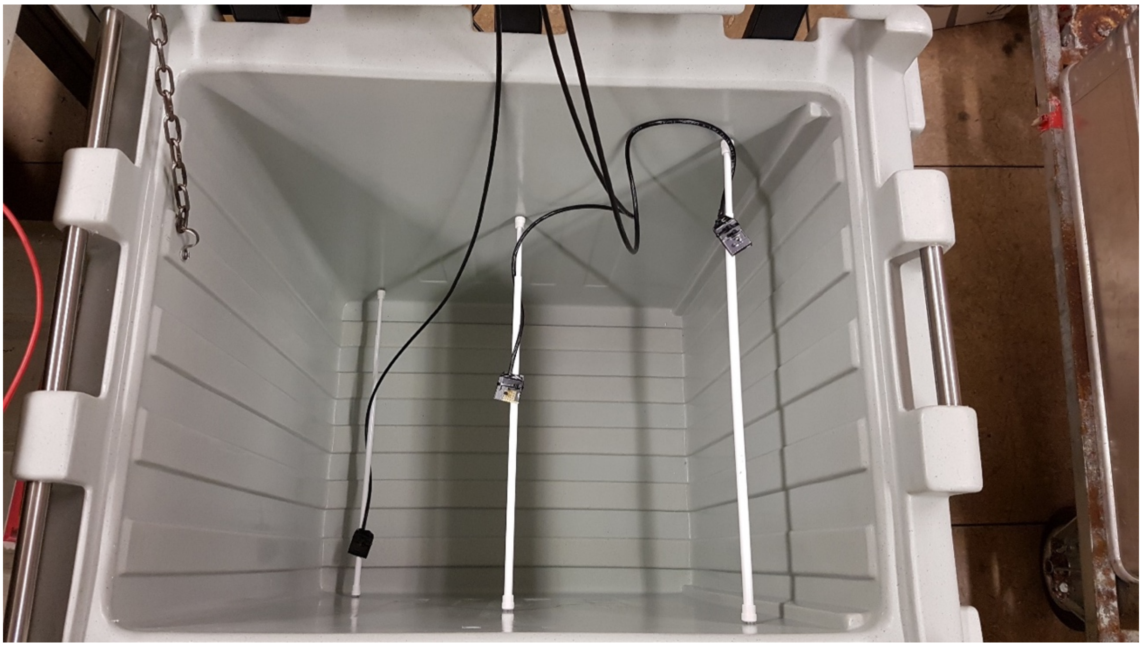


Figure 53 The three temperature sensors installed in the box.

Figure 54 shows the temperature inside the box at the 3 different heights (TNear being the sensor close to the heater, installed in the high part of box, TCentral the sensor positioned in the center and used by the electronic to drive the heater, TFar the sensor far from the heater, i.e. at the bottom of the box), as well as the heater temperature (THotSide).

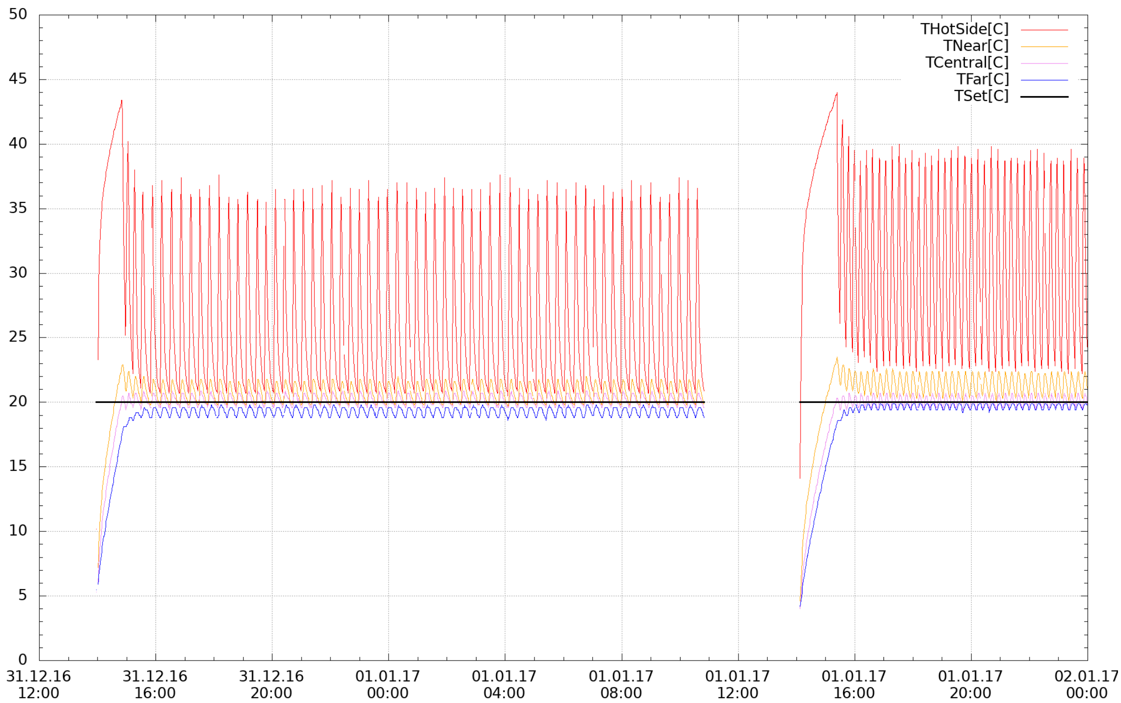


Figure 54 The three temperatures measured inside the box, as well as that of the heating element.

The temperature difference between the "Far" and "Near" sensors was about 5 °C during the heating phase, while in the maintaining phase the value reduced to around 2 °C.

These data give indications of the degree of ventilation and, more important, coupled with the values of the THotSide, on the suitability of the heating device coupled with the fan. If the difference between this temperature and the air temperature inside the box is too high, a more efficient dissipation system should be adopted.

Figure 55 show the theoretical relation between temperature difference (inside-outside) and thermal power required to maintain this difference. Also in the same graph the curve (in red) presenting the electric power effectively used by the system. The red curve presents the overall power consumption, including power used by electronic boards and the fan, and for this reason need to be different from the theoretical curve. However, difference in the two curves it also derives from non-perfect efficiency of the insulation, thermal bridges, inefficiency of electronics component and heater heat conversion. Since heater system is heating resistance, we can not consider the last. The average of this difference, arising out of all just indicated factors, for the data set we are presenting was 6.9 W. Scientific instrumentation placed in the box will operate positively contributing to the heating thanks to dissipation of part of electric power it will receive, but also negatively reducing efficacy of fans in redistributing energy inside the box and keep as minimum as possible thermal gradients.

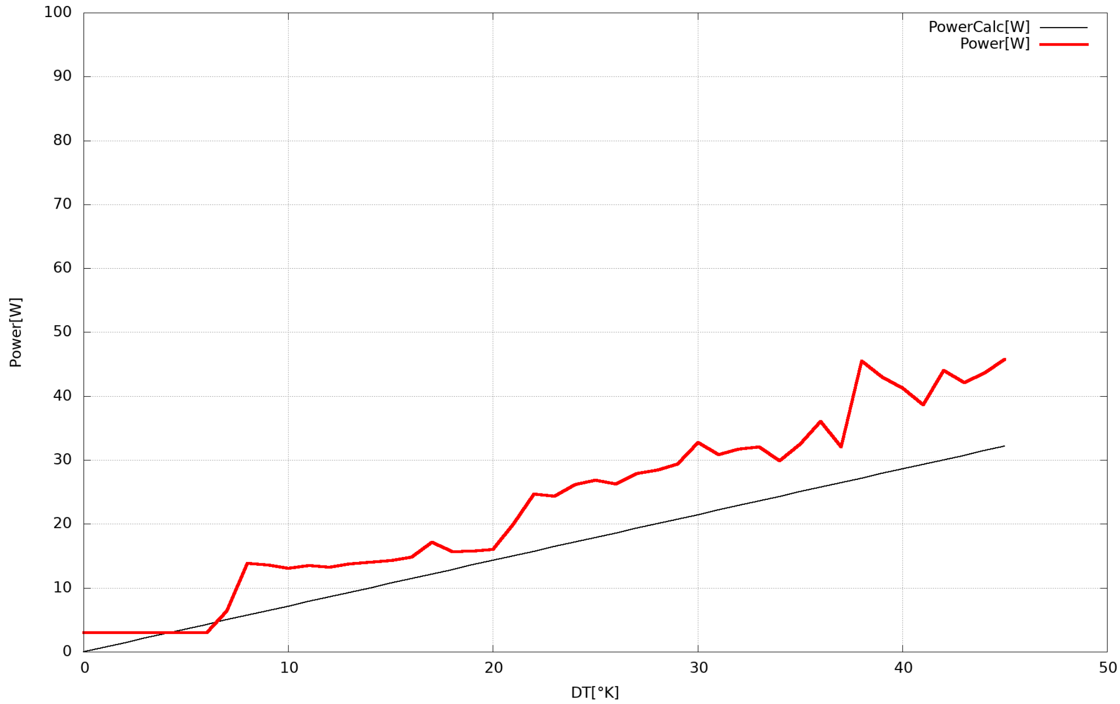


Figure 55 Theoretical curve showing the relation between the temperature difference between inside and outside the box (black curve), together with the actual data collected by the system (red curve).

