Design of the Air Management System for the EDEN Next Gen Ground Test Demonstrator

Master Thesis

Submitted by

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[34119 words]

Annika Flechsig
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Abstract

There is a growing interest in human space exploration missions to Moon and Mars and the establishment of planetary outposts and habitats. Greenhouse modules contribute to the fresh food supply of the in-situ crew in order to minimise resupply from Earth and to benefit the psychological aspect of the team members.

The aim of this master thesis is the development and design of the atmosphere management system of the EDEN Next Gen greenhouse module from the German Aerospace Centre in Bremen, with special focus on the ground test demonstrator. Challenges like the air flow, trace gas accumulation or the power supply arise and have to be taken into account.

A concurrent engineering study was performed to compile assumptions, interfaces and requirements for a first preliminary design. Calculations of the numerical values provide a first design and dimensioning of the components. A CAD-model visualises the design and provides information on further improvement potentials.

A major trade-off to be conducted for the AMS during the CE-study has been deciding between water- or air-cooled LED-systems for the illumination of the plants, due to the current size limitation of the service section inside the module. The air-cooled LED-system is selected and sets the baseline for the further design.

This size limitation is a key challenge throughout the entire design of the system. The selected components that fulfil the performance requirements had to be significantly reduced in size. This means that there is no assurance that the system will be able to meet the defined requirements. This must be verified in a CFD simulation. Emphasis was placed on accessibility and redundancy concepts in the design and these concepts were implemented where possible. In addition, the adaptation for a possible space application was considered and necessary adjustments were provided.

In the further course of the project, the feasibility and functionality of the developed system must be verified through tests and simulations.

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List of Abbreviations

DLR	Deutsches Zentrum für Luft- und Raumfahrt
ISECG	International Space Exploration Coordination Group
BLSS	Bio-Regenerative Life Support Systems
MTF	Mobile Test Facility
ISPR	International Standard Payload Rack
NDS	Nutrient Delivery System
AMS	Atmosphere Management System
GTD	Ground Test Demonstrator
ILS	Illumination System
ICS	Illumination Control System
DHCS	Data Handling and Control System
PCDS	Power Control and Distribution System
RCC	Reinforced Carbon-Carbon
PVC	Polyvinylchloride
CEA	Controlled Environmental Agriculture
P.A.L.A.C.E	Permanent Astrobase Life-Support Artificial Closed Ecosystem
HEPA	High Efficiency Particulate Air
VOC	Volatile Organic Compounds
CHX	Condensing Heat Exchanger
D/C	Direct Current
A/C	Alternating Current
FEG	Future Exploration Greenhouse
LEO	Low Earth Orbit
TCS	Thermal Control System
C.R.O.P	Combined Regenerative Food Production
CE	Concurrent Engineering
MLI	Multilayer Insulation
CFD	Computational Fluid Dynamics
ISS	International Space Station
CWPU	Condensed Water Purification Unit
SFS	Scroll Filter System
PTFE	Polytetrafluorethylene
COTS	Commercial Off-The-Shelf
GUI	Graphical User Interface
FDIR	Failure Detection, Isolation and Recovery

List of Formula Symbols and Constants

Symbol	Unit	Description
A	m^2	area
A_{total}	m^2	total area of outer wall
C_c	---	conduction constant
C_r	---	radiation constant
$c_{p_{air}}$	$\frac{kJ}{kgK}$	specific heat capacity
O_2	---	Oxygen
CO_2	---	Carbon Dioxyde
I_{peak}	A	current peak
$d_{Service\ Section}$	m	diameter of the service section
$d_{Cultivation\ Area}$	m	diameter of the cultivation area
g_M	$\frac{m}{s^2}$	gravity acceleration on the Moon
$l_{\text{Service}\ Section}$	m	length of service section
$l_{Cultivation\ Area}$	m	length of the cultivation area
$l_{Service\ Section\ conical\ part}$	m	length of the conical section inside the service section
$l_{Cultivation\ Area\ conical\ part}$	m	length of the conical section inside the cultivation area
$L_{Overhead\_air}$	m	total length of components in the overhead section for the air-cooled LED-system
$L_{Overhead\_water}$	m	total length of components in the overhead section for the water-cooled LED-system
$L_{Underfloor\_air}$	m	total length of components in the underfloor section for the air-cooled LED-system
$L_{Underfloor\_water}$	m	total length of components in the underfloor section for the water-cooled LED-system
L_N	dB	sound power level
$M_{total_{air}}$	kg	Mass estimation of the air-cooled LED-system
$M_{total_{water}}$	kg	Mass estimation of the water-cooled LED-system
$\dot{m}_{air}$	$\frac{kg}{s}$	constant air mass flow rate
$\dot{m}_{condensation}$	$\frac{kg}{s}$	maximum condensation rate
N	$\frac{layers}{cm}$	MLI density

List of Formula Symbols and Constants

n	---	number of facing pairs of low-emittance surfaces (MLI)
V_{GHM}	$\mathrm{m^3}$	volume of the greenhouse module
$V_{Service\,Section\,conical\,part}$	$\mathrm{m^3}$	volume of the conical part inside the service section
$V_{Cultivation\,Area\,conical\,part}$	$\mathrm{m^3}$	volume of the conical part inside the cultivation area
q	$\frac{W}{m^2}$	heat flux
$\dot{Q}_{subsystems\,day}$	W	maximum thermal load of subsystems during the day-time period
$\dot{Q}_{subsystems\,night}$	W	maximum thermal load of subsystems during the night-time period
$Q_{dehumidifier\_air}$	kW	total thermal capability of the dehumidifier for the air-cooled LED-system
$Q_{dehumidifier\_water}$	kW	total thermal capability of the dehumidifier for the water-cooled LED-system
$\dot{Q}_{heater\_air}$	kW	Required heating capability of the air-cooled LED-system
$\dot{Q}_{heater\_water}$	kW	Required heating capability of the water-cooled LED-system
$\dot{Q}_{extern}$	W	heat transfer of the GTD
D_{air}	mm	duct diameter of the air-cooled LED-system
D_{water}	mm	duct diameter of the water-cooled LED-system
ΔH_{water}	$\frac{kJ}{kg}$	enthalpy of vaporization
ρ_{air}	$\frac{kg}{m^3}$	desnity of air
ρ_{water}	$\frac{kg}{m^3}$	density of water
Δp_{loss}	Pa	pressure loss
Δp_{total}	Pa	total pressure cabaility
$T_{ambient}$	K	ambient temperature of the GTD
$T_{surface}$	K	temperature inside the GTD
T_m	K	mean temperature
T_{inside}	K	temperature inside greenhouse
T_{Lunar}	K	regolith subsurface temperature
T_D	K	dew point temperature
$\dot{v}_{max}$	$\frac{m^3}{h}$	maximum air flow rate
$\dot{V}_{max-air}$	$\frac{m^3}{h}$	maximum air flow rate required for the air-cooled LED-system
$\dot{V}_{max-water}$	$\frac{m^3}{h}$	maximum air flow rate required for the water-cooled LED-system
W_{air}	W	total internal thermal load (air-cooled LED-system)
W_{water}	W	total internal thermal load (water-cooled LED-system)
ε	---	emissivity of material
σ	$\frac{W}{m^2\,K^4}$	Stefan-Boltzmann constant

1 Introduction

This chapter provides the motivational aspect of this master thesis as well as the aim & objectives to be achieved. Furthermore, an outline on the structure of this thesis is given.

1.1 Motivation

Various space agencies and nations show a growing interest in human space exploration missions to Moon and Mars. For example, NASA’s Artemis program: A long-time human exploration mission to the Moon surface. [1] The International Space Exploration Coordination Group (ISECG) published the global exploration roadmap, a summary of activities and planned projects, in 2018 and also set the main focus on the exploration of Moon and Mars (Figure *1-1*). Therefore, a strong trend on the exploration of extra-terrestrial planets can be observed. [2]

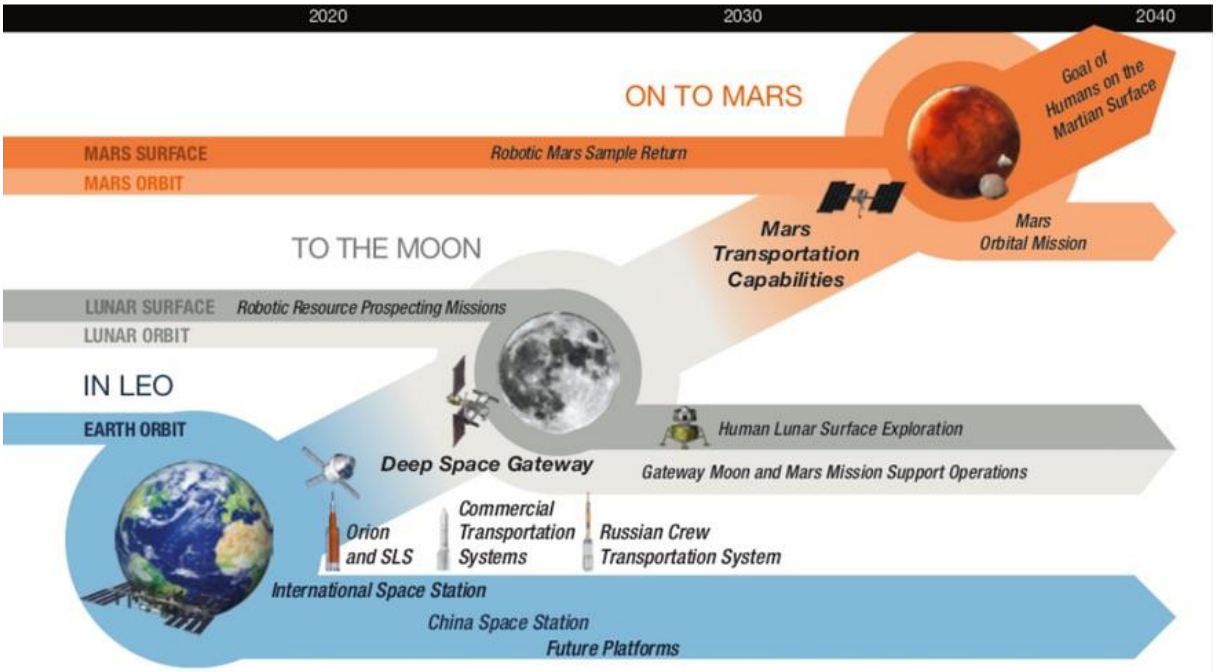


Figure 1-1 Global Exploration Roadmap 2018 - ISECG [2]

The establishment of planetary outposts and habitats on extra-terrestrial planets will help encourage further exploration of the solar system. Therefore, in the future, in-situ operating crews might live and work in habitats on other planets, driven by scientific, commercial or exploration motivated tasks. With longer mission times and further distances, the resupply from Earth will become inconvenient. To minimise resupply needs and improve system resiliency bio-regenerative closed-loop systems and principles for higher plants, should be implemented. Greenhouse modules contribute to closing loops regarding oxygen, carbon dioxide and water supply. Additionally, a greenhouse provides fresh food for the crew and can also have a benefit on the psychological aspect of the team members. To ensure safe living conditions for the astronauts in future habitats, the subsystems of the greenhouse module have to be safe and reliable. Ground testing is an important factor in the development and verification of space systems. Within the DLR Institute in Bremen, the EDEN team analyses and develops concepts and systems for bio-regenerative life support systems (BLSS) for future human space exploration, especially with focus on technologies for plant cultivation in space. The EDEN initiative started in 2011 with the EDEN ISS mission, a space analogue Mobile Test Facility (MTF) operated in Antarctica. [3] [4] The EDEN ISS mission was completed in 2022 and will be followed by the EDEN Next Gen mission, a closed-loop BLSS with independent fresh food production for humans in form of a greenhouse module for extra-terrestrial habitats. The following program steps involve the design of the ground test demonstrator as part of the EDEN Next Gen project. More detailed information about the EDEN Next Gen greenhouse is given in 3.2. [5]

1.2 Aim & Objectives

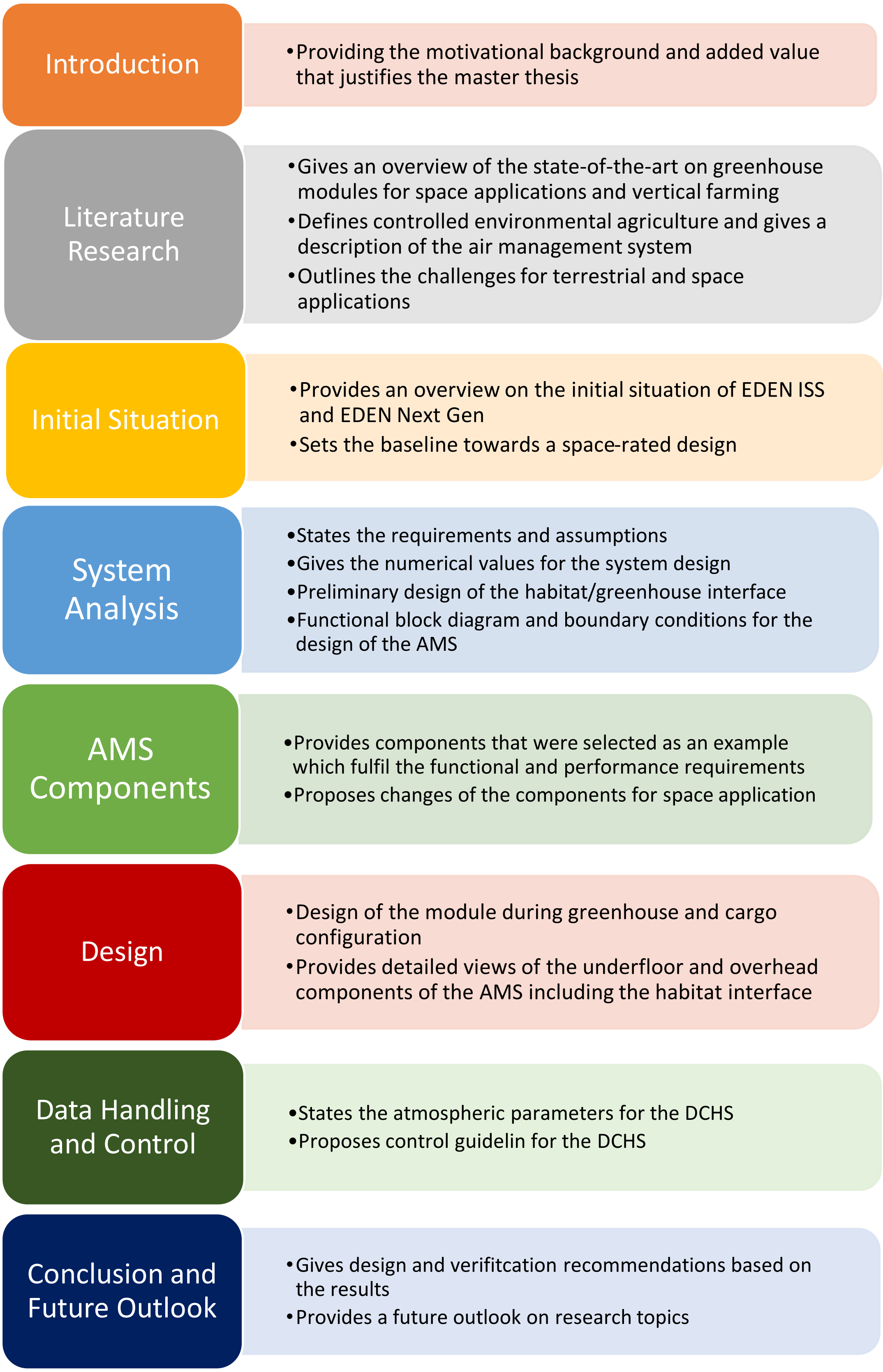
The aim of this master thesis is the development and design of the atmosphere management system (AMS) of the EDEN Next Gen greenhouse module, with special focus on the ground test demonstrator (GTD). The AMS incorporates functions related to maintaining an atmosphere suitable for the plants. The system regulates the temperature, humidity, composition and flow velocity of the air, and is a key factor for the performance and capability of the entire greenhouse module. Due to interfaces to other subsystems, the AMS also influences the internal configuration of the module.

To achieve the objective, first the requirements as well as the lessons-learned from the previous EDEN ISS mission are collected and considered. A concurrent engineering study is carried out to further clarify the requirements and generate a preliminary design of the greenhouse module, including the subsystems and their interfaces. A list of components and respective performance requirements are compiled. Performance values have to be adapted to the design changes of the greenhouse module. Interfaces from the AMS to other subsystems such as the habitat, the thermal control system and cargo environment have to be defined. Along with technology and component research, a trade-off study is done, and suitable components and materials are being selected. A functional block diagram gives an overview on the model structure. The last design step is the CATIA modelling of the AMS inside the greenhouse module.

The next part covers the control of the AMS during various modes of operation. For that the set point, maximum and minimum of the atmospheric parameters are defined. Flow-charts of the CO_2, O_2 and ethylene/VOC concentration are derived from this. Lastly, design and verification recommendations are given for the designed AMS. An outlook on future research topics is introduced.

1.3 Thesis Structure

The outline and content of the master thesis is shown in Figure *1-2*. Each chapter has a brief introduction about its content and will be labelled accordingly.



Introduction
- Providing the motivational background and added value that justifies the master thesis

Literature Research
- Gives an overview of the state-of-the-art on greenhouse modules for space applications and vertical farming
- Defines controlled environmental agriculture and gives a description of the air management system
- Outlines the challenges for terrestrial and space applications

Initial Situation
- Provides an overview on the initial situation of EDEN ISS and EDEN Next Gen
- Sets the baseline towards a space-rated design

System Analysis
- States the requirements and assumptions
- Gives the numerical values for the system design
- Preliminary design of the habitat/greenhouse interface
- Functional block diagram and boundary conditions for the design of the AMS

AMS Components
- Provides components that were selected as an example which fulfil the functional and performance requirements
- Proposes changes of the components for space application

Design
- Design of the module during greenhouse and cargo configuration
- Provides detailed views of the underfloor and overhead components of the AMS including the habitat interface

Data Handling and Control
- States the atmospheric parameters for the DCHS
- Proposes control guidelin for the DCHS

Conclusion and Future Outlook
- Gives design and verifitcation recommendations based on the results
- Provides a future outlook on research topics

Figure 1-2 Structure and content of the thesis

2 Literature Research

This chapter gives an overview of the state-of-the-art on greenhouse modules for space applications and vertical farming. In addition, it provides an introduction on controlled environmental agriculture with respect to the air management system. The literature research lastly outlines the challenges for both, terrestrial and space applications.

2.1 Greenhouse Modules for Space Application

In addition to the projects of the EDEN team of DLR Bremen, other space agencies are researching and designing possible greenhouses for space applications.

The research project "Prototype Lunar/Mars Greenhouse" is a collaboration between NASA scientists and the University of Arizona. The BLSS module is, similar to the EDEN ISS module, outfitted with a hydroponic plant growth chamber. The greenhouse provides nutrition, air revitalisation, water recycling and waste recycling to support the plant and crop production. Its objective is to support ongoing investigation to grow vegetables for food and cultivating plants in space to sustain life support systems. The design of the greenhouse module can be seen in the following Figure *2-1*. [6] [7]

Figure 2-1 Prototype Lunar/Mars Greenhouse [7]

The terrestrial test habitat "Lunar P.A.L.A.C.E 1" (Permanent Astrobase Life-Support Artificial Closed Ecosystem) is located at Beihang University in China (Figure 2-2). One goal is to further develop BLSS theory and technology. [8]

Figure 2-2 Inside Lunar PALACE 1 [8]

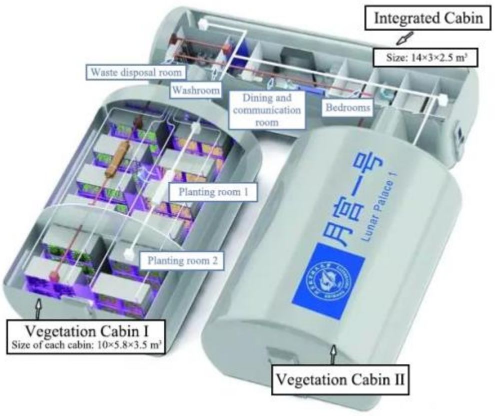


Figure 2-3 Modules of the Lunar PALACE 1 [9]

The facility is structured into three modules. The *Comprehensive Module* houses the living quarters of the crew and the waste treatment. It is connected to the two *Plant Modules*, used for the cultivation of higher plants (Figure 2-3). The BLSS used in Lunar Palace 1 is a critical technology to ensure human survival during extra-terrestrial missions. The goal is to recycle 100 % of CO_2 and O_2, regenerate 100 % of the waste in the system and the production of 80 % of the food that is consumed. It is a hybrid life support system, utilizing microbial-degradation and photo bioreactors for waste treatment. [9]

Plant growth in space is successfully demonstrated not only on Earth, but also on board the ISS. The “Veggie Plant Growth System” provided by NASA (Figure *2-4*) enables the astronauts to have access to fresh food during their time in space. In the process, plant growth is studied under microgravity and in a closed-loop environment. The plant growth unit utilises passive wicking to provide water to the plants as they grow. Veggie has no stand-alone air management system but a fan system, which draws in cabin air for the growing plants to ensure optimal atmospheric parameters. [10] [11]

Figure 2-4 Veggie Plant Growth System [10]

2.2 Terrestrial Application - Vertical Farming

Vertical farming is an agricultural concept in which crops are grown vertically in a controlled indoor environment, with precise light and nutrients supply and temperature control. By growing indoors, crops can be harvested all year round and without being dependent on the weather. Vertical farming is similar to the greenhouse modules for space application described in the previous chapter, but as a terrestrial application. [12] An example for the layout of a vertical farm is shown in Figure *2-5*.

Figure 2-5 Example of a vertical farming facility [13]

In vertical farming commercial agriculture is controlled by sensor technology, which leads to an optimisation of the produced biomass. Soilless methods such as hydroponics, aeroponics and aquaponics are used for the vertical cultivation of crops. All three methods supply the plants with a nutrient solution, mixed from nutrients dissolved in water. The use of a nutrient solution allows for more efficient and intensive crop cultivation, due to the adequate supply of water and nutrients. Closed loops for air- and wastewater-treatment, shorter distances and the use of renewable energies create ecological advantages. The closed-system approach supports the satisfaction of climate-change commitments, which is a key political advantage. Vertical Farming also creates social advantages through the provision of new jobs in multiple sectors. [14] [15]

The use of artificial sunlight in the form of LEDs spikes the energy consumption in these indoor farms, which is a key disadvantage of the system. In addition, there is often a requirement for cooling when temperatures increase due to the lamps, which is done by the system. [16]

Vertical farming is a is a new innovative way to grow crops. There are different variations of vertical farming being tested throughout the world. One being Nordic Harvest, located in Denmark, which is Europe's largest vertical farm. Their goal is sustainable food production and to reintegrate agricultural land with nature. On 14 floors, 20 different salads and herbs are grown, destined for restaurants and retail. To further improve production, robots are used to carry out sowing as well as the care of the crops. The stacked racks, including the LED-system, and robots can be seen in Figure *-2-6*. [17]

Figure -2-6 Inside Nordic Harvest [17]

Product prices are still high due to the energy consumption caused by the system. Over time, new innovations and technologies will increase the energy efficiency and profit margins of vertical farms in the future. [18]

2.3 Controlled Environmental Agriculture

In indoor greenhouses for both space and Earth application, the approach of controlled environmental agriculture (CEA) is used. CEA is the method of soil less cultivation in a controlled environment. It can be an open or closed ecosystem. Autonomous technologies that control numerous variables can be used to optimise cropping systems, crop quality and production efficiency. The CEA approach varies for the different applications in autonomy, product variation and energy efficiency. [19]

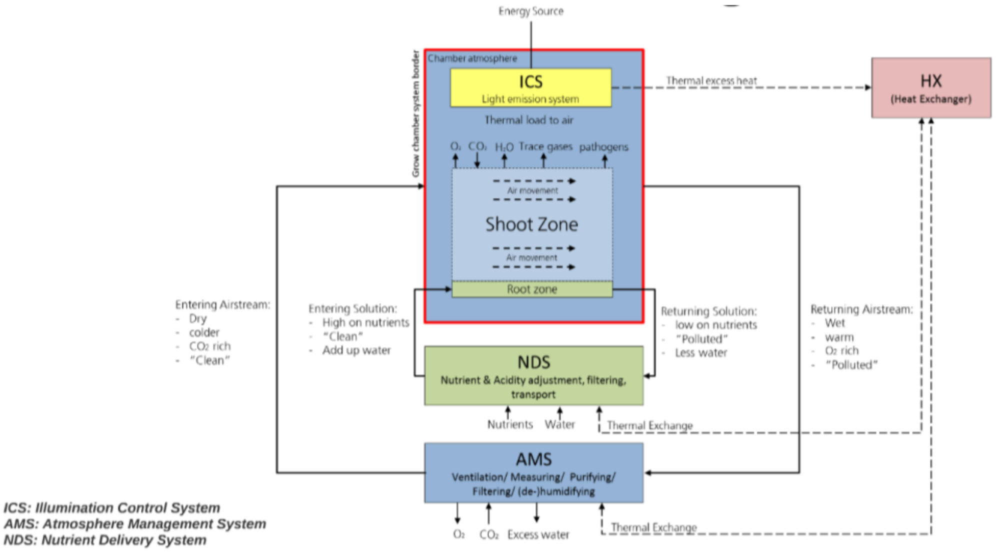


Figure 2-7 CEA system overview *[20]*

One CEA system configuration can be seen in Figure *2-7*. It consists of different subsystems, such as the illumination control system (ICS) and the nutrient delivery system (NDS). Their mode of operation is briefly described in 3.2. The focus is set on the atmosphere management system, which is covered in detail in this thesis.

The Atmosphere Management System (AMS) incorporates functions related to maintaining an atmosphere suitable for the plants. Tasks include the circulation of air, the revitalisation of air, the water recovery, and the monitoring and control of temperature and humidity. The AMS unit consists of various common subsystems and their components, the adequate design properties are important for air treatment. The subsystems include air revitalisation as well as temperature and humidity control. As an example, some components are given for the performance of the AMS tasks.

Fans and Air Ducts

A fan creates air flow as a driving force in the air ducts of an air management system. The air circulation shall ensure a uniform flow velocity at all areas. [21] Several fans can be installed in one ventilation system. Parallel mounting is recommended to increase the air flow rate and linear installation is recommended to increase the operating pressure. As there are different areas of application with various requirements, a number of models with characteristic properties are available. The main difference between these models is the design: this can be axial or radial flow, different shapes. [22] The structure of an axial fan is similar to that of an aircraft propeller. The fan generates airflow in the direction of the axis of rotation, which can be seen in Figure *2-8*. [23]

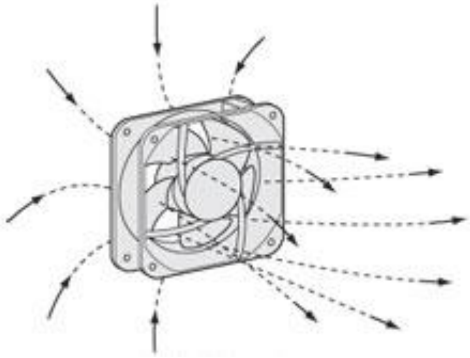


Figure 2-8 Example design and air flow direction of an axial fan [24]

Features of the axial fan:

- Low required space, due to the compact design and linear ventilation.
- Steep performance curve of the axial fan means, that the system pressure must be calculated precisely for connected components of a ventilation system.
- High noise emission.
- Control of the air flow rate.
- Easy to assemble and disassemble.
- Space flight approved.
- Provision of high air flow performance with medium pressure increase.

[25] [26]

Centrifugal fans provide a 90° turned air flow by maximising static pressure, making them optimal for ducted applications. An example for the direction of air flow can be seen in Figure *2-9*. [23]

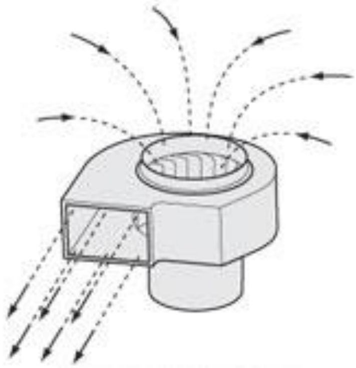


Figure 2-9 Example design and air movement of a radial/centrifugal fan [27]

Features of the centrifugal fan (in comparison to the axial fan):

- Higher pressure and lower air flow capabilities than axial fans.
- Increased space requirement due to air deflection by 90°.
- Better efficiency.
- The lower circumferential speeds result in less noise.
- Higher available pressures → Ideal for use in ventilation systems with upstream or downstream units such as air filters, heat exchangers, etc.
- Smoother performance curve → The centrifugal fan is more tolerant of increases in pressure drop, e.g., due to gradually clogging filters.
- Control of the air flow rate.

[28] [25]

Sensors

Sensors are electric devices used for air quality assessment monitoring and management to ensure suitable atmospheric conditions as well as disease and pest control for optimal plant growth and human health. [29] The measured parameters include temperature, relative humidity, static pressure, air flow as well as CO_2 and O_2 concentration.

Filter

Filters are used to filter out contaminants such as dust, pollen, mould and bacteria from the air. Filters using an adsorbent or catalyst, such as charcoal (carbon), may also remove odours as well as gaseous contaminants like volatile organic compounds (VOC). [30] Examples of filter types are briefly described below.

High efficiency particulate air (HEPA) filter are particle filters that remove 99.9% of airborne particles (Figure *2-10*). They are manufactured with a mat of arbitrarily arranged fibres of different materials. Their performance is dependent on fibre density, diameter and linear thickness. [31]

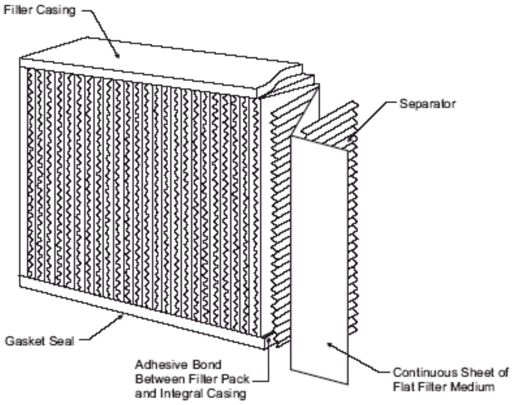


Figure 2-10 HEPA filter design [31]

Activated carbon filters are used for VOC removal. The filter acts by adsorption, meaning that certain gases present in the air become trapped in the pores of the carbon with the result that the air leaving the filter is purified of these adsorbed gases. [32]

UV light filters are mainly used for disinfection of surfaces or water sterilisation. The filter uses ultraviolet light to eliminate pathogens in the treated medium. Due to the length of the UV light waves, they have the ability to destroy the genetic material of microorganisms so that they can no longer reproduce. The working process of UV light filters on the example of water disinfection is shown in Figure *2-11*. [33]

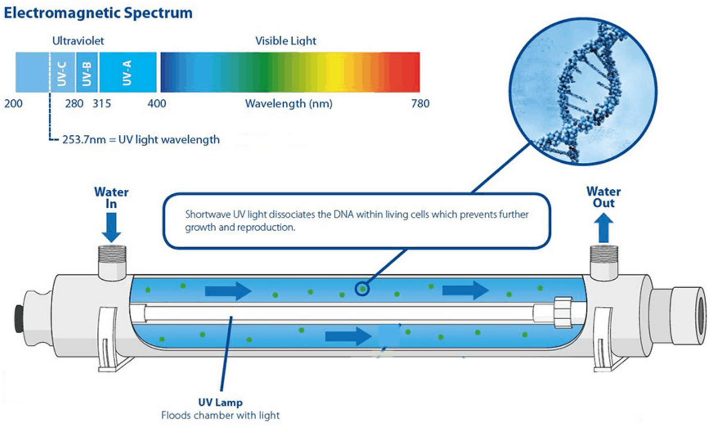


Figure 2-11 Working principle of an UV light filter on the example of water desinfection [34]

Water recovery unit and post-processing

To remove excess moisture from the air different water recovery concepts on Earth are used. Concepts include condensation by pressure, condensation on cooling coil and absorption. Condensation on cooling coil, for example, is the used method in both, the EDEN ISS and the EDEN laboratory at DLR Bremen. A dehumidifier or condensing heat exchanger (CHX) removes moisture from the air flowing through it by cooling the air below the dew point. To do so, a coolant flows through spiral finned tubes that line the inside of the heat exchanger. The exhaust heat from the air is conducted through the fin tube raising the temperature of the coolant while lowering the overall exhaust air temperature. Cooling below the dew point produces condensate, which is collected in the process. [35] The operating concept can be seen in Figure *2-12*.

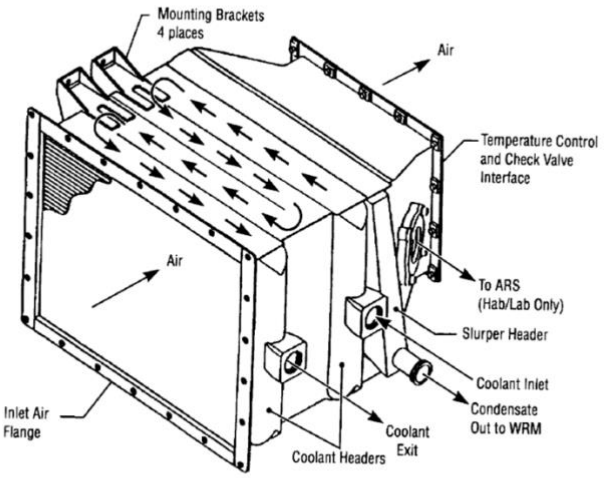


Figure 2-12 Operating method of a heat exchanger using a cooling coil for water recovery by condensation [36]

A possible arrangement of the individual components to ensure a suitable atmospheric condition for plant growth in the greenhouse, is shown in Figure 2-13. This example is taken from the EDEN laboratory at DLR Bremen. The layout combines components to ensure air revitalisation, water recycling and atmosphere control of the closed-loop system.

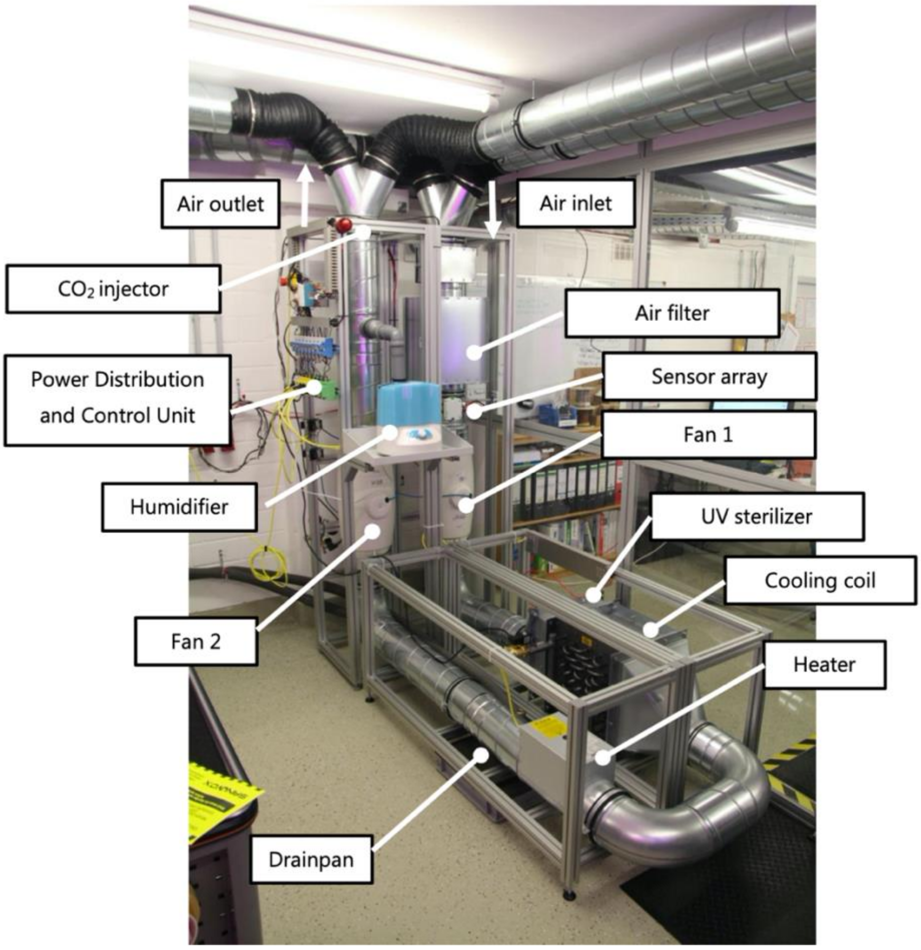


Figure 2-13 Prototype of the atmosphere management system [37]

The *Air Inlet* is the starting point of the AMS. Air from the cultivation area goes first through the *Air Filter Unit* to prevent the elements of the AMS from dust and contamination. The *Sensor Array* measures all parameters needed to ensure an optimal air composition. After the filters, a *Ventilation Unit* (Fan 1) is placed. The *UV Steriliser* is placed before the *Dehumidification Unit* to prevent pollution of the coils inside the dehumidifier. The *Dehumidification Unit* lowers the humidity by cooling the air below the dew point, which leads to condensation. A collecting tray collects the condensed water. The air stream temperature is then increased by the *Heater*. After passing a second fan (Fan 2), the humidity of air is increased by a *Humidifier*. Before entering the cultivation area through the *Air Outlet*, CO_2 could be injected into the air stream to ensure optimal plant growth.

2.4 Challenges

Challenges exist in both terrestrial and space applications. The challenges include various aspects that can impact the system differently. The focus here is on the challenges which could impact the AMS on Earth and in space. These must be identified and considered in the design of the EDEN Next Gen AMS.

2.4.1 Power Supply

The power supply ensures that all components are in operation and can perform their defined tasks. The power supply on Earth and in space differs due to the different environment and the different current and voltage settings. The power supply on Earth uses an alternating current (A/C). A local power socket on the ground, such as a household power socket in Europe, has a nominal voltage of 230 V. In space application a direct current (D/C) is used. The ISS, for example, has a nominal voltage of approximately 120 V. To supply all components with the necessary voltage, so-called D/C D/C voltage converters are used. [38] [39] The following Table *2-1* gives an overview of the fundamental differences between terrestrial and space electronics, that influence the design and cost of these components.

Table 2-1 Overview of the fundamental differences between terrestrial and space electronics [40]

Terrestrial Electronics	Space Electronics
Low radiation requirement	High radiation requirement
Short design cycles	Long design cycles
Easy replacement of components	Difficult or impossible to replace components
High volume applications	Low volume applications
Cost and performance driven	Reliability and robustness driven
Cooled by convection	Cooled by radiation
Stable temperature and static charge environment	Harsh temperature and varying charge environment

One key challenge for the power supply is the inrush current of an electric device. The current jumps above the normal operating current for a few milliseconds after the electrical device is switched on. After that, the current evens out at the nominal current. The inrush current should not exceed a defined time limit being higher than the nominal current to prevent damage of the electrical devices. An overcurrent protection device in the form of a fuse is installed for this purpose. The fuse will trip after the defined switch-off time if the current is still too high. The higher the inrush current, the faster the fuse switches. This can be shown with a time-current diagram. An example diagram is presented in Figure *2-14*. [41]

The x-axis gives the time in milliseconds and the y-axis gives the current in ampere. The peak (I_{peak}) is a summation of all the electrical devices switched on at the same time. After 20 ms, the current settles to the nominal current flowing through the device during standard operation. [42]

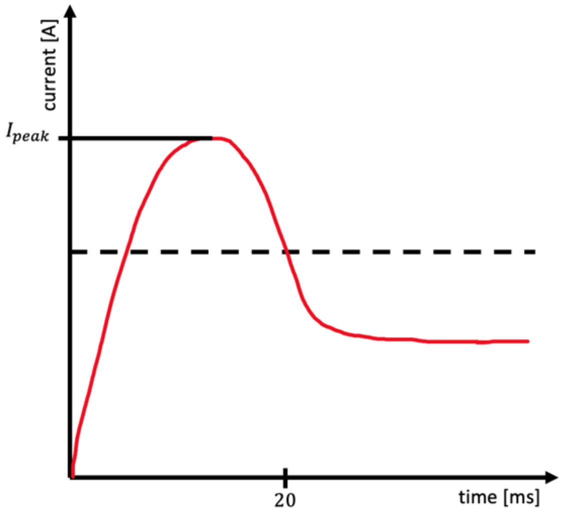


Figure 2-14 Example time-current-diagram of the inrush current

A local power socket on Earth allows an inrush current 10 times higher than the limit for a maximum of 1 second. If the inrush current stays too high for a longer period of time, the safety fuse switches and turns off the power to prevent a fire. [43] In space applications, the system switches off the circuit after only a few milliseconds if the input current exceeds the limit. On the ISS for example, the station itself regulates the power supply. The inrush current rises to the limit, as can be seen in Figure *2-15*. If the current does not decrease below the limit after a few milliseconds, the station breaks the circuit to prevent fire on board the ISS. The time limit can be manually adjusted by the crew via a control module but should not exceed a few milliseconds. [39]

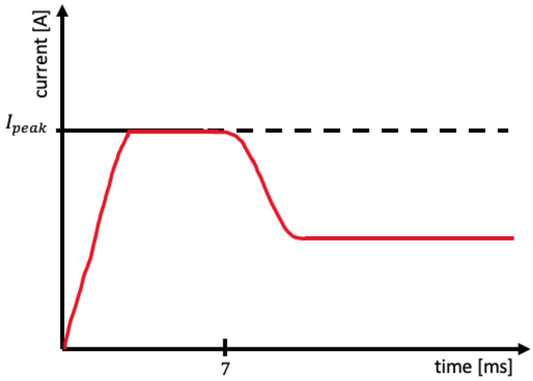


Figure 2-15 Example diagram of the inrush current on board the ISS

Another option is to separate the electronic devices of the system into groups to keep the inrush current below the limit, which is shown in Figure *2-16*. This is done to prevent the system from switching off the circuit.

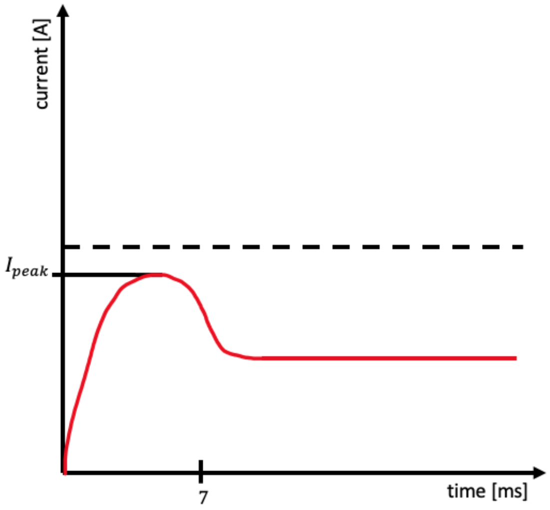


Figure 2-16 Example diagram of the inrush current staying below the defined limit

Another key challenge is the radiation environment in space. For example, electrons and protons coming from the solar wind can hit the electronic device and could cause a short circuit. This leads to the total failure of the component. Therefore, the electronic device may have to be hardened against radiation. [40] This can be done by methods such as shielding the device to reduce exposure, using insulating substrates on microcontroller level or redundancy of the critical components. [44] [45]

In summary, electrical components in space applications have to meet specific requirements. This often increases the price, complexity and dimensions of the components, which must be taken into account for the design of the EDEN Next Gen AMS. The challenges in power supply imply for the design of the AMS that the electrical components should not all be switched on at the same time. Therefore, they should be divided into groups and started one after the other to prevent overloading. Radiation is a critical parameter in space application and electrical devices either have to be hardened against radiation or need to be redundant.

2.4.2 Air flow

Tightly spaced racks lead to air turbulences or air stagnation, caused by air friction with surfaces in the space between the crops and the lighting system. Air turbulences reduce the air flow quality, causing insufficient amount of air at the crops. Air stagnation prevents the air circulation and can lead to CO_2 depletion, temperature rises, fungal diseases and mould growth between the racks. For this reason, the air flow in a greenhouse should move laminar to keep temperatures, CO_2 levels and humidity levels in a defined range. This means a regulated air speed and direction with enough space between the different levels of the racks. [46] The air speed across the plants depends on the type of crop, but in general the desired range of air speed is $0.3 - 0.5\ \frac{m}{s}$. Another challenge for the air flow is the temperature rise across the racks, due to air with a higher temperature rising upwards, called the chimney effect. This can be counteracted with small fans on the racks to blow air directly over the racks or with air ducts designed to distribute air consistently and evenly across the racks. [47]

2.4.3 Trace Gas Accumulation

The closed loop could risk trace gas accumulation (e.g. ethylene) and the formation of a biofilm in the waste water recovery system, as there is no interface for discharging the gases to the outside. Ethylene, for example, is a plant hormone that influences different processes throughout the plant life cycle, such as plant growth and development. [48] An excess of ethylene, on the other hand, can harm the crops and leads to accelerated aging of flowers, deformations of plants and growth can be impeded. [49] For this reason, the AMS of the greenhouse has to measure, analyse and control the composition of air to reduce this risk.

2.4.4 Gravitational Environment

In terrestrial applications gravity enables the natural air movement. Whereas there is no natural air movement in space due to microgravity. This results in the risk of the formation of local air pockets with no “gas exchange”. In these air pockets the temperature increases linearly and cannot be removed, resulting at a temperature that is too high and harmful for the plants. [50] [20]

In addition, vacuum and temperature have an influence on materials in the form of outgassing. Outgassing is the release of gas when a non-metallic material is exposed to heat or vacuum. The chemical compounds emitted during outgassing can be volatile and may accumulate on the surface of critical components. This can cause short circuits between components, wires and connectors. [51] This challenge only refers to the material selection for space applications and can be neglected for terrestrial applications. Detailed information on challenges and the selection of suitable materials for space and terrestrial application is given in 2.4.5.

Another challenge, interesting for the general application of greenhouses in space, is the effect of microgravity on plants. Plants on Earth are adapted to the Earth's gravity. Experiments during spaceflight show, that microgravity has effects on plant growth, and they need to be considered in the design and operational concepts. [52] [53]

2.4.5 Restrictions on Component Selection

For a space mission to succeed, devices and instruments must work at great distances from Earth and under extreme environmental conditions: extreme temperatures, radiation, and vacuum. For a long-term mission (> 15 years) it requires high reliability and robustness against failure. Furthermore, the greenhouse module designed in this thesis is part of a long-term habitat in space and could therefore endanger human lives through critical parts. To avoid this, components and materials need to be space qualified to be used in space applications. [54] [55] [56] [51]

Spacecraft offer a limited space for the payload in the fairing. In addition, sending components to space and in this case, to the Moon surface, is associated with high cost. Every increase in payload mass or travel distance adds additional fuel needs. Therefore, the components require minimal volume and mass. [57]

Critical parameters for the material selection include:

- Light weight – to reduce mission cost
- Strength and stiffness – to withstand acting forces
- Thermal stability – to withstand constant temperature flux
- Environmental stability – to withstand radiation and microgravity of space

[58] [59]

The following gives a short overview on some of the materials already used for space applications:

Aluminium – Aluminium is simultaneously strong and lightweight. It is commonly used in space applications on its own, or as aluminium alloy to lower the weight of the product while keeping strength. [60]

Titanium and Titanium Alloys – Used in space application due to its ability to withstand extreme hazards of space including temperature fluctuations, as well as cosmic and solar radiation. [60]

Reinforced Carbon-Carbon Composite (RCC) – RCC is a lightweight heat-shielding material as it uses the strength and modulus of carbon fibres to reinforce a carbon matrix to resist the toughness extreme environments. [60] [61]

The material selection is not only influenced by the harsh environment of space, but also the conditions of the greenhouse module itself. The optimal relative humidity set point for plant growth is around 80%. [62] In addition, plants release water through the process of transpiration and its evaporation from aerial parts, like leaves. [63]Therefore, the selected materials have to be tolerant against high humidity and dampness. Aluminium, Polyvinylchloride (PVC) as well as galvanized steel are often used in greenhouses as they do not rust and supply the required stability. [64] Components for terrestrial greenhouse applications are dependent on the atmosphere conditions in the greenhouse and are not constrained by the conditions of the harsh space environment. Mass and volume restrictions might occur. However, the costs of exceeding the limits are expected to be less than for space applications.

Considering the material requirements for space applications and greenhouses, the focus is set on lightweight and stiff materials with good environmental sustainability. The first mission step is the design of the GTD. The components in the preliminary design for ground test environment only have to be suitable for ground applications, and do not have to be approved for space application yet. Therefore, commercial off-the-shelf components are selected for the preliminary design. To comply with the size restrictions for the future mission scenario, a compact design is further aimed at in this thesis. More detailed information on the selection of components is given in the respective chapters.

2.4.6 Conditions of Transport

During launch the vibration, shock and impact loads are severe and can break circuits and components. In particular, the fairing separation, the payload release and separation give maximum shock loading on the payload. Moreover, the payload experiences axial together with lateral acceleration and vibrations caused by the thrust of the solid rocket boosters during launch. [65] [66] It is critical that the components can withstand these loads and not get damaged nor detached from the structure. These loads have to be considered for the structural design and analysis. Vibration and shock tests have to be performed in order to ensure safe transportation during launch. [51] This challenge does not apply to terrestrial applications, as the transport on ground does not exert high loads on the system.

2.5 Summary of the Literature Research

In this chapter, the focus has been on providing an overview on the state-of-the-art of greenhouse modules for space applications and vertical farming. Multiple countries including Germany, China and the United States of America carry out research into food production for future long-term space missions. The closed ecosystem approach is also not unique to the space sector and is applied on Earth in so-called “vertical farming” applications. Vertical farming is a new, innovative method in commercial food production to grow food in a space-saving and resource-efficient way.

In indoor greenhouses for space and vertical farming, the produce grows within a controlled environment to protect crops against climatic and environmental extremes. This method is called controlled environmental agriculture (CEA). It consists of various common subsystems, including the illumination control system (ICS) and the nutrient delivery system (NDS). The focus in the literature research is on the atmosphere management system (AMS) and its components, since the design of this subsystem is the objective of this thesis. The AMS incorporates functions related to maintaining an atmosphere suitable for the plants. Tasks include the circulation and the revitalisation of air, as well as the water recovery and the adjustment of both temperature and humidity.

Challenges arise in both terrestrial and space applications due to the complex design as well as the influence of internal and external interfaces. The challenges include the restriction on component selection, the power supply, the sufficient air flow, extreme environment, the trace gas accumulation and the conditions of transport.

