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Innovative microgravity condenser for future fully closed Environmental Control and Life Support Systems

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Acknowledgments

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Abstract

Nowadays space missions are designed to reach extremely high distances and consequently the time spent on mission by manned space modules is constantly increasing. Therefore, there is the need to minimize, and if possible exclude, the possibility of refueling from the ground of materials of first necessity that are needed for the sustenance of life on board (oxygen, water, food) in order to reduce the relative costs to new refueling-oriented space expeditions. The above is the reason why there is constant research in the aerospace field focused on the possibility of creating closed-loop systems, which would allow recycling air, water, and organic waste to obtain materials of first necessity usable by the crew. The Environmental Control and Life Support System (ECLSS) represents the fulcrum of the research regarding the realization of closed-cycle subsystems. The following dissertation was proposed by Center for Near Space (CNS), a non-profit organization founded in Italy in 2015 that has as its main objective the spread of usability of space by an increasing number of humans, in view to allow a different and more positive orientation of the public towards the astronautical activities in the outer terrestrial space. The object of the following research work is the study and design of the prototype of an innovative condensing heat exchanger (CHX) which must operate in microgravity and which would perform the function of recovering water directly from the air present in the environment inhabited, on board the space module, or from possible growth chambers of any plants that would produce food for the crew. Therefore, this component would be part of the closed cycle that could be realized in an ECLSS subsystem dedicated to water recovery. The final geometric configuration was designed to separate air and condensed water during the condensation process so as to keep the air always in contact with at least a part of the surfaces of the ducts through which the heat exchange takes place. The final objective is the design of a test bench with which it is possible to carry out some tests that allow to verify the operation of the CHX and confirm what has been explained above. Finally, the exact procedures to follow for the correct execution of the proposed tests have been described. The following work was carried out in collaboration with Thales Alenia Space (TAS). The requirements and constraints considered during the design phase are closely connected with the RUCOLA structure (Rack-like Unit for Consistent on-orbit Leafy crops Availability), a unit developed and tested in TAS's Recyclab laboratory in Turin. RUCOLA contains two parallel plant growth chambers, each of which has an independent subsystem for controlling temperature and relative humidity. The CHX, object of this thesis work, is designed to operate in RUCOLA's Air Management Subsystem, from which requirements and constraints for the design have been obtained.

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1 General overview

In the present chapter a general view of the context in which the present work is located will be carried out, namely Human Space Flight. In a vision of space travel that is ever closer to a greater number of humans, more research is needed to be able to develop systems that can support human life aboard Spacecraft independently, trying to minimize and, if possible, cancel, supplies necessary for the long-term operation of the spacecraft.

This thesis is the result of a collaboration with the Center for Near Space (CNS), a non-profit organization whose main mission is to spread the usability of space by an increasing number of people, to introduce an idea of outer terrestrial space made closer than ever to the common man. In the thinking of the CNS, the concept "Near" can be associated with the region that goes from the surface of the Earth to the low orbit (Low-Earth-Orbit, LEO) and that is the spatial region closest to the earth. "Near" can also be associated with a concept of approach to man and therefore thinking the space as a new future environmental component of human life.

The CNS believes that in the years between 2060-2070, scientific missions on Mars will be routine and by that date, the geo-lunar space will host a community of a thousand people with a traffic of about 100,000 passages per year for transfer flights between the Earth and the various places of this possible Cislunar city that could be a starting point for space expeditions to Mars:

- Earth surface;
- Low-Earth-Orbit (LEO);
- Low-Moon-Orbit (LMO);
- Geo-lunar Lagrangian point (L1-L4-L5).

The birth of these possible departure stations in the so-called Fourth Environment leads to the definition of high technical and functional standards as well as to guarantee a quality of life on board comparable to that available on Earth. The design of space systems will play a more important role than it has been until now, first between all the Environmental Control and Life Support System, that is the indispensable system for inhabited aircraft dedicated to supporting human life.

The present work could be placed within the scenario described above because the main objective is the recovery of water from humid air present in the environment inhabited by astronauts through a condensing heat exchanger usable in the environment with microgravity. This thesis project was carried out in collaboration with Thales Alenia Space.

The condensing heat exchanger (CHX) is a component of the Water Recovery System, that is a subsystem of the Environmental Control and Life Support System.

1.1 Environmental Control and Life Support Systems

Considering that in order to complete a space mission successfully and safely all the subsystems that are part of the spacecraft must work and more specifically, in order to keep the entire crew alive, only the Environmental Control and Life Support System (ECLSS) exists, which therefore provides a physiologically acceptable environment for space vehicles, space stations or planetary bases. The thermal control subsystem (which can be considered part of the ECLSS in the case of inhabited spacecraft) must maintain a comfortable temperature for the crews in living spaces as well as having to guarantee operating temperatures for all the components of the spacecraft in the standard values for operation in safety.

Earth's natural life support system provides the air we breathe, the water we drink and other conditions that support life. For people to live in space, however, these functions must be done by artificial means.

The most important environmental factors for life which must be controlled or reproduced by the ECLSS system are:

- Atmosphere – It is necessary to consider that when the spacecraft is moving away from the earth, all the functions that the earth's atmosphere exerts to maintain optimal conditions for guaranteeing life on earth will no longer be present. The main functions that will be missing and therefore must be reproduced are relative to the lack of oxygen and therefore of an acceptable composition of the air to be breathed. Furthermore, the radiation protection exercised by the earth's magnetic field will also be missing. It will be necessary to recreate an environment protected by the multiple radiations that will hit the spacecraft, in which it must be possible to breathe air with the same composition as on the earth to which the human is accustomed;

- Temperature – The temperature is extremely variable and obviously depends on the destination of the space mission. Therefore, it will be necessary to know the temperature profile that the spacecraft will encounter in order to guarantee a comfortable environment for humans and an operating temperature for the various systems in the standard conditions;
- Acceleration – Obviously during a space mission starting from the initial launch phase the spacecraft will undergo much greater accelerations than those that man undergoes on earth.
- Noise – It is linked to both the initial and return phases;
- Vibrations;
- Lighting;
- Isolation.

All the factors listed above will be considered more or less important based on the type of mission being carried out, in fact they depend on the duration of the mission, the destination, the number of people that are part of the crew and many other factors.

The Environmental Control and Life Support System (ECLSS) for the Space Station performs several functions:

- Provides potable water for consumption, hygiene and food preparation uses;
- Provides oxygen for metabolic consumption;
- Removes volatile organic trace gases from the cabin air;
- Removes carbon dioxide from the cabin air;
- Filters particulates and microorganisms from the cabin air;
- Monitors and controls cabin air partial pressures of nitrogen, oxygen, carbon dioxide, methane, hydrogen and water vapor;
- Maintains cabin temperature and humidity levels;
- Maintains total cabin pressure;
- Distributes cabin air between connected modules.

In *Table 1* taken from the "Human Spaceflight", a fundamental text for inhabited space systems, it is possible to see the reference values of some fundamental properties relating to the atmosphere of the International Space Station. It should be noted, for example, that it is necessary to check the partial pressure value of oxygen and nitrogen because it is very important to reproduce the typical composition of the air since a high partial pressure of oxygen would lead to a great risk of flammability.

Table 1 - Nominal values of atmosphere management requirements

Atmosphere Management Requirements	**International Space Station Nominal Values**
Total pressure	$99.9\ kPa - 102.7\ kPa$
Oxygen, partial pressure (pO_2)	$19.5\ kPa - 23.1\ kPa$
Nitrogen, partial pressure (pN_2)	$79\ kPa$
Carbon dioxide, partial pressure (pCO_2)	$0.4\ kPa$
Temperature	$18.3\ °C - 23.9\ °C$
Relative humidity	$30\% - 70\%$
Concentration of trace gases	$< SMAC\ Levels$
Ventilation	$0.08\frac{m}{s} - 0.2\frac{m}{s}$

The document [1] guides the design and development of environmental control and life support systems with a license or experimental authorization issued by the Federal Aviation Administration (FAA). The requirements for ECLSS are based on performance rather than on the design of the individual component of the system. The considerations of this guide are based on ECLSS case histories related to aircraft or spacecraft. Depending on the type of aircraft and the mission profile, the considerations that are listed below may or may not be relevant to the design of the ECLSS.

One of the objectives of this document is to provide information on factors that influence the monitoring and control of atmospheric conditions through an ECLSS.

Monitoring provides information on atmospheric conditions so that changes can be made to maintain a nominal and safe atmospheric condition to sustain life. The measured values can be continuously updated or periodically updated, depending on the danger that an unmonitored atmospheric condition could present to the vehicle occupants. The monitoring can be carried out directly by the crew on board or by an on-board computer system or by a remote operator who can alert the crew if an irregularity is present.

Control can be obtained using open or closed loop systems.

The FAA takes the following questions into consideration in order to determine whether monitoring and control of an atmospheric parameter is necessary:

- What is the severity of the hazard presented to humans in the event the atmospheric condition is uncontrolled during nominal, degraded, or emergency operating conditions within the vehicle?

- Does the uncontrolled atmospheric condition create a noticeable, non-debilitating, physiologic effect upon the flight crew at the onset of exposure under plausible flight conditions, such that a flight crew could identify a flight hazard at the onset of exposure before flight safety is compromised?

- Is the uncontrolled atmospheric condition unlikely to change rapidly or in large magnitude, such that a flight crew could identify a flight hazard at the onset of exposure before flight safety is compromised?

- Following the onset of exposure to uncontrolled atmospheric conditions stemming from a failed component, what corrective actions are possible?

- What is the maximum period of time between onset of exposure to the uncontrolled atmospheric condition and the completion of corrective actions?

The main atmospheric conditions reported above that must be monitored and controlled by the ECLSS are described by the guidance document [1] considering mainly the following factors:

- **Hazard and characteristics:** the risks relating to the crew are described, as a result of any atmospheric conditions not in the norm;

- **Operational considerations for suborbital launch vehicles:** the considerations that the FAA has identified regarding the monitoring and control carried out by the ECLSS are described;

- **Available monitoring techniques:** the guide describes in-flight measurement techniques and devices for monitoring the main parameters;

- **Available control techniques:** in-flight control techniques and devices are described and there is an assessment of the availability and effectiveness of open and closed-circuit systems.

A brief summary will be made below, for some main atmospheric conditions, about the consideration of the factors listed above for a correct design of an ECLSS according to FAA.

Total pressure in the cabin

- **Hazard and characteristics.** Despite the low probability of impact of the pressure shell of the vehicle with space debris or micrometeorites, or the possibility of a failure in the shell of pressure or in the gaskets of the shell, if one of the listed events occurs this could cause a loss of air in the cabin. Consequently, there would be a rapid and uncontrolled decrease in the total cabin pressure which depends on the volume of the cabin and the size of the breach in the shell. Thus, the pressure would fall below the level necessary for human life. The maximum cabin pressure altitude the agency would find acceptable for a period not to exceed 30 minutes is 14,000 feet, unless the cabin ppO2 composition is increased above standard or the flight crew is provided with and uses supplemental oxygen for that part of the flight at those altitudes;

- **Operational consideration for suborbital launch vehicles.** One of the most important aspects to consider for the correct design of this system is the reaction time of the flight crew or the automated system that activates pressure loss mitigation measures. In the case of an automated mitigation system that releases substitution gases in the cabin such as nitrogen, the maximum speed of gas release can limit the usefulness of the technique of preventing depressurization. The big difference between commercial and suborbital aircraft is that the former are able to descend to lower altitudes when it is necessary in the event of depressurization, the others follow a ballistic trajectory after a rocket burn is terminated, so they are not able to go down to quotas lower in a short time. Another aspect to consider is the possibility of designing components that increase the possibility of containing the cabin pressure and therefore reduce the risk associated with depressurization events but having a small increase in the mass and complexity of the vehicle as a negative aspect. These components can be for example double panel windows, double gaskets with coupled surfaces, double insulation bulkheads, etc.

- **Available monitoring techniques.** The FAA considers direct reading total pressure monitoring devices acceptable. For example, an ideal device would include a warning and caution signal that includes a warning light positioned so that it is easily noticed by the flight crew if the monitoring system detects a rapidly decaying total pressure. In this way, the pilot or crew can take corrective action in the shortest time available before they lose consciousness.

- **Available control techniques.** The presence of a redundant component that prevents the cabin depressurization is necessary for the safety of the crew's life. There are two general approaches to supporting environmental control: containment of the cabin and the suit. In fact, the suit wearing the crew incorporates a supply of oxygen that can be used as a redundant system to prevent the mistakes of the crew, furthermore this type of protective clothing can use gas pressure, direct mechanical pressure or a combination of gas and mechanical pressure to apply pressure to the body. Regarding the use of a redundant component in the cabin, this consists of an autonomous system for releasing compressed gas that is activated when the pressure drops below a nominal pressure value, provided that the partial pressure of O_2 is kept within certain acceptable limits. , also considering the presence of nitrogen or mixed gas to avoid excessive partial pressure of oxygen with related flammability problems.

Atmospheric temperature

- **Hazard and characteristics.** To ensure that the crew can carry out their work and more precisely specific critical safety tasks, adequate temperature and humidity control is required. The FAA notes that from 25% to 70% relative humidity and 65 to 80 °F are acceptable humidity and temperature ranges to meet the requirements. A closed environment that contains humans receives metabolic heat that includes the latent heat of water vapor. In fact, the temperature and humidity in the cabin are subject to sensitive and latent heat that can be removed or added to the environment. Sensitive heat, besides being produced by human metabolism, presents a certain percentage produced by avionics and other electrical equipment located in the cabin. The vehicle's pressure shell can be a means of conveying sensible heat, and this depends on the mission profile and the design of the aircraft.

- **Operational consideration for suborbital launch vehicles.** When performing a suborbital flight, the typical mission profile does not include flight phases in which the external conditions are constant or stationary. The temperature, pressure and speed of the aircraft can change significantly during all phases of flight and this can complicate the thermal management of inhabited spaces. If we consider a subsonic flight at high altitude it will be necessary to add heat to the cabin because the outside air is much colder than the standard conditions at sea level. In a suborbital launch vehicle, the internal cooling of the cabin must also be considered due to the introduction of the pressurized gas that cools to adiabatic expansion from the tank.

- **Available monitoring techniques.** There are several temperature monitoring systems that have been tested for aerospace applications through tests, demonstrations and flight operations. The operational flight environment includes the total temperature range for which the monitoring device is expected to operate. For example, if the nominal, degraded and emergency temperature ranges for an aircraft are between 40 and 90°F, the temperature monitoring device designed to operate within this range would be acceptable to FAA.

- **Available control techniques.** Temperature control in the manned spaceship is typically achieved by removing the heat from the air circulating in the cabin, with forced air circulation through one or more heat exchangers that use chilled water, ethylene glycol or freon acts as refrigerant. For space habitats with continuous recirculation air flow, the temperature control method may be to bypass a variable portion of the air flow around the heat exchanger. Since the thermal loads can be different depending on the area of the cabin, it is necessary to have "control zones". Each zone has an independent temperature sensor and an adjustable air conditioning supply. One of the passive control design techniques is to use load matching as a means of controlling temperature by combining a heat sink with a heat source. Another passive control technique consists in using the thermal capacity of a material to absorb or emit thermal energy in response to thermal loads.

Atmospheric Humidity

- **Hazard and characteristics.** An important increase or decrease in humidity does not represent an immediate risk to the crew's health if considered for short periods of space flight. Despite this, high or very low humidity can affect the crew's physical comfort. If, for example, high temperature and high humidity are considered, there is a decrease in the processes of regulation of the natural body temperature (i.e. sweating). On the other hand, a low humidity has a "drying" effect on the human body and is particularly noticeable in the face of man. So, the humidity can be related to the crew's ability to perform critical safety functions successfully. The air in the passenger compartment of the spacecraft receives moisture in the form of water vapor and sweat evaporated by humans in the vehicle. The average metabolic rate is 5.02 pounds of respiration and perspiration water generated per person per day (0.21 pounds per hour). Stressed or excited people will produce water vapor at above average speeds. Design considerations should consider the different rates of humidity generation over the duration of the mission to determine how the cabin humidity will change during the mission. As mentioned above, the acceptable humidity rate is between 25% and 70%. This range of humidity must also be supported by other safety-critical systems present in the cabin or in the passenger compartment (for example window surfaces or avionics) which therefore must maintain their ability to operate safely without failure.

- **Operational consideration for suborbital launch vehicles.** In the suborbital launch vehicles or in the spaceships the cabin volumes are reduced, if the crew members are physically active or stressed, the speed of water vapor production can be expected to exceed the average values. Thermal management must therefore be appropriate to prevent condensation within critical systems to ensure safety. If the temperature of the vehicle display windows is low enough, condensation can accumulate as liquid or ice on the windows even if the relative humidity in the cabin does not approach 100%. Condensation can also contribute to increased corrosion of the vehicle shell or biological growth during the operating life of the vehicle which could affect the air quality of the cabin. Gravity is an external environmental factor that must be considered in the design of an ECLSS and can create special design considerations in particular for humidity management systems.

- **Available monitoring techniques.** Portable and stationary sensors for monitoring humidity or dew point temperature that are commercially available have acceptable accuracy (+ - 5%). These systems are acceptable to the FAA when it is shown that the monitoring device can operate in nominal humidity conditions (10% - 70%).

- **Available control techniques.** Humidity control for limited duration missions may be achieved by the adsorption of airborne moisture using silica gel, activated alumina, or molecular sieve materials. Commercially available desiccants may contain color coding to indicate when the materials have been saturated with moisture. Canisters containing these materials may be regenerated between missions, using heat or vacuum to remove the moisture. Dry make-up gases are injected continuously, automatically, or on demand into an enclosed volume, while a separate valve system vents excess gas to maintain a nominal pressure range, removing excess humidity. In some cases, atmospheric capacity may be sufficient for short duration missions. Humidity control for longer duration missions may be achieved simultaneously with temperature control, by removing heat from the circulating cabin air, with forced continuous circulation of the cabin air through condensing heat exchanger(s). Chilled water, ethylene glycol/water, or Freon serves as the coolant in these condensing heat exchangers. Under reduced gravity conditions, the condensed liquid water is separated from the circulating air with a hydrophilic “slurper” bar and is collected using a centrifugal separator.

Ventilation and air circulation

- **Hazard and characteristics.** The greatest risk regarding the circulation of air is the possible stagnation of the latter which occurs due to the microgravity conditions for which natural convection is reduced or non-existent. Therefore, an effective circulation of the atmosphere in the cabin is foreseen, to avoid that the crew has discomfort in the presence of stagnant air that could contain unmixed gas. The qualitative or quantitative assessment of flow paths and velocity can be performed during ground tests using a small source of smoke. The direction and speed of a smoke trail is observed as smoke particles are emitted from the smoke source. A smoke source is also useful for identifying regions of stagnant air associated with flow obstructions such as seats and display panels. NASA has determined that the minimum linear air speed for maintaining crew comfort is 10-15 ft/min.

- **Operational consideration for suborbital launch vehicles.** The operation of the rotating component that allows the circulation is equivalent to the monitoring of ventilation and circulation.

- **Available monitoring techniques.** Measurement of the volumetric flow may be accomplished using a variety of different flow-meters or through the direct monitoring of fan speed or related current.

- **Available control techniques.** Circulation fans that are commercially available which have been designed for aerospace and general industrial applications would be an acceptable means to the FAA for providing adequate ventilation and circulation if the operator can successfully verify the integrated performance of a vehicle's hardware.

The considerations made previously for some of the most important atmospheric conditions are also made for the following factors (as can be seen on [1]): Concentration of Oxygen, Concentration of Carbon Dioxide, Concentration of Hazardous gases or vapors, Particulate Contaminants.

From the following figure it is possible to notice the interaction between the crew and the four major ECLSS subsystems for the management of atmosphere, water, waste and food. It should be noted that some loops always remain open, so it will be necessary to continuously have input from external sources. However, it is possible to make closed loops using a correct procedure for retrieving usable resources as inputs. The arrows in this diagram indicate the passage of material between one subsystem and other.

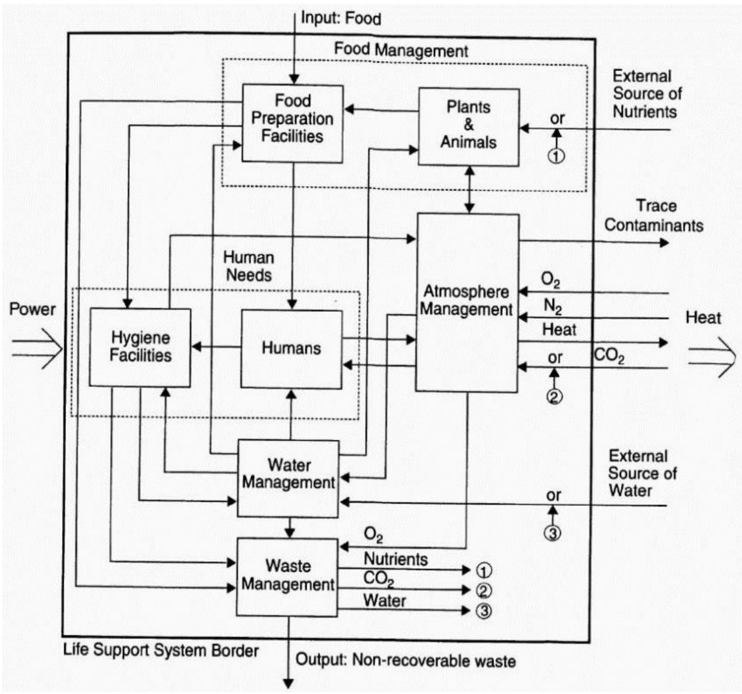

Figure 1 - Block diagram of a typical ECLSS

1.2 Need for a closed loop ECLSS

There are two approaches to the design and operation of an ECLSS: open system and closed system.

An open-loop approach is used when the life support system is designed for short-term missions. In this case there is a need for supplies of oxygen, food and water, transporting them on board spacecraft. Likewise, the waste is stored and sent to the ground station via spacecraft. Thus, a system of this type relies completely on an external supply of resources periodically. There is an addition and removal of material continuously to guarantee the functionality of the system. One of the positive aspects of an open-loop system is the simplicity and reliability it presents during its operational life. On the contrary, a big disadvantage is that the resources required for the mission increase linearly as the duration and size of the crew increase. The cost-effectiveness of open-loop systems depends on transport costs and on the value of the storage volume of a spacecraft.

A totally different approach is the use of a closed loop life support system. In this case the primary objective is to try to process and use waste as useful resources to avoid transportation and supply of resources from the Earth. So, the central theme of this approach is the recycling of material rather than taking it from an external source. In order to define the closure level of a life support system it is necessary to calculate the percentage of resources obtained from recycling compared to the total necessary to guarantee life on board of a certain number of crew members. Having a greater closure of the system means decreasing the supply of resources and consequently having a complete closure of the system implies autonomous operations. The disadvantages are related to the high costs for the development of the technology, demand for greater power and greater heat loads, in addition to greater complexity and therefore probabilities of reliability and maintenance.

The following image shows a diagram of the interactions between the various subsystems of the ECLSS of the ISS.

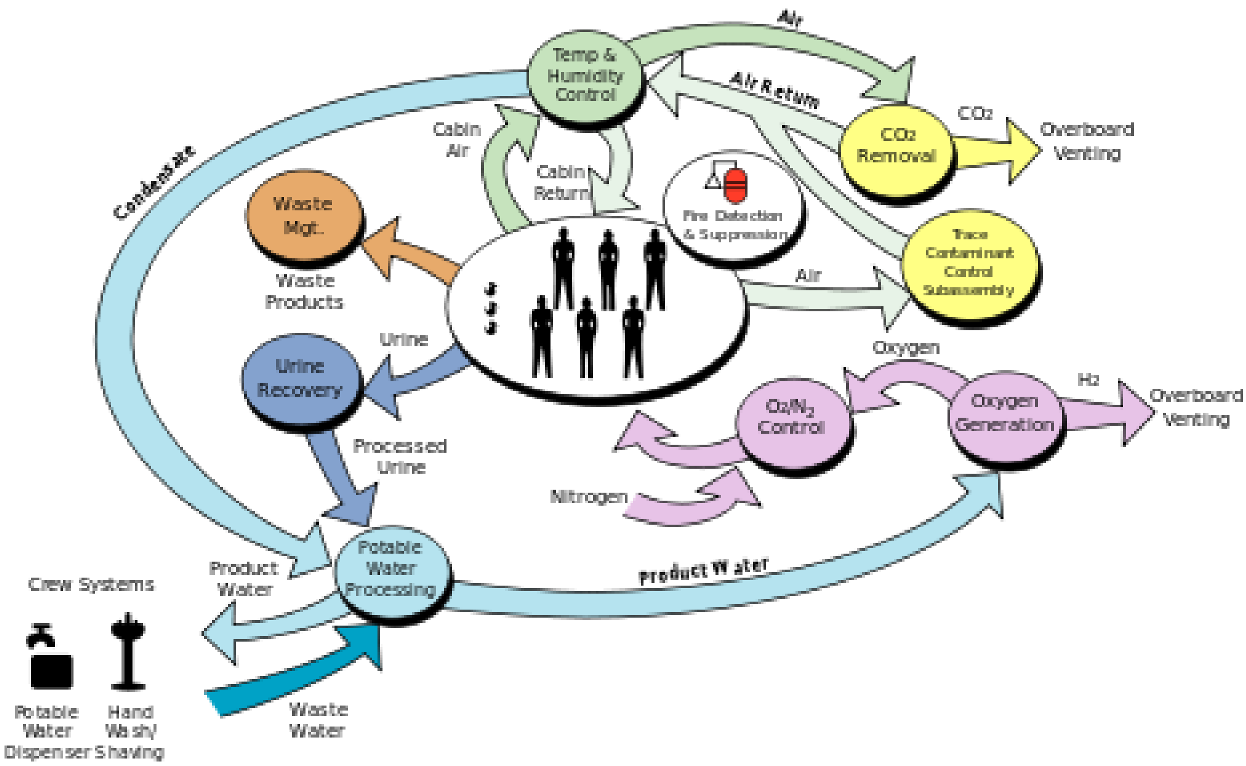

Figure 2 - The interactions between the components of the ISS Environmental Control and Life Support System (ECLSS);

From *Figure 2* it is possible to notice that at the center of the system there is the crew. This is important because thermodynamically speaking, man represents an open-loop system that is closed thanks to the ECLSS. In fact, as already seen, the ECLSS is the system that allows man to be able to live in an environment with conditions close to those on land for a short or long period. On Earth it is assumed that actions such as oxygen production as well as the removal of carbon dioxide from the air that is breathed by humans are done by plants. In an environment sealed like a space cabin, different methods are used, as already seen, to recover water and oxygen and to remove unwanted components from the atmosphere recreated in the cabin. The term recover refers to the fact that new supplies are produced by combining or knocking down unwanted by-products from other processes. It is therefore a question of recycling water and air as the "closure of the ring" of a system in which there is man as a central figure. It would be impractical to completely store oxygen and water needed for missions of long periods of time in the ISS, since the costs and the volume necessary to contain the necessary resources would suddenly increase. Wanting to quantify the portions of oxygen, water and food that meet the basic requirements of astronauts for life on board, it is possible to first consider that it has been estimated that almost an octillion (10^{27}) of water molecules flow through the human body every day, therefore the daily consumption of water must be guaranteed by trying to contain the costs and the volume/weight necessary for the subsystems that carry out this task. Without water, the person lives on average about three days, without air permanent brain damage can occur within three minutes. Scientists have determined the amount of water, air and food a person needs per day in the Earth and in an environment such as the space cabin. The table below shows the reference values:

Table 2 - Life requirements on earth and in space

Item	On Earth		In Space	
	Kg per person per day	Gallons per person per day	Kg per person per day	Gallons per person per day
Oxygen	0.84		0.84	
Drinking Water	10	2.64	1.62	0.43
Dried Food	1.77		1.77	
Water for Food	4	1.06	0.80	0.21

[2], [3].