During the test period, the energy used by the fan was estimated to be of 2.6 W on average. Considering the average consumption of the electronic boards, about 2 W, is possible to estimate the total heat power losses to be 2.3 W (6.9 W – 2.6 W – 2 W). As indicated, not only to heat leaking trough connections and apertures, but also to not ideal components (box and heater first of all) are responsible for them. During the whole test period we do not experienced inside the box very high humidity conditions. So humidity control device was never in operation.

Testing of a Peltier system in Bologna during summer

This Peltier box (Figure 56) is made with a commercial aluminum case, where the internal walls were covered with an insulating material, in this case polyethylene with thickness of 30 mm and thermal conductivity coefficient equal to λ = 0.33 W/m K. Thermal conductivity coefficient λ like heat transmission coefficient U, refers to the intrinsic ability of a material to transfer heat. The difference is that it refers not only to unit area but also unit depth. So it is provided (and useful) when material can be employed using different thickness.

The external dimensions of the aluminum box are 580x385x250h mm, while and the inner size is 550x350x220h mm, which reduces to 490x290x160h mm considering the insulating material, with corresponding volume of 0.023 m^3.

With the aforementioned insulator, the heat Qt nominally dissipated by the system is calculated as follows:

- Calculation of the insulator heat transmission coefficient U =λ / S, where λ is the thermal conductivity coefficient of the material and S is the thickness we are using:
  U1=0.33 (W/m K) / 0.03 (m) = 11 W/m^2 K
  U2=0.33 (W/m K) / 0.06 (m) = 5.5 W/m^2 K
  The first value U1 is for all the walls of the box, except the one in the back, which is covered with two layers of insulating material for mechanical reasons (Figure 41). For this last wall we need to use the value U2.
- Calculation of the total heat Qt nominally dissipated by the box:
  A1 = (0.49 m*0.16 m) + (0.49 m *0.26 m *2) + (0.26 m *0.16 m *2) = 0.42 m^2
  A2 = (0.49 m *0.16 m) = 0.078 m^2
  Qt1 = K1 * A1 = 11 W/m^2 K * 0.42 m^2 = 4.58 W/K
  Qt2 = K2 * A2 = 5.5 W/m^2 K * 0.078 m^2 = 0.43 W/K
  Qt = Qt1 + Qt2 = 4.58 W/K + 0.43 W/K = 5.01 W/K

The Qt value is the amount of heat transfer (dissipated) by the entire box when 1 °K temperature difference exist between inside and outside it. As obvious if environmental temperature is higher of the temperature inside the box, the same amount of thermal energy is transferred by the ambient to the box, heating it.

This is an estimate of the energy that is necessary to maintain a preset temperature, knowing the environment temperature of the place where we want to install the system. This is not equal to the electrical power needed as the efficiency of the heating/cooling system need to be taken into account. Furthermore, other heat losses could be present and should be considered. Also always is necessary to consider the role of scientific instrumentation and its dissipation producing heat that can help the work if we have to heat, or need to be removed if we have to cool.

Figure 56 The aluminium box for the Peltier system on the roof of CNR-ISAC in Bologna.

The herating/cooling system used in this test is commercial and producted by Marlow Industries (Figure). It has 4 peltier cells, packed between two heatsinks of different size, the smaller one is on the cold side, and the bigger on the hot side.

Figure 57 The refrigerator system used for the Peltier box.

Figure 58 lists the system characteristics. The maximum cooling power of the Peltier system is 132 W. As the maximum electrical power that can be provided to the system is 24 V * 7.5 A = 180 W, it's possible to have an idea of the thermal efficiency of this system.

Manufacturer	Marlow Industries, Inc.
Series	Climatherm 300
Part Status	Active
Heat Transfer Type	Air to Air
Power - Cooling	132W
Current	7.5A
Voltage	24V
Fan Location	Cold Side / Warm Side
Operating Temperature	-10°C ~ 60°C
Weight	8.5 lbs (3.9kg)
Dimensions - Overall	300mm L x 150mm W

Figure 58 The characteristics of the refrigeration system adopted in the box.

Figure 59 shows a side view of the box, where is possible to see the support for the temperature and humidity sensors, as well as the connections for power and ethernet cables.

Figure 59 Side view of the Peltier box.

The system was tested on the roof of the CNR-ISAC institute in Bologna (Italy) during summer 2018. Different target temperatures were settled during different periods. Figure 60 shows the internal temperature, the external temperature and the corresponding power required during the entire period. After some short tests with different internal temperatures, the system was settled to maintain fixed 15 °C. Resistance to simulate instrumentation was always powered to dissipate 10 W. This power is not considered in the following discussion. Being the thermo-regulating system always in cooling modality, simulated instrumental dissipation have to be removed.

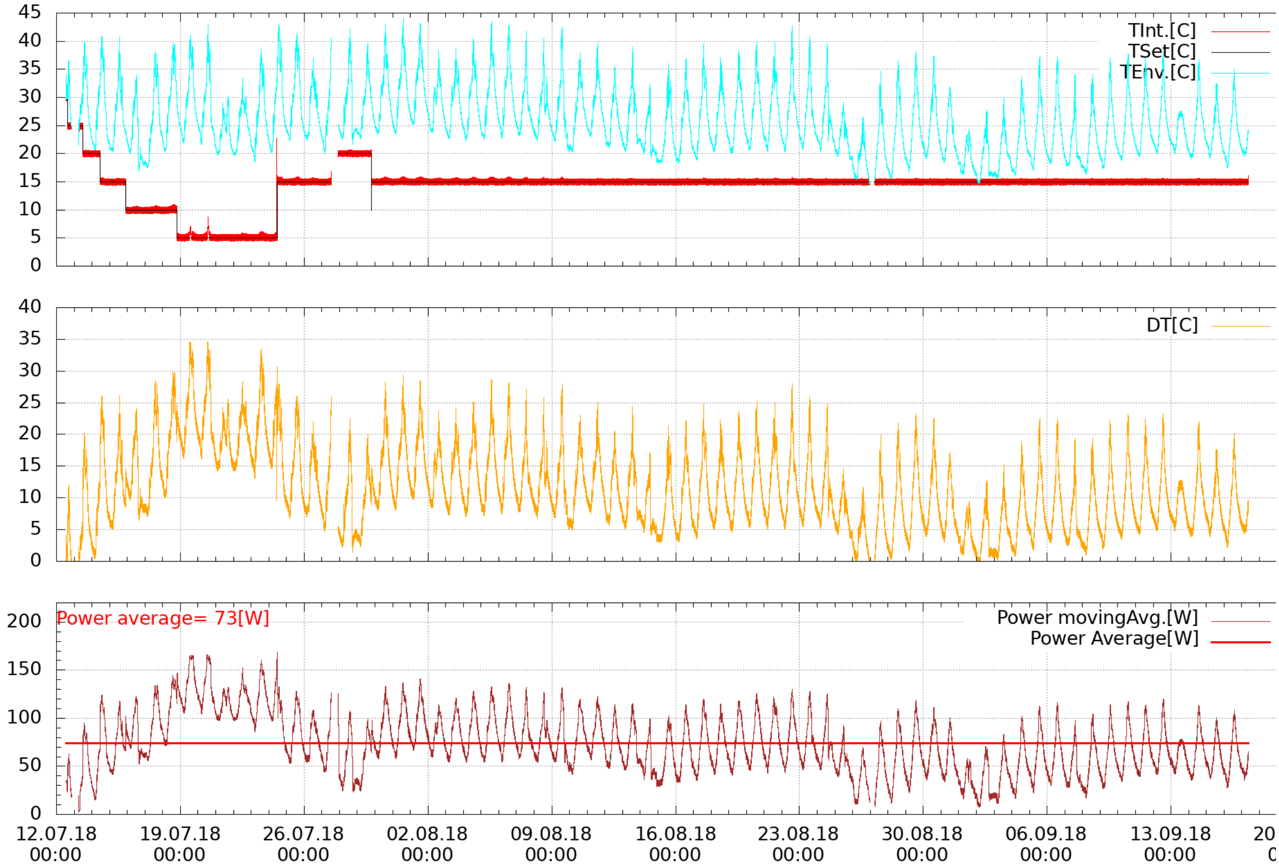


Figure 60 Internal and external temperatures, the temperature difference and power required during the summer test.

Figure shows , besides internal and external temperatures, the temperatures of the two heatsinks: the external (hot) "THSExtSide" and the internal (cold) "THSIntSide", for one day during August.