However, this research showed that these challenges have different impacts on space applications as they do in vertical farming on Earth. Each of the key challenges described in this literature research is either directly or indirectly related to the performance requirements of the AMS and will have to be considered during the design

3 Initial Situation

This chapter provides an overview on the initial situation and sets the baseline for the design towards a space-qualified system (EDEN Next Gen). The chapter also provides a comparison between the previous and current design of the greenhouse module.

3.1 EDEN ISS

The EDEN ISS is a European Union Horizon 2020 funded project of a space analogue Mobile Test Facility (MTF) in Antarctica. In January 2018, the MTF was deployed in Antarctica close to the German research station Neumayer III, to run experiments on plant cultivation technologies for safe food production in space. Since then, there have been four overwintering operation phases, the last one to conduct experiments in cooperation with NASA. The final operating phase was completed in the beginning of 2022, which defines the end of the mission. Figure *3-1* shows the EDEN ISS MTF from the outside in Antarctica and the inside view of the cultivation area. [67] [3]

Figure 3-1 EDEN ISS Mobile Test Facility (left side: outside view in Antarctica; right side: inside view of the cultivation area) [68] [69]

The MTF is integrated in two 20-foot-long high cube shipping containers, as can be seen in Figure *3-2*. The first container includes the service section, with the so called “cold-porch”, which serves as an interface between the Antarctic outside and the container inside. The service section includes subsystems such as the air management, power management and control system. A working area and an international standard payload rack (ISPR) with a plant cultivation system are also located in the first container.

The future exploration greenhouse (FEG) container includes the actual cultivation area. A selection of different types of crops are cultivated in vertical stacked plant racks which can be accessed by a middle gangway.

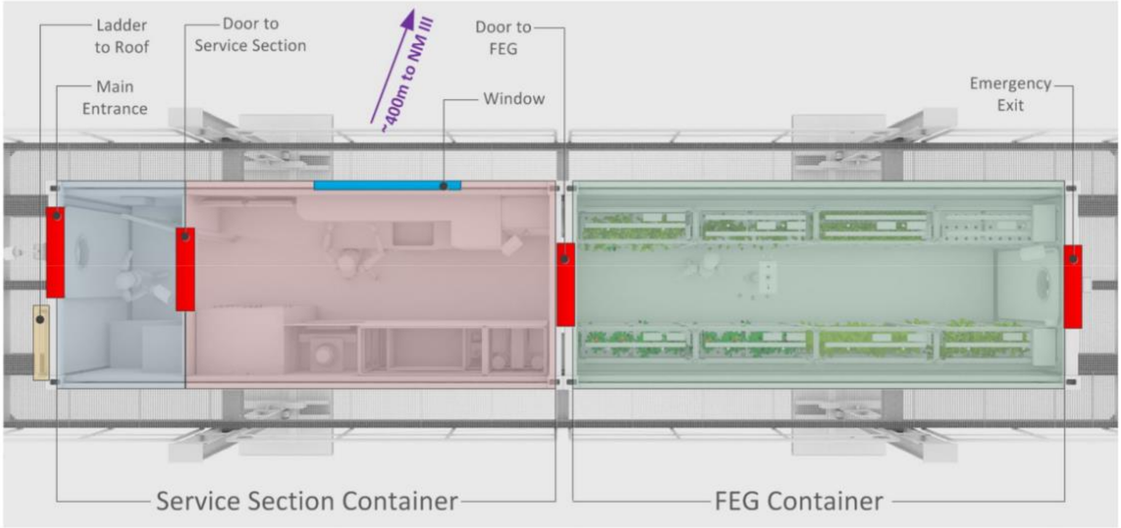


Figure 3-2 Layout of the EDEN ISS Mobile Test Facility (blue area: cold porch; red area: service section; green area: cultivation area (FEG)) [3]

The AMS in the MTF itself is divided into two sections. The service section contains the first part of the AMS, which is responsible for processing and monitoring the air (Figure 3-3).

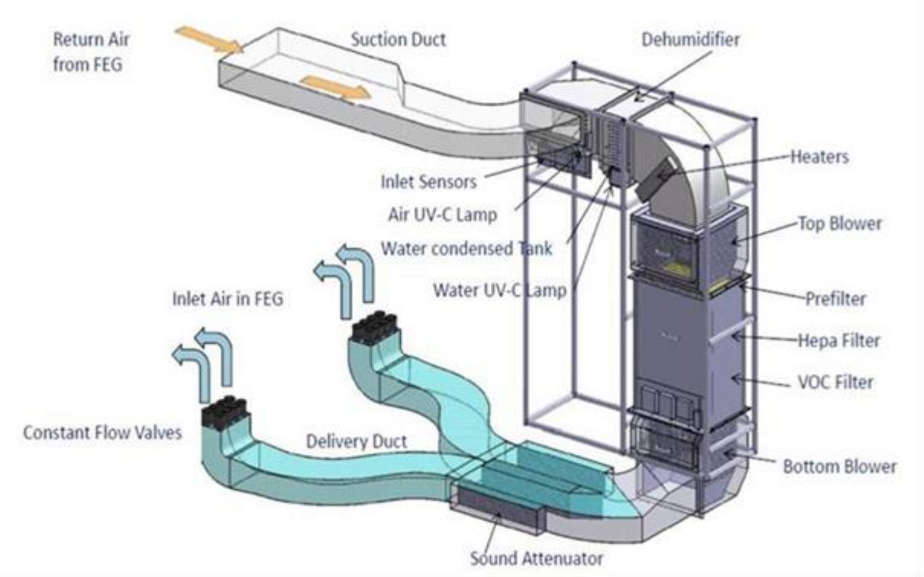


Figure 3-3 Components of the AMS of the EDEN MTF located in the service section [70]

The treatment of the return air from the FEG starts with a UV-C lamp to prevent microbiological build-up. The dehumidifier extracts the transpired water from the plants via condensation. The condensed water is collected in a suitable tank. Post-processing of the water is done via a UV-C lamp for water disinfection. This processed water is then re-introduced into the circuit and used, for example, in the NDS of the greenhouse. The air, in the meantime, is heated up again to a suitable temperature for the plans. Afterwards the air is filtered from particles, dust and volatile organic compounds (e.g. ethylene) by a filter unit,

consisting of a pre-filter, HEPA filter and VOC filter. After passing the second fan, the air stream is distributed into two horizontal ducts and led along the walls of the container. At the FEG outlet the O_2 level is measured and documented to observe the O_2 production by the plants. Additionally, the CO_2 level is measured at the FEG outlet and inlet. If the CO_2 level declines below a certain threshold, CO_2 is injected at the FEG inlet from an external gas cylinder. [70]
The second part contains the components responsible for the air distribution in the FEG (Figure *3-4*).

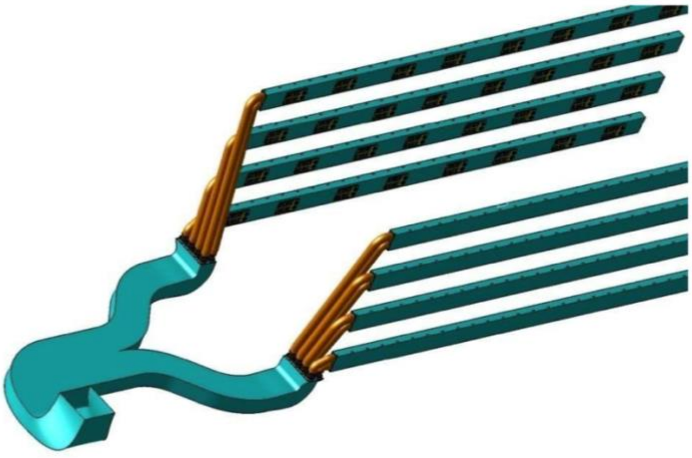


Figure 3-4 Components of the AMS of the EDEN ISS MTF located in the FEG [70]

The air inlet into the FEG is realised with two horizontal ducts. Each of the two ducts is again divided into four separate ducts located on different height-levels. To ensure balanced air distribution at the crops, the diameter of the horizontal ducts decreases to their ends. Settable and closable louvers placed at defined intervals in the ducts allow for the manual adaption of distributed air flow into the FEG. This gives the possibility of zones with different ventilation rates. In order to mix the air and obtain a more homogeneous climate in the FEG, eight tangential fans are located overhead at both sides of the aisle. [70] During the operation phase of the MTF prototype in Antarctica insight on the system was gained and lessons were learned. These led to adjustments for the future design of the EDEN Next Gen module. The lessons learned concerning the AMS and their consequences were collected and elaborated by the EDEN team.

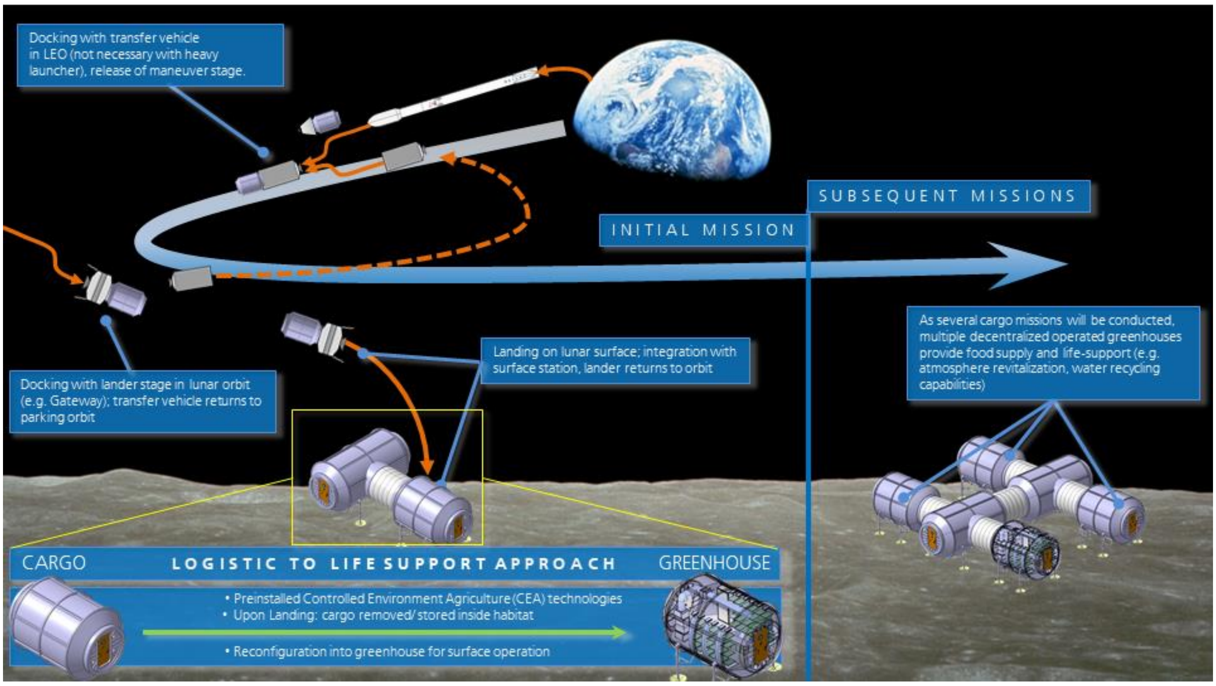
Table 3-1 summarises these lessons learned and the consequences for the EDEN Next Gen module updated for the design in 2023.

Table 3-1 Selection of lessons learned from the EDEN ISS MTF important for the AMS (with reference to [71])

ID	Lesson Learned	Consequences for EDEN Next Gen - Status 2023
LL-AMS-01	CHX performance not sufficient enough to reduce the relative humidity to the set value, since the water load was larger than originally expected.	Three setting parameters for the CHX available: increase of the cooling fluid mass flow rate, the condensation area or the mass flow rate of the air. Check which of the parameters can be implemented.
LL-AMS-02	Sensors for measuring trace contaminants increases the saftey for the crew working in the greenhouse.	Redundancy of sensors for monitoring trace contaminants.
LL-AMS-03	Microbial loads pose a problem in the greenhouse. The CHX microbial growth is critical and the UV-C lamp used was not sufficient. In addition, the access to clean the CHX from microbial growth was limited due to the confined space and the interfaces with the secondary structure.	The filter unit (pre- and HEPA filter) shall be placed upstream the CHX/at the inlet of the AMS, if applicable, to reduce the risk of contamination. The HEPA filter must be made of water repellant material to filter efficiently at high relative humidity. TBD if UV-C lap is necessary.
LL-AMS-04	The UV-C disinfection lamp should be reduced in size, and the lamp should be cooled. Furthermore, redundancy is necessary.	No additional cooling or redundancy strategy is foreseen for the UV-C lamp. The UV-C lamp is adapted to the irradiation of the air duct.
LL-AMS-05	No actual use of the possibility to regulate the air sizing of the supply air ducts on the four different levels.	No adjustable louvers are applied anymore.

3.2 EDEN Next Gen

The EDEN Next Gen mission is the next step to reach the goal of future closed-loop habitats for extra-terrestrial missions. As for now, only a preliminary mission scenario is given as no detailed plans exist for actual space-qualified missions. In the near future, the first long-term mission requiring a greenhouse module will most likely target Moon surface as the final destination. [5] The EDEN Next Gen mission scenario can be seen in Figure *3-5*. It will possibly be split into two parts: the initial mission, followed by subsequent missions.



Docking with transfer vehicle in LEO (not necessary with heavy launcher), release of maneuver stage.

Docking with lander stage in lunar orbit (e.g. Gateway); transfer vehicle returns to parking orbit

Landing on lunar surface; integration with surface station, lander returns to orbit

As several cargo missions will be conducted, multiple decentralized operated greenhouses provide food supply and life-support (e.g. atmosphere revitalization, water recycling capabilities)

- Preinstalled Controlled Environment Agriculture (CEA) technologies
- Upon Landing: cargo removed/ stored inside habitat
- Reconfiguration into greenhouse for surface operation

Figure 3-5 Possible mission scenario for the EDEN Next Gen module [internal source – DLR]

In the initial mission, the module first docks with the transfer vehicle in low earth orbit (LEO) and releases the manoeuvre stage. After that, it docks with the lander stage in lunar orbit, while the transfer vehicle returns to the designated parking orbit. Finally, the module lands on the lunar surface and is integrated with the surface station while the lander returns to the orbit. In the subsequent missions, several cargo missions will be conducted, and multiple decentralised operated greenhouses provide food supply and life-support to the long-term habitants on Moon. The module follows the logistics-to-life support approach. In the initial mission it will be used as a cargo module for the supply of the habitat and the future greenhouse. The CEA technologies are already pre-installed. After the descent to the planet's surface, the cargo is removed, and in the second mission the module will be converted into the actual greenhouse for service operation.

A ground test demonstrator is the research basis to achieve the planned mission scenario and the next step in the EDEN Next Gen project. The mission shall demonstrate the ground-based verification of a closed-loop BLSS with independent fresh food production for humans in form of a greenhouse habitat. The focus shall be on self-sustainable food production with biological waste treatment systems, air revitalisation, water recycling and well-being. The test demonstrator will consist of the greenhouse test demonstrator and a habitat simulator, which are connected via an airlock/transfer corridor. The habitat simulator is used to test the closed-loop approach of CEA with humans involved in the loop. The thermal control system is placed next to the simulator for easy access. [72] The preliminary set-up can be seen in Figure *3-6*.

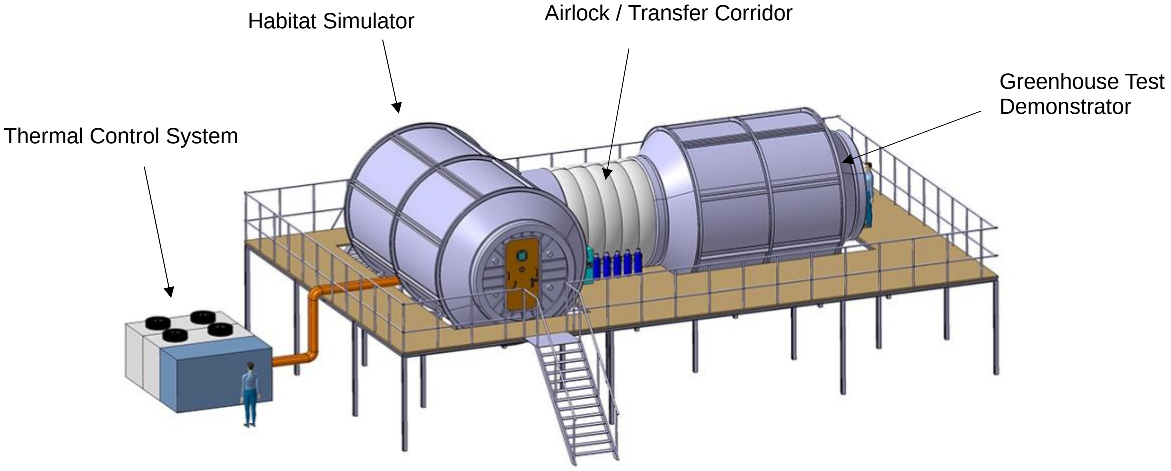


Figure 3-6 Possible layout of the ground test demonstrator [72]

Original Design for the Lunar Greenhouse Module

The first design of the future planetary greenhouse was developed in 2020/2021, as an adaption of the EDEN ISS MTF. Based on the lessons learned compiled during the Antarctic operating phase of the MTF and the mission scenario of the future greenhouse module, the system requirements were defined. [5]

This draft was therefore the baseline of prior calculations and design steps. The first configuration was designed to fit into the fairing of a SpaceX Falcon 9 launcher. This is why the diameter of the module was adjusted to the available dimension of the rocket (Figure *3-7*). The required amount of cultivation area was set to be twice as much as the area in the MTF. This led to the previous design consisting of a deployable cylindrical structure, with rigid end caps, including the service section, and an inflatable membrane shell in between. The structure can be seen in Figure *3-7*.

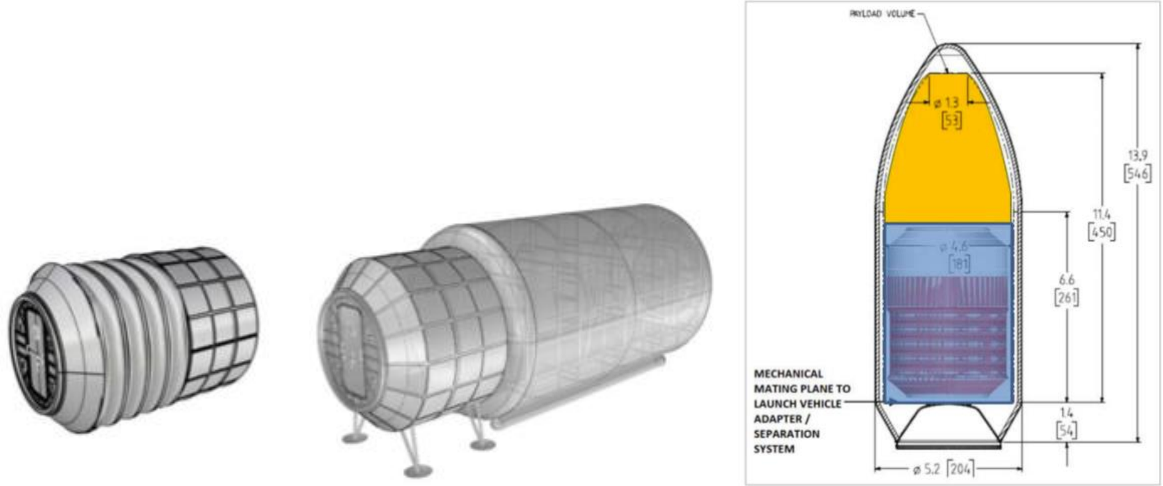


Figure 3-7 Previous EDEN Next Gen greenhouse module (left side: stowed configuration; middle: deployed configuration) and stowed configuration of the greenhouse module inside the Falcon 9 launcher, inclusive protection shield (blue) and volume for the service [5]

The complete module consists of the cultivation area and the service section. In the cultivation area the crop cultivation and harvesting are done. The service section contains the AMS and other subsystems, like the NDS and the secondary payload. Also, it is used as storage and working area for the astronauts. Figure *3-8* gives an overview on the preliminary placement of the subsystems inside the module. The illumination system, parts of the NDS, thermal control system and AMS are housed in the deployable part. The other subsystems of the greenhouse are located in the rigid part.

A brief overview of the subsystems and their tasks is given below:

Power Control and Distribution System (PCDS)

The PCDS divides and supplies the incoming power from the habitat to the different subsystems. [5]

Atmosphere Management System (AMS)

The task of the AMS is to guarantee defined atmospheric conditions in the greenhouse module. Therefore, the air is revitalised in different process steps before being distributed and dimensioned in the cultivation area. [5]

Nutrient Delivery System (NDS)

The NDS is responsible to adjust the mixing ratio of the nutrient solution according to the crops, as well as the continuous supply of the solution to the plants. [5]

Thermal Control System (TCS)

The task of the TCS is to keep the temperature in the greenhouse in a prior defined range, to ensure optimal growing conditions for the plants. [5]

Control and Data Handling System (CDHS)

All systems are monitored and controlled by the CDHS. Data from cameras and sensors are also processed by the CDHS. [5]

Illumination System (ILS)

The ILS illuminates all the different sections of the greenhouse module, including the working area, the subsystems and the cultivation area. Lights with specific wavelength optimal for plant growth are used in the cultivation area. [5]

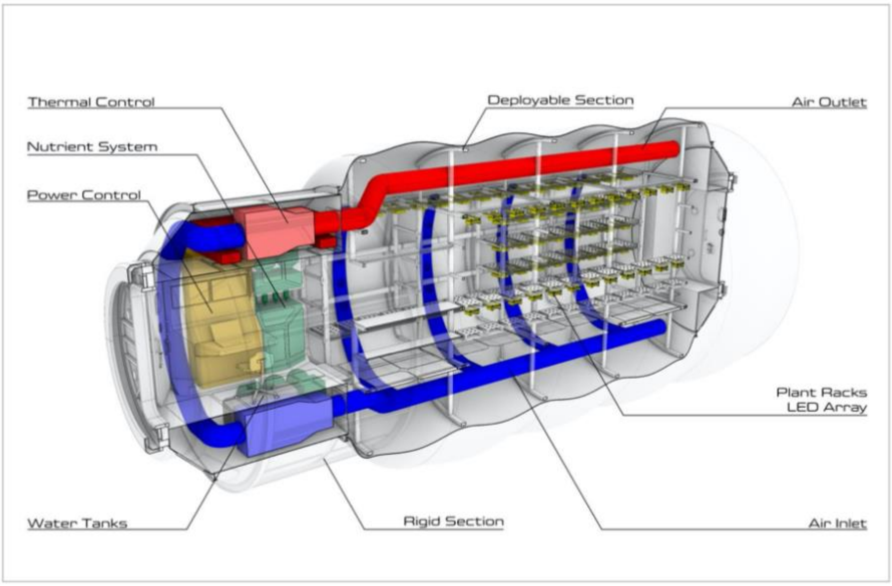


Figure 3-8 View inside the greenhouse module with the preliminary placement of the different subsystems [5]

The layout of the AMS was developed by Julius Schroth within his thesis on the development of the AMS of the EDEN Next Gen greenhouse module. An overview of the main components of the AMS and their preliminary placement can be seen in Figure *3-9*.

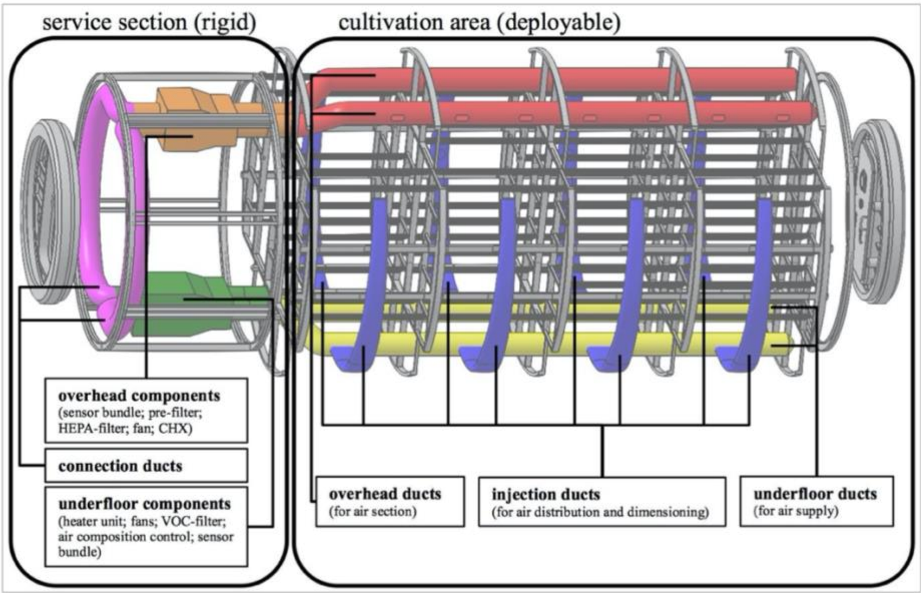


Figure 3-9 Overview of the main components of the AMS and their preliminary placement [71]

The components of the AMS responsible for the monitoring and treatment of the air are located in the top and bottom segment of the service section. The overhead and underfloor components are responsible for different tasks and are linked through the connection ducts in the conical part of the module. The deployable section contains the components for the air distribution. The overhead ducts (here in red) suck the air out of the cultivation area into the AMS. The underfloor ducts (here in yellow) and the injection ducts (here in blue) supply the cultivation area with revitalised air as well as distribute it in the cultivation area. Figure *10-1* shows the preliminary layout of a possible sequential arrangement of the technical components, which was created as a result of a previous technology trade-off.

New Design: Lunar Agriculture Model

The design of the greenhouse module was changed in the beginning of 2022. In the following, the current preliminary design of the Lunar Agriculture Model is introduced, the additional flexible secondary life support elements are briefly described and the preliminary placeholder of the AMS is presented.

In the new design approach, the deployable aspect of the greenhouse configuration is dropped and changed to a completely rigid structure. The configuration is still designed to fit into the SpaceX Falcon 9 launcher. For now, the overall design of the AMS and the components from the old design will be adapted as a baseline for this thesis. This is the starting point of this thesis.

Figure *3-10* shows the new concept design of the EDEN Next Gen greenhouse module. On the left side, the outer shell of the model is shown. The inner configuration, including the different sections, can be seen on the right side.

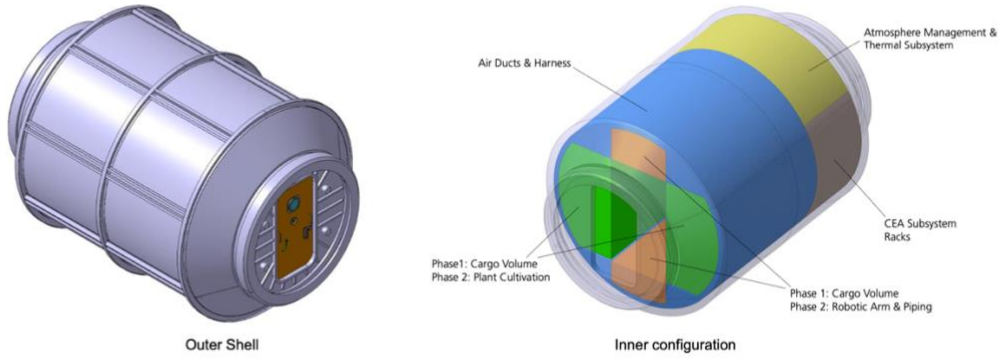


Figure 3-10 New concept design of the EDEN Next Gen greenhouse module (left side: outer shell; right side: inner configuration) [internal source – DLR]

Figure *3-11* and Figure *3-12* show the internal layout of the greenhouse module including the preliminary placement of the subsystems. The cultivation area in this design configuration is reduced to 14.6 m^2, which corresponds to an area comparable to the MTF. As a result, the number of trays decreased as well. This design concept foresees 40 trays with a tray size of 50 mm x 70 mm and four trays with a tray size of 30 mm x 50 mm.

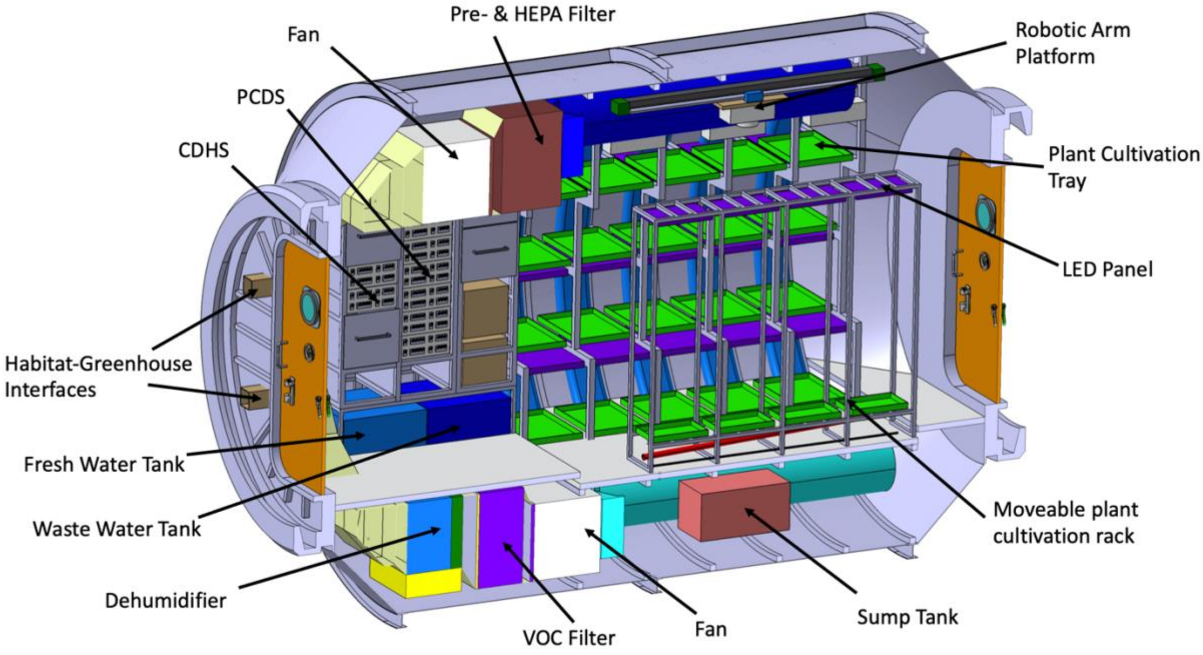


Figure 3-11 Section view 1 of the greenhouse [72]

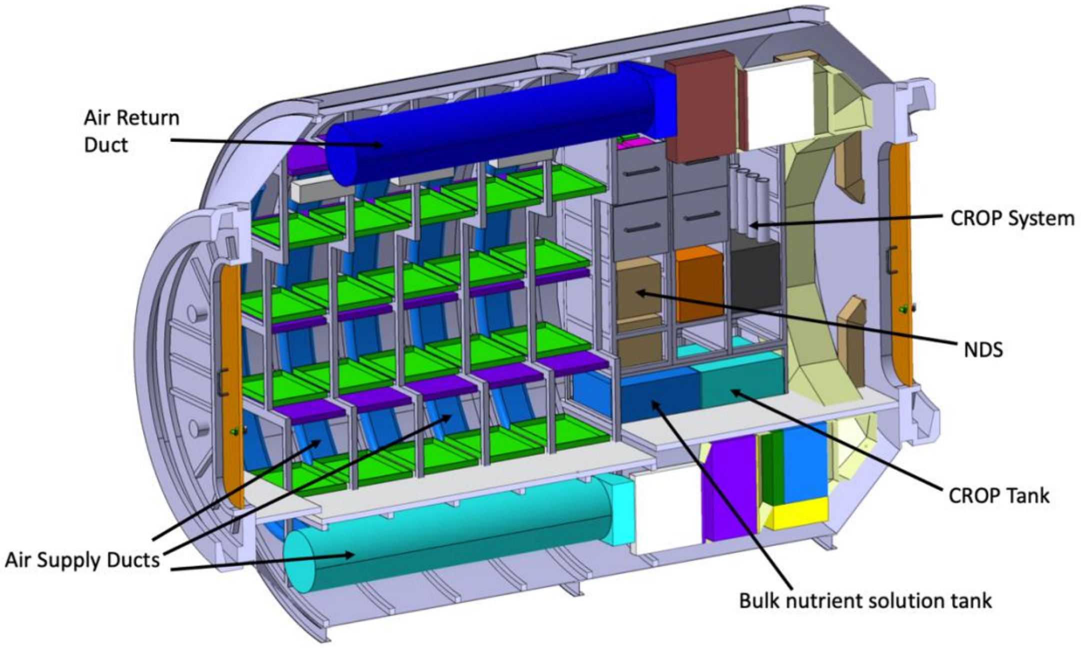


Figure 3-12 Section view 2 of the greenhouse [72]

The placement of the AMS is the same as in the old design. Therefore, the components of the AMS responsible for the air-revitalisation are located in the overhead and underfloor segment of the service section. The components for the air distribution and dimensioning are still located in the overhead and underfloor segment of the cultivation area. A new feature is the integration of flexible secondary life support elements located on multipurpose rack systems in the service section. The secondary payload for the GTD will be the combined regenerative food production (C.R.O.P) by DLR, a bacteria filter unit for the treatment of urine to use in plant cultivation or fertiliser production. [73]

The design changes have an influence on the calculations and therefore on the dimensioning of the components. All calculations have to be adapted to the new design and the changed parameters. The new geometric parameters important for the design of the AMS are given in the following Table *3-2*. Details on the dimensions and the outline of the module can be found in Appendix 10.1.

Table 3-2 Dimensions of the greenhouse module important for the design of the AMS

Characteristic	Value for configuration	Comment
effective inside volume	$V_{GHM} \approx 84\ m^3$	important for the air flow rate
inside diameter of the service section	$d_{Service\ Section}$ = 4.20 m	important for maximum size of components for air revitalization
length of the service section	$l_{Service\ Section}$ = 1.47 m	important for maximum size of components for air revitalization
inside diameter of the cultivation area	$d_{Cultivation\ Area}$= 4.20 m	important for air inlet infrastructure
length of the cultivation area	$l_{Cultivation\ Area}$ = 3 m	important for air inlet and outlet infrastructure
space to connect underfloor and overhead components (conical part in the service section)	$l_{Service\ Section\ conical\ part}$ = 0.95 m $V_{Service\ Section\ conical\ part\ total} \approx 9.76\ m^3$	important for the connecting ducts for overhead and underfloor components and the interface to the habitat for the CO_2/O_2 exchange
conical part in cultivation area	$l_{Cultivation\ Area\ conical\ part}$ = 1.18 m $V_{Cultivation\ Area\ conical\ part\ total} \approx 12.12\ m^3$	possible space to mount the overhead and underfloor ducts
space for vertical air distribution ducts	Not specified but limited by the design of the racks for the plant trays and by the stowage strategy.	important for the vertical curved air distribution ducts
cultivation area	$14.6\ m^2$	important for the calculation of transpired water, as well as O2 production and CO2 uptake
number of trays	50 mm x 70 mm = 40 trays, 30 mm x 50 mm = 4 trays total number of trays: 44	important for the performance requirements of the AMS components

3.3 Summary of the Initial Situation

In this chapter, the focus has been on providing an overview of the initial situation within the EDEN team to achieve the design of the AMS for the EDEN Next Gen module. It was stated that space-rated systems require extensive testing on Earth before being considered reliable for space applications. Figure *3-13* illustrates the need for research and testing of new developments. Therefore, the next step in the EDEN Next Gen project is the design, set-up and operating phase of a BLSS ground test demonstrator.

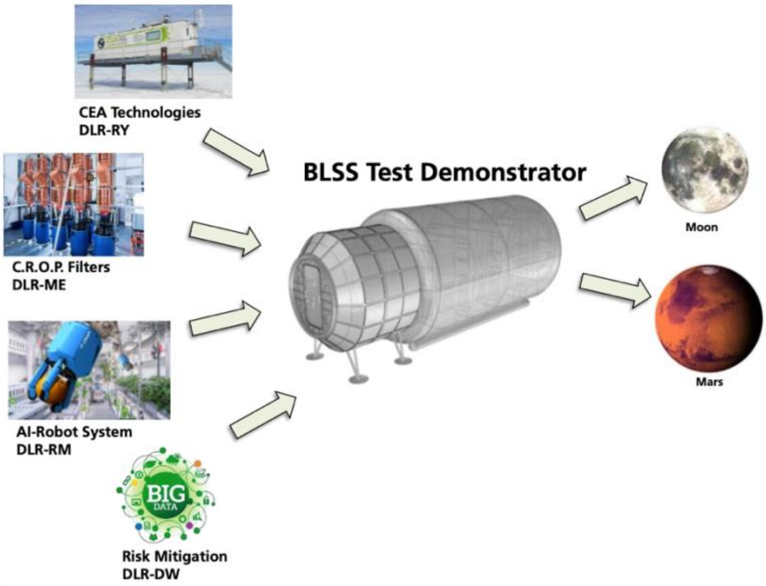


Figure 3-13 Research roadmap for future space missions [74]

The EDEN ISS Mobile Test Facility was briefly described, while the emphasis has been on the design process of the old design as well as the recent design changes of the EDEN Next Gen greenhouse module. The consideration of these design changes is important for the layout of the AMS as well as for the re-calculation of necessary performance and geometric values with regard to the subsystem. For now, the preliminary layout and arrangement of components of the AMS stay unchanged and are the baseline for this thesis.

4 System Analysis

This chapter outlines the defined requirements and assumptions for the design of the EDEN Next Gen greenhouse module. The components, boundary conditions and functional block diagram of the AMS are given. In addition, the internal and external thermal loads are calculated for the dimensioning of the AMS components.

4.1 Requirements and Assumptions

In order to design the AMS of the EDEN Next Gen greenhouse framework conditions have to be determined. To calculate the numerical values of the system design, requirements and assumptions for the system have to be defined. The following subchapter provides these requirements and assumptions.

In September 2022, a Concurrent Engineering (CE) study was carried out in the CE-facility at DLR Bremen. Prior to the study, the requirements for the AMS on subsystem level were defined with the lessons learned from the operation in Antarctica. Additional requirements were added over the course of the study. The requirements are listed in Table *4-1*.

In order to calculate the numerical values for the system design assumptions had to be made about the greenhouse module. Table *4-2* outlines these assumptions and gives reason for the decisions made. Given are the main top-level assumptions for this design. Further assumptions are presented where needed.

Table 4-1 Requirements for the design of the AMS

ID	TITLE	DESCRIPTION	RATIONALE	VERIFICATION METHOD
AMS-0001	Temperature control	The AMS shall monitor the inside temperature within the following range: - temperature 16 °C - 27 °C (accurate to a set point of ± 1 K)	The temperature must be monitored by the AMS and controlled by the DCHS in the set temperature range to ensure successful plant growth and an acceptable environment for human comfort.	analysis, test
AMS-0002	Humidity control	The AMS shall monitor the interior relative humidity within the following range: - relative humidity between 55 and 80% at accurace of +/- 5%	The rel. humidity must be monitored by the AMS and controlled by the DHCS in the set range to ensure successful plant growth and an acceptable environment for human comfort. The rel. humidity must be controlled so that dew point does not lead to condensation on internal surfaces (risk of microbial and fungal growth).	analysis, test
AMS-0003	O2 concentration	The AMS shall monitor the inside O2 concentration within the following range: - O2 concentration 19.5 % - 23.5 % (accurate to a set point of ± 1 %)	The O2 concentration needs to be monitored by the AMS and controlled by the DCHS to ensure optimal for plant growth and an accepatble environment for human comfort.	test
AMS-0004	CO2 concentration	The AMS shall monitor the inside CO2 concentration within the following range: - CO2 concentration 500 ppm – 1500 ppm (accurate to a set point of ± 50 ppm)	The O2 concentration needs to be monitored by the AMS and controlled by the DCHS to ensure optimal plant growth and an accepatble environment for human comfort. A CO2 concentration above 1000 ppm can cause first symptoms (headache) in human health and should therefore be avoided.	test
AMS-0005	Total pressure	The AMS shall monitor the inside total atmospheric pressure within the following range: - total atmospheric pressure 101.3 kPa (accurate to a set point of ± 10 kPa)	The total atmospheric pressure needs to be monitored by the AMS and controlled by the DHCS to ensure optimal plant growth and an acceptable environment for human comfort. Therefore the total atmospheric pressure shall be kept around standard atmosphere pressure.	test
AMS-0006	AMS air flow control	The AMS shall monitor the air flow rate and air flow velocity at the plants within the following ranges: - air flow rate that is required to guarantee a safe environment for plants and humans (determined later) - reference value for air flow rate: EDEN ISS 1400 m³/h - air flow speed at plant 0.3 m/s – 0.7 m/s (accurate to a set point of ± 0.1 m/s)	The air flow must be monitored by the AMS and controlled by the DHCS to revitalise the air and to dissipate the heat in the cultivation area. This ensures optimal plant growth and an acceptable comfort level for humans. A regulated air flow speed exchanges the air at the plants without harming them.	test
AMS-0007	Ethylene control	The AMS shall monitor the ethylene level within the defined range. The ethylene level shall not exceed 50 ppb.	The ethylene level must be monitored by the AMS and controlled by the DCHS to ensure optimal plant growth. Ethylene is a plant hormone, which is important for plant growth and well-being, but too much ethylene in the atmosphere can harm the plant growth, resulting in loss of yield.	test
AMS-0008	VOC concentration	The AMS shall monitor the level of all volatile organic compounds (VOC). The VOC level shall not exceed 200 ppb.	The VOC level must be monitored by the AMS and controlled by the DHCS to ensure optimal plant growth and an acceptable environment for human comfort. Exposure to VOC vapors can cause a variety of health effects, including headaches.	test
AMS-0009	AMS gas exchange	The AMS shall be designed to exchange O2 and CO2 with the habitat.	The CO2/O2 interfcae to the habitat injects CO2 enriched cabin air into the greenhouse and O2 enriched greenhouse air into the habitat. This exchange shall close futher loops in the BLSS approach.	review of design
AMS-0010	AMS maintenance	The AMS modular design shall allow easy access to each equipment group to guarantee quick maintenance.	The easy access to each equipment group facilitates and speeds up maintenance and replacement of parts. The downtime of the AMS is shortened and plant growth is not affected.	review, test
AMS-0011	AMS failure tolerance	The AMS shall be one failure tolerant.	Redundancy of equipment critical for the maintaining of the atmoshperic conditions ensures continuous plant production and a save environment for humans.	review, test

Table 4-2 Assumptions made for the design of the AMS [71]

ID	Assumption	Reason
A01	Due to a protecting regolith layer is the ambient temperature of thegreenhouse module constant at Ta = 254 K	The (subsurface) temperature is expected to be stable at a regolith layer thickness of tR > 0.5 m. At equatorial regions temperature stability is guaranteed at regolith layer thicknesses of tR ≥ 0.3 m).
A02	Due to a protecting regolith layer is the radiation (particles, solar, galactic cosmic) on a safe level	For radiation protection the regolith cover is expected to be tR > 0.5 m.
A03	At the outside surface of the greenhouse module there is only radiation for heat transfer.	Due to the negligible atmosphere on the Moon heat transfer via convection can be neglected.
A04	Internal thermal loads, including the AMS, all other subsystems, and plants, will be estimated by scaling the (empirical) values from the EDEN ISS MTF.	More details on scaling and resulting values in chapter 4.2.2.
A05	Unexpected changes of external and internal thermal loads can first be buffered by: 1. the TCS of the greenhouse module and 2. the connected TCS of the habitat.	Unexpected changes of external and internal thermal laods include higher outside temperatures and failure of critical components. Due to applied safety margins it is very unlikely that the two backup systems are needed.
A06	The gravity acceleration of the entire operation phase of the greenhouse module is constant at gM = 1.625 m/s².	This value is the mean normal gravity acceleration on the Moon surface.
A07	Pressure losses (e.g. due to leakage) are neglected. The atmospheric pressure inside the greenhouse module is guaranteed by the AMS and the structural design of the habitat.	The seals and surrounding structure of the structural design are as close as possible. The greenhouse module of the GTD is connected to the habitat module.
A08	All metabolic rates concerning plants are considered to be static.	Since the design process of this thesis is only a very first step for rough performance estimation it is sufficient to consider the process of photosynthesis to be static even though it is a light driven process and dependent on the dynamic light intensity.
A09	To determine the metabolic loads of the plants a sample plant configuration is used.	Due to the early stage of the development process but also during the mission this configuration might change. To cover that a margin is applied.
A10	Plants effects on trace contaminants in atmosphere is not considered.	The influence of higher plants on the concentration of trace gases is very slight and can be neglected.
A11	Thermal loads induced by humans working in the greenhouse are not considered.	The influence of emitted heat by humans is neglected at the first development step (Q ≈ 150 W per person expected at greenhouse work). The working hours in the MTF were around 20 h/$week$. It is expected that this time can be reduced with more reliability and more automation.
A12	The metabolic impact of O_2 to CO_2 conversion by humans working in the greenhouse is not considered.	Expected O_2 consumption of mi _0_2 ≈ 0.05 kg/h and CO_2 output of mi _CO_2 ≈ 0.065 kg/h at a working time of tw ≤ 20 h/week are neglected.
A13	The metabolic impact of transpiration (perspiration and vaporized exhaling air) from humans working in the greenhouse is not considered.	Expected transpiration rate of mi _H_2O ≈ 0.12 kg/h at a working time of tw ≤ 20 h/week is neglected.
A14	The metabolic impact on trace contaminants by humans working in the greenhouse is not considered.	Expected metabolic impact on trace contaminant concentration during working time of tw ≤ 20 h/$week$ is negligible.

4.2 Numerical Values for the System Design

In addition to conditioning and distributing air, the tasks of the AMS also include removing heat from the greenhouse to keep the temperature in a defined range to enable optimal plant growth. For the design of the various components of the AMS, the relevant thermal loads must therefore be considered. The thermal loads are composed of system internal and external loads. Relevant to the internal loads, aside from the selected crops, are the heat loads of the different sub-systems of the greenhouse. Thermal energy is dissipated by the subsystems, which has to be taken into account for the overall thermal load. [71]

With the completion of the first CE-study, the design is still at an early stage, which demands an upscaling of the subsystems used in the EDEN ISS MTF. External loads (see Chapter 4.2.4) cover all factors outside of the module that have an influence on the thermal balance of the overall system. As stated before in Table *4-2* the metabolic impact and thermal loads of humans working in the greenhouse are not considered. In addition, all metabolic rates concerning plants are considered to be static.

4.2.1 Relative and Absolute Values of Selected Crops

Photosynthesis is the process by which plants use water, sunlight and carbon dioxide (CO_2) to create oxygen (O_2) and energy in the form of sugar. This process also happens in the greenhouse and can be used for the CO_2/O_2 exchange between habitat and module. [75] Plants also have an influence on the internal thermal balance of the greenhouse.

Transpiration is the process of evaporation of water (from plants' leaves, stems and flowers) and is used by the plants to cool (themselves) down if the temperature of the environment rises beyond their comfort zone. [76] For the change of physical state from liquid water to vapor the plant needs to overcome an energy barrier, which is called the latent heat of vaporization. To do so, the plant uses the internal thermal load inside the module, which results in a negative effect on the total thermal balance. [77] Figure *4-1* shows plant processes like vaporisation and photosynthesis that influence the atmospheric parameters.

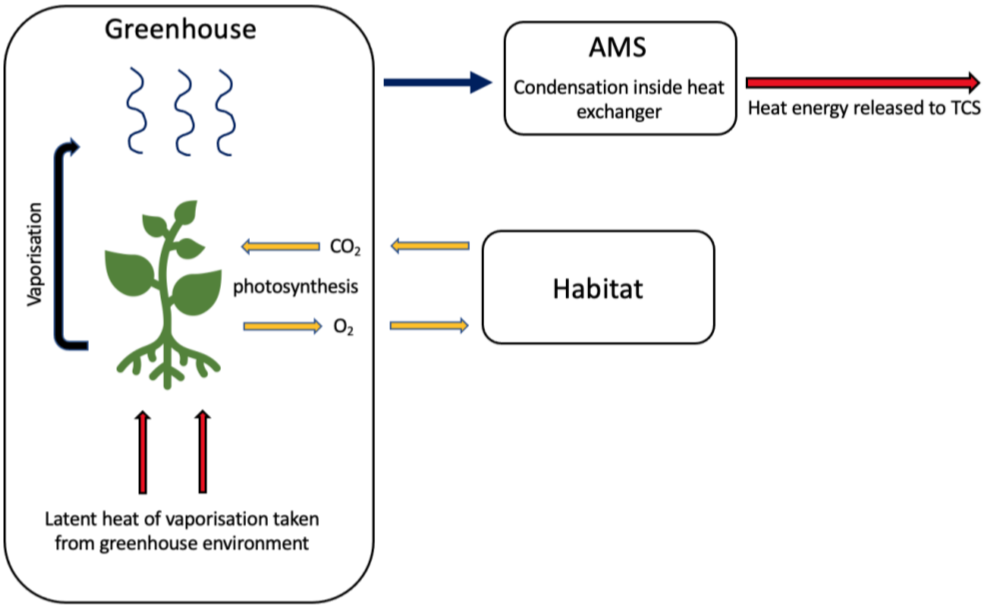


Figure 4-1 Inputs and outputs of plants with effect on the atmospheric parameters

Table *4-3* shows a possible crop selection suitable for the greenhouse module. The selection was chosen from [3]. It was adapted to the total cultivation area of 14.6 m^2 and the total tray number of 44. The absolute values are calculated by taking the average of the relative values and multiplying by the tray area. Table *4-3* states the relative and absolute values of O_2 production, CO_2 usage and the transpiration rate on average by the plants.

Table 4-3 Relative and absolute values of the selected crops [3] [78] (based on [71])

Relative values				
Crop	**Trays (area)**	**Average O_2 production rate**	**Average CO_2 uptake rate**	**Average transpiration rate**
	[-] / [m²]	[g/m²d]	[g/m²d]	[kg/m²d]
lettuce and leafy greens	24 (8.4)	9.01	12.40	1.77
herbs	5 (1.75)	10	15	1.5
fruits	9 (2.35)	26.36	36.24	2.77
tubers	6 (2.1)	11.86	16.31	1.77

Absolute values				
Crop	**Trays (area)**	**Average O_2 production rate**	**Average CO_2 uptake rate**	**Average transpiration rate**
	[-] / [m²]	[g/d]	[g/d]	[kg/d]
lettuce and leafy greens	24 (8.4)	75.68	104.16	14.87
herbs	5 (1.75)	17.5	26.25	2.63
fruits	9 (2.35)	61.95	85.16	6.5
tubers	6 (2.1)	24.9	34.25	3.72
Total	44 (14.6)	≈ 180	≈ 250	≈ 28
Total + margin (100 %)	**44 (14.6)**	**≈ 360**	**≈ 500**	**≈ 56**

Important for further calculations are the absolute values of the selected crops with the addition of a margin of 100 %, to include all possible crop selections and therefore the variation of values. The average O_2 production rate is $360\ \frac{g}{day}$, while the average CO_2 uptake, is $500\ \frac{g}{day}$, both including the margin. The average transpiration rate, including margin, is $56\ \frac{kg}{day}$. The transpiration rate is used to calculate the negative effect of plant growth on the total thermal load inside the greenhouse.

