# M ELiSSA

Technical Note

Memorandum of Understanding 19071/05/NL/CP

UNIVERSITEIT GENT

FACULTEIT WETENSCHAPPEN

MELiSSA Food Characterization: phase 1

# Technical note: 98.8.1

# Consolidation of specifications for the design of a plant characterization unit

| | |
|---|---|
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| reference/*réference* | Contract number 22070/08/NL/JC |
| issue/*édition* | 4 |
| revision/*révision* | 0 |
| date of issue/*date d'édition* | 27.01.2011 |
| status/*état* | Final |
| Document type/*type de document* | Technical Note |
| Distribution/*distribution* | FC1 consortium, ESA/ESTEC |

**CONFIDENTIAL DOCUMENT**

## APPROVAL

| | | | |
|---|---|---|---|
| Title<br>*titre* | Consolidation of specifications for the design of a plant characterization unit | issue 4<br>*issue* | revision 0<br>*revision* |

| | | | |
|---|---|---|---|
| author<br>*auteur* | Martin Weihreter<br>Olivier Gerbi | date<br>*date* | 15.03.2010<br>17.09.2010 |

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| UGuelph | Mike Dixon | | 20.12.2010 |

## CHANGE LOG

| reason for change /*raison du changement* | issue/*issue* | revision/*revision* | date/*date* |
|---|---|---|---|
| Draft for intermediate HVAC design version | 1 | 0 | 15.03.2010 |
| Second draft for HVAC design | 1 | 1 | 28.04.2010 |
| Final draft of intermediate HVAC design version | 1 | 2 | 04.05.2010 |
| Draft version including control system specs | 2 | 1 | 24.09.2010 |
| Comments from partners implemented, submitted to ESA | 2 | 2 | 29.09.2010 |
| Second, corrected submission to ESA | 3 | 0 | 23.12.2010 |
| Final version | 4 | 0 | 27.01.2011 |

## CHANGE RECORD

Issue: 4 Revision: 0

| reason for change/*raison du changement* | page(s)/*page(s)* | paragraph(s)/*paragraph(s)* |
|---|---|---|
| | | |

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## List of abbreviations

| | |
|---|---|
| CFD: | Computational Fluid Dynamics |
| CS: | Control System |
| CW 12: | Delhi Chilled Water Cooling Coil CW 12 |
| EC: | Electrical Conductivity |
| FC: | Food Characterization (project) |
| HC 12: | Delhi Hot Water Heating Coil HC 12 |
| HPC: | Higher Plant Chamber |
| HPS: | High Pressure Sodium |
| HVAC: | Heating, Ventilation and Air Conditioning |
| I/O: | Analog and digital inputs, analog and digital outputs |
| IR: | Infra Red |
| LED: | Light Emitting Diode |
| MELiSSA: | Micro-Ecological Life Support System Alternative |
| MH: | Metal Halide |
| MPP: | MELiSSA Pilot Plant |
| P&ID: | Piping (or Process) and Instrumentation Diagram |
| PAR: | Photosynthetically Active Radiation |
| PCU: | Plant Characterization Unit |
| RH: | Relative Humidity |
| TN: | Technical Note |
| UGent: | University of Gent (B) |
| UGuelph: | University of Guelph (CAN) |
| VPD: | Vapor Pressure Deficit |
| WP: | Work Package |

## Glossary

| | |
|---|---|
| Gully: | Also known as trough or gutter. Inclined channel used in hydroponic systems to hold the roots, and where the nutrient solution flows through. |
| PCU: | An array of three independent chambers used to grow plants in separate environments. The three separate subunits are used to achieve statistical reliability through independent parallel repeats by keeping a maximum of flexibility. Several PCUs (composed of three subunits each) will be installed in different laboratories. |
| PCU subunit: | A single independent plant growth chamber. Three PCU subunits outline one complete PCU as it is installed in a laboratory. |

## Reference documents

Ref 1 Statement of Work MELiSSA Food Characterization Phase 1; ESA Directorate of Technical and Quality Management; TEC-MCT/2008/3633/In/CP.

Ref 2 MELiSSA Food Characterization Phase 1; TN 98.7 Definition of PCU requirements; Contract No. 22070/08/NL/JC.