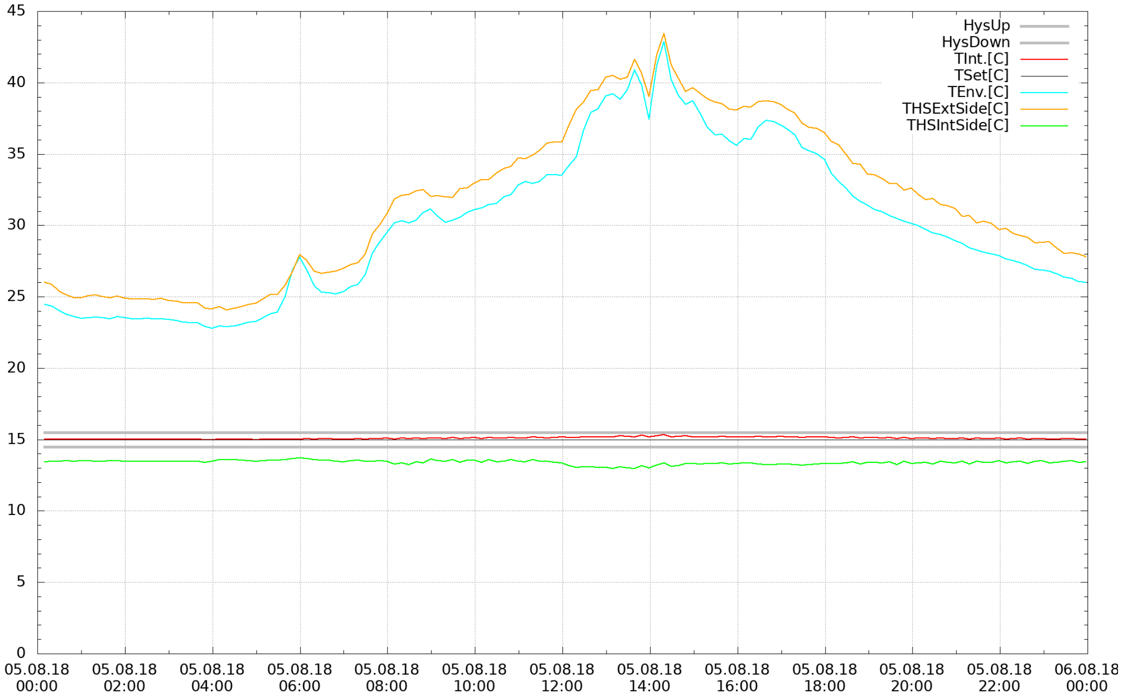


Figure 61 Temperatures of the two heat sinks, together with the internal and external one.

Figure 62 shows a typical situation where the system is able to maintain the preset temperature of 15 °C within the hysteresis (maximum deviation) set at 0.5 °C, regardless of very high external temperature absolute value and variations.

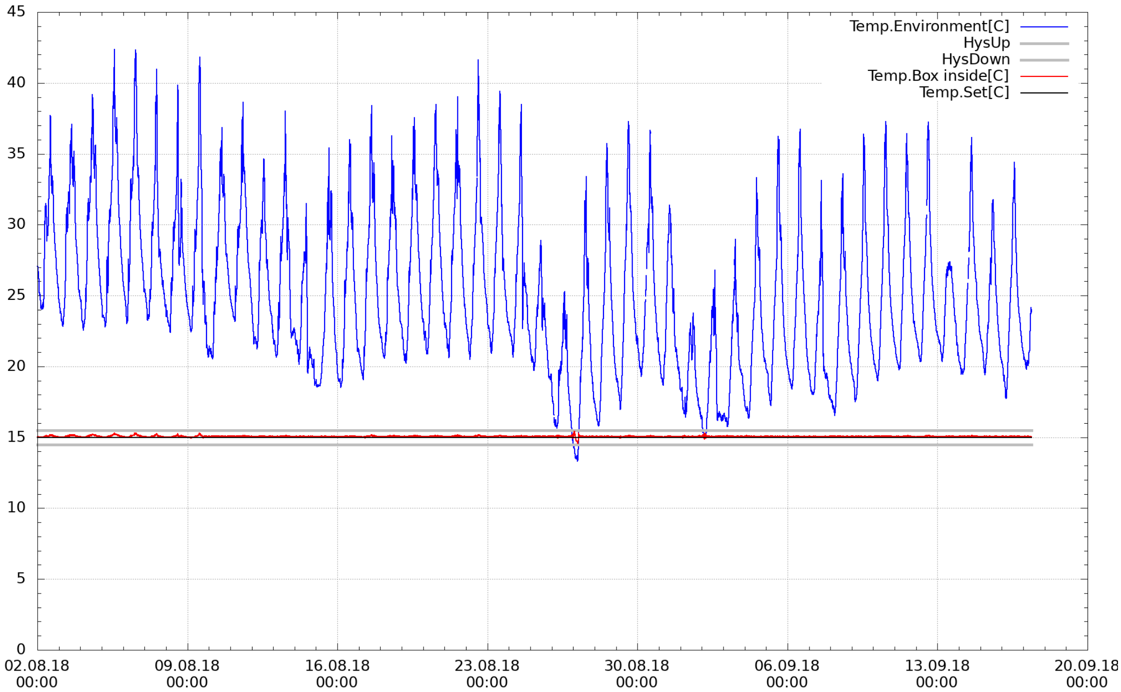


Figure 62 Test for a fixed temperature of 15 °C.

Figure shows the situation in which the system was not able to maintain the preset temperature, equal to 5 °C. As can be seen, the system was working in conditions around or above the maximum permitted power.

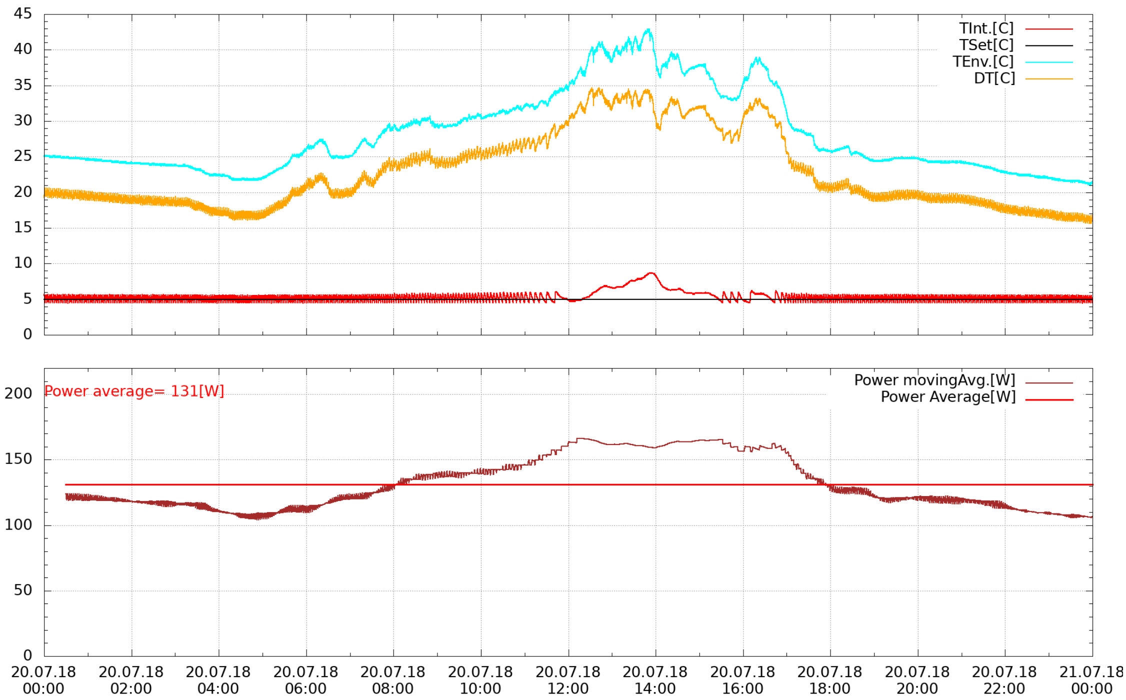


Figure 63 Test case with preset temperature equal to 5 °C.

Here follow some charts showing typical situations.