It would be reasonable to think of using the plants on board the ISS to meet the oxygen production/carbon dioxide removal requirements and therefore to create a closed-cycle system, but they would consume too much space, mass, water, soil, nutrients and energy for the lamps, making their use impractical. At NASA's Exploration Life Support (ELS) there is a human metabolic simulator called MANIAC ("man in a can") in Houston, which simulates up to eight people by consuming oxygen and producing carbon dioxide, heat and moisture, providing one of the most complete breathing models of an absolute living human being. In the ELS laboratory, in recent years tests have been carried out that include the coexistence of the human in a closed environment with plants for periods of 2 weeks to 3 months, in order to determine the cost-effectiveness of the supply of plants in the ISS.

The Integrated Advanced Water Recovery System Lab at NASA’s Johnson Space Center in Houston, tests the effectiveness of future models of water recovery, which could include the following:

- Urine treatment: urine is heated to evaporate water and eliminate salts. The water vapor would then move into a condensing heat exchanger and become purified water. The salts remain, forming a brine solution with part of the residual water. The brine should be recovered or thrown away periodically. This process would require a lot of energy to heat all the water to boiling and then cool the water vapor sufficiently to condense it.

- Bioreactor: A processor that uses microbiological organisms to purify the water. The water is cleaned as a result of the microbes using the contaminants for food (similar to municipal water treatment facilities).
- Multifilters: A series of chemical and physical beds that remove contaminants by chemical reaction and ion exchange and filter particles based on size to purify.
- Reverse Osmosis: Using high pressure across a very fine filter or membrane to purify water. The water is separated from the salts. Brine is created from the concentrated salts that have to be recovered or periodically thrown away. This technology is often used in arid regions to convert and purify sea water into potable water.
- Brine Processing: Recovering water from a brine solution by pouring the brine on a fabric (felt) wick and blowing warm air across it to evaporate the water. The salts are captured in the fabric and thrown away. Water vapor collected is condensed by a condensing heat exchanger.
- Post Processing: A series of chemical beds that remove any final remaining contaminants left behind from all other treatments. A chemical reaction and ion exchange purify the water (similar to a household tap water filter).

Considering what has been seen previously, it is clear that the most important elements to take into account for supporting astronauts are oxygen and water. The space station's ECLSS includes two main components: Water Recovery System (WRS) and the Oxygen Generation System (OGS).

The Water Recovery System provides clean water by reclaiming wastewater, including water from crewmember urine, cabin humidity condensate and Extra Vehicular Activity (EVA) wastes. The recovered water, as already seen, must meet stringent purity standards before it can be used to support crew, EVA, and payload activities. The Water Recovery System is designed to recycle crewmember urine and wastewater for reuse as clean water. By doing so, the system reduces the net mass of water and consumables that would need to be launched from Earth to support six crewmembers by 15,000 pounds (6800 kg) per year. The Water Recovery System consists of a Urine Processor Assembly (UPA) and a Water Processor Assembly (WPA). First the water is recovered from the urine through a low-pressure vacuum distillation process. The process includes the separation of liquids and gases. Urine product processor is combined with all other wastewaters and delivered to the Water Processor for treatment. The Water Processor removes free gas and solid materials any remaining organic contaminants and micro-organisms removed by high-temperature catalytic reactor assembly. [4] The purity of the product is checked by the electrical conductivity of the sensors. Unacceptable water is reprocessed, ready to use by the crew.

Figure 3 - Space Station Water Processor Test Area

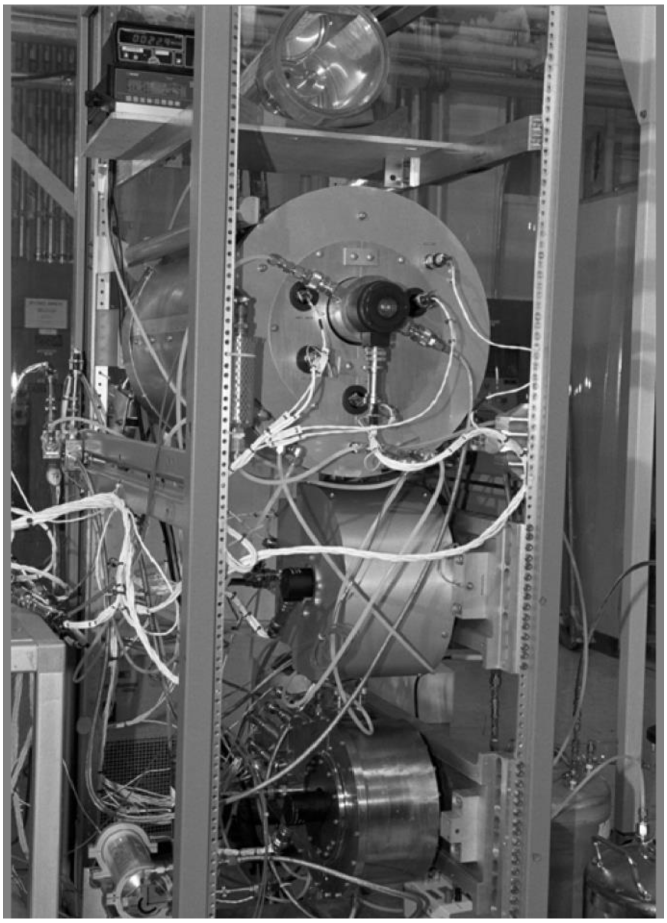

Figure 4 - Urine Processor Flight Experiment

The Oxygen Generation System produces oxygen for breathing air for the crew and laboratory animals, as well as for replacement of oxygen lost due to experiment use, airlock depressurization, module leakage, and carbon dioxide venting. The system consists mainly of the Oxygen Generation Assembly (OGA) and a Power Supply Module. The heart of the Oxygen Generation Assembly is the cell stack, which electrolyzes, or breaks apart, water provided by the Water Recovery System, yielding oxygen and hydrogen as byproducts. The oxygen is delivered to the cabin atmosphere while the hydrogen is vented overboard. The Power Supply Module provides the power needed by the Oxygen Generation Assembly to electrolyze the water. The Oxygen Generation System is designed to generate oxygen at a selectable rate and is capable of operating both continuously and cyclically. It provides from 5 to 20 pounds (2.3 to 9 kg) of oxygen per day during continuous operation and a normal rate of 12 pounds (5.4 kg) of oxygen per day during cyclic operation.

Thus, the consumable components of the life support system are not suitable for long manned missions due to refueling requirements. It appears to be quite expensive to continue to launch new supplies of air, water and life support equipment to the International Space Station and to return used equipment to the Earth. In the space missions of the future, refueling will not be possible due to the distances involved and it will not be possible to carry all the water and air necessary due to the volume and mass of materials needed for a mission lasting months or years. Regenerative life support hardware, which can be used repeatedly to generate and recycle life support elements required by astronauts, is essential for long-term space travel. It is therefore necessary to be able to obtain an ECLSS with a closed loop approach.

1.3 Orbitecture: SpaceHub, Controlled Ecological Life Support System

The CNS project team is addressing the issue of long-term stay in space with a new approach in line with the principles of OrbiTecture and that is an innovative idea of contemporary spatial architecture. The real revolution is in fact to examine the various professions as: doctors, psychologists, engineers, biologists and architects, leaving each of them the maximum freedom of expression in their field. The objective of the CNS is to design a new Space Station that reflects the idea of a cislunar city continuously inhabited by many people, the SpaceHub. [5], [6], [7].

Starting from the state of the art (ISS) and the needs according to the scenario imagined for 2060-2070 which was discussed above, the guidelines for design were identified, which will allow the new orbital infrastructure to offer: Autonomy from the Earth, Permanence in Orbit, Capacity for Experimentation, New frontier for Exploration.

- **AUTONOMY:** Considering that the new infrastructure will be continuously inhabited it is essential to build and achieve independence as far as possible from the Earth, both in the construction phase and during operation and maintenance. The design criteria adopted are: Recycle as much as possible the orbital waste; Make many parts with Additive Manufacturing; Assemble parts using robots; Produce energy and plant foodstuffs.
- **PERMANENCE:** Space tourism will soon be a significant component of human activities in space, complementing the more traditional research and management activities on board. The design criteria adopted are: Realize a comfortable and functional habitat; Overcome/limit the effects due to the absence of gravity and the stress of confinement, but also in particular cases give the possibility to limit the motor disability on Earth by living longer in orbit; Counteract radiation emissions during solar storms especially for long-term missions.
- **EXPERIMENTATION:** The search in the absence of gravity or simulated gravity at various levels will always remain a fundamental element. Areas of sure interest and development of knowledge will be: biotechnologies (growth of high purity protein crystals), fluid physics (behaviors deriving from surface tension phenomena), materials science (production of new generation crystals), combustion (generation and extinction of flames in space environment), basic physics.
- **EXPLORATION:** it is important to identify a new frontier of permanence in space that can guarantee lower costs, creating a real interchange node to other destinations (Moon, Mars, and beyond). The SpaceHub will have to provide Orbital Spaceport functions including: use of spaceship to the Earth and other places of the "cislunar city", management of space navigation, storage of propellant.

The guidelines include the minimization of weight and the maximization of space, the integration of different activities that are currently unthinkable within the restricted spaces of the ISS.

SpaceHub is designed to host about a hundred people on average, divided as follows:

- 1/3 station operators
- 1/3 tourists
- 1/3 astronauts and researchers

The infrastructure, to simulate lunar and Martian gravitation, revolves around its axis with a speed of 2 rpm.

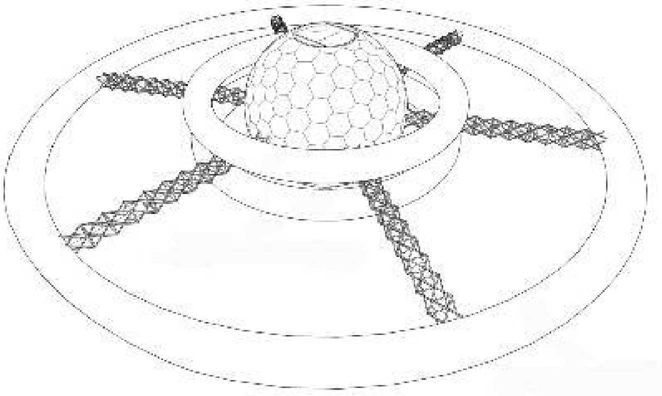

Figure 5 - SpaceHub, layout of principal elements

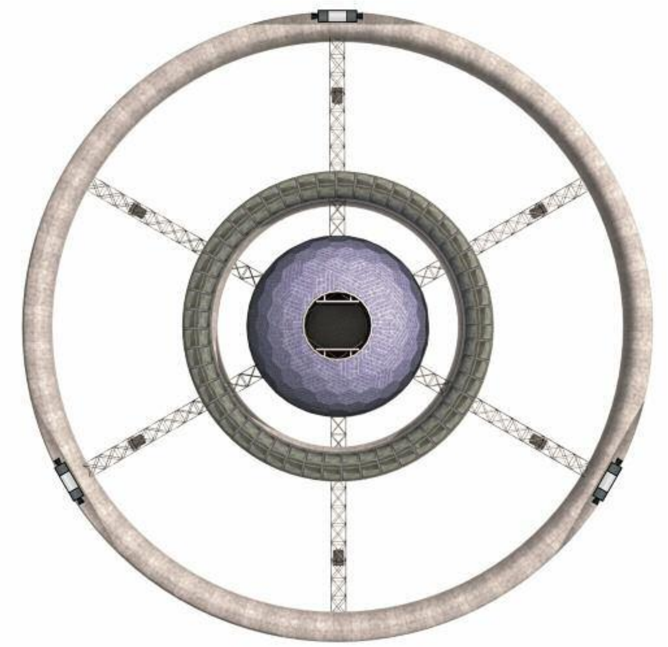

Figure 6 - SpaceHub, plan view

Looking from the outside, the SpaceHub (Figures 5,6) looks like a planetomorphic concept, with a central sphere having a diameter of 44 m, called Miranda, crossed by a cylinder with a diameter of 20 m passing through the origin where the hangar and the microgravity laboratory are located. Around the sphere, 38 meters away from the axis, it is possible to find 2 superimposed toroids, together called Aristarchus, with lunar gravity (1/6 of the terrestrial one); one of the two is the Green Ring, the cultivation field for the production of food plants and oxygen for the self-maintenance of the inhabitants of the space station. At 83 meters from the axis there is a second toroidal element called Galilaei with Martian gravity (1/3 of the terrestrial one), it represents the outermost structure, along the external surface of which are also housed the 3 thrusters that allow rotation maintenance of the space station, guaranteeing different gravities in the three sections.

The toroids of Aristarchus, except for the Green Ring, and Galilaei will host living and socializing spaces for all the inhabitants. The tourists present in the space station will vary between a minimum of 30 to a maximum of 40 people and will have small rooms of about $25\ m^2$ each. In Aristarco and in Galilaei it is also possible to find refreshment rooms, religious spaces, green areas and areas for sports. An environment dedicated to holographic cinema and theater is instead available in Miranda for size reasons, operating in very low gravity conditions.

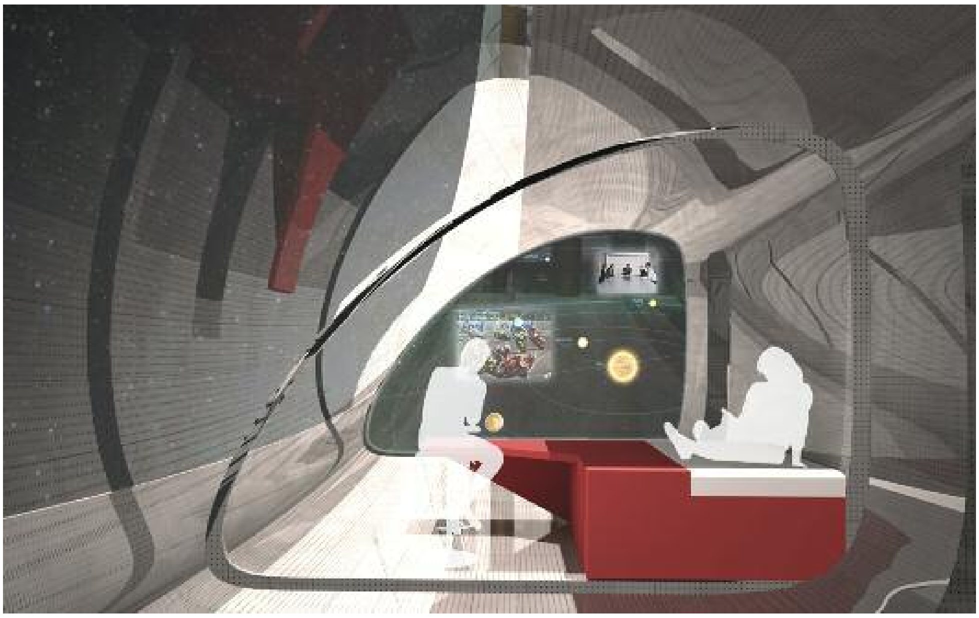

Figure 7- Environments for relaxing in a toroid

Figure 8 - Green spaces for sports activities in a toroid

The SpaceHub project needs a closed system from the point of view of the material (but open from that of energy) that reproduces the cycles that are developed on Earth. This system is commonly called CELSS (Controlled Ecological Life Support System). This closed-loop bioregenerative system must contribute to the production of fresh vegetables, the generation of oxygen and the removal of carbon dioxide from the internal air (due to human respiration) through photosynthesis, to the purification of water through the transpiration process, to the use of biomass residues and organic waste from processes and physiological waste, after appropriate treatment, and the psychological well-being of the crew. Men breathe oxygen (O_2) and exhale carbon dioxide (CO_2) as a waste product. Plants absorb CO_2 from the air and use the energy of sunlight, water and inorganic elements to produce organic matter, and emit O_2 as a waste product. This creates a cycle between plants and men in which the former produce food and oxygen for the latter, while these emit carbon dioxide and organic material that can be used (directly or indirectly) by plants. To these two important components is added a third one, consisting of decomposers, organisms capable of transforming organic matter (feces and human urine, vegetative and reproductive parts of plants) into forms easily reusable by the first two groups. This natural terrestrial cycle can be repeated, very simplified, in space.

A complete CELSS consists of the three functional sub-systems mentioned above:

1. Consumers (human crew);
2. Producers (plants);
3. Decomposers (recycling systems).

The system must be able to provide for the crew's basic needs, such as supplying food, water (both drinking and hygiene) and breathing air. it is necessary to pay close attention to the constituents of the atmosphere, in particular the oxygen and carbon dioxide, favoring the exchange between producers and consumers; it is of vital importance to eliminate, or at least control, the possible air and water contaminants; it is necessary to produce foods that support consumers even for long periods of time; waste produced by both consumers and producers must be made usable again by them.

The main functions that a CELSS must perform are:

- Air regeneration;
- Food production;
- Waste recycling;

Air regeneration

Air regeneration systems are needed to maintain adequate conditions for human metabolism in space bases. The functions of these systems include oxygen production, removal of excess carbon dioxide and organic contaminants, and relative humidity control. The internal thermal conditioning system keeps the temperature at optimal levels and generally includes other functions such as humidity control, the elimination of particulates and microorganisms from the air flow. These systems use heat exchangers (Peltier elements) on which it is possible to condense the water vapor removing it from the previously filtered air. The water thus produced can be used as drinking water. Current CO_2 removal systems are based on the absorption by the porous structures of zeolites. Furthermore, several systems have been developed for chemical CO_2 removal. Among these, the use of lithium hydroxide ($LiOH$), silver oxide (Ag_2O) and solid phase amines. Oxygen, on the other hand, can be produced directly through electrolytic decomposition. The main atmospheric "contaminants" in a space station are CO_2 and water vapor. However, other organic contaminants can also be found, in amounts such as to be harmful to the crew. Normally active carbon bed filters are used. The use of plant organisms is a sustainable alternative to these systems, based on the photosynthetic process carried out by the plants and on the plants' ability to purify the atmosphere by organic and particulate contaminants.

Food production

The ability to continuously produce food during a space mission is an important limiting factor of a system based only on physicochemical reactions controlled by machines. If it is possible, with these instruments, to purify both the air making it breathable and the water making it drinkable, it is not possible to make organic waste again edible. Producers, essential constituents of a CELSS, must be represented by efficient agricultural crops able to provide to the crew, in the long term, an adequate diet (such as quantity and quality). Plants can also meet the other basic needs of a human crew by providing oxygen, as a product of photosynthesis waste and drinking water, following the phenomenon of transpiration, which can be collected. However, not all agricultural crops are suitable for the purposes of a CELSS. Considering that within any spatial structure (infrastructure or spacecraft) one of the limiting factors is certainly the space, the plants in question should provide high production in small spaces, they must be, therefore, small, easily cultivated in hydroponics and have a high harvest index (the ratio between the edible fraction and the total biomass of the plants).

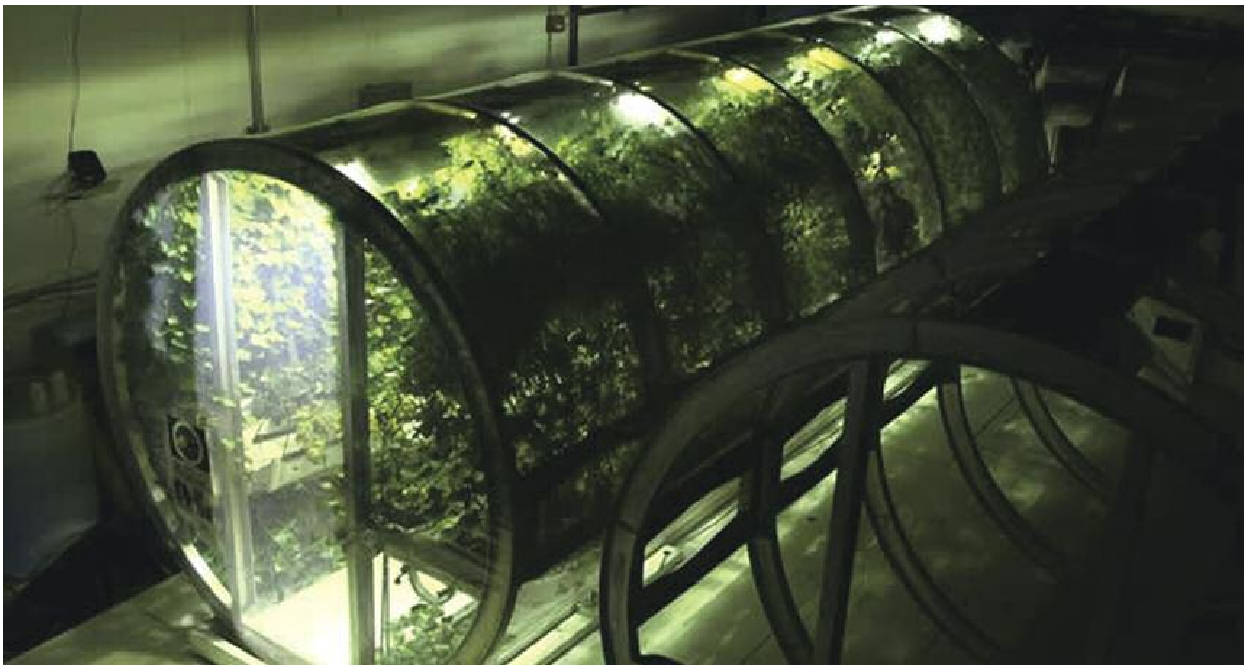

Figure 9 - Space Greenhouse Prototype

Waste Recycling

It is the foundation on which a CELSS is based: all the matter, in a closed system like this, must be recycled. Recycling flows are basically three:

- Solid Substances
- Liquid Substances
- Gaseous Substances

The choice of appropriate subsystems for waste management in a CELSS should be made through selective criteria based on reliability, resistance, security, energy efficiency, weight and size. For the recycling of the various flows, different technologies are used, including the use of biological treatments and chemical-physical treatments. There are many researchers who claim that it is possible to use both systems simultaneously. This ensures the survival of the crew in the event of failure about one of the two systems.

An example of recycling of liquid substances could be water recovery. In a CELSS system, water consists of gray water, urine, drainage water and leaf transpiration water. The latter is rather pure and can be collected directly from the growth chambers, to then be used as drinking water. For the disinfection of the recovered water, physical-chemical and biological processes are used (as already mentioned). On board space stations, water is used for needs of the crew, including direct hiring, food preparation, personal hygiene, oxygen generation and other uses (scientific research). Water can also be used for the destruction of solid waste through supercritical water oxidation techniques or vaporization-based reactions. In the future, it should be used to supply plant growth chambers for oxygen and food production.

In a closed system, the purification of water becomes fundamental, as the costs of refueling from the ground are prohibitive. The water present in the onboard atmosphere (thanks to evaporation and transpiration) is condensed and collected using condensing heat exchanger. Water used for personal hygiene (polluted of substances such as salts, soap, etc.) it is collected to be purified. Urine is also collected for treatment. These are currently the three main sources of water supply in the space cabin. Water dispersed through faeces and other solid waste leaves the closed system and must be replaced by water production on board or by refueling.

So the proposal of the CNS is oriented to the realization of an efficient CELSS that can guarantee the self-sustaining of all the crew on board of SpaceHub.

1.4 Project objectives

In this research work the main objective is the design of a passive condensing heat exchanger that can operate in microgravity and the design of a test bench with sensors in which it is possible to carry out some tests described as the final goal of the thesis.

As seen in the previous paragraphs, a condensing heat exchanger can be used in different ECLSS subsystems and in a future view of a closed-cycle system, this component will become indispensable for the recovery and production of water usable as potable water for consumption, hygiene and food preparation.

For example, in the guide for the design and development of an ECLSS issued by the FAA [1], one of the ways to control atmospheric humidity and temperature is a condensing heat exchanger that is used to remove heat and control humidity in cabin for long-term missions. Water condensed by wet steam, under reduced gravity conditions, must be separated from the air through a centrifugal separator, to be conserved and used.

In this research work, one of the tests proposed is to investigate if using a spiral geometry, it is possible to separate the condensate from the air during the flow path in the condensing heat exchanger (CHX), to avoid the formation of liquid film over the entire exchange surface, and consequently to maintain along the path a portion of surface in contact with the air flow.

In the Integrated Advanced Water Recovery System Lab at NASA's Johnson Space Center in Houston, one of the processes that is being studied for future water recovery systems is the brine processing. To recover the water from a brine solution, after creating the water vapor, a condensing heat exchanger is used.

Another goal of this work is to design a condensing heat exchanger in which the inlet flow circulates in the axial direction respect to the pipe from which it comes during the condensation process but flowing along a spiral path, which induces a centrifugal force to separate the liquid from the air.

Finally, during the proposed test phase, a test was planned through which it is possible to know the amount of condensed water compared to the total amount of air passed through the CHX in a certain time.

2 Condensing Heat Exchanger

A heat exchanger is an apparatus in which thermal energy is exchanged between two fluids having different temperatures. In aerospace engineering, heat exchangers play a fundamental role both in general aviation and in the use in spacecraft that must perform a space mission. In most cases of aerospace engineering, the role of the heat exchanger is to reduce the temperature of a fluid. For example, in general aviation heat exchangers are used to reduce the temperature of the fuel and consequently increase the efficiency of the aircraft engine. Other common applications could be power systems cooling, electronics cooling, and air conditioning. In the space ambit, as already mentioned previously, they are used for example to control humidity and temperature on board inhabited space modules. In ECLSS, heat exchangers can be used for the recovery of water used by astronauts for various common purposes. In this case they are called condensing heat exchangers (CHX). A CHX is a particular heat exchanger that has the purpose of condensing a substance or a mixture, and then bringing it from the gaseous state to the liquid state, generally by cooling (decrease in temperature). Given their use in particularly critical environments, the main aspects considered by the engineering field are the need for light, lean, easy to assemble and maintain equipment. Enhanced heat transfer (EHT) techniques provide: reduction of thermal resistance by decreasing the thickness of the exchange wall or increasing the contact surface area; passive or active enhancement; single or two phase flow; free or forced convection; laminar or turbulent flow; mode of heat transfer and other characteristics.

It is possible to classify the heat exchangers by way of contact between the fluids in operation: in direct or indirect contact. [8] In the first case, the interfaces of the fluids that exchange heat are directly in contact with each other, so they are not separated by a wall and therefore there is an exchange of heat and matter. In the second case the fluids do not come into direct contact with each other, therefore between the fluid interfaces, there is a surface that is crossed by a thermal flow. The latter are the most commonly used heat exchangers. Fluids absorb or release heat to the surfaces that separate them. These surfaces can be provided with fins in order to further facilitate heat exchange. In a surface heat exchanger, two sides are distinguished in which flow fluids, hot side and cold side. Fluids can be gaseous or liquid. In surface heat exchangers it is possible to use thermoelectric units to control the surface temperature in direct contact with the fluid with which heat is to be exchanged. For example, one of the thermoelectric units used for this purpose is the Peltier cell. The Peltier thermoelectric device has two sides, the p-type and n-type semiconductor. When a DC current flows through the device, it transfers heat from side to side. By applying the Peltier thermoelectric device to the contact surface that the fluid touches while crossing the heat exchanger, it is possible to subtract or add heat to the fluid, causing evaporation or condensation. Below is reported a diagram showing the different types of heat exchangers.