Ref 3 MELiSSA Food Characterization Phase 1; TN 98.4.21 Cultivar tests I; Contract No. 22070/08/NL/JC.

Ref 4 Spaceflight life support and biospherics; Peter Eckart; Kluwer Academic Pub, Dordrecht Space Technology Library, 1996.

# 1 Introduction

WP 8100 defines the specifications for a Plant Characterization Unit (PCU) which will be used to characterize the relative performance of cultivars of the crops selected for food production in a space based Food Production Unit (FPU) within the MELiSSA Food Characterization (FC) project. This WP builds on the PCU requirement definition (WP 7000) and several other WPs defining scientific requirements for crop cultivar evaluation, food processing tests and plant and chamber model validation. The specifications are deduced from the requirements specified in Ref 2.
WP 8100 is followed by three other WPs to lead to the final design of the PCU. These are:

- WP 8200: Preliminary design of the PCU.
- WP 8300: Study of critical subsystems and selection of most suitable technologies.
- WP 8400: Detailed design of the PCU.

A very detailed system description has been elaborated in Ref 2. Please refer to chapter 2 of Ref 2 for further details on the overall functioning and concept of the PCU.

As Ref 2 was elaborated to a very high level of detail partially including specifications next to the requirements. As the work approach in the consortium had to be adapted in the course of the project, this technical note does not strictly follow the structure of a specifications document. This document was used as a working document to allow different partners to work in an efficient way on their respective work packages by ensuring a proper coherence of each individual work.

# 2 System specifications

## 2.1 Overall partitioning and volume envelopes

The following schematic gives an overview of the partitioning of the PCU subunits and their volume envelopes. A definition of overall dimensions is important at this point for logistic reasons and to allow independent work on different compartments. More detailed descriptions of the functionality and definition of each compartment are given below.