4.2.2 Internal Thermal Loads – Subsystems

The different subsystems dissipate thermal energy to the module. In order to keep the environment in the defined temperature range these loads have to be removed from the module by the AMS. The following Table *4-4* outlines the internal thermal loads per subsystem for the day-time period and the night-time period. expressed in watts. It also includes the conversion strategy and the upscaling calculation for a better understanding of the calculated parameters in relation to the MTF.

Compared to the EDEN ISS MTF and the previous design of the EDEN Next Gen module, the heat dissipation of the ILS is completely air-cooled. This is the result of the trade-off study of air-cooled versus water-cooled LED-system as stated in Chapter 4.2.3. This is why the applied conversion strategy had to be adjusted and the thermal loads for the subsystem increased. With regard to Table *4-4*, it can be observed that the ILS has the strongest influence on the loads. A maximum thermal load of $\dot{Q}_{subsystems\ day} = 8058\ W$ during the day-time period and $\dot{Q}_{subsystems\ night} = 2063\ W$ during the night-time period was calculated (Table *4-4*). For the design of the AMS components the maximum internal thermal loads, without the impact of plants, is assumed. This is done to ensure the sufficient sizing of the components and to prevent the malfunctioning of the system. It has to be noted that an uncertainty regarding the accuracy of these values exists. This can result in a larger thermal load than calculated.

Table 4-4 Internal thermal loads of the different subsystems of the greenhouse module (based on [71])

Subsystem	Applied conversion strategy	Upscaling calculation		Day-time period [W]	Night-time period [W]
AMS Main heat dissipation from the fans and ~ 20 % is dissipated to environmental air [70]	Volume, the air is distributed to, is taken as equivalent to the required fan power. A margin of 10 % is applied due to the additional gas exchange interface. This strategy is applied to the in-duct fans and to the overhead air distribution fans.	In-duct fans: Heat disspiated in MTF: day-time 400 W [70] night-time 400 W [70] MTF: 31 m^3 x 12.9 ≈ 400 W EDEN Next Gen: 84 m^3 x 12.9 x 1.1 ≈ 1192 W	Overhead fans: Heat disspiated in MTF: day-time 115 W [70] night-time 115 W [70] MTF: 31 m^3 x 3.7 ≈ 115 W EDEN Next Gen: 84 m^3 x 3.7 x 1.1 ≈ 342 W	1534	1534
ILS Heat disspiation only during day period	The LEDs are air-cooled, therefore the AMS has to compensate the dissipated heat. Tall plants: The LEDs have an electrical power consumption of 250 W and have a heat production of 100 %. Small plants: The LEDs have an electrical power consumption of 124 W and have a heat production of 100 %.	Load calculation tall plants: 250 W x 4 = 1000 W air cooled Load calculation small plants: 124 W x 40 = 4960 W air cooled		5960	0
CDHS Thermal load fraction ~ 20 % [70]	In comparison the the EDEN ISS MTF, more data is recorded (increase in cameras, gas-, humidity-, and temperature sensors). Number of cultivation trays is takes as equivalent to the required power for the CDHS.	Heat dissipated in MTF: day-time 202 W [70] and night-time 170 W [70] day-time: MTF: 40 trays x 5.05 W = 202 W EDEN Next Gen: 44 trays x 5.05 W ≈ 222 W night-time: MTF: 40 trays [3] x 4.25 = 170 W EDEN Next Gen: 44 trays x 4.25 ≈ 187 W		222	187
PCDS Thermal load fraction ~ 20 % [EDEN ISS DESIGN DOCUMENT VINCENT]	Power similar to the MTF is required. Number of cultivation trays is taken as equivalent to the required power for the PCDS. The same heat dissipation is assumed at day- and night-time.	Heat dissipated in MTF: day-time 23.2 W [70] and night-time 23.2 W MTF: 40 trays x 0.58 W = 23.2 W EDEN Next Gen: 44 trays x 0.58 W ≈ 26 W		26	26
NDS Thermal load fraction ~ 20 % [70]	Number of cultivation trays is taken as equivalent to the required power for the NDS. A margin of 20 % is applied due to longer nutrient supply ducts.	Heat dissipated in MTF: day-time 125.5 W [EDEN ISS DESIGN DOCUMENT VINCENT] night-time 125.5 W [EDEN ISS DESIGN DOCUMENT VINCENT] MTF: 40 trays x 3.14 W ≈ 125.5 W EDEN Next Gen: 44 trays x 3.14 x 1.2 ≈ 166 W		166	166
Workbench area and scientific needs Electronic equipment	Service section in the new MTF is the workbench area in the EDEN Next Gen greenhouse module. The same heat dissipation is assumed at day- and night-time. To guarantee enough capability for extensive processes the dissipated heat of the MTF is quintupled.	Heat dissipated in service section of MTF: day-time 30 W [70] night-time 0 W [70] 30 W x 5 ≈ 150 W		150	150
Plants Plants do not define as a subsystem, but they have a thermal imapct on the system due to latent heat with regards to the transpiration process	As for the MTF the amount of transpired water determined the latent heat by applying the vaporization heat. [70] density water: ρ_water = 998 kg/m^3 enthalpy of vaporization: ΔH_water = 2257 kJ/kg ≈ 627 Wh/kg	Transpired water in EDEN Next Gen: maximum (day-time and full-grown plants): 55 l/day ≈ 2.3 l/h (from thermal transpired water calculations) minimum (before germination): 0 l/day maximum: 2.3 l/h x 0.998 kg/l x 627 Wh/kg ≈ 1439 minimum: 0 W		-1439	0
Total	-	-		6619	2063
Total, without plants (for first design)	(more details should be in the loads for different AMS components)	-		**8058**	**2063**

4.2.3 Trade-Off Air-Cooled LEDs vs Water-Cooled LEDs

A trade-off analysis has been conducted for the AMS during the CE-study to decide between water- or air-cooled LED-systems for the illumination of the plants. The current limitation for the cooling system is the size of the Service Section inside the greenhouse module. The AMS has to absorb 20 % of the generated heat in the water-cooled version and 100 % of the generated heat in the air-cooled version. The AMS has to compensate the additional 80% thermal load which impacts the air flow rate, duct diameter, subsystem mass and component size. For the total component length and mass of the air-cooled system in the overhead and underfloor section the example components selected in Chapter 5 are used. Exemplary off-the-shelf components were likewise selected for the water-cooled system but are not described any further. For both options risk, number of components and complexity of the subsystem are expected to differentiate marginally. Table *4-5* shows a comparison between the parameters for the air-cooled and water-cooled LED-system.

Table 4-5 Estimated parameters of the air-cooled and water-cooled LED-system

Parameters	**Air-Cooled LEDs [estimated]**	**Water-Cooled LEDs [estimated]**
Total internal thermal load	$W_{air} = 8058\ W$	$W_{water} = 3298\ W$
Air flow rate	$\dot{V}_{\max\_air} = 7256\ \frac{m^3}{h}$	$\dot{V}_{\max\_water} = 2567\ \frac{m^3}{h}$
Duct diameter	$D_{air} = 566\ mm$	$D_{water} = 337\ mm$
Component size Examples: Dehumidifier - total thermal capability (initial crop balance) Heater - required heat	$Q_{dehumidifer\_air} \approx 18.6\ kW$ $\dot{Q}_{heater\_air} \approx 9.8\ kW$	$Q_{dehumidifer\_water} \approx 8{,}3\ kW$ $\dot{Q}_{heater\_water} \approx 4{,}3\ kW$
Overhead - Total length of components (pre-filter; HEPA-filter; fan; CHX)	$L_{Overhead\_air} = 1.64\ m\ (w/o\ connectors, sensors, interface, etc.)$ $L_{Overhead\_air} \approx 2.20\ m\ (w\ connectors, sensors, interface, etc.)$	$L_{Overhead\_water} = 1.6\ m\ (w/o\ connectors, sensors, etc.)$ $L_{Overhead\_water} \approx 2\ m\ (w\ connectors, sensors, etc.)$
Underfloor - Total length of components (heater; fan; VOC-filter; air composition control; sensor)	$L_{Underfloor\_air} = 1.74\ m\ (w/o\ connecots, sensors, interface, etc.)$ $L_{Underfloor\_air} \approx 2.20\ m\ (w\ connecots, sensors, interface, etc.)$	$L_{Underfloor\_water} = 1.53$ m (w/o connectors, sensors, etc.) $L_{Underfloor\_water} \approx 2$ m (w connectors, sensors, etc.)
Mass estimation (w/o margin)	$M_{total_{air}} \approx 558\ kg\ (w/o\ connectors, sensors, interface, etc.)$	$M_{total_{water}} \approx 384\ kg\ (w/o\ connectors, sensors, interface, etc.)$

A comparison of the values for the water-cooled and air-cooled option shows that the air-cooled option is almost three times larger than the water-cooled option, with almost three times the total heat load and air throughput.

The design of the greenhouse module foresees for the service section a length of approximately 1.5 m plus a length of 0.95 m for the conical part. With the water-cooled LED-system the components of the AMS fit into the overhead and underfloor space in the service section without adjustment. It may be possible to manufacture components in a more compact way to reduce the overall length even further. The preliminary selected components in Chapter 5 do not fit into the overhead and underfloor configuration of the service section without protruding into the cultivation area. Again, a compact design may be possible but otherwise the cultivation area has to be decreased or the length of the greenhouse module itself has to be increased.

It must be noted that the impact on the TCS of both options has to be evaluated. The water-cooled option increases the risk, complexity and number of components for the subsystem due to risk of leaking water into sensitive equipment as well as the pipes, connectors and pumps that have to be implemented in the cultivation area. Taking into account the successful operation heritage from EDEN ISS with a water-cooled ILS cooling system, the water-cooled LED system is a suitable option. The risks need to be tackled in the future design.

In this thesis, however, the air-cooled LED-system with 100 % of generated heat to be tackled is selected for the further design of the AMS. The advantages are that the system is designed for the worst-case scenario and, if the decision is made to change to the water-cooled LED-system, the AMS will be decreased in size and lighter in any case.

4.2.4 Thermal Loads – External Loads

As already mentioned, the external loads cover all environmental parameters of the module that have an influence on the thermal balance of the overall system. In this thesis, both the GTD and the possible mission to the Lunar surface, have to be considered.

Ground Test Demonstrator

The GTD will be set-up in a controlled environment on Earth, which will have a different influence on the thermal balance than the Moon surface. Due to the location of the GTD convective heat transfer will be neglected for the calculations. Heat conduction through the preliminarily defined wall thickness of 4 mm is neglected. Only thermal radiation is considered to keep the design comparable to the lunar mission.

The surrounding temperature of the GTD is considered constant and set to $T_{ambient} = 291\ K$ as a first approach. With the temperature above the dew point ($T_{DP} = 289.7\ K$, see Figure *10-4*), condensation problems are being prevented. The temperature inside the GTD is set to $T_{surface(warm\ case)} = 295\ K$ for the warm case and $T_{surface(cold\ case)} = 291\ K$ for the cold case. Aluminium is chosen as the surface material of the module. The net rate of heat transfer is estimated with the Stefan-Boltzmann law with the assumption that the surface temperature is equal to the one inside temperature of the GTD. The radiation power can be calculated with the following formula [79]:

$$\dot{Q}_{extern} = \varepsilon \cdot \sigma \cdot A \cdot \left(T_{ambient}^4 - T_{surface}^4\right) \tag{1}$$

With ε being the emissivity of the material, σ being the Stefan-Boltzmann constant, A being the area of the radiating object and $\left(T_{ambient}^4 - T_{surface}^4\right)$ being the difference between the fourth power of the inside and outside temperatures. [78] Inserting the values from Table *10-1* into the formula results in a heat transfer of $\dot{Q}_{extern(warm)} = -200\ W$ and $\dot{Q}_{extern(cold)} = 0\ W$ via the outside walls of the greenhouse, and therefore has a negative impact on the total thermal load inside the module.

Lunar Application

The mission scenario foresees a future mission to the Moon surface. On the Moon surface the temperature ranges between -160°C and 160°C, depending on the location. For this reason, the final location of the greenhouse module and the protecting regolith layer composition (texture and density), is of importance to the calculation of the external loads.

The analysis of Ramash B. Mall and Kevin M. Brown shows that regolith fluff has very strong insulating capabilities, causing the Lunar regolith subsurface temperature to remain relatively constant at $T_{Lunar} \approx 254\ K$ at a depth of 30 cm. [81]

Multilayer insulation (MLI) is used to prevent the wall temperature from dropping below the dew point to avoid condensation. An MLI thickness of 2 mm is defined for the preliminary estimation. The greenhouse wall thickness of approximately 4 mm must be verified regarding conductivity in further design steps.

The thermal loads and lunar gravity are taken into account for the design of the AMS. The influence of primary radiation is neglected due to the thickness of the protecting regolith layer, as stated in Table *4-2*. After being exposed to radiation, the regolith itself radiates. For this reason, there remain a significant amount of secondary radiation regardless of the thickness of the protective layer. The secondary radiation has to be considered for the design of the AMS electronics but is neglected for the calculations of the external loads. Gravity is assumed to be constant $g_M = 1.625\ \frac{m}{s^2}$ according to Table *4-2*.

The empirical formula (2), developed by NASA, is used in this thesis to calculate the heat flux q via the MLI with regard to radiation (q_r) and conductance of the space material (q_c) for the warm and the cold case. The given values from Table *10-2* are inserted into [82]:

$$q = q_c + q_r = \frac{C_C \cdot N^{2.56} \cdot T_m}{n}(T_{Lunar} - T_{inside}) + \frac{C_r \cdot \varepsilon}{n}(T_{Lunar}^{4.67} - T_{inside}^{4.67}) \qquad (2)$$

With C_C being a conduction constant, N being the MLI density in $\frac{layers}{cm}$, T_m being the mean MLI temperature, n being the number of facing pairs of low-emittance surfaces within the structure of the MLI, C_r being a radiation constant, ε being the emissivity of the MLI shield layer, T_{Lunar} being the regolith subsurface temperature and T_{inside} being the temperature inside the greenhouse module. [82] With the values from Table *10-2* a total heat flux of

$q_{warm} \approx -7.13\ \frac{W}{m^2}\ (q_{cold} \approx -6.39\ \frac{W}{m^2})$

is calculated. The area of the outside wall of the new design is roughly calculated to

$A_{total} = A_{cylinder} + A_{truncated\ cone\ (left\ side)} + A_{truncated\ cone\ (right\ side)} = 58.98\ \mathrm{m}^2 + 20.42\ \mathrm{m}^2 + 17.81\ \mathrm{m}^2 = 97.21\ \mathrm{m}^2$.

By multiplying the total heat flux with the total area, a heat flow rate of

$\dot{Q}_{extern\ (warm)} \approx -693\ W$ and ($\dot{Q}_{extern\ (cold)} \approx -621\ W$)

via the outside walls of the greenhouse module is determined, and therefore has a negative impact on the total thermal load inside the module.

For the further design of the AMS, the heat flux calculated for the Lunar application is used to ensure sufficient performance for future missions. The dimensioning of the loads in the system analysis and the subsequent component selection for the AMS include conservative margins, which is why a translation to the GTD is possible.

It should be noted that the heat transfer process in this thesis is assumed to be static and that the inside and outside temperature stay constant. Under real conditions, the transfer is dynamic and must be designed for the different modes. The heat transfer process via the outside wall of the module should be analysed in more detail in later design steps.

4.2.5 Set Point Values

For simplification purposes, the cultivation area and the service section are combined into a single area with the same atmospheric parameters (decision made during the CE-study). It is possible that in the future these two areas will be divided by a door to enable different atmospheric parameters in both areas. For now, the values are stated in Table *4-6*. The atmospheric parameters are given for the set point of the warm and cold period and their desired accuracy. A set point is a defined value for a certain parameter, like temperature, which shall be achieved and maintained.

Table 4-6 Overview of set points of atmospheric parameters (based on [70])

Atmospheric parameter	Set Point Warm Period	Set Point Cold Period	Accuracy
Temperature [K]	295	291	0,5
Relative humidity [%]	65	65	5
O_2 concentration [%]	21.5	21.5	1
CO_2 concentration [ppm]	1000	1000	50
Ethylene/VOC concentration [ppb]	50	50	-
Air flow speed at plant [m/s]	0.4	0.4	-
Atmospheric pressure [kPa]	101.3	101.3	10

4.3 Components

The AMS consists of different components to fulfil the defined tasks, as already stated in Chapter 3.2. The components can be divided into functional groups and monitor-and-control groups. Functional components directly perform a task, like the ventilation or the dehumidification of air. A detailed description and dimensioning of the functional unit and the selection of suitable components is given in Chapter 5. Monitor-and-control components ensure the observation of critical parameters and the control to keep them in a defined threshold. The sensors measure the different values and the controller unit collects, reads and regularly compares the reading with the ranges set by the operator. If the value is outside these ranges, then the controller acts upon the pre-set actions that are defined by the operator. The following Table *4-7* presents the functional, monitor-and-control components and their function in the system.

Table 4-7 Functional, monitor and control components and their functions (based on [71])

Functional Components	**Function**
Fan	- air circulation - pressure loss compensation
Dehumidifier	- dehumidify air - condensate storage and transfer
Heater	- temper air
Air Inlet	- air distribution and dimensioning
Air Outlet	- air suction
Filter	- cleaning air
Monitor and Control Components	**Function**
Air Composition Control	- control level/concentration of trace contaminants as well as CO_2 and O_2
Sensors	measure and monitor: - temperature, - static pressure, - CO_2, - O_2, - volatile organic compounds (VOC), - relative humidity and - flow rate

4.4 AMS Functional Block Diagram

The block diagram provides a functional view of the greenhouse module to give a better understanding of the system's functions and interfaces. The block elements visualise processes, hardware and sensor signals of the system. The arrows in between represent the flow direction of different media and help to visualise the interconnection of the different elements. [83] With reference to the EDEN laboratory at DLR Bremen and the preliminary design, changes in the original block diagram were made to adapt the design changes and include the interfaces from the AMS to the habitat, the NDS and TCS. Here, the total AMS is separated into two different segments: the cultivation area and the service section, with the air stream as the interface between the two segments (Figure 4-2).

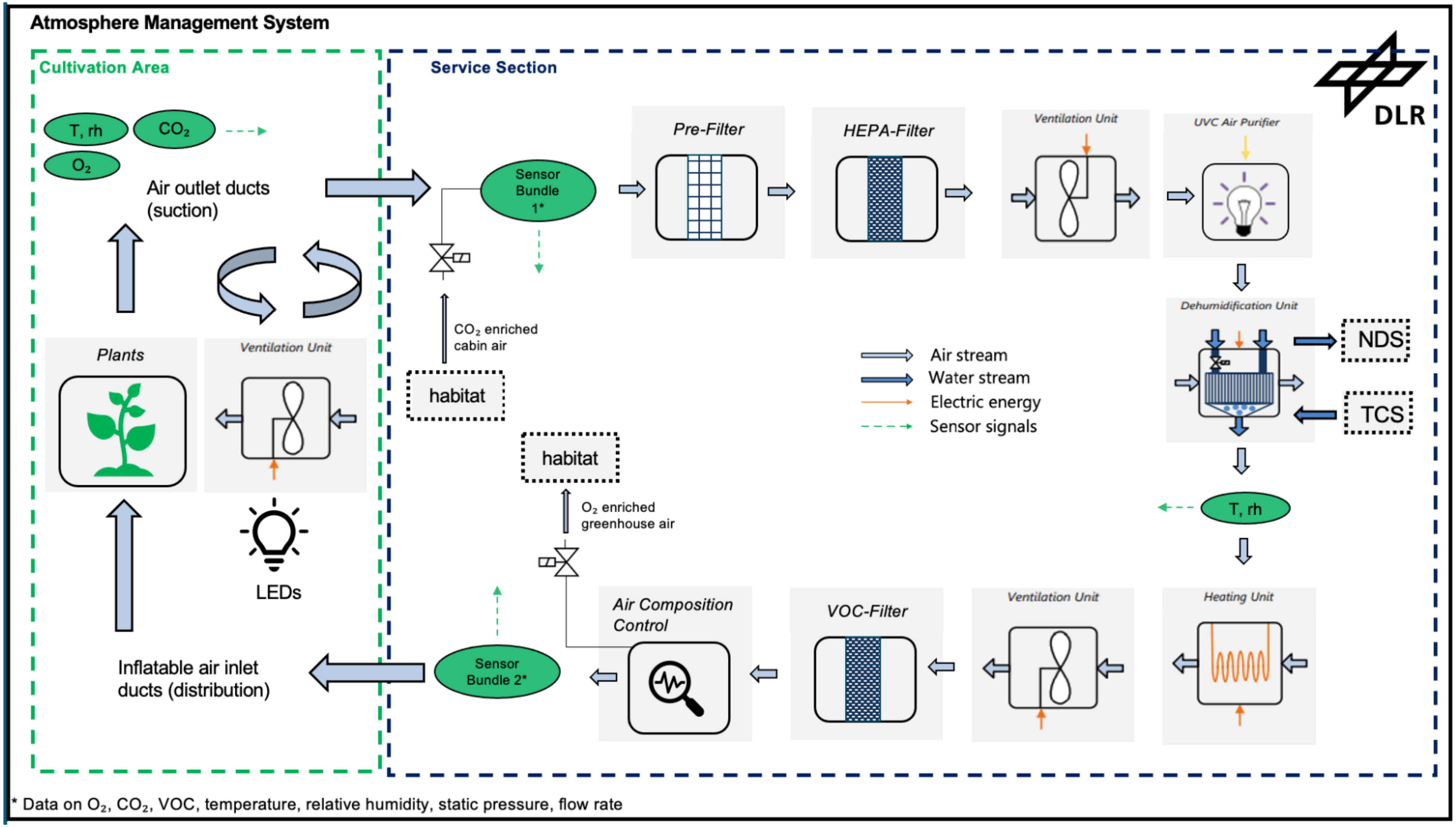


Figure 4-2 Functional block diagram of the AMS for the GTD

Cultivation Area

The cultivation area contains the air inlet and outlet of the AMS. The air inlet ducts are located at the top of the module. The air outlet ducts are placed at the bottom of the module, with additional vertical ducts going up at the sides to ensure an even distribution of the air at the crops. A *Ventilation Unit* will be installed inside the cultivation area to ensure a sufficient air mixture and to prevent air pockets. In addition, sensors to measure the temperature, relative humidity, the CO_2 and O_2 concentration are installed.

Service Section

The first *Sensor Bundle* is placed at the inlet of the AMS to measure the current relative humidity, temperature, static pressure, CO_2 -, O_2 - and VOC- concentration and the flow rate of the air stream. The *Air Filter* is placed behind the sensors to protect the other units from dust and contamination. After the filters, a *Ventilation Unit* provides the necessary air flow and pressure head. The *UV Steriliser* is placed before the *Dehumidification Unit* to prevent pollution of the coils inside the dehumidifier. The *Dehumidification Unit* lowers the humidity by cooling the air below the dew point, which leads to condensation. The condensed water shall be re-used and is therefore treated in a separate process. A detailed description of this process is given in Chapter 5.5.

Before entering the *Heater*, a *Sensor Array* measures the temperature and humidity of the air. The air stream temperature is then increased by the *Heater*. After passing a second fan, the *VOC Filter* filters the air stream. Before the air enters the greenhouse, the second *Sensor Bundle* measures the same parameters as the first to control the air quality and possible pressure drop. A direct interface at to be defined time intervals to the habitat is established to enable the exchange of O_2 and CO_2 between habitat and greenhouse. The CO_2 enriched cabin air is injected right before the first *Sensor Bundle,* to measure and monitor the air composition, and before the *Filter Unit,* to clean the air of any unwanted particles, bacteria and fungi. The interface of O_2 enriched greenhouse air to the habitat is located after the second *Ventilation Unit* due to space limitations.

4.5 Air Direction for Optimal Plant Growth

Air flow and air movement are important to keep temperatures, CO_2 levels and humidity levels in a defined range which is comfortable for the plants. The air flow is a key challenge of the

AMS, as described in the literature research. Reduced air flow quality can cause an insufficient quantity of revitalised air at the crops. This can lead to CO_2 depletion; temperature rise as well as fungal diseases and mould. This means that a regulated air speed and direction must be ensured. [46]

The commonly used air direction in greenhouses is the horizontal air flow. The air movement over the top of the plants provides air flow over the whole racks and therefore removes humidity, introduces more CO_2 in between the racks and removes heat between the racks.

As described in the literature research, the horizontal air flow can lead to air turbulences caused by air friction with surfaces in the space between the crops and the lighting system. [47] The horizontal flow may also provide insufficient air movement between the plants if they are too tightly packed. This can lead to fungal diseases and mould. Therefore, it is important to leave enough space between the individual plants and in between the racks to allow for optimal air movement. [84] A general guideline for the diameter of small to medium sized plants like cabbage, small tomatoes and various salads is 22 cm. This is equivalent to 6 plants per tray. For larger plants such as cucumbers, 1-2 plants per tray are sufficient, which corresponds to a diameter of about 40 cm. [85]

Another option is the air flow from top to bottom or bottom to top through the plants. This enables sufficient air flow through the plants and reduces the risk of fungal diseases, mould, CO_2 depletion and temperature rise. [86] This method can only be used if the plants are freely accessible and not surrounded by structures or components.

In addition to the air direction, the air speed has to be considered. The air speed must be selected so that the plants and the spaces between them are supplied with a sufficient amount of air. A too high air velocity can negatively affect plant growth. The air speed across the plants depends on the type of crop, but in general the desired range of air speed is $0.3 - 0.5 \frac{m}{s}$. [87]

Short Growing Plants

For the short-growing plants, such as lettuce and beans, the horizontal air flow is chosen in the EDEN Next Gen greenhouse module due to the limited space between the racks. Each level has a height of approximately 60 cm and includes the LED-system, NDS supply lines and the crop tray (see Figure 10-2). The air direction between the racks with short growing crops is shown in Figure *4-3*.

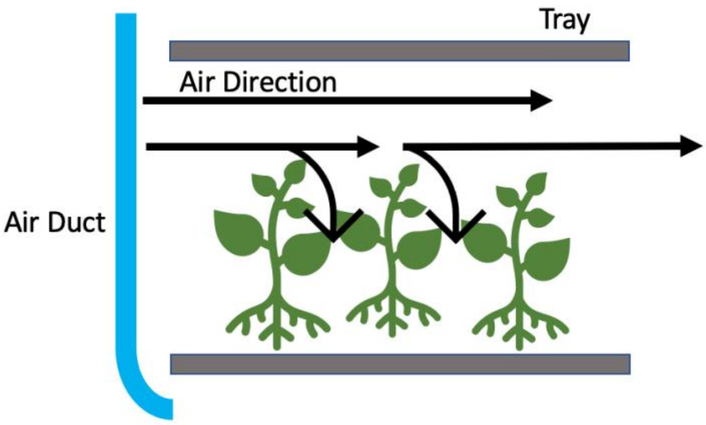


Figure 4-3 Air direction between racks with short growing crops

Tall Growing Plants

The tall-growing plants, such as tomatoes and cucumber, in the middle shelf of the greenhouse module are supplied with the horizontal air flow of the short-growing plants. Overhead fans also provide an angled air flow from the top. The air direction on the middle racks with tall growing crops is shown in Figure *4-4*.

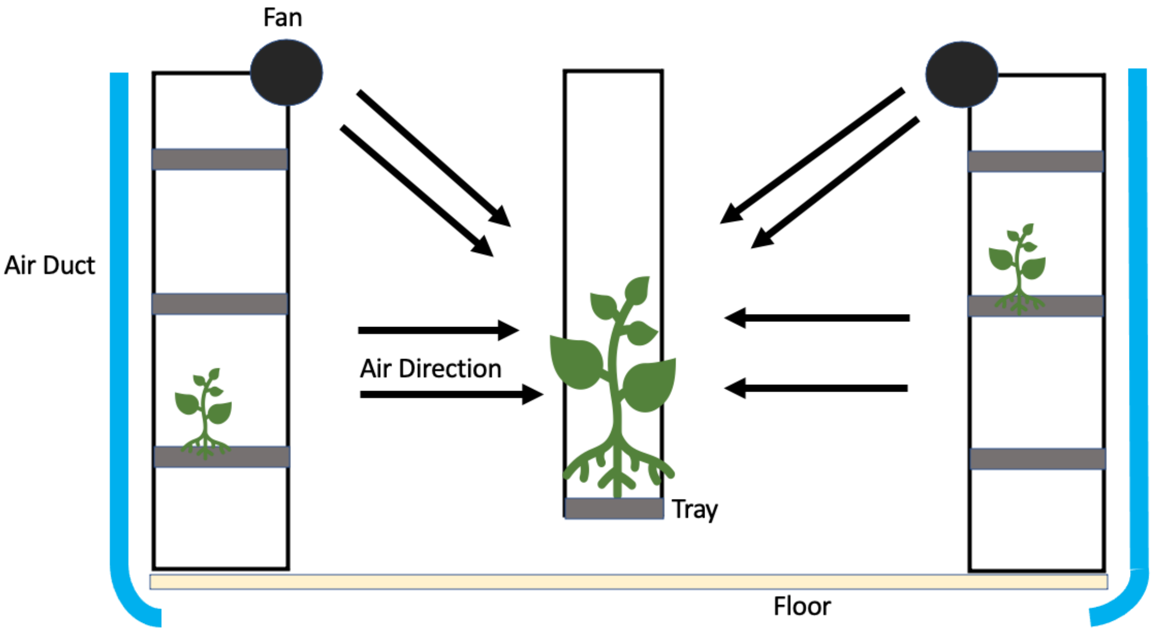


Figure 4-4 Air direction on middle racks with tall growing crops

The given air direction and air speed is only a recommendation. It is recommended to simulate the internal air circulation using computational fluid dynamics (CFD) models hence analysing the air movement in the greenhouse.

4.6 Boundary Conditions

In Chapter 3.2 the tasks of the different subsystems of the greenhouse module were briefly described. These subsystems are all in direct or indirect connection to each other. The interfaces between the subsystems can be seen in Figure *4-5*. Fluids and energy are exchanged at these interfaces. Since the focus which is set on the interfaces to and from the AMS, the atmosphere related interfaces are highlighted.

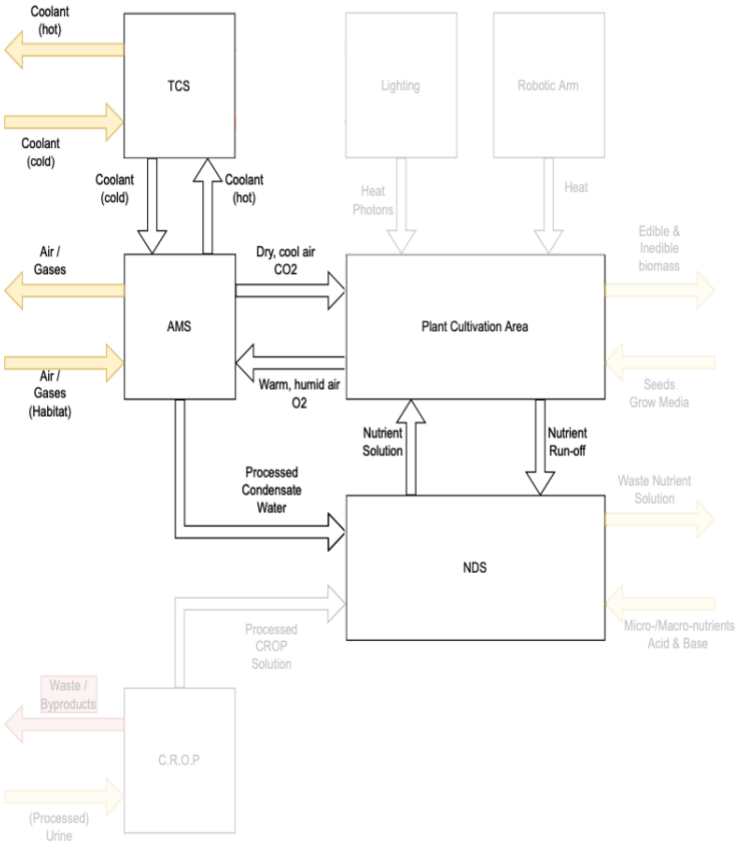


Figure 4-5 Atmosphere related interfaces

The focus in this thesis is set on the direct interface between the AMS and the NDS as well as the O_2/CO_2 exchange with the habitat. The NDS delivers nutrient enriched water to the plant roots via, in this case, an aeroponic system. The water taken up by the plants is partially released to the air through plant transpiration. In the AMS, the water is first extracted from the air before being filtered and then pumped to the fresh-water tank for further use. The necessary air vents and water pipes are also a fundamental part of the system. More details on the parameters and chosen components can be found in Chapter 5.

The O_2/CO_2 exchange interface between the AMS and the habitat is realised via a direct air exchange at set time intervals. Detailed information on the O_2/CO_2 exchange can be found in the next chapter. However, indirect interference of subsystems with the AMS also has to be considered. For instance, the ILS providing the necessary lighting for the plants will, in turn, produce heat, influencing the thermal characteristics of the air. In addition, the TCS provides coolant for the removal of heat energy and also processes the hot coolant from the return line. [88]

4.7 Design of the O_2/CO_2 Exchange with the Habitat

An interface between the AMS and habitat is to be fulfilled as outlined in the previous chapter. The purpose of this interface is the realisation of the CO_2 and O_2 exchange with the habitat. This requires the specification of the method, time interval, inlet and outlet placement, as well as component selection and process control. The direct method of CO_2/O_2 exchange in periodical time intervals was defined as the suitable method for this application during the CE-study.

At the interface from the greenhouse to the habitat, different atmospheric conditions and compositions are combined. These can have varying sanitation standards and compositions, which have to be taken into account in the layout of the CO_2/O_2 exchange.

The exchange with the habitat shall supply the greenhouse with CO_2 produced by the crew. Simultaneously, the greenhouse should supply the habitat with O_2 produced by the plants. This exchange forms a closed loop, which supports the reduction of supply goods from Earth. According to NASA, the average person needs 0.84 kg of O_2 per day and produces, in the unfavourable case, up to 1 kg of CO_2 per day. [89] [90]

Table *4-3* shows the absolute values of the average O_2 production rate and the average CO_2 uptake of the preliminarily chosen crops per day under the assumption that the entire area is fully populated with mature plants. The average O_2 production rate, including margin, is estimated at $360\ \frac{g}{day}$. The average CO_2 uptake, including margin, is estimated at $500\ \frac{g}{day}$. Compared to the values of O_2 need and CO_2 production of an average person, the greenhouse module is capable to compensate for approximately 50% of the daily processes. This indicates, that additional O_2 must be supplied to the habitat. Enough CO_2 is produced by the crew (/recovered from the habitat) to meet the requirements of the crops. The excess CO_2 shall be used in other processes, for example, in a Sabatier reactor to recover water through its hydrogen and CO_2 conversion system. [91]

The atmospheric conditions inside the GTD, and later the long-term habitat on other planets should be within a range that is comfortable for both, humans and plants. The International Space Station (ISS) is used as an example of a habitat for the definition of parameters. On board the ISS, the relative humidity is kept at around 60 %. With increasing relative humidity up to 70 % or higher, problems for both the astronauts and the ISS itself can occur. Condensation on the ISS, for example, can collect on electronics, trigger a short-circuit and possibly start a fire. Microorganisms, due to a high relative humidity, can lead to health problems for the astronauts, corrosion of parts and clogging of air and water filters. [92] Inside the ISS, the temperature is kept constant at around 22°C. [93] Figure *4-6* shows a diagram of the comfort zones of plants and humans with regards to the temperature in ℃ and the absolute humidity in $\frac{g}{kg}$. The overlapping area shows the comfort box for both, plants and humans.

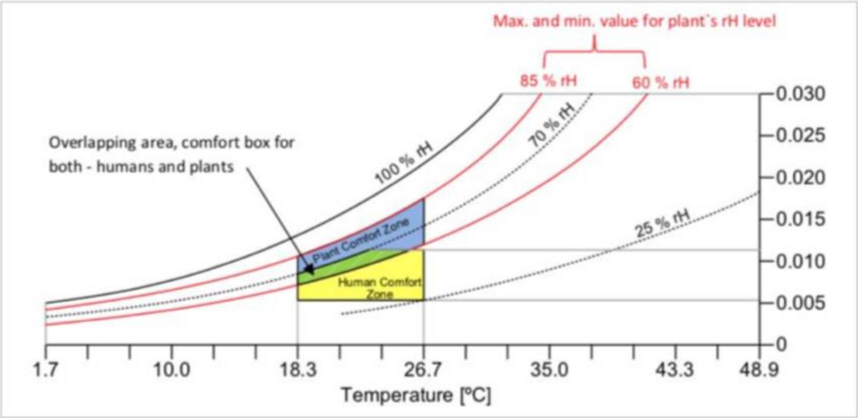


Figure 4-6 Comfort areas of plants (blue area) and humans (yellow area) and their common comfort sector (green area) [94] with data from [95]

This box indicates that plants grow in similar conditions to those which are comfortable for humans as well. Nonetheless, the optimal relative humidity setpoint for plant growth is around 80 %. [62]

As stated above, exceeding the limit in the habitat can lead to condensation and the built-up of microorganisms. Therefore, the environmental conditions in the greenhouse module and habitat should either be similar or be compensated by the corresponding AMS to achieve the defined conditions.

The sanitation standards in the habitat and the greenhouse module have to be considered because the contamination by microorganisms can be harmful to plant growth and can cause loss of yield. [96] Used as an example for the habitat, the ISS was chosen again. The space station has a stable population of about 55 different types of microorganisms, including bacteria, mould and viruses. [97] Strict precautions are taken to ensure the cleanliness of the ISS, like a filtration system and cleaning carried out by the crew. The air on the ISS is clean, but a relatively high concentration of microorganisms was detected on surfaces. [98] To avoid microbial exposure in the greenhouse from the habitat, the microbial load of the air should be monitored and a filtration system is required.

Considering the similarities in the atmospheric conditions, a direct air exchange between the greenhouse and the habitat does not pose a problem, e.g. during entry. Even though the air on the ISS is treated to a high standard, the inlet and outlet of the O_2/CO_2 exchange is placed in such a way that the air standard in the greenhouse remains the same and that the risk of contamination by microorganisms is minimised. The air inlet from the habitat into the greenhouse is therefore located right before the first sensor bundle and pre-filter. For the simplification of the integration process, the air outlet interface from the greenhouse to the habitat is set at the entrance door of the module. The design of the door already foresees the possibility of an air duct interface to the habitat. To allow the air exchange, fans shall be installed in the inlet and outlet air ducts. Due to limited space in the greenhouse and the restricted diameter for the planned interface integrated into the door of the module, the duct diameter must be estimated accordingly. The duct diameter in the overhead section is set to $D_{interface\_inlet} = 150\,mm$. With an air speed of $4\frac{m}{s}$, the estimated flow rate is $\dot{v}_{interface\_inlet} \approx 255\ \frac{m^3}{h}$. During the CATIA design, it became apparent that the available installation space in the floor only allowed room for a duct diameter of $D_{interface\_outlet} = 120\,mm$. With an air speed of $4\frac{m}{s}$, the estimated flow rate is $\dot{v}_{interface\_outlet} \approx\ 163\ \frac{m^3}{h}$. A suitable fan for the calculated flow rates is an inline axial fan, as it requires little space and is flight approved. The MultiVent MV 125 and MV 150 inline fans manufactured by Helios are chosen as an example design for the interface as they meet the requirements regarding duct diameter and flow rate, and they suit the available installation space in the service section. The performance parameters and the design are given in 10.3.The amount of air exchanged between the two modules shall be measured in the two directions via a flow sensor. No additional sensor bundle is required for the air inlet to measure parameters such as temperature, relative humidity and ethylene concentration, as the air is blown in directly in front of the first sensor bundle of the AMS. For the air outlet, an additional sensor bundle measuring temperature, relative humidity and O_2 concentration is placed inside the ducts. To allow the air supply at set time intervals, controllable valves are placed inside the inlet and outlet air ducts. The AMS software application of the DHCS then regulates the opening and closing intervals of the air supply and the simultaneous starting and stopping of the fans. To prevent uncontrolled air exchange between the habitat and greenhouse in the event of a valve failure, a second valve shall be installed in both air ducts. The design, including fans, valves and sensors is presented in Chapter 6. The sensors and valves will be selected later in the design process and are currently shown as placeholders.

4.8 Summary

The aim of this chapter was the outline of requirements and assumptions for the design of the AMS, an overview of the AMS structure and the calculations of the internal and external loads. This is achieved by determining the framework conditions for the design of the AMS. The system analysis provided an overview of the functional structure of the AMS, the boundary conditions and the necessary components to achieve optimal crop growth. In addition, calculations of the internal and external loads were completed, which were essential for the dimensioning and selection of the preliminary components and manufacturers in Chapter 5. The first design of the CO_2/O_2 exchange is proposed. The focus is set on the air composition and the comfort zone for both humans and plants, and on the production and usage rate of CO_2 and O_2. More design details are given in the CATIA design in Chapter 6.

5 AMS Components

This chapter provides a preliminary dimensioning of the various AMS components. This is done with the implementation of trade-offs, the selection of suitable commercial off-the-shelf (COTS) parts and materials. The changes of the components regarding their space application are given.

With the calculation of the internal and external thermal loads of the greenhouse module, the different loads of the AMS components are determined. Table *5-1* gives an overview of the different loads during nominal stage of the components of the AMS, which are essential for the determination of the performance requirements of the components. A safety margin is added on the calculated values for a conservative design. A more detailed information on the individual components, including design and performance requirements as well as a first selection of suitable off-the-shelf components and manufacturers is provided in the following subchapters. The selected components are only examples that meet the performance requirements and are used to establish a first mass and power budget. Applicability of the COTS components for space application are discussed. The preliminary selected components may change in the development process to custom-made components. The components shall fit in the designated space in the service section of the greenhouse module.

Defined are the following dimensions (L x H x W):

- Overhead (red): 1.47 m x ≈1.1 m x 1.5 m
- Underfloor (yellow): 1.47 m x ≈0.9 m x 1.5 m

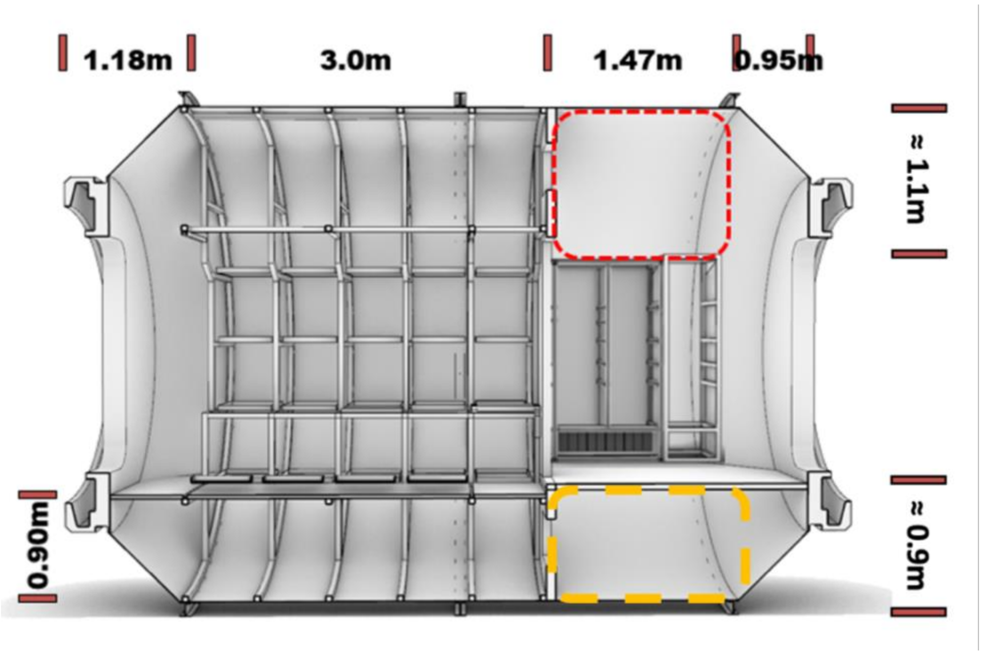


Figure 5-1 Available space in the service section for the AMS (based on [internal source DLR])

During the CATIA design of the AMS in Chapter 6 it became apparent that a separation into two parallel air streams is an effective option to reduce the size of components. This decision is taken into account when calculating and selecting the components.

Table 5-1 Loads of the different components of the AMS for the GTD (based on [70])

Load	Component	Recalculated Value	Design Value (including margin)
Pressure Loss	Fans	3556 Pa	3734 Pa (5 % margin; redundancy strategy gives possibility for more performance)
Transpired Water	CHX	≈ 28 kg/days	56 kg/day (100 % margin)
Heat Balance	CHX + heaters	[internal heat] - [heat loss via outside walls] = [thermal load to be covered] day period (warm/cold): 8058 W - 693 W = 7365 W 8058 W - 621 W = 7434 W night period (warm/cold): 2063 W - 693 W = 1370 W 2063 W - 621 W = 1442 W	warm: 7365 W cold: 7434 W (margins are applied at the upscaling process of the subsystems; no additional margin for the heat loss via the outer walls, because, dependent on the total heat balance, this has a positive or negative effect)
Air Flow Rate	Fans	warm case: 7256 m^3/h cold case: 7327 m^3/h	warm case: 7256 m^3/h cold case: 7327 m^3/h (margin applied on the thermal load (only variable influencing the parameter))
Partical Removal	Particle Filters (pre- and HEPA-filter)	continuous removal at a high level	continuous removal at a high level
Microbial Loads	UV-C lamp	continuous removal at a high level	continuous removal at a high level
VOC Removal	VOC filter	continuous removal at a high level	continuous removal at a high level
O_2 Production	O_2 removal module	180 g/day	360 g/day (100 % margin)
CO_2 Uptake	CO_2 resupply module	250 g/day	500 g/day (100 % margin)
Air Distribution and Dimensioning	Duct System	continuous air movement in the cultivation area	continuous air movement in the cultivation area

5.1 Pressure Losses

Pressure loss or a pressure drop is the difference in pressure between two locations in a system carrying air. This occurs due to frictional forces acting on the air while it is flowing through an air duct. [99] Pressure drop and flow rate are dependent on each other. The higher the flow rate trough a reduction, the higher the pressure drop and vice versa. [100] Table *5-2* shows a rough estimation on the pressure loss in the AMS. The values were adopted and adjusted from the datasheets of the preliminary selected components, from [70] and [71]. The margin of the geometric loss was reduced to 50 % due to the new design of the module being reduced in size. The margin of the components was reduced to 20 % as it is a new development with off-the-shelf components as a reference point. A total pressure loss of $\Delta p \approx 3560\ Pa$ was estimated.

Table 5-2 Estimation on the pressure loss in the AMS (based on [71])

Geometric loss	**Pressure loss Δp in Pa including margin (50 %)**
Air Inlet (suction)	225
Horizontal Overhead Air Ducts	100
Conical Connecting Air Duct of the Overhead and Underfloor Section in the Service Section	200
Horizontal Underfloor Air Distribution Ducts + Vertical Curved Air Distribution Ducts	900
Air Outlet (air distribution)	450
Component	**Pressure loss Δp in Pa including margin (20 %)**
Pre-Filter	144
HEPA-Filter	300
VOC-Filter	264
Dehumidifier	792
Heaters	23
Interface to Habitat	120
Sensor Bundles	38
Total	**3556**

At this stage of the design, the values are only a rough estimation with a margin of 50 % and therefore require verification. For this purpose, a CFD simulation of the airflow in the system must be performed. With the flow simulation or a flow analysis, it becomes visible where flow or pressure losses occur. The CFD is not included in this thesis as the simulation would exceed the time scope.

5.2 Air Circulation

The air flow in the greenhouse module is created by fans placed inside the duct system and directly in the cultivation area. Inlet fans inside the duct system enable the re-supply of treated air to the cultivation area. [21] In combination with the fans located in the cultivation area, a uniform air flow at all areas shall be provided to counteract challenges such as the chimney effect and the formation of air pockets as already stated in the literature research. A trade-off on the flow velocity and noise inside the air ducts has been performed and a solution for the prevention of air pockets is given.

The driving parameters for the selection of the fans are:

- Performance – Flow rate versus pressure curve where the total pressure of two fans in series is the sum of the single pressure,
- Temperature range during operation and transport,
- Suitable geometric parameters for the application, and
- Material. [70]

To select the fans according to the performance parameters, the maximum required air flow rate must be calculated to identify the maximum size. There are two methods for the calculation:

- The atmosphere exchange rate inside the greenhouse module.
- The temperature gradient of the air within the cultivation area.

The critical parameter for the first method is the number of air volume exchanges in a certain time frame. These exchanges prevent the built-up of hot pockets as a consequence of insufficient air movement. [70] A standard exchange rate for terrestrial greenhouses is 60 air exchanges per hour. [101] Human rated modules in space missions have a smaller volume and a better insulation than terrestrial greenhouses resulting in lower heat loads. Therefore, less air exchange rates can be applied. The air flow rate interval of the ISS crew quarters is $96 - 162\ \frac{m^3}{h}$, which corresponds to 45 – 77 hourly air exchanges. [102] The higher the exchange rate, the higher the air speed. However, a higher fan speed causes more friction in the bearings, which in turn causes higher levels of noise. [103] To keep the noise exposure moderate and in a comfortable range for plants and humans, the interval is set to 50 hourly air exchanges. The air flow equals to $84\ m^3 \cdot 50\ \frac{1}{h} = 4200\ \frac{m^3}{h}$.