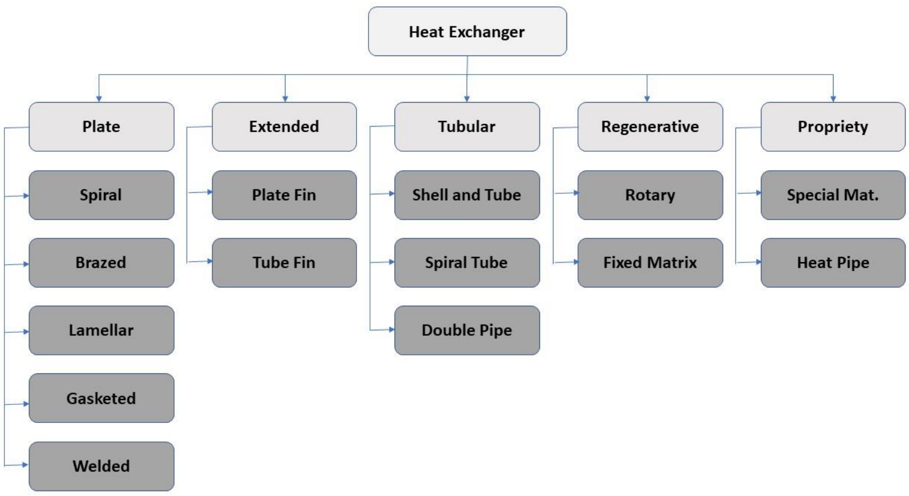

Figure 10 - Brief classification of heat exchangers

2.1 State of Art

Condensing heat exchangers have been used for thermal and humidity control in every manned space flight system launched by the United States [9]. In the International Space Station, a two-step process is used to recover water from a condensing heat exchanger. The first step is the condensation of the humid air that passes through the fins of a plate-fin heat exchanger, recovering condensed water that is pushed through the "slurper bars" by the air flow. The slurper bars are crossed by a mixture of air and water which will then be separated by a rotating separator. It is reported in the figure below the components of the ISS condensing heat exchanger of which it is possible to read a brief description in [10].

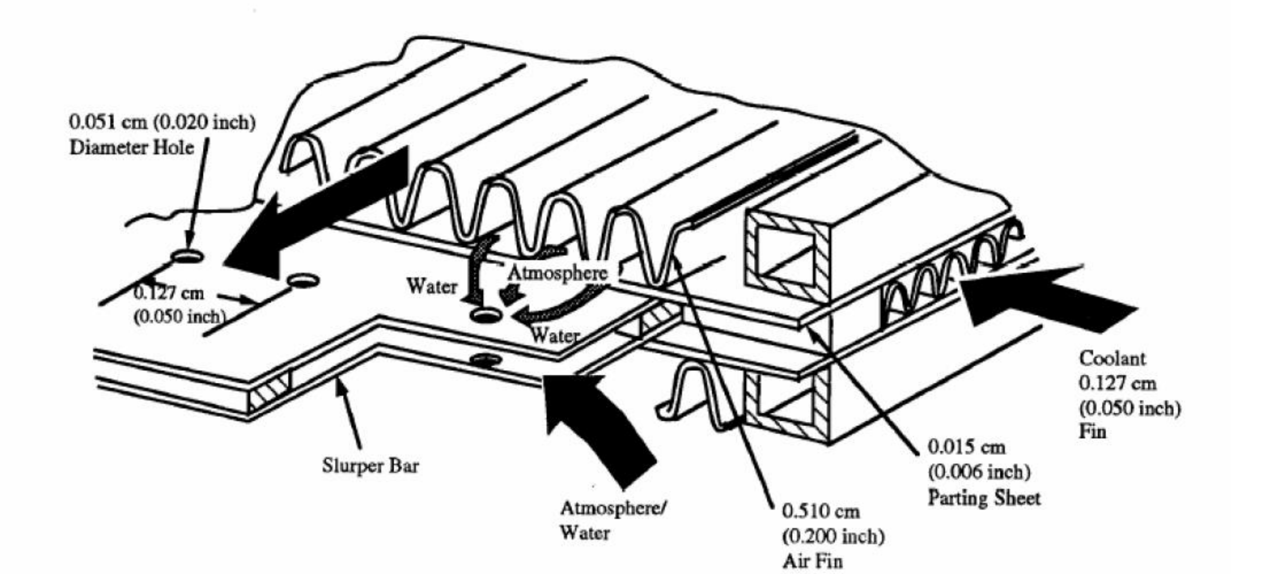

Figure 11 – ISS Condensing Heat Exchanger

It would be advisable to carry out a more efficient design from the point of view of weight, trying to reduce the components necessary for water recovery on board the ISS. In this regard, a test bench was built at the NASA Glenn Research Center to provide a moist air flow to a condensing heat exchanger that exploits the capillary forces generated on a wall with a porous substrate to remove water directly from the air stream that is condensed, without the need for an additional rotational separator downstream.

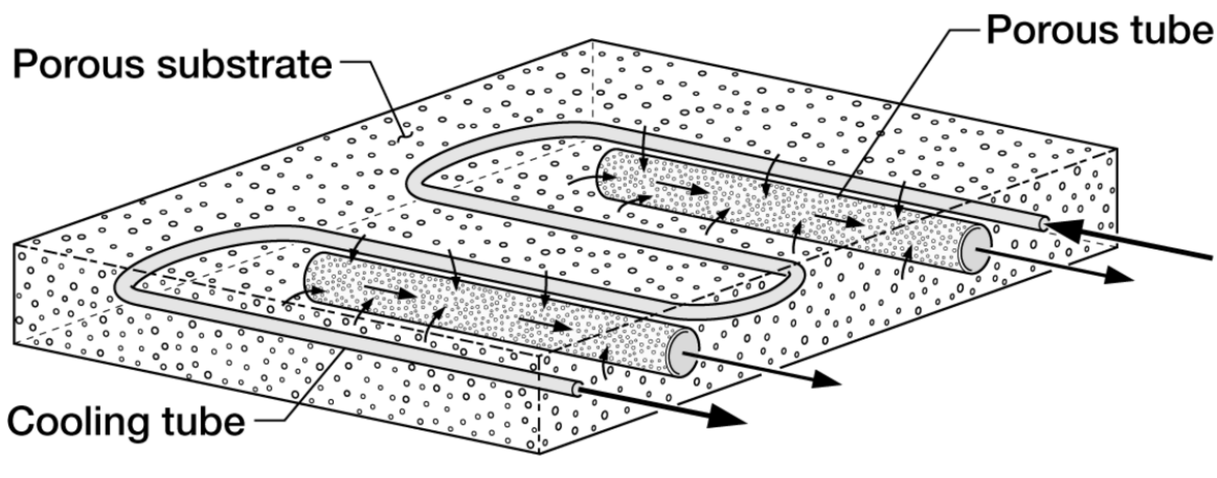

Figure 12 - Condensing heat exchanger with a porous substrate

As can be seen in the previous figure, the system consists of a porous substrate with embedded porous tubes positioned at regular intervals and connected to a suction device by a manifold. The porous substrate also contains cooling copper tubes through which chilled water is circulated. Moist air condensation occurs inside and above the porous substrate when it is cooled below the dew point. The porous plate absorbs the condensate by capillary action and the water accumulated inside the porous plate is selectively removed by the incorporated porous tubes. Air penetration into the porous tubes is avoided by selecting tubes with a bubble pressure higher than the porous substrate. Porous tubes should be used under a suction head, below the pressure of the bubble of porous tube. [9]

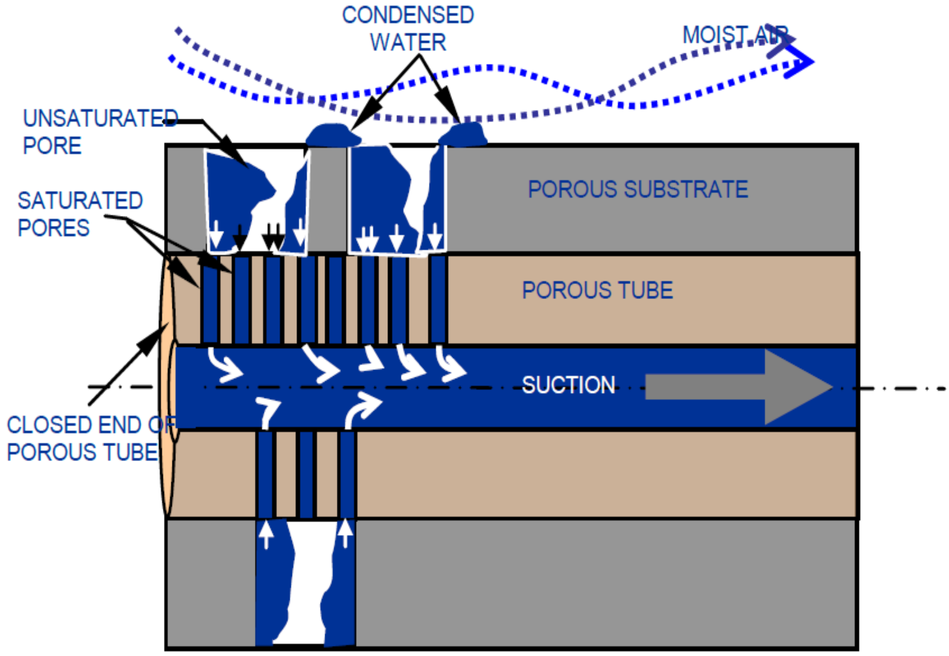

Figure 13 - Operation scheme of condensing heat exchanger with a porous substrate

A drawing of the assembled test-section of heat exchanger used in the test bench is shown in the following figure.

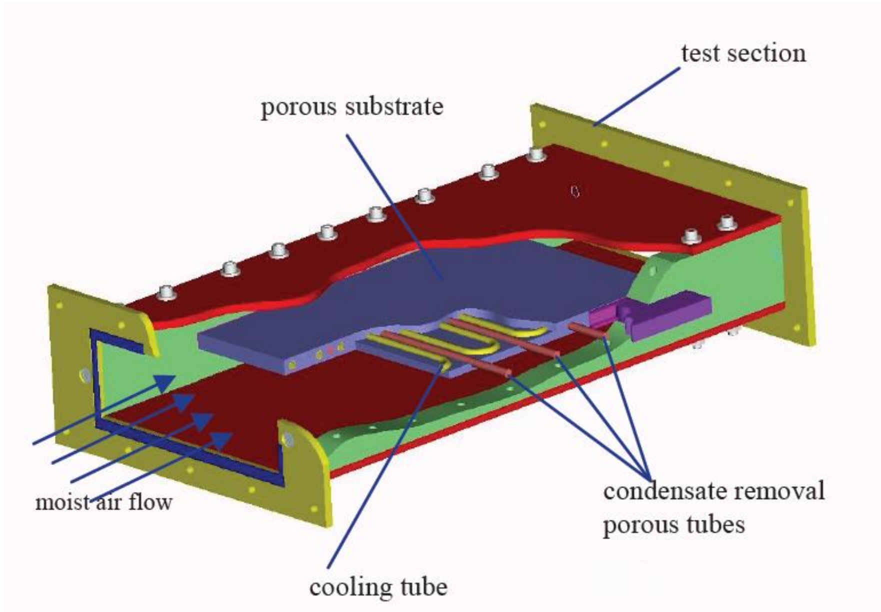

Figure 14 - Flat-plate condensing heat exchanger installed in the test-section

Graphite was used for the construction of the external porous substrate and ceramic for the internal porous tubes that recover the condensed water. The extraction of the liquid from the graphite block was initiated at a known degree of saturation. The porous tubes primed to complete saturation were inserted into the graphite block and subjected to a desired suction pressure ΔP. The suction pressure was applied with a Drummund vacuum pump. Pressure and water outflow were recorded at different time intervals.

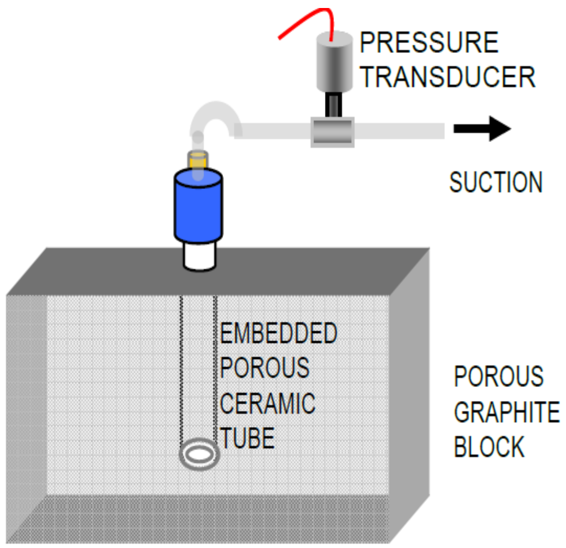

Figure 15 - Schematic illustration of the test bench apparatus

The operation can start with the condensing substrate fully saturated or dry, but the condensate withdrawal tube must be primed to saturation. When the degree of saturation becomes high, the porous tubes will begin to extract water from the plate whose flow rate will be a function of saturation. Assuming that the hydraulic conductivity expressed as a function of saturation can explain the decrease in the reduced saturation flow rate, the system will reach a steady state condition when the flow rate corresponds to the condensation speed. At this point the pump can be stopped to saturate the plate because the flow becomes more efficient at higher saturation.

Preliminary bench tests have demonstrated the feasibility of this concept. Further work is underway to optimize the geometric design of the condensation surface and to demonstrate the function of this heat exchanger in a long-lasting microgravity environment. [10]

In 2011, Thomas et al. have obtained a patent (US 7,913,499 B2) relating to a condensing heat exchanger that can operate in microgravity. [11] The components that perform the function of the heat exchange of the condenser in question are aluminum fins. The condenser contains a plurality of fins which are stacked and clamped between two cold plates. The latter are aligned radially along a plane that extends through the axis of a cylindrical duct. They hold the fins stacked and locked, exchanging heat and therefore decreasing the temperature of the fins. The fins extend outward from the part blocked by the cold plates, along planes that can be defined as radial. The spacing between the fins is symmetrical with respect to the cold plates, and they are much closer near the radial plane that forms a 90 degree angle with the cold plates. The capillary spaces are created in the vertices formed between the adjacent fins. The variation in angles between the fins creates a capillary gradient that passively pumps condensate from the cold plates toward the center fin where it is pumped out of the fin assemblies. When the corners are narrower between the adjacent fins, greater capillary storage is facilitated. Below is a figure in which it is possible to observe the geometry of the condenser.

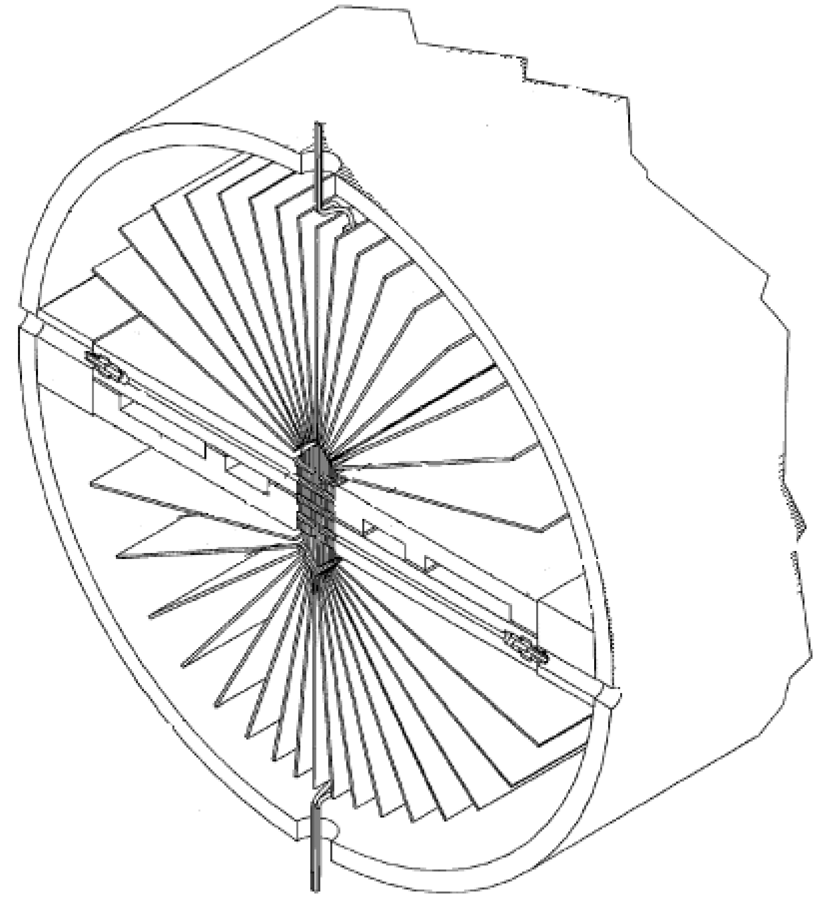

Figure 16 - Condensing heat exchanger (US 7,913,499 B2)

The capillary spaces formed by the angles between adjacent fins in which the condensed water is collected, are connected through the slits created in the fins to allow the communication of the condensed water between adjacent capillary spaces. These capillary spaces are also in communication with the passages formed in the stacked and blocked portions of the fins, which in turn communicate with water drains which extend outside the duct. Water with a little or no trapped air can be drawn from the capillary spaces using a low-volume liquid pump. To minimize weight, aluminum is used as a material for the construction of thermally conductive fins. They have a thickness of 0.032 inches and a condensation surface that extends in the radial direction of 3 inches (7.6 cm) and 6 inches in the axial direction (15.2 cm). The condensing heat exchanger has an internal diameter of 8.25 inches (21 cm). Only in the central fin is mounted a water depth sensor that uses the water conductivity to detect the filling level of the capillary space. Below is a figure in which it is possible to observe the geometry of the fin.

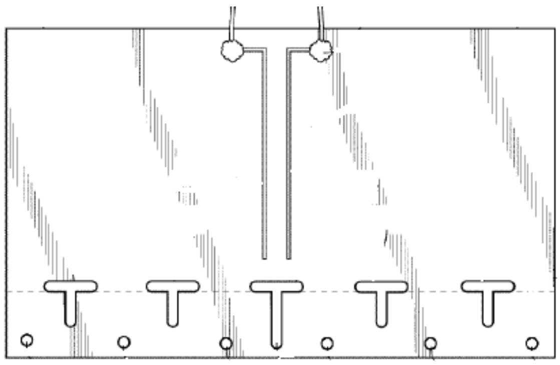

Figure 17 – Fin of condensing heat exchanger (US 7,913,499 B2)

The condensing heat exchanger is inserted in a duct, where in the initial part a fan is mounted followed by an air filter, a pre-cooler and at the end of the duct, there is the CHX. The fan draws air from a cabin and supplies it to the duct where it flows through the filter to remove particulates. After passing through the filter, the air is cooled by the precooler and then passed through the condensing heat exchanger. The temperature is measured by a temperature sensor placed between the fan and the air filter. Furthermore, before the air enters the condensing heat exchanger, it passes through temperature and relative humidity sensors placed between the precooler and the CHX. Suitable control techniques are used and the airflow supplied by the fan, the cooling load of the precooler and the cooling load of the CHX can be controlled. In this way, it is possible to not cause any condensation in the precooler, and the air passing through the duct is brought close to the saturation condition before entering the condensing heat exchanger. Thus the cooling capacity of the condensation heat exchanger is used to recover the condensed water by cooling below the dew point. The duct is uninsulated so that a small amount of heat moves into the duct to prevent the condensation of water on the interior surfaces of the duct, particularly in that portion of the duct which surrounds the condensing heat exchanger. The duct is arranged with various cross-sections connected by sections arranged to contain the various components, fan, filter, pre-cooler and heat exchanger and to create a uniform airflow with minimum resistance to the flow.

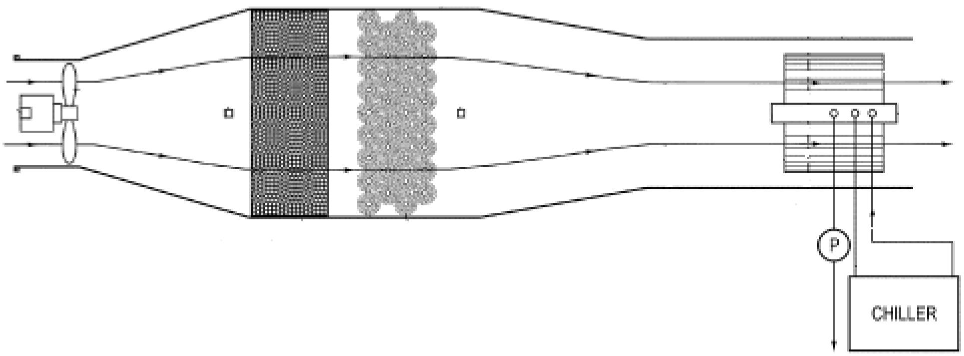

Figure 18 - Assembly of the condensing heat exchanger components (US 7,913,499 B2)

In 2012, Burke (NASA) have obtained a patent (US 8,163,243 B1) [12] relating to a microgravity condensing heat exchanger with a different operating principle than the previous one. The system of the invention also acts as an air-water separator, in addition to being a condensation heat exchanger. The system includes an upper and a lower housing. In the upper housing there are the inlet and outlet of the coolant, and the inlet and outlet of the air to be cooled. The condensed water in the upper housing is transported and removed through the lower housing. In order to remove water from the lower housing, it is necessary to have a component that creates the suction of condensed water. In this regard a spring-loaded bellows is used.

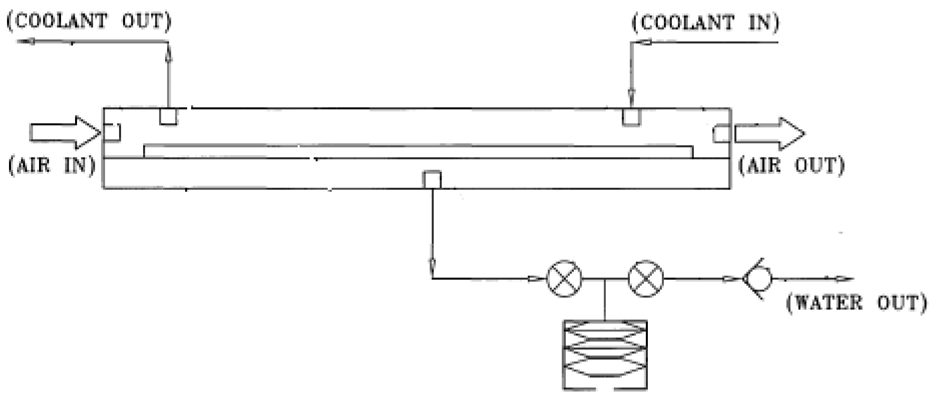

Figure 19 - Microgravity condensing heat exchanger (US 8,163,243 B1)

Showing in the figure below a cross-sectional view of the planar air/water separator, it is possible to see that it comprises a cavity (54) capable of holding water and which is occupied by a water cavity support screen (56). A hydrophilic membrane (58) is arranged on the upper surface of the water cavity support screen. As can be seen, the upper housing comprises a plurality of channels (60) which are interconnected to each other and which entirely cover the hydrophilic membrane. From these channels there is the passage of the air to be condensed. At the top of the upper housing there are the interconnected square cavities from which passes the coolant. Above the coolant channels there is a cover (64). The upper housing is selected to be of a relatively high thermal conductive material that also has a relatively low density, so as to minimize mass. The material may be selected from the group comprising aluminum, magnesium, titanium, metal filled, or carbon filled plastics, and high thermal conductivity carbon composites. The upper housing acts essentially as a liquid-air heat exchanger and as a air-water separator because when droplets of condensed water are formed, they have a greater density than air and are pushed by the flow of air towards the external part of the channels. The hydrophilic membrane has a circular shape and has a very thin thickness. It is composed of a plurality of very small pores from which the condensed water will pass. In the *Figure 21* it is also possible to observe the spiral path of the canals, all interconnected. The spiral path therefore creates a radial acceleration of the air flow, which helps in the separation of the water droplets from the air flow. The air channels provide changes in a direction of the flow path within the air channels that imparts acceleration, which assists in separating water droplets. Changes in the width and depth of the air channels known in the art to create turbulence, also imparts acceleration which assists in separating water droplets. The separation is accomplished while minimizing the difference between the air inlet pressure and air outlet pressure. The imparted accelerations assist in moving the water droplets to the surface of the hydrophilic membrane, in particular, to the film and into the peaked portion. The turbulence in the air channels also enhances heat transport from the air in the air channels to the cooled walls of the coolant cavities.

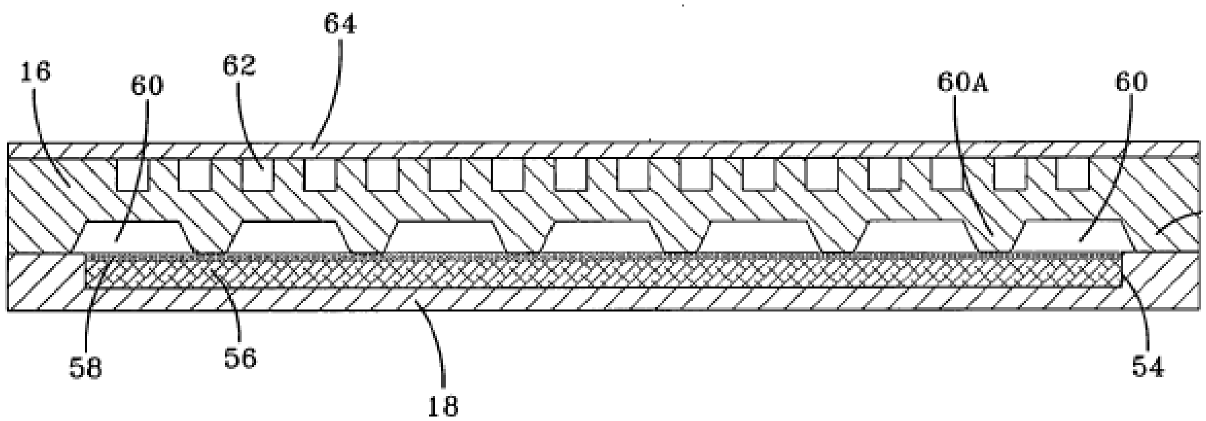

Figure 20 - Cross-sectional view of the condensing heat exchanger (US 8,163,243 B1)

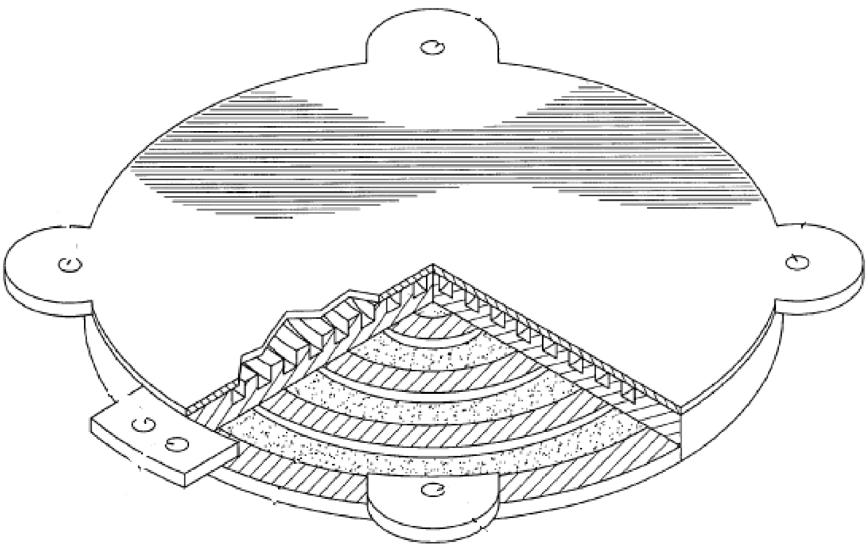

Figure 21 - Microgravity condensing heat exchanger (US 8,163,243 B1)

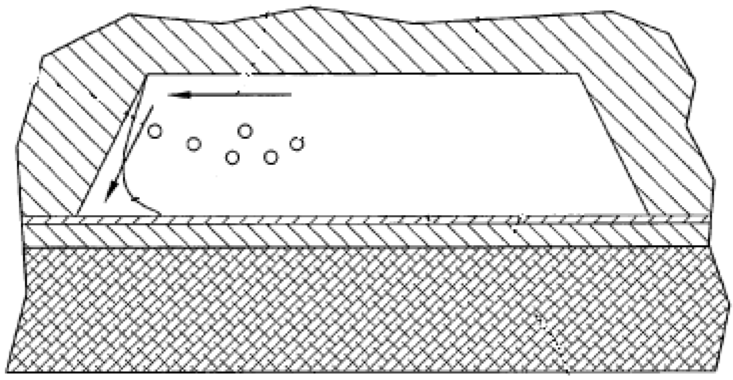

Figure 22 - Formation of droplets of condensed water in the channels of passage of the air flow

Below is reported a table with the main features of the 3 condensing heat exchanger models considered in the state of the art.