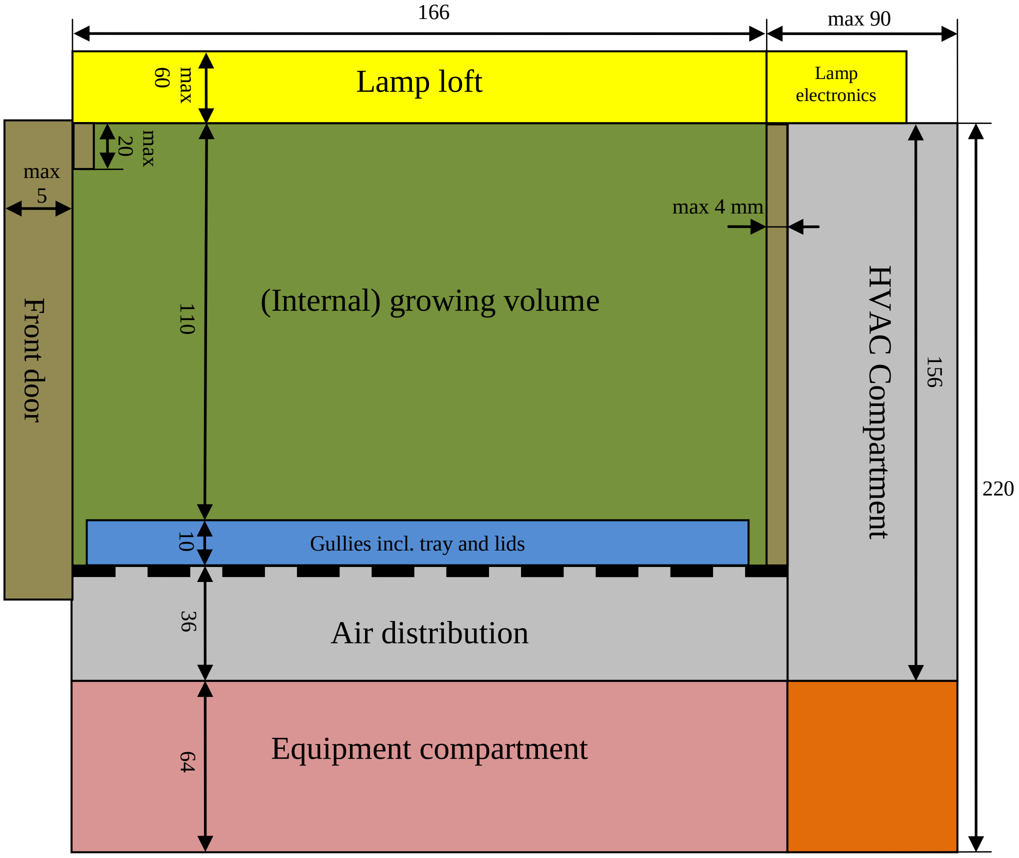



**Fig. 1** Schematic of a PCU subunit; dimensions in cm; side view.

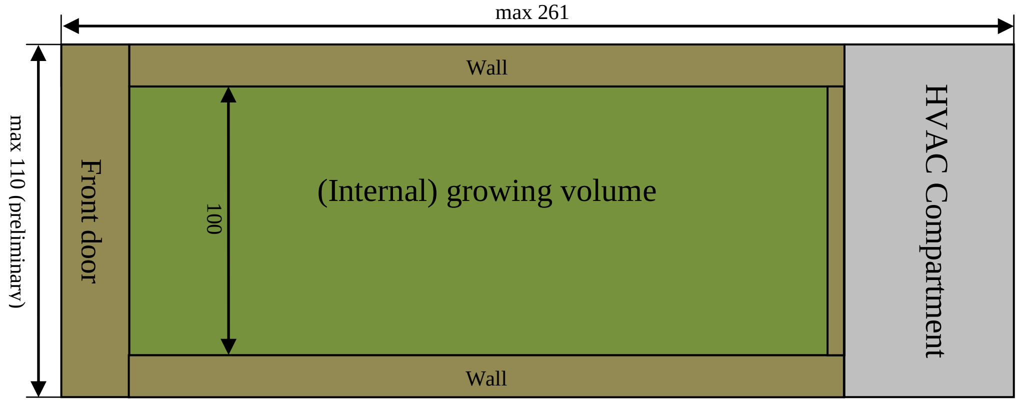



**Fig. 2** Schematic of a PCU subunit; dimensions in cm; top view (lamp loft hidden).

The total size of the chamber is limited by the delivery approach as explained in detail in Ref 2. Each PCU subunit will have a removable lamp loft for delivery. The height of the delivered packages can be up to 200 cm. For the UGent installation, a separable HVAC compartment will be delivered to avoid problems with narrow corners and corridors. The maximal depth of each delivered package is 180 cm.
The total width of the chamber will depend on the design of the insulation. The maximum width for delivery is 110 cm. A larger thickness is possible for insulation if installed on site after transport into the lab. The insulation must however be removable for UGent as the PCU will be moved to a different lab a few years after installation. The total width of the chambers including insulation must be sufficiently small, to place the chambers in the laboratory as seen below taking into account access of personnel.