For the second method the maximum cooling requirement is used for the air flow rate estimation. It is based on the temperature gradient of the air within the cultivation area. Based on the experiences from the EDEN ISS FEG, the temperature gradient for the EDEN Next Gen greenhouse was set to 3 K. The formula for the maximum required air flow $\dot{v}_{max}$ is [69]:

$$\dot{v}_{max} = \frac{\dot{Q} \cdot 3.6}{\Delta T_{ca} \cdot cp_{air} \cdot \rho_{air}} \tag{3}$$

With the conversion factor being $1\ W = 3.6\ \frac{kJ}{h}$, and the other values being taken from Table *10-3*, this results in a maximum required air flow rate of $\dot{v}_{max} = 7256\ \frac{m^3}{h}$ for the warm case (see Chapter 4.2.5 for the warm case and cold case). With the distribution into two air streams, this results in a maximum required air flow rate of $3628\ \frac{m^3}{h}$ per air duct. Here, only the warm case is considered and provides the basis for the further design of the AMS. [70]

5.2.1 Fan Selection – Service Section

Considering the challenges, size limitations and calculations, the characteristics for the fan application inside the duct system ideally are the following: low required space, low noise load, high available static pressure and high flow rate. Two types of fans were advised beforehand as a result of the trade-off study:

- Centrifugal fan
- Axial fan [71]

In the literature research, the characteristics of the axial and centrifugal fan models are given. Considering the high flow, the high static pressure and the space saving requirement, a centrifugal tube fan is selected. This fan combines a higher available pressure with the advantages of axial air flow, allowing a linear design of the ventilation section. [25] The proposed fan model is the RadiPac 310 EC centrifugal fan (K3G310PV6903) manufactured by ebm-papst.

Material:
- Support bracket: steel, black lacquered
- Support plate and inlet nozzle: sheet steel, galvanised
- Impeller: aluminium sheet
- Rotor: black lacquered
- Electronics enclosure: Die-cast aluminium

Number of blades: 5
Direction of rotation: Clockwise, seen on rotor
Condensate discharges: Rotor-side
Mode of operation: Continuous operating (S1)
Bearings: Maintenance-free ball bearings

Figure 5-2 Centrifugal fan and nominal data [104]

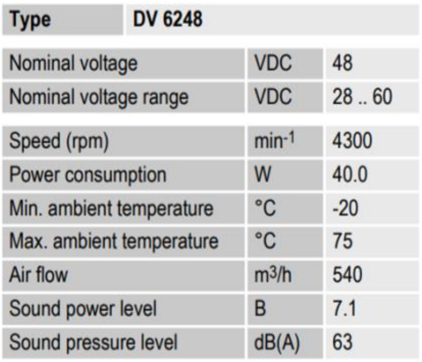
The rotation speed of the centrifugal fan can be controlled variably. Considering the pressure loss of $\Delta p_{loss} \approx 3560\ Pa$, a minimum pressure capability of 3560 Pa is required by the fans. The two fans are installed in a linear way to increase the total pressure. Each fan provides a pressure capability of $\Delta p \ \approx 1700\ Pa$ at a maximum delivery flow rate of $\dot{v}_{max} \approx 3700\ \frac{m^3}{h}$, resulting in a total available pressure of $\Delta p_{total} = 3400\ Pa$. Taking into account that the worst-case scenario is considered, a margin of 50 % is included for the geometric loss and a margin of 20 % is included for the components in the total pressure loss estimation, the selected fans should be sufficient to compensate for pressure loss. The preliminary placement of the centrifugal fans is shown in the CATIA model in Chapter 6. The power consumption of each fan is 3050 W per fan with new filters, resulting in a total power of 6100 W for both fans. This value may increase in case the filters are clogged and the fans are required to provide more pressure head. The noise emission of the fans is ≈ 89 dB, which is above the limit considered comfortable for humans during long working hours (see Chapter 5.9.3). Fan silencers could be installed to achieve noise control by means of absorption. This would increase the size and weight of the design. More information on the technical description of the selected fan can be found in Appendix 10.3.

5.2.2 Fan Selection - Cultivation Area

Microgravity has to be considered for the air circulation and thermal control of the future greenhouse module as stated in the literature research. Due to gravity being necessary for density differences to arise, convection (heat transfer) cannot occur in a microgravity environment such as space. This can lead to the formation of air pockets in the cultivation area. These air pockets lead to an increase in temperature, which can rise above the defined threshold. [50] Air pockets can be avoided by supplying every area of the cultivation area with fresh air. Therefore, forced convection must be used. With forced convection, the air is forced to move in order to create the heat transfer. To create the forced air movement additional fans in the cultivation area are implemented. [105] For the overhead fans in the cultivation are a stable air flow rate, space-saving design and a low acoustic impact required for the selection. The static pressure is not critical for these fans as they are free-blowing fans. A diagonal fan, which is a special design of the axial fan, is suitable for this application. Diagonal fans have a conical housing, which generates a cone-shaped air outlet and provides a distribution of the air to a larger volume compared to conventional axial fans. [71]

In addition, diagonal fans generate a higher pressure and have a greater air flow rate than axial fans. At the same time, they are quieter than centrifugal fans because they require a lower speed than the latter. [106]

The proposed fan model is the DV 6248 DC diagonal compact fan manufactured by ebm-papst.



Type	DV 6248	
Nominal voltage	VDC	48
Nominal voltage range	VDC	28 .. 60
Speed (rpm)	min^{-1}	4300
Power consumption	W	40.0
Min. ambient temperature	°C	-20
Max. ambient temperature	°C	75
Air flow	m^3/h	540
Sound power level	B	7.1
Sound pressure level	dB(A)	63

Figure 5-3 Diagonal compact fan and nominal data [107]

Considering the performance curve in Figure *10-10*, the delivery flow rate will be between 300 - 400 $\frac{m^3}{h}$. For a good coverage and uniform air distribution a total of eight fans is selected, which are evenly distributed on both sides of the cultivation area. The preliminary placement of the diagonal compact fans is shown in the CATIA model in Chapter 6.1. The power consumption of each fan is 40 W per fan, resulting in a total power of 320 W for all eight fans. More detailed information on the performance data can be found in Appendix 10.3.

Space Application

D/C is used in space applications as mentioned in Chapter 2.4.1. The fans selected for the cultivation area require a nominal voltage range of 28 – 60 V, which can be supplied by the power and control unit. A D/C D/C voltage converter has to be used to convert the nominal voltage of approximately 120 V to the required voltage of the fans. The fans selected for the application inside the air ducts require A/C and a nominal voltage range of 380 – 480 V. For the conversion, an additional A/C D/C converter is necessary, which is not recommended to use. In this case, a custom-made fan with D/C is the better option. Radiation during the transportation and stored in the regolith layer can harm the electronics. Radiation-hardening of the fans could be a suitable solution here, since no redundancy concept is provided for the fans. The disadvantage is that the price and weight of the fans rises significantly. These challenges have to be reviewed in a later design phase.

5.3 UV-C Lamp

UV light destroys bacteria, spores and viruses, which can build up on surfaces due to the high levels of humidity and is to be avoided. A UV-C lamp placed inside the dehumidifier irradiates the coils and ensures the decontamination of the dehumidifier surface and the elimination of the microbial load. [108] Key parameters for the selection of the lamp are the height and width of the coils, the air flow rate and the available space. Considering these parameters, the selected UV-C lamp is the IL18 for coil irradiation manufactured by Sanuvox (Figure *5-4*). The dimensioning of the UV-C lamp has already been done for the compact design with a size reduction of the dehumidifier of about 15%. The distance between coil and lamp is 300 mm and the lamp shall be positioned upstream in relation to the coil. More information on the performance data and positioning is provided in Appendix 10.3.

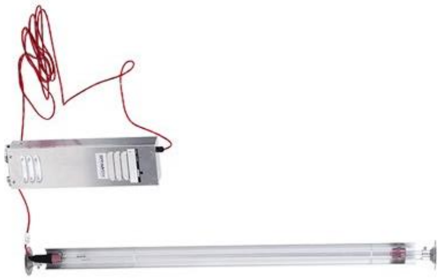


Figure 5-4 UV-C lamp manufactured by Sanuvox [109]

Space Application

The use of UV-C light in space applications does not pose a problem. Aboard the ISS, Violeds technology by Seoul Viosys is used for sterilisation to ensure experiment validity and crewmember safety. [110] What needs to be considered in the design of the UV-C lamp is the hardening against radiation and the power supply.

5.4 Heat Exchanger

The heat exchanger is needed for the cool down of the greenhouse, especially as the plants in the initial crop phase do not influence the thermal loads. Based on the requirements for space application of the EDEN Next Gen greenhouse module, a lightweight and space-saving design is required. This is why a compact condensing heat exchanger (CHX) was chosen to be the suitable option as it meets the defined requirements. [111] The condensation on cooling coil method has proven to be the method of choice during the EDEN ISS mission and in the EDEN laboratory at DLR Bremen. The dehumidification function is done by a gas-liquid heat exchanger with the gas being the air flow rate coming from the cultivation area and the cooling liquid being supplied by the thermal control system. As it is a CHX, the condensation water is collected via a drop separator, which is used to separate droplets from gaseous media. The condensed water can be treated and reused, for example for the NDS, to close further loops of the greenhouse module. In order to dehumidify the air from the cultivation area and obtain the maximum water condensation, the temperature of the cold surface inside the heat exchanger shall be as close as possible to the dew point of the air. The air enters the cultivation area with a temperature $T_{input} = 293.7\ K\ (\approx 20.5\ °C)$ and an acceptable temperature rise of 3 K across the cultivation area was defined. The air is expected to leave the cultivation area with a temperature $T_{output} = 296.7\ K\ (\approx 23.5\ °C)$ and a relative humidity of $rH_{input} = 65\%$ the dew point will be $T_{DP} = 289.7\ K\ (\approx 16.5\ °C)$. [70] The determination of the dew point is presented graphically in the Mollier Diagram in Appendix 10.2. For the dimensioning of the heat exchanger, the total thermal capability $Q_{total} = Q_{sensible} + Q_{latent\ heat\ of\ condensation}$ has to be calculated. The following formula to calculate the sensible heat is used [112]:

$$Q_{sensible} = \dot{m}_{air} \cdot c_{p_{air}} \cdot \Delta T \qquad (4)$$

With $\dot{m}_{air}$ being the constant air mass flow rate, $c_{p_{air}}$ being the specific heat capacity at constant pressure of the air and ΔT being the temperature difference between the output temperature and the dew point.

The following formula for the calculation of the latent heat of condensation is used [113]:

$$Q_{latent\ heat\ of\ condensation} = \Delta H_{water} \cdot \dot{m}_{condensation} \qquad (5)$$

With ΔH_{water} being the enthalpy of condensation of water and $\dot{m}_{condensation} = \dot{m}_{transpiration}$ being the maximum condensation rate. To guarantee sufficient performance, the calculations are done for both cases: the initial crop balance and the mature crop balance. No additional safety factor is applied due to the adequate margins already applied at the transpiration rate (100 %) and the thermal loads (upscaling process), which are the main influencing parameters.

The Initial Crop Balance

The initial crop balance includes the internal and external thermal loads without the consideration of the latent heat of plant transpiration during the starting phase of the project. The required cooling power is $\dot{Q} = 7365\ W$, which results in a constant volume flow rate $\dot{v}_{air} = 7256\ \frac{m^3}{kg}$ and a constant air mass flow rate $\dot{m}_{air} = 8707\ \frac{kg}{h}$. Inserting the values of Table *10-4* in equations (4) and (5) result in a total thermal capability of the heat exchanger of $Q_{total} = 18650\ W$. Dehumidification of the air might not be necessary during the initial phase with plants being at germination state and no plant transpiration occurring. For further developmental steps, a humidifier should probably be considered. Sufficient for the GTD is a portable humidifier that can be dismantled after the first phase. Tests will show whether a humidifier will be necessary for later space applications. In that case, other requirements for the humidifier will arise, which are not considered further in this thesis.

The Mature Crop Balance

The mature crop balance includes the internal and external loads with the consideration of the latent heat of plant transpiration during the full growth phase of the plants. The required cooling power is $\dot{Q} = 5926\ W$, which results in a constant volume flow rate $\dot{v}_{air} = 5838\ \frac{m^3}{kg}$ and a constant air mass flow rate $\dot{m}_{air} = 7006\ \frac{kg}{h}$. Inserting the values of Table *10-5* in equations (4) and (5) result in a total thermal capability of the dehumidifier of $Q_{total} = 15291\ W$. A mixture of 80 % water and 20 % propylene glycol was considered as cooling fluid for the dimensioning of the dehumidifier. The selected materials are copper coils with aluminium fins and the cooling fluid which is compatible with the copper.

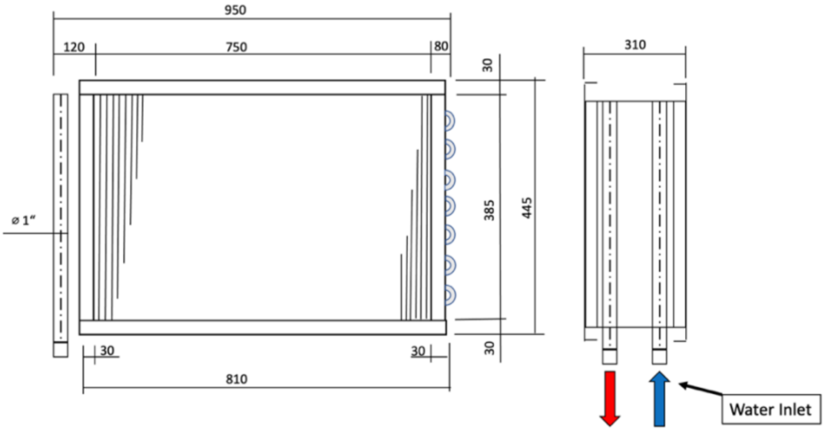


Figure 5-5 Preliminary dimensions of the heat exchanger

For the EDEN Next Gen greenhouse module, a cooling capacity of $\approx 19\ kW$ is required. The CHX calculated with the SPC Online Coil Selector has a cooling capacity of $\approx 24\ kW$ (see Figure *10-7*). Differences arise from not considering efficiencies and the selection of the cooling liquid. The dimensioning of the heat exchanger was performed with an inlet temperature of cooling fluid equal to 6°C and an outlet temperature of 12°C ($\Delta T = 6\ °C$), 12 coils stacked vertically and eight coil rows. The dimensions of the CHX are 750 mm x 310 mm x 385 mm with multiple rows of piping to get the desired area for heat exchange.

The drop separator is not included in the dimensioning of the CHX. It shall have the same surface area and a minimum width. The total weight is estimated to 25 – 35 kg. More parameters can be obtained from Table *10-9*. The given parameters for the preliminary design of the CHX must be verified by more precise calculations and confirmed by a manufacturer.

Space Application

On Earth, the drop separator is used to collect the condensed water generated during the dehumidification. Water is collected by gravity in a tank below the dehumidifier. For the moisture removal and humidity control on the ISS a two-stage process is used due to the microgravitational environment. The water first condensed onto fins and is the pulled through “slurper bars”, which take in a mixture of water and air that is then separated by a rotary separator. This process increases the number of components and the space required in the service section, which has to be considered when designing future space missions. Researchers at the NASA Glenn Research Center in collaboration with NASA Johnson Space Center designed a condensing heat exchanger which uses capillary forces to collect and remove water directly from the air so that no additional water separator downstream is needed. It is operable in varying gravitational conditions including lunar-, Martian-, and microgravity. It is still unclear when the concept will be applicable and how much additional space to the designed heat exchanger for the GTD is needed. [114]

5.5 Condensed Water Purification Unit (CWPU)

The condensed water coming from the dehumidifier shall be treated and reused in the greenhouse system. The condensed water purification unit consists of two condensation pumps attached to the dehumidification unit. A 3-way magnetic valve is used in front of the pumps to individually shut off and open an inlet to divert water from the dehumidifier to one of the pumps. A check valve after each pump ensures the flow in one direction only. The water is transported through an inlet carbon filter and an UV-C lamp for the sterilisation of the water. To measure the amount of condensed water, a flowmeter is used. It is placed behind the filter unit to prevent it from clogging. After processing, the water is then transported into the freshwater tank for further use (Figure *5-6*).

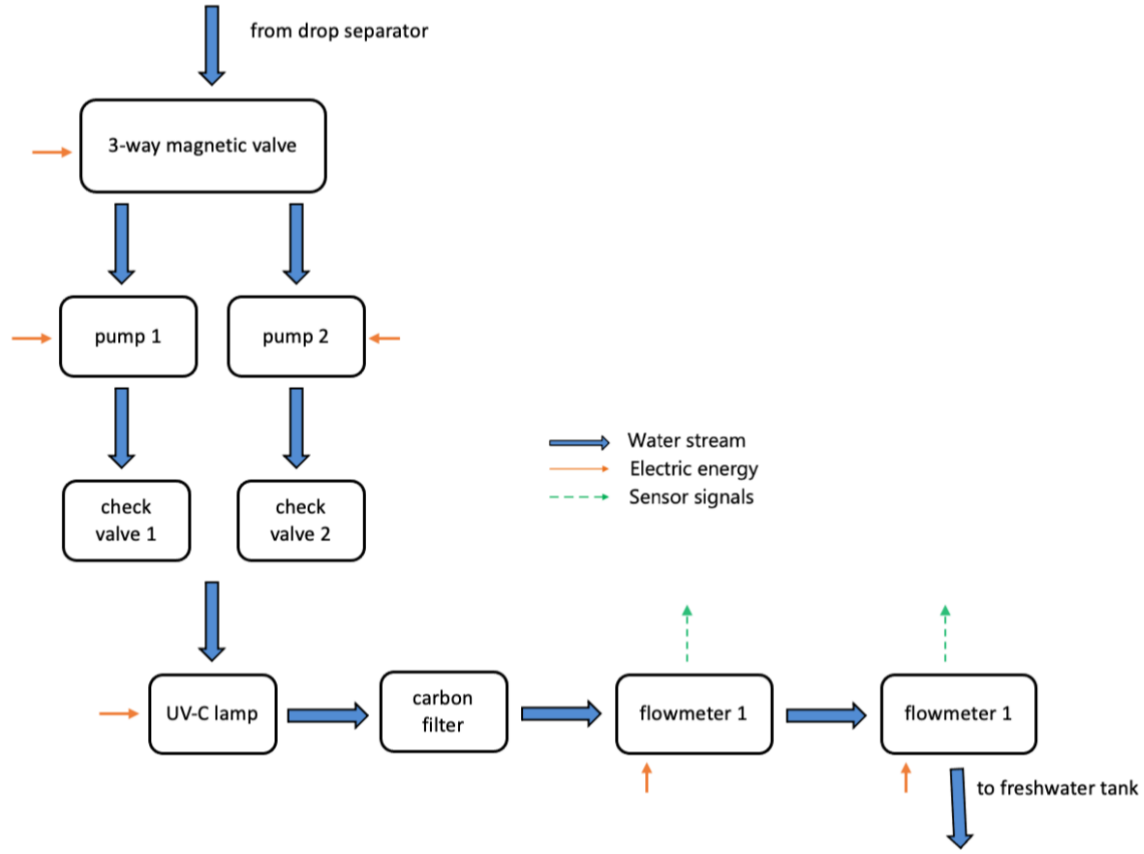


Figure 5-6 CWPU

With regard to maintenance and cleaning, the filter unit should be placed right after the drop separator to prevent possible algae growth and bacteria settlement in the components of the CWPU. This solution cannot be realised with commercial components. If the condensation pumps run without water for long period or repeatedly, they may overheat and lose performance. Regular maintenance and cleaning of the pumps is therefore required to ensure the water purification and possible re-use in other subsystems of the greenhouse module. In addition, the use of an opaque hose protects the condensed water from light and possible algae growth. In average, the plants produce 56 l of transpired water per day for a total crop area of 14.6 m^2, resulting in an average estimation of 2.3 l per hour.

The selected condensate pump is the Maxi Orange manufactured by ASPEN Pumps.

Figure 5-7 ASPEN pump Maxi Orange [115]

It provides a maximum flow of 35 $\frac{l}{h}$, a maximum delivery head of 15 m and a noise emission of 35 dB(A) at 1 m. More information on the performance data is given in Appendix 10.3.

The selected inline filter is the K2533 JJ Inline-Carbon Filter manufactured by Omnipure.

Figure 5-8 Omnipure K2533 JJ inline-carbon filter [116]

Activated carbon inside the filter shall reduce chlorine, taste, colour and odour of the condensed water. The filter shall be replaced after a flow of ≈ 5680 l. Performance data can be obtained from Table *10-7*.

The selected flowmeter is the FCH-m-POM-HD mini-flowmeter manufactured by BIO-Tech. Detailed information on the performance data of the flowmeter is given in Appendix 10.3

Figure 5-9 BIO-Tech mini flowmeter; Type: FCH-m-POM-HD [117]

The selected UV-C LED product for water disinfection is the 9D PearlAqua manufactured by AquiSense Technologies.

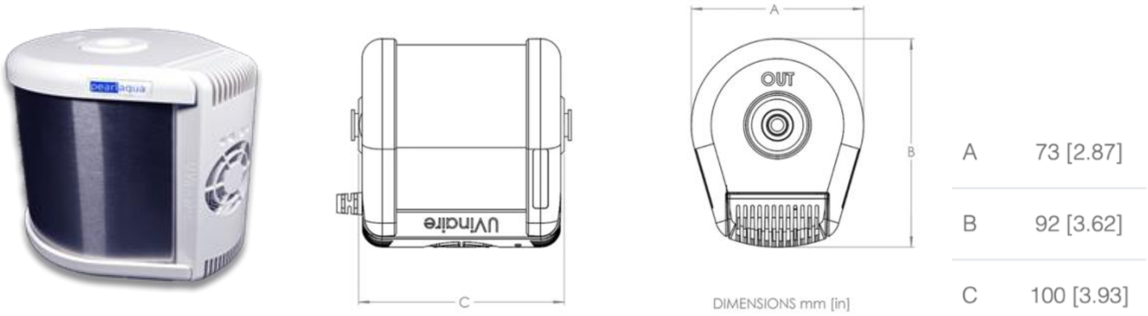


Figure 5-10 UV-C LED water steriliser [118]

The product provides a remote start/stop operation with unlimited cycles per day. A performance indicator signals the lamp operation and alarm conditions. Easy maintenance is ensured by a replaceable LED lamp module with a 10000-hour life, including a safety switch and on-board data logging. Detailed information on the performance data of the lamp is given in Appendix 10.3.

The selected valve is a 3-way normally open solenoid valve. Applications of the valve include water treatment and it can be used for process control and transportation. The normally open design ensures a water flow from the drop separator to pump 1 without an electrical current. In the case of the first pump failing, the port is closed and the other one opened to transport the water to pump 2.

Space Application

As mentioned in the space application chapter of the dehumidifier, the drop separator designed for the GTD is not suitable for the application in microgravitational environment. The CWPU has to be connected to the rotary separator for the treatment and transportation of the condensed water. The components are off-the-shelf and not designed for space application. It might be necessary to harden the electrical components, like the sensors, against radiation and to ensure the use of DC for better connection to the electrical infrastructure. The redundancy concept may also work in a space application and can be applied after verification.

5.6 Heater

Based on the requirements of the EDEN Next Gen greenhouse module, the heater must raise the temperature of the air leaving the dehumidifier to the defined inlet temperature into the growing area. The heating power is calculated under consideration of the following boundary conditions:

- Temperature of air leaving the dehumidifier: 16.5 °C with 93 % of RH
- Temperature of air entering the FEG: 20.5 °C with related RH

For the dimensioning of the heater, the heating power $P_{heater} = Q_{sensible}$ has to be calculated. Formula (4) is used to calculate the sensible heat, with ΔT being the temperature difference between the output air temperature leaving the dehumidifier and the input air temperature entering the cultivation area. Including the values of Table *10-6* in Formula (4) results in a total heating power of $P_{heater} = 9820\ W$ for the warm case. For the cold case the calculations are carried out accordingly, but only the warm case is considered here. The calculations for the mature crop balance are neglected as the influence of the constant air mass flow rate is less than that of the initial crop balance.

Finned heaters are selected to increase the air temperature inside the AMS due to the large heat dissipation area, space-saving and lightweight characteristics. [119] The heating elements, see Figure *5-11*, are supplied by Helios Heizelemente and shall be directly placed inside the air ducts. The performance data can be taken from Appendix 10.3.

Figure 5-11 Finned-tube heating element ∅ 28 mm [120]

Seven finned-tube heater elements can be placed in a row in the calculated duct diameter of 566 mm. The heater elements provide 12 kW of total heating power (8 x 1.5 kW each), which ensures a margin of roughly one heater element per air stream in the underfloor section of the service section. In later design steps, it is necessary to verify whether the heater can increase the air temperature quick enough at an air velocity of $4\,\frac{m}{s}$.

Space Application

No special requirements or challenges arise for the use in space applications as the same technology can be used. It has to be verified if the material choice of the stainless steel is compatible with the environmental conditions in terms of outgassing and magnetism.

5.7 Filtration System

5.7.1 Pre-Filter

The objective of the pre-filter is a continuous removal of course particles at a high level inside the air ducts to prevent early clogging of the pre-filter. The selection of the pre-filter is dependent on the air flow rate of the system. Based on the maximum air flow rate of $\dot{v}_{max} = 7256\,\frac{m^3}{h}$ in case of the initial crop balance, the use of two pre-filters in parallel is recommended. The chosen model is the HS-Mikro Pak 65 B manufactured by HS Luftfilterbau GmbH.

Type: HS-Mikro Pak 65 B
Filter class EN 779: M6
Initial - ΔP [Pa] at nominal air flow: 120
Temperature resistance: 65 °C
Dimensions [mm]:
Width: 592
Height: 490
Length: 292
Nominal air flow: 4100 $\frac{m^3}{h}$
Weight [kg]: 5

Figure 5-12 Pre-filter and filter characteristics [121]

The filter can be used as a pre-filter when high air flow occurs. Its construction with robust plastic frame ensures a high degree of stability, prevention of corrosion and a lightweight design. The filter medium is water-resistant and also suitable for volume flows with high humidity. Optionally, a fully synthetic filter medium can be selected for maximum moisture resistance. This can be an advantage if the air from the cultivation area has a high humidity. More information on the technical description of the selected filter can be found in Appendix 10.3.

5.7.2 HEPA

The objective of the HEPA filter is a continuous removal of airborne particulate matter at a high level in the greenhouse atmosphere. The selection of the HEPA-filter is dependent on the air flow rate of the system. Based on the maximum air flow rate of $\dot{v}_{max} = 7256\ \frac{m^3}{h}$ in case of the initial crop balance, the use of two HEPA filters in parallel is recommended. The chosen model is the HS-Mikro SFV manufactured by HS Luftfilterbau GmbH.

Type: HS-Mikro SVF
Filter class EN 1822: H13
Efficiency EN 1822 at MPPS: > 99.995 %
Initial - ΔP [Pa] at nominal air flow: 250
Temperature resistance: 65 °C / 120 °C
Dimensions [mm]:
Width: 610
Height: 610
Length: 292
Nominal air flow: 4000 $\frac{m^3}{h}$
Number of filter packages: 10

Figure 5-13 HEPA filter and filter characteristics [122]

The filter elements consist of pleated, ultra-fine micro glass fibre media with thermoplastic spacers. The filter packs are arranged in a V-shape to achieve a higher filter area and thus higher air flow rates with the lowest possible pressure differences. It combines the characteristics of a high air flow with that of a low-pressure difference, which is preferable for the AMS. More information on the technical description of the selected filter can be found in Appendix 10.3.

5.7.3 VOC Filter

The objective of the activated carbon filter is a continuous removal of volatile organic compounds, mainly ethylene, and odours at a high level in the greenhouse atmosphere. The selection of the activated carbon filter is dependent on the air flow rate of the system. Based on the maximum air flow rate of $\dot{v}_{max} = 7256\ \frac{m^3}{h}$ in case of the initial crop balance, the use of two carbon filters in parallel is recommended. The chosen model for reference parameters is the Carbocone K4606-315 manufactured by Prima Klima.

Type: K4606-315
Pre-filter: K3706 by Prima Klima
Dimensions [mm]:
Flange: 315
Diameter: 435
Length: 1280
Maximum air flow: 4700 $\frac{m^3}{h}$
Weight [kg]:
Total: 46
Activated carbon: 34.4

Figure 5-14 Carbon filter outside and inside view [123]

The filter consists of 100 % granulated pure activated carbon to ensure effective adsorption of particles and removal of ethylene. Detailed information on the technical description of the selected sample filter can be found in Appendix 10.3. For the inline air filtering application, the design of the filter has to be similar to the example shown in Figure 5-15. The operation of the filter unit is as follows: The air stream enters the filter on one side and is directed through the filter substrate by an obstacle in the duct. On the other side of the obstacle, the air flows again through the filter substrate and leaves the filter unit.

Figure 5-15 Example of an active air inline carbon filter [124]

Space Application

Replacement filters are lightweight and storable in the service section of the module. In further design steps, the safe replacement of the filters should be studied. The filters should be insulated in a protective bag to seal and dispose them to prevent any direct contact. This method may also be very safe for the environment. [108] Some minor challenges arise for the space application of the filter units. Outgassing of the plastic frame should be avoided. The frame requires to be made out of material with low outgassing rate, like aluminium [125], to prevent outgassing and therefore the contamination of the atmosphere with undesired gases. Accessibility of the VOC filter shall be provided to ensure a quick and uncomplicated maintenance or replacement of the filter cassettes. HEPA filters are suitable for the space application because they are flight-proven and are currently used on the ISS within the bacteria filter elements to prevent airborne particulate matter in the cabin atmosphere. [126] However, the space suitability of the selected filter types needs to be looked at more closely and discussed with the manufacturers. An outlook on a multi-filter system for space applications is given by NASA. The filter system for cabin ventilation systems on the ISS and future deep space missions foresees a design fashioned after the scroll filter system (SFS), which consist of scroll media filter, a screen roll filter and a regenerable impactor filter. [127] It may be possible to look at this system in later design steps and consider it for the EDEN Next Gen module.

5.8 Sensors

The sensors installed as part of the AMS measure the following parameters:

- Temperature [K] and relative humidity (RH) [%]
- O_2 [%]
- CO_2 [ppm]
- Air flow rate $\left[\frac{m^3}{h}\right]$
- Ethylene / VOC level concentration [ppb]
- Pressure Differential [Pa]

The design of the sensors for measuring the different parameters of the greenhouse air is based on the EE650 air flow sensor for duct mounting from E+E Elektronik.

Figure 5-16 EE650 air flow sensor for duct mounting [128]

The sensor is intended for reliable and accurate measurement in ventilation systems. It is highly resistant to mechanical stresses and highly insensitive to pollution, guaranteeing a long-term performance. The measured data is available either on current output or an analogue voltage, on BACnet MS/TP protocol or the RS485 interface with Modbus, which offers various options for the design of the PCDS.

Space Application

The possible radiation exposure through stored radiation in the regolith layer has to be taken into account for the application of sensors in a space environment. It could cause damages to the electronics of the sensors resulting in a failure of the unit. To reduce the radiation effects on sensors, radiation-hardening techniques can be applied resulting in higher costs. Redundancy of the sensor enables existing functionality in case of failure of single sensors. The custom-made design should ensure a suitable power supply and digital output signal. It general, it should be aimed for a mass and power reduction.

5.9 Air Ducts

In the greenhouse module, the air ducts ensure the air revitalisation by connecting the components of the AMS and the air distribution inside the growth area. The preliminary placement of the ducts is in the overhead and underfloor parts of the cultivation area and in the service section. Vertical air ducts are initially placed along either side of the walls in the cultivation area. A first design and placement of the air ducts is shown in Figure *5-17*.

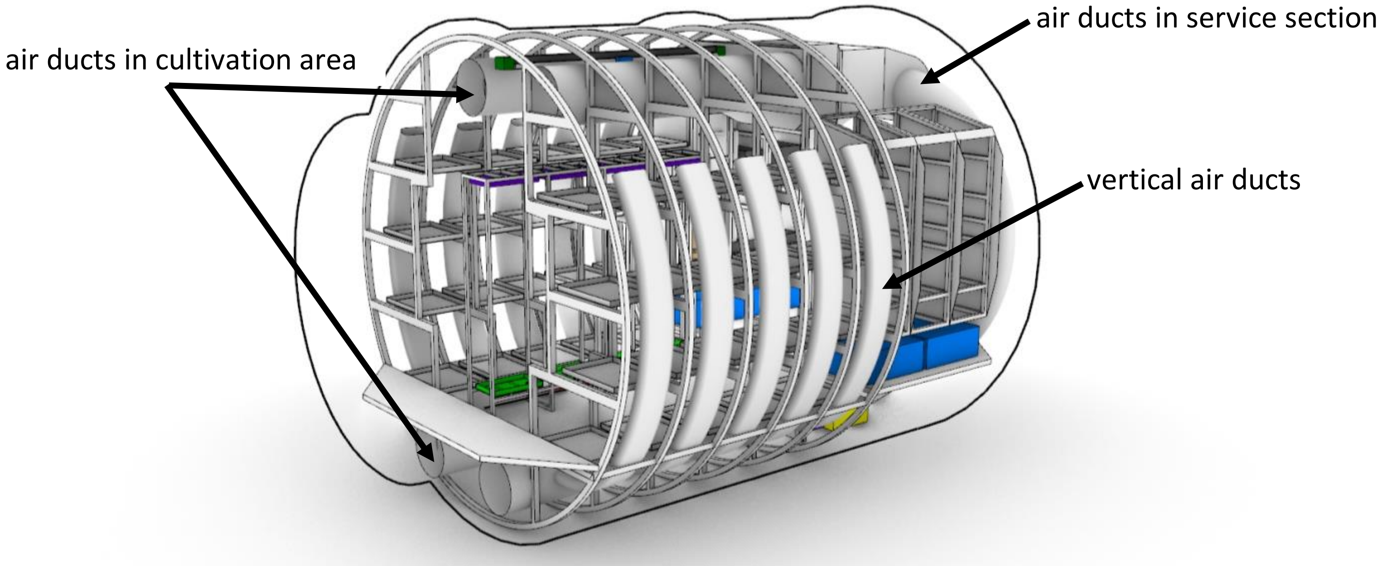


Figure 5-17 Preliminary design and placement of the air ducts in the EDEN Next Gen greenhouse module (based on [internal source DLR])

5.9.1 Main Air Ducts

A separation of the main air ducts into two parallel air streams was chosen during the CATIA design presented in Chapter 6. This decision is taken into account when calculating and selecting the air ducts.

The next step is the estimation of the necessary air duct diameter. The air flow rate required for cooling $\dot{v}$ and the air velocity are needed for the calculation. The pre-defined air velocity for the EDEN Next Gen module is set to $3\ \frac{m}{s}$, to reduce the noise level for humans working in the module. An increase of the air velocity is considered to test the change in air duct diameter. The new value is set to $4\ \frac{m}{s}$ to keep the conditions agreeable with humans working inside the module. With an increase of the air velocity to $4\ \frac{m}{s}$ the duct diameter becomes significantly smaller as can be seen in Table *5-3* for the air duct diameter estimation.

Table 5-3 Comparison of the air duct diameter with different air speeds

Main Air duct	**Warm Case**	**Cold Case**	**Warm Case**	**Cold Case**
Air speed [m/s]	3	3	4	4
Air flow rate required for cooling: $\dot{V}_{cooling}$ [m^3/h]	3628	3664	3628	3664
Minimal Duct Cross-section [m^2]	0,336	0,339	0,252	0,254
Diameter [mm]	**≈ 654**	**≈ 657**	**≈ 566**	**≈ 569**

For the design only the warm case will be considered. The air duct diameter is estimated to $d_{warm;\,4\frac{m}{s}} = 566\,mm$. This results in a difference of around 100 mm in diameter compared to the value with an air velocity of 3 $\frac{m}{s}$.

A flexible hose with robust helix design is used for the air suction ducts in the overhead space of the cultivation area. The hose can be transported tightly packed in a horizontal direction to provide more storage space during the cargo application and retains its shape when unfolded to convey air from the cultivation area into the AMS.

The selected example hose is the A-Klip A8C17 PTFE hose manufactured by ATAG Europe.

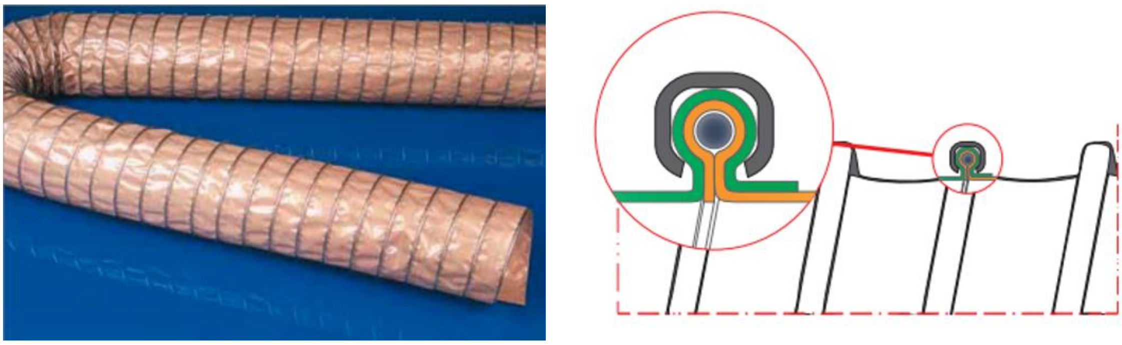


Figure 5-18 Flexible PTFE hose with galvanised steel helix manufactured by ATAG Europe [129]

The hose is constructed from a Polytetrafluoroethylene (PTFE) coated glass fibre fabric wall with external galvanised steel helix, making the outer hose wall robust but also highly flexible. It has an excellent chemical, heat and cold resistance. Detailed information on the performance data can be found in Appendix 10.3.

The air duct between the components of the AMS and the connecting air duct in the conical section of the service section are manufactured from sheet metal tubing to simplify the assembly and connection of the individual components.

5.9.2 Vertical Air Ducts

The same process as for the main air ducts is used for the estimation of the vertical air ducts diameter. The number of vertical air ducts is set to five per side, which sums up to ten in total. For the calculation, the air flow rate per duct as well as the air speed was considered. Calculations were conducted for round ducts and square ducts. For the design, only the warm case will be considered.

Table 5-4 Comparison of the vertical air duct dimensions with different air speeds

Vertical Air Ducts	**Warm Case**	**Cold Case**
Number of vertical ducts	5 per side / 10 in total	5 per side / 10 in total
Maximum required air flow rate: $\dot{V}_{max}$ [m^3/h]	7256	7327
Air flow rate per duct [m^3/h]	726	733
Air speed [m/s]	4	4
Cross-section area [m^2]	0,0504	0,0509
Diameter (round duct)	**≈ 253 mm**	**≈ 255 mm**
Dimensions (square duct)	**252 mm x 200 mm**	**254 mm x 200 mm**

The increase in air velocity also has an impact on the parameters of the vertical air ducts. The diameter of the round ducts is calculated to be about $d_{round_{warm};4\frac{m}{s}} = 253\ mm$. This results in a difference of around 40 mm per duct, compared to the value with an air velocity of 3 $\frac{m}{s}$ (Table *5-4*). Considering the overall reduction in diameter with an increase of the air velocity from 3 $\frac{m}{s}$ to 4 $\frac{m}{s}$, the required space in the overhead and underfloor part of the module decreases resulting in more space available for cargo storage. In addition, the overall mass of the ducts is also decreasing, as less material is being used. Nonetheless, there is a direct relationship between duct air velocity and the noise generated by the airflow. Therefore, the increase in air velocity causes more turbulence and more noise, which is a disadvantage to the system and the crew working in the module. A detailed look on noise limitations and a comparison of noise exposure is given in the next subchapter.

An inflatable flat hose design is used for the air distribution ducts in the underfloor section of the cultivation area. The vertical air ducts are inflatable for space-saving transport and to create storage space during cargo application. A custom-made design foresees the manufacturing in one piece to simplify assembly on site and to avoid leakage at the interfaces. The selected example hose is the GüloFlat M flat hose manufactured by Grüning + Loske.

Figure 5-19 PVC Flat Hose manufactured by Grüning + Loske [130]

The hose is a medium-weight construction made of PVC and reinforced with polyester yarn. The flat hose is rollable and space-saving. Detailed information on the performance data can be found in Appendix 10.3.

5.9.3 Noise

Air velocities in pipes and ducts should not surpass certain limits to avoid high pressure loss and noise generation. [131] Noise is measured in decibel (dB). The comfortable range for humans is set in between 40 to 65 dB. [132] Higher noise levels, especially at the workplace, should be avoided. For example, there are laws in Germany to protect workers from excessive noise exposure. This is because excessive noise can lead to mental and physical harm. [133] These limit regulations have to be taken into account to find a suitable air velocity.
The noise generated in air ducts can be estimated with the following equation [134]:

$$L_N = 10 + 50 \cdot \log(v) + 10 \cdot \log(A) \tag{6}$$

where L_N is the sound power level in the duct [dB], v is the air velocity [$\frac{m}{s}$] and A is the air duct cross sectional area [m^2]. By inserting the corresponding values into the calculations, the sound power level was calculated for option 1 of the air duct layout. The results can be seen in the following Table *5-5*.

Table 5-5 Sound power level of air ducts

Parameter		
Air velocity [m/s]	3	4
Air duct cross sectional area [m²]	0,34	0,25
Noise [dB]	**29,1**	**34,1**

With a flow velocity of 3 $\frac{m}{s}$ a noise of $\approx 29.1\ dB$ in the ducts is expected. With an increase of the air velocity to 4 $\frac{m}{s}$, the noise increases to $\approx 34.1\ dB$. The difference of 5 dB is quite high due to its logarithmic scaling. However, as stated before, the comfortable range for a human is between 40 to 65 dB. This limit is not exceeded with an increase of the air velocity to $4\frac{m}{s}$. The air velocity is not increased any further, as a velocity of 0.3 to 0.5 $\frac{m}{s}$ should be reached at the plants after the air leaves the vertical supply ducts. It has to be noted that because of the noise generated by the fans, the noise generated inside the ducts by air flow can mostly be neglected.

5.9.4 Material Selection and Challenges for Space Application

The selected material shall meet the requirements for ground application in the first mission step. In the further course, it shall also meet the requirements for space applications.
The criteria for the choice of material for the air ducts inside the greenhouse module are:

- Space-saving storage
- Tear flexibility
- Outgassing
- Surface roughness (noise)
- Antistatic
- Resistance to fats, chemical agents, solvents, UV-light and oils
- Light weight

Materials that fulfil some of these criteria and are applicable in space application include aluminium, PTFE, silicone and fiberglass. Aluminium is characterised by its light weight and strength as already mentioned in the literature research. The material is UV-light resistant, and an anti-static coating can be applied. [135] Aluminium is a suitable material for the connecting air duct in the conical section of the service section and for the helix structure of the flexible hose construction.

Fiberglass is used in space applications such as in space suits [136]. Properties of the material include high tensile strength with low weight, insensitive to variations in temperature and hygrometry, fire and chemical resistance, insensitive to sunlight, fungi or bacteria and electrically insulating. Fiberglass is a component without significant outgassing in vacuum. [137] Therefore, it is a suitable material as a basis for the flexible hose design.

A PTFE coating gives the hose characteristics such as flexibility, partial abrasion resistance, chemical resistance and antistatic properties. [138] PTFE is suitable for the utilisation in ultra-high vacuum conditions as the detected outgassing by machined Teflon was under the measurable limit in a study of the University of Natal, South Africa, from 1980. It was also noted that the main gases evolved by extruded Teflon were H_2O, CO and CO_2, which shall be filtered by the AMS. [139]

A silicone coating gives the hose properties such as flexibility, tear strength and resistance to high temperatures. [140] Outgassing of silicone elastomers is inevitable under high temperatures and low pressures. [141] Heat treatment can reduce it by two orders of magnitude, all measured in a vacuum. The pre-treatment leads to the absorption of half of the original gas content resulting in a lower outgassing load. [142]

The challenge for the space application lies in transporting the module for example to the moon. As already stated in Chapter 2.4.6, the launch loads do severely impact the payload. The payload itself experiences axial together with lateral acceleration and vibrations caused by the thrust of the solid rocket motors and boosters. This has an impact on the connecting air ducts made of sheet metal inside the module. The force of the acceleration lies perpendicular to the air ducts placed in the conical section of the module. Therefore, the air ducts need an increase in wall thickness or stringer stiffened design.

5.10 Mass Budget

The first configuration of the greenhouse module is designed to fit into the fairing of a SpaceX Falcon 9 launcher. The payload capacity of the rocket is indicated at 8300 kg to geostationary orbit and 4020 kg to Mars. An estimated payload capacity of 7000 kg is assumed, which is the limit for the total weight of the module. [143] The goal is a lightweight design as mission cost increases significantly with an increase in weight. An estimation of the mass budget is done for the AMS. A design maturity mass margin at equipment level is applied in an early development stage to cover uncertainties and design changes. The margin requirements are:

- 5 % for “Off-The-Shelf” items
- 10 % for “Off-The-Shelf” items requiring minor modifications
- 20 % for new designed / developed items or items requiring major modifications or re-design [144]

Table *5-6* shows a total mass with margin of $\approx 751\ kg$ for the AMS. The values will change in the further development process. A higher margin was allocated to most of the components as it will be customer-specific components. Mass budget estimations have to be compiled for all subsystems of the module to ensure that the total weight does not exceed the limit.

Table 5-6 AMS mass budget estimation

Budget	Mass							
Totals					658,66			750,794
Unit	Component	Part	No	Mass /unit [kg]	Total Mass [kg]	Status	Margin [%]	Mass w/ Margin [kg]
Ventilation unit	Diagonal compact fan (cultivation area)		8	0,82	6,56	To be modified	10	7,216
	Centrifugal fan (service section)		4	21,42	85,68	To be developed	20	102,816
Dehumidification unit	UV-C air purifier		1	3,6	3,6	To be modified	10	3,96
	Dehumidifier		1	35	35	To be developed	20	42
	Condensed water purification unit	Condensation pump	2	0,5	1	To be modified	10	1,1
		Carbon filter	1	0,3	0,3	To be modified	10	0,33
		Flowmeter	2	0,04	0,08	To be modified	10	0,088
		UV lamp	1	0,74	0,74	To be modified	10	0,814
		Miscellaneous	1	0,5	0,5	To be modified	10	0,55
Heating unit	Finned-tube heater element		8	0,6	4,8	To be modified	10	5,28
Filter unit	Pre-filter		2	5	10	To be modified	10	11
	HEPA		2	5	10	To be modified	10	11
	VOC		2	46	92	To be developed	20	110,4
Sensor unit	Sensor		16	0,3	4,8	To be modified	10	5,28
Air ducts	Service section		6	20,6	123,6	To be modified	10	135,96
	Cultivation area		18	10	180	To be modified	10	198
CO2 interface	(including ducts, sensors, fans, etc.)		1	50	50	To be developed	20	60
Consumable material	Screws, connectors, mounting aids, etc.		1	50	50	To be modified	10	55

5.11 Power Budget

The electrical components of the AMS are divided into groups for the power supply. Advantages arise during the start of the components and in the case of a failure. With the separation of the electronic devices of the system into groups, the inrush current is kept below the limit. This prevents the system from switching off the circuit as stated in Chapter 2.4.1. In case of a short-circuit or failure of the components only the components of the group lose the power supply and stop working. The FDIR (Failure Detection, Isolation and Recovery) of the DHCS ensures the correct reaction so that the components of the other groups continue working to minimise the risk of crop loss or of a possible dangerous environment for humans.

Table 5-7 Classification of the electrical components into groups

	Components
Group 1	1 x sensor bundle 1 x ventilation unit
Group 2	1 x sensor bundle 1x ventilation unit
Group 3	Dehumidification unit Heating unit
Group 4	UV-C air purifier CWPU
Group 5	CO2 interface (valves, fan, sensors, etc.)

The division is done in five groups (Table *5-7*). The first two groups contain sensors and a ventilation unit to ensure the monitoring of the parameters and a constant air exchange through the filters. Group 3 contains the dehumidification unit and the heater because the air temperature has to be increased after the dehumidification. Group 4 contains the UV-C air purifier and the CWPU to ensure filtration of air and water in case group 3 fails. Group 5 contains the CO_2 interface with valves, fans and sensors because it is not vital for the prevention of a hazardous environment in the greenhouse module.

For the power budget estimate the values are taken from the selected example components where available, otherwise the values are estimated from reference objects used in previous projects of the EDEN group.

A design maturity power margin at equipment level is applied in an early development stage to cover uncertainties and design changes. The margin requirements are the dame as the ones for the mass estimation from the previous subchapter.

Table *5-8* shows a total power of $\approx 16551\,W\ = 16.55\,kW$ for the AMS including a margin. The values will change in the further development process. A higher margin was allocated to most of the components as it will be customer-specific components. Power budget estimations have to be compiled for all subsystems of the module to ensure that the total power needed does not exceed the limit.

Table 5-8 AMS power budget estimation

Budget	Power							
Totals					13879,8			16550,78
Unit	Components	Part	No	Power /unit [W]	Total Power [W	Status	Margin [%]	Power w/ Margin [W
Sensor Unit	Sensor		16	1,6	25,6	To be modified	10	28,16
Ventilation unit	Diagonal compact fan (cultivation area)		8	40	320	To be modified	10	352
	Centrifugal fan (service section)		4	3050	12200	To be developed	20	14640
Dehumidification unit	UC-C air purifier		1	30,6	30,6	To be modified	10	33,66
	Dehumidifier		1	800	800	To be developed	20	960
	Condensed water purification unit	Condensation pump	2	16	32	To be modified	10	35,2
		UV-light	1	8,6	8,6	To be modified	10	9,46
		Flow meter	2	1	2	To be modified	10	2,2
		3-way magnetic valve	1	1	1	To be modified	10	1,1
Heating unit	Finned-tube heater element		7	60	420	Off the shelf	5	441
CO2 interface			1	40	40	To be developed	20	48

5.12 Summary

The preliminary dimensioning and selection of the AMS components fulfilling the performance requirements was the aim of this chapter. This is achieved firstly through the definition of the available space in the service section and the determination of the different loads of the AMS components. Calculations are performed and suitable off-the-shelf components selected as an example selection meeting the functional and performance requirements. They are used to establish a first pressure loss estimation and a mass and power budget. The space applicability is discussed for each unit. The result is that in most cases the selected components are not suitable for space applications and require customisation.

The components are either not designed for the required power supply, made out of unsuitable material or not hardened against radiation. In addition, conservative margins are used in all calculations and the worst case is assumed. The estimated performance requirements may not be utilised completely in the test phase. As a result of the component selection for the GTD, the components are reduced in size in the next step, the CATIA design, and adapted to the given installation space. This is possible because the components are manufactured specifically according to the requirements and no COTS components are used. In the further development, it has to be checked whether the concept is functional this way and whether the given suggestions on the space application can be implemented.

6 CATIA Design

This chapter provides the CATIA design of the elaborated concept of the AMS for the GTD. It shows the overall structure, including that of the components, and it provides detailed views of the components and connections where applicable.