Table 3 - Main features of the State of the Art CHX

	CHX with porous substrate	CHX US 7,913,499 B2	CHX US 8,163,243 B1
Geometry	Rectangular	Cylindrical Duct	Planar and Circular
Main Dimensions	$15x20x4.6\ cm$	$D_i = 21\ cm$ $L = 15.2\ cm$	Not mentioned
Flow rate of condensed water	$2.5 - 3\ \left[\frac{ml}{min}\right]$	$26\ \left[\frac{ml}{min}\right]$	Not mentioned

The flow rate of condensed water about CHX with porous substrate, reported in Table 3, relates to tests carried out with CHX in a horizontal position, with 86-88% of substrate saturation. The flow rate of condensed water about CHX US 7,913,499 B2, reported in Table 3, is a value obtained from tests with air dew point at 12 °C, with 9 grams of water for each kilogram of air.

2.2 Scenario

The condensing heat exchanger can be used for various functions in multiple scenarios, as already seen in the previous chapter. One of the possible scenarios in which the use of a condensing heat exchanger proves to be necessary is the microgravity food production unit belonging to the ECLSS. Thales Alenia Space (TAS), a company with which this thesis work is carried out in collaboration, is working on the EDEN ISS Horizon2020 project whose main objective is to advance controlled environment in laboratory and space-analog environment. The capability to produce crops in space is a key development for a sustainable human presence beyond Low Earth Orbit. The use of higher plants-based systems provides multiple additional benefits, such as contribute to air revitalization and water processing, as well as carrying the potential of providing psychological benefit to the crew, obviously in addition to the main function that is the food production. TAS worked mainly on the development of a rack-like facility targeting at short-term safe food production and operation in microgravity, starting from a demonstration phase on-board the International Space Station (ISS), to be followed by more extensive testing in future orbiting habitats (e.g. the Lunar Orbital Platform-Gateway). It was developed as a potential payload for the European Drawer Rack (EDR) MK II. It is transported to the ISS in the second half of 2019 and provides interfaces for multiple experimental inserts (EI). The project EDEN ISS ISPR is called RUCOLA (Rack-like Unit for Consistent on-orbit Leafy crops Availability). RUCOLA has been developed and tested in the TAS Recyclab technological area in Turin. It was then shipped to the DLR Institute of Space Systems in Bremen for integration in a container-sized greenhouse Mobile Test Facility (MTF) for integrated testing and subsequent shipment in later 2017 to the German Neumayer III station in Antarctica. Beyond logistics, Antarctica provides also a microbial environment with characteristics analog to space, with the need to manage only the microbial contamination that is transferred by the crew and the equipment. The main objective of the Antarctica RUCOLA system demonstration is to advance the TRL of the plant growth facility technologies, as well as to identify necessary design and operational procedures updates in view of a near term experiment on the ISS. The structure was organized to increase the current in-flight capabilities represented by the NASA Veggie system in terms of:

- Higher available growth surface (0.5-1.0 m^2 range);
- Longer production cycle possible by complete nutrient solution circulation (and not only watering of substrate with slow release fertilization);
- Robust and reliable safe and high-quality food production (while Veggie control capability may be considered limited);
- Taller crop can be accommodated (up to 60 cm available for tall growth chamber shoot zone).

In the following figure it is possible to see the EDEN ISS RUCOLA system 3D image with a description of the main components. The lower section of the rack is dedicated to the interfaces (power, data and cooling water) with the Mobile Test Facility, mimicking the EDR MKII functions. Above this section are placed the interfaces between the rack and the plant growth facility, exactly as for EDR MKII Experimental Insert (EI) interface panels. In the central portion of the system, the following payload drawers are accommodated:

- Power, Command and Data Handling Module;
- Nutrient Storage and Distribution Module;
- Growth chamber Modules (1 for short plants, 1 for taller plants), including each chamber dedicated air management systems, root modules and crop shoot-zone volumes;
- Illumination Modules (one for each growth chamber).

In the top portion of the rack, a panel for manual monitoring and control via a LabVIEW based interactive graphical user interface of the rack's functional parameters is present, together with a storage volume.

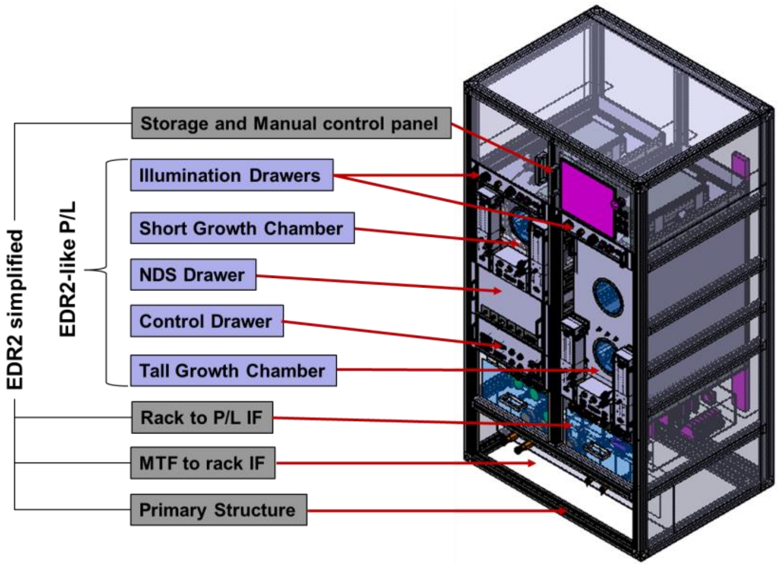

Figure 23 – The EDEN ISS RUCOLA cultivation system 3D image

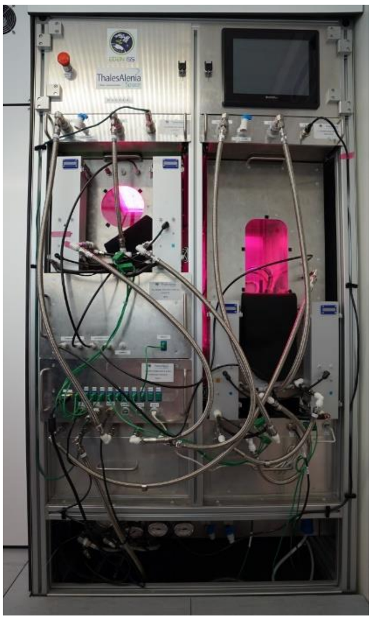

Figure 24 - Antarctica installed hardware

Each of the 2 plant growth volumes has an independent temperature and humidity control subsystem. Identical components have been used for both the Tall Growth Chamber (GCT, 192L volume) and short growth chamber (GCS, 84L volume), despite the different volumes. The air extracted from the shoot-zone volume is cooled by a Thermo-Electric Cooler (TEC, using Peltier effect) to remove sensible heat loads as well as latent heat loads through condensation of water vapor. The water vapor is then collected by gravity in a custom designed recipient, and then pumped through a 0.2µm filter to the De-Ionized (DI) water reservoir within the Nutrient Storage Module. The TEC is an air to water heat exchanger, and the heat collected at the water side is removed by a cooling water loop connected to a chiller external to the rack, designed to provide similar performance to the EDR II rack cooling provision (up to 180 l/h of water at 16-20°C). Each Growth chamber has two fully redundant temperature and humidity control easily replaceable units, nominally operating in parallel at about 50% of their maximum capabilities. Each of those can sustain the basic atmosphere control functions alone, in order to cope with the special logistics conditions of the Antarctica operating framework. A failure of the one element of the cooling HW (e.g. fan, TEC, etc.) would not be catastrophic for the crop growth, also in the eventuality of not being able to access the MTF for multiple days (e.g. in case of heavy storm). The same logic is applied to the airborne contaminants control system, placed in series to each of the above-mentioned air management lines, and consisting into a particulate filter, a 0.2μm HEPA filter including active charcoal in the mesh, followed by an additional filter for low molecular weight organics (like ethylene). The condensing heat exchanger, object of this thesis work, should be used replacing the TEC present in the EDEN ISS RUCOLA system to recover the water from the condensation of the air present in the plant growth chambers.

2.3 Requirements and Constrains

The purpose of the condensing heat exchanger object of this work is to recover water by condensing the air that is in standard conditions livable by humans or plants. Within the crew cabin, thermal considerations are dictated by two concerns. The first is crew comfort and maintaining equipment within its thermal bounds. The second concern is to maintain humidity within an acceptable range. If the overall cabin atmospheric temperature drops below the local dew-point temperature, allowing water vapor to condense. Because liquid water is a significant hazard to electronics especially in weightless situations, maintaining cabin atmospheric and humidity within prescribed limits is important. Below it is reported a table with values about crew cabin thermal ranges [14].

Table 4 - Crew Cabin Thermal Ranges

Parameter	Units	Lower	Upper
Air Temperature	K	291.5	299.8
Dew-Point Temperature	K	277.6	288.7
Relative Humidity	%	25	70
Ventilation	m/s	0.076	0.347

The coolants that can be used in a heat exchanger are multiple and with different thermal characteristics. Among the various coolant liquids, water is the most appropriate coolant for the present work, because it does not present a toxicity hazard and is not irritant, besides being the best phase-change material available. Below is reported a table with the main thermal properties of some coolants.

Table 5 – Main thermal properties of some coolants

		Temperature 280 K			Temperature 300 K		
Fluid	**Hazard**	**Density** $\left[\frac{kg}{m^3}\right]$	**Specific Heat** $\left[\frac{kJ}{kg \cdot K}\right]$	**Viscosity** $\left[\frac{kg}{m \cdot s}\right]$	**Density** $\left[\frac{kg}{m^3}\right]$	**Specific Heat** $\left[\frac{kJ}{kg \cdot K}\right]$	**Viscosity** $\left[\frac{kg}{m \cdot s}\right]$
Water		1,002.08	4.204	0.00148	998.35	4.187	0.00083
60%Ethylene Glycol/40%Water	Irritant	1,083.84	3.130	0.00796	1,071.70	3.216	0.00417
Ammonia (liquid)	Toxic	628.20	4.679	0.000232	600.46	4.854	0.00021

Considering that the condensing heat exchanger object of this work is placed on board the spacecraft in which there is the presence of humans, the use of water as a cooling liquid is a constraint. In this way the previously exposed risks are avoided.

Regarding the minimum temperature that the coolant can reach (in this case water), the condensing heat exchanger is considered to be tested in European Drawer Rack (EDR), and as mentioned above, this is equipment for experiments dedicated to space research useful for reducing research costs and development times. The rack provides the accommodation and resources to test the modules, including the coolant (water) that must be used in the condensing heat exchanger. The minimum water temperature supplied by the rack cannot be lower than 16-18 °C, therefore this represents a constraint for the design of the heat exchanger.

In addition, ranges of temperature and relative humidity of the air entering the condensing heat exchanger have been chosen, considering both the values shown in Table 4 and the availability of the EDR air supply. It is considered to have an input flow at a constant flow rate of $q = 100\ l/min$ which is divided into the two parallel lines of the EDEN ISS RUCOLA system with a flow rate of $q = 50\ l/min$ per line. The values chosen are shown in the following table.

Table 6 - Input air requirements

	T_{min} [°C]	T_{max} [°C]	RH_{min}	RH_{max}
Input air	22	26	60%	80%

An important aspect for the design of the condensing heat exchanger is the cooling technology: it is possible to cool by conduction and convection of a cooling fluid that flows directly in contact with the wall of the heat exchanger or it is possible to use a thermoelectric device applied to the heat exchanger wall that allows heat transfer. Therefore, it is necessary to consider the requirements and constraints previously set out, during the phase in which the technology to be used for air cooling is chosen. This topic will be discussed in the next section. Furthermore, since the heat exchanger must be placed in a very narrow space, the geometric parameters to be respected are an external diameter of 10 cm and a total length without junctions of 20 cm.

3 Design

In order to design a heat exchanger, first of all, it is necessary to evaluate which heat transmission technology is to be used: cooling with fluid coolant or cooling by means of a thermoelectric device. After selecting the cooling technology according to the requirements and constraints previously set, it will be necessary to study the classic sizing of a heat exchanger by methods known in the state of the art and then it is possible to set up the analytical model that describes the behavior of the fundamental properties of the heat exchanger. Finally, it is possible to create the geometry of the heat exchanger using CAD software and investigate which is the best technology to achieve it. In the following paragraphs the topics previously mentioned will be discussed.

3.1 Selected Cooling Technology

To be able to choose which cooling technology is better it is necessary to investigate the types of heat exchangers and the ease of application of the cooling technologies in question. As already briefly mentioned in the previous chapter, the surface heat exchangers comprise a surface impermeable to the mass that separates the two fluids (which can be of different nature). The transmission of heat occurs by convection, between the fluids and the respective solid surfaces lapped, and by conduction through the wall of the pipe that separates them. The following is a brief classification of heat exchangers of this type to be able to investigate which could be suitable for this work. The simplest heat exchanger that uses a cooling fluid is made up of coaxial tubes in which the respective fluids pass through the smaller tube and through the annular region formed by the larger tube. The two fluids can flow in the same direction or in the opposite direction. Only in the second case the temperature of the outgoing cold fluid may be greater than the outlet temperature of the hot fluid. Another characteristic of heat exchangers with reverse flow of fluids is that the thermal power exchanged remains almost constant along the entire surface of the heat exchanger, this occurs because the temperature difference between the two fluids remains almost constant along the entire path. On the contrary, heat exchangers with flow in the same direction, have a lower thermal power exchanged near the output due to a low ΔT with respect to the portion of the duct near the inlet, where the thermal power exchanged is greater.

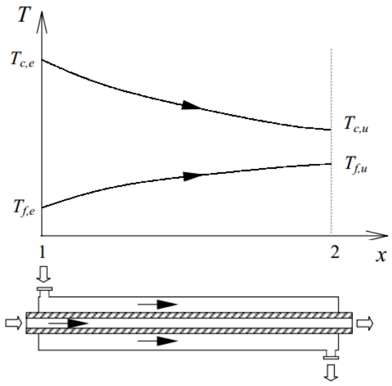

Figure 25 – Temperature difference with flow in the same direction

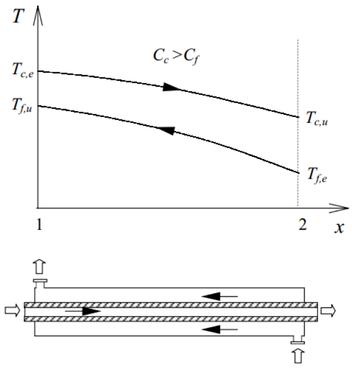

Figure 26 - Temperature difference with flow in reverse direction

The heat exchanger previously described is used mostly when the fluids in operation are both liquids. If one or both fluids are in the gaseous phase, as in the case of the condensing heat exchanger object of the present work, the most utilized heat exchangers are those in which the two fluids in exercise run through two crossing paths. In them it is possible to reduce the effect of degradation of the heat exchange due to the low thermal conductivity of the gases by increasing the exchange surface by means of fins. This type of heat exchangers must have a very high heat exchange area density, therefore it is necessary that they are very compact, only in this way it is possible to reduce the power loss due to pressure drops. Below are some geometries of cross-flow heat exchangers.

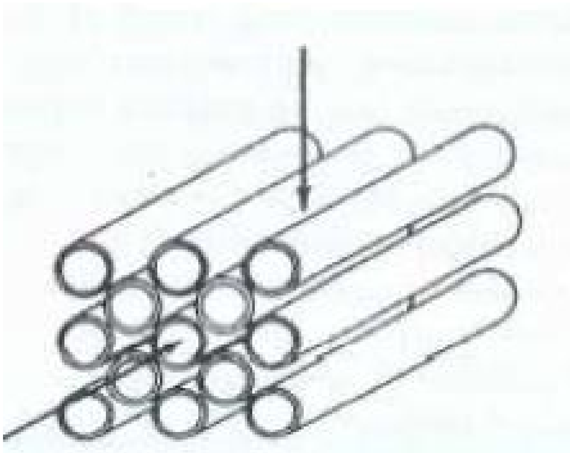

Figure 27 - Heat exchanger with bundle of tubes

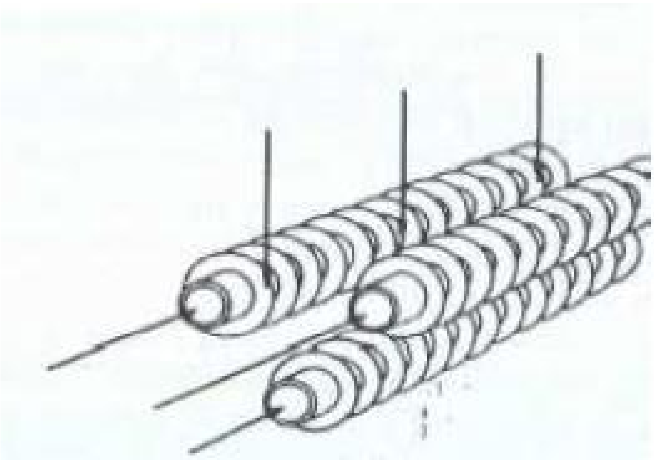

Figure 28 - Heat exchanger with fins around tubes

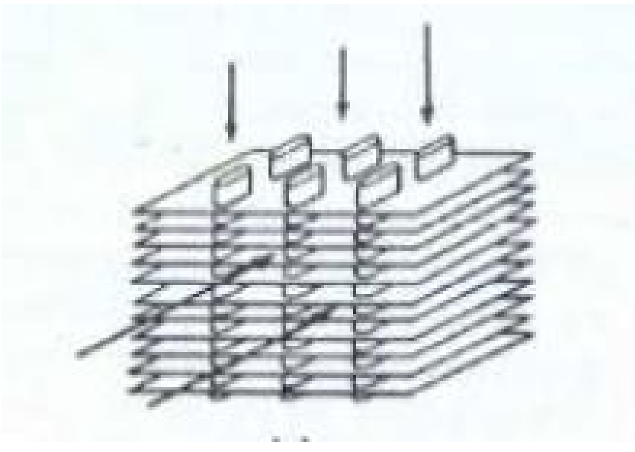

Figure 29 – Heat exchanger plane fins

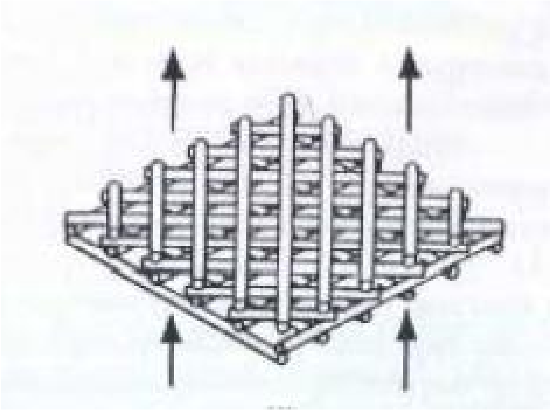

Figure 30 - Heat exchanger with matrix geometry

The geometry that could be suitable for the condensing heat exchanger object of the present work, using a coolant liquid, and therefore having the presence of two fluids of different nature, is that represented in *Figure 27*. Using a bundle of tubes, of small diameter to increase the density of heat exchange surface, through which the air, that must be condensed, passes and making the coolant (water) flow in the direction perpendicular to the tubes, it could be sized the condensing heat exchanger. But there may be some problems such as the difficulty in producing the geometry due to the small diameter of the pipes that could be solved by exploiting the additive manufacturing technology. A problem that could be of greater importance would be the temperature of the coolant used (water), on this depends the temperature of the pipe walls, through which the air to be condensed passes. As already mentioned in the paragraph relating to the constraints and requirements, the condensing heat exchanger must operate in the EDR, in which it is possible to supply water as coolant liquid at a minimum temperature of 16/18 ° C. Because of this, the choice of a heat exchanger that uses a technology with refrigerant fluid could be inefficient because the wall temperature necessary to start the condensation phenomenon could be considerably lower than that which can be reached with a liquid refrigerant at a temperature of 16/18 ° C. This depends on the properties of the incoming air that must condense. Several cases will be studied combining values of temperature and relative humidity of the incoming air chosen based on the ranges established as a requirement in Table 6. Therefore, the use of a cooling liquid technology is inefficient in this case.

Using a heat exchanger with thermoelectric unit represents a valid alternative to be able to choose the temperature to which the CHX wall must be brought. A component that can be inserted as a thermoelectric unit is the Peltier cell. It can be applied directly in contact with the geometry of the condensation heat exchanger by means of a fixing with screws, or by using a thermal paste to be able to transmit heat easily from the geometry through which the air passes (which must be cooled) towards the cell Peltier. The Peltier cell is basically a solid-state heat pump that looks like a thin plate. One of the two surfaces absorb the heat while the other one emits it. The direction in which the heat is transferred depends on the direction of the direct current applied to the ends of the plate.

Figure 31 - A common Peltier cell

A common Peltier cell is formed by two semiconductor materials, type N and type P, connected by a layer of copper. If a positive voltage is applied to the N type and a negative voltage to the P type, the upper part cools while the lower part heats up. Reversing the voltage, the thermal energy shift is reversed. There are isolated Peltier cells and non-isolated Peltier cells: the former are coated below and above with ceramic material and guarantee higher yields than the latter [15].The common use of the cell is the removal of heat by adhesion of the cold side to the body to be cooled; the removal of heat is favored by the creation of appropriate thermal bridges (thermally conductive adhesives or, for better thermal transfer, graphite sheets with thickness of some tenths of a millimeter) that allow the best conduction [16]. The stolen heat is transferred to the warm side, along with the operating heat (which is most). On the warm side heat must be transferred to the external environment.

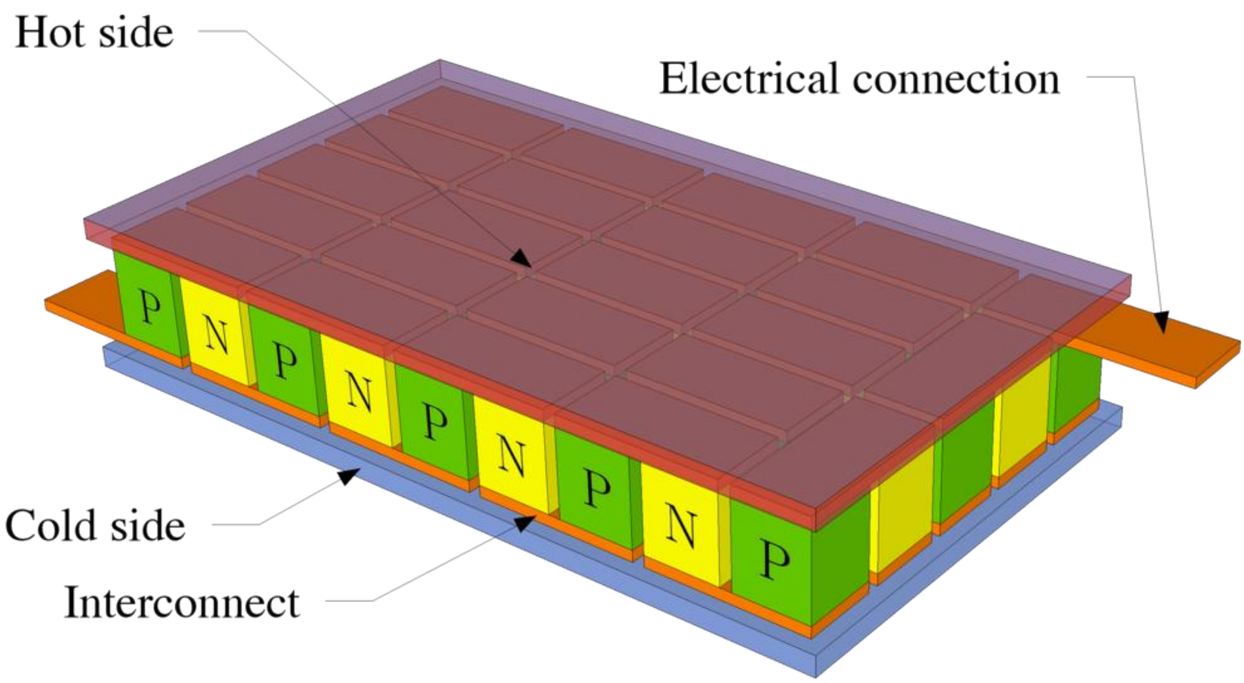

Figure 32 - Structure of a Peltier cell

Peltier cells also have some important limitations. One of these is the efficiency of the Peltier cell, which is very low: the incoming electrical energy is much greater than the thermal energy taken from the cold side or, in other words, the efficiency is low. This means that the amount of heat dissipated by the cell is much greater than the amount that can be removed from the cold side or in reverse use, only a small fraction of the thermal energy passing into the cell is actually converted into electrical energy. This limits the use of the Peltier cell to applications whose power is very low. Despite this important limitation, using the Peltier cells to cool the surfaces of the condensing heat exchanger is more convenient because in this way it is possible to have the necessary temperature of the walls to start the condensation phenomenon. Furthermore, considering the minimum water temperature limitation available in the EDEN ISS RUCOLA system, it can be exceeded by using the Peltier cell at the expense of the electrical energy used to subtract thermal energy. Therefore, the preliminary design of the condensing heat exchanger will be carried out taking into consideration the use of a Peltier cell to be able to cool the surfaces of the geometry through which the moist air to be condensed passes.

3.2 Sizing of a Standard Heat Exchanger

The purpose of this paragraph is to provide the knowledge necessary to perform both the design thermal calculation and the thermal calculation of verification of a heat exchanger with coolant fluid. The design thermal calculation has the purpose of dimensioning and appropriately choosing an exchanger that must realize the desired heat exchange between two fluids of which they are known: the mass flow rates, the inlet temperatures and a desired outlet temperature. The calculation essentially consists in selecting a type of heat exchanger and in determining the heat exchange area A necessary to obtain the desired outlet temperature. The thermal calculation of verification is performed on an existing heat exchanger of which are known: the total area of heat exchange, the mass flow rates and the inlet temperatures of the two fluids. In this case the objective is to determine the thermal power exchanged and the outlet temperatures of the two fluids. The thermal calculation of the exchangers is normally performed using the equations of equilibrium of mass and energy. These equations are normally obtained by considering heat exchangers as fully open systems, globally adiabatic. By applying the mass and energy equilibrium equations, the following formulas are obtained for the calculation of the global thermal power, W_t. In them, the subscripts h and c refer respectively to the hot and cold fluids and the subscripts i and o to the inlet and outlet section.

$$W_t = G_h(h_{h,i} - h_{h,o})$$

$$W_t = G_c(h_{c,o} - h_{c,i})$$

In the hypothesis that the two fluids have no phase changes and that the corresponding specific heats and pressures are constant, the previous equations become:

$$W_t = G_h C_{p,h}(T_{h,i} - T_{h,o})$$

$$W_t = G_c C_{p,c}(T_{c,o} - T_{c,i})$$

In the study of heat exchangers, it is useful to refer to the so-called thermal flow rate, C, given by the product between the mass flow rate and the specific heat:

$$C_h = G_h C_{p,h}$$

$$C_c = G_c C_{p,c}$$

In this case the two previous balance equations can be written in the following form:

$$W_t = C_h(T_{h,i} - T_{h,o})$$

$$W_t = C_c(T_{c,o} - T_{c,i})$$

These two energy balance equations can be combined with a heat exchange equation. The latter associates the thermal power exchanged between the two fluids at the inlet and/or outlet temperatures, at the flow rates, at the global heat transfer coefficient and at the exchange area. In the following, two different methods are presented to obtain a heat exchange equation to be associated with the two energy balance equations seen previously. The first is the logarithmic average method of temperature differences (LMTD) and the second is the $\epsilon - NUT$ method. To make use of it, it is assumed that the unitary thermal conductance remains constant along the entire wall of the exchanger. it is important to note that, having available only three independent equations (the energy balances for the two fluids and the heat exchange equation), it is possible to obtain at most three unknown variables of the exchanger between: the four temperatures, the two flow rates, the exchanged power and the exchange surface.