- Correct functioning of the system during one day with very high temperature (31-07-2018)

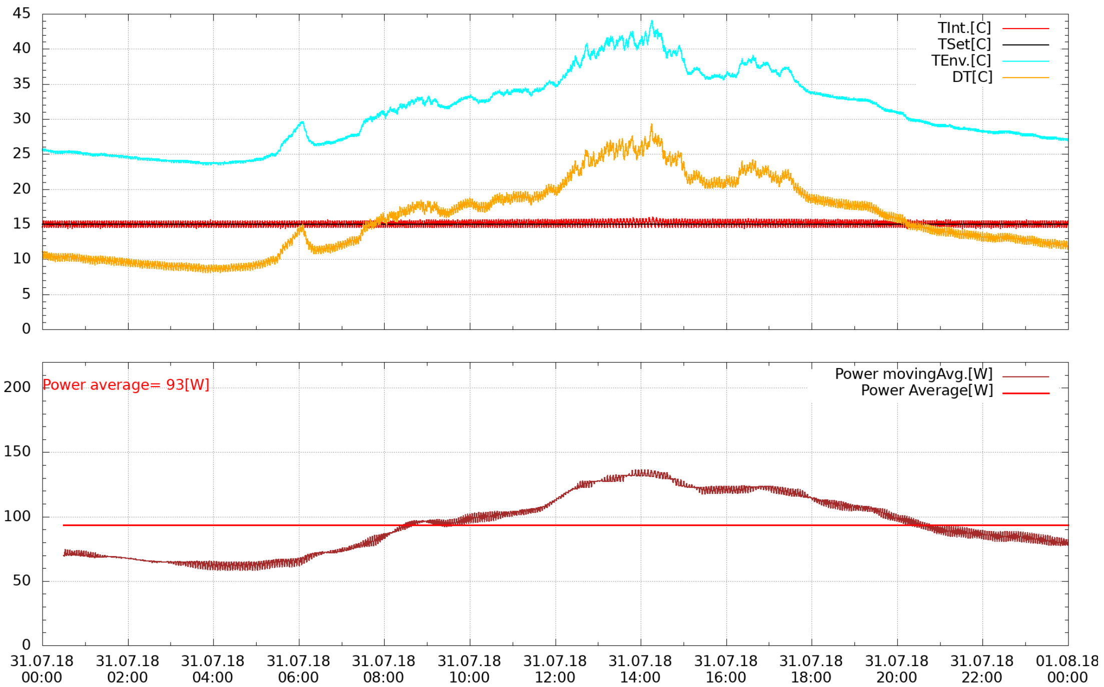


Figure 64 Functioning of the system during one hot summer day (31-07-2018).

- Response of the system to a temperature set change from 25 °C to 20 °C and than to 15 °C (13 and 14-07-2018). As the temperature target was lowered, the system reacted increasing the power to the Peltier cells.

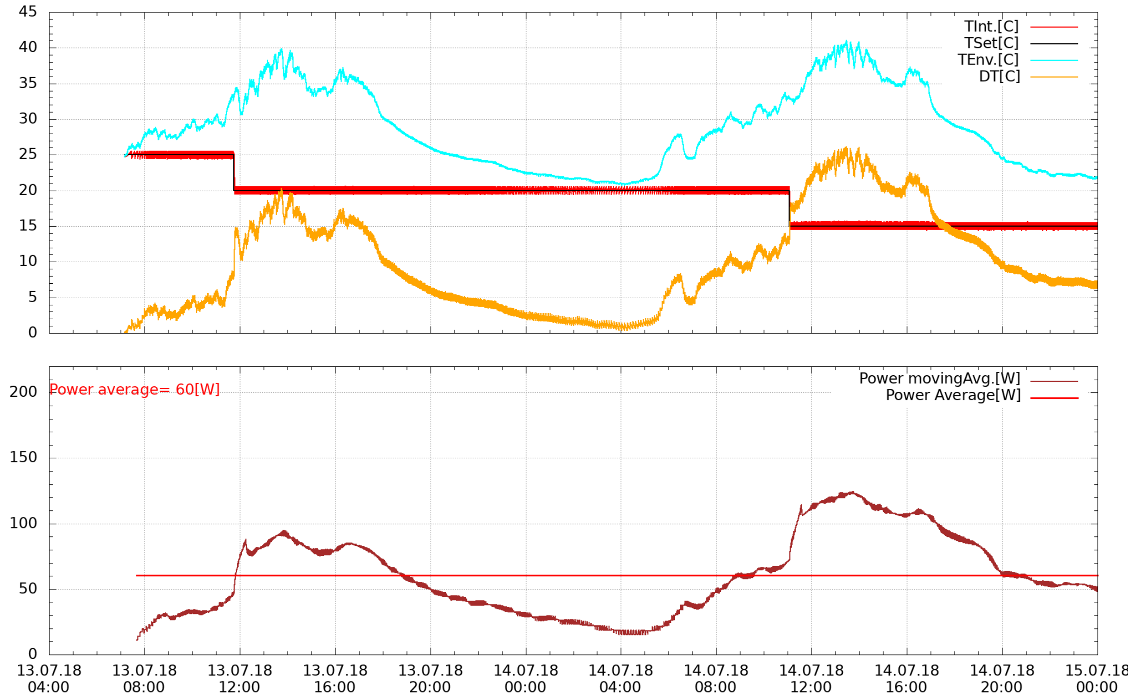


Figure 65 System response to temperature set changes (13 and 14-07-2018).

In the following charts, the data obtained from the test period were subdivided by temperature-difference ranges (environ-internal): 0-5, 5-10, 10-15, 15-20, 20-25, 25-30, and 30-35. For each interval, the average power consumption was estimated.

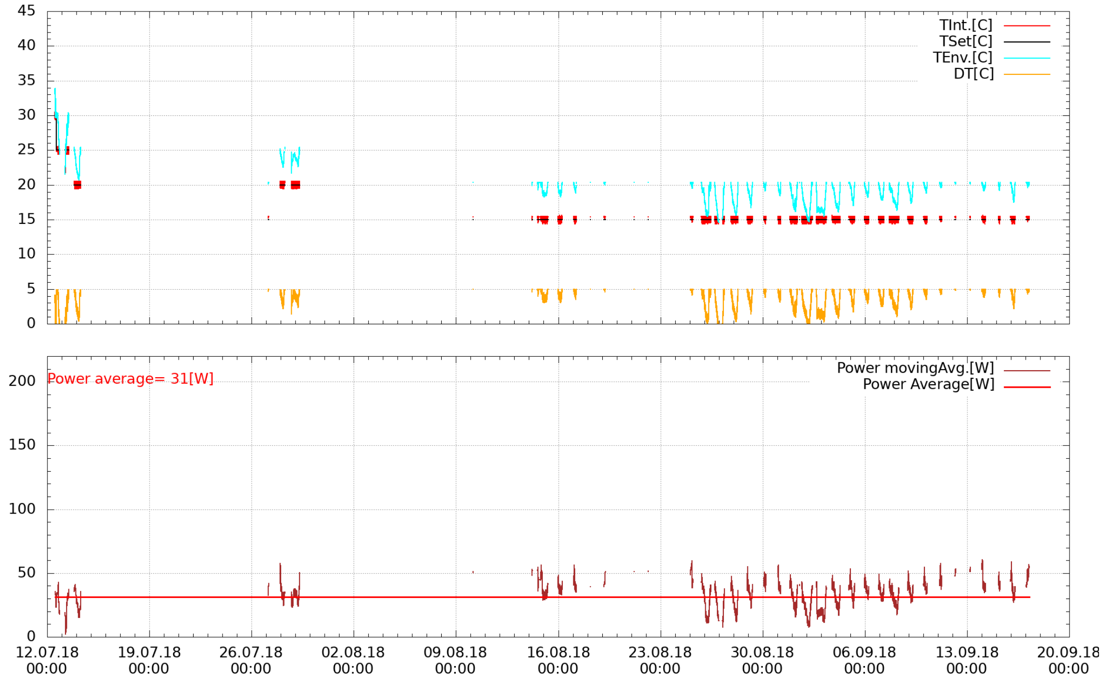


Figure 66 Data for temperature difference of 0-5 °C.

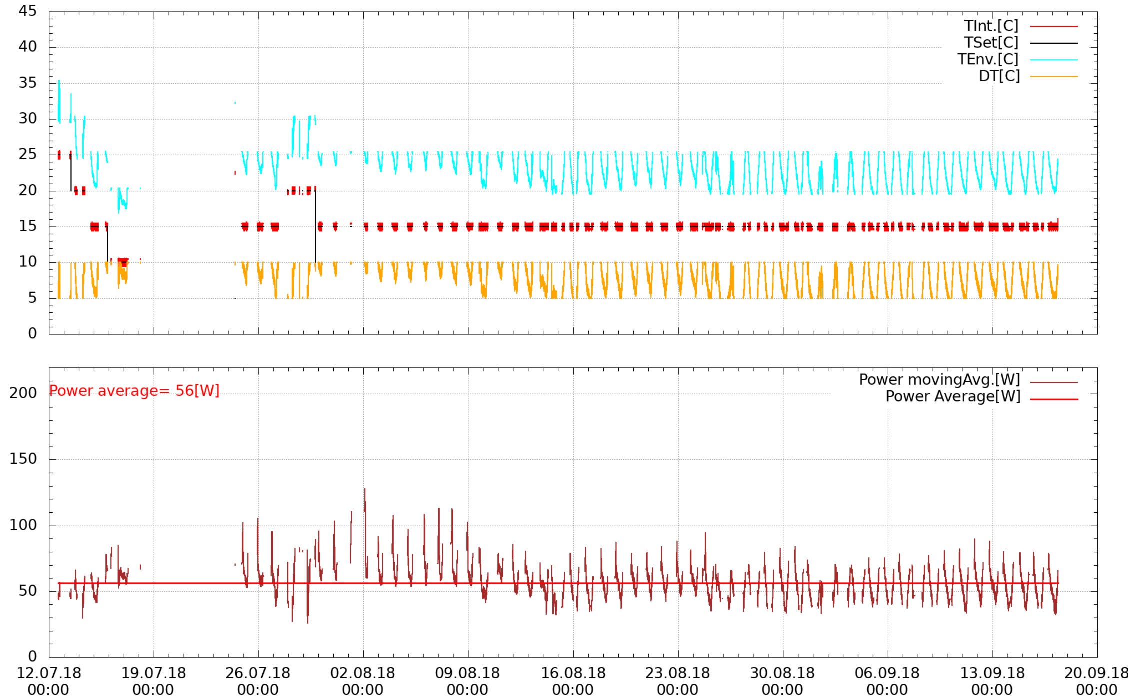


Figure 67 Data for temperature difference of 5-10 °C.