A CATIA design of the elaborated concept for the AMS is created for illustration and further development. The shell, floor and inner shelf structure were already designed and are now used to place the AMS inside.

As already mentioned, the selected components from Chapter 5 are used as a reference model as they fulfil the necessary performance requirements. However, they are reduced in size to fit into the available space in the service section. For this, custom-made components have to be manufactured.

During the CATIA design of the AMS and fitting it into the greenhouse structure it became apparent that the limited length of the service section poses a challenge for the placement of the components. Therefore, the decision is made to divide the system into two parallel air streams instead of one, resulting in a decreased component length and a redundancy of the components. If one side fails, for example due to a clogged filter or a defective fan, the other side ideally still provides an air exchange rate to maintain the parameters of the atmosphere. This ensures the growth of the plants and does not endanger the safety of the crew until the other side is repaired or maintained. The redundancy/accessibility concept is explained in detail for the individual components in the following subchapters. The heat exchanger unit, including the UV-C lamp and the drop separator, is not redundant as the dimensions of the installation space do not allow a second unit. A redundant heat exchanger unit is not necessary as it is a passively controlled system. What is important is the maintenance and cleaning of the components to maintain performance and prevent microbial contamination.

To verify the feasibility of the CATIA design, the placement and dimensions of the components shall be analysed in a fluid dynamic simulation.

6.1 Greenhouse Configuration Model

Design concept: The AMS is placed inside the module with regards to the rigid structure and floor design. In the design, care was taken to ensure that the individual units have a uniform cross-section, if possible, to save space in the length and to not be affected by connectors. The AMS design consists of:

- Air suction ducts
- AMS overhead section
- Conical air ducts
- AMS underfloor section
- Air distribution ducts

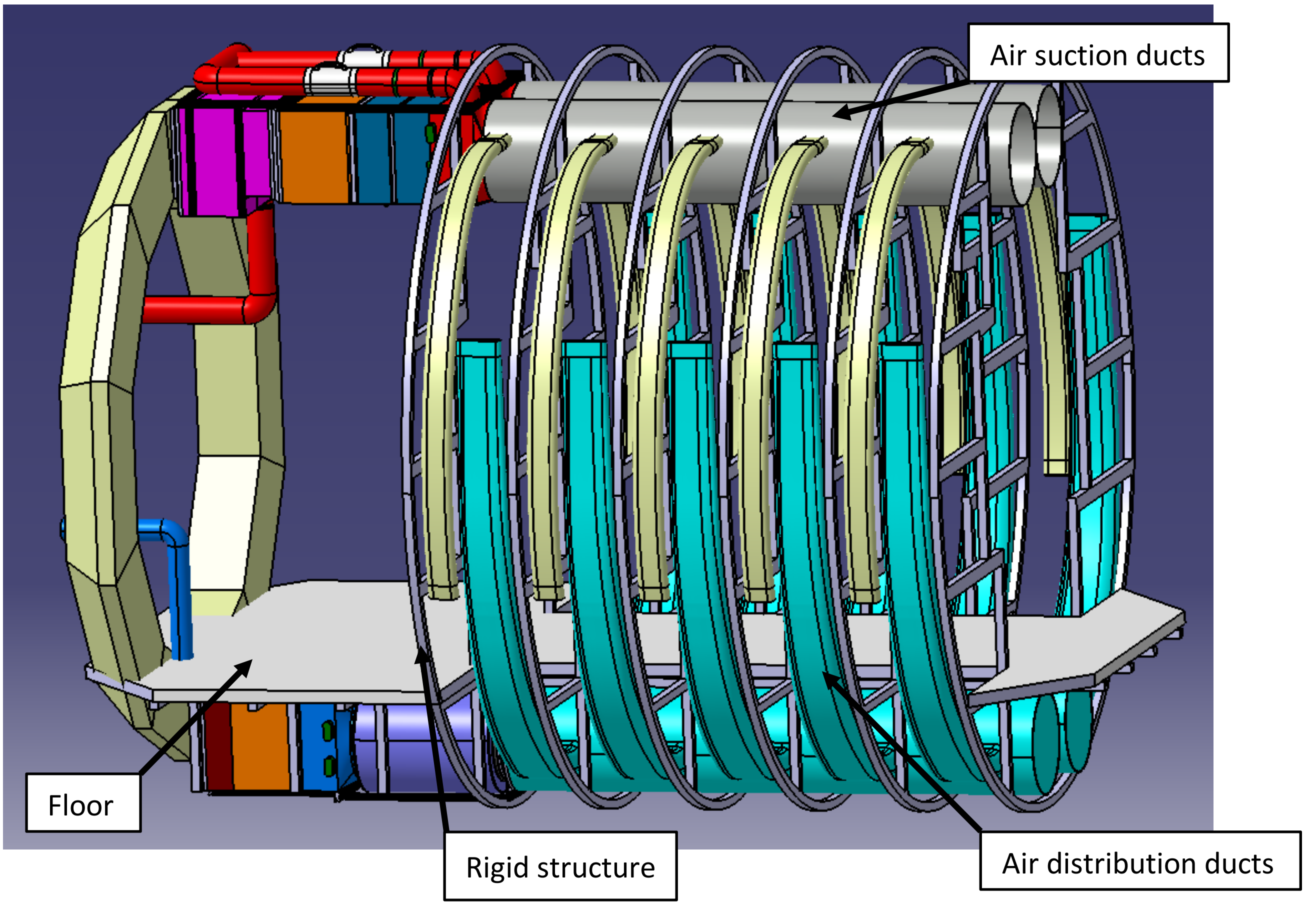


Figure 6-1 Design of the AMS for the greenhouse configuration placed in the module

In the greenhouse configuration, the **air ducts** in the cultivation area are deployed and mounted to the fastening mechanism (fastening mechanism not shown in the image). The air distribution and air suction ducts split into five vertical air ducts each that extend between the racks of the rigid structure (Figure *6-1*).

The racks shall contain 4 levels of crop cultivation each, hence the vertical air ducts have to provide a vent for air outlet at every level of the racks. The air suction ducts on the module ceiling also provide vents for air inlet. These vents for air inlet and outlet are not included in the CATIA design of the air distribution and could be added in a later design step. The diameter of the vertical air ducts decreases towards the end to keep the pressure constant. The design foresees rails on the module wall where the vertical pipes are mounted and can be hooked in to hold them in place. This fastening mechanism is not included in the CATIA design and could be added after the analysis in the design process later on.

The **fans** inside the cultivation area are mounted to the rigid structure of the module at an angle of 110° (Figure *6-2*). A simulation shall be done to visualise the air movement in the greenhouse and at the tall growing crops, and to verify the preliminarily defined angle. A total of 8 fans are located in the greenhouse, 4 on each side, which provide forced convection to avoid air pockets and to ensure an even distribution of fresh air into the growing area. In the case of a fan failure, the other fans provide sufficient air movement in the growth area. During the downtime, a crew member can change the defective fan.

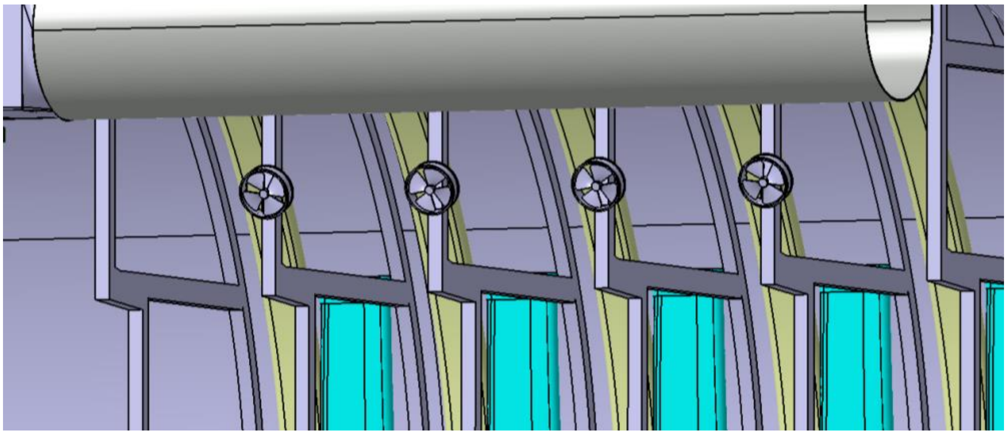


Figure 6-2 Preliminary design of the ventilation unit inside the cultivation area

The overhead and underfloor section of the AMS are connected by a **conical air duct**, which is fitted to the conical installation space of the module (Figure *6-3*). The cross-section of the conical air ducts is slightly smaller than the air inlet and outlet ducts, resulting in a maximum flow rate of $2560\ \frac{m^3}{h}$ at an air speed of $4\ \frac{m}{s}$. To provide the same maximum flow rate of $3628\ \frac{m^3}{h}$, the air speed increases to $\approx 5.7\ \frac{m}{s}$. The cross-section of the conical air ducts cannot be increased due to restrictions of the module.

The overhead and underfloor section of the AMS include the CO_2/O_2 interface to the habitat. A detailed description of the design structure is given in the corresponding design concepts of the overhead and underfloor section.

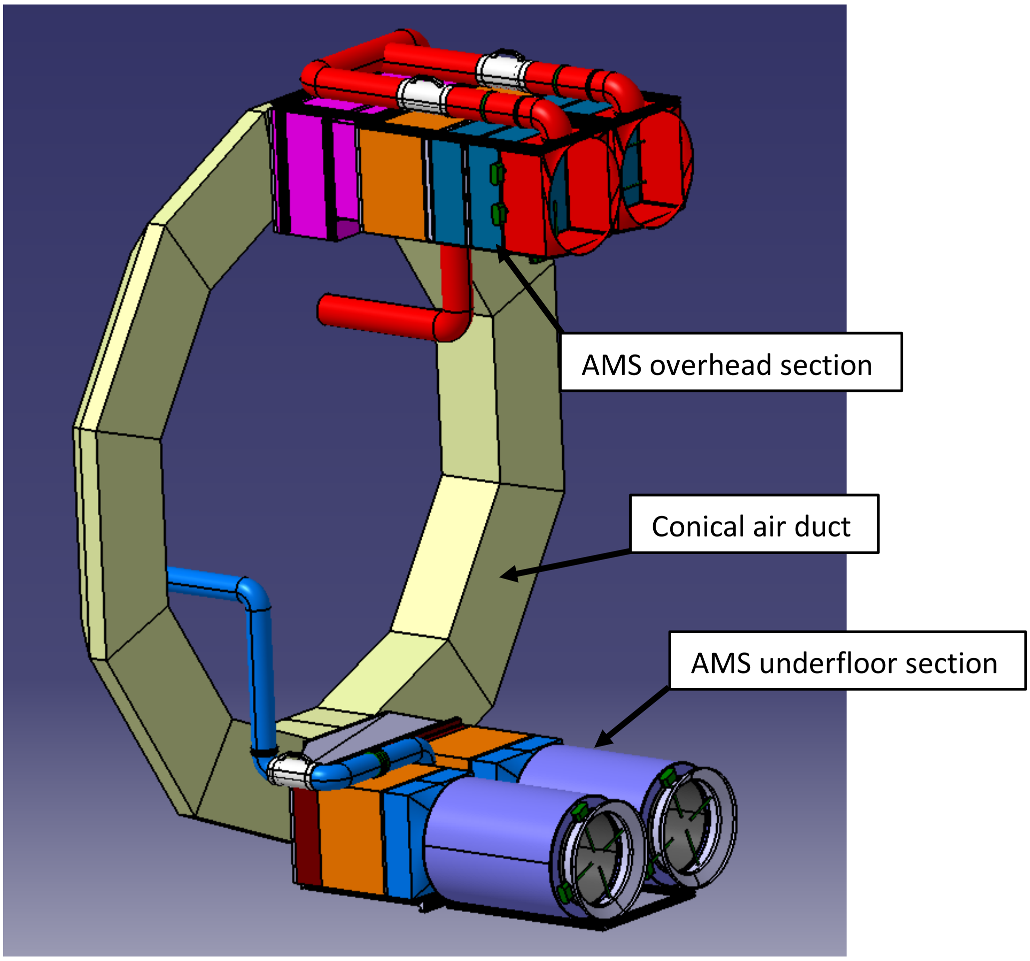


Figure 6-3 Detailed view on the air treatment components and the connecting conical air duct placed in the service section

6.2 Overhead Section

Design concept: The overhead section of the AMS is shown in Figure *6-4* and consists of:

- The heat exchanger unit
- The ventilation unit
- The HEPA filter unit
- The pre-filter unit
- The support structure
- The sensor bundle
- CO_2 interface (habitat to greenhouse)

The **sensor bundle** is placed right at the air inlet to monitor and analyse the incoming air from the cultivation area. The housing design and mounting flange ensure easy installation and replacement. Custom fabrication allows multiple sensors to be used in a bundle at different locations in the air duct, providing redundancy.

The **support structure** stabilises components, reduces structural loading of the components and prevents unwanted movements. A simple CATIA design of aluminium profiles is provided for the time being, which could be further elaborated in the next steps.

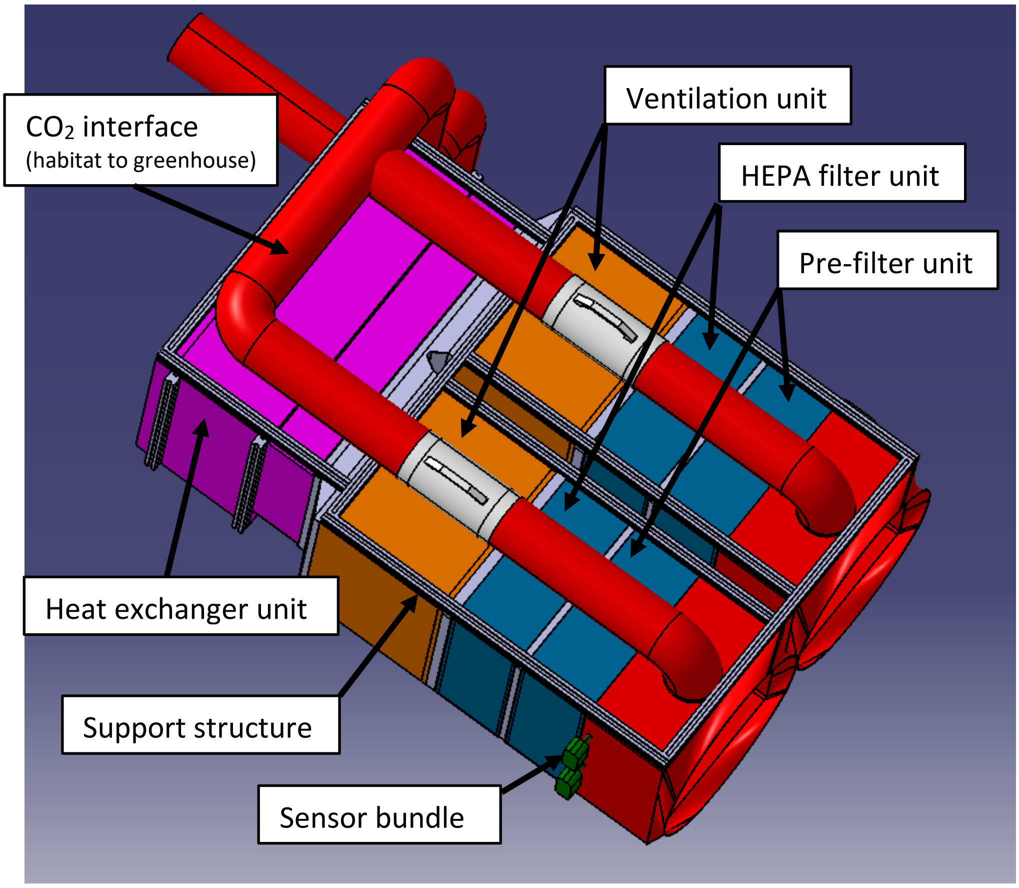


Figure 6-4 Detailed view on the overhead section of the AMS

CO2 interface (Figure *6-5*)**:** The CO_2 interface from the habitat to greenhouse is closed by the first valve located in the air duct. The air duct divides into two parallel air streams and is connected to the overhead part of the AMS in front of the first sensor bundle. It measures and analyses the air parameters as they flow into the circuit and no further monitoring is required in the interface air duct. A flow sensor located behind the fan monitors the amount of air coming in from the habitat. In case the first valve malfunctions, a second valve is placed inside each air stream. A detailed view and description of the units is given in the following subchapters. Cables and additional lines are neglected in the CATIA design in order to make the model more comprehensible.

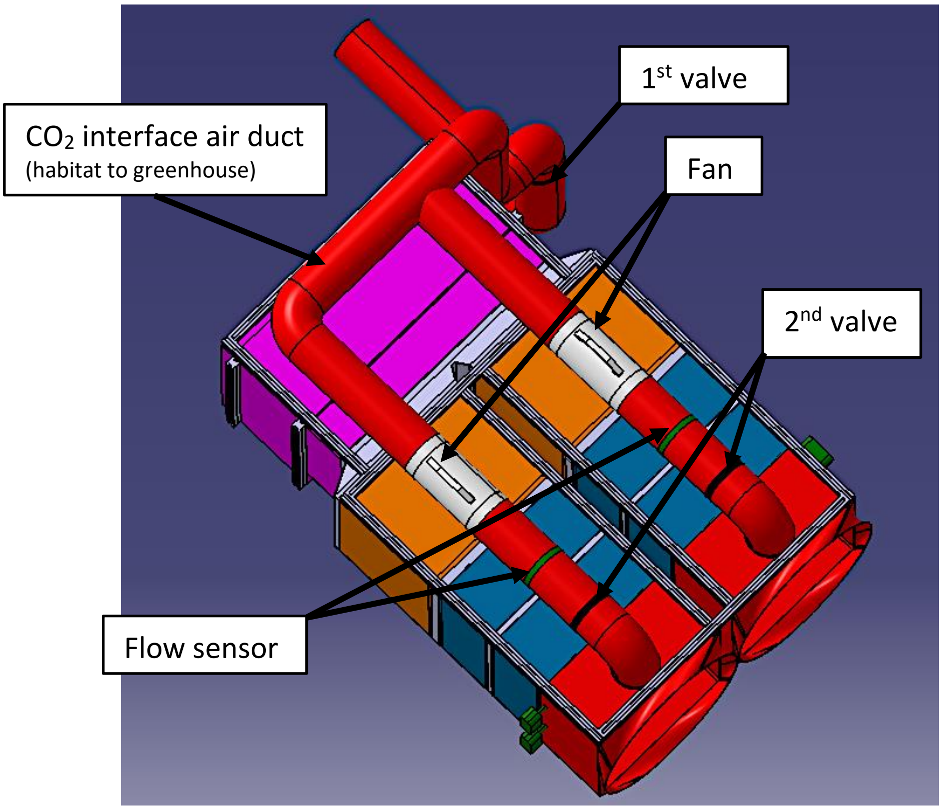


Figure 6-5 Detailed view on the CO2 interface (habitat to greenhouse)

6.2.1 Filter (Pre- und HEPA)

Design concept: The pre- and HEPA- filters are placed in series and linked with connectors to ensure sufficient filtration of the incoming air from the cultivation area. The cross-sectional area of both filters is the same in order to not have any space lost for adapters and to realise a space-saving design. Each filter consists of a filter casing, a filter drawer and the filter inlet as can be seen in Figure *6-6*.

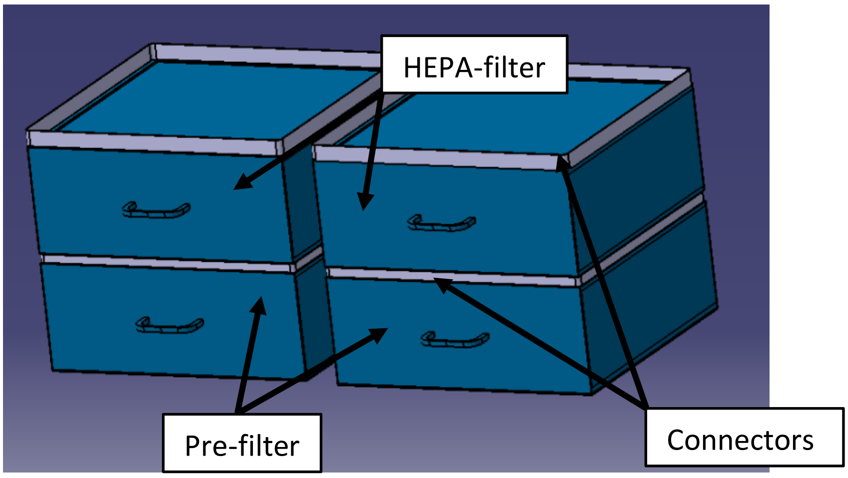


Figure 6-6 Design of the HEPA and pre-filter unit

Redundancy/accessibility concept: Apart from the two parallel air streams with one filter each, no additional redundancy concept is foreseen for the pre-filter and the HEPA filter. In case of failure or clogging of the filters, easy access is ensured by a drawer system. The filter drawers can be pulled out by a crew member and the filter elements can be replaced.

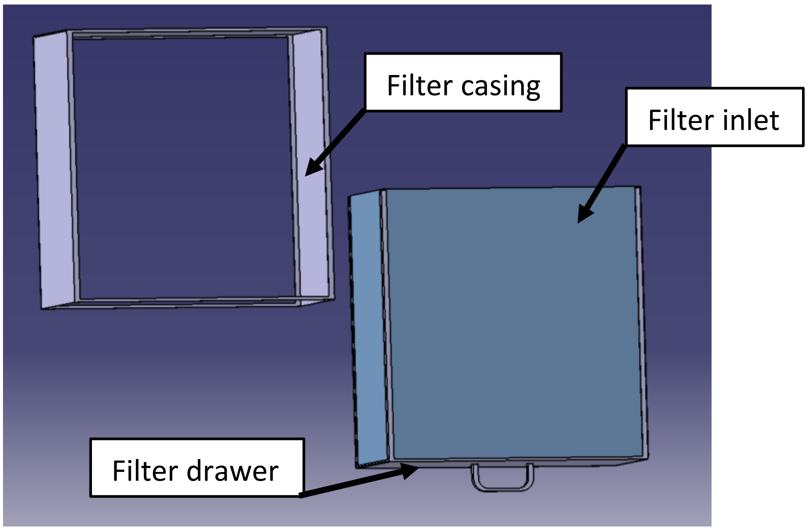


Figure 6-7 Accessibility concept of the filter unit

6.2.2 Ventilation Unit in the Service Section

Design concept: The ventilation unit design consists of a fan placed inside a fan casing for the installation of the unit. The design is based on the example centrifugal fan selected from the ebm-papst company, which was presented in Chapter 5. The design could change in the further development process.

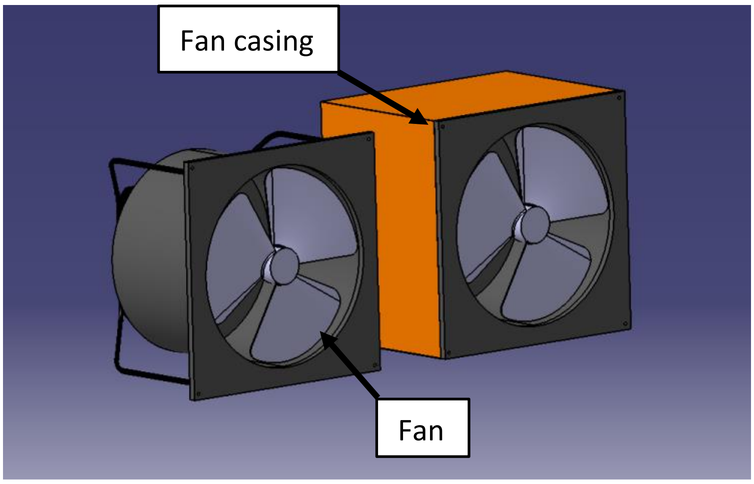


Figure 6-8 Design of the ventilation unit

Redundancy/accessibility concept: There is no additional redundancy concept for the fans besides the two parallel air streams. Accessibility is not simplified; the entire fan must be changed in the event of a failure.

6.2.3 UV-C Lamp

Design concept: The UV-C lamp unit consists of a casing, a drawer and the UV-C lamp (Figure *6-9*). The lamp is hanging freely in hooks, which are attached to the drawer. Fasteners are fitted to the structure to secure the drawer. They can be loosened easily by a single crew member to ensure minimum workload.

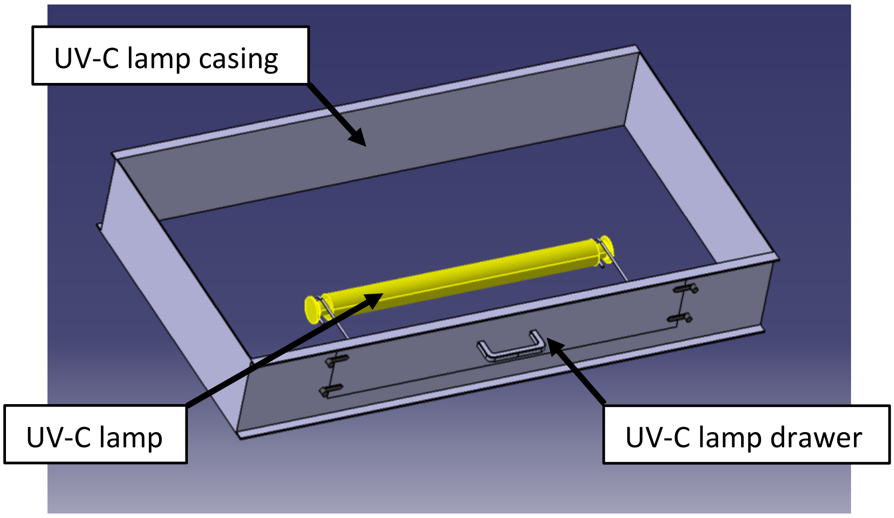


Figure 6-9 UV-C lamp unit

Redundancy/accessibility concept: One 30.6 W lamp has a sufficient disinfection efficiency for the estimated air flow rate. Currently, there is no need for a redundancy concept for the lamp as it is not certain to what extent the lamp will be used. This will become clearer in the course of testing. Easy accessibility is realised by a drawer which can be pulled out after the closing mechanism has been released. Then, the lamp can be easily removed from the hooks and replaced by a new one.

6.2.4 Heat Exchanger Unit

Design concept: The heat exchanger unit consists of the dehumidifier, the drop separator and the CWPU (Figure *6-10*). The dehumidifier lowers the temperature of the incoming air from which condensation forms. The droplets are separated from the air by the drop separator and are redirected to the CWPU for further treatment. For now, the dehumidifier and drop separator are presented as black boxes and no detailed design is given. The design will be influenced by the implementation of the manufacturer. The coolant inlet and outlet have not been included in the design.

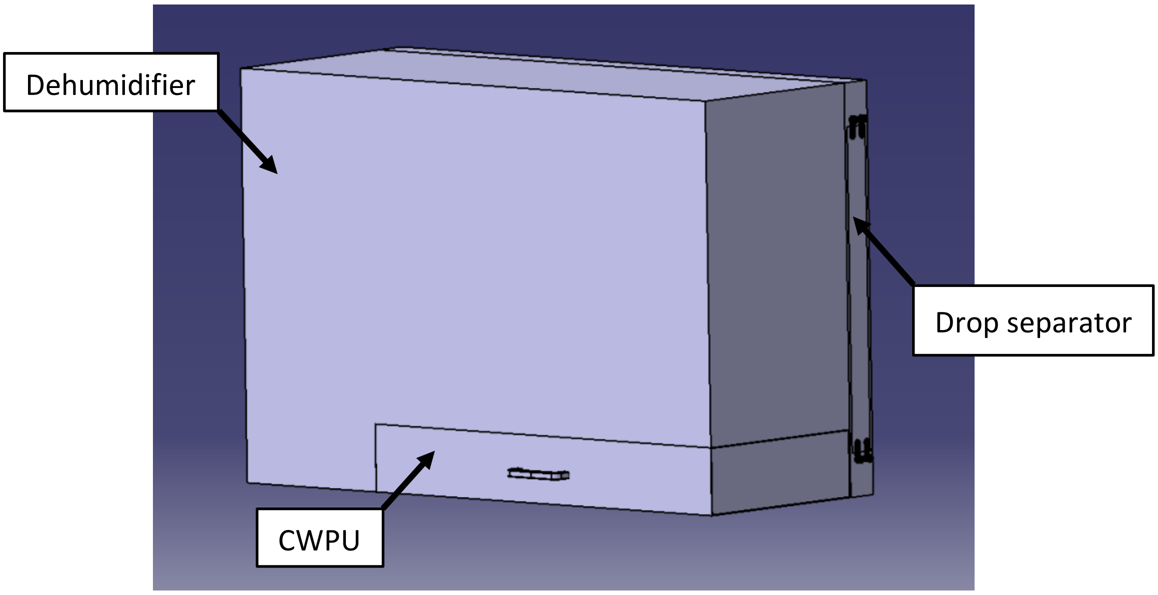


Figure 6-10 Heat exchanger unit with drop separator and CWPU

Redundancy/accessibility concept: No redundancy concept can be proposed for the dehumidifier due to size limitations. For this reason, the design shall provide easy access for cleaning, maintenance and exchange of parts. This can be realised by placing the heat exchanger unit on telescopic rails. The entire unit can be pulled down to working height using a handle. A preliminary design of the working principle is shown in Figure *6-11*. It is important to ensure that all connections and hoses are long enough and can be easily pulled down with the unit and stowed again. In addition, a holding mechanism must be designed so that the load can be carried by the heat exchanger unit so that there is no uncontrolled lowering of the telescopic rails. This could, for example, be achieved by using a step-by-step mounting into which the unit is hooked.

The drop separator is placed in a drawer on rails and can be pulled out independently for quick access. The maintenance schedule of the CHX and drop separator allow the units to be covered with a metal sheet attached to the structure with a fastener, to be loosened easily by a single crew member to ensure minimum workload. The cover sheet is insulated to prevent the surrounding air from condensing on the cold surface of the cooling coil.

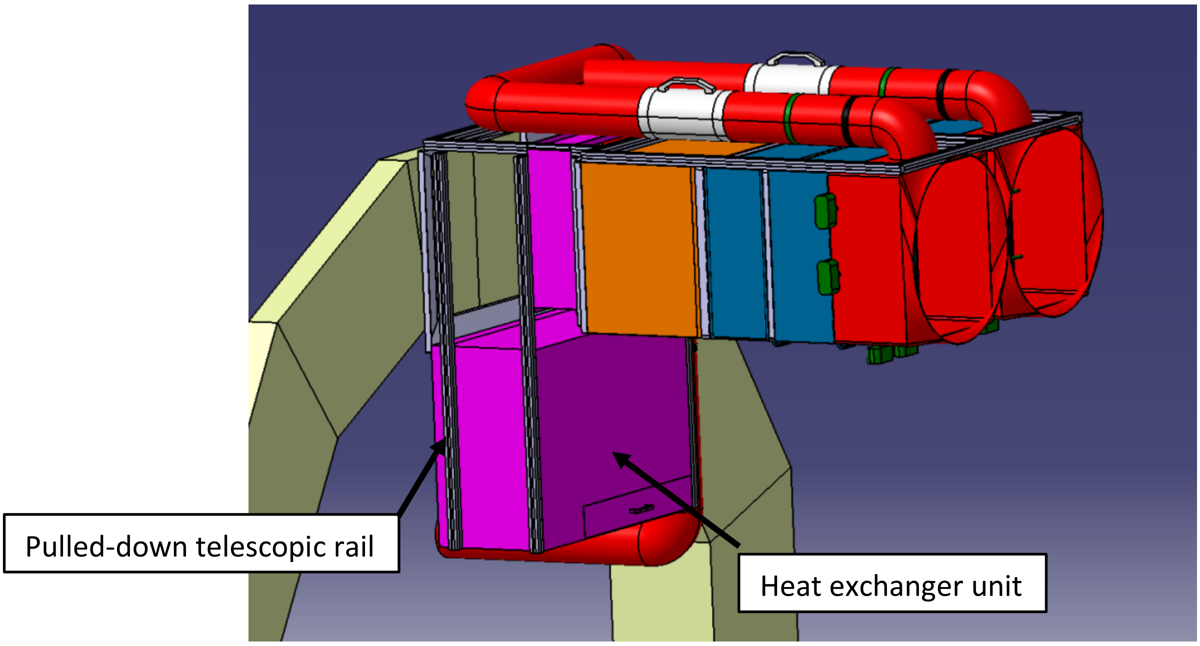


Figure 6-11 Overhead section of the AMS with pulled down heat exchanger unit for easy maintenance and accessibility

6.2.5 CWPU

Design concept: The CWPU is placed inside a drawer on the bottom of the heat exchanger unit. It collects and reprocesses the condensed water from the drop separator. The unit consists of a magnetic valve, a condensation pump, a UV-steriliser, a carbon filter and a flow sensor. The design is based on the example CWPU components selected from the different companies, which were presented in Chapter 5. The design could change in the further development process. The design does not include the rail system of the drawer and the water transfer from the drop separator to the CWPU, which have to be developed at a later stage when the dimensions and functionality have been verified. The reserve tank is neglected in this design as it could be placed on one of the racks in the service section which are not included in the design of the AMS.

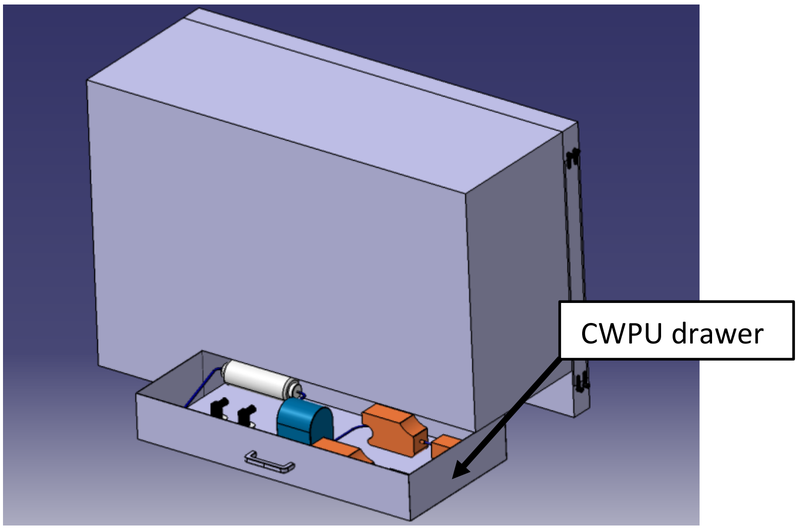


Figure 6-12 Heat exchanger unit with pulled out CWPU drawer

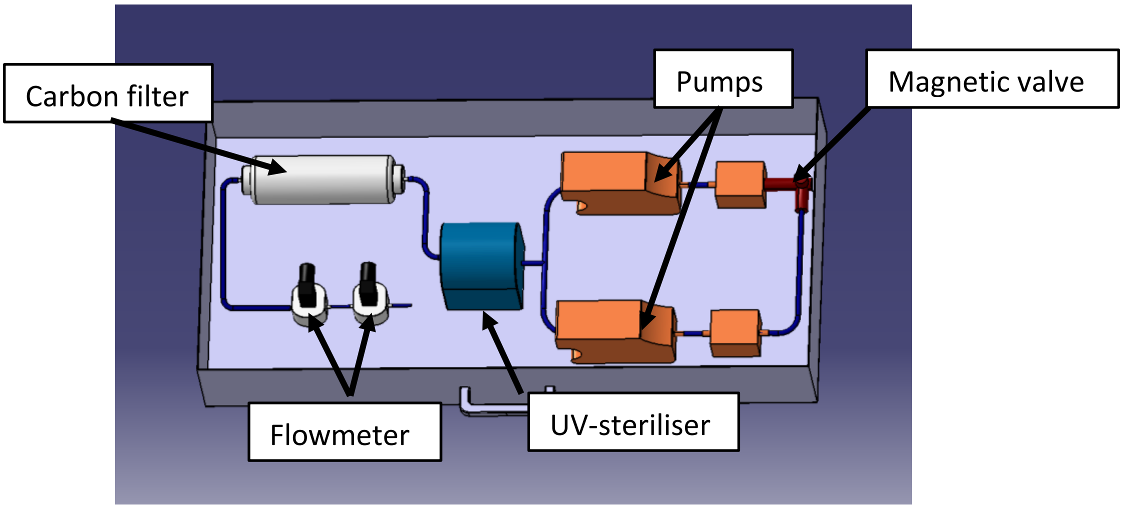


Figure 6-13 Detailed view of the CWPU

Redundancy/accessibility concept: The CWPU design is one failure tolerant. It foresees a second pump and flowmeter. If one pump stops working, the other pump compensates for the disfunction. In order for the second pump to work, a signal must be output as soon as the first pump stops working. Then the 3-way magnetic valve is activated and opens the flow path to the second pump. Overflow protection is provided by a condensed water tank with the volume of 60 l, to collect condensed water for 24 hours in the case that both pumps fail.

The design shall provide easy access for cleaning, maintenance and exchange of parts. This can be realised by mounting the different units in a drawer beneath the dehumidifier. The components can then easily be pulled out and exchanged. Since the entire CHX unit can be lowered to working height, the CWPU as part of the unit is also easily accessible.

6.3 Underfloor section

Design concept: The underfloor section of the AMS is shown in Figure *6-14* and consists of:

- The heater unit
- The ventilation unit
- The VOC filter unit
- The support structure
- The sensor bundle
- O_2 interface (greenhouse to habitat)

The **sensor bundle** is placed right at the air outlet to monitor and analyse the outgoing air after the treatment. It also measures the static pressure and a comparison to the static pressure at the inlet is carried out to identify possible clogging of the filters. The housing design and mounting flange are the same as the sensor bundle in the overhead part of the AMS. Custom fabrication allows multiple sensors to be used in a bundle at different locations in the air duct, providing redundancy.

The **support structure** stabilises components, reducing structural loading, and prevents unwanted movement. A simple CATIA design of aluminium profiles is provided for the time being, which could be elaborated in the further course. The VOC filter is secured with tube clamps.

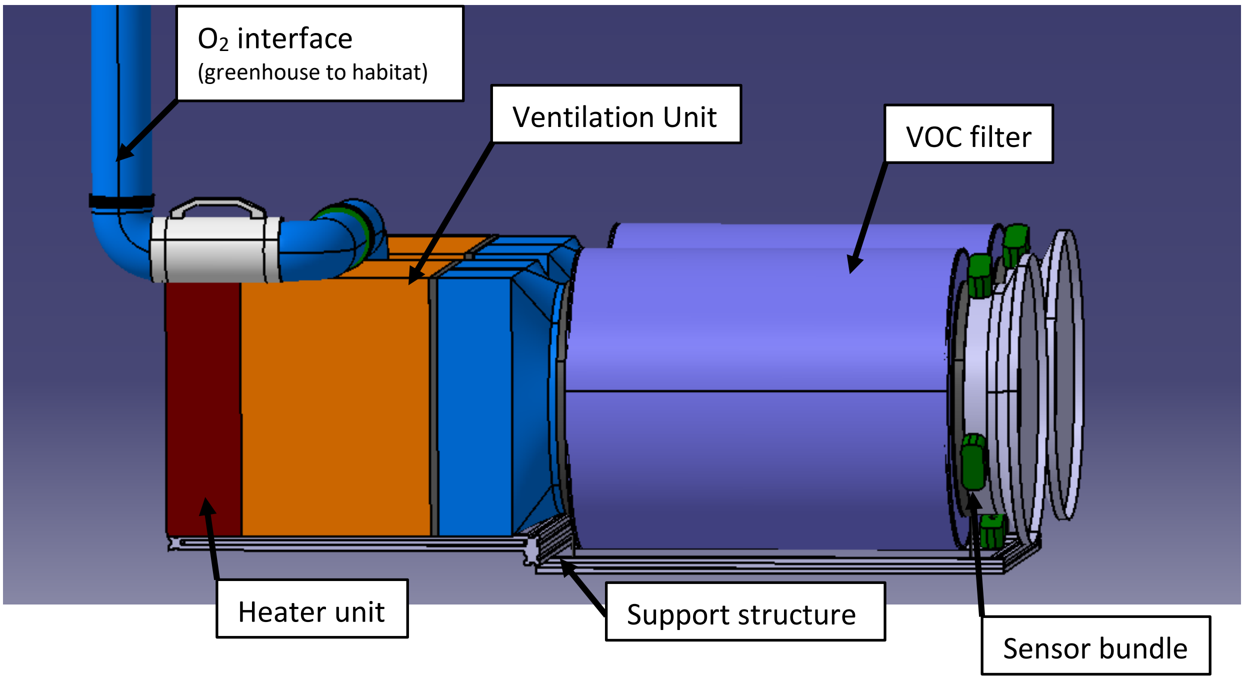


Figure 6-14 Design of the AMS underfloor section

O2 interface (Figure *6-15*)**:** The O_2 interface from the greenhouse to the habitat is closed by the first valve located in the air duct. The air duct divides into two air streams and is connected to the underfloor part of the AMS after the ventilation unit. Two redundant sensor bundles measure and analyse the air parameters in the interface air duct to determine whether further treatment of the air is required. Either the habitat provides the air treatment, or the valves can be closed. In case the first valve malfunctions, a second valve is placed inside each air stream. As the air is redirected before passing the VOC filter, an additional filter could be placed inside the interface air duct to remove ethylene and other volatile organic compounds from the air.

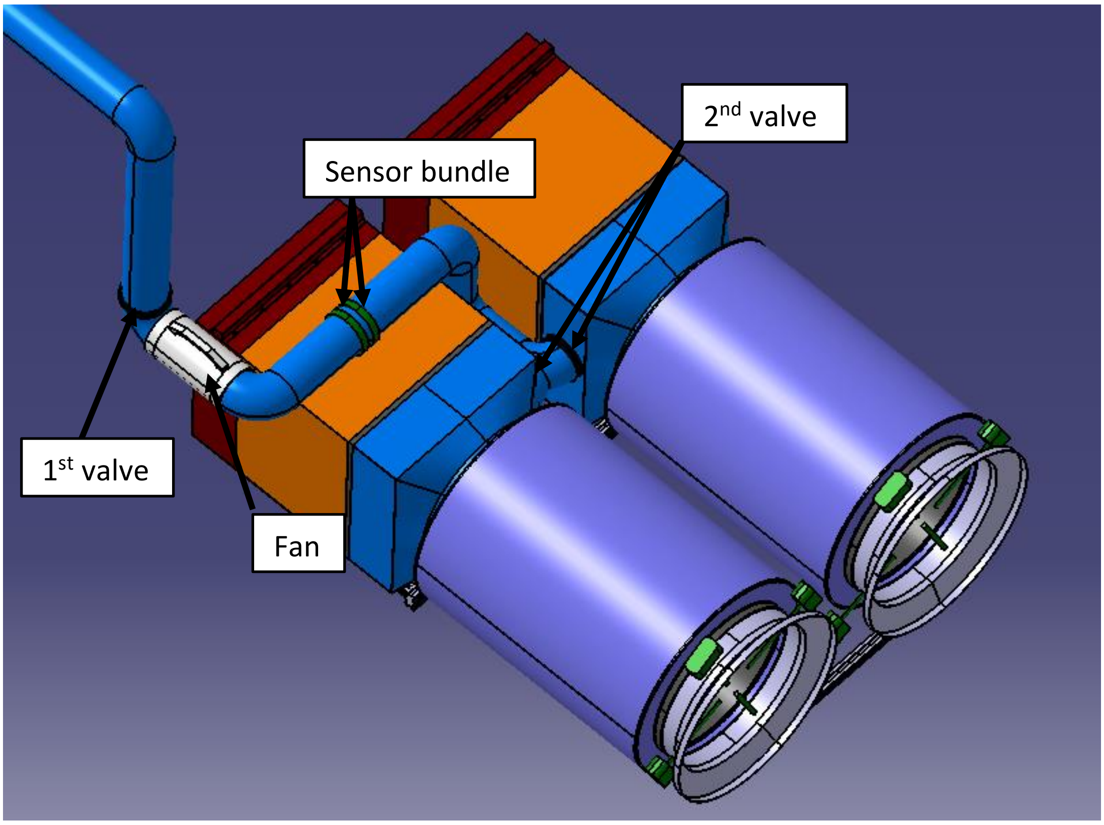


Figure 6-15 Design of the O2 interface (greenhouse to habitat)

6.3.1 Heater

Design concept: The heater unit consist of finned-tube heater elements placed inside the heater casing (Figure *6-16*). On top of the casing is a cover placed to protect the heating elements, which can be removed by unscrewing it. The heating elements are arranged evenly next to each other inside the casing to ensure a uniform temperature increase of the air. Verification of the heating capability by simulation or test is needed.

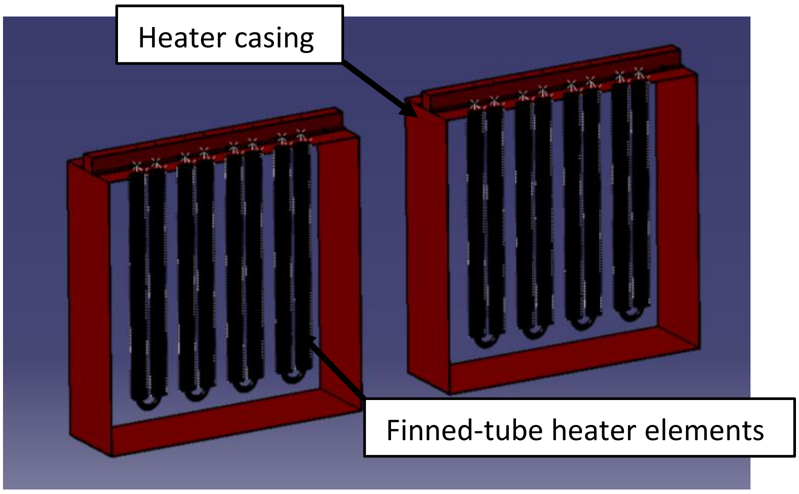


Figure 6-16 Design of the finned-tube heater elements inside the heater casing

Redundancy/accessibility concept: An additional redundancy of 1 heater per air stream is given. This type of heater can also work in static air, providing a useful safety margin. For maintenance and replacement of defective heating elements the air duct shall be accessible and removable. The unit is accessible from the top and single elements can be replaced without removing the whole unit. The space-saving design and the light weight resulting in the possibility of storing several individual heating elements in the greenhouse module.

6.3.2 VOC

Design concept: The VOC filter consist of a filter casing, filter granules and an iris shutter that is automatically controlled by the CDHS of the AMS (Figure *6-17*). The VOC filter provides two modes of operation which are influenced by the measured ethylene and VOC concentration in the air. If the concentration is equal or below the defined setpoint the shutter is open and the air passes through the filter but not the filter medium. It has to be verified whether the air also passes through the filter medium in the open shutter configuration. If the concentration is above the defined setpoint the shutter is closed and the air passes through the filter medium twice. The filter granules are made of activated carbon and form a layer inside the VOC filter. Both modes of operation are visualised in Figure *6-18*.

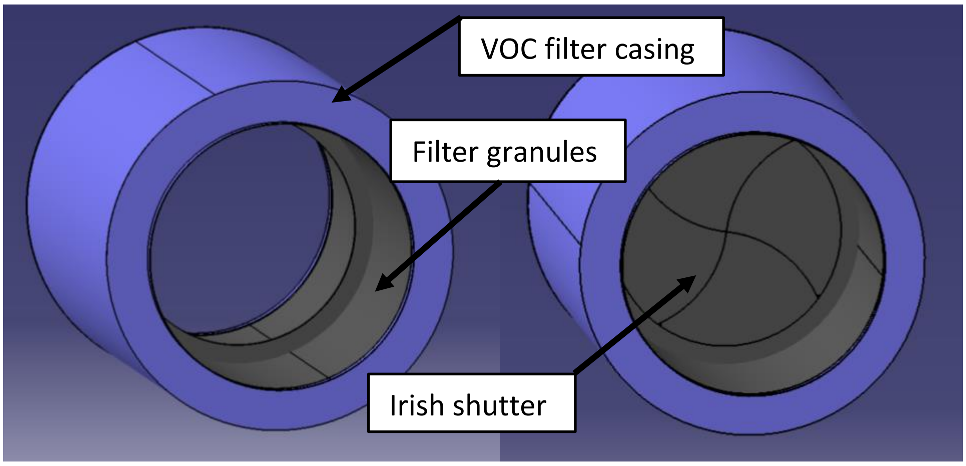


Figure 6-17 Design of the iris shutter inside the VOC filter (left side: open shutter; right side: closed shutter)

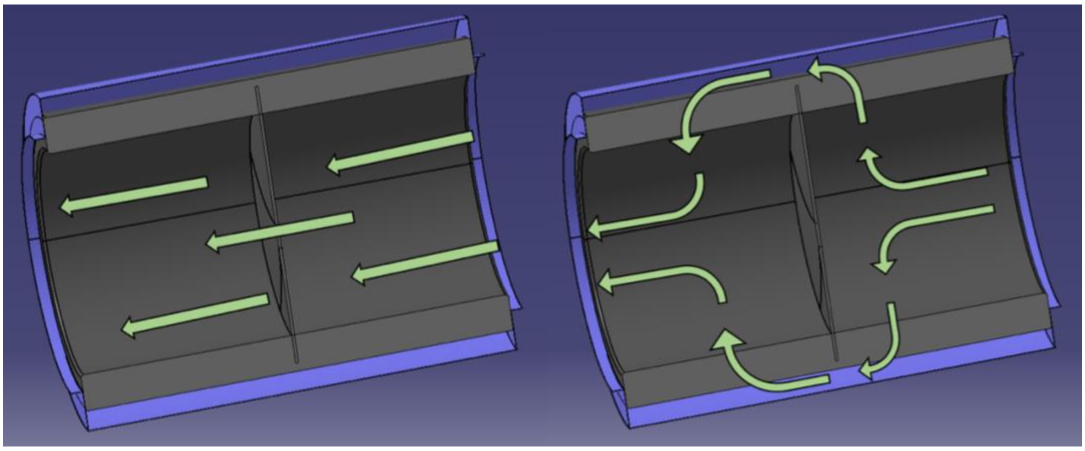


Figure 6-18 Cross-section view of the air flow inside the VOC filter (left side: open shutter; right side: closed shutter)

Redundancy/accessibility concept: Apart from the two parallel air streams with one filter each, no additional redundancy concept is foreseen for the VOC filter. In case of failure or clogging of the filters they have to be removed for maintenance or replacement. To slow down the clogging of the filters, a lid is built into the filter that can be opened and closed as needed to regulate the ethylene concentration. The design of the lid is intended to resemble an iris shutter that is directly placed inside the duct of the filter unit. It is possible that the custom-made filter design can provide better accessibility by allowing the filter cassette to be removed without removing the casing.