With the LMTD method the thermal power exchanged between the two fluids is linked to the temperature difference between the hot fluid and the cold fluid, $\Delta T = T_h - T_c$, that is:

$$W_t = UA(T_h - T_c) = uA\Delta T$$

However, since ΔT varies with the position inside the heat exchanger it is necessary to use a suitably averaged temperature difference. In the case of co-current or counter-current heat exchangers, if the wall conductance does not vary along the surface, it is possible to prove that the temperature difference to be used is the logarithmic mean between the differences existing upstream and downstream of the exchanger, obtaining the following heat exchange equation:

$$W_t = UA\Delta T_{ml}$$

Where:

- U is the overall heat transfer coefficient, $\left[\frac{W}{m^2K}\right]$;
- A is the exchange area;
- ΔT_{ml} is the average logarithmic difference in temperature and is calculated as follows.

$$\Delta T_{ml} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)}$$

$\Delta T_1 = T_{h,i} - T_{c,i}$; $\Delta T_2 = T_{h,o} - T_{c,o}$ for co-current heat exchangers;

$\Delta T_1 = T_{h,i} - T_{c,o}$; $\Delta T_2 = T_{h,o} - T_{c,i}$ for counter-current heat exchangers.

For the other types of heat exchanger, the effective average temperature difference to be used in the heat exchange equation is given by the product of that obtained as a logarithmic mean (as if it were a countercurrent exchanger) and a correction factor, F, less than one:

$$W_t = UA\Delta T_{ml}F$$

The correction factor depends on the type of heat exchanger and on the inlet and outlet temperatures of the two fluids. It is therefore plotted for each heat exchanger according to the temperatures of the two fluids. The LMTD method is used for the analysis of heat exchangers when, in addition to the inlet temperatures and flow rates of the two fluids, at least one outlet temperature is known (or when it is known, in addition to the entry and exit temperatures of the two fluids, at least one flow), and that is in the case of the design problem.

To develop the thermal calculation of verification the easiest method to use is the $\epsilon - NUT$ method. In this case, to obtain an expression of the heat exchange equation that does not include any outlet temperature, the efficiency ϵ of a heat exchanger is defined as the ratio between the thermal power effectively exchanged in the exchanger and the maximum exchangeable thermal power:

$$\epsilon = \frac{W_t}{W_{t,max}} \qquad (0 < \epsilon < 1)$$

The maximum exchangeable thermal power is that which can be achieved in an exchanger in which the fluid with the lowest thermal capacity undergoes the maximum possible temperature jump without violating the second principle of thermodynamics, and this occurs when it leaves the exchanger at a temperature equal to that of second inlet fluid. In other words:

$$W_{t,max} = C_{min}(T_{h,i} - T_{c,i})$$

This power could be obtained with a countercurrent heat exchanger with an infinite exchange surface; in this exchanger the cold fluid outlet temperature equals the hot fluid inlet temperature when $C_h > C_c$, while the outlet temperature of the hot fluid equals the cold fluid inlet temperature when $C_h < C_c$.

$$W_{t,max} = C_c(T_{h,i} - T_{c,i}) \quad \text{if} \quad C_h > C_c$$

$$W_{t,max} = C_h(T_{h,i} - T_{c,i}) \quad \text{if} \quad C_h < C_c$$

If the efficiency and the inlet temperatures of the exchanger are known, then the exchanged thermal power can be calculated using the following exchange equation:

$$W_{t,max} = \epsilon C_{min}(T_{h,i} - T_{c,i})$$

For a given type of heat exchangers it is possible to prove that the efficiency can be expressed as a function of two dimensionless parameters:

$$\epsilon = f(NUT, C)$$

where NUT is called the number of heat transfer units, defined as:

$$NUT = \frac{UA}{C_{min}} = \frac{1}{R_t C_{min}}$$

With R_t that is the total thermal resistance coefficient. C is the ratio between the thermal flow rate of the two fluids:

$$C = \frac{C_{min}}{C_{max}}$$

The efficiency of a heat exchanger can be obtained from specific diagrams (*Figure 33/34*) according to the two parameters mentioned above. The $\epsilon - NUT$ method can be applied indifferently both for design and verification calculations without requiring iterative procedures: in the first case, note ϵ, it is possible to derive NUT, from which the exchange surface is obtained, in the second known NUT, it is obtained ϵ , from which the exchanged power is determined.

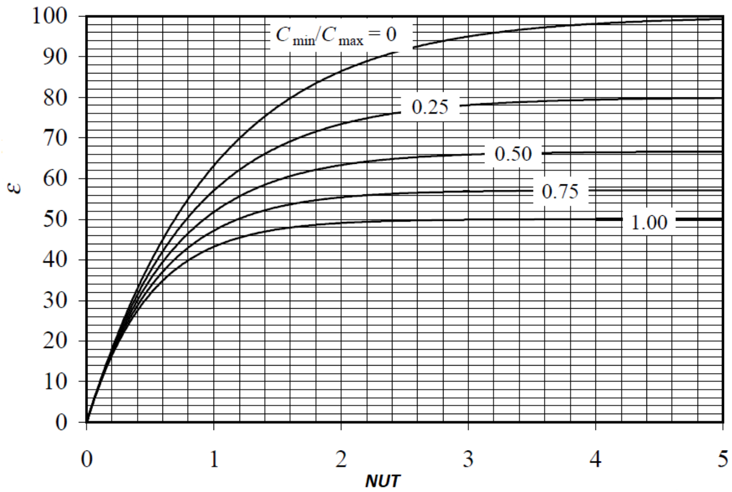

Figure 33 - Co-Current heat exchangers

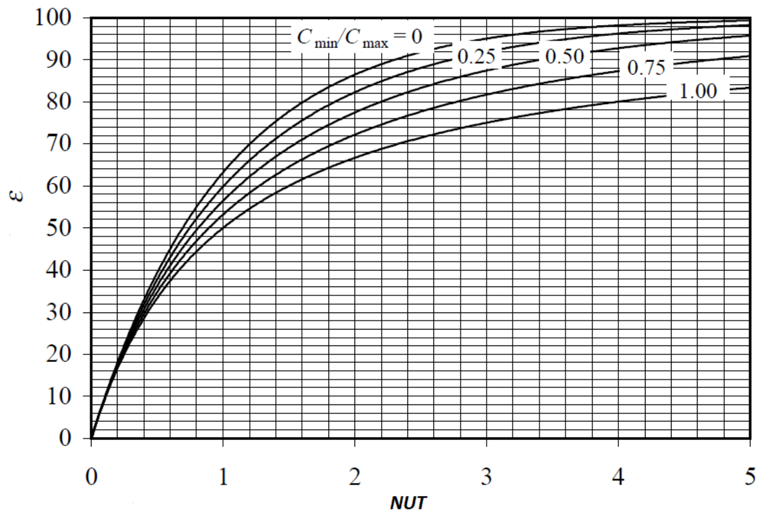

Figure 34 - Counter-Current heat exchangers

3.3 Preliminary Design

At the beginning of the preliminary design phase, the possibility of creating a condensing heat exchanger with cooling fluid was also considered. In this regard, the geometry that has been taken into consideration is similar to that represented in Figure 27, that is a geometry in linear configuration with a bank of tubes, through which the humid air to be condensed passes. The bank of tubes is enclosed within a cylinder through which the cooling fluid passes. The bank of tubes is supported by plates (in blue and red in the following figures) which allow the passage of the refrigerant fluid, so that it can be in contact with the entire bank of tubes along the entire path. In fact, the cooling fluid initially passes through the first plate (in red) to the center of the tube bank, after which it passes through the outer end crown of the tube bank formed by the blue plate.

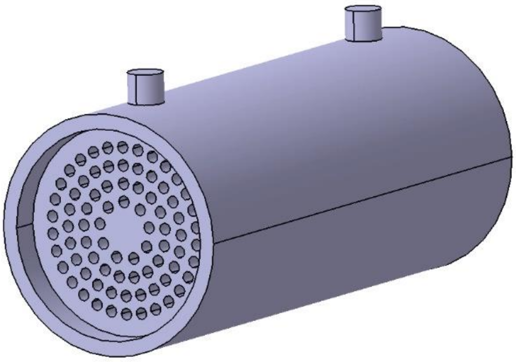

Figure 35 - 3D image of linear geometry with bundle of tubes

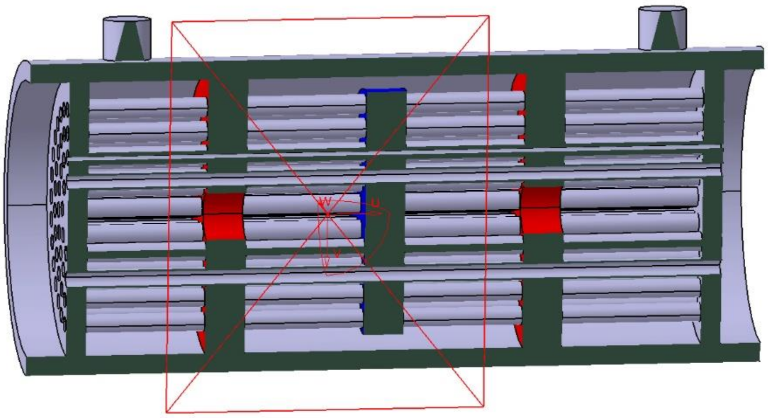

Figure 36 – Longitudinal section of linear geometry with bundle of tubes

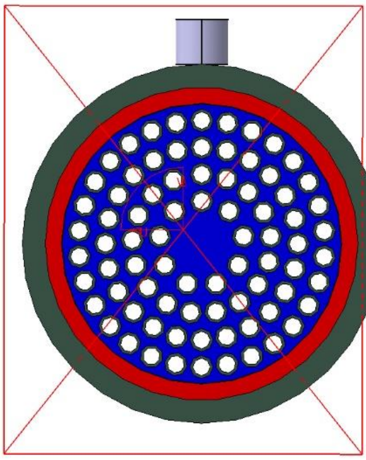

Figure 37 – Cross-section of linear geometry with a bundle of tubes

As it is possible to see from Figure 36, the coolant enters through the duct at the top right of the outer cylinder and passes through the cylinder passing through the plates that support the tubes, remaining constantly in contact with the tubes, up to the exit duct of the refrigerant fluid that is placed at the top left of the external cylinder. The two flows of fluids, air and refrigerant fluid, are crossed since two fluids of different nature are being used, and as mentioned above, the best configuration to reduce the effect of degradation of the heat exchange to the low thermal conductivity of the gases is cross-flow. Furthermore, having a fairly large number of tubes allows the heat exchange area to be increased. The problems encountered with this geometry are linked both to the constraint of the minimum temperature of the refrigerant fluid (16/18 ° C) that can be provided to the heat exchanger located inside RUCOLA, and to the geometry in linear configuration. The geometry in linear configuration, in the absence of gravity, allows the droplets of condensed water inside the tubes to move freely, and sometimes it is possible that a liquid film forms around the inner wall of the tubes which would reduce the efficiency of the condensation phenomenon, since it would add a thermal resistance between the air to be condensed and the cooling fluid. Therefore, the geometry in linear configuration with a tube bank was discarded.

Subsequently, the possibility of designing a condensing heat exchanger with thermoelectric unit was considered. As already mentioned, in this way it is possible to avoid the problem of the minimum temperature of the coolant, using a Peltier cell as a thermoelectric unit that allows to lower the temperature up to the necessary. Furthermore, as it is possible to see from the following figures, it has been considered the possibility of using a spiral geometry to increase as much as possible the length of the path that the air to be condensed must follow, keeping the space occupied in terms of volume reduced. The first spiral geometry designed has a rectangular section that follows the spiral along the entire path. The rectangular section is a multicell section with triangular cells of different sizes. The choice of a multicell section is due to the advantage of increasing the contact area and therefore the heat exchange area between the moist air to be condensed and the coolant. In this first configuration of the spiral geometry it was thought to connect the spiral through small cylinders to a larger central cylinder that extends along the axis of the spiral. It was thought to use two small Peltier cells, applying them to the upper and lower flat surface (red surfaces) of the cylinder (Figure 39). Obviously, the two Peltier cells would have been applied to the cylinder keeping in contact the cold surface of the Peltier cells with the central cylinder. In this way, the central cylinder is subjected to a lowering of the temperature which is transmitted through the cylinders to the spiral geometry, inside which the air to be condensed flows.

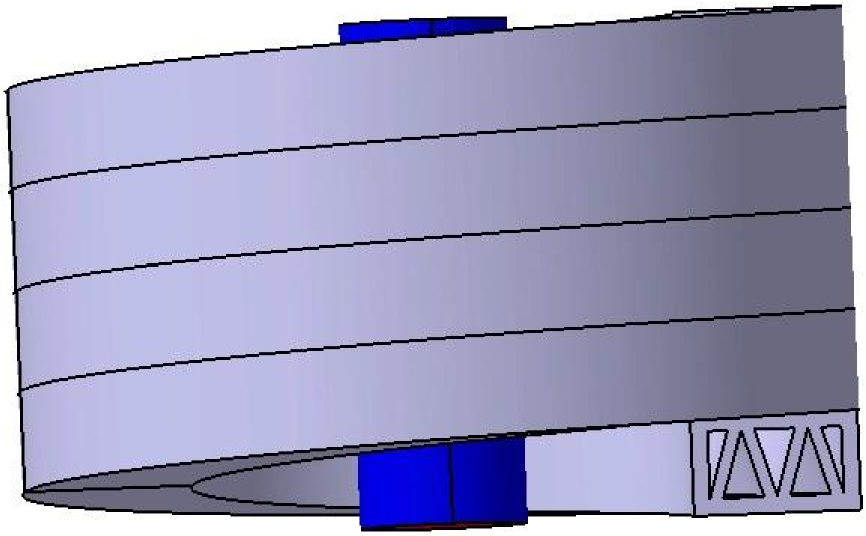

Figure 38 - First spiral geometry configuration. Side view.

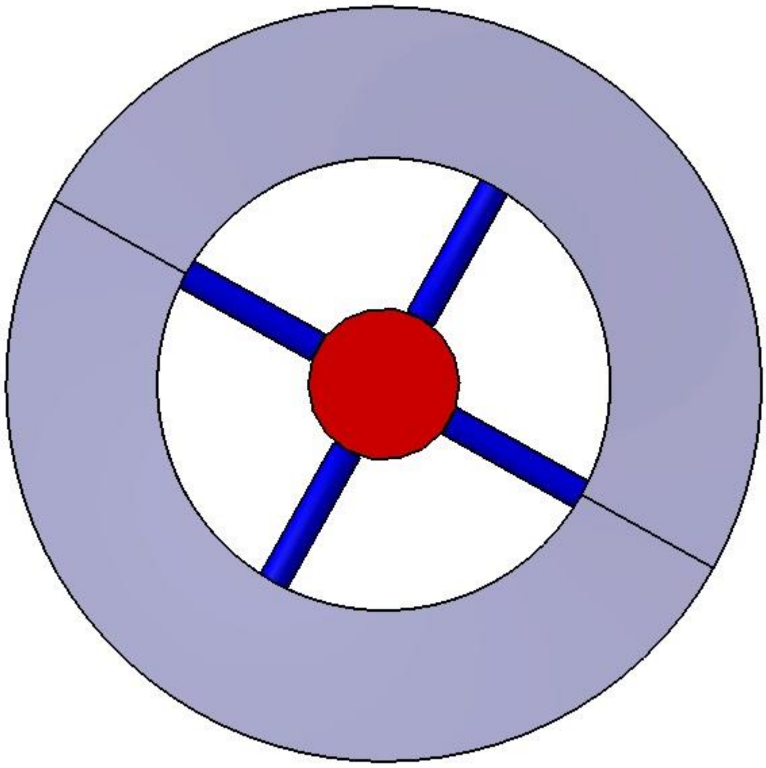

Figure 39 - First spiral geometry configuration. High view.

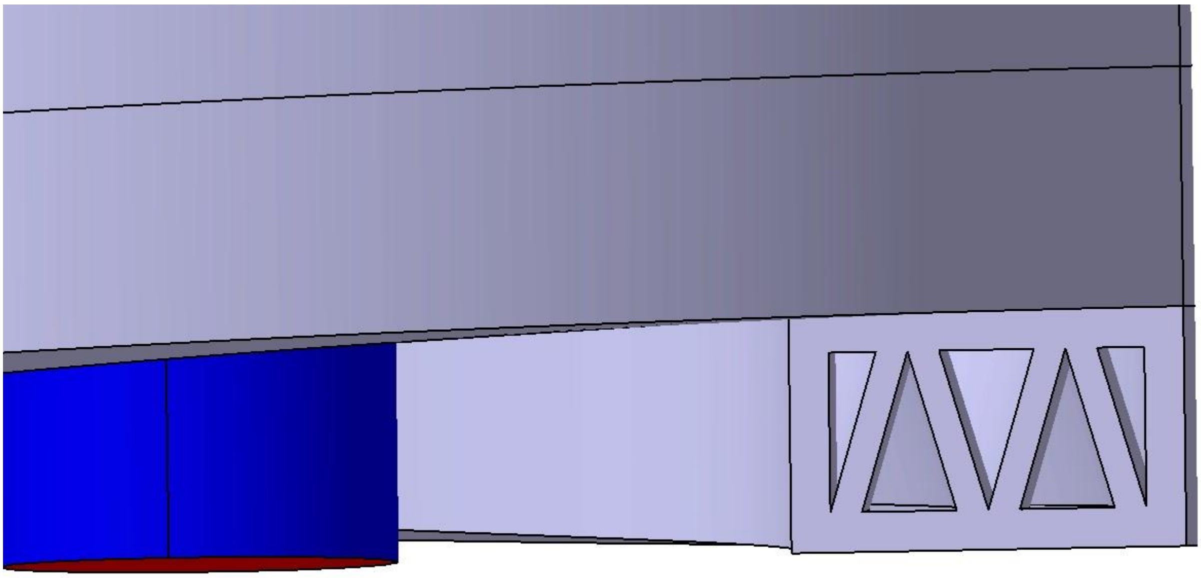

Figure 40 - First spiral geometry configuration. Detail of rectangular section

There are some improvements that have been considered for this spiral geometry configuration before being discarded:

- The first improvement that has been devised is to increase the number of cylinders that connect the central cylinder to the spiral geometry. In this way, by covering the space between the central cylinder and the spiral geometry as much as possible, increasing the number of small cylinders, the material through which the heat exchange takes place would be increased, trying to limit the dispersion and therefore the slowing down of the process of cooling down;
- With reference to the previous improvement, a more convenient configuration was envisaged from the point of view of heat transmission. It was thought to minimize the space between the central axis of the spiral configuration and the spiral itself, simultaneously increasing the width of the rectangular section that extends along the spiral. Furthermore, it was thought to apply Peltier cells (number to be defined based on subsequent thermal calculations) on an external geometry that is applied to the spiral. This external geometry has a flat surface on which the Peltier cells can be applied. In the subsequent spiral configuration, it will be possible to observe this improvement;
- Another improvement that has been thought is having the cells inside the rectangular section all with the same area. In this way the heat transmission occurs more uniformly within the rectangular section between the various ducts formed by the succession of cells along the spiral. Furthermore, having all the equal areas of the internal cells makes the calculation of the equivalent diameter easier, which will be used to perform the thermal calculations to investigate if one Peltier cell is sufficient or if it is necessary to insert more than one.

As mentioned above, in the second configuration of the spiral geometry a first improvement was made regarding the minimization of the space between the central axis of the spiral and the spiral geometry itself. The internal cells were made in a rectangular shape to increase the contact area, in addition to having increased the number of cells inside the rectangular section. The number of repetitions of the spiral pitch has been increased to reach an overall length of the geometry of about 20 cm. In this way the length of the path following the air to be condensed has been considerably increased.

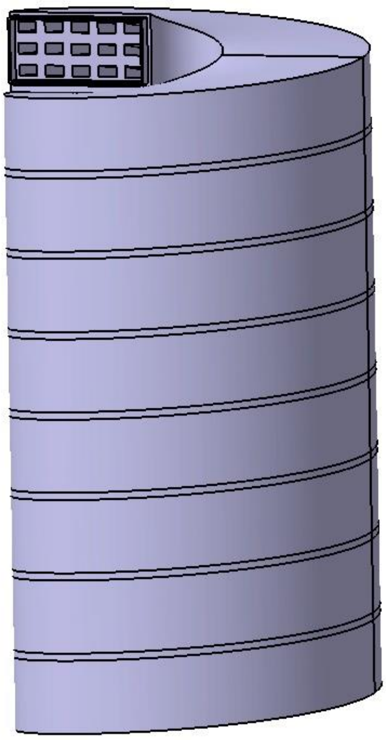

Figure 41 - Second spiral geometry configuration. Side view.

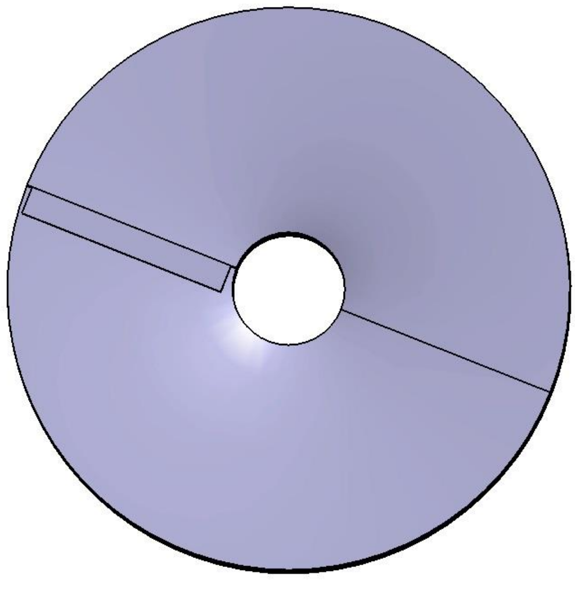

Figure 42 - Second spiral geometry configuration. High view.

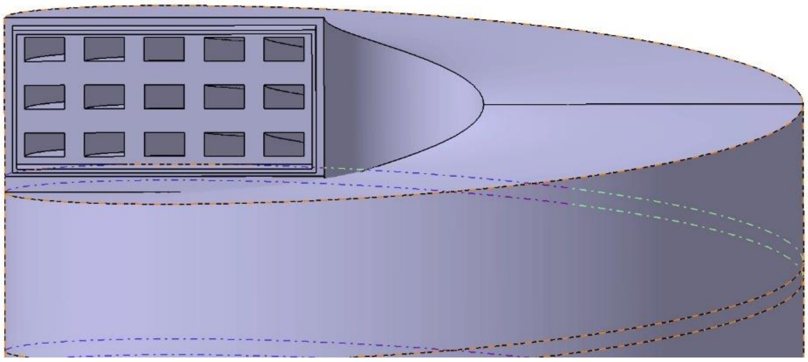

Figure 43 - Second spiral geometry configuration. Detail of rectangular section

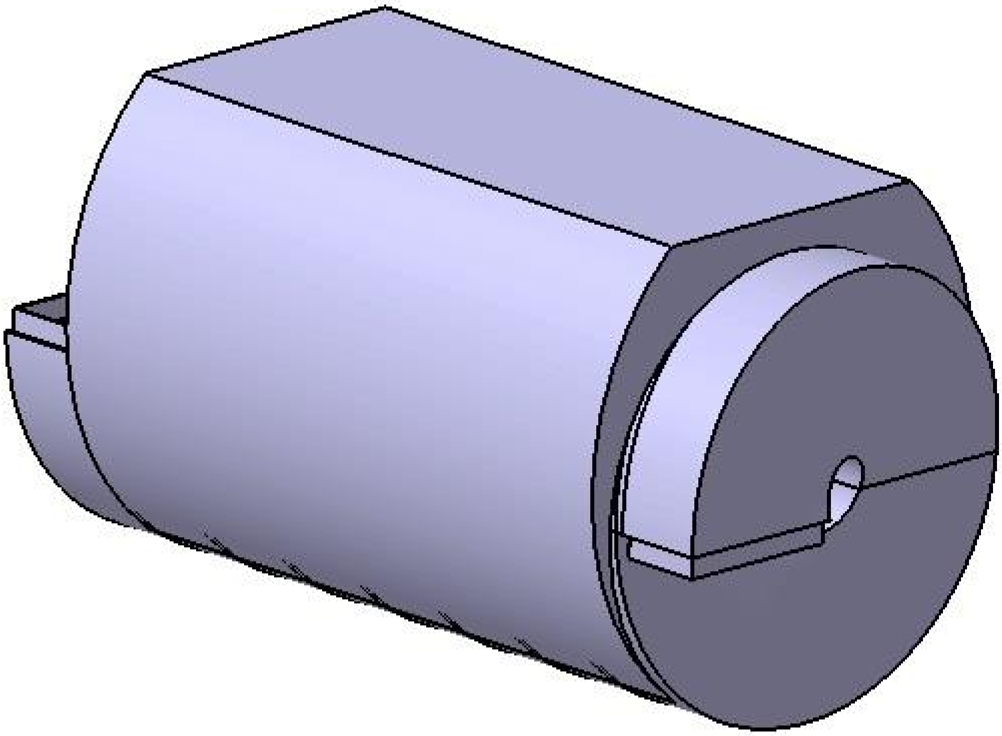

Figure 44 - Second spiral geometry configuration. Assembly with external geometry for Peltier

In the second configuration of the spiral geometry, as it is possible to see from the previous figures, a frame has been added in the rectangular input and output section, to be able to insert a tubular connector which can be connected axially with the duct through which the air flow to condense passes. Furthermore, the external geometry in which Peltier cells can be attached has been sized. In this way it is possible to transmit the subtraction of heat to the spiral geometry. Starting from this spiral configuration, it has been investigated which could be the best production technology in terms of time of realization, cost and quality. Given that this type of geometry is difficult to achieve with conventional production technologies, the possibility of exploiting additive manufacturing technology has been considered. By envisaging the use of a metallic material to realize the spiral geometry for obvious reasons of high thermal conductivity of the material, the additive manufacturing technique that has been taken into consideration is Selective laser melting (SLM). It is a rapid prototyping, 3D printing technique designed to use a high power-density laser to melt and fuse metallic powders together. To produce a component in SLM, however, some design constraints must be considered. The most important constraint to consider is to avoid flat surfaces facing down. This is because as the 3D printing takes place level by level, if the insertion of supports inside the cavities with flat surfaces facing downwards is not taken into account in the design phase, it is possible that the geometry will give way, rendering useless the work done previously. This constraint does not allow the creation of rectangular cells inside the rectangular section because internal supports would be required. These supports should then be removed, but given the shape of the geometry, their removal would not be possible. In this regard, investigating the design techniques to subsequently use additive manufacturing for production, it was announced that the production of a circular hollow duct, with a diameter not exceeding 5mm, does not require the insertion of supports. This is possible because the diameter is very small, therefore the weight weighs towards the ends of the diameter of the circular shape. Therefore, in the final configuration of the spiral geometry the shapes of the internal cells have been modified from rectangular to circular, avoiding the need for supports.