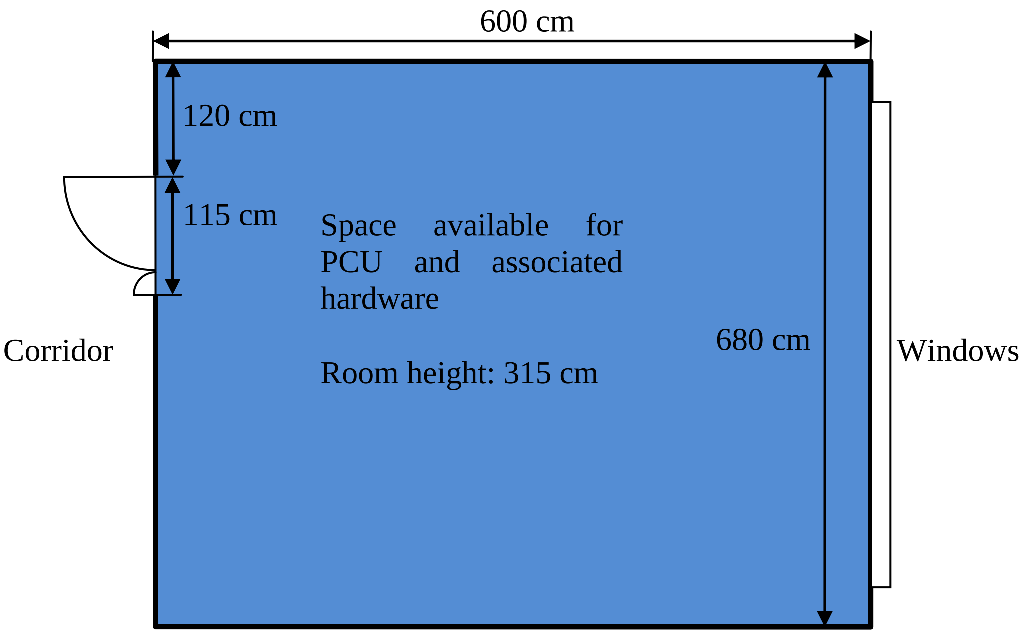



**Fig. 3** Layout of the laboratory

### 2.1.1 Growing volume

The internal dimensions of the chamber are defined by plant growth requirements. The internal growing volume has the following boundaries:

- The upper face of the air grilles of the air distribution system underneath the gullies. The growing volume comprises the gullies and their tray/support structure but not the air grilles.
- The lower face of the lamp loft glass. The glass is not included in the plant growing volume but is permanently attached to the chamber structure. The thickness will be around 1 cm and has to be taken into account for the total height of the chamber parts to be delivered.
- The inner face of the door. The door is not included in the growing volume envelope. It is side hinged and thus structurally supported by the side wall. A protrusion into the growth volume for the gaskets (and locks) on the upper part of the chamber is possible if it does not exceed 20 cm below the lamp loft glass (to avoid damaging plants when pulling the gullies out). See Fig. 6.
- The inner face of the wall separating the growth compartment from the HVAC compartment. The wall will be between 2 and 4 mm thick. As this adds to the total size of the chamber, the largest value is used to estimate the total size of the chamber. The inner depth of the chamber is 166 cm. The length including the rear wall and excluding the door is 170 cm maximum.
- The sidewalls are not accounted for in the growing volume. The inner chamber width shall be 100 cm. The external width of the chamber shall not exceed 110 cm for delivery.

The internal volume of growth compartment is specified by the growth compartment height and the total surface. The growth compartment height is defined by the largest crop to be grown in the PCU, the gully system and the minimal free distance between the crop and the lamping loft. These are:

**Tab. 1** Internal height of the growth compartment

| | |
|---|---|
| Height of largest crop to be grown | 90 cm |
| Height of one gully including the tray/support and the lids | 10 cm |
| Free headspace to lamping loft | 20 cm |
| **Total internal height of the growth compartment** | **120 cm** |

The total surface area is defined by the required growing area as no margin towards the walls is applied. The plants will only be limited in their horizontal growth by walls and in some cases fences (future addition if required – the gully system will accommodate this with minimal modification) between the gullies. The growing area depends on the harvest requirements for nutritional analysis and intermediate samples targeted towards plant model validation. As described in Ref 2, sufficient harvest to perform all processing tests on PCU grown harvest would require a too large surface area. Processing tests will be performed on commercially available crops for the first tests and will only be conducted on hydroponically grown harvest with scaled down equipment. Therefore the sizing of the growing area relies only on the intermediate samplings and the requirements for statistical reliability. The minimal surface area was determined in Ref 2 to be 1.275 $m^2$ to obtain 5 subsequent samplings sufficiently large for nutritional analyses and plant model validation. This value is supplemented by a 30% margin. This leads to a **surface area for each subunit of 1.66 $m^2$** respectively a **total growing surface of 5 $m^2$** for 3 subunits. This allows 5 harvests for nutritional analyses at different time points for each subunit. When the three subunits are harvested at once, sufficient harvest for basic processing tests will be available. Furthermore up to 15 intermediate sampling points can be achieved when harvesting single gullies in just one of the PCU subunits at once. The harvested samples will in this case not be sufficiently large for nutritional analyses but can provide valuable intermediate biomass information for plant model validation. In this case however the statistical reliability is smaller since no triple samplings are taken.