6.4 Cargo Configuration Model

Design concept: The cargo configuration of the module at the start of the mission shall store as much cargo as possible. Therefore, the air suction ducts and the air distribution ducts are deployed, folded and tightly stored in one compartment of the module (Figure *6-19*). When changing to greenhouse operation, the air ducts can be unfolded, deployed and placed in the space provided. A placeholder is positioned in the model and no detailed CATIA design of the cargo configuration air ducts is given. The exact dimensions of the folded unit have to be estimated after the selection of the duct material and wall thickness.

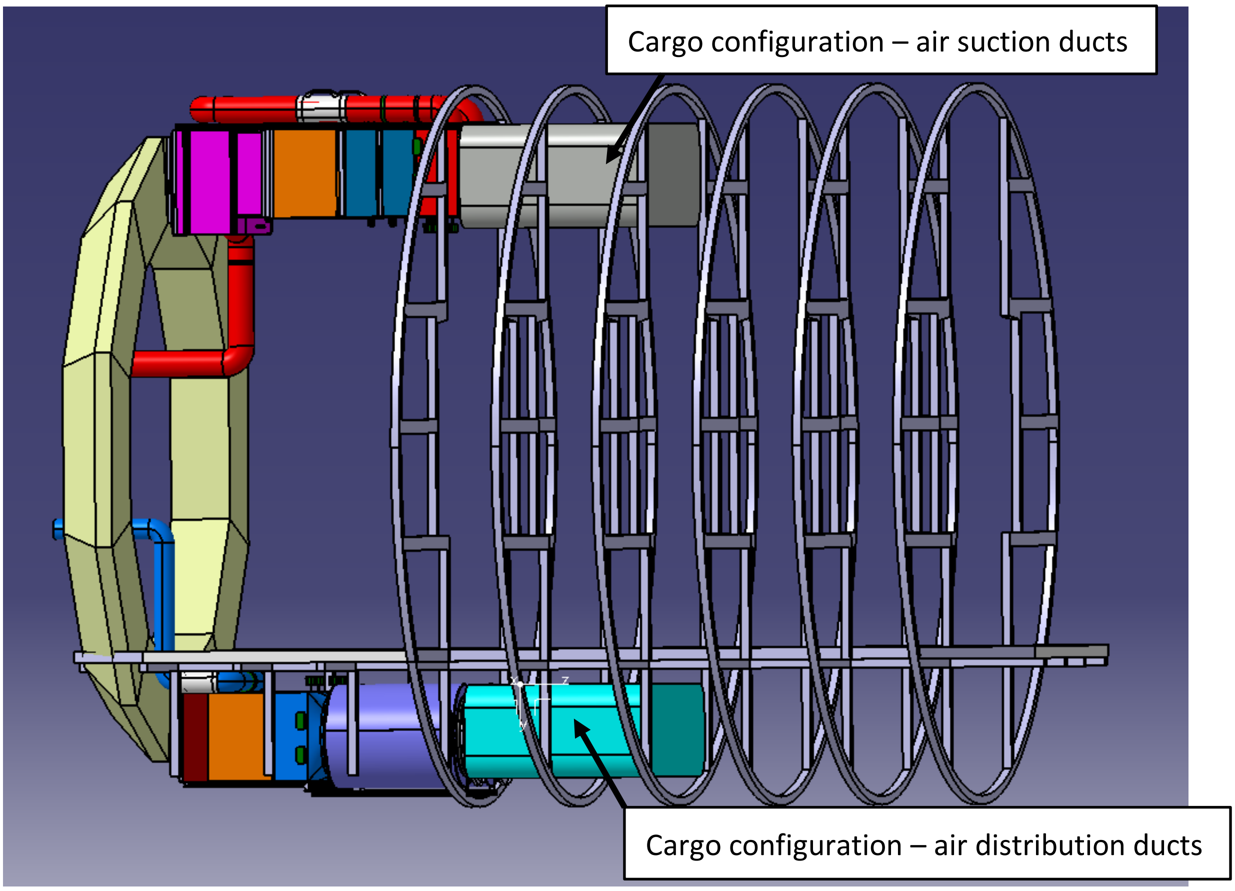


Figure 6-19 Cargo configuration - air ducts

6.5 Summary - Design

The CATIA design and implementation of the AMS in the overall structure of the module for both the cargo and the greenhouse configuration was achieved in this chapter. The major issue during the design has proven to be the provided installation space for the AMS in the service section. With an available length of approximately 1.5 m in the overhead and underfloor areas of the service section, the components that meet the performance requirements of the calculated worst-case thermal load scenario exceed the length limit by 20-50 cm (see Table *4-5*), not taking into account connectors, interfaces or sensors. The selected components from Chapter 5 were therefore only used as a reference model and adapted in size to the available installation space. An adjustment of the components to the same cross-section area resulted in the reduction of the adapter size between the components. During the design, it became apparent that a design of two parallel air streams is the suitable option. The components are reduced in size and a redundant system is created, which is favourable for a later space application. If one of the dual components malfunction, a reduced but continuing air flow rate is still provided to maintain the parameters of the atmosphere within the greenhouse. This ensures the growth of the plants and does not endanger the safety of the crew until the other side is repaired or maintained.

Accessibility is a key factor in the design, which has been partly achieved. The overhead section of the AMS offers easy accessibility by implementing a drawer system for the UV-C lamp, the CWPU and the pre- and HEPA filter units. The filters and their inlets can be easily pulled down with a handle for replacement and reinsertion. An easy-to-open locking mechanism is needed for the drawers to prevent unintentional opening. This could be realised by the same locking mechanism that is provided for the sheet metal cover of the droplet separator and the drawer of the UV-C lamp. Accessibility is also provided for the heat exchanger unit as it is placed on telescopic rails and can be pulled down to working height with a handle. The issue is that the cables, supply and discharge lines for the cooling liquid must be long and flexible enough to be pulled down. There might be a problem with the sealing of the interfaces which needs to be tested. The underfloor section provides limited accessibility as the flooring blocks the access and the O_2 interface air ducts above the heater and the ventilation unit due to the limited height of the installation space. No drawer system could be achieved for the components of the underfloor section.

The next step is to perform a CFD analysis to verify the functionality of the AMS. Some adjustments to the design need to be made in advance, as some components such as the CHX the air ducts and the support structure are not yet designed in detail. The CHX unit is still a black box that needs to be further developed in later design steps.

7 Data Handling and Control System of the AMS

This chapter gives an overview on the function of the CDHS and the use of a software for data tracking and parameter control. It states the set point and threshold values for the atmospheric parameters and gives a guideline for the programming of the CDHS with regards to the AMS.

The functions of the DHCS are the onboard operations and internal communication autonomously performed by software. The aim is to automatically control the processes of the AMS to ensure smooth operation by the interaction of the components to achieve optimal plant growth.

Important for the optimisation of the AMS design is also the evaluation and backup of data over a longer period of time to identify issues or patterns. LabView is the software used in the EDEN laboratory to track data and to control the actuators, such as filter units, for an optimal atmospheric environment. It provides a graphical user interface (GUI) for data monitoring and management, giving crew members an easily accessible overview of the parameters and the ability to manually change the setpoints (Figure *7-1*). [145]

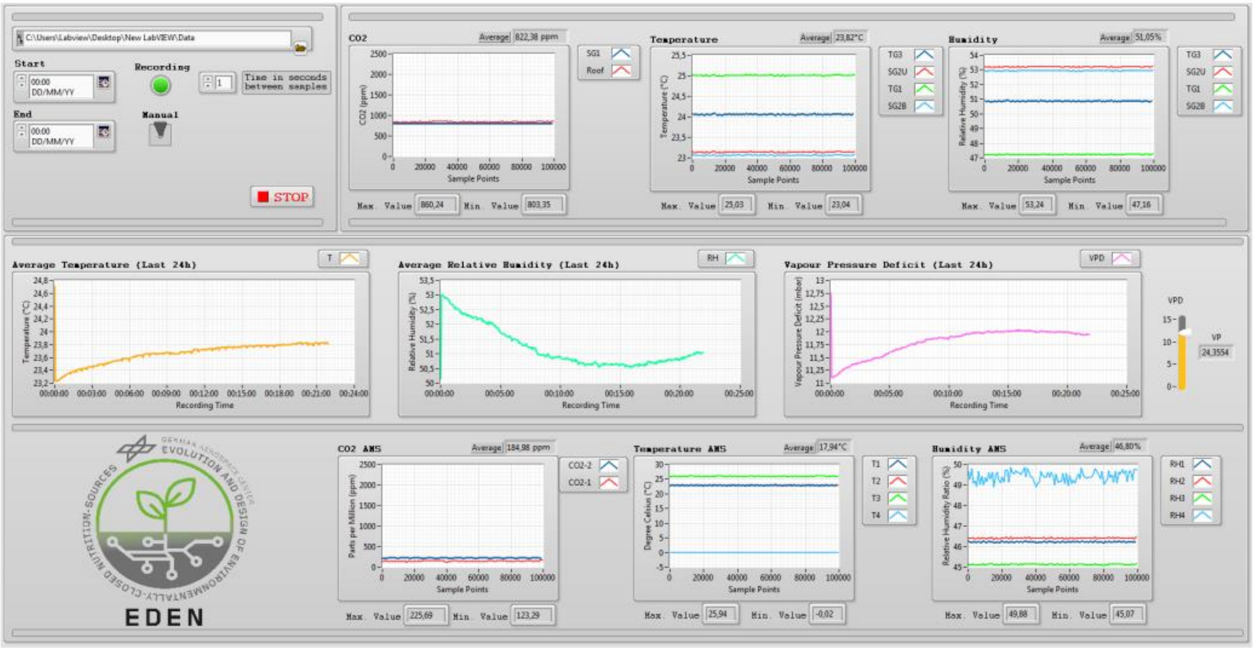

C:\Users\Labview\Desktop\New LabVIEW\Data
Start: 00:00 DD/MM/YY
End: 00:00 DD/MM/YY
Time in seconds between samples: 1
CO2 Average: 822,38 ppm
CO2 Max. Value: 860,24 Min. Value: 803,35
Temperature Average: 23,82°C
Temperature Max. Value: 25,03 Min. Value: 23,04
Humidity Average: 51,05%
Humidity Max. Value: 53,24 Min. Value: 47,16
VP: 24,3554
CO2 AMS Average: 184,98 ppm
CO2 AMS Max. Value: 225,69 Min. Value: 123,29
Temperature AMS Average: 17,94°C
Temperature AMS Max. Value: 25,94 Min. Value: -0,02
Humidity AMS Average: 46,80%
Humidity AMS Max. Value: 49,88 Min. Value: 45,07

Figure 7-1 Data handling management GUI [145]

7.1 Atmospheric Parameter for DHCS

Greenhouse regulation and control is quantified by measurement via sensors located in the air ducts and the cultivation area. The measured values are compared with the set points. The difference between the values is managed by means of one or more actuators.

The set points of the AMS are defined for the day and night period inside the greenhouse module. Important for maintaining optimal conditions for plant growth is also the definition of a maximum and minimum value, which shall not be exceeded. Table *7-1* states the preliminary definition of the atmospheric parameters with their set point and threshold values. The values are the monitoring parameters for the FDIR of the DHCS. The selection is influenced by the overlapping comfort zones of plants and humans. However, the values still need verification through testing.

Table 7-1 Atmospheric parameters of the AMS for the DHCS [146] [147] [148] [149] [150] [151] [152] [153]

Atmospheric Parameter	Day			Night			Action DHCS	
	Minimum	Set Point	Maximum	Minimum	Set Point	Maximum	Minimum	Maximum
Temperature [K]	292	295	300	289	291	293	decrease mass flow rate of cooling fluid	switch off the heating elements
Relative humidity [%]	60	70	80	55	63	70	decrease mass flow rate of cooling fluid (if possible) increase temperature of cooling fluid	increase mass flow rate of cooling fluid (if possible) decrease temperature of cooling fluid
O_2 concentration [%]	19.5	21.5	23.5	19.5	21.5	23.5	close interface to habitat	open interface to habitat
CO_2 concentration [ppm]	500	1000	1500	500	1000	1500	open interface to habitat	close interface to habitat
Ethylene/VOC level concentration	10	50	200	10	50	200	open iris shutter in VOC filter	close iris shutter in VOC filter (additional) increase rotational speed of fans
Atmospheric pressure [kPa]	100.3	101.3	102.3	100.3	101.3	102.3	-	-

7.2 Control guideline for the DCHS

A guideline for the DHCS with respect to the AMS is developed in this chapter. Measures to automatically maintain and regulate the set point values of the atmospheric parameters are presented. If a deviation from the temperature, relative humidity or ethylene/VOC concentration is measured, the control system may increase the rotational speed of the fans in the service section to increase the cycle rate through the AMS. After normalisation of the values, the speed is reduced to standard operation. The heaters shall be automatically switched on or off if the temperature is either too low or too high respectively. The time for cooling down and heating up the heating elements has to be tested in order to check the feasibility.

The individual process steps for regulating and controlling the CO_2, O_2 and ethylene/VOC concentration are shown graphically in flow diagrams. A flow diagram visualises a process to provide easy understanding of the process steps. The flow diagram in this thesis consists of four symbols: oblong, rectangle, diamond and parallelogram linked with arrows that show the direction of the flow. The legend of the flow diagram is shown in Figure *7-2*.

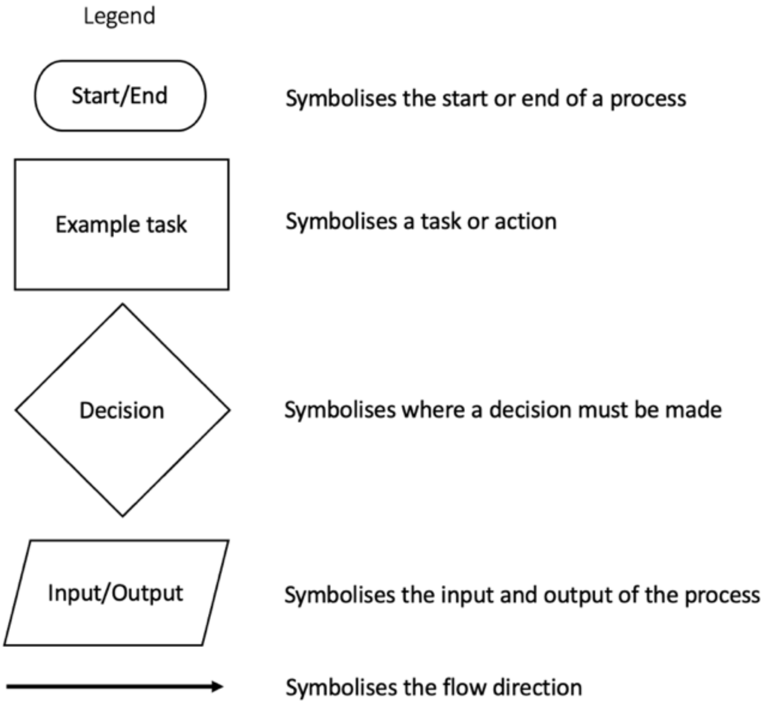


Figure 7-2 Symbols of the flow diagram [154]

Flow Diagram – CO_2/O_2 Concentration

The only planned source of CO_2 in the greenhouse is the interface from the habitat and, in case of the GTD, crew working inside the greenhouse. The amount of CO_2 produced by the crew members is not taken into account in this thesis, but it will have an influence on the CO_2 concentration during the operating phase of the GTD. The only planned source of O_2 in the greenhouse is photosynthesis by the plants. This guideline is focusing on the mature crop balance, with a stabilized CO_2 need and O_2 production. Ambient air containing CO_2 and O_2 may also enter the module through gaps in the sealing and by the crew entering the module

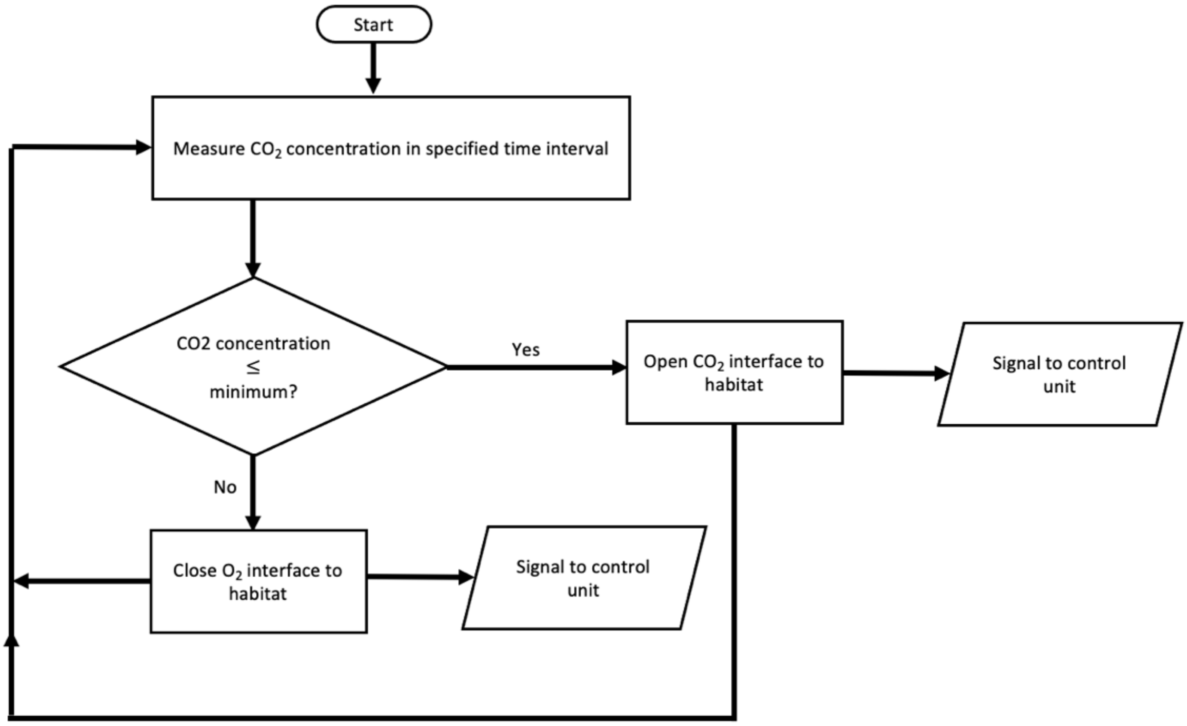


Figure 7-3 Flow diagram – regulation of CO2 concentration

The CO_2 control is carried out via the CO_2 interface from the habitat to the greenhouse. The sensors measure the CO_2 concentration in the greenhouse in set time intervals (e.g. 20 minutes) and for the case it is less than or equal to the minimum value, a signal to the control unit is transmitted to open the valves and simultaneously start the fans to transfer the CO_2' enriched air from the habitat to the greenhouse. When the concentration reaches the set point, the valves close and the fans stop operating. The opening and closing frequencies could be analysed to determine specific time intervals for the opening and closing of the interface to keep the CO_2 parameter at the set point. If an unexpected hazard such as a fire occurs, the valves can be closed manually (see Figure *7-3*).

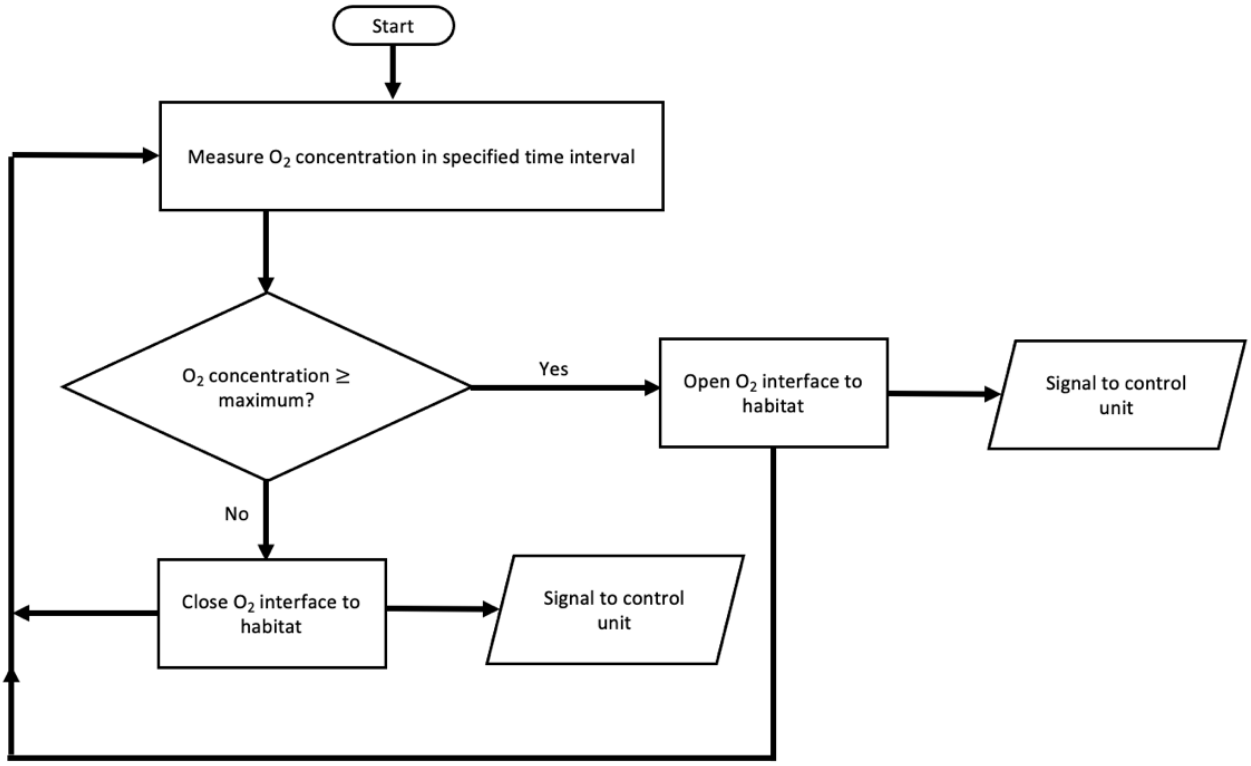


Figure 7-4 Flow diagram – regulation of O_2 concentration

The O_2 control is similar to the CO_2 control and is done via the O_2 interface from the greenhouse to the habitat. The sensors measure the O_2 concentration in the greenhouse in defined time intervals, and when it is greater than or equal to the maximum value, a signal to the control unit is transmitted to simultaneously open the valves and start the fans to transfer the O_2' enriched air from the greenhouse to the habitat. When the concentration reaches the set point, the valves close and the fans stop operating. The opening and closing frequencies could be analysed to determine specific time intervals for the opening and closing of the interface to keep the O_2 parameter at the set point. If an unexpected hazard occurs, the valves can be closed manually. (see Figure *7-4*)

Flow Diagram – Ethylene / VOC Level Concentration

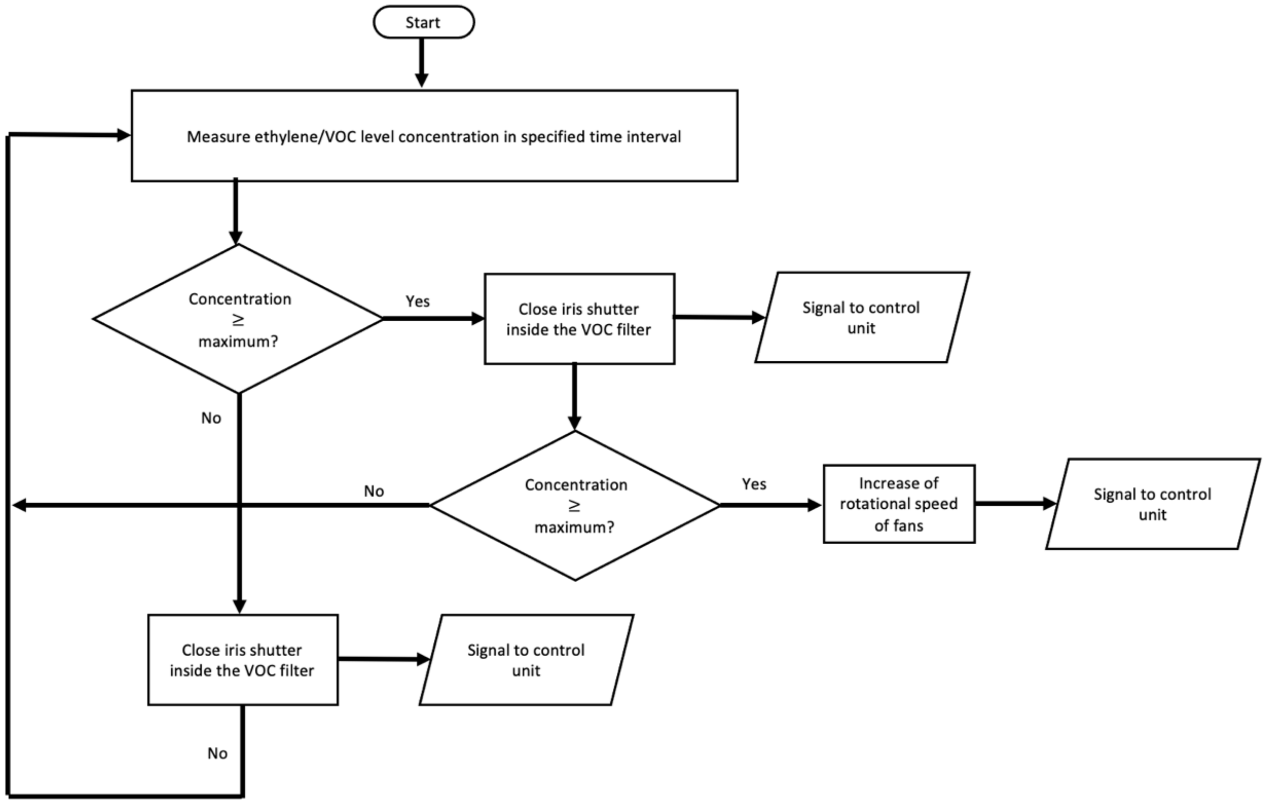


Figure 7-5 Flow diagram – regulation of ethylene/VOC level concentration

The sensors in the AMS measure the ethylene/VOC level concentration in prior defined time intervals. If the concentration is higher or equal to the set maximum, the iris shutter in the VOC filter has to close in order to force the air through the filter medium. A signal to the control unit is transmitted for autonomous control of the iris shutter.

If the concentration is still not in the defined range, the rotational speed of the fans is increased to provide a higher air exchange rate through the filters. A signal to the control unit is transmitted for autonomous control of the corresponding fans. If the concentration is in the defined range, the iris shutter inside the VOC filter is closed to prevent early clogging of the filter. A signal to the control unit is transmitted for autonomous control of the iris shutter (see Figure *7-5*).

8 Conclusion & Future Outlook

This chapter provides design recommendations in relation to the design presented in Chapter 6. It also introduces a brief outlook on verification recommendations and to further research topics interesting for the EDEN Next Gen greenhouse design.

8.1 Design and Verification Recommendations

The components placed in the CATIA design of the AMS are based on the selected components in Chapter 5, which fulfil the performance requirements calculated in this thesis. However, these had to be heavily modified in their dimensions in order to fit in the limited space in the service section. The margin applied in this thesis could be adjusted in the later design steps to a less conservative one. This would result in a decrease in component size. If the adapted design cannot meet the requirements as expected, a solution could be to remove one rack of the crop cultivation or to increase the size of the module. The increase in size does not pose a problem for the GTD but could do so for the space application. The module has to fit in the payload capability of the launcher to be able to transport the module in one go.

With regard to the sizing, the dimension of the VOC filter has to be verified. At the moment, the distance between the housing and the filter medium is small and the expected pressure drop is high, which could pose a challenge for the air flow inside the AMS. It also should be checked how thick the layer of the filter medium has to be in order to sufficiently filter the air from ethylene and VOC concentration. The available space in the underfloor part of the service section is limited and the size of the filter has been reduced to fit. It is therefore necessary to verify whether the filter capacity is still sufficient and how long the granulate will last if it is not used as much. A further point is that the iris shutter inside the filter does not disappear completely in the membrane during the open configuration. The effects on possible air turbulence still need to be researched. It has to be elaborated how thick and strong the shutter has to be so that no air is flowing through unintentionally. A manufacturer should be sought, and it must be checked whether the iris shutter can be realised as envisaged.

The connecting air ducts between the components are short and normally the components, especially fans, need space before and after to ensure optimal air flow parameters. The cross-sectional area of the designed components is the same for all of them. It is not clear whether this can be realised in production. If the interfaces between the components are then too

small or the interface angle is too steep, air turbulence, pressure drop and noise can occur. The connector sizing has to be taken into account for later design steps.
During the CE-study, the idea arose that the air distribution ducts may run in the unused space at the corners of the inside structure, so that the space could be used for other subsystems or as storage area. At approximately 566 mm, the duct diameter estimated in this design is too wide to fit in the limited space. An estimation showed that the air duct should not exceed a diameter of ≈ 400 mm to be placed in the opening. This would result in a flow rate of $1810\ \frac{m^3}{h}$ at an air speed of $4\ \frac{m}{s}$ or an increase to $8\ \frac{m}{s}$ for the same flow rate of $3628\ \frac{m^3}{h}$ per air duct. The duct diameter for the water-cooled option decreases to $D_{water}\ = 337\ mm$, which allows placement of the ducts in the previously unused area and thus provides more space for subsystems and cargo. If the air-cooled option is still used, then it must be weighed up whether the changes are recommendable or whether the current design should be retained.

It is not clear whether the two parallel air ducts between the shelves are able to draw in and discharge the air on each level of the shelves at the same time, without treated air being directly drawn back in by the intake. This could result in insufficient treated air reaching the plants. Drawing in and distributing the air at the same time may damage the plants. It might be better to provide air intake only at the top of the greenhouse and air distribution between the shelves. A simulation should be carried out for both options to ensure sufficient air movement between the plants and a suitable air velocity. Tests should provide further results.

Accessibility concepts were introduced in Chapter 6 to simplify maintenance and the exchange of parts. The accessibility could not be realised for the components in the underfloor part of the AMS due to the flooring and the layout of the O_2 interface air ducts. Accessibility for the fans might be realised with the same design as the one for the fans of the interface to the habitat. A handle and simple fastening mechanism could simplify the replacement or maintenance of the fans. The accessibility concept of the heat exchanger unit developed in this thesis simplifies the maintenance or replacement of components by placing the unit on telescopic rails, which can be pulled down to working height. The detailed design of these rails and fastening mechanism has to be completed in later design steps. It is important to pay attention to the cable connections, the connection for the cooling liquid and the hose for the treated condensation water. The tubes have to be flexible and long enough to be pulled down with the CHX unit without leakage and they should not kink or become entangled. Space for the tubes has to be provided in the overhead section.

To reduce the noise emission in the module for the crew members working inside, silencers should be fitted around the noisiest components. This could affect the size of the components, which is not a problem in most cases, especially in the overhead area of the AMS. It does pose a problem in the underfloor part of the AMS, because the floor and rigid structure of the greenhouse limit the available space. Only limited space is provided to place silencers around the fans and other parts where necessary. Noise suppression does not have to be implemented for the air ducts because, as mentioned before, the air ducts are often not the problem. This was calculated in Chapter 5.9.3, where an increase in air speed from 3 $\frac{m}{s}$ to 4 $\frac{m}{s}$ in the air ducts does not exceed the noise limit for humans, but the air speed might increase the noise generated by the fans.

Space application: Important for the design and the design recommendations given are the changes that have to be made in order to use the devices in space. As mentioned in the literature research, there are certain challenges that apply to the design of the components in order to make them flight proven. For the design of the GTD only COTS components are used, which do not have to be flight proven as they do not have to withstand the extreme conditions of transport or environment. To test the components, it would be advantageous to already have the flight proven ones implemented in the system. For the space application, the components have to be adjusted to the D/C power supply, reinforced for transport and made out of suitable material for greenhouse and space application. This could possibly lead to a change in the component design and has to be verified by a manufacturer.

Tests on the air ducts, structure and components have to be conducted to verify the design of the AMS and to approve it for space flight. Eigenfrequencies must be determined and compared with the frequencies that occur at launch so that the oscillation does not reach a maximum, damaging components. A shaker test should provide the required results. A vertical load test or simulation of the conical air ducts should be performed as they are placed in the conical section of the greenhouse and therefore experience a high vertical load at the launch. The result should indicate which wall thickness to use and whether further support structures are needed.

8.2 Outlook

The aim of this master thesis was the development and design of the atmosphere management system of the EDEN Next Gen greenhouse module with special focus on the ground test demonstrator.

This objective was achieved through:

- Collection and consideration of the requirements and lessons learned.
- Conducting a CE-study for the preliminary design of the AMS, including trade-offs on the system and defining interfaces to the thermal control, cargo environment and the habitat.
- Estimation of performance values and the selection of suitable COTS components as design examples.
- A CATIA design of the AMS included in the module structure.
- Providing a control guideline of the atmospheric parameters for the DHCS.
- Providing design and verification recommendations.

A decision yet to be made is between the option of an air-cooled or water-cooled LED-system. The trade-off study in this thesis only considered the impacts on the AMS and neglected the effects on the TCS. Even though the water-cooled option is the better one from the point of view of the AMS, the air-cooled option was selected as the one to be investigated during the CE study. It is possible that this decision will change as the project progresses as it has already become clear in the CATIA design that the installation space is limited and the components selected according to performance have been greatly reduced in size. The change to a water-cooled LED system does simplify and reduce the size of the AMS as mentioned in the trade-off, but it also bears issues for the TCS. Every connector of the cooling water pipe increases the risk of leakage. That is an issue for the electronic devices in the greenhouse as the water could cause damage to the devices, which can lead to a failure of the system. With reference to the space application, water can collect on surfaces and can cause damage to electrical equipment. Spare parts are only available in small quantities as the supply from Earth is expensive. In terms of safety, the air-cooled variant is therefore preferable. However, the decision between the option of an air-cooled or water-cooled LED-system will become clear in the course of the project.

The next steps are a further detailing of the design, whereby the design recommendations should be taken into account. Furthermore, a CFD simulation should be carried out as a next step to ensure the functionality of the designed system and to drive changes where required.

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10 Appendix

10.1 Geometric and Functional Characteristics of the Greenhouse

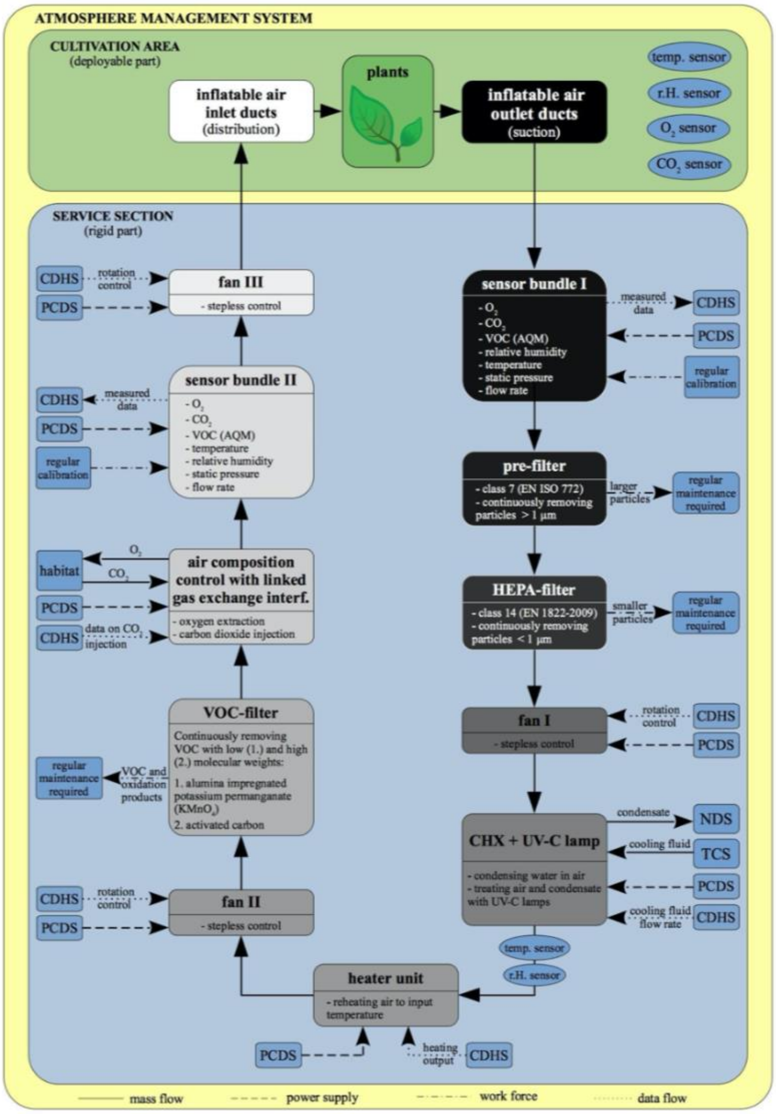


Figure 10-1 Preliminary layout of the AMS components in a functional diagram [71]

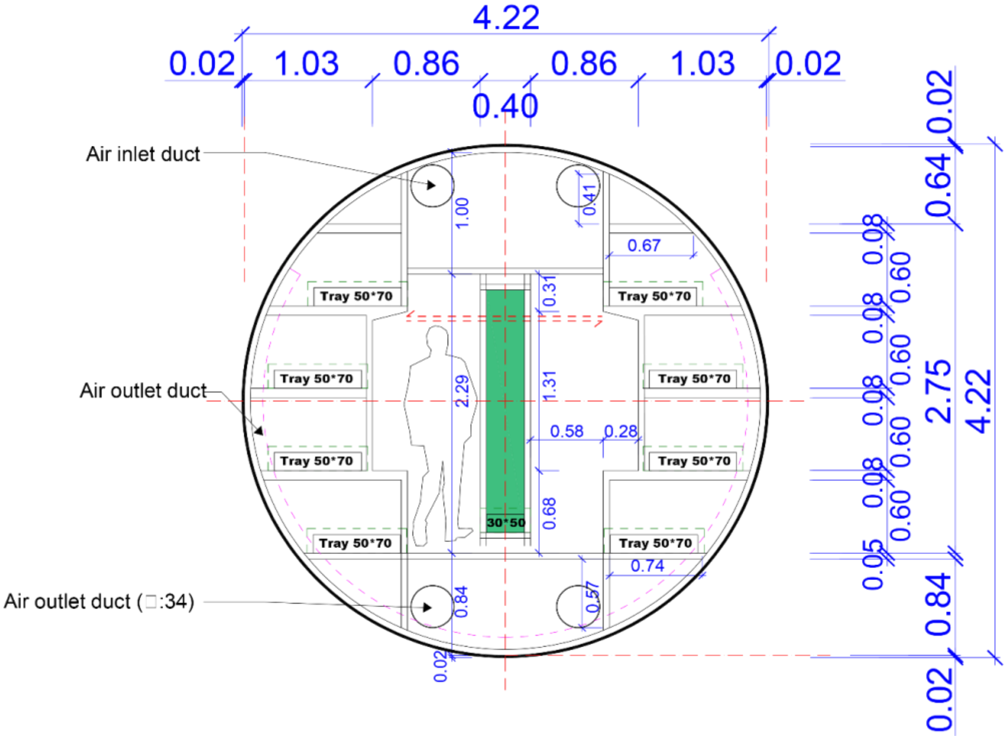


Figure 10-2 Detailed sizing of the greenhouse [internal source DLR]

10.2 Calculations and Parameters

Heat Transfer

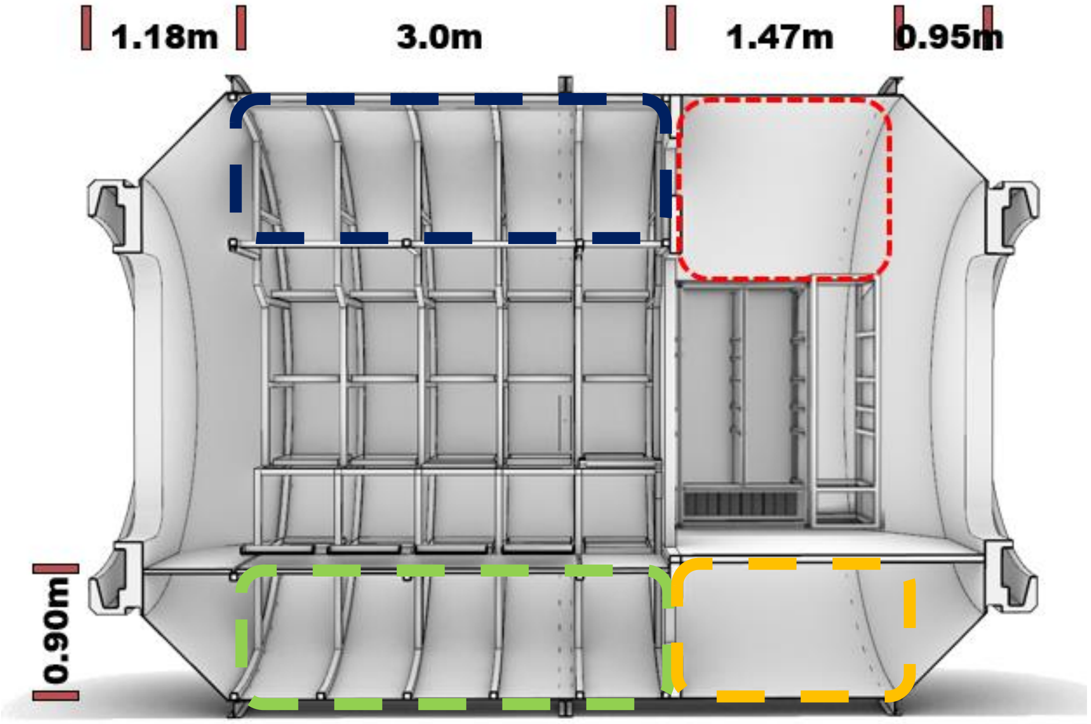


Figure 10-3 Dimensions of the greenhouse and sections of the AMS (blue: overhead section in cultivation area; green: underfloor section in cultivation area; red: overhead section in service section; yellow: underfloor section in service section) (based on [internal source DLR])

Table 10-1 Values for the calculation of the net rate of heat transfer for the GTD

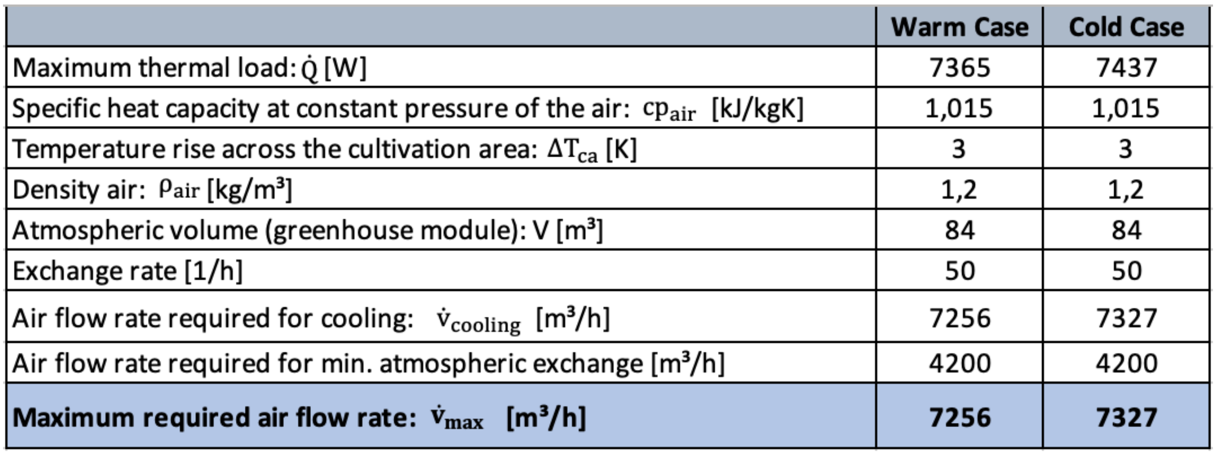
	Value
Emissivity ε (Aluminium)	0.09
Surface area [m²]	97.21
Stefan-Boltzmann constant σ $[\frac{J}{s \times m^2 \times K^4}]$	5.67×10^{-8}
Surrounding temperature [K]	291
Surface temperature (warm case) [K]	295
Surface tmperature (cold case) [K]	291

Table 10-2 Values for the heat radiation via the outside wall of the greenhouse module for the Lunar application [71]

	Value
Emissivity ε (MLI)	0.031
Regolith subsurface temperature [K]	254
Inside temperature (warm case) [K]	295
Inside temperature (cold case) [K]	291
Mean temperature of MLI (warm case) [K]	274
Mean temperature of MLI (cold case) [K]	272.5
Conduction constant	8.95×10^{-5}
Radiation constant	5.39×10^{-7}
MLI thickness [mm]	2
Number of facing pairs within the MLI structure	19 (20 layers in total)
MLI density [layers/cm]	100

Air Flow Rate

Table 10-3 Calculation of the maximum required air flow rate

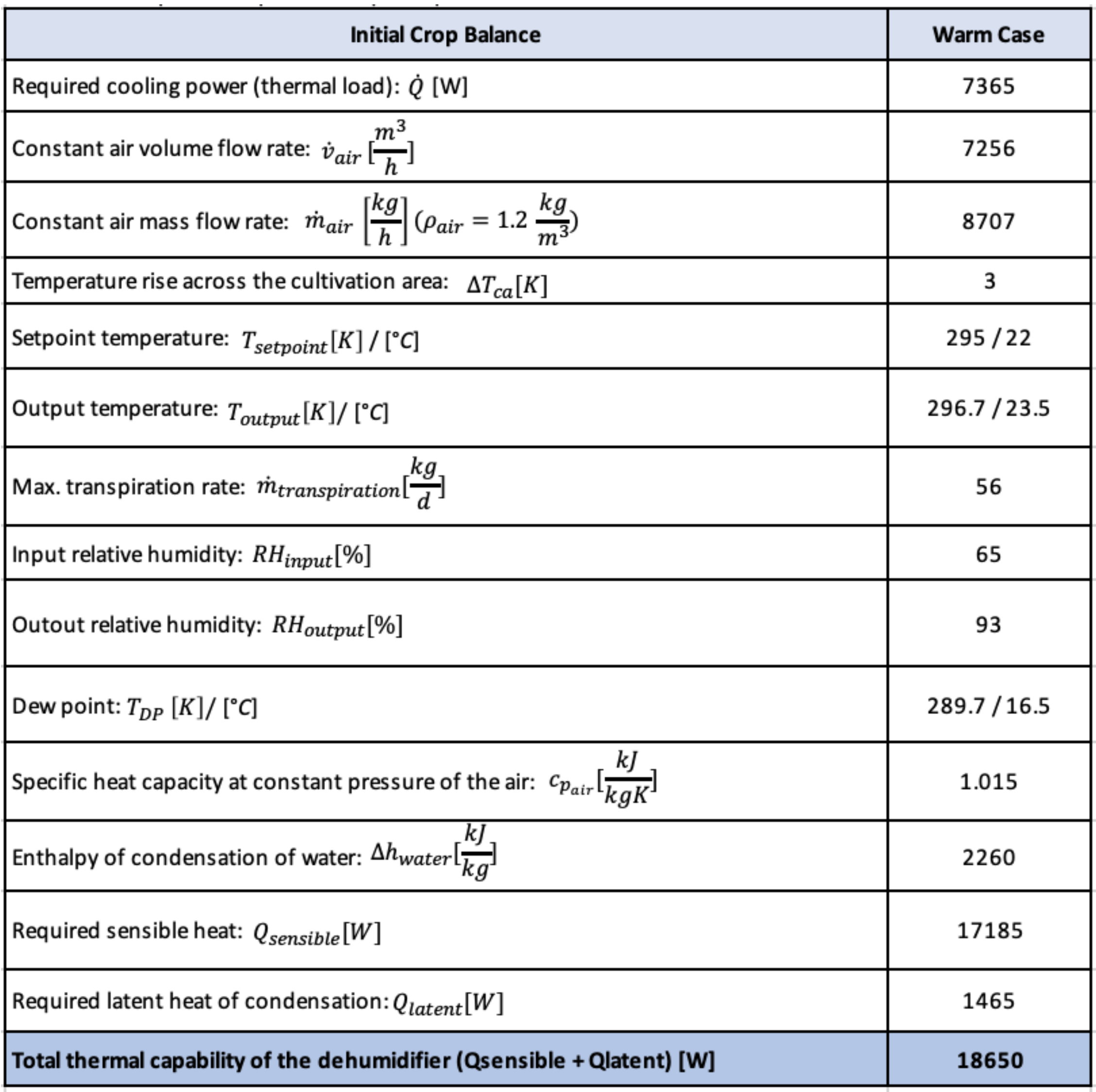


	Warm Case	Cold Case
Maximum thermal load: $\dot{Q}$ [W]	7365	7437
Specific heat capacity at constant pressure of the air: cp_{air} [kJ/kgK]	1,015	1,015
Temperature rise across the cultivation area: ΔT_{ca} [K]	3	3
Density air: ρ_{air} [kg/m³]	1,2	1,2
Atmospheric volume (greenhouse module): V [m³]	84	84
Exchange rate [1/h]	50	50
Air flow rate required for cooling: $\dot{v}_{cooling}$ [m³/h]	7256	7327
Air flow rate required for min. atmospheric exchange [m³/h]	4200	4200
Maximum required air flow rate: $\dot{v}_{max}$ [m³/h]	**7256**	**7327**

Dehumidifier

Initial Crop Balance

Table 10-4 Required performance of the CHX for the initial crop balance



Initial Crop Balance	Warm Case
Required cooling power (thermal load): $\dot{Q}$ [W]	7365
Constant air volume flow rate: $\dot{v}_{air}\ [\frac{m^3}{h}]$	7256
Constant air mass flow rate: $\dot{m}_{air}\ \left[\frac{kg}{h}\right] (\rho_{air} = 1.2\ \frac{kg}{m^3})$	8707
Temperature rise across the cultivation area: $\Delta T_{ca}[K]$	3
Setpoint temperature: $T_{setpoint}[K]$ / [°C]	295 / 22
Output temperature: $T_{output}[K]$/ [°C]	296.7 / 23.5
Max. transpiration rate: $\dot{m}_{transpiration}[\frac{kg}{d}]$	56
Input relative humidity: $RH_{input}[\%]$	65
Outout relative humidity: $RH_{output}[\%]$	93
Dew point: $T_{DP}\ [K]$/ [°C]	289.7 / 16.5
Specific heat capacity at constant pressure of the air: $c_{p_{air}}[\frac{kJ}{kgK}]$	1.015
Enthalpy of condensation of water: $\Delta h_{water}[\frac{kJ}{kg}]$	2260
Required sensible heat: $Q_{sensible}[W]$	17185
Required latent heat of condensation: $Q_{latent}[W]$	1465
Total thermal capability of the dehumidifier (Qsensible + Qlatent) [W]	**18650**