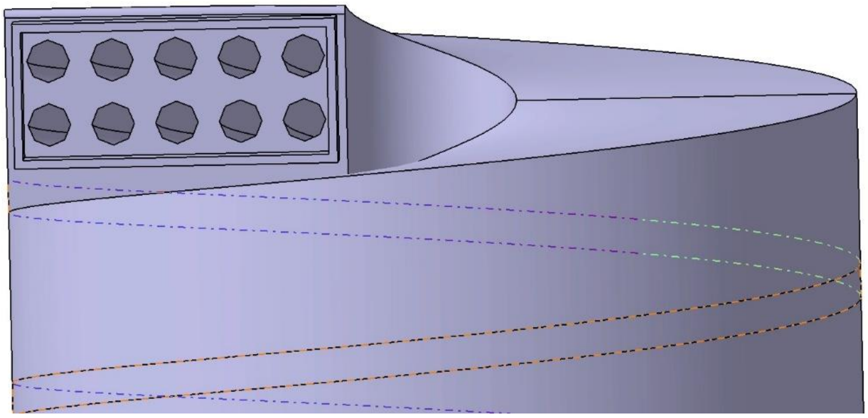

Figure 45 - Final spiral geometry configuration. Detail of rectangular section

The next paragraph shows more images of the final configuration with a detailed description.

Before moving on to detailed design, some calculations were carried out to understand whether using the final configuration of the spiral geometry would have taken only one Peltier cell or if it would have been necessary to use more than one. To understand this, it was considered a thermoelectric device with a Peltier cell and knowing which is the thermal power that can subtract this device based on the ΔT between the two sides of the Peltier cell, it was possible to understand whether using only one device would have been sufficient. That device is Direct-to-Liquid Thermoelectric Assembly DL-120-24-00-00-00.

The procedure for knowing the result is the following:

1) First of all, it is necessary to consider the ranges within which the temperature and relative humidity of the air entering the heat exchanger can vary. In this regard, several cases have been defined in combination of temperature and relative humidity of the incoming air:

    - Case A: $T_{min} = 22°C$ - $RH_{max} = 80\%$;
    - Case B: $T_{max} = 26°C$ - $RH_{max} = 80\%$;
    - Case C: $T_{min} = 22°C$ - $RH_{min} = 60\%$;
    - Case D: $T_{max} = 26°C$ - $RH_{min} = 60\%$;
    - Case E: $T_{med} = 24°C$ - $RH_{med} = 70\%$;

    The following hypotheses are considered:

    - Adiabatic transformation;
    - Dry air and water vapor are ideal gases;
    - Changes in kinetic and potential energy are negligible.

2) The next step is to calculate the dew point temperature of the air flow for each case through the psychrometric chart. The psychrometric chart indicates the properties of the air, calculated on the basis of normal atmospheric pressure $p_{atm} = 1.013\ [bar]$. For other pressure levels, appropriate

corrections must be applied. On the ordinate axis is indicated the absolute humidity in $\left[\frac{g_{H2O}}{kg_{Air}}\right]$ which indicates the mass of water vapor contained in the mass unit of dry air. On the abscissa axis we find the dry bulb temperature values $[°C]$. On inclined axes which are the oblique lines that intercept the curves, there are: specific volume $[mc/Kg]$ which is the volume occupied by the mass unit of dry air, which coincides with the specific volume of dry air. Specific enthalpy $[kj/kg]$ which is given by the sum of the individual components of dry air and water vapor. On the curves there are: hygrometric degree (relative humidity) that is the ratio between the heated steam pressure present in the mixture and the dry saturated steam pressure at the mixture temperature. Knowing the temperature and relative humidity for each case, it is possible to derive the dew temperature by moving to the horizontal on the left up to the 100% relative humidity curve.

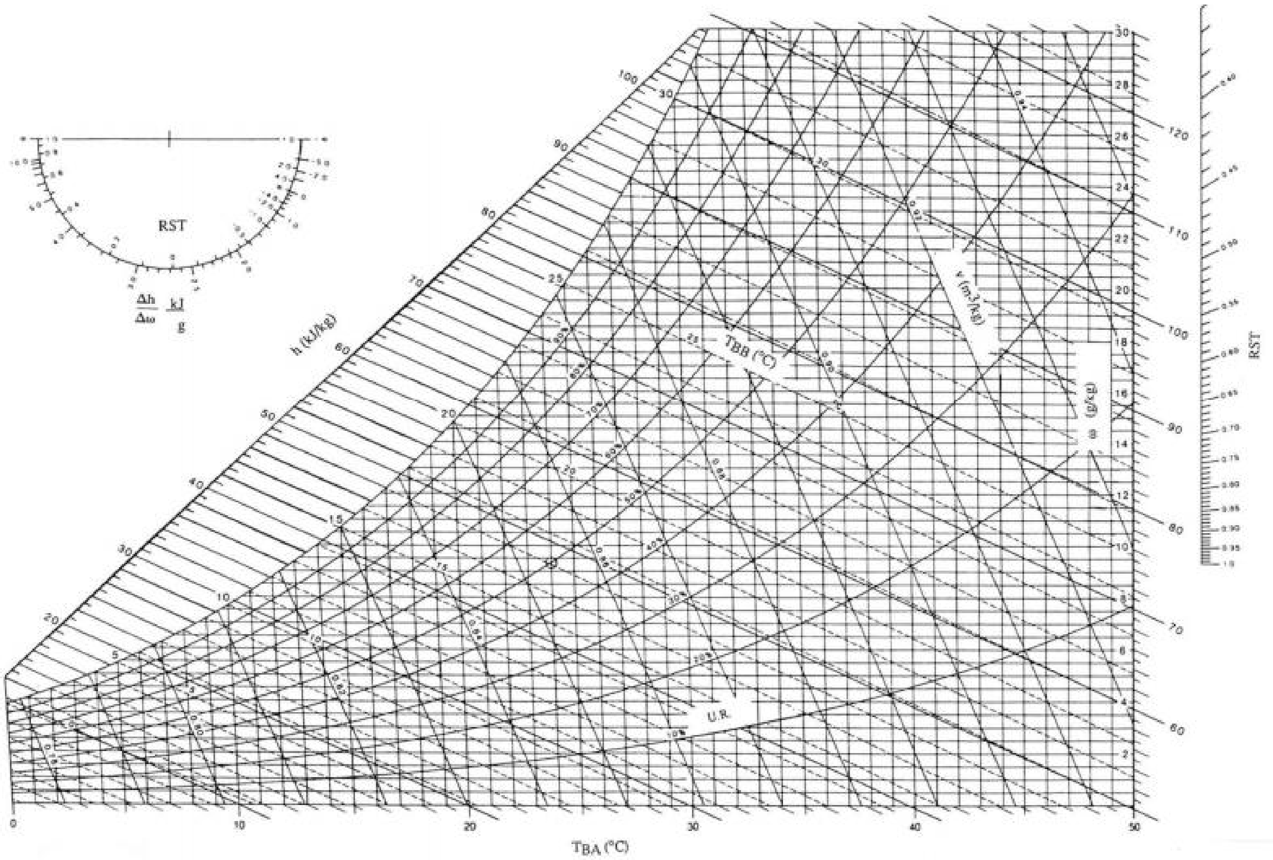

Figure 46 - Psychrometric chart

It was obtained for each case:

- Case A: $T_{dew} = 18.5°C$;
- Case B: $T_{dew} = 22.3°C$;
- Case C: $T_{dew} = 14°C$;
- Case D: $T_{dew} = 17.8°C$;
- Case E: $T_{dew} = 18.2°C$;

It is also possible to obtain the mass of water vapor contained in the mass unit of dry air X for each case:

- Case A: $X = 0.013 \left[\frac{kg_{H2O}}{kg_{air}}\right]$;
- Case B: $X = 0.017 \left[\frac{kg_{H2O}}{kg_{air}}\right]$;
- Case C: $X = 0.009 \left[\frac{kg_{H2O}}{kg_{air}}\right]$;
- Case D: $X = 0.012 \left[\frac{kg_{H2O}}{kg_{air}}\right]$;
- Case E: $X = 0.013 \left[\frac{kg_{H2O}}{kg_{air}}\right]$;

Considering an air flow rate of $q = 50 \left[\frac{l}{min}\right]$, and knowing the values of $c_{p_{air}} = 1.0045 \left[\frac{kJ}{kg \cdot K}\right]$ and $\rho_{air} = 1.20 \left[\frac{kg}{m^3}\right] = 0.0012 \left[\frac{kg}{l}\right]$, the mass of air delivered in an hour is:

$$m_{air} = 50 \left[\frac{l}{min}\right] \cdot 60 \left[\frac{min}{h}\right] \cdot 1[h] \cdot 0.0012 \left[\frac{kg}{l}\right] = 3.6\ [kg]$$

The amount of heat that is necessary to subtract to bring the air to the desired temperature is calculated for each case considered as:

$$Q = m_{air} \cdot c_p \cdot \Delta T$$

- Case A: $Q = 3.6[kg] \cdot 1.0045 \left[\frac{kJ}{kg \cdot K}\right] \cdot (291.7 - 295)[K] = -12.6[kJ]$;
- Case B: $Q = 3.6[kg] \cdot 1.0045 \left[\frac{kJ}{kg \cdot K}\right] \cdot (295.5 - 299)[K] = -13.4[kJ]$;
- Case C: $Q = 3.6[kg] \cdot 1.0045 \left[\frac{kJ}{kg \cdot K}\right] \cdot (287.2 - 295)[K] = -28.9[kJ]$;
- Case D: $Q = 3.6[kg] \cdot 1.0045 \left[\frac{kJ}{kg \cdot K}\right] \cdot (291 - 299)[K] = -29.7[kJ]$;
- Case E: $Q = 3.6[kg] \cdot 1.0045 \left[\frac{kJ}{kg \cdot K}\right] \cdot (291.4 - 297)[K] = -21[kJ]$;

Making the conversion from $[kJ]$ to $[W \cdot h]$ of the heat exchanged, it is possible to calculate the thermal power to be subtracted to reach the dew point temperature for each case by dividing by time (1 hour).

- Case A: $Q = -13\ [kJ] = -3.5\ [W \cdot h]$;
- Case B: $Q = -13[kJ] = -3.7\ [W \cdot h]$;
- Case C: $Q = -29\ [kJ] = -8\ [W \cdot h]$;
- Case D: $Q = -30\ [kJ] = -8.2\ [W \cdot h]$;
- Case E: $Q = -21\ [kJ] = -5.8\ [W \cdot h]$.

- Case A: $\dot{Q} = -3.5[W]$;
- Case B: $\dot{Q} = -3.7\ [W]$;
- Case C: $\dot{Q} = -8\ [W]$;
- Case D: $\dot{Q} = -8.2\ [W]$;
- Case E: $\dot{Q} = -5.8\ [W]$.

3) Being known:

- The necessary thermal power exchanged for each case;

- The coefficient of thermal conductivity of aluminum $\lambda_{Al} = 290 \left[\frac{W}{m \cdot K}\right]$;
- The dew point temperature to which the flow of air passing inside the geometry is to be brought to bring about the phenomenon of condensation;
- The convective heat transfer coefficient of the air, for forced convection $h_{air} = 100 \left[\frac{W}{m^2 \cdot K}\right]$;
- The internal and external rays of the duct that are calculated starting from the internal and external equivalent diameter as: considering $N_c = 10$ ducts with a circular section of internal radius $r_i = 2.5\ [mm]$, the equivalent area is calculated as $A_{eq_{int}} = N_c \cdot \pi \cdot r_i^2$ from which it is possible to calculate the equivalent internal diameter $D_{eq_{int}} = \left(A_{eq_{int}} \cdot \frac{4}{\pi}\right)^{0.5} = 0.0158\ [m]$. Regarding the external equivalent diameter, it is calculated considering a rectangular profile of the duct from which it is derived $A_{eq_{ext}} = 40 \cdot 20\ [mm^2]$, $D_{eq_{ext}} = \left(A_{eq_{ext}} \cdot \frac{4}{\pi}\right)^{0.5} = 0.0319\ [m]$.
- The length of the equivalent cylindrical duct that is calculated unrolling in a plane the cylinder formed by the spiral line. A line winding corresponds to the hypotenuse of a right-angled triangle that has cathets $2\pi r$ and H, in which $H = 24\ mm$ is the pitch of the spiral and $r = 30\ mm$ is the distance from the axis of the spiral to the central point of the rectangular section that develops in a spiral. The number of windings that form the spiral is $n = 7.5$. Finally, the total length of the unrolled spiral is calculated as $L = \sqrt{(2\pi r)^2 + H^2} \cdot n = 1.42\ [m]$.

It is possible to calculate the total thermal resistance which is the sum of the conductive thermal resistance due to the material of which the geometry is made and the convective thermal resistance due to the air flow moving inside the duct as:

$$R_{tot} = \frac{1}{2 \cdot \pi \cdot r_{int} \cdot L \cdot h_{air}} + \frac{\ln\left(\frac{r_{ext}}{r_{int}}\right)}{2 \cdot \pi \cdot L \cdot \lambda_{Al}} = 0.142 \left[\frac{K}{W}\right]$$

Now it is possible to calculate the temperature value to which the duct wall must be brought so that the air can be brought to the dew temperature:

$$\dot{Q} = \frac{(T_w - T_{dew})}{R_{tot}}$$

$$T_w = \dot{Q} \cdot R_{tot} + T_{dew}$$

- Case A: $T_w = -3.5 \cdot 0.142 + 291.7 = 291\ [K] = 18°C$;
- Case B: $T_w = -3.7 \cdot 0.142 + 295.5 = 295\ [K] = 21.7°C$;
- Case C: $T_w = -8 \cdot 0.142 + 287.2 = 286\ [K] = 12.86°C$;
- Case D: $T_w = -8.2 \cdot 0.142 + 291 = 290\ [K] = 16.6°C$;
- Case E: $T_w = -5.8 \cdot 0.142 + 291.4 = 290\ [K] = 17.4°C$.

4) Knowing that the thermoelectric unit uses a cooling fluid for heat exchange which, as previously stated, can be at least 16/18 ° C and therefore is assumed to be equal to $T_f = 18°C$, it is possible to calculate the temperature jump on the Peltier cell and consequently, through the graph provided by the datasheet of the thermoelectric unit, the available exchangeable power of the thermoelectric unit is obtained:

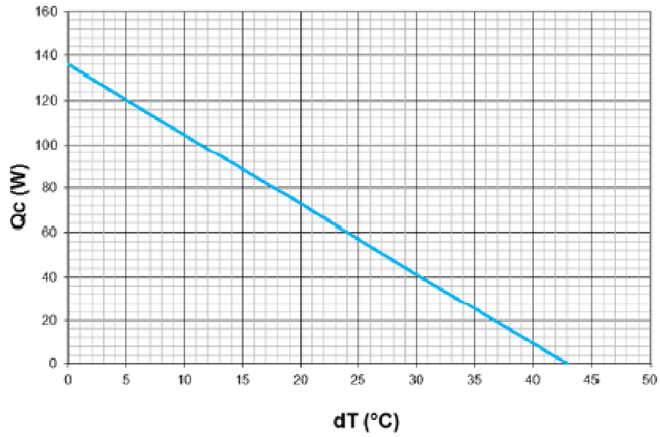

Figure 47 -Exchangeable thermal power vs. temperature jump of the thermoelectric unit

Table 7 - Final results of thermal calculations for Peltier cell

	ΔT [$°C$]	Thermoelectric unit exchangeable thermal power [W]	Thermal power needed [W]	Margin
Case A	0	135	3.5	131.5
Case B	-3.7	135	3.7	131.3
Case C	5.1	120	8	112
Case D	1.4	132	8.2	123.8
Case E	0.6	134	5.8	128.2

Therefore, it is possible to affirm that, considering the final configuration of the spiral geometry with the geometric parameters previously exposed during the calculations, only one thermoelectric unit with a Peltier cell is sufficient in all cases to allow the condensation phenomenon within the geometry of the heat exchanger.

3.4 Detail Design

In this paragraph the final geometric configuration chosen for the production will be described. Starting from the detailed description of the rectangular section (detail in the following image) which includes the 10 circular ducts, and which develops in a spiral, it is possible to highlight that the horizontal side is 40mm while the vertical 20mm. The ducts inside the rectangular section all have the same diameter equal to 5mm. This is because, as mentioned above, in order to take advantage of the SLM additive manufacturing technique and avoid the creation of internal supports in hollow sections, it is necessary that the duct diameter does not exceed 5 mm. The first row (top) of ducts is placed at a distance of 6.25mm from the top horizontal side of the rectangular section. The second row (bottom) of ducts is placed at a distance of 6.25mm from the lower horizontal side of the rectangular section. Therefore, the distance between the two rows of ducts measured from center to center of the circumferences is 7.5mm. The first ducts to the left of the two rows are placed at 5mm from the left vertical side of the rectangular section. Similarly, the last ducts to the right of the two rows are placed at 5mm from the right vertical side of the rectangular section. The ducts are 7.5mm apart from each other. All previously reported distances are measured from the center of the circular duct. From the rectangular input and output section two frames are designed, useful to be able to connect a junction that connects the CHX with the main duct on which the inlet air flow (near the inlet section of the CHX) and the mixed air/water flow (near the outlet section) flows.

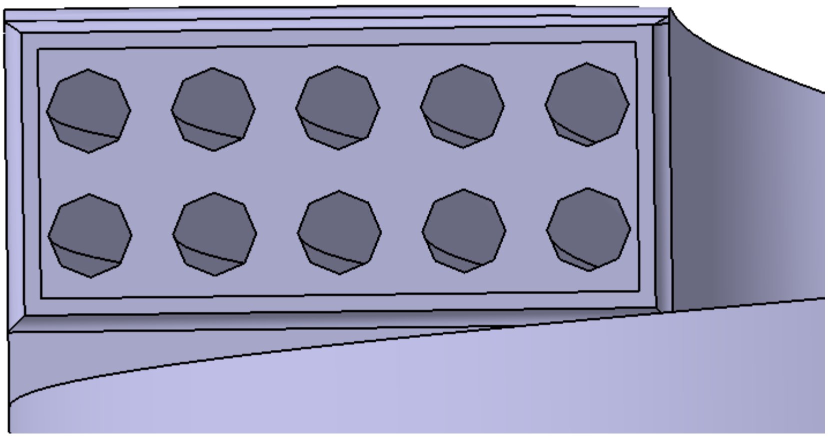

Figure 48 - Rectangular section detail

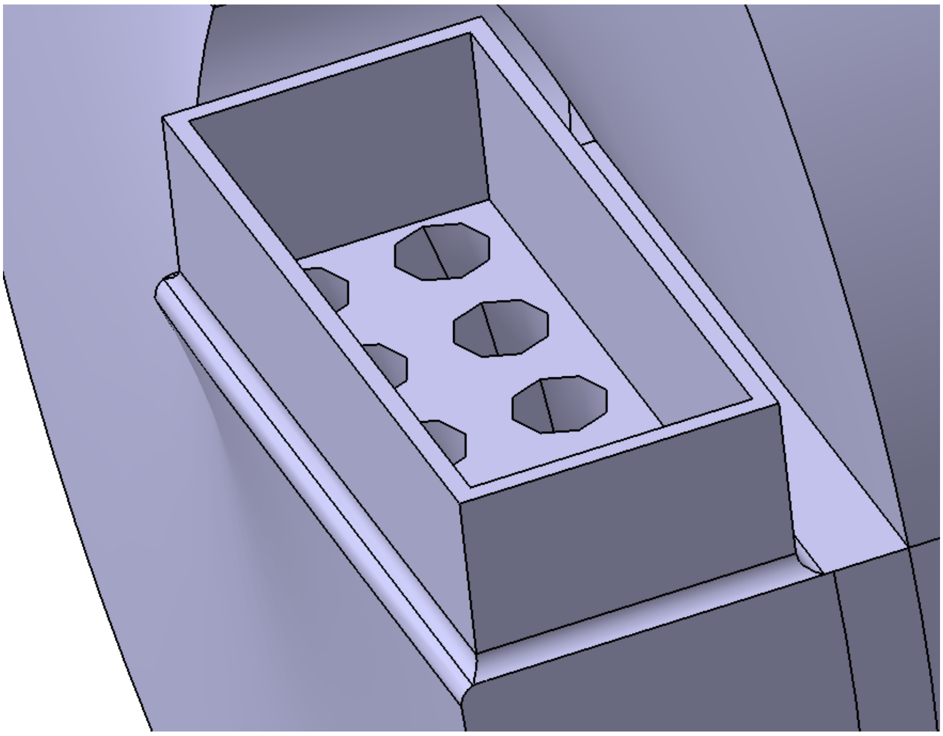

Figure 49 - Rectangular section frame detail

As already mentioned, the rectangular section develops along a spiral and more precisely the center of the rectangular section describes the development of the spiral line. The turns in which the spiral develops are 7.5 to have the rectangular inlet and outlet section on the same plane and facing the same side. The pitch of the spiral is 24mm and considering the measures of the rectangular section previously reported, the total length of the geometry is 200mm. Therefore, the constraint of the maximum CHX length of 20cm was respected.

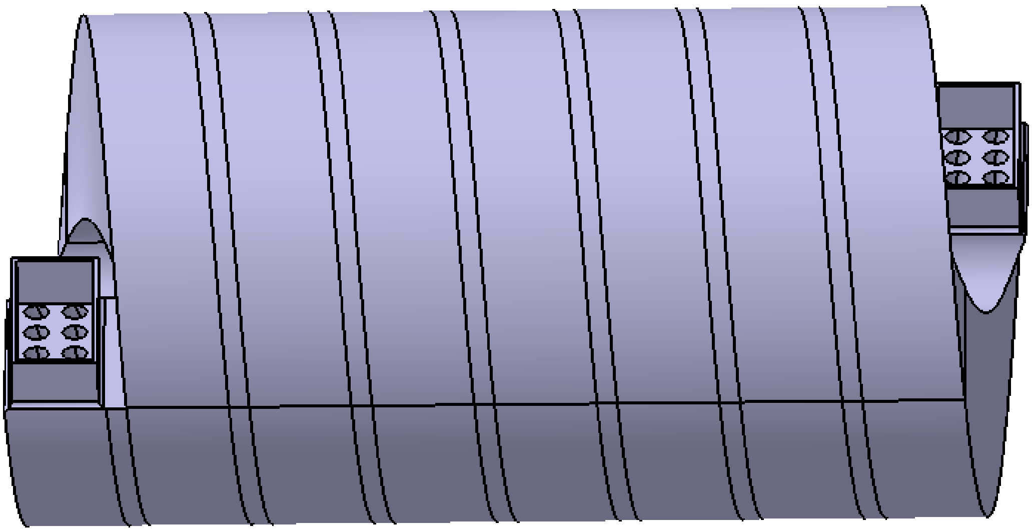

Figure 50 - Rectangular section development along the spiral

Considering the dimensions of the rectangular section, it is necessary to have a certain space at the center of the geometry, in such a way as not to intersect the geometry that develops in a spiral with itself. The central hollow space of the geometry is 2 cm. Therefore, the total diameter of the CHX is 10cm.

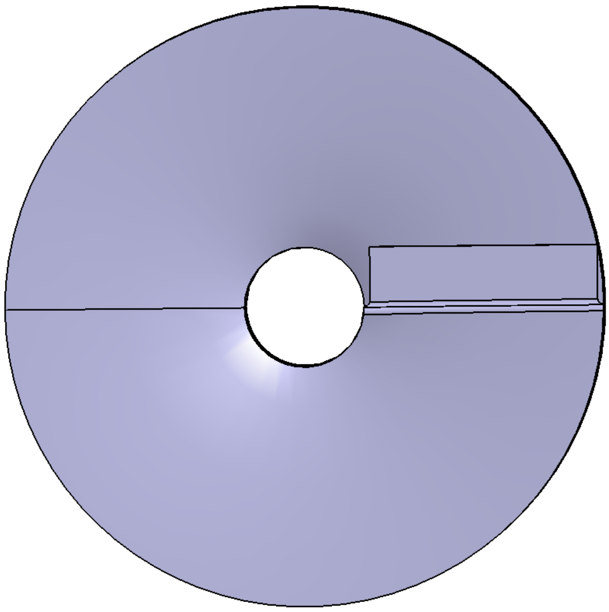

Figure 51 - Front view of the CHX

To be able to fix the thermoelectric unit with Peltier cell to the spiral geometry of the CHX it is necessary to arrange the CHX of a flat surface. As seen in the previous paragraph, a geometry has been designed that covers the CHX spiral with a flat wall in order to fix the thermoelectric unit. On the flat surface there are 3 holes with a 4mm diameter that could be used for the fixing components (screws) of the thermoelectric unit with the CHX. If the screws are used as fixing components, the 3 holes with a 4mm diameter on the flat surface must be tapped to be able to tighten M5 screws as shown in the datasheet of the thermoelectric unit. An alternative for fixing the thermoelectric unit to the CHX geometry could be to use thermal adhesive paste that would allow a quite high thermal conductivity, without using mechanical fixing elements. Obviously, the external geometry with flat surface and the geometry of the CHX are assembled in the CAD design phase, so as to be able to present a unique geometry to be produced using the Additive Manufacturing technique. Moreover, it is possible to underline that the thickness of the flat surface is 8mm, so that in the case of fixing screws are used, it is possible to screw them up to such a length that to be able to guarantee the fixing between CHX and thermoelectric unit.

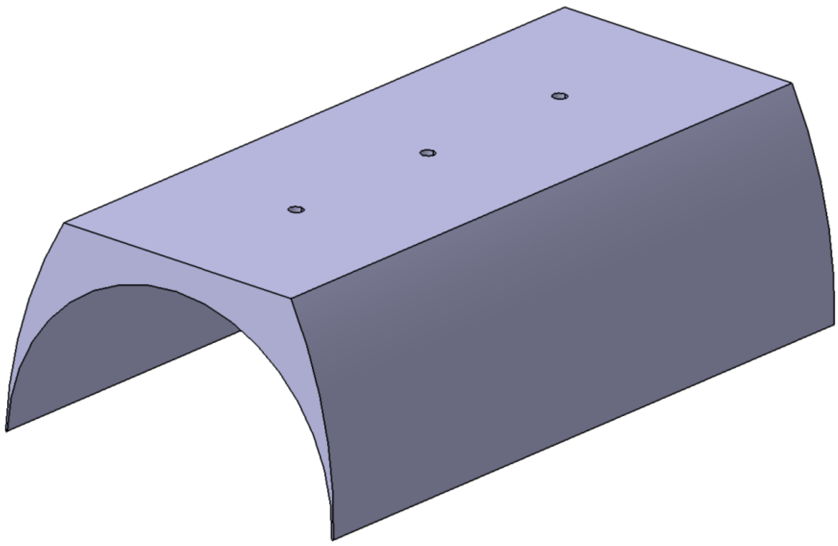

Figure 52 - External CHX geometry with flat surface.