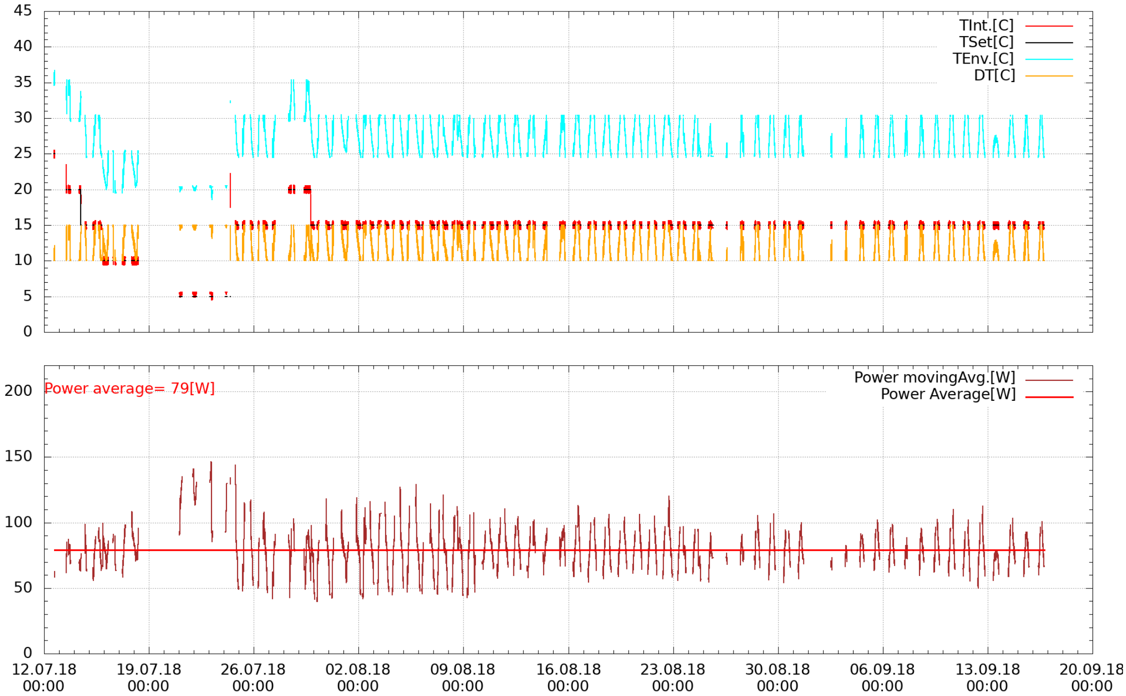


Figure 68 Data for temperature difference of 10-15 °C.

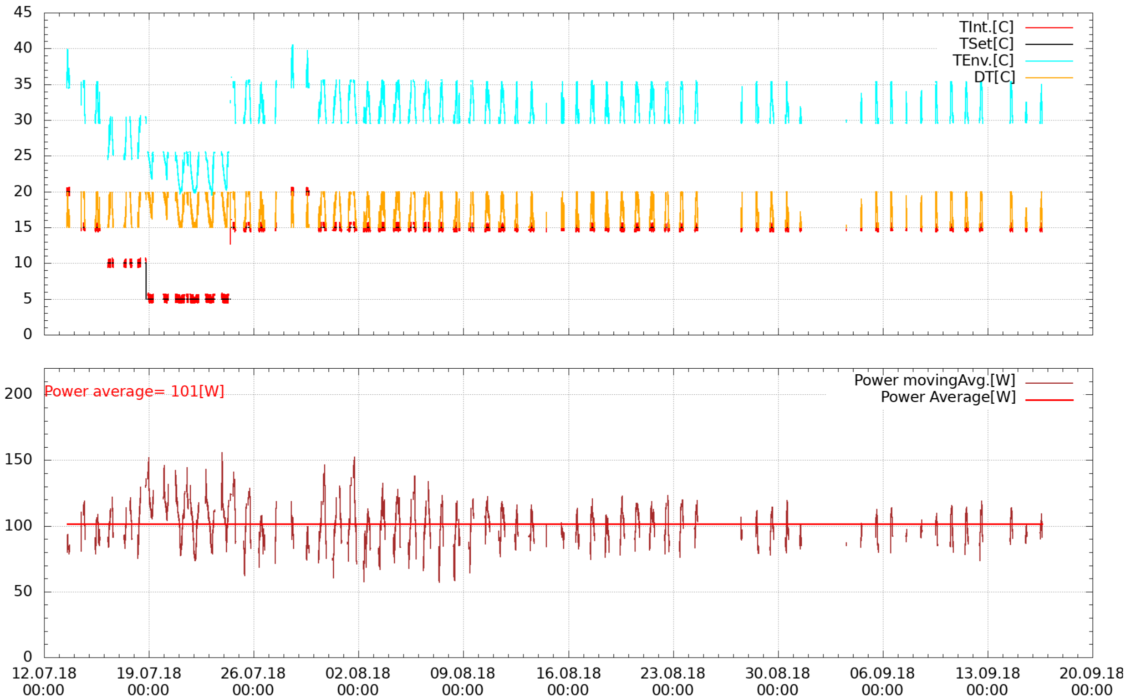


Figure 69 Data for temperature difference of 15-20 °C.

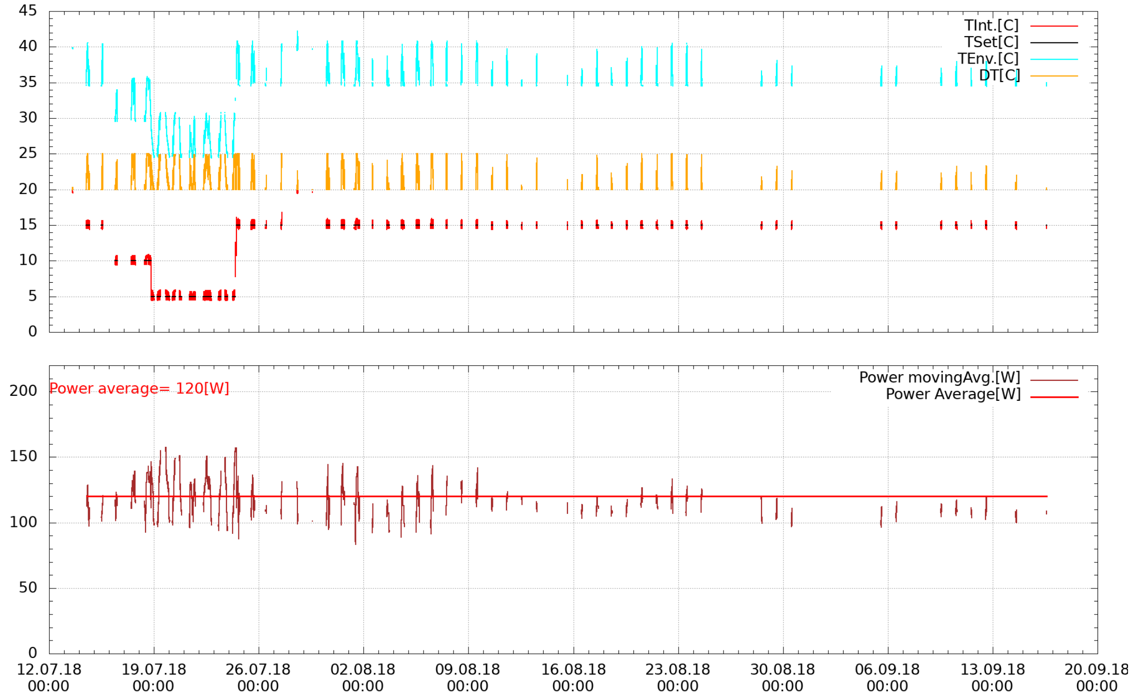


Figure 70 Data for temperature difference of 20-25 °C.