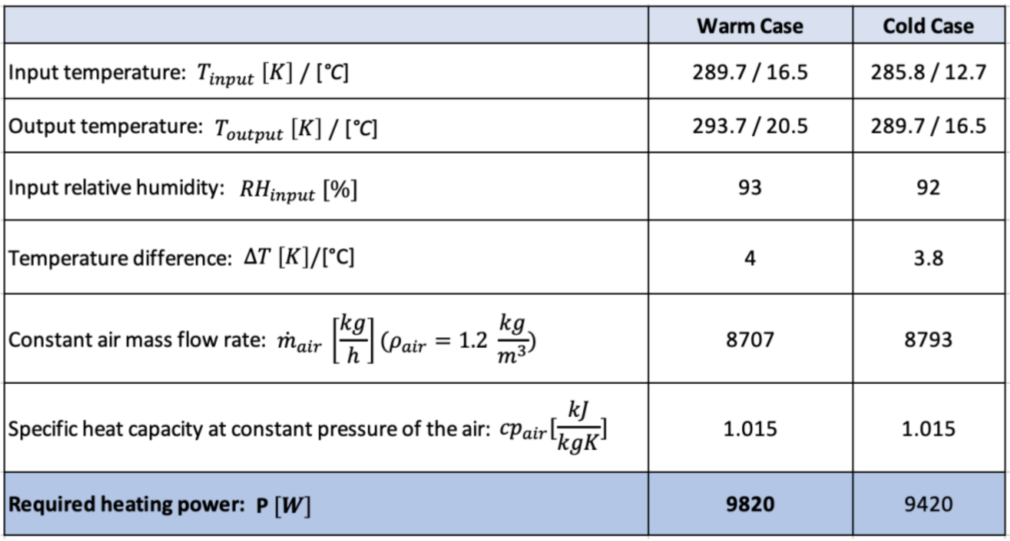
Mature crop balance

Table 10-5 Required performance of the CHX for the mature crop balance

Mature Crop Balance	**Warm Case**
Required cooling power (thermal load): $\dot{Q}$ [W]	5926
Constant air volume flow rate: $\dot{v}_{air}\,[\frac{m^3}{h}]$	5838
Constant air mass flow rate: $\dot{m}_{air}\left[\frac{kg}{h}\right](\rho_{air}=1.2\,\frac{kg}{m^3})$	7006
Temperature rise across the cultivation area: $\Delta T_{ca}[K]$	3
Setpoint temperature: $T_{setpoint}[K]$ / [°C]	295 / 22
Output temperature: $T_{output}[K]$	296.7 / 23.5
Max. transpiration rate: $\dot{m}_{transpiration}[\frac{kg}{d}]$	56
Input relative humidity: $RH_{input}[\%]$	65
Outout relative humidity: $RH_{output}[\%]$	93
Dew point: $T_{DP}\ [K]$/ [°C]	289.7 / 16.5
Specific heat capacity at constant pressure of the air: $c_{p_{air}}[\frac{kJ}{kgK}]$	1.015
Enthalpy of condensation of water: $\Delta h_{water}[\frac{kJ}{kg}]$	2260
Required sensible heat: $Q_{sensible}[W]$	13826
Required latent heat of condensation: $Q_{latent}[W]$	1465
Total thermal capability of the dehumidifier (Qsensible + Qlatent) [W]	**15291**

Heater

Table 10-6 Comparison for the maximum required performance of the heater



	Warm Case	**Cold Case**
Input temperature: T_{input} $[K]$ / [°C]	289.7 / 16.5	285.8 / 12.7
Output temperature: T_{output} $[K]$ / [°C]	293.7 / 20.5	289.7 / 16.5
Input relative humidity: RH_{input} [%]	93	92
Temperature difference: ΔT $[K]$/[°C]	4	3.8
Constant air mass flow rate: $\dot{m}_{air}$ $\left[\frac{kg}{h}\right]$ $(\rho_{air} = 1.2\ \frac{kg}{m^3})$	8707	8793
Specific heat capacity at constant pressure of the air: $cp_{air}[\frac{kJ}{kgK}]$	1.015	1.015
Required heating power: P $[W]$	**9820**	9420

Mollier Diagram

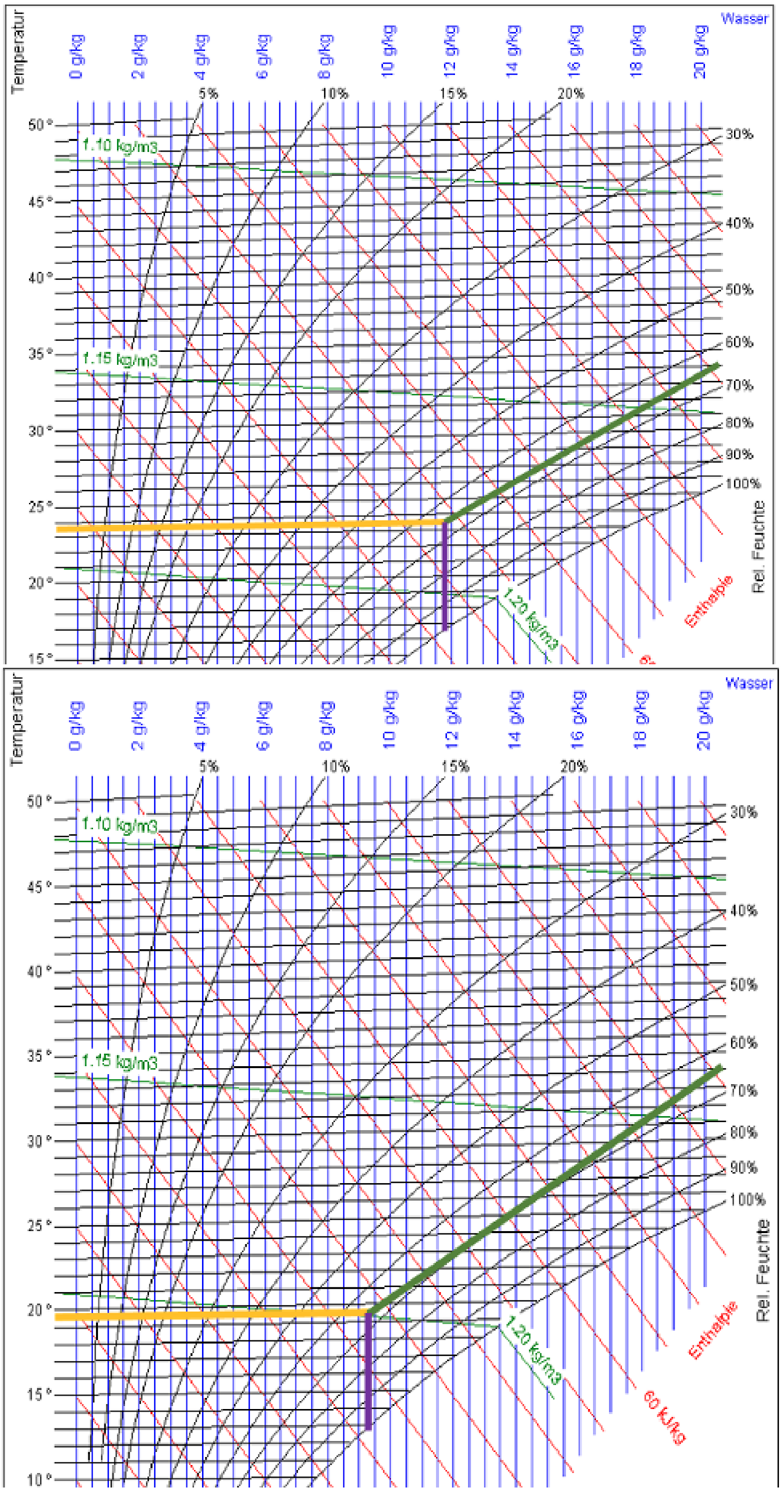


Figure 10-4 Determination of the Dew Point (top: warm case, bottom: cold case) [155]

10.3 User Manuals and Performance Data

Condensation Pump

DE

Maxi Orange

KONDENSATPUMPE

Brauchen Sie mehr Leistung? Die Pumpe Maxi Orange ist für größere Anlagen vorgesehen und liefert die zusätzliche Leistung, die Sie brauchen.

Max. Förderleistung 35 l/h

Max. Förderhöhe 15 m (Förderleistung 10 l/h)

35 dB(A) @ 1 m

HAUPTMERKMALE

- Hochleistungsmotor
- Überlegene Leistung
- Offener zweiter Behälter enthalten

EIGNUNG

- Bis 46 kW
- Wandgeräte, Kanalgeräte, Bodenkonvektoren, Deckenkassetten

✓**Ideal für...** größere gewerbliche Anlagen

MAXI ORANGE KENNDATEN

Max. Förderleistung	35 l/h bei 0 m Förderhöhe
Max. empf. Förderhöhe	15 m
Max. Ansaughöhe	2 m
Geräuschpegel @ 1 m	35 dB(A)
Versorgungsspannung	230 V~, 0,11 A, 16 W, 50/60 Hz
Auslegung	Getaktet
Geräteklasse	II▢
Max. Anschlussleistung	46 kW
Max. Wassertemperatur	40 °C / 104 °F
Druckleitung	6 mm ID
IP-Schutz	IP 21
Sicherheitsschalter	Öffnerkontakt 3,0 A
Hitzeschutz	✓
Vollständig vergossen	✓
Selbstansaugend	✓

Alle Angaben entsprechen dem Stand der Drucklegung.

MAXI ORANGE BESTELLDATEN

Bezeichnung	Artikel-Nr.
Maxi Orange	FP2210

LIEFERUMFANG

Maxi Orange-Pumpe
- 1,5 m ansteckbares Netzkabel
- Behälter
- Behälterdeckel mit 1,5 m Sensorkabel
- Offener Behälter
- Antihebereffektventil
- Schwimmer & Filter
- 1,5 m Saugschlauch 6 mm ID
- 220 mm Orange-Einlassschlauch 14 mm ID
- 150 mm PVC-Entlüftungsschlauch 6 mm ID
- Zulaufadapter
- Befestigungssatz
- Installationshandbuch

EMPFOHLENES XTRA-ZUBEHÖR

Beschreibung	Artikel-Nr.
1 A Sicherung	FP2620
Ablaufstutzen selbstdichtend	FP2038
PVC-Schlauch 1/4" (6 mm ID)	AX5100
Vorfilter 16 mm	FP2640
6 m Mini Orange Verlängerungkabel	MS-105

Weiteres Installationszubehör finden Sie unter Aspen Xtra

Handbuch herunterladen unter aspenpumps.com

20 GB DESIGNED 2004 aspenpumps.com ☎ +49 (0)211/467979 info@aspen-pumpen.de zuverlässig | leise | einfach

Figure 10-5 Data sheet of condensate pump [115]

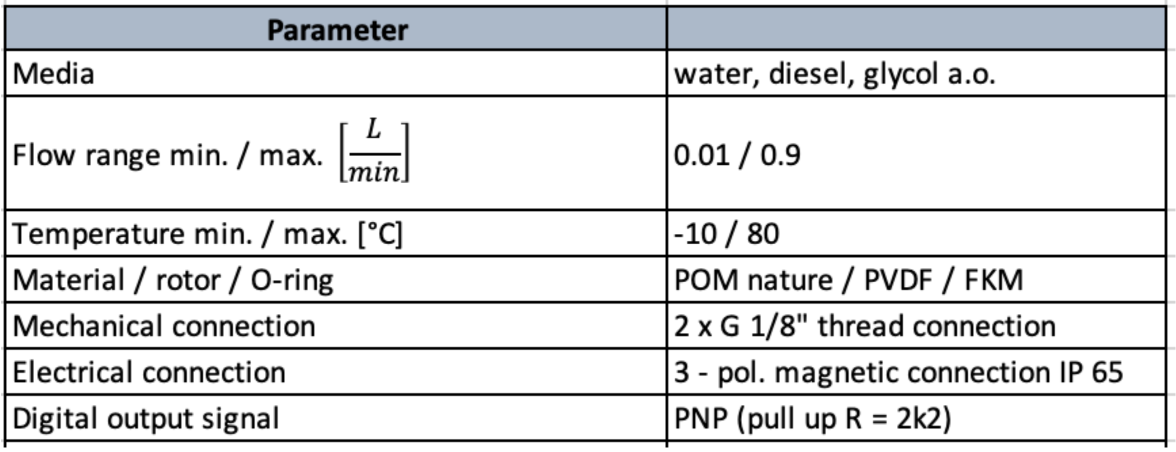
Carbon filter

Table 10-7 Performance data of the carbon filter [116]

Parameter	
Flow rate $\left[\frac{l}{min}\right]$	1.9
Shelf life	up to 12 months
Max. pressure [bar]	8.6
Max. temperature [°C]	38
Min. temperature [°C]	2
Content	high-quality activated carbon rinsed in acid
Length [cm]	25.1
Diameter [cm]	6

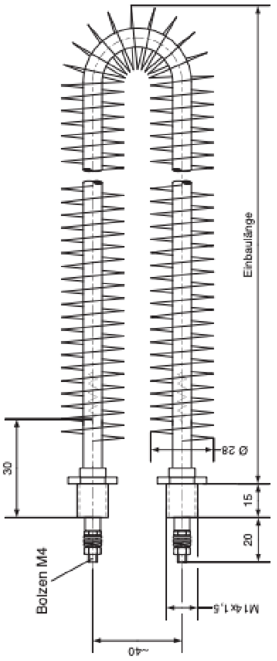
Flowmeter

Table 10-8 Performance data of the flowmeter [117]



Parameter	
Media	water, diesel, glycol a.o.
Flow range min. / max. $\left[\frac{L}{min}\right]$	0.01 / 0.9
Temperature min. / max. [°C]	-10 / 80
Material / rotor / O-ring	POM nature / PVDF / FKM
Mechanical connection	2 x G 1/8" thread connection
Electrical connection	3 - pol. magnetic connection IP 65
Digital output signal	PNP (pull up R = 2k2)

Heater elements



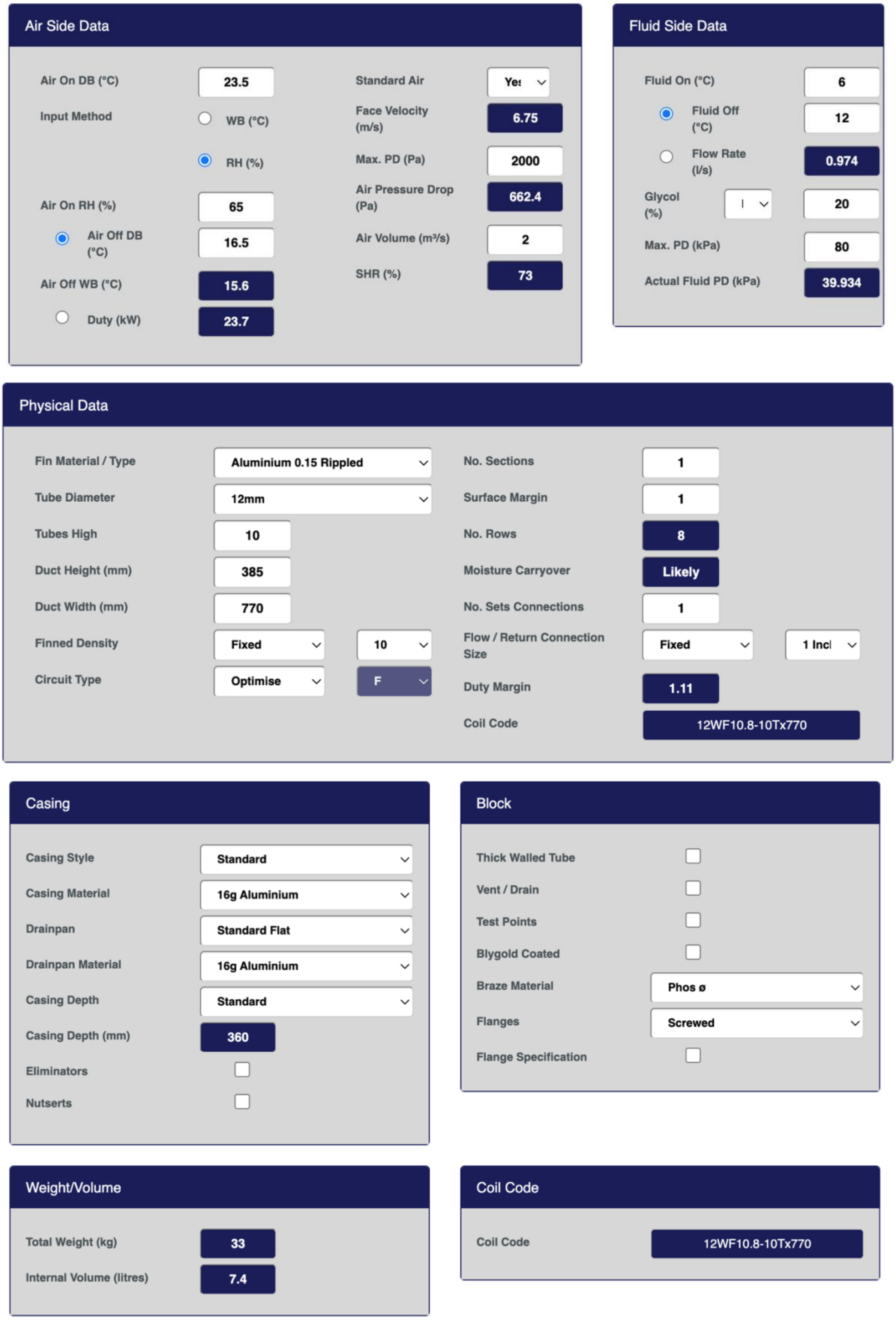
Parameter	Heater
Material	Stainless steel jacket (max. 550 °C)
Power [kW]	12 (1.5 each)
Quantity	2 x 4
Diameter [mm]	28
Installation length [mm]	460
Total length [mm]	495
Height [mm]	68
Connector [mm]	M14 x 1.5 x 15
Weight [kg]	max. 5.6 (0.5 - 0.7 each)

Figure 10-6 Schematic and performance data of a finned-tube heating element [120]

Heat Exchanger

Table 10-9 Heat exchanger performance data

Parameter	**CHX**
Cooling capacity $[kW]$	≈ 24
Lenght $[mm]$	770
Height $[mm]$	385
Width $[mm]$	310
Weight $[kg]$	25 - 35
External Gas	**Air**
Flow rate $\left[\frac{m^3}{s}\right]$	2
Inlet/outlet temperature $[°C]$	23.5 → 16.5
Inlet/outlet relative humidity $[\%]$	65 → 93
Pressure loss $[Pa]$	662
Coolant: Propylene glycol 20 %	
Flow rate $\left[\frac{l}{s}\right]$	0.974
Inlet/outlet temperature $[°C]$	6.0 → 12.0
Pressure loss $[kPa]$	40



Air Side Data

Air On DB (°C): 23.5
Input Method: ○ WB (°C) ● RH (%)
Air On RH (%): 65
● Air Off DB (°C): 16.5
Air Off WB (°C): 15.6
○ Duty (kW): 23.7
Standard Air: Yes
Face Velocity (m/s): 6.75
Max. PD (Pa): 2000
Air Pressure Drop (Pa): 662.4
Air Volume (m³/s): 2
SHR (%): 73

Fluid Side Data

Fluid On (°C): 6
● Fluid Off (°C): 12
○ Flow Rate (l/s): 0.974
Glycol (%): I 20
Max. PD (kPa): 80
Actual Fluid PD (kPa): 39.934

Physical Data

Fin Material / Type: Aluminium 0.15 Rippled
Tube Diameter: 12mm
Tubes High: 10
Duct Height (mm): 385
Duct Width (mm): 770
Finned Density: Fixed 10
Circuit Type: Optimise F
No. Sections: 1
Surface Margin: 1
No. Rows: 8
Moisture Carryover: Likely
No. Sets Connections: 1
Flow / Return Connection Size: Fixed 1 Incl
Duty Margin: 1.11
Coil Code: 12WF10.8-10Tx770

Casing

Casing Style: Standard
Casing Material: 16g Aluminium
Drainpan: Standard Flat
Drainpan Material: 16g Aluminium
Casing Depth: Standard
Casing Depth (mm): 360
Eliminators: ☐
Nutserts: ☐

Block

Thick Walled Tube: ☐
Vent / Drain: ☐
Test Points: ☐
Blygold Coated: ☐
Braze Material: Phos ø
Flanges: Screwed
Flange Specification: ☐

Weight/Volume

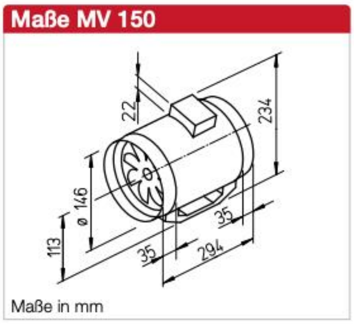
Total Weight (kg): 33
Internal Volume (litres): 7.4

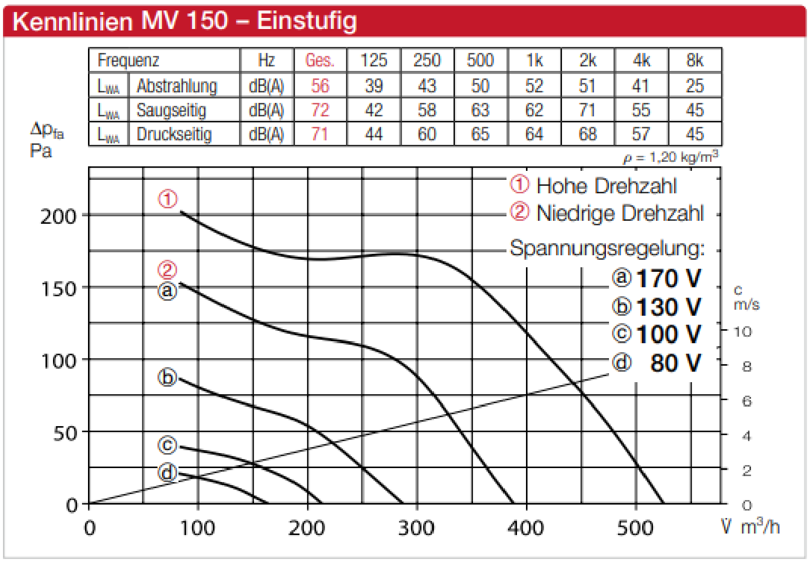
Coil Code

Coil Code: 12WF10.8-10Tx770

Figure 10-7 Obtained parameters for the HX from the SPC Coil Selector [156]

Fan CO_2 Inlet

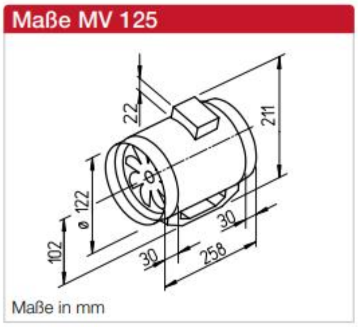


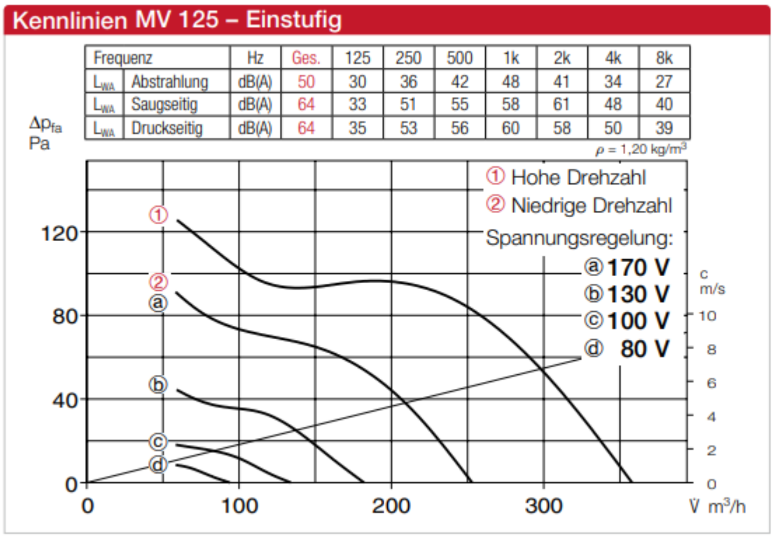


Frequenz		Hz	Ges.	125	250	500	1k	2k	4k	8k
L_{WA}	Abstrahlung	dB(A)	56	39	43	50	52	51	41	25
L_{WA}	Saugseitig	dB(A)	72	42	58	63	62	71	55	45
L_{WA}	Druckseitig	dB(A)	71	44	60	65	64	68	57	45

Figure 10-8 Helios MV 150 [157]

Fan O_2 Inlet

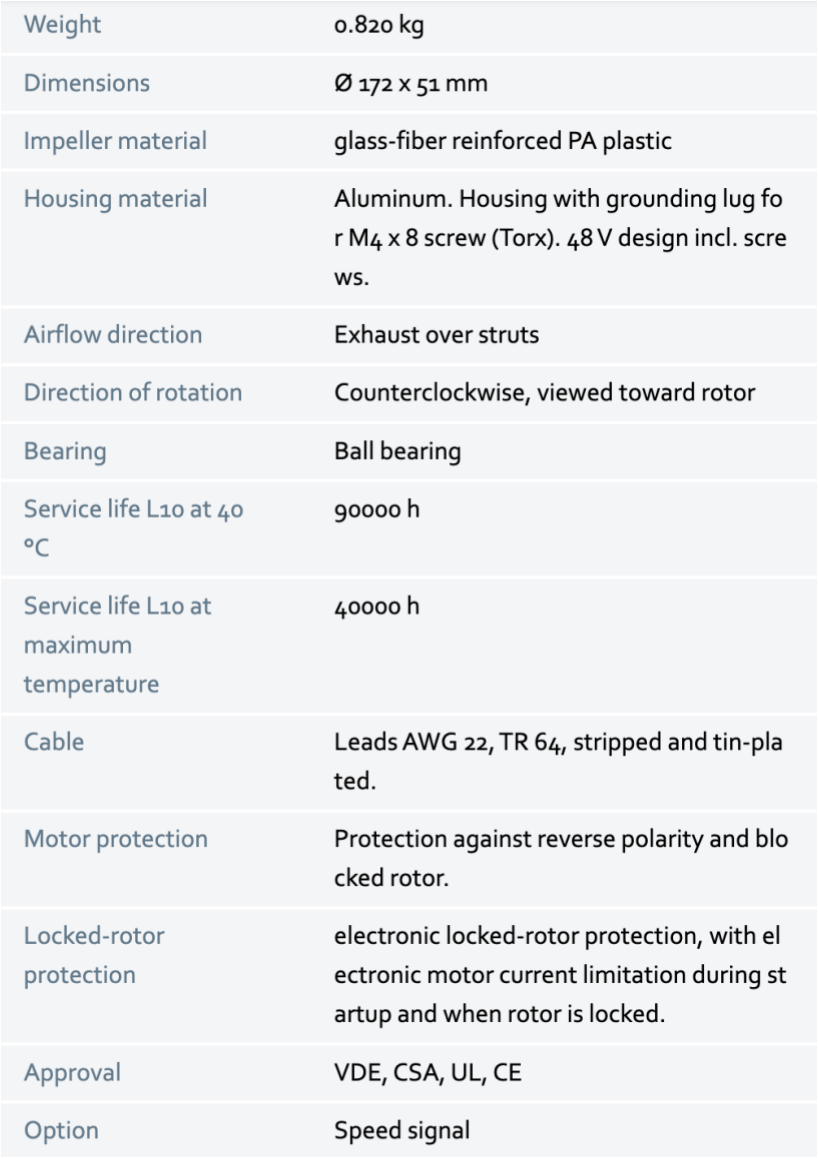




Frequenz		Hz	Ges.	125	250	500	1k	2k	4k	8k
L_{WA}	Abstrahlung	dB(A)	50	30	36	42	48	41	34	27
L_{WA}	Saugseitig	dB(A)	64	33	51	55	58	61	48	40
L_{WA}	Druckseitig	dB(A)	64	35	53	56	60	58	50	39

Figure 10-9 Helios MV 125 [157]

Cultivation area - diagonal compact fan



Weight	0.820 kg
Dimensions	Ø 172 x 51 mm
Impeller material	glass-fiber reinforced PA plastic
Housing material	Aluminum. Housing with grounding lug fo r M4 x 8 screw (Torx). 48 V design incl. scre ws.
Airflow direction	Exhaust over struts
Direction of rotation	Counterclockwise, viewed toward rotor
Bearing	Ball bearing
Service life L10 at 40 °C	90000 h
Service life L10 at maximum temperature	40000 h
Cable	Leads AWG 22, TR 64, stripped and tin-pla ted.
Motor protection	Protection against reverse polarity and blo cked rotor.
Locked-rotor protection	electronic locked-rotor protection, with el ectronic motor current limitation during st artup and when rotor is locked.
Approval	VDE, CSA, UL, CE
Option	Speed signal

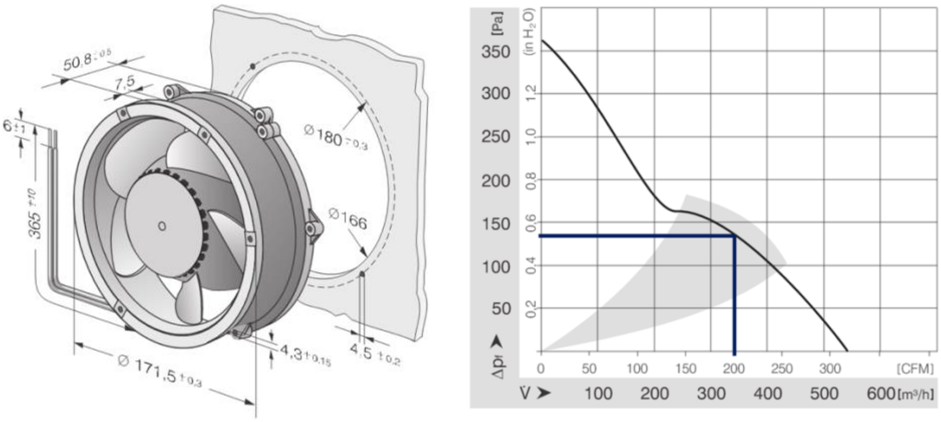
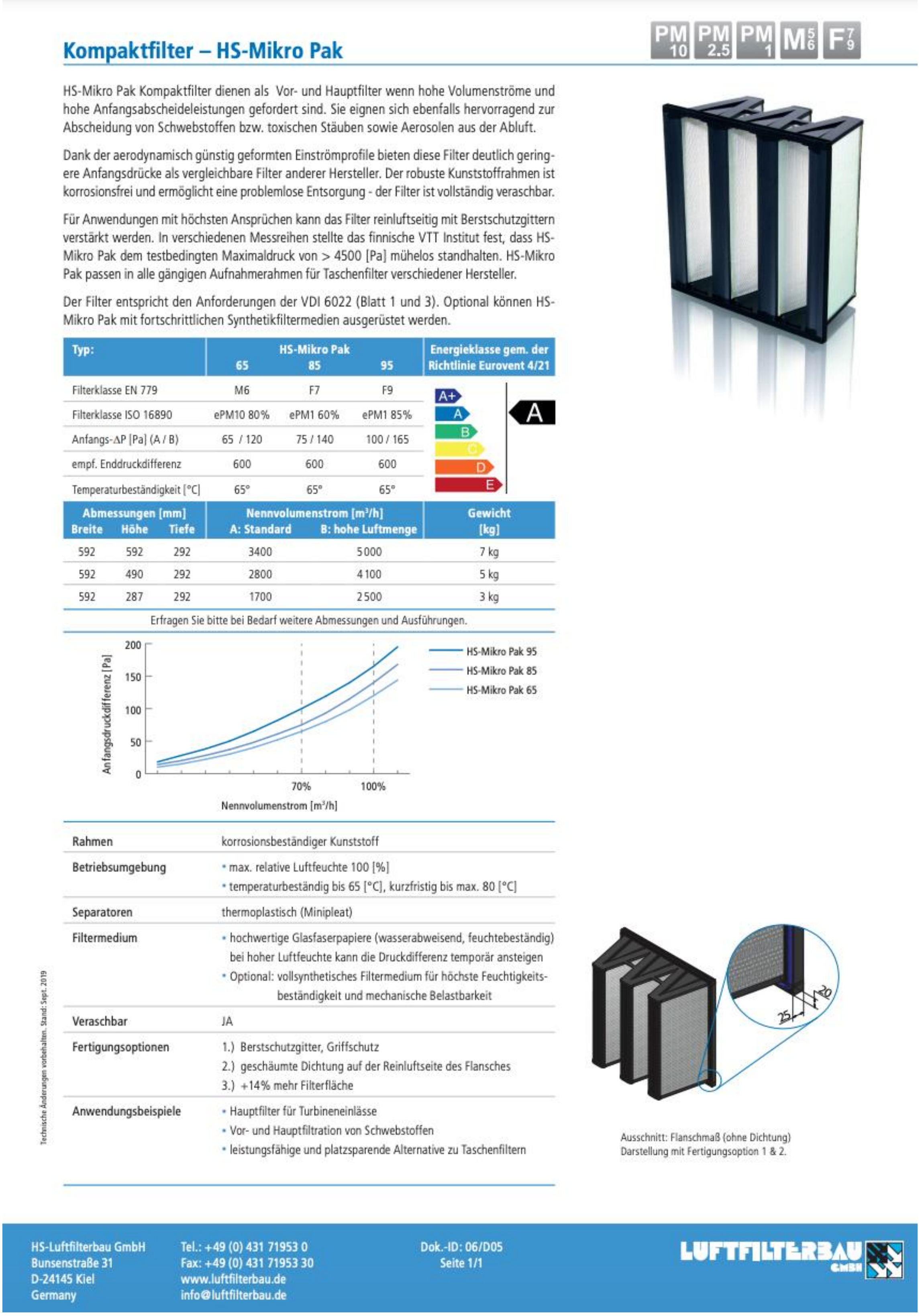


Figure 10-10 Data sheet of the diagonal compact fan [107]

Filter Unit



Kompaktfilter – HS-Mikro Pak

HS-Mikro Pak Kompaktfilter dienen als Vor- und Hauptfilter wenn hohe Volumenströme und hohe Anfangsabscheideleistungen gefordert sind. Sie eignen sich ebenfalls hervorragend zur Abscheidung von Schwebstoffen bzw. toxischen Stäuben sowie Aerosolen aus der Abluft.

Dank der aerodynamisch günstig geformten Einströmprofile bieten diese Filter deutlich geringere Anfangsdrücke als vergleichbare Filter anderer Hersteller. Der robuste Kunststoffrahmen ist korrosionsfrei und ermöglicht eine problemlose Entsorgung - der Filter ist vollständig veraschbar.

Für Anwendungen mit höchsten Ansprüchen kann das Filter reinluftseitig mit Berstschutzgittern verstärkt werden. In verschiedenen Messreihen stellte das finnische VTT Institut fest, dass HS-Mikro Pak dem testbedingten Maximaldruck von > 4500 [Pa] mühelos standhalten. HS-Mikro Pak passen in alle gängigen Aufnahmerahmen für Taschenfilter verschiedener Hersteller.

Der Filter entspricht den Anforderungen der VDI 6022 (Blatt 1 und 3). Optional können HS-Mikro Pak mit fortschrittlichen Synthetikfiltermedien ausgerüstet werden.

Typ:	HS-Mikro Pak 65	HS-Mikro Pak 85	HS-Mikro Pak 95	Energieklasse gem. der Richtlinie Eurovent 4/21
Filterklasse EN 779	M6	F7	F9	A+ A B C D E
Filterklasse ISO 16890	ePM10 80%	ePM1 60%	ePM1 85%	A
Anfangs-ΔP [Pa] (A / B)	65 / 120	75 / 140	100 / 165	
empf. Enddruckdifferenz	600	600	600	
Temperaturbeständigkeit [°C]	65°	65°	65°	

Abmessungen [mm]			Nennvolumenstrom [m³/h]		Gewicht [kg]
Breite	Höhe	Tiefe	A: Standard	B: hohe Luftmenge	
592	592	292	3400	5000	7 kg
592	490	292	2800	4100	5 kg
592	287	292	1700	2500	3 kg

Erfragen Sie bitte bei Bedarf weitere Abmessungen und Ausführungen.

Rahmen	korrosionsbeständiger Kunststoff
Betriebsumgebung	• max. relative Luftfeuchte 100 [%] • temperaturbeständig bis 65 [°C], kurzfristig bis max. 80 [°C]
Separatoren	thermoplastisch (Minipleat)
Filtermedium	• hochwertige Glasfaserpapiere (wasserabweisend, feuchtebeständig) bei hoher Luftfeuchte kann die Druckdifferenz temporär ansteigen • Optional: vollsynthetisches Filtermedium für höchste Feuchtigkeitsbeständigkeit und mechanische Belastbarkeit
Veraschbar	JA
Fertigungsoptionen	1.) Berstschutzgitter, Griffschutz 2.) geschäumte Dichtung auf der Reinluftseite des Flansches 3.) +14% mehr Filterfläche
Anwendungsbeispiele	• Hauptfilter für Turbineneinlässe • Vor- und Hauptfiltration von Schwebstoffen • leistungsfähige und platzsparende Alternative zu Taschenfiltern

Ausschnitt: Flanschmaß (ohne Dichtung)
Darstellung mit Fertigungsoption 1 & 2.

Technische Änderungen vorbehalten. Stand: Sept. 2019

HS-Luftfilterbau GmbH
Bunsenstraße 31
D-24145 Kiel
Germany

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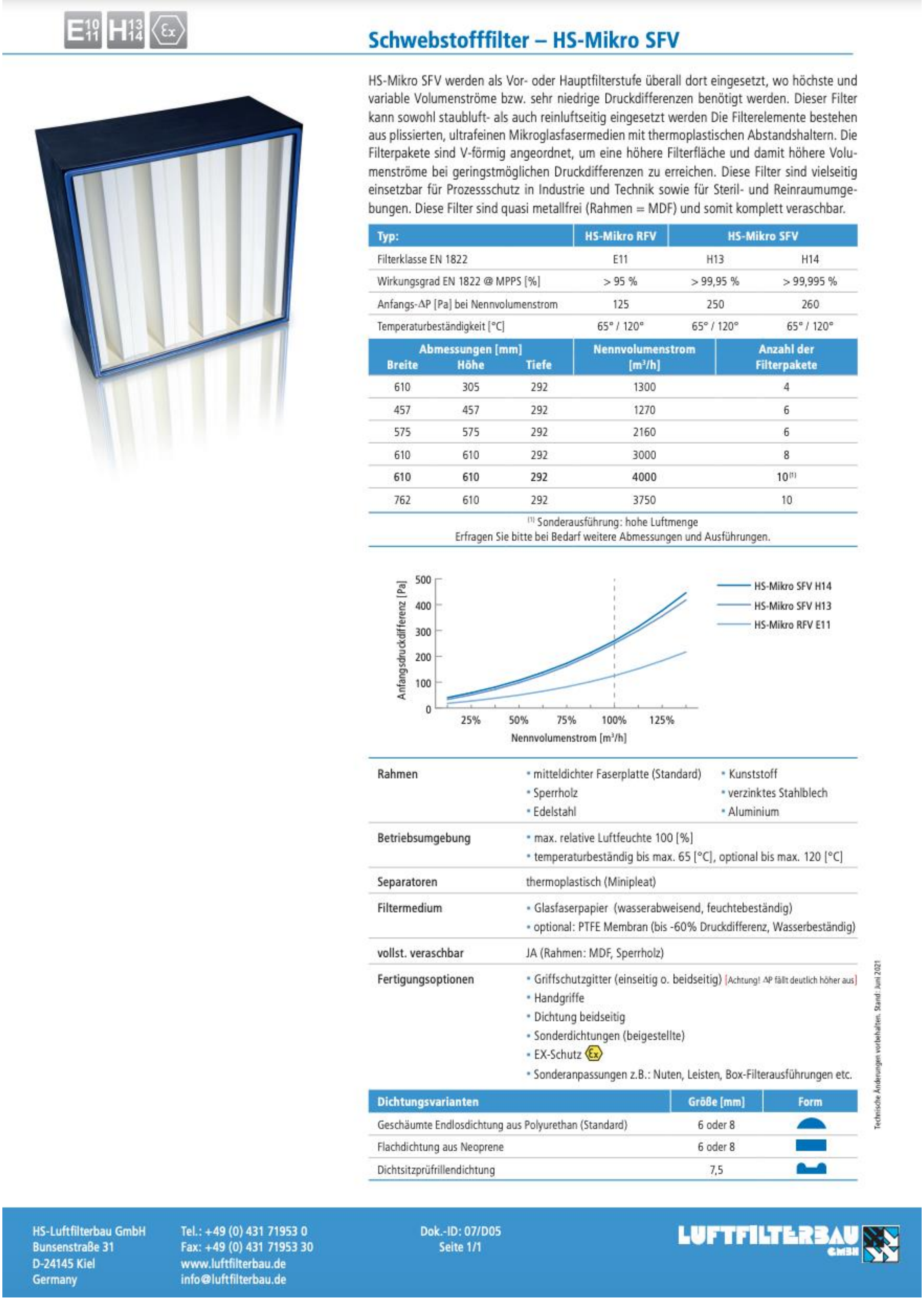
Dok.-ID: 06/D05
Seite 1/1

LUFTFILTERBAU GMBH

Figure 10-11 Data sheet – HS-Mikro Pak [121]



Schwebstofffilter – HS-Mikro SFV

HS-Mikro SFV werden als Vor- oder Hauptfilterstufe überall dort eingesetzt, wo höchste und variable Volumenströme bzw. sehr niedrige Druckdifferenzen benötigt werden. Dieser Filter kann sowohl staubluft- als auch reinluftseitig eingesetzt werden Die Filterelemente bestehen aus plissierten, ultrafeinen Mikroglasfasermedien mit thermoplastischen Abstandshaltern. Die Filterpakete sind V-förmig angeordnet, um eine höhere Filterfläche und damit höhere Volumenströme bei geringstmöglichen Druckdifferenzen zu erreichen. Diese Filter sind vielseitig einsetzbar für Prozessschutz in Industrie und Technik sowie für Steril- und Reinraumumgebungen. Diese Filter sind quasi metallfrei (Rahmen = MDF) und somit komplett veraschbar.

Typ:	HS-Mikro RFV	HS-Mikro SFV	
Filterklasse EN 1822	E11	H13	H14
Wirkungsgrad EN 1822 @ MPPS [%]	> 95 %	> 99,95 %	> 99,995 %
Anfangs-ΔP [Pa] bei Nennvolumenstrom	125	250	260
Temperaturbeständigkeit [°C]	65° / 120°	65° / 120°	65° / 120°

Abmessungen [mm] Breite	Höhe	Tiefe	Nennvolumenstrom [m³/h]	Anzahl der Filterpakete
610	305	292	1300	4
457	457	292	1270	6
575	575	292	2160	6
610	610	292	3000	8
610	**610**	**292**	**4000**	**10**[1]
762	610	292	3750	10

[1] Sonderausführung: hohe Luftmenge
Erfragen Sie bitte bei Bedarf weitere Abmessungen und Ausführungen.

Rahmen	• mitteldichter Faserplatte (Standard) • Sperrholz • Edelstahl	• Kunststoff • verzinktes Stahlblech • Aluminium
Betriebsumgebung	• max. relative Luftfeuchte 100 [%] • temperaturbeständig bis max. 65 [°C], optional bis max. 120 [°C]	
Separatoren	thermoplastisch (Minipleat)	
Filtermedium	• Glasfaserpapier (wasserabweisend, feuchtebeständig) • optional: PTFE Membran (bis -60% Druckdifferenz, Wasserbeständig)	
vollst. veraschbar	JA (Rahmen: MDF, Sperrholz)	
Fertigungsoptionen	• Griffschutzgitter (einseitig o. beidseitig) [Achtung! ΔP fällt deutlich höher aus] • Handgriffe • Dichtung beidseitig • Sonderdichtungen (beigestellte) • EX-Schutz Ex • Sonderanpassungen z.B.: Nuten, Leisten, Box-Filterausführungen etc.	