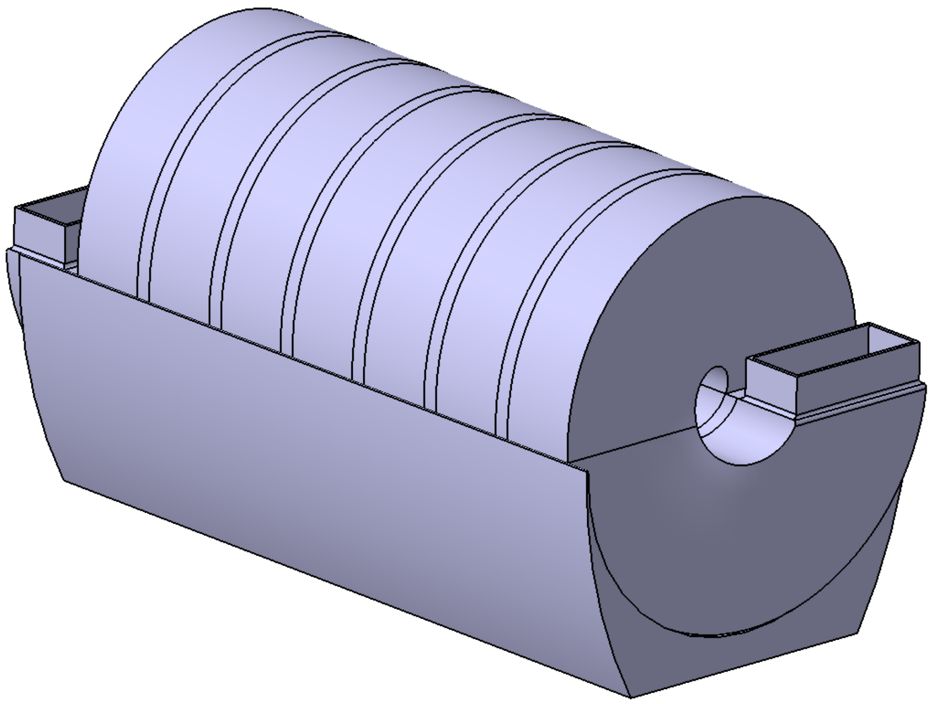

Figure 53 - Assembly of external geometry with flat surface and spiral geometry

As mentioned above, in order to be able to connect the CHX geometry to the tubes in which the fluid flows, it was necessary to design a fitting as a junction. The junction has the suitable dimensions to be able to fit with the outgoing frame from the rectangular input and output sections of the CHX. The angle of the junction is 90°, to have parallelism between the direction in which the fluid flows in the pipes and the axis around which the spiral geometry develops. The junction obviously begins with a rectangular geometry and then converges in a circular section to facilitate the connection between the tubes and the junction. The outer diameter of the circular section of the joint is 10mm because the diameter of the tubes used to perform the test on the test bench is the same. Obviously, it is possible to vary the outer diameter of the circular section, reproducing only the junction, to be able to adapt the CHX to different cases with different tubes.

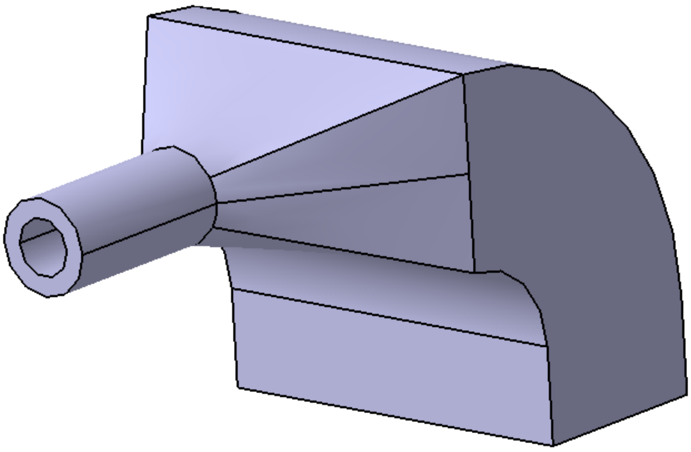

Figure 54 – Junction

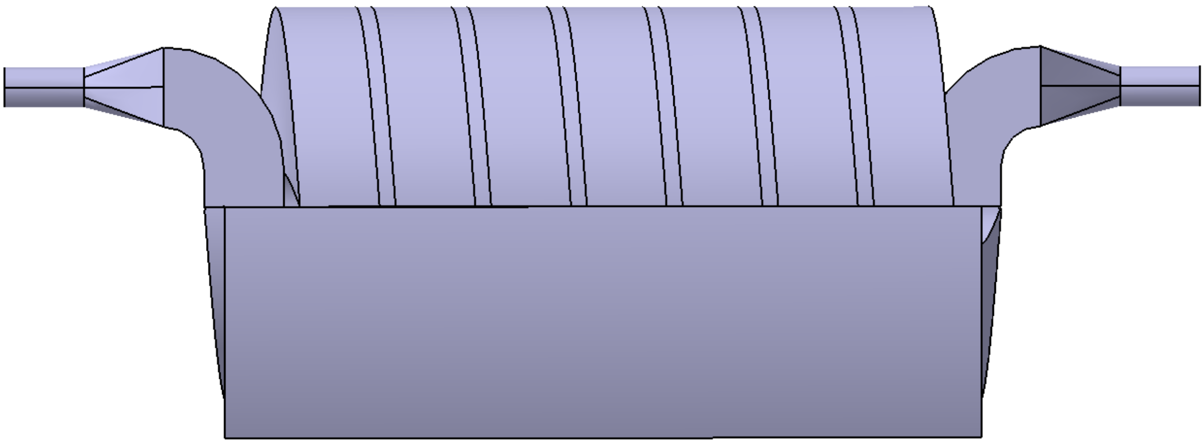

Figure 55 - Final assembly configuration. Side view

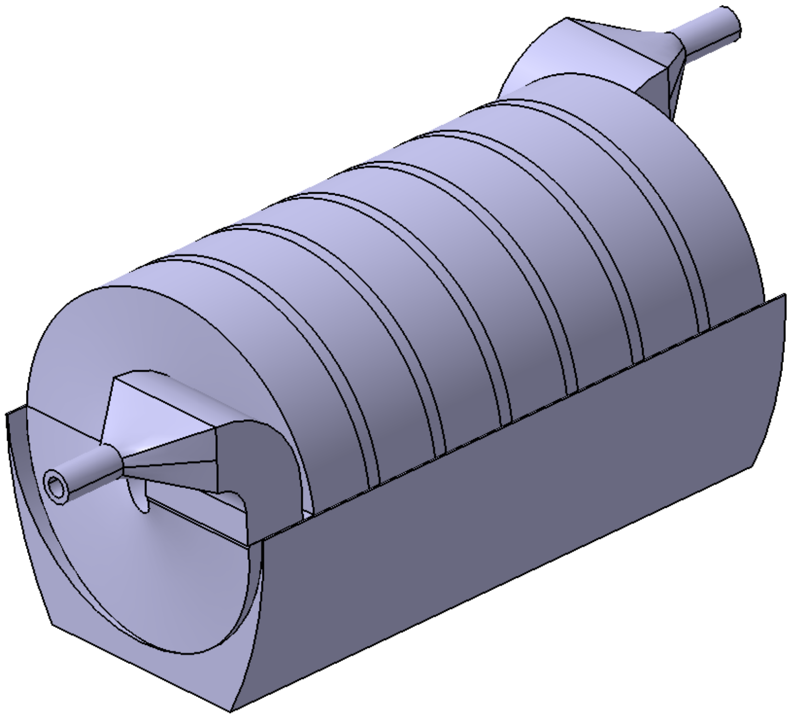

Figure 56 - Final assembly configuration. Isometric view

The total length of the final assembly configuration including the two junctions is 30cm.

To validate the calculations made in the previous paragraph, which state that only one thermoelectric device is sufficient to subtract the thermal power necessary to occur condensation, a simplified geometric model of the CHX on ESATAN-TMS (ESA Thermal Analysis Network-Thermal Modelling Suite) has been implored, so as to simulate the thermal process and to predict from which point of the CHX the condensation begins. ESATAN, developed by ITP Aero under ESA contract, is the most used numerical simulation package in Europe and it is composed of many components based on the type of analysis to be performed. In this case, to perform the thermohydraulic analysis of the CHX, it has been used ESATAN FHTS that is an extension with the ability to provide a steady state and transient analysis solving for pressure, mass flow rate and temperature in the fluid loop and for temperature in the thermal model. The code implemented on ESATAN to simulate the various cases considered in the calculations in the previous paragraph was performed by Thales Alenia Space. The CHX model implemented on ESATAN is a simplified model that can be summarized as a circular duct with internal diameter of $0.0158\, m$ and an area of $0.0002\ m^2$. The length of the duct is $1.42\, m$. The surface roughness of the duct in contact with the fluid was set at $2.9 \cdot 10^{-7}$. Furthermore, the duct has been divided into 7 stations, so that it can be understood at which station the condensation starts by analyzing the data that is supplied in output. For each simulated case, the different input data are specific humidity, temperature, power applied through the thermoelectric unit (TEC) to the duct. Dividing the duct into 7 stations, the criteria used to validate the calculations carried out previously is to start the condensation phenomenon in the first 15% of the duct, which corresponds to having relative humidity close to 100% already in the first station. Therefore, it is expected a similar output data for each simulation on ESATAN. In this way, 85% of the duct corresponds to a useful length to continue the condensation phenomena. Since the power required to start the condensation previously calculated for each case is the power referred to the entire length of the CHX duct, to be able to condense at the first station, this power must be multiplied by 7 (number of stations). Therefore, for each simulated case, the necessary power calculated previously multiplied by 7 was entered as input. The pressure set for each simulated case is equal to the ambient pressure $p = 101325\, Pa$. The input data for each case are shown in the following table.

Table 8 - Input data for simulation in ESATAN FHTS

	Specific Humidity [gv/Kga]	Volumetric Flow Rate [l/min]	Mass Flow Rate [Kg/s]	Source Temperature [°C]	Power applied via TEC [W]
Case A	13	50	10^{-3}	22	-24.5
Case B	17	50	10^{-3}	26	-26
Case C	9	50	10^{-3}	22	-56.3
Case D	12	50	10^{-3}	26	-57.7
Case E	13	50	10^{-3}	24	-40.8

The data that the simulation in ESATAN provides for each case are the relative humidity and source temperature in each station of the duct model. Below is the table with the output data for each case calculated in the first station.

Table 9 - Output data from ESATAN FHTS simulations

	First Station of the duct	
	Source Temperature [°C]	Relative Humidity [%]
Case A	18.5	97
Case B	22	99
Case C	14	90
Case D	18	94
Case E	18	98

As it is possible to see from *Table 9*, in any case the relative humidity of the air flow is greater than or equal to 90% already at the first station. In cases A, B and E it reaches almost 100% as was foreseen by the previous thermal calculations. In cases C and D, which are the worst cases due to the combination of temperature and relative humidity of the incoming air, a percentage close to 100% is not reached at the first station, but immediately afterwards. Observing the following graph which relates the temperature of the wall to trigger the condensation phenomenon, previously calculated, and the temperature reached by the fluid at the first station, it can be noted that only in cases C and D they differ slightly. In cases A, B and E the temperature between fluid and wall is almost identical. This confirms the high relative humidity value close to 100% and the correctness of previous thermal calculations.

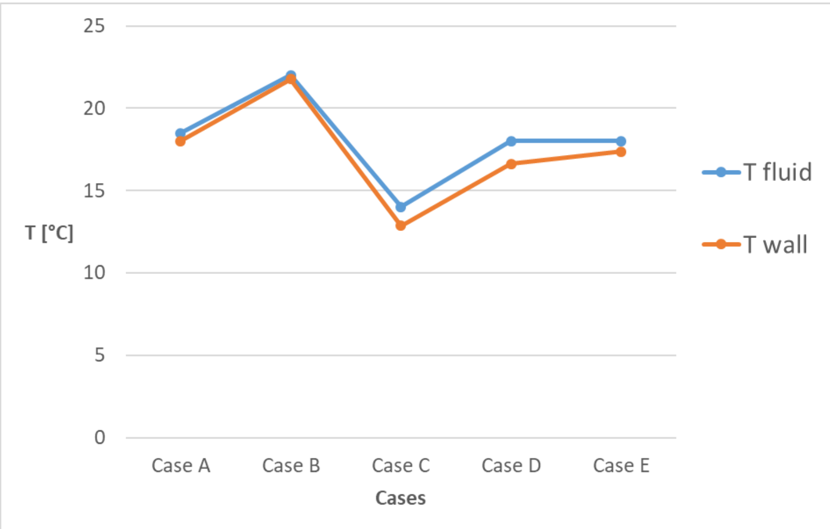

Figure 57 - Wall and fluid temperature comparison at the first station

3.5 Production Technology

To be able to produce a component with spiral geometry and internal ducts it would not be possible to use conventional production technologies, given the complexity in terms of production of the geometry itself. An alternative could be to make the geometry modular and simplify the work in terms of production to be able to use conventional techniques, but nevertheless it would not be easy to produce the geometry object of the present thesis work. For this reason, it was decided to design the geometry to be able to carry it out using innovative techniques such as 3D printing in additive manufacturing. The aerospace, medical and automotive industries have already successfully implemented additive technologies in their production systems, not only in the now consolidated polymer industry, but lately also in the metal sector. In order to exploit the great potential and advantages of this production technique, a digital 3D model is required. After being designed using dedicated CAD software, it is processed to be built layer by layer through a 3D printer. There are different technologies for 3D printing and their main differences concern the way in which the layers are printed. Some methods exploit the heat produced by radiation from an electromagnetic radiation source or from an electron beam to melt or sinter different materials (selective laser melting SLM and fused deposition modeling FDM). Other methods use different technologies to harden liquid materials that are deposited layer by layer. Each method has advantages and disadvantages which mainly depend on the type of material to be used and consequently on the type of printing process. The main factors taken into consideration are the speed, the cost of the printed prototype, the cost of the 3D printer, the choice of materials, the colors available, etc. The techniques that were most taken into consideration for the design and consequently the production of the CHX are SLM and FDM [21].

Fused deposition modeling techniques:

The FDM works on an "additive" principle releasing the material on layers. A plastic filament or a metal wire is unwound from a coil, which supplies the material to an extrusion nozzle, with which it is possible to manage the flow. The nozzle is heated to dissolve the material and can be guided both in a horizontal and vertical direction by a numerical control mechanism, then following a path traced by a CAM software. The most known polymers that are used with the FDM method are PLA (Polylactic acid) and ABS (Acrylonitrile butadiene styrene). The PLA is normally extruded at a melting temperature varying between 180 ° C and 220 ° C, while the ABS between 220 ° C and 250 ° C. Unlike ABS, PLA does not emit potentially harmful fumes when melted and extruded. Objects molded in ABS are less fragile, more resistant to high temperatures and more flexible than objects molded in PLA. [22]

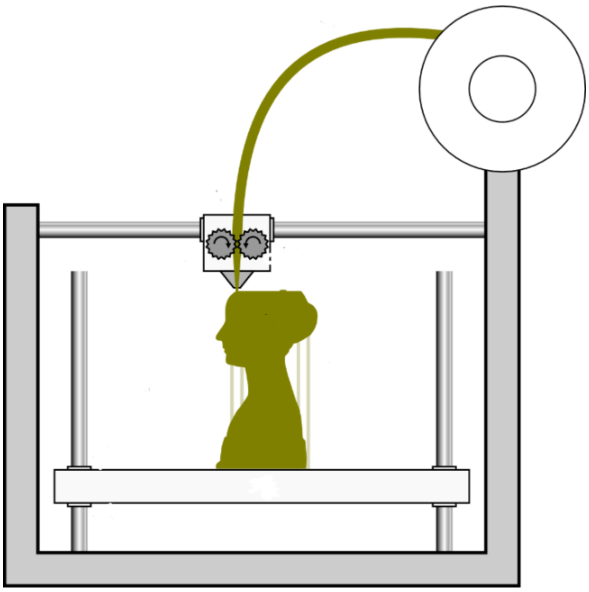

Figure 58 - Representation of the 3D printing technique known as Fused Deposition Modeling

The disadvantages of this type of printing are different and depend very much on the quality of the 3D printer used. Common problems are: printed object rough to the touch, a little-defined object with decidedly showy layers, irregular wavy wall pattern (wobble), accentuated porosity, etc. Obviously the CHX object of this thesis work cannot be realized through this 3D printing technique because the material must be metallic in order to have greater thermal conductivity and moreover it would be necessary to avoid as much as possible porosity to retain the condensed water inside the ducts and then recover it in a container. Despite this, it was decided to produce the CHX also with this 3D printing technique only to have a polymer prototype and evaluate the possibility of printing with the FDM technique of a spiral geometry with internal hollow ducts. The 3D printer used is the Anet A8 model and the chosen material is PLA. The type of kinematics of the Anet A8 printer is Gantry: The print head moves along X, the plate along Y, the head moves away from the plane as Z increases. The print area is 220x220x240mm and the nozzle is single. The nozzle diameter is 0.4mm and the temperature it reaches is 260 °C. The plate on which the printing takes place maintains a temperature of 96 °C. The thickness of the layers is between 0.1-0.3mm and the printing speed depends on the complexity of the model to be printed. The filament diameter of material is 1.75mm. Positioning accuracy along X and Y is 0.015mm while long Z is 0.005mm. The dimensions of the 3D printer are 50x45x40cm and the weight is 8.5 kg. The total printing time of all the components of the CHX was 6 days.

Figure 59 - 3D Printer Anet A8

Below are pictures of the CHX made with the Anet A8 printer.

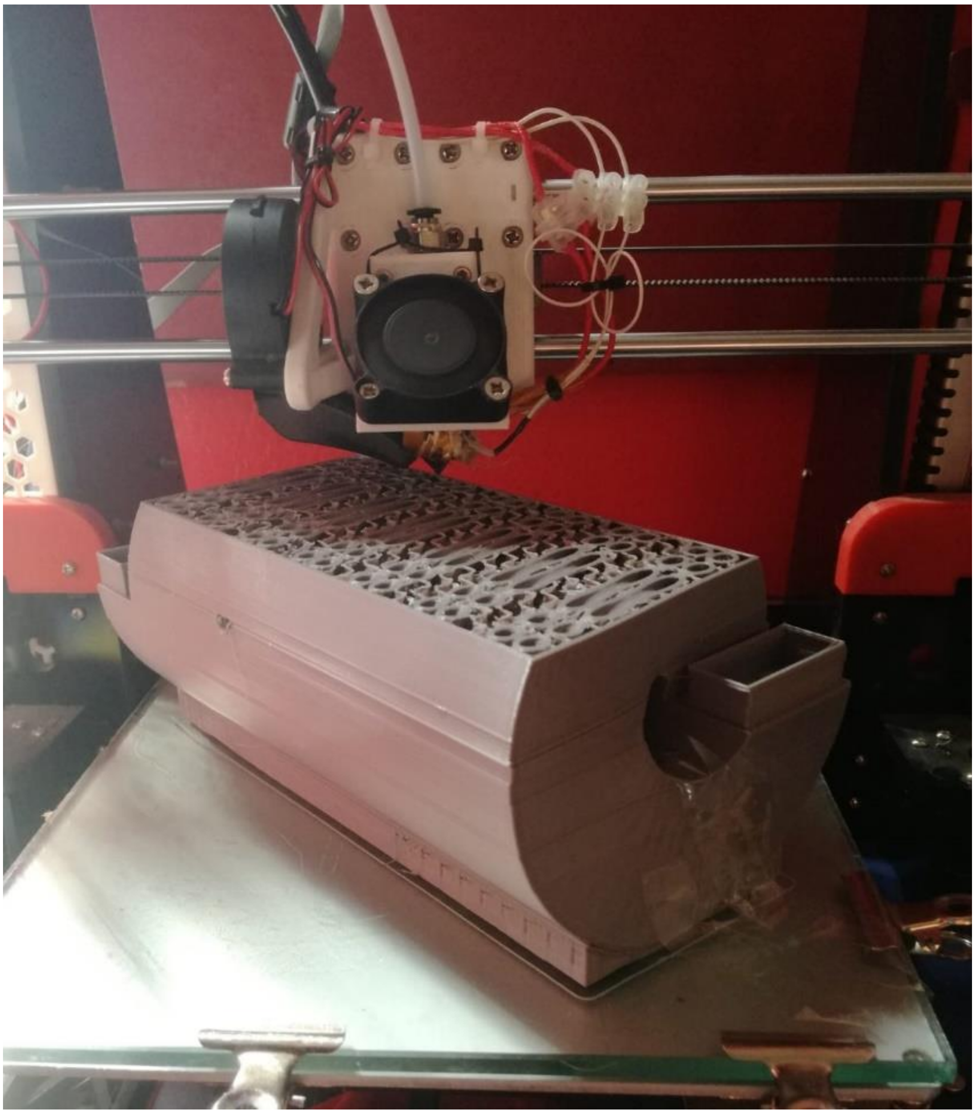

Figure 60 - Printing process in progress with Anet A8 3D printer

Figure 61 - CHX produced in FDM

Figure 62 - CHX produced in FDM - Detail to observe spiral geometry

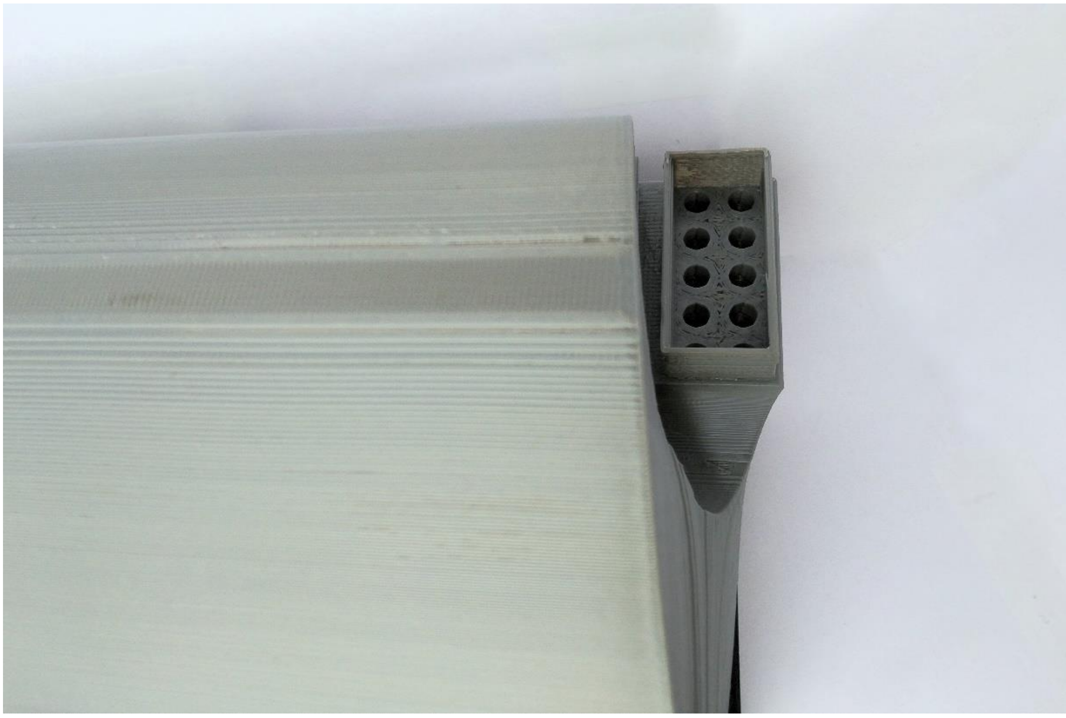

Figure 63 - CHX produced in FDM - Detail to observe rectangular section

Selective laser melting techniques:

It is designed to use a high power-density laser to melt and fuse metallic powders together. The SLM 3D printing technique is considered an evolution of the selective laser sintering technique (SLS). The SLM process has the ability to fully melt the metal material into a solid three-dimensional part unlike SLS which is a true sintering process. The process begins with the analysis of the 3D CAD file and the division of the latter into layers that usually have a thickness of 20 to 100 micrometers. In this way, 2D images of each layer were created. The next step is to load the file previously analyzed in a dedicated software that assigns the parameters, values and physical supports that allow to interpret the file and build it using 3D printers of different types. Using a 3D printer that practices SLM printing technology, the raw material that allows the realization of the component is atomized thin metal powder. This powder is distributed uniformly using a precise mechanism on a support plate which is usually made of metal and which moves along the vertical axis Z. Once the powder layer is distributed, each 2D slice of the part geometry is melted selectively fusing the powder. A high-power laser beam (usually hundreds of watts) is used to melt the powder. The laser beam moves in the X and Y directions with two high-frequency scanning mirrors. Given the high power developed by the laser beam, the powder is completely melted and consequently the particles are welded, thus producing a solid metal. This occurs inside a chamber containing a tightly controlled atmosphere of inert gas, argon or nitrogen at oxygen levels below 500 parts per million. The process is repeated layer by layer until the part is completed.

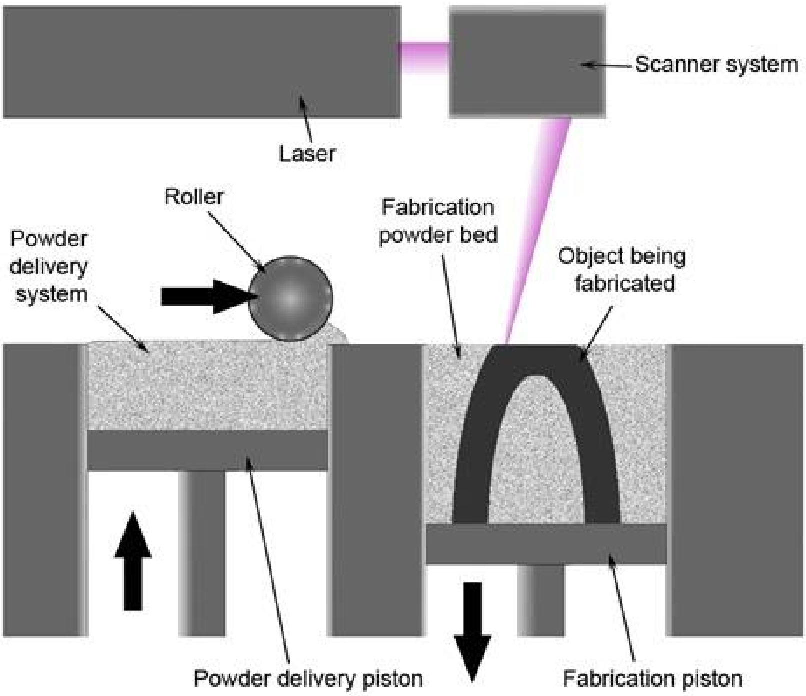

Figure 64 - Schematic of selective laser melting

Some of the materials used for this technique are aluminum, copper, stainless steel, titanium, and other types of metals. The aluminum alloy that could be used to produce the CHX object of this thesis is AlSi10Mg. AlSiMg samples produced using selective laser melting exhibit a higher yield (engineering) then those constructed of commercial as-cast A360.0 alloy by 43% when constructed along the xy-plane and 36% along the z-plane [23]. There are several advantages to using this 3D printing technique including: it is possible to make components with different materials during the printing process; it is possible to make the final alloy in the machine; there are no limits on the size as deposition and fusion are localized; Possibility of obtaining geometries not achievable with conventional technologies; etc. But of course there are also several disadvantages: need for a cover gas to avoid oxidation; need for sophisticated process control to guarantee the metallurgical quality of the deposited layer; limits on achievable geometries; need for finishing with machine tools; the supports are necessary to avoid detachment of the component from the platform due to the solidification withdrawal; it is not possible to obtain tolerances and surface roughness comparable to those obtainable with material removal operations, consequently in the coupling areas it is necessary to provide an added metal thickness of between (0.5-1) mm; difficulty in removing powder in geometries with internal hollow parts; etc.

The 3D printing of CHX in metallic material will be carried out by ELLENA Spa, a specialized company in precision machining on chip removal machine and on additive manufacturing technology. ELLENA Spa practices 3D printing production technology using Prima Additive machines. The 3D printer they use is the Print Sharp 250. It offers great flexibility in every application in terms of dimensions, materials and complexity of the parts that can be printed. With the Sharp Print 250 it is possible to adjust the calibration of the machine and the setting of the process parameters according to the type of application. It is a medium volume machine for Power Bed Fusion applications, developed for the industrial production of complex components. Depending on the desired goal (productivity or quality) it is possible to create different sets of customized process parameters to adapt them to different applications. The volume of construction of this 3D printer is 250x250x300mm, therefore it is possible to produce the CHX which has smaller dimensions. The Print Sharp 250 has a construction speed of $12 - 30\ cm^3/h$ (depending on the material and the geometry of the part). The height of each powder deposition layer can be 0.02-0.1mm. The width of the layer intended as a single-track width is 0.1mm. The laser power used to melt and weld the powder during the 3D printing process is 200W/500W. The 3D printing suite allows file repair, design modification, supports generation and part slicing. The print parameters of Print Sharp 250 have been improved based on the specifications and the behavior of the powders during printing, allowing an excellent production of the components. Print Sharp 250 allows the use of AlSi10Mg powder. The following are some images of the Print Sharp 250.