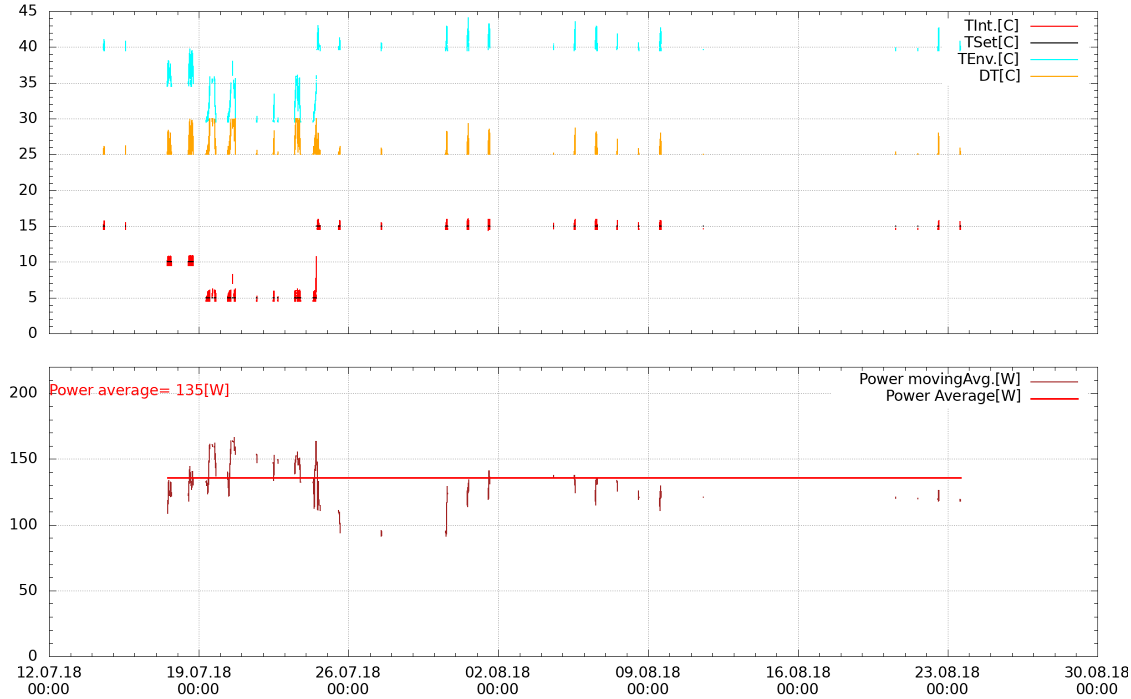


Figure 71 Data for temperature difference of 25-30 °C.

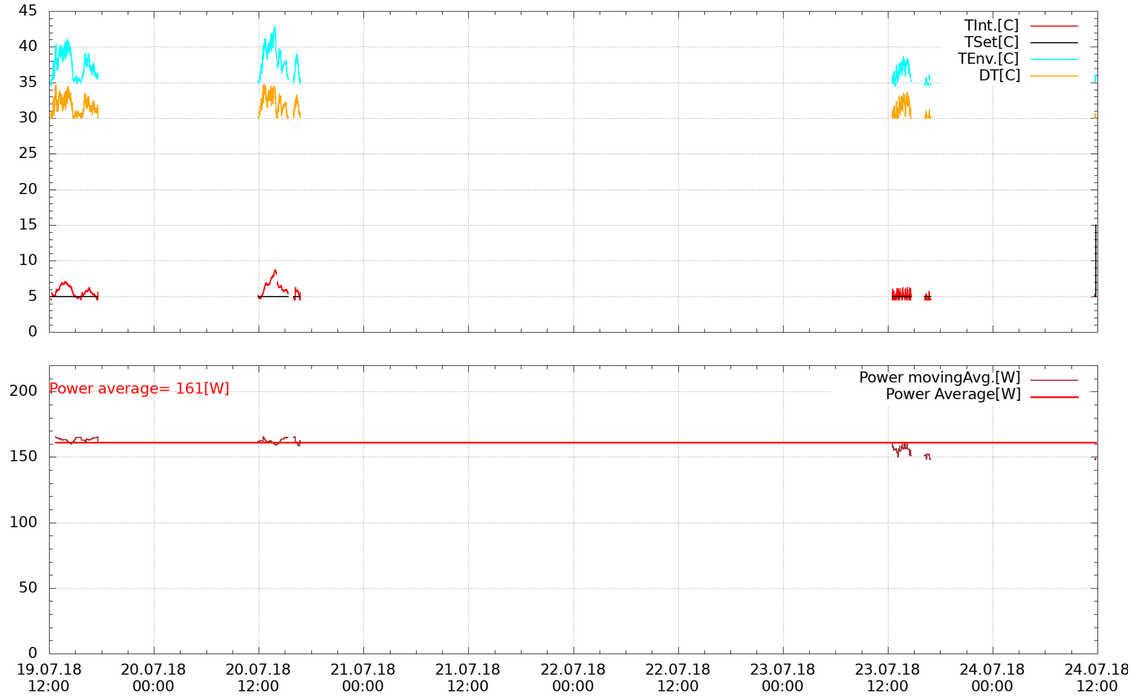


Figure 72 Data for temperature difference of 30-35 °C.

Figure 73 shows the comparison between the theoretical and actual power used by the system as a function of the temperature difference (environ-internal). The difference between the two curves gives the power used by the electronic boards and the fans to increase the heat exchange from the heat sink to air. This energy gap varies between 1.9 W and 34 W, with an average of 25 W. This high range of variation is linked to the regulation of the speed of the fans according to the heat to dissipate.

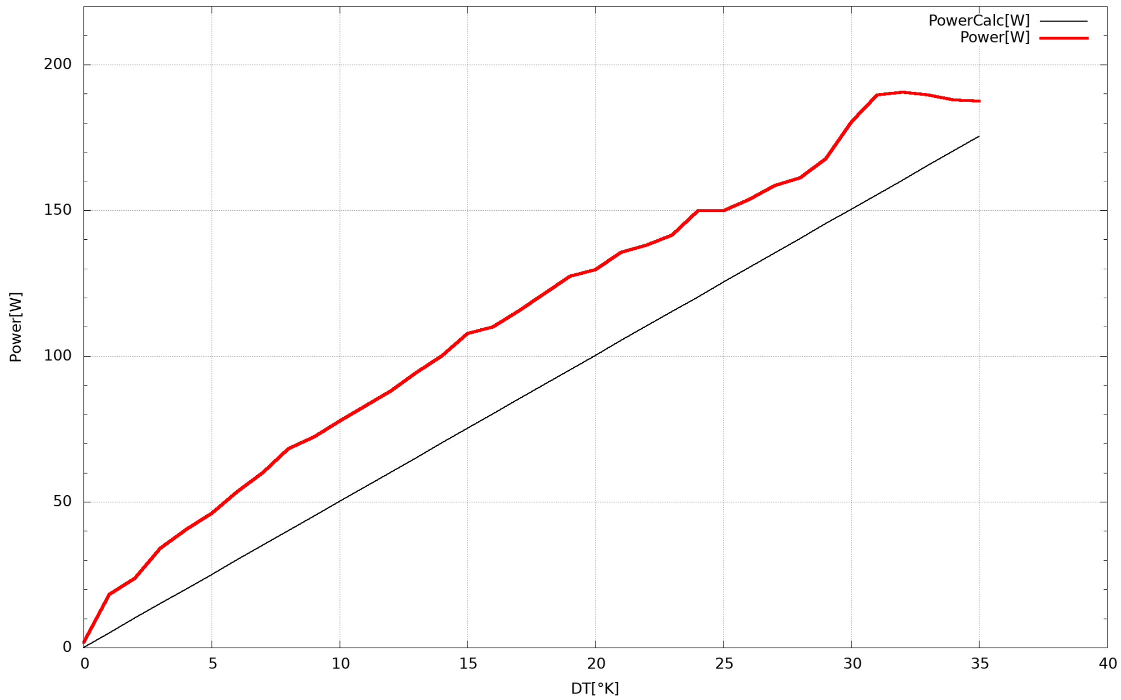


Figure 73 Theoretical (black) and actual (red) curves of the power used by the Peltier system as function of the temperature difference (polyethylene as insulator).

Figure 74 shows power consumption of the fans as sampled during the test period. The total average power consumption was estimated to be about 13 W. Considering the average power required by the electronic boards (2 W), the power losses/inefficiencies of the system can be estimated to be 25 W – 13 W -2 W =10 W on average.

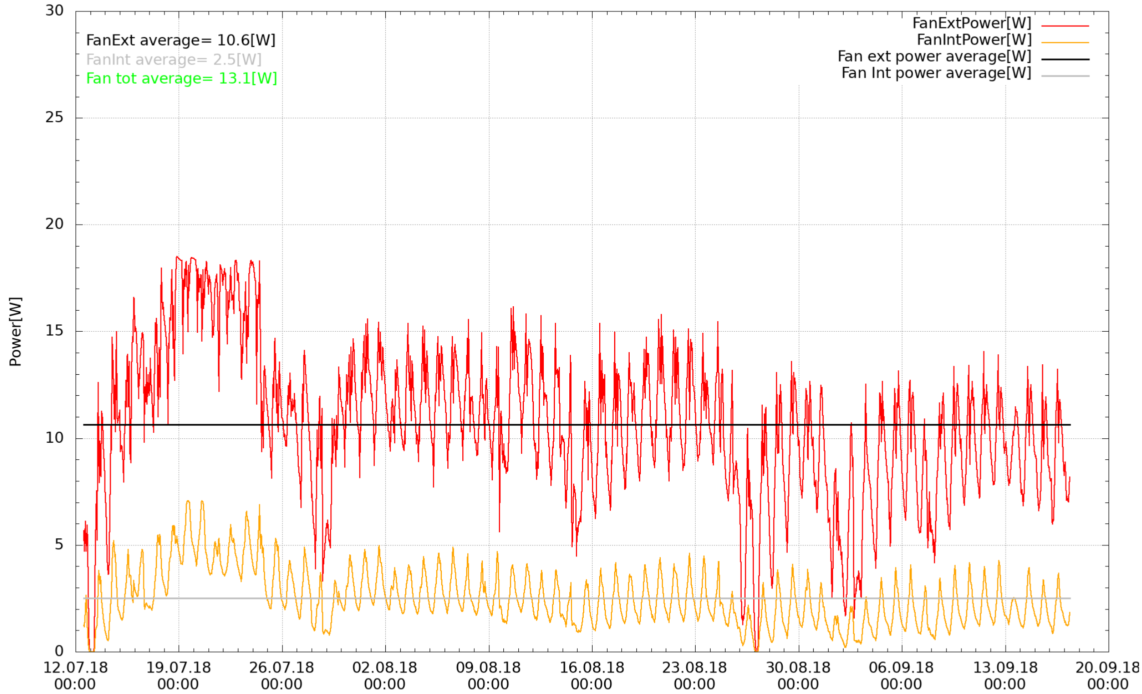


Figure 74 Power absorbed by the internal and external fans, together with their averages.