Dichtungsvarianten	Größe [mm]	Form
Geschäumte Endlosdichtung aus Polyurethan (Standard)	6 oder 8	◠
Flachdichtung aus Neoprene	6 oder 8	▬
Dichtsitzprüfrillendichtung	7,5	▬

Technische Änderungen vorbehalten. Stand: Juni 2021

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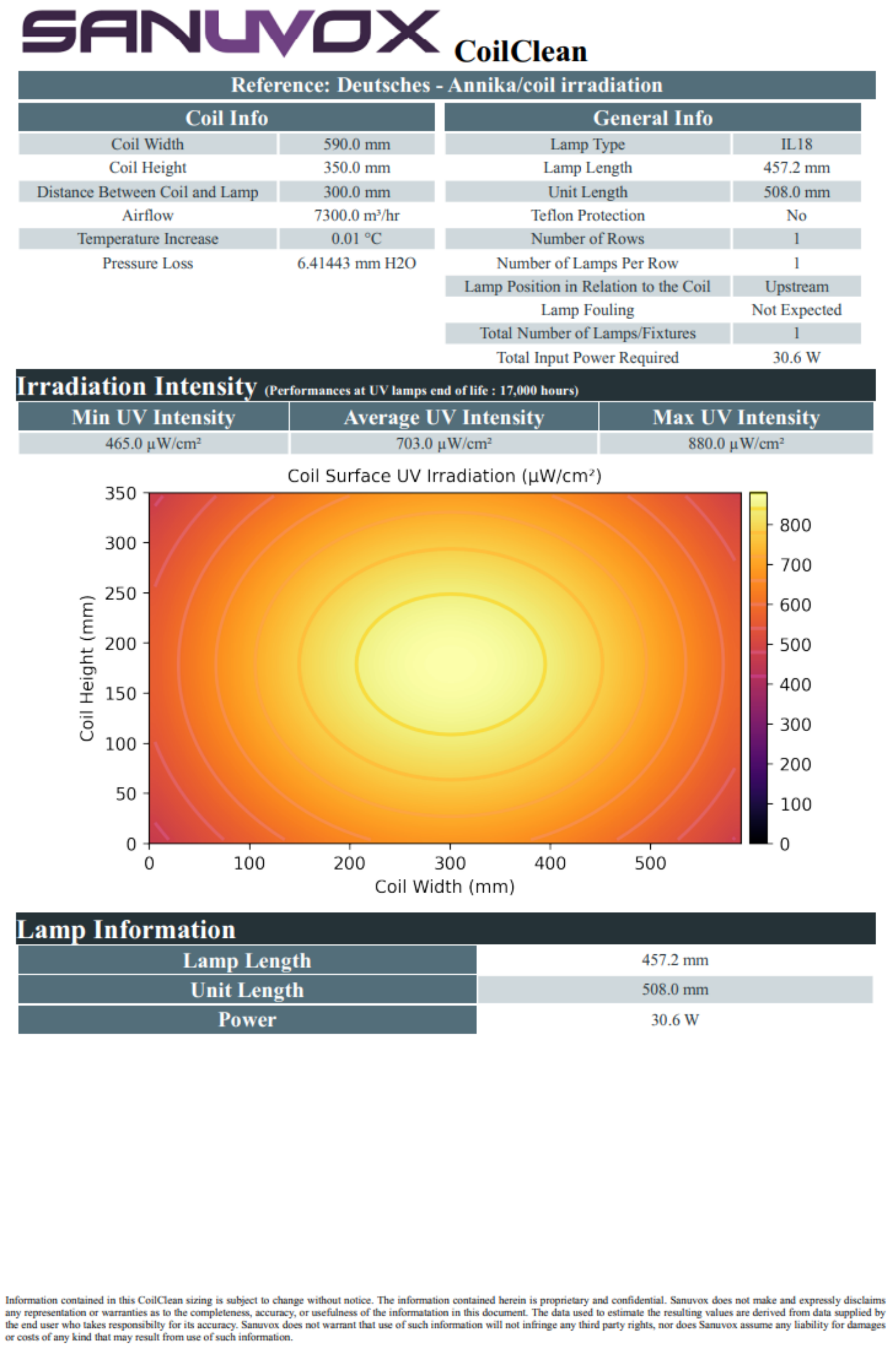
Figure 10-12 Data sheet - HS-Mikro SFV [122]

Appendix

UV-C Lamp



SANUVOX CoilClean

Reference: Deutsches - Annika/coil irradiation

Coil Info	
Coil Width	590.0 mm
Coil Height	350.0 mm
Distance Between Coil and Lamp	300.0 mm
Airflow	7300.0 m^3/hr
Temperature Increase	0.01 °C
Pressure Loss	6.41443 mm H2O

General Info	
Lamp Type	IL18
Lamp Length	457.2 mm
Unit Length	508.0 mm
Teflon Protection	No
Number of Rows	1
Number of Lamps Per Row	1
Lamp Position in Relation to the Coil	Upstream
Lamp Fouling	Not Expected
Total Number of Lamps/Fixtures	1
Total Input Power Required	30.6 W

Irradiation Intensity (Performances at UV lamps end of life : 17,000 hours)

Min UV Intensity	Average UV Intensity	Max UV Intensity
465.0 µW/cm^2	703.0 µW/cm^2	880.0 µW/cm^2

Lamp Information

Lamp Length	457.2 mm
Unit Length	508.0 mm
Power	30.6 W

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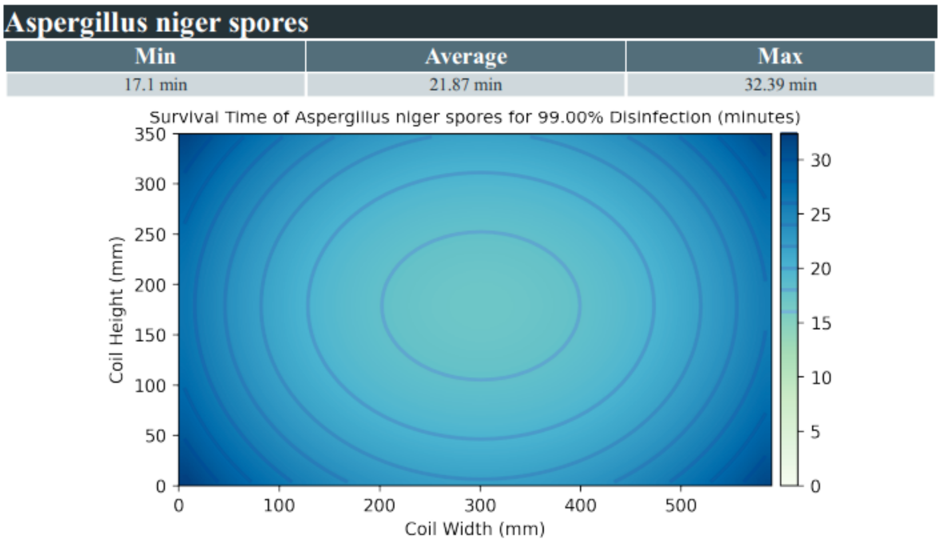
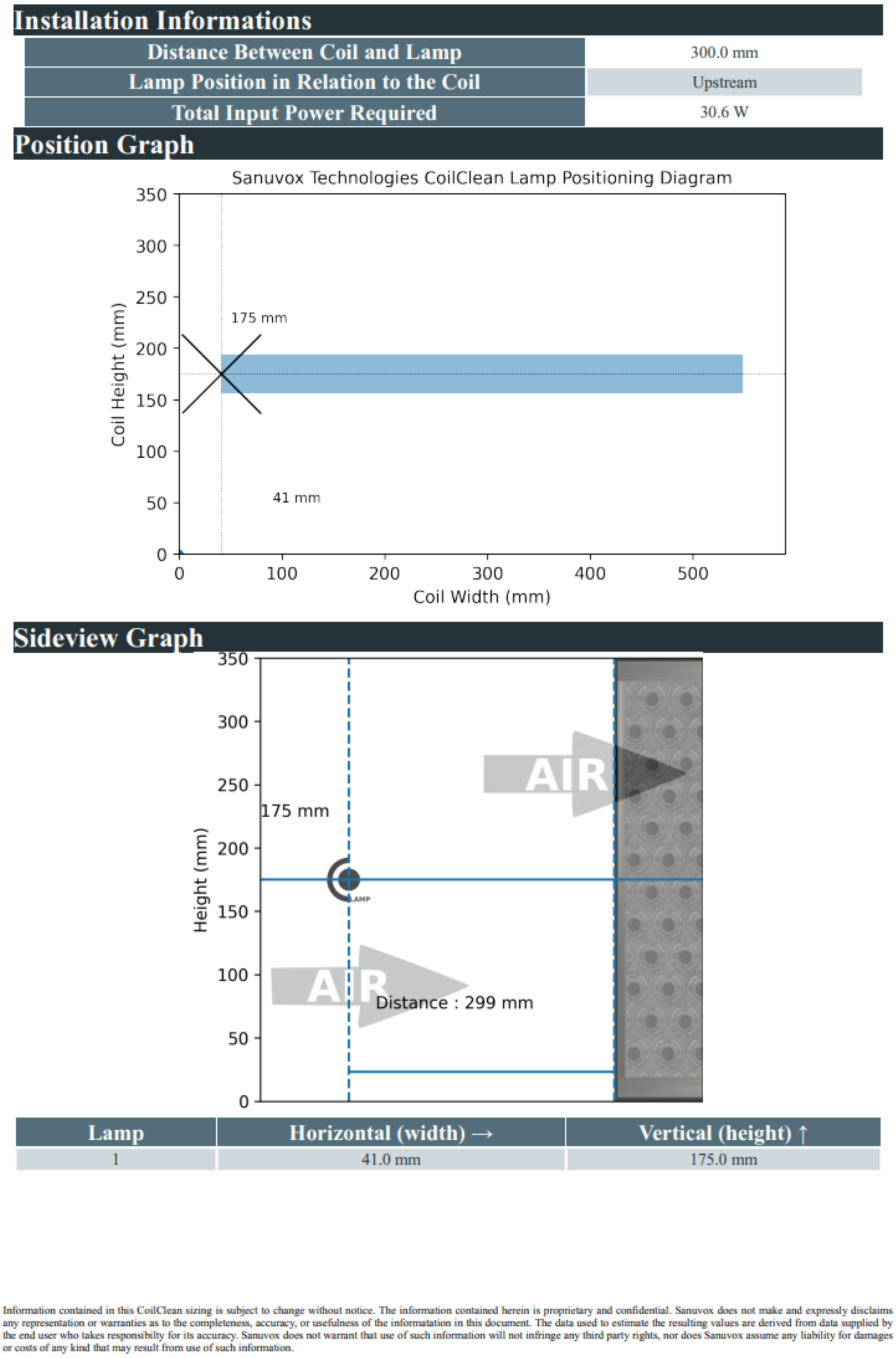


Aspergillus niger spores

Min	Average	Max
17.1 min	21.87 min	32.39 min

Survival Time of Aspergillus niger spores for 99.00% Disinfection (minutes)



Installation Informations

Distance Between Coil and Lamp	300.0 mm
Lamp Position in Relation to the Coil	Upstream
Total Input Power Required	30.6 W

Position Graph

Sideview Graph

Lamp	Horizontal (width) →	Vertical (height) ↑
1	41.0 mm	175.0 mm

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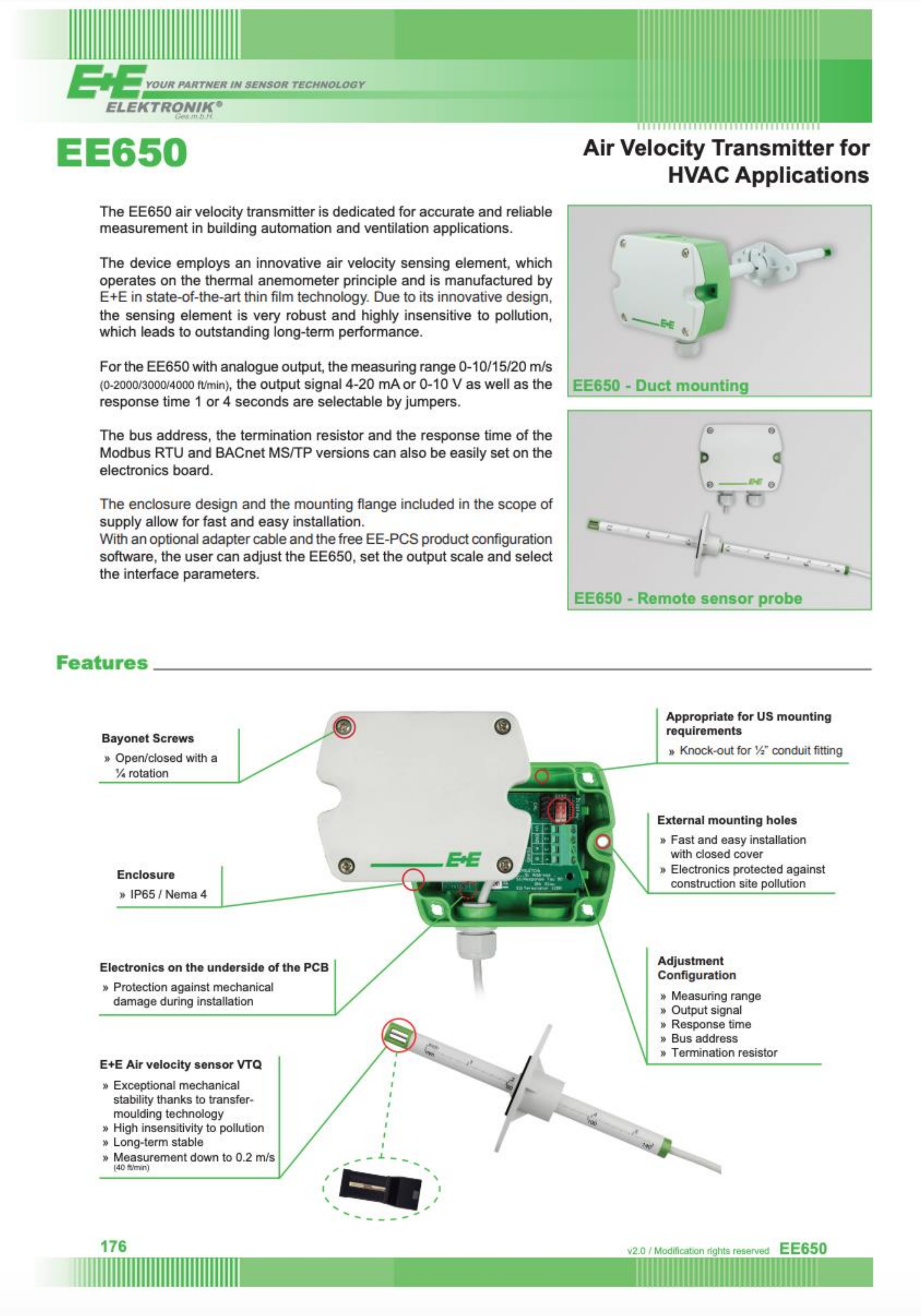
Figure 10-13 Sanuvox UV-C Lamp [Offer received on 28.11.2022]

Sensor



YOUR PARTNER IN SENSOR TECHNOLOGY

E+E ELEKTRONIK® Ges.m.b.H.

EE650

Air Velocity Transmitter for HVAC Applications

The EE650 air velocity transmitter is dedicated for accurate and reliable measurement in building automation and ventilation applications.

The device employs an innovative air velocity sensing element, which operates on the thermal anemometer principle and is manufactured by E+E in state-of-the-art thin film technology. Due to its innovative design, the sensing element is very robust and highly insensitive to pollution, which leads to outstanding long-term performance.

For the EE650 with analogue output, the measuring range 0-10/15/20 m/s (0-2000/3000/4000 ft/min), the output signal 4-20 mA or 0-10 V as well as the response time 1 or 4 seconds are selectable by jumpers.

The bus address, the termination resistor and the response time of the Modbus RTU and BACnet MS/TP versions can also be easily set on the electronics board.

The enclosure design and the mounting flange included in the scope of supply allow for fast and easy installation.
With an optional adapter cable and the free EE-PCS product configuration software, the user can adjust the EE650, set the output scale and select the interface parameters.

EE650 - Duct mounting

EE650 - Remote sensor probe

Features

Bayonet Screws
- » Open/closed with a ¼ rotation

Enclosure
- » IP65 / Nema 4

Electronics on the underside of the PCB
- » Protection against mechanical damage during installation

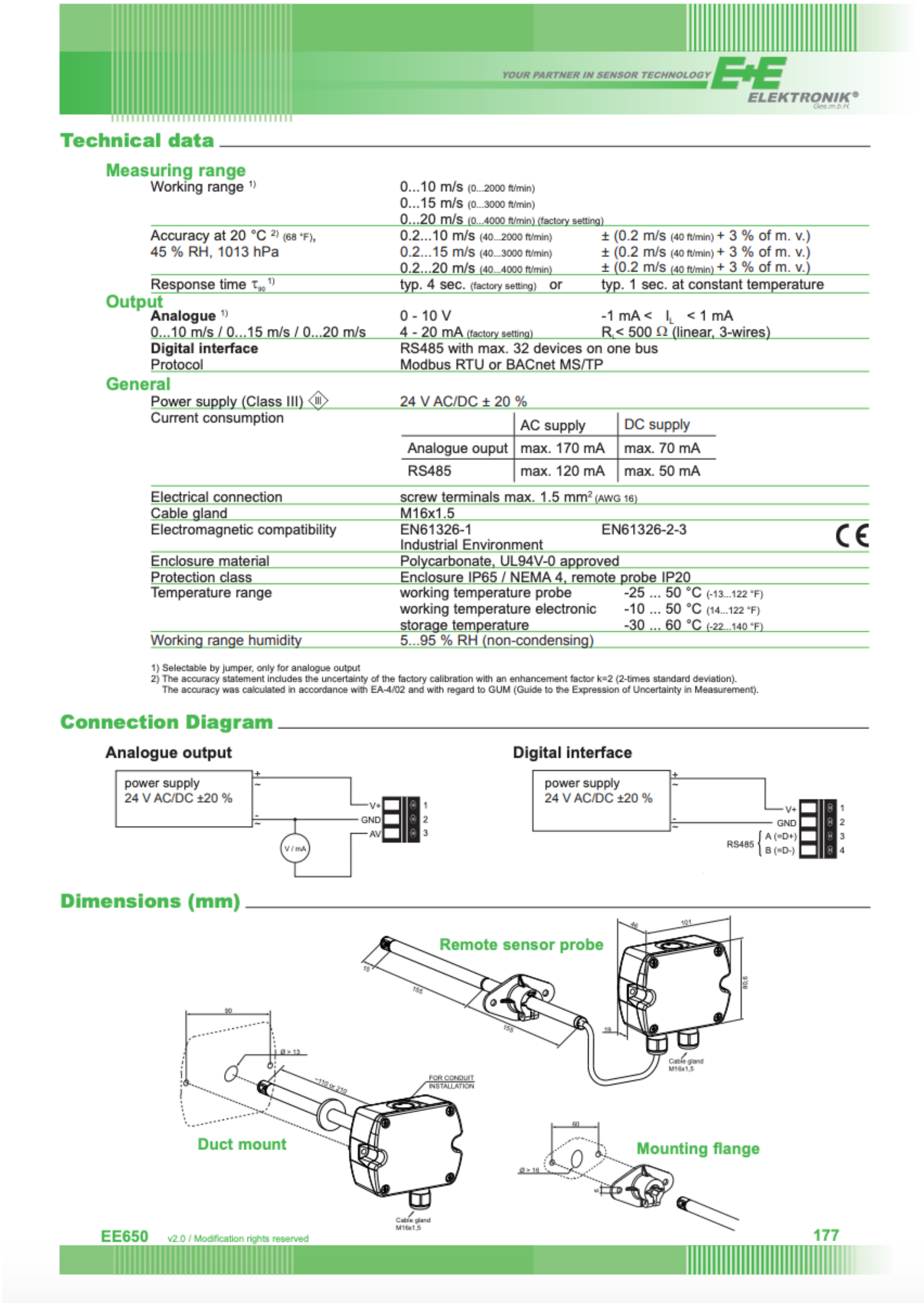
E+E Air velocity sensor VTQ
- » Exceptional mechanical stability thanks to transfer-moulding technology
- » High insensitivity to pollution
- » Long-term stable
- » Measurement down to 0.2 m/s (40 ft/min)

Appropriate for US mounting requirements
- » Knock-out for ½" conduit fitting

External mounting holes
- » Fast and easy installation with closed cover
- » Electronics protected against construction site pollution

Adjustment Configuration
- » Measuring range
- » Output signal
- » Response time
- » Bus address
- » Termination resistor

176 v2.0 / Modification rights reserved EE650



YOUR PARTNER IN SENSOR TECHNOLOGY E+E ELEKTRONIK® Ges.m.b.H.

Technical data

Measuring range		
Working range 1)	0...10 m/s (0...2000 ft/min) 0...15 m/s (0...3000 ft/min) 0...20 m/s (0...4000 ft/min) (factory setting)	
Accuracy at 20 °C 2) (68 °F), 45 % RH, 1013 hPa	0.2...10 m/s (40...2000 ft/min) 0.2...15 m/s (40...3000 ft/min) 0.2...20 m/s (40...4000 ft/min)	± (0.2 m/s (40 ft/min) + 3 % of m. v.) ± (0.2 m/s (40 ft/min) + 3 % of m. v.) ± (0.2 m/s (40 ft/min) + 3 % of m. v.)
Response time τ_{90} 1)	typ. 4 sec. (factory setting) or	typ. 1 sec. at constant temperature
Output		
Analogue 1) 0...10 m/s / 0...15 m/s / 0...20 m/s	0 - 10 V 4 - 20 mA (factory setting)	-1 mA < I_L < 1 mA R_L < 500 Ω (linear, 3-wires)
Digital interface	RS485 with max. 32 devices on one bus	
Protocol	Modbus RTU or BACnet MS/TP	
General		
Power supply (Class III) ◇	24 V AC/DC ± 20 %	
Current consumption		

	AC supply	DC supply
Analogue ouput	max. 170 mA	max. 70 mA
RS485	max. 120 mA	max. 50 mA

Electrical connection	screw terminals max. 1.5 mm² (AWG 16)	
Cable gland	M16x1.5	
Electromagnetic compatibility	EN61326-1 Industrial Environment	EN61326-2-3 CE
Enclosure material	Polycarbonate, UL94V-0 approved	
Protection class	Enclosure IP65 / NEMA 4, remote probe IP20	
Temperature range	working temperature probe working temperature electronic storage temperature	-25 ... 50 °C (-13...122 °F) -10 ... 50 °C (14...122 °F) -30 ... 60 °C (-22...140 °F)
Working range humidity	5...95 % RH (non-condensing)	

1) Selectable by jumper, only for analogue output

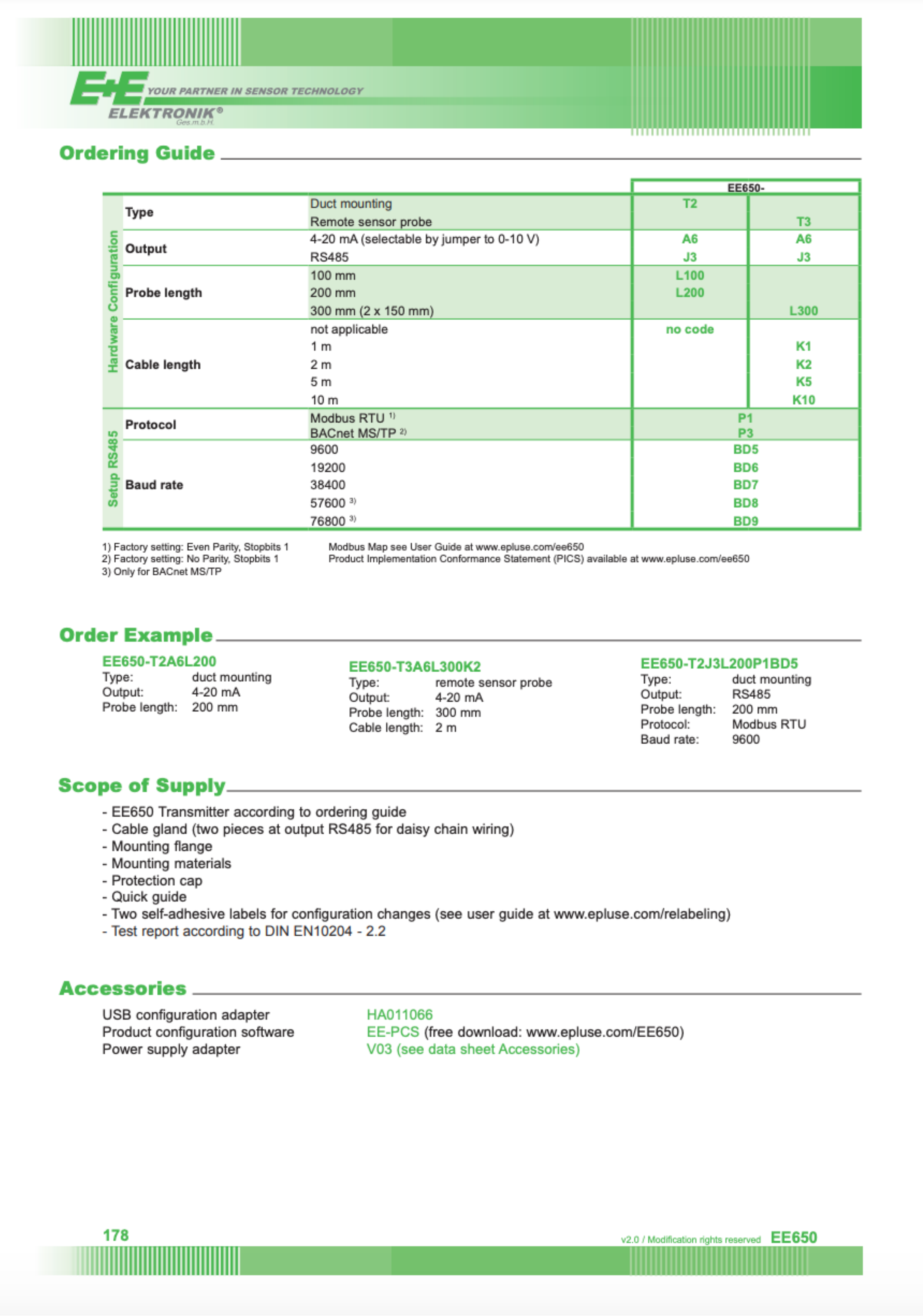
2) The accuracy statement includes the uncertainty of the factory calibration with an enhancement factor k=2 (2-times standard deviation). The accuracy was calculated in accordance with EA-4/02 and with regard to GUM (Guide to the Expression of Uncertainty in Measurement).

Connection Diagram

Analogue output

Digital interface

Dimensions (mm)



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Ordering Guide

			EE650-	
Hardware Configuration	**Type**	Duct mounting	T2	
		Remote sensor probe		T3
	Output	4-20 mA (selectable by jumper to 0-10 V)	A6	A6
		RS485	J3	J3
	Probe length	100 mm	L100	
		200 mm	L200	
		300 mm (2 x 150 mm)		L300
	Cable length	not applicable	no code	
		1 m		K1
		2 m		K2
		5 m		K5
		10 m		K10
Setup RS485	**Protocol**	Modbus RTU 1)	P1	
		BACnet MS/TP 2)	P3	
	Baud rate	9600	BD5	
		19200	BD6	
		38400	BD7	
		57600 3)	BD8	
		76800 3)	BD9	

1) Factory setting: Even Parity, Stopbits 1
2) Factory setting: No Parity, Stopbits 1
3) Only for BACnet MS/TP

Modbus Map see User Guide at www.epluse.com/ee650
Product Implementation Conformance Statement (PICS) available at www.epluse.com/ee650

Order Example

EE650-T2A6L200

Type:	duct mounting
Output:	4-20 mA
Probe length:	200 mm

EE650-T3A6L300K2

Type:	remote sensor probe
Output:	4-20 mA
Probe length:	300 mm
Cable length:	2 m

EE650-T2J3L200P1BD5

Type:	duct mounting
Output:	RS485
Probe length:	200 mm
Protocol:	Modbus RTU
Baud rate:	9600

Scope of Supply

- EE650 Transmitter according to ordering guide
- Cable gland (two pieces at output RS485 for daisy chain wiring)
- Mounting flange
- Mounting materials
- Protection cap
- Quick guide
- Two self-adhesive labels for configuration changes (see user guide at www.epluse.com/relabeling)
- Test report according to DIN EN10204 - 2.2

Accessories

USB configuration adapter	HA011066
Product configuration software	EE-PCS (free download: www.epluse.com/EE650)
Power supply adapter	V03 (see data sheet Accessories)

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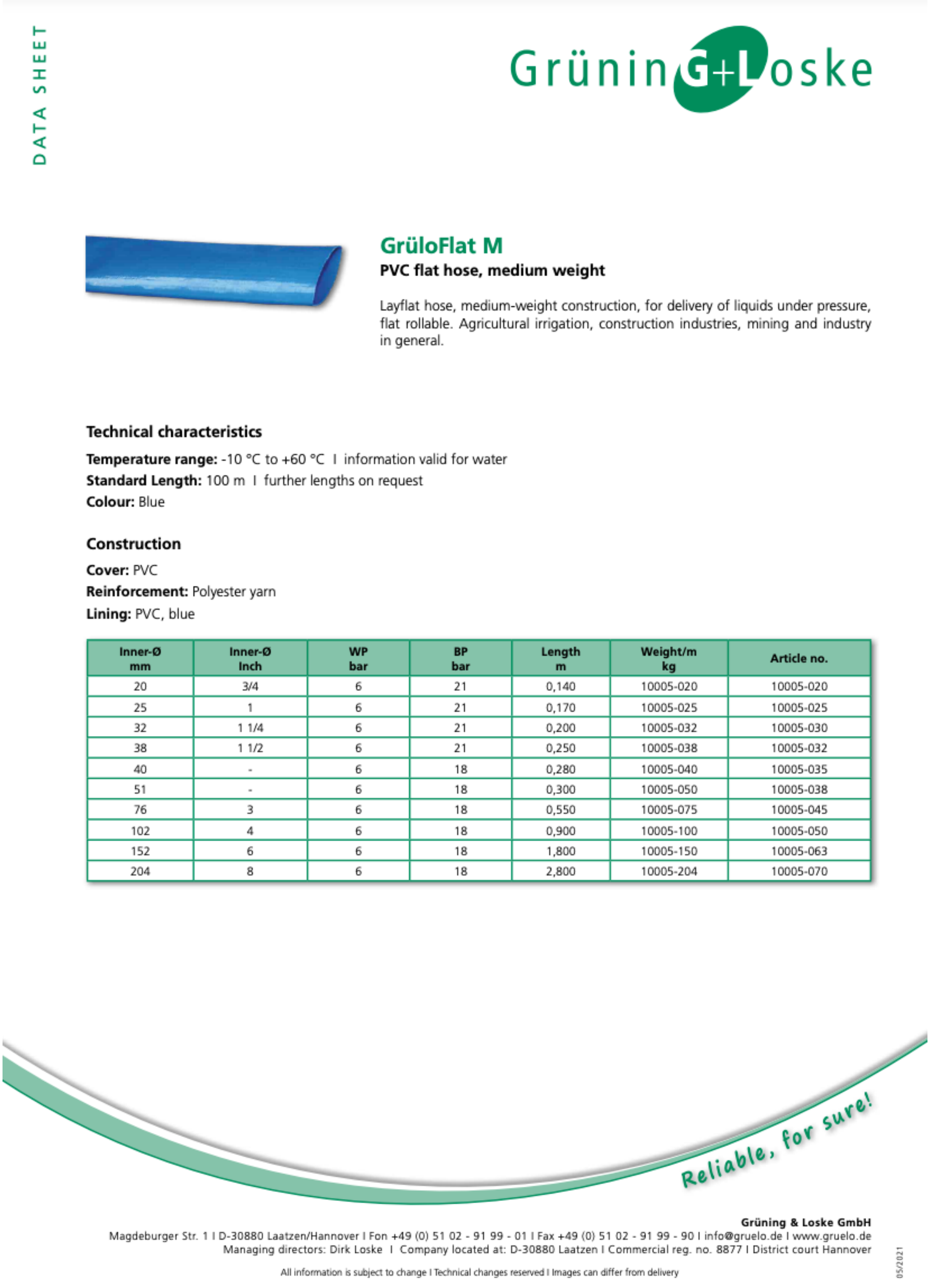
Figure 10-14 Data sheet sensor [128]

Air Ducts



DATA SHEET

Grüning+Loske

GrüloFlat M

PVC flat hose, medium weight

Layflat hose, medium-weight construction, for delivery of liquids under pressure, flat rollable. Agricultural irrigation, construction industries, mining and industry in general.

Technical characteristics

Temperature range: -10 °C to +60 °C I information valid for water
Standard Length: 100 m I further lengths on request
Colour: Blue

Construction

Cover: PVC
Reinforcement: Polyester yarn
Lining: PVC, blue

Inner-Ø mm	Inner-Ø Inch	WP bar	BP bar	Length m	Weight/m kg	Article no.
20	3/4	6	21	0,140	10005-020	10005-020
25	1	6	21	0,170	10005-025	10005-025
32	1 1/4	6	21	0,200	10005-032	10005-030
38	1 1/2	6	21	0,250	10005-038	10005-032
40	-	6	18	0,280	10005-040	10005-035
51	-	6	18	0,300	10005-050	10005-038
76	3	6	18	0,550	10005-075	10005-045
102	4	6	18	0,900	10005-100	10005-050
152	6	6	18	1,800	10005-150	10005-063
204	8	6	18	2,800	10005-204	10005-070

Reliable, for sure!

Grüning & Loske GmbH
Magdeburger Str. 1 I D-30880 Laatzen/Hannover I Fon +49 (0) 51 02 - 91 99 - 01 I Fax +49 (0) 51 02 - 91 99 - 90 I info@gruelo.de I www.gruelo.de
Managing directors: Dirk Loske I Company located at: D-30880 Laatzen I Commercial reg. no. 8877 I District court Hannover

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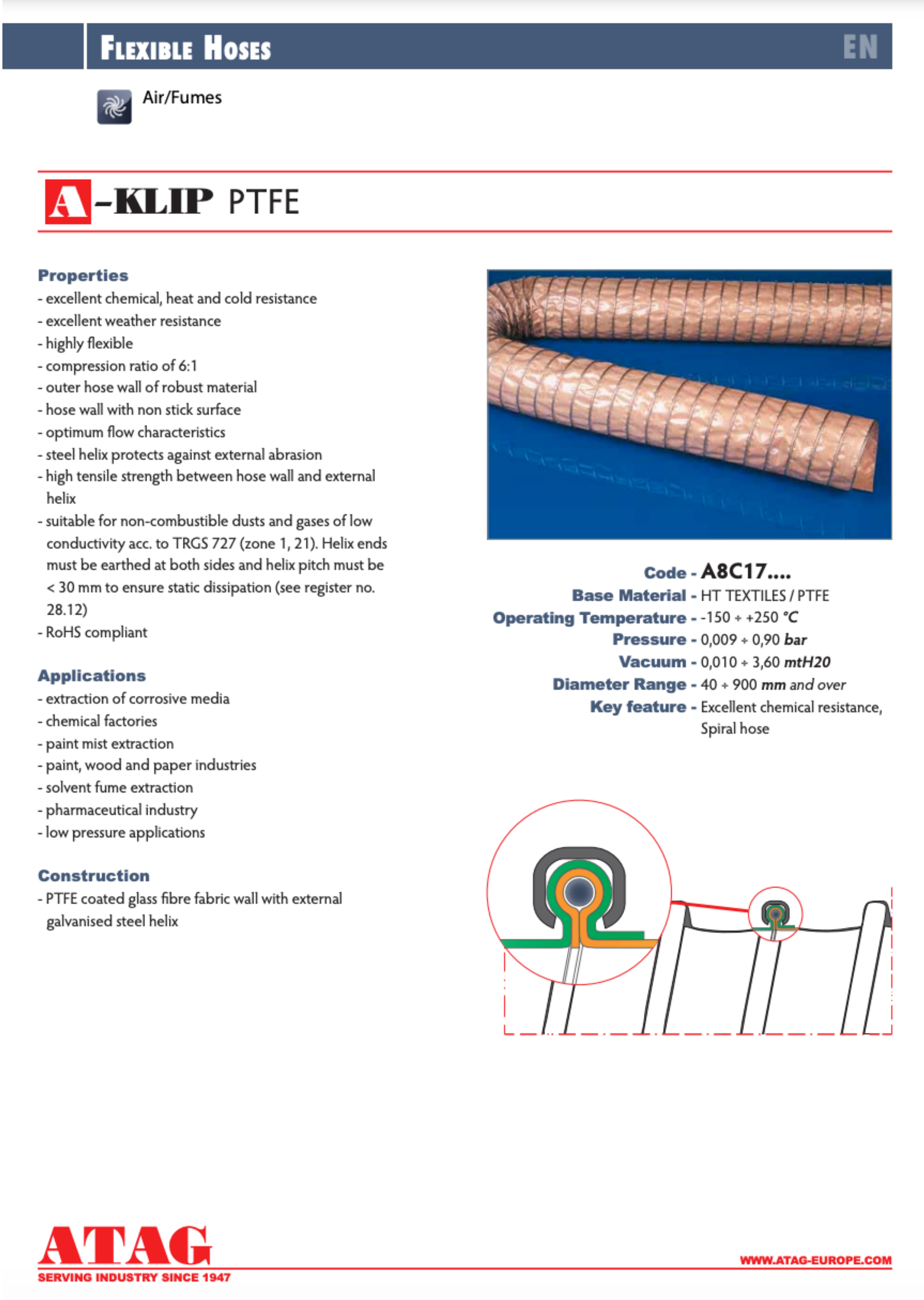
05/2021

Figure 10-15 Data sheet flexible hose [130]



FLEXIBLE HOSES

EN

Air/Fumes

A-KLIP PTFE

Properties

- excellent chemical, heat and cold resistance
- excellent weather resistance
- highly flexible
- compression ratio of 6:1
- outer hose wall of robust material
- hose wall with non stick surface
- optimum flow characteristics
- steel helix protects against external abrasion
- high tensile strength between hose wall and external helix
- suitable for non-combustible dusts and gases of low conductivity acc. to TRGS 727 (zone 1, 21). Helix ends must be earthed at both sides and helix pitch must be < 30 mm to ensure static dissipation (see register no. 28.12)
- RoHS compliant

Applications

- extraction of corrosive media
- chemical factories
- paint mist extraction
- paint, wood and paper industries
- solvent fume extraction
- pharmaceutical industry
- low pressure applications

Construction

- PTFE coated glass fibre fabric wall with external galvanised steel helix

Code - A8C17....
Base Material - HT TEXTILES / PTFE
Operating Temperature - -150 ÷ +250 *°C*
Pressure - 0,009 ÷ 0,90 ***bar***
Vacuum - 0,010 ÷ 3,60 ***mtH20***
Diameter Range - 40 ÷ 900 ***mm*** *and over*
Key feature - Excellent chemical resistance, Spiral hose

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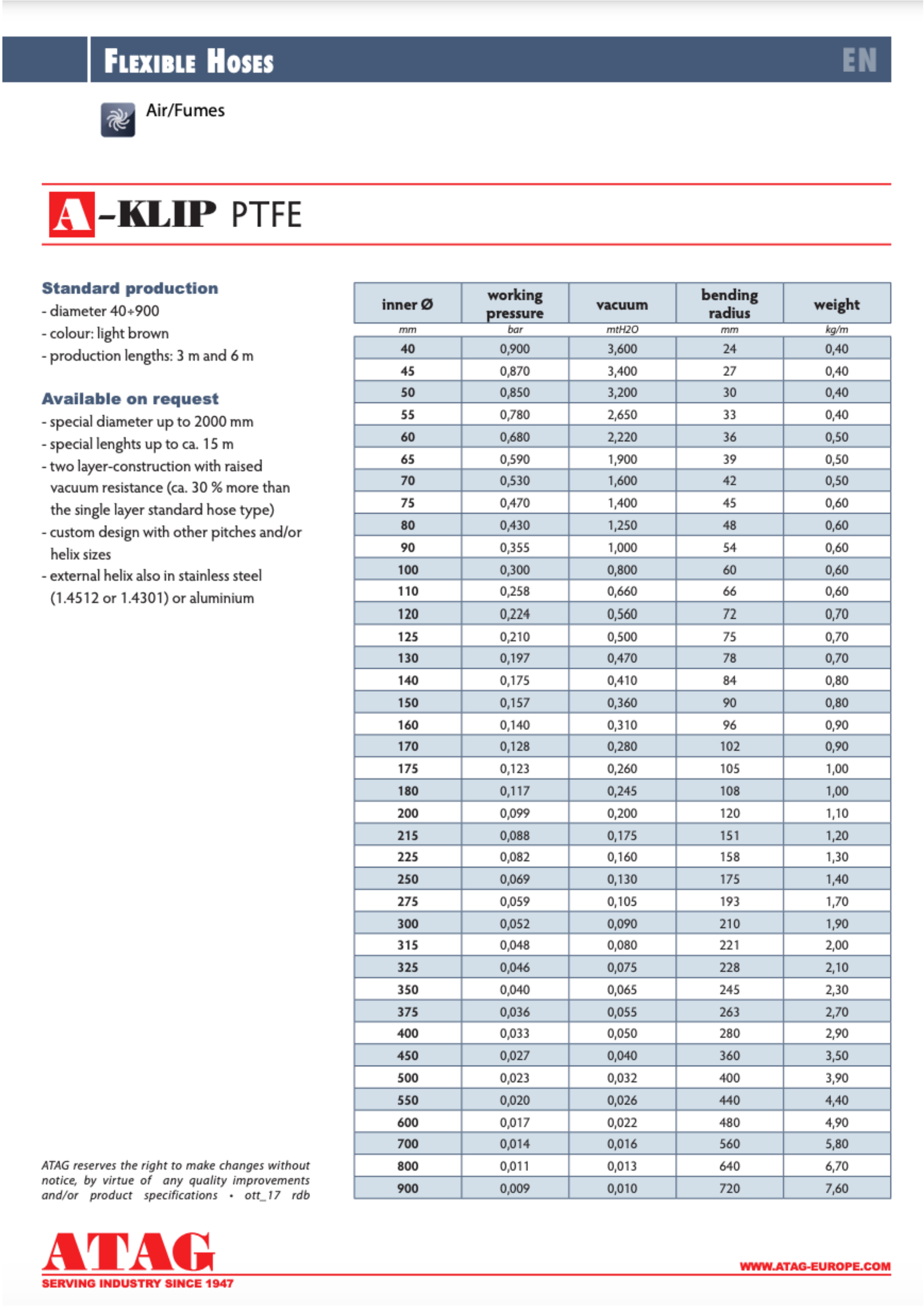

FLEXIBLE HOSES EN

Air/Fumes

A-KLIP PTFE

Standard production
- diameter 40÷900
- colour: light brown
- production lengths: 3 m and 6 m

Available on request
- special diameter up to 2000 mm
- special lenghts up to ca. 15 m
- two layer-construction with raised vacuum resistance (ca. 30 % more than the single layer standard hose type)
- custom design with other pitches and/or helix sizes
- external helix also in stainless steel (1.4512 or 1.4301) or aluminium

inner Ø *mm*	working pressure *bar*	vacuum *mtH2O*	bending radius *mm*	weight *kg/m*
40	0,900	3,600	24	0,40
45	0,870	3,400	27	0,40
50	0,850	3,200	30	0,40
55	0,780	2,650	33	0,40
60	0,680	2,220	36	0,50
65	0,590	1,900	39	0,50
70	0,530	1,600	42	0,50
75	0,470	1,400	45	0,60
80	0,430	1,250	48	0,60
90	0,355	1,000	54	0,60
100	0,300	0,800	60	0,60
110	0,258	0,660	66	0,60
120	0,224	0,560	72	0,70
125	0,210	0,500	75	0,70
130	0,197	0,470	78	0,70
140	0,175	0,410	84	0,80
150	0,157	0,360	90	0,80
160	0,140	0,310	96	0,90
170	0,128	0,280	102	0,90
175	0,123	0,260	105	1,00
180	0,117	0,245	108	1,00
200	0,099	0,200	120	1,10
215	0,088	0,175	151	1,20
225	0,082	0,160	158	1,30
250	0,069	0,130	175	1,40
275	0,059	0,105	193	1,70
300	0,052	0,090	210	1,90
315	0,048	0,080	221	2,00
325	0,046	0,075	228	2,10
350	0,040	0,065	245	2,30
375	0,036	0,055	263	2,70
400	0,033	0,050	280	2,90
450	0,027	0,040	360	3,50
500	0,023	0,032	400	3,90
550	0,020	0,026	440	4,40
600	0,017	0,022	480	4,90
700	0,014	0,016	560	5,80
800	0,011	0,013	640	6,70
900	0,009	0,010	720	7,60

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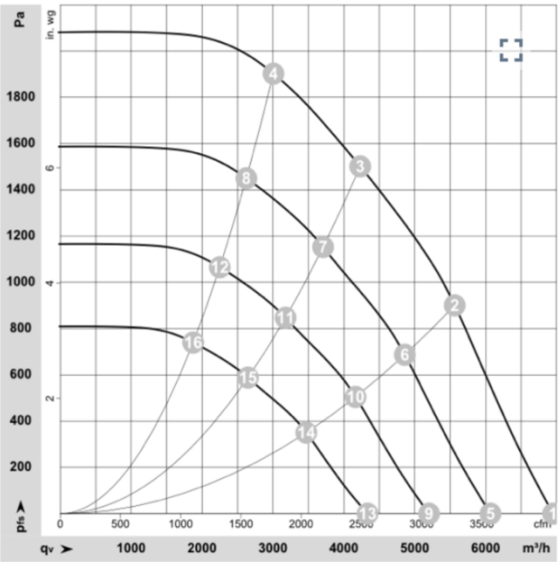
Figure 10-16 Data sheet - flexible hose with ring structure [129]

Service Section – Radial fan

Nominal data

Phase		3~
Type of voltage		AC
Nominal voltage	in V	400
Nominal voltage range	in V	380 .. 480
Frequency	in Hz	50/60
Type of data definition		maximum load
Speed	in min^{-1}	4000
Power input	in W	3050
Current draw	in A	4,7
Min. ambient temperature	in °C	-40
Max. ambient temperature	in °C	40

Curves



Air flow 50 Hz

Air flow 50 Hz

Measured values

	n	P_e	I	LpA_{in}
	in min^{-1}	in W	in A	in dB(A)
1	4000	2199	3,44	100
10	3000	1198	1,85	78
11	3000	1315	2,02	74
12	3000	1254	1,93	75
13	2500	533	0,83	88
14	2500	693	1,07	74
15	2500	761	1,17	70
16	2500	726	1,12	71
2	4000	2856	4,41	86
3	4000	3050	4,70	82
4	4000	2993	4,61	83
5	3500	1463	2,29	97
6	3500	1903	2,94	82
7	3500	2088	3,21	78
8	3500	1991	3,07	79
9	3000	921	1,44	93

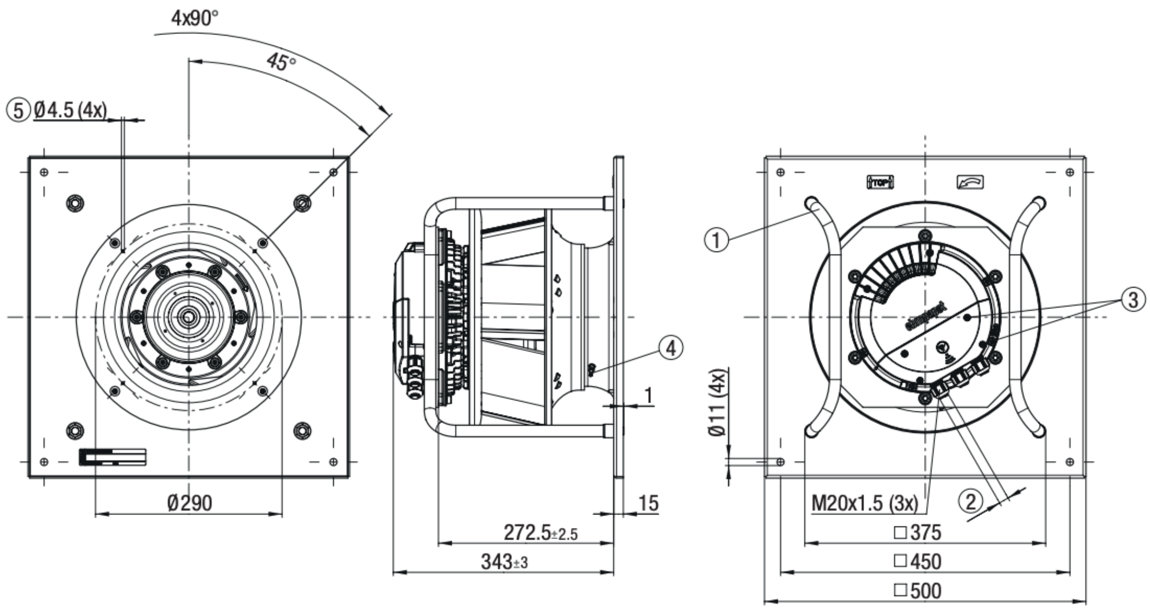


Figure 10-17 Data sheet centrifugal fan [158]

10.4 CATIA Image Selection

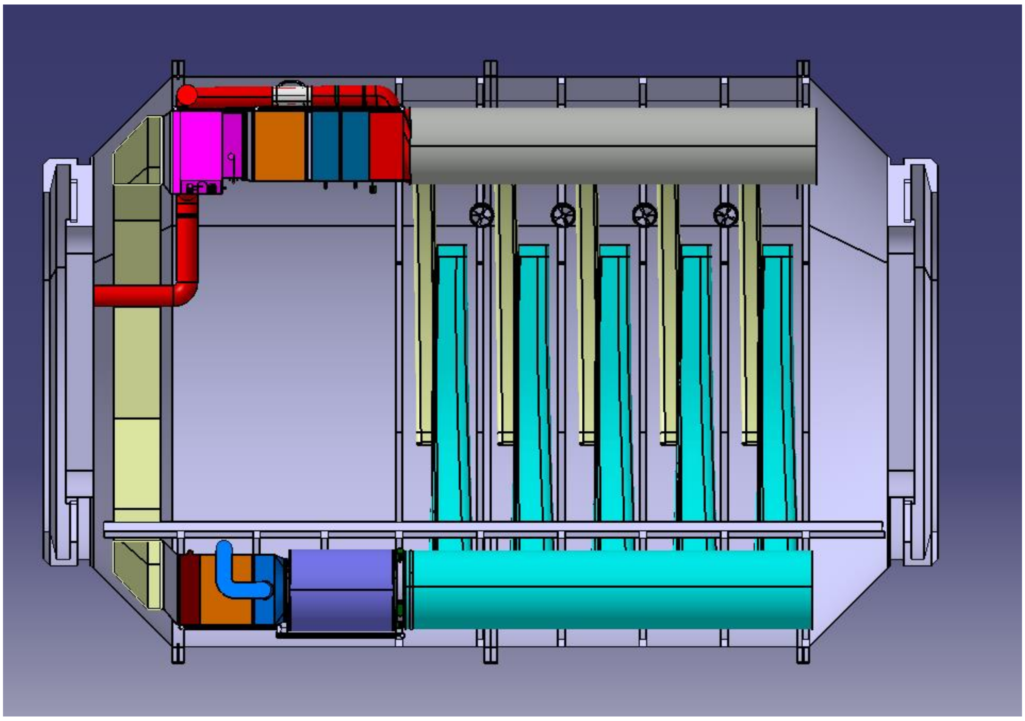


Figure 10-18 Side view 1

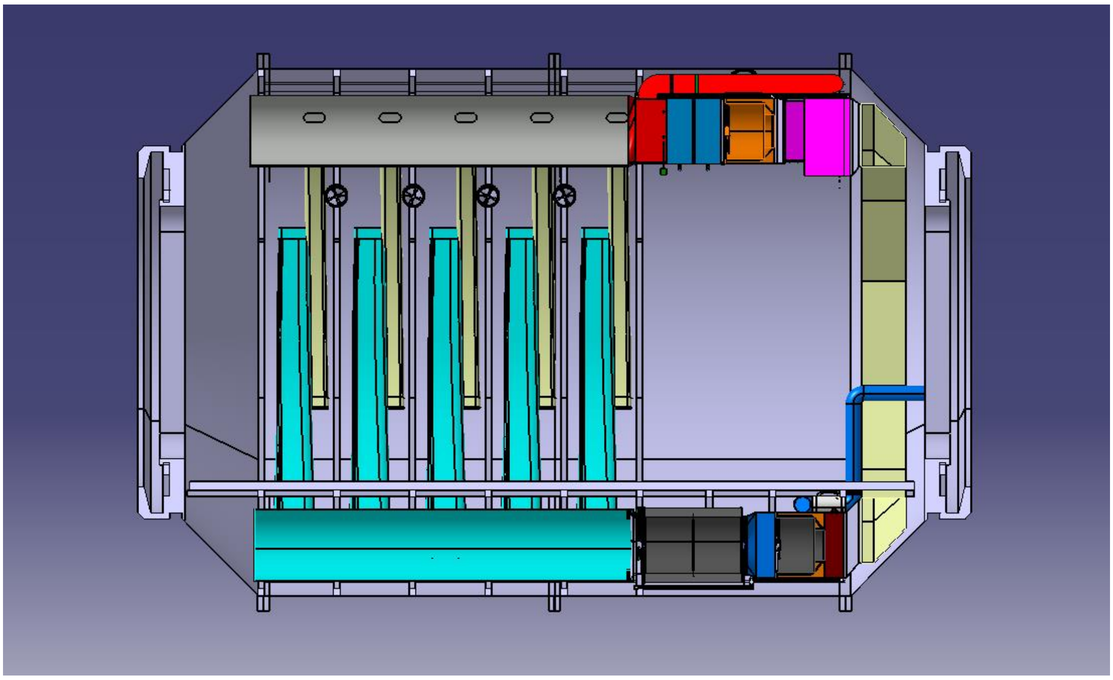


Figure 10-19 Side View 2

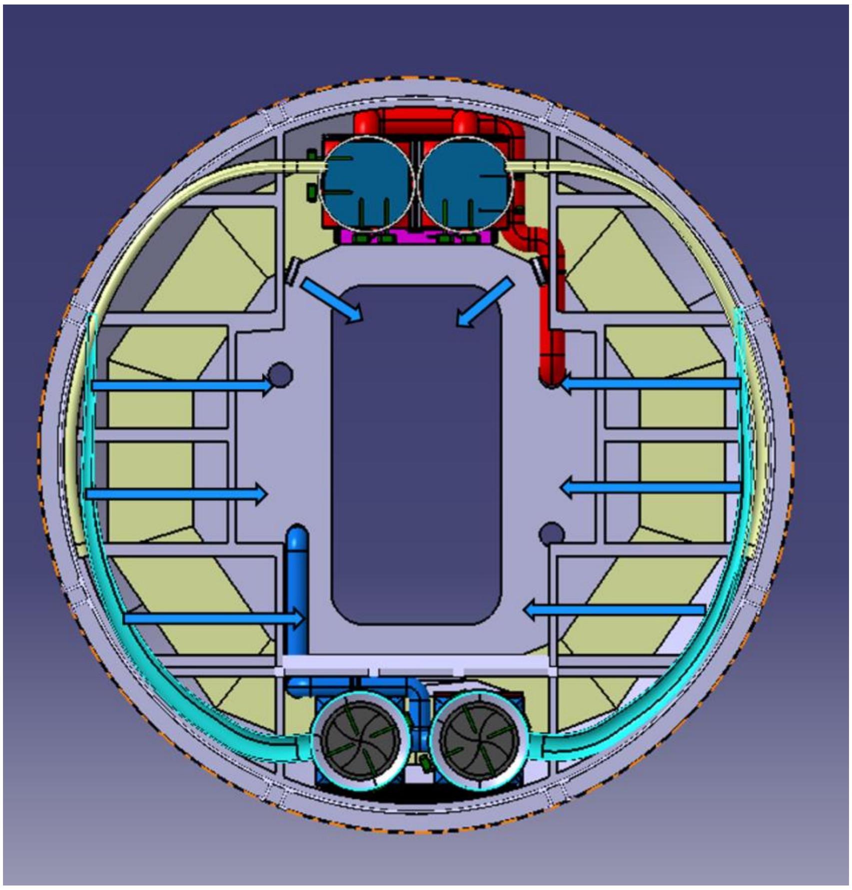


Figure 10-20 Cross view (blue arrows: air distribution)