Figure 65 - Print Sharp 250

Figure 66 - Print chamber of the Print Sharp 250

4 Test Plan

A test to verify some important aspects concerning CHX model should be performed.

4.1 Test Procedure

The most important information about the operation of the CHX are mainly two relating to the tests proposed: the test could highlight the efficiency of the geometric shape of the CHX concerning the positioning of the condensed water film. Furthermore, the test is useful for measuring the amount of condensed water during a certain period of CHX operation time. In this way, knowing the flow rate of the incoming air flow and the operating time, it will be possible to establish the amount of condensed air with respect to the total air quantity that has passed through the condensing heat exchanger. The procedure involves the use of the air present in the environment in which the test bench is assembled to perform the test. The air should have temperature and relative humidity included in the previously considered ranges. The air is taken from the environment and introduced into the duct which is connected to the CHX by an air pump. Before passing through the CHX, the air passes through a 10μm mesh filter which allows to avoid the introduction of particulates or substances that could alter or damage the operation of the CHX and of the entire test to be performed. After passing through the CHX, the air/condensed water mixture flows through the duct to a vessel where the condensed water is collected. The vessel is placed on a scale to measure the amount of water collected over the test-time. As mentioned above, in addition to the possible test of measuring the quantity of condensed water, it is another proposed test to investigate whether the geometry of the CHX allows the formation of the condensed water film only in a portion of the ducts present inside the rectangular section along the path spiral. In order to verify this, a further test could be performed in which the CHX is disconnected from the downstream duct and the outgoing section of the CHX spiral path is displayed and photographed. During the path that the air follows in the condensation process, temperature and relative humidity measurement sensors could be placed along the ducts, before and after the CHX, to keep the values of these properties under control during the process.

4.2 Test Equipment/Instrumentation and Set-up

In order to use a test bench to perform the heat exchanger tests, it was necessary to develop a schematic test setup to highlight the components necessary for the construction of the test bench in addition to showing the various connections of the electric and hydraulic lines between components.

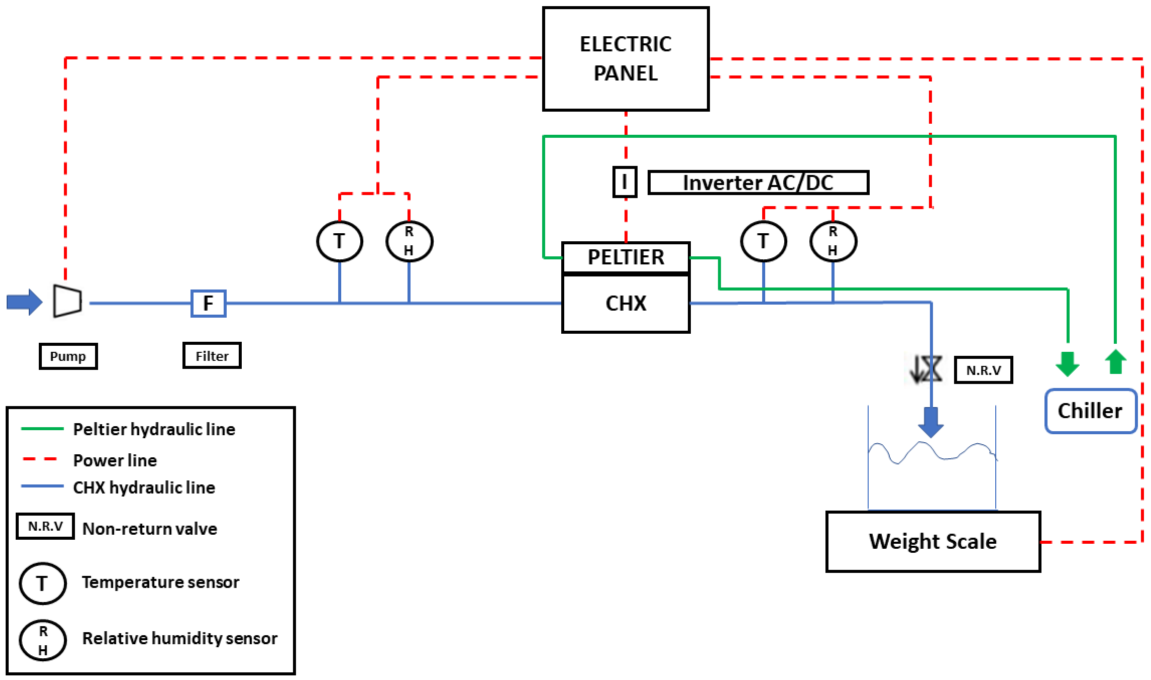

Figure 67 - Schematic test setup of the CHX test bench for Test 01

As it is possible to see from *Figure 67* that shows the test setup related to Test 01, there are 2 different hydraulic lines represented in blue and green lines. The first (in blue) is the hydraulic line dedicated to CHX. The air flow to be condensed enters in the duct represented by the blue line driven by an air pump and initially it passes through a filter, where the microparticles that could create problems in the operation of the CHX are blocked. The device that acts as an air pump is equipped with a by-pass for the regulation and control of flows as well as flow meters to be able to know the flow rate delivered. Before entering the CHX, temperature and relative humidity are measured using appropriate sensors. After that the air flow passes through the CHX where the condensed water is produced. Outgoing from the CHX there will be a mixture of air/condensed water that passes through the non-return valve and then falls into a container placed on a weight scale. The latter is useful for weighing the amount of water recovered in relation to the amount of air used for the single test. The green hydraulic line dedicated to the Peltier cell is connected only to a chiller that allows to have water as a cooling liquid for the Peltier cell at the desired temperature (about 18 °C as the imposed constraint). All the components that need electricity for normal operation are connected to the general electrical panel. The need for an inverter is necessary to use the Peltier cell.

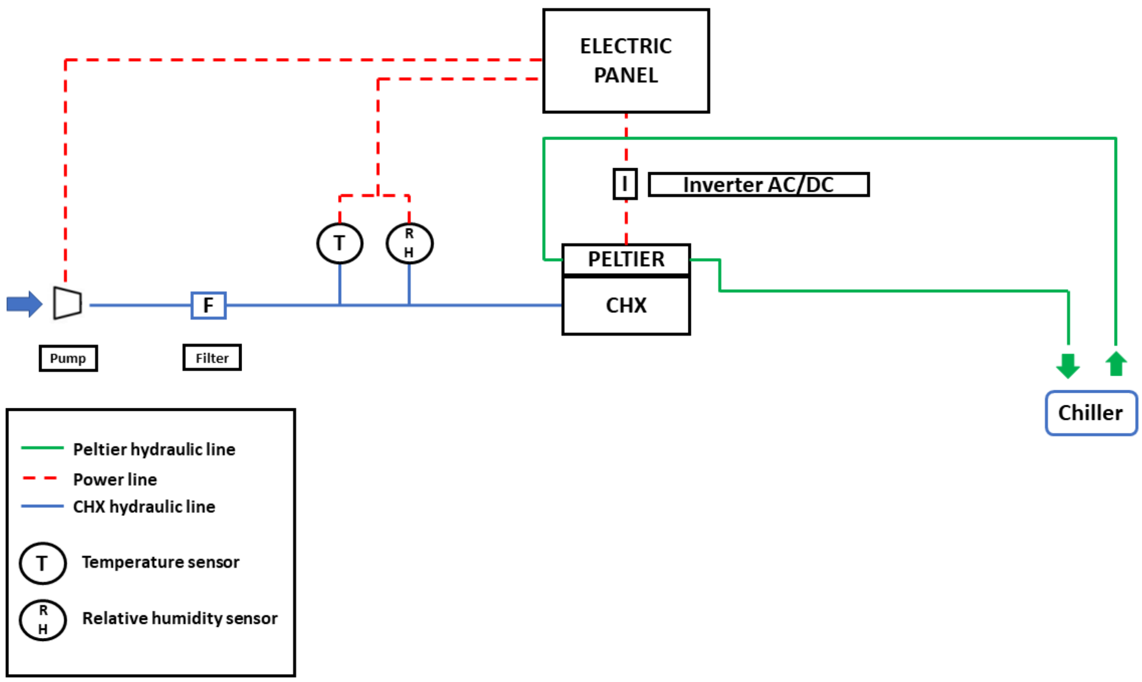

Figure 68 - Schematic test setup of the CHX test bench for Test 02

The test setup related to the Test 02 (*Figure 68*) is very similar to the previous one, because the elements used are identical except for the hydraulic line exiting the CHX. It is not necessary for carrying out the Test 02 since the objective is to observe the CHX outlet section to see if the condensed water remains in contact only with a part of the internal surface of each duct due to the centrifugal force.

Below is a brief description of the various instruments used for the test bench:

- **Air-pump**: The air-pump that could be used is AirCube Basic 600/A30001B. It has dimensions 26x26x26 cm with a weight less than 8kg. Its main function is to sample air to perform analyzes but having the desired characteristics to be used as a pump in the test bench, it was decided to propose this component. A main reason that influenced the choice of this component is that it allows to visualize the temperature and the flow rate of the air entering the test bench, without the need to add a flowmeter downstream. In this way it is possible to compare the inlet air temperature measured by AirCube with that measured by the downstream sensor. The maximum flow rate that AirCube can deliver is 25 l / min. This is excellent for use in the test bench since it was decided to carry out the tests with only 2/10 operating ducts, and consequently deliver a flow rate of 10 l/min rather than 50 l/min. Below is an image of the AirCube Basic 600/A30001B [24];

Figure 69 - AirCube Basic 600/A30001B

- **Filter**: The filter that could be used is based on a pleated Metal Fibre Filter Disc. It is a 10µm mesh filter and it include also an AISI316L housing with threaded connections to the line. The filter is made by Porvair Filtration Group. The following is a technical image of the filter [25];

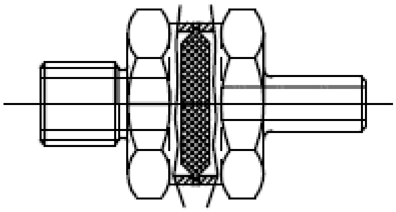

Figure 70 - Filter

- **Temperature and relative humidity sensor**: Temperature and relative humidity could be measured by DELTA OHM transmitters. The model is HD2008TV1. The temperature range is configurable. They convert humidity and temperature values into two linear current signals (2 wires) in the field 4÷20 mA. In the humidity-temperature combined version, the two circuits and the related outputs are completely independent one from the other. The linearization based on digital technique grants best accuracy and stability. Programming is carried out very easily by pressing a button. No operation by means of jumpers, potentiometers, etc. is requested. The humidity input can be recalibrated using two saturated solutions: the first one at 75%, the second one at 33%; the 0% R.H./100% R.H. relative humidity range is fixed and 4 mA correspond to 0% R.H., while 20 mA to 100% R.H. In HD 2008 model, the operator can configure 4÷20 mA (or 20÷4 mA) temperature output in any range going from -50°C up to +200°C with 25°C minimum amplitude. the relative humidity sensor may work in a -40/+150°C temperature range. Beyond this range till +180°C it can work for brief periods. The configuration supplied with this type of instrument is vertical version (TV) suitable for wall-mounting. [26] Below is an image of the version that could be used with the mechanical dimensions.

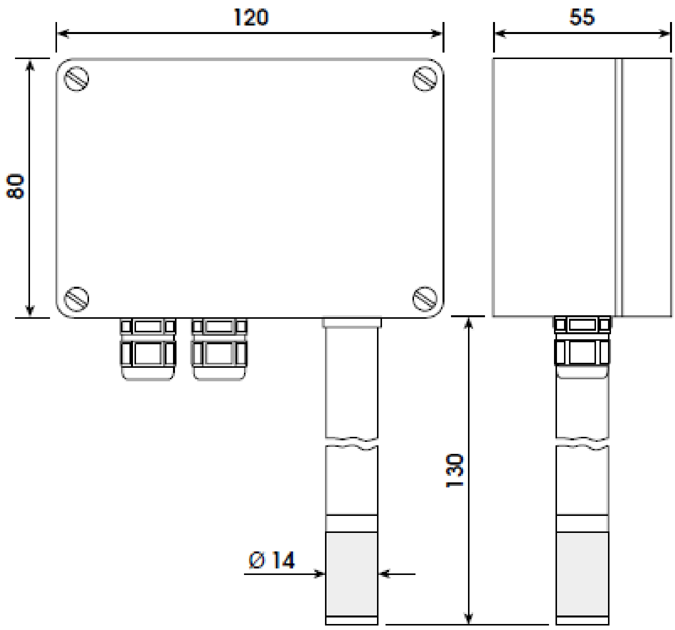

Figure 71 - DELTA OHM sensors HD2008TV1

- **Peltier cell:** To decrease the CHX wall temperature, as already mentioned above, a thermoelectric unit must be applied to the flat surface of the CHX. It is a Direct-to-Liquid Thermoelectric Assembly. The Direct-to-Liquid Series thermoelectric assembly (TEA) offers dependable, compact performance by cooling objects via liquid to transfer heat. Heat is absorbed through a cold block and dissipated thru a second liquid heat exchanger. The thermoelectric modules are custom designed to achieve a high coefficient of performance (COP) to minimize power consumption. The liquid heat exchanger is designed to accommodate distilled water with glycol. Corrosion resistant turbulators are enclosed inside channels to increase heat transfer. The temperature range of the environment in which the thermoelectric unit can operate is -40/+62 °C. The nominal voltage of the thermoelectric unit is 24 VDC. Below is an image of the TEA [27];

Figure 72 - Thermoelectric Unit Assembly

- **Non-return valve:** It is the Super Speedfit Acetal Single Check Valve and it ensures protection against reversal of flow. The low headloss design and fast installation time make the valve the ideal selection. The valve is designed for use with liquids, it is not suitable for air and vacuum applications. It can operate up to a pressure of 16 bar if the fluid temperature does not exceed +20 °C. From +20 °C to

+65 °C it can operate up to a pressure of 10 bar. The material of which the valve is made is polypropylene. Below is an image of non-return valve [28];

Figure 73 – Non-return valve

- **Weight scale:** The scale that could be used for the test has a maximum range of 30kg with a resolution of 30000. It can operate in a temperature range of + 5 / + 35 ° C. The maximum air humidity at which the scale can operate is 80%. Below is an image of the scale used [29];

Figure 74 - Weight scale

- **Chiller:** The chiller that could be used is a compact machine and meets the need for cooling power in confined spaces. The model used is ZCM102 of the Chiller-Frigoriferi company. It has an ideal air condensation battery to satisfy the need for cold water to be used in industrial processes. It offers a cooling capacity from 2 to 6 kW and has a thermally insulated 25-liter stainless steel tank. The chiller also has a peripheral device with an impeller to flow the fluid into an external duct. It is also equipped with a pressure gauge and an anti-freeze probe. It uses an R134a refrigerant gas. Below is an image of the scale used [30];

Figure 75 – Chiller

- **Power Supply for electric panel:** The power supply that could be used in the electric panel is one of the Keysight Technologies series of linear-regulated 80-100 W DC power supplies. It is designed to maximize the throughput of DUTs through the manufacturing test process. Both programming and measurement are optimized for speed. The active programmer can sink up to the full rated current of the power supply, which quickly brings the power supply output to zero volts. The output ratings are 0 to 50 V about voltage and 0 to 2 A about current. The programming accuracy at $25\,°C\ \pm 5\,°C$ are 20 mV of voltage and 1 mA about current. It can operate at a temperature range of 0/55 °C. Below is an image of power supply used [31];

Figure 76 - Power supply for electric panel

- **Power supply for thermoelectric unit:** The thermoelectric unit needs to use an inverter to be powered. A power supply dedicated to the thermoelectric unit could be used for the test. About environment, the working temperature must be into a range of -10/+70 °C and the working humidity 20/90%. It has a universal AC input and protections for short circuit, overload, over voltage and over temperature. It has four channels with different DC voltage and rated current. Below an image of the power supply for thermoelectric unit used [32];

Figure 77 - Power supply for thermoelectric unit

- The pipes for the hydraulic lines could be in polypropylene and could have an external diameter of 10mm.

Below is a summary table with the list of test setup equipment proposed.

Table 10 - Test Equipment

Instrument	Brand	Reference Model	Number of Units
Air-pump	AMS Analitica	600/A30001B	1
Filter	Porvair Filtration Group	3300-33-0010B	1
T and RH sensors	Delta OHM	HD2008TV1	2
Thermoelectric Unit	Supercool	DL-120-24-00	1
Non-return valve	John Guest	6SCV	1
Weight scale	KERN	FCB30K1	1
Chiller	Chiller Frigoriferi	ZCM102	1
Main Power Supply	Keysight	6633B	1
Peltier Power Supply	RS Pro	QP-320F	1

4.3 Exact Procedure

In this paragraph the exact procedure for a correct execution of the proposed tests will be illustrated. The following tables show the procedure described step by step, the required result for each step, the result obtained for each step and a column in which it is possible to report remarks during each step. Table 11 shows the exact procedure relating to proposed Test 01 that is the test through which it is possible to process information regarding the quantity of condensed water recovered in a certain time of operation. Table 12 shows the exact procedure relating to proposed Test 02 that is the test through which it is possible to confirm that the condensed water inside the CHX flows in contact with the outermost surface of each circular duct by means of centrifugal force.

Table 11 - Exact procedure: Test 01

STEP No.	ACTIVITY DESCRIPTION	REQUIRED RESULT	ACTUAL RESULT	REMARKS
1	Plug all the CHX circular ducts except the 2 central ducts (third duct in the first and second row) which must be left open.	DONE/OK		
2	Prepare the test setup as per Figure 64.	DONE/OK		
3	Check that all valves are open.	DONE/OK		
4	Verify that all sensors are within calibration validity.	T and RH calibration exp. data		
5	Fill the chiller with water as indicated as acceptable range by the chiller level meter.	DONE/OK		
6	Set the chiller water temperature to 18 °C and wait until the water temperature in the chiller is 18 °C.	DONE/OK		
7	Place the outlet container on the scale, then turn on the scale and set the weight to 0.	DONE/OK		
8	Turn on the air pump and set the flow rate to 10 l/min.	l/min data		
9	Measure the temperature and relative humidity values in the sensors before entering the CHX.	T and RH data		
10	Turn on the thermoelectric unit and set it to the power chosen for the test depending the case to be performed (Look at Table 8).	W data		
11	Measure the temperature and relative humidity values of the mixed air/condensed water flow exiting the CHX using the appropriate sensors.	T and RH data		
12	Wait for 60 minutes for the test and measure the amount of condensed water recovered in the container using the weight scale every 1 minute.	Kg recorded data vs time		

Table 12 - Exact procedure: Test 02

STEP No.	ACTIVITY DESCRIPTION	REQUIRED RESULT	ACTUAL RESULT	REMARKS
1	Prepare the test setup as per Figure 65.	DONE/OK		
2	Check that all valves are open.	DONE/OK		
3	Verify that all sensors are within calibration validity.	T and RH calibration exp. data		
4	Fill the chiller with water as indicated as acceptable range by the chiller level meter.	DONE/OK		
5	Set the chiller water temperature to 18 °C and wait until the water temperature in the chiller is 18 °C.	DONE/OK		
6	Turn on the air pump and set the flow rate to 10 l/min.	l/min data		
7	Measure the temperature and relative humidity values in the sensors before entering the CHX.	T and RH data		
8	Turn on the thermoelectric unit and set it to the power chosen for the test depending the case to be performed (Look at Table 8).	W data		
9	Wait for 15 minutes and observe the CHX outlet section to check if the condensed water is only in contact with the outer surface of each circular duct.	Yes, it is/ No, it isn't		

4.4 Test Success Criteria

The following considerations were made to establish a criterion that affirms the success of Test 01:

- Knowing the properties of the air entering the CHX reported in the following table

Table 13 - Air input data

	Input Data		
	Temperature T_{in} [°C]	Relative Humidity RH_{in} [%]	Humidity Ratio X_{in} $\left[\frac{kg_{H20}}{kg_{DA}}\right]$
Case A	22	80	0.013
Case B	26	80	0.017
Case C	22	60	0.009
Case D	26	60	0.012
Case E	24	70	0.013

- The value of the enthalpy of the incoming air is obtained through the psychrometric diagram:

Table 14 - Enthalpy of air entering the CHX

	Enthalpy h_{in} $\left[\frac{kJ}{kg}\right]$
Case A	55.96
Case B	69.55
Case C	47.37
Case D	58.48
Case E	57.59

- The mass of air passing through the CHX in an hour is calculated considering an air flow rate of $q_{air} = 10\ l/min$, and knowing the values of $c_{p\,air} = 1.0045\left[\frac{kJ}{kg\cdot K}\right]$ and $\rho_{air} = 1.20\left[\frac{kg}{m^3}\right] = 0.0012\left[\frac{kg}{l}\right]$, the mass of air delivered in an hour is:

$$m_{air} = 10\left[\frac{l}{min}\right]\cdot 60\left[\frac{min}{h}\right]\cdot 1[h]\cdot 0.0012\left[\frac{kg}{l}\right] = 0.72\ [kg]$$

- Since the tests on the test bench will be carried out with a flow rate of $q_{air} = 10\ l/min$, the heat to be subtracted is calculated considering that flow rate and it is multiplied by a factor 7, so as to condense already at the first station (as on the ESATAN FHTS simulation). The heat to be subtracted in different cases is:

Table 15 - Heat to be subtracted

	Heat Q $[kJ]$
Case A	-17.7
Case B	-18.76
Case C	-40.53
Case D	-41.51
Case E	-29.33

It is assumed that the relative humidity is $RH = 100\%$ even when air leaving the CHX.
In accordance with the first principle of thermodynamics, by not doing work because simple cooling is performed, it is possible to write:

$$Q = m_{air}(h_{out} - h_{in})$$

Through this relation it is possible to obtain the value of the enthalpy at the end of the CHX for each case:

Table 16 - Enthalpy of air exiting the CHX

	Enthalpy $h_{out}\left[\frac{kJ}{kg}\right]$
Case A	31.36
Case B	43.49
Case C	-8.92
Case D	0.83
Case E	16.85

- Knowing the enthalpy of the outgoing air, and assuming to have relative humidity in output equal to $RH = 100\%$, through the psychrometric diagram it is possible to derive the temperature and the humidity ratio of the air in output for each case:

Table 17 - Temperature and humidity ratio of the air in output

	Temperature T_{out} [°C]	Humidity Ratio X_{out} $\left[\frac{kg_{H20}}{kg_{DA}}\right]$
Case A	10.8	0.00811
Case B	15.42	0.01103
Case C	-12.14	0.00132
Case D	-5.2	0.00244
Case E	4	0.00508

- Finally, it is possible to obtain the mass of condensed water in one hour for each case through the relation:

$$m_{H20} = (X_{in} - X_{out}) \cdot m_{air}$$

Table 18 - Mass of condensed water

	Water mass m_{H20} $[kg]$
Case A	0.00352
Case B	0.00430
Case C	0.00553
Case D	0.00688
Case E	0.00570

Therefore, the criterion for determining whether the Test 01 will be successful is to recover the quantity of water indicated in Table 18.

However, in cases C and D, it will not be possible to recover the indicated quantity of condensed water because it is expected that the temperature will drop below zero in the CHX end stations, so it is possible that the freezing phenomenon will occur which will reduce the amount of water recovered.

Instead, to confirm the success of Test 02, the criterion to be respected is simply to observe that the condensed water in the outlet section remains attached to the outer surface of the circular ducts.

Conclusion

The study and design of a microgravity condensing heat exchanger was carried out in the present thesis work. The latter is carried out in collaboration with Center for Near Space and Thales Alenia Space. In particular, the thesis is a proposal of the CNS with aims related to the study of a component that can contribute to the realization of Environmental Control and Life Support System in a closed cycle, so as to minimize or even avoid any ground supplies of raw materials such as water during long-term manned space missions. The main function of CHX is the recovery of water by condensation of the air, useful for different needs of the crew. In addition to the design of the CHX, another goal of the thesis work was to design a test bench in which tests can be performed to confirm the operation of the CHX. The scenario in which CHX should operate is a plant growth chamber. This scenario has been decided by TAS as they have contributed to the realization of EDEN ISS Horizon2020 project whose main objective is to advance controlled environment in laboratory and space-analog environment. TAS worked mainly on the development of a rack-like facility targeting at short-term safe food production and operation in microgravity, in which two plant growth chambers are included. CHX should receive air from plant growth chambers and recover water through condensation. After carefully analyzing the state of the art and identifying the requirements and constraints taken from the scenario to be respected for the study and design of the CHX in question, the design phase has begun. First of all, a study was carried out on the various cooling technologies available to cool and condense the air. Initially, by analyzing the cooling technology with coolant (water, for safety reasons), a possible geometric configuration was chosen with counter-current flows of air and coolant in order to establish the CHX wall temperature more uniform and then uniform the heat exchange along the air path. But considering the constraints imposed by the scenario in which the CHX should operate, and more specifically the minimum temperature of the water supplied by the EDR (16/18 °C), and given the requirements in terms of temperature and relative humidity of the inlet air to CHX, the possibility of using a cooling technology with coolant was discarded because in some cases it was not possible to have the desired wall temperature to cause the condensation phenomenon to arise. Therefore, the possibility of using a thermoelectric unit to lower the CHX wall temperature was considered. From this study it was possible to state that, to the detriment of the amount of electrical energy used to develop sufficient thermal power to lower the CHX wall temperature up to the desired value, the thermoelectric unit allowed the condensation phenomenon in all the cases imposed by the requirements. So, the use of a thermoelectric unit with a Peltier cell was considered for the sizing of the CHX. Several geometric configurations have been considered for the design of the CHX. The concept common to all the geometric configurations considered is to form a spiral air path so as to be able to induce the centrifugal force that pushes the condensed water towards the outermost wall of the ducts, so as to keep a portion of the duct surface free in contact with the air to be condensed throughout all the path, thus decreasing the thermal resistance that could create a film of water on the wall, and finally avoiding the possibility of the formation of condensed water droplets that wander freely within the duct in weightlessness. Several changes have been made to the various geometric configurations oriented to the possibility of 3D printing to produce CHX. After finding the geometric configuration optimized for 3D printing, some thermal calculations were carried out to size the CHX in terms of thermal energy to be subtracted, in order to understand what type of thermoelectric unit it is necessary to use. The CHX was designed to be produced both with Fused Deposition Modeling technology and Selective Laser Melting. The CHX was realized in PLA through FDM only for demonstration purposes, it is currently in production at the company specialized in SLM, Ellena Spa. To have a further verification of the correctness of the thermal calculations, a simplified model was implemented on ESATAN FHTS, a software that allowed to simulate the condensation process, and the verification took place correctly. Finally, a test bench was designed to be able to carry out tests to verify the correct functioning of the CHX. During this final phase of the thesis work all the components necessary to build the test bench were selected, the exact procedures to follow were described to perform the tests in the right way. Furthermore, criteria have been established to be respected in order to be able to state whether the tests will be successful.

Future work

The future perspective of the CHX object of this thesis is certainly linked to the tests proposed previously. In fact, having carried out the verification tests, it could be possible to highlight any characteristics and properties of CHX, even geometric, which could be improved.

A modification that could be made in the future could be to use a porous material for the production of CHX so as to create additional ducts adjacent to the outermost surfaces of already existing ducts, so as to totally separate condensed water (which is absorbed by the porous material and transported to the new ducts) and air during the condensation process.

Another interesting proposal for the future could be to create small transparent windows in the areas where it is expected that condensed water droplets will form. In this way it is possible to study the droplet size during the condensation phenomenon. Obviously, it would be necessary to use transparent glassy material with a thermal conductivity almost like that of the aluminum alloy of which CHX is made.

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