A similar test was repeated with a different insulating material, i.e. polystyrene, which present a thermal conductivity coefficient value λ = 0.035 W/m K, 10 times less the first one (Figure 7).

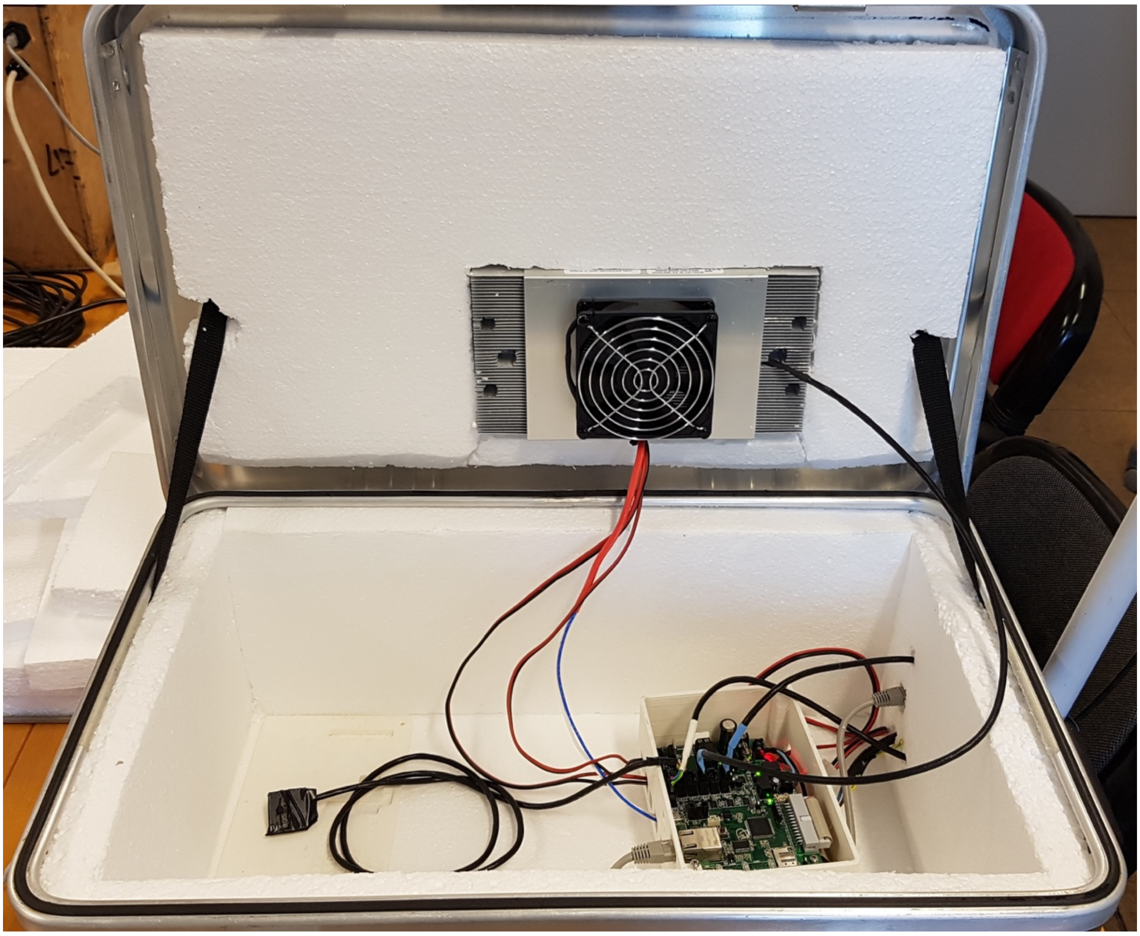


Figure 75

With the aforementioned insulator, the Qt nominal heat transfer of the whole system can be estimated in a way similar to the previous case:

$U=0.035\ (W/m\ K)\ /0.03\ (m) = 1.17\ W/m^2\ K$

$A = (0.49\ m * 0.29\ m * 2) + (0.49\ m * 0.16\ m * 2) + (0.29\ m * 0.16\ m * 2) = 0.53\ m^2$

$Qt = U * A = 1.17\ (W/m^2\ K) * 0.53\ (m^2) = 0.63\ W/K$

As expected, considering the difference in thermal conductivity characteristics of the two material used, the total amount of heat Qt nominally dissipated for each degree of difference results to be about one tenth of that of the previous example. Using this as intrinsic property of the system, the difference between the theoretical and the effective power needed by the system remains around 20 W (Figure 76) as the electronic boards and the fans absorb similar power in the two cases.

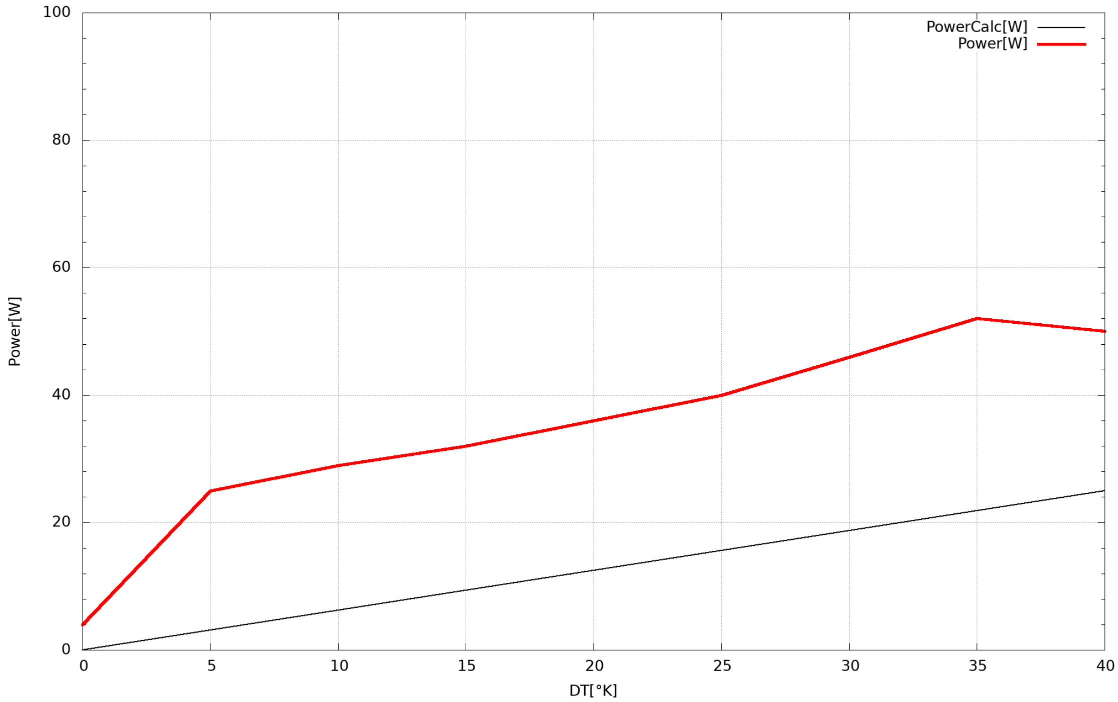


Figure 76 As in Figure but for the Peltier system with polystyrene.

6 - Discussion of achieved results, recommendations and future work

Figure 55, 73 and 76 in the previous chapter enable us to evaluate the performance of our control unit (hardware and firmware) when we use heating resistance or Peltier cell technologies. Comparison of effective and nominal (theoretical) Qt heat transferred between test systems and environment indicates that our control unit is able to drive with a good efficiency the heating/cooling devices up to temperature differences DT between internal and external temperatures of about 40°C. Volume engaged in the two test cases is in both cases significant, even if very different: 148 liters for the system used in the test performed in the Arctic, only 23 liters for the tests with the Peltier cells. However, for each system, since evaluation of heat transfer Qt includes this parameter, comparisons between effective and nominal heat transfer Qt are independent of the specific volume used. This is completely true for the theoretical curve, while for the real (red) curve the specific volume can have a little influence in the absolute values considering the origin of losses (cfr. below).

Larger datasets could for sure help us to evaluate with more accuracy this efficiency on the overall 0-40° DT range, as well as for narrow intervals. Indeed, from the figures in the data, we can (not surprisingly) conclude that a little degradation in the performances exists for higher values of DT, and that the difference between theoretical amount of energy to maintain target temperature and effective power the system use increases slightly with the increase of DT. This difference, after taking out energy used for electronics and fans, represents a **quantitative estimate** of the efficiency of the system as a whole. As indicated in chapter 5, total heat power losses can derive from heat leaking through connections and apertures, not perfect insulation, inefficiency of single electronic components (heaters device, fans) but also inefficiency of the control algorithm. With the available data, it is not possible to go deeper in the analysis, and identify what can be the margin of improvement for the control algorithm. In any case, our tests demonstrate that for majority of cases, up to relatively high DT, system inefficiency causes a few watts more of energy being used. In this case, however, volume plays a role in determining the overall heat power loss amount. For specific cases where even a few watts are very important, the best choice is to reduce the volume that we need to heat as much as possible.

In implementing the proofs of concept we decided to keep at a reasonable level the maximum power the system could provide and use for heating and work, even if in both installations we had access to an unlimited power supply. Heating system power was limited to 120 W in the case of heating resistances (cfr. chapter 5 pag. 52), while for Peltier cells we selected a model that can absorb maximum 180 W with a real useful power of 132 W (cfr. chapter 5 pag 60). This choice simulates better the possibility to eventually, in real conditions, reach the limits of the system capability. This occurred with the Peltier cells system when we used the least performing insulation. As can be clearly seen in figure 73, in this case theoretical thermal conductivity reaches the power limit at DT of about 28-30°C and the system reaches its limit for DT ranging between 25 and 30°C. Conditions with a DT around or above 30°C occurred quite often in the second half of July (cfr. Figure 60). In the first part of August, DT was several times not too far from 30°C. In all these cases the system was no longer able to maintain the target temperature in the box, simply making its best providing all available energy.

The test cases performed also enabled us to evaluate the great importance of a suitable insulation in reducing power consumption. The thermal conductivity λ was 0.059 W/ m K for the system we tested in the Arctic, based on heating resistances, whereas it ranged between 0.33 W/mK and 0.035 W/m K for the Peltier system, depending on the insulation material used. Corresponding nominal heat transfer Qt were 0.715 W/K, 5.01 W/K and 0.63 W/K, respectively. The Melform box and the aluminum box with most performing insulator, present rather similar performance in terms of power consumption. The much bigger Melform box, even if less performing in insulation relative to the polystyrene insulator, called only for about 10 W more of thermal energy when DT was 40°C. Vice versa, when we reduced insulation performance of a factor of 10 (not changing volume) we needed 10 times more energy, and rapidly the system reached the limit of the power it could supply to Peltier cells, being no longer able to thermostat the target volume.

Additional heat power necessary to hold target temperature with an accuracy of 0.5° was on average of about 3 W in the case of the test system based on heating resistances, while ranged from 10 W to 20 W for the test systems based on Peltier cells and different insulation. It is not surprising that "inefficiency" in thermostating the system grew significantly when insulation became much more performing: heat bridges and any source of heat loss became automatically "stronger" with respect to an ideal system without them and then with respect to the nominal value.

In evaluating our results, we need to consider the influence of the scientific devices operating in the box. Using a resistance, we have simulated dissipation effect of working instruments. We have in general fixed this to 10W. This is heat released in the box. If we have to maintain internal temperature higher with respect the external, dissipated heat provide a useful (positive) contribution, while if we have to maintain a temperature lower with respect the external, it has to be removed by the box and than provide a negative contribution to the issue of temperature control. However, there are at least other two aspects that is not possible to simulate: (i) scientific devices have a thermal coefficient higher than air, so in general they need more heating or cooling energy with respect to air; (ii) the reduce the efficiency of fans in circulate air inside the box. As a consequence of these two effects, our results about capability to maintain a DT can be considered overestimated with respect real cases. However, (1) since achieved results are quite good and promising, and (2) a suitable application of principles presented in this report and below summarized can be always made, we can expect that thermoregulating system we developed could be reasonable able to maintain DT up to at least 30°C.

The above discussion of the results achieved and presented in chapter 5 clearly demonstrates the good performances of our control unit and in particular of the control algorithm implemented to drive and control different heating/cooling devices. Initial tests presented in this report, made using proof of concept devices realized specifically for our purposes, have been able to indicate that with a power of no more 150-180 W we can control the temperature inside relatively large volumes up to temperature differences DT between our box/instrument and the environment of 35-40°C. This performance is for sure sufficient for most of the environmental conditions RIs can experience even in extreme environments. Results presented in figures 73 and 76 also indicate that work can be done to ameliorate the driving of Peltier cells and, therefore, the performance and "efficiency" of systems based on this technology, reducing the need for additional thermal power with respect to what theoretically we should need. Additional tests are planned to further evaluate performances, extend environmental conditions for which we have data, and to test the control unit also with heat pipes systems (very useful in very hot environments). Applications to specific real cases requested by partners of ENVRIPLUS also will provide in any case useful information from this point of view, and will represent a very cost-effective way to reach the same result.

Elements provided along the whole report should enable a user to identify best modalities to design and then realize an optimum system for their specific case. On the other hand, since such an optimal thermoregulating system and strategy depend from a very large amount of factors and conditions, it is almost impossible to make a comprehensive list of recommendations valid for all cases. Below we try to underline some of the fundamental principles that should be applied/considered. They arise from long experience, including that acquired in the work related to this report. However, they have not the presumption to be general principles and/or exhaustive.

- As first step, define well the range of environmental conditions (temperature, humidity, wind speed) and your needs in terms of operation temperature for your instrument
- determine the power that you can have available for thermal control
- based on the above information, identify the best technology and a suitable strategy to keep your instrument operational in extreme environmental conditions. In particular, define what combination of insulation and heated volume can be able to assure that available power is sufficient for all (or almost all) expected environmental conditions.
- select components for the thermoregulating system on the basis of instrument/system characteristics and above analysis.

7 - References

1 http://www.resistorguide.com/thermistor/

2 http://www.resistorguide.com/ptc-thermistor/

3 Enciclopedia Britannica - https://www.britannica.com/science/Peltier-effect

4 Enciclopedia delle Scienze Fisiche, Institute Treccani, Vol VI, pag. 185, Roma, 1995.

5 Martin Forsén, HEAT PUMPS – TECHNOLOGY AND ENVIRONMENTAL IMPACT, Swedish Heat pump Association, SVEP, European Heat Pump Association EPHA, July 2005, pp. 40 + 80 - http://ec.europa.eu/environment/ecolabel/about_ecolabel/reports/hp_tech_env_impact_aug2005.pdf

6 https://www.energy.gov/energysaver/heat-and-cool/heat-pump-systems

7 IEA's Technology Collaboration Programme Heat Pumping Technologies - https://heatpumpingtechnologies.org/

8 Gregory K. McMillan , *Advanced Temperature Measurement and Control*, Second Edition, 250 pages, 2011, ISBN: 978193600-7387

9 https://www.amci.com/industrial-automation-resources/plc-automation-tutorials/what-plc/

10 Fanjie Wei, The PLC-based Industrial Temperature Control System: Design and Implementation, MATEC Web of Conferences **100**, 03031 (2017), DOI: 10.1051/ 201710003031 https://www.matec-conferences.org/articles/matecconf/pdf/2017/14/matecconf_gcmm2017_03031.pdf

11 http://www.melform.com/product/containers-for-catering-companies-thermax-line-af/c22/af-150v

12 Omega, Introduction to Temperature Controllers https://www.omega.com/temperature/z/pdf/z110-114.pdf

13 http://www.coldway.com/en/products/about-alcatherm

14 M ichael J. Felton, *Baths and Circulators*, TODAY'S CHEMIST AT WORK, pp.49-50, 2004 https://pubs.acs.org/subscribe/archive/tcaw/13/i10/pdf/1004prodprofile.pdf

15 https://www.thermofisher.com/us/en/home/life-science/lab-equipment/water-baths-circulators-chillers.html

16 http://www.thermoline.com.au/products/temperature-and-humidity/

17 https://www.alibaba.com/showroom/temperature-and-humidity-control-cabinet.html

18 http://www.mecour.com/about

19 https://www.electrotechsystems.com/product-category/environmental-control/chambers/

20 https://www.terrauniversal.com/glove-boxes/process-gas-heaters-coolers.php

21 Smithsonian web site on fuell cells http://americanhistory.si.edu/fuelcells/index.htm

22 https://www.efoy-pro.com/en/energy-solutions/

23 https://www.globalsources.com/si/AS/Zhengzhou-Dison/6008838347469/pdtl/Medical-Cooler-Box/1055996202.htm

24 B. Petkov, V. Vitale, et al., *Narrowband filter radiometer for ground-based measurements of global ultraviolet solar irradiance and total ozone*, Applied Optics, 45, 2006, pp. 4383-4395.