The above mentioned dimensions of the growing area also comply with the statistical reliability requirements to have at least 10 plants per gully. The crop with the largest surface requirements is potato. In the FC bench tests each plant occupies a 10 x 20 $cm^2$ surface area (10 cm parallel and 20 cm perpendicular to the gully). A 1.66 m long growing area would thus provide sufficient room for 16 individual plants. With a halved occupation 8 plants are possible per gully with a surface area of approximately 20 x 20 $cm^2$ per plant. With 5 gullies per PCU subunit and a growing area 1 m wide, 20 cm are available for each plant. The UGuelph hypobaric chambers use gullies of 14 cm width. This value is used as a first guideline. In this case an inter-gully space of 6 cm is available. The ratio of the gully width to the inter-space is important for the flow turbulence within the foliage. Large gullies combined with a thin gap will provoke jet streams and high turbulence in the gullies vicinity. This is to be avoided by providing a sufficiently large gap. Whether the ratio of 14/6 is sufficient will have to be determined by Computational Fluid Dynamics (CFD) simulations.

To be able to harvest single gullies without disturbing neighboring plants, the use of fences between the gullies is proposed for crops with risk of entanglement (e.g. soybean and potato). The fences can be added to the PCU for the specific experiments and will not be delivered with the PCU. The design of the PCU will allow such a system to be implemented. An adequate interface will be provided on the gully trays. More details will be given in the following TNs.

The growing area is defined as the whole internal surface of the chamber as no free space is needed towards the walls. Thus the growing areas of the outer gullies are limited by walls. The sizing takes this into account and the distance between the outer gullies and the walls is equal to half the distance between two gullies. The gully positioning is flexible so other ratios of inter-gully space to gully/wall space are possible if required by experimental protocols. For the HVAC design, the above mentioned dimensions are used. The flow inhomogeneity in the boundary layer of the walls is assumed to be sufficiently low to have any considerable impact on the plants. The impact and size of the boundary layers will be validated with CFD simulations at later stages. To avoid unequal growing areas for the first and last plants of the gullies, the gully feeds and outlets must be as close to the walls as possible. For a first design step, both are assumed to protrude maximal 5 cm into the growing area. This means, that in case of 16 plants the first and last plant grow directly next to the inlet and outlet. For the plant closest to the outlet this means that the roots are mostly growing inside the outlet. For potatoes

this can be a problem since the stolons can have lengths of up to 40 cm. Since the chamber is closed and the gullies cannot be opened during the whole cultivation, the stolons might grow into the outlet. For simple roots this is not a problem since the diameter is chosen sufficiently large to avoid clogging. Stolons will however cause problems since the forming tubers will occupy a much larger volume and thus clog the outlet. Therefore a larger distance between the last plant and the outlet is favorable by keeping the growing surface above the gully equal. If no design solution is found, the last slots of each gully will have to be left empty to keep sufficient distance to the outlet. The area above the gullies must then be limited by fences to keep the growing area for each plant approximately equal.
The following figure gives an overview of the dimensions:

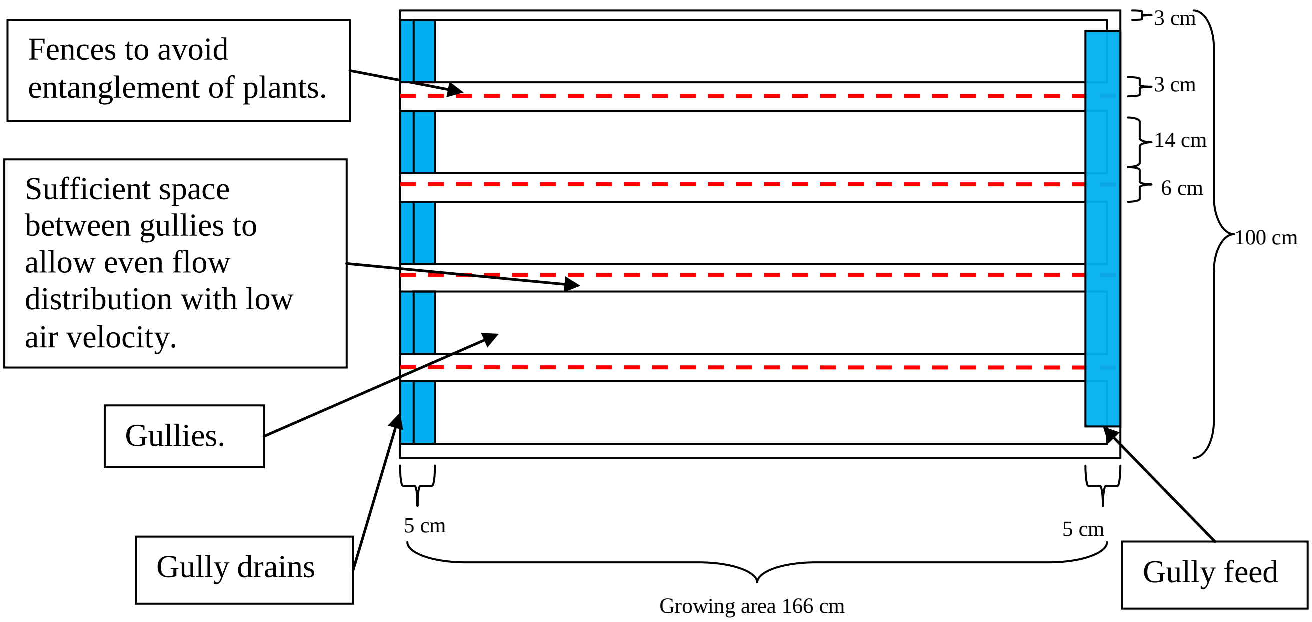



**Fig. 4** Schematic of gully arrangement and fences

Applicable requirements:

SYS-PHYS-VOL-1: The internal volume shall be sized to comply with all functional requirements.
Rank 1

SYS-PHYS-VOL-2: The free headspace (defined as the distance between the leaf level and the lamping loft glass) shall be at least 20 cm for the largest crop at maximal size.
Rank 1

SYS-PHYS-VOL-3: The growing surface area of the PCU shall be at least 1.25 $m^2$ large.
Rank 1

SYS-PERF-REP-2: Each gully shall be sized to contain at least 10 individual plants at full occupation.
Rank 1

### 2.1.2 HVAC compartment

As described above, the volume envelope of the HVAC compartment implies external walls (back and sides) and the wall to the growth compartment. The wall between the HVAC compartment and the growth compartment is 2-4 mm thick and made of stainless steel. The HVAC compartment contains the following parts:

- Cool heat exchanger.
- Hot heat exchanger.
- Condensate recovery system (included in the chosen cold heat exchanger).
- Condensate quantification system.
- Condensate recirculation tube.
- Blower.
- Ducting (if needed).
- Baffles (if needed).
- Sensors.

These elements are specified in more detail in the HVAC subsystem chapter (3.3).
The following elements will be positioned either in the HVAC compartment or the air distribution compartment depending on the final design:

- Connection ports for the pressure compensation bag. The exact position of the bag itself is not yet fixed. It could be located in the equipment compartment or on top of the chambers.
- Connection ports for experimental gas sampling or addition and for $CO_2$ feed and $O_2$/Ethylene removal (optimal positions to be determined by CFD simulations according to local air velocity and mixture).

The $CO_2$ gas bottles can be positioned next to the PCU subunits as well as within the subunits volume envelope depending on the detailed design. Safety related design aspects (e.g. fixed mounting of bottles) must either be provided by the PCU structure or the laboratory, if the bottles are positioned externally. The same applies to oxygen and ethylene removal devices.

### 2.1.3 Air distribution compartment

The air distribution compartment contains the following elements:

- Air grilles to the growth compartment. Everything above the air grilles is not considered as part of the air distribution compartment.
- The ducting and associated hardware (e.g. baffles or dampers) to distribute the air evenly over the whole growing surface.
- Side and front walls. The maximal width including the side walls is 110 cm. The dimensions of the air grilles shall be equal to the growing surface area (1.66 x 1 $m^2$). The sidewalls do not necessarily need to be 5 cm thick if a larger internal volume is helpful for the air distribution (see Fig. 6).
- The interface to the HVAC compartment (e.g. blower).

- Sensors.
- Depending on the design, the gas connection ports for pressure compensation and gas sampling or addition will be positioned in the air distribution compartment or the HVAC compartment as described in the previous chapter.
- The gully nutrient solution feed tube and the gully drainage system. The design of the air distribution elements must keep sufficient space for the feed and drain. The drainage system is explained in more detail in chapter 3.1.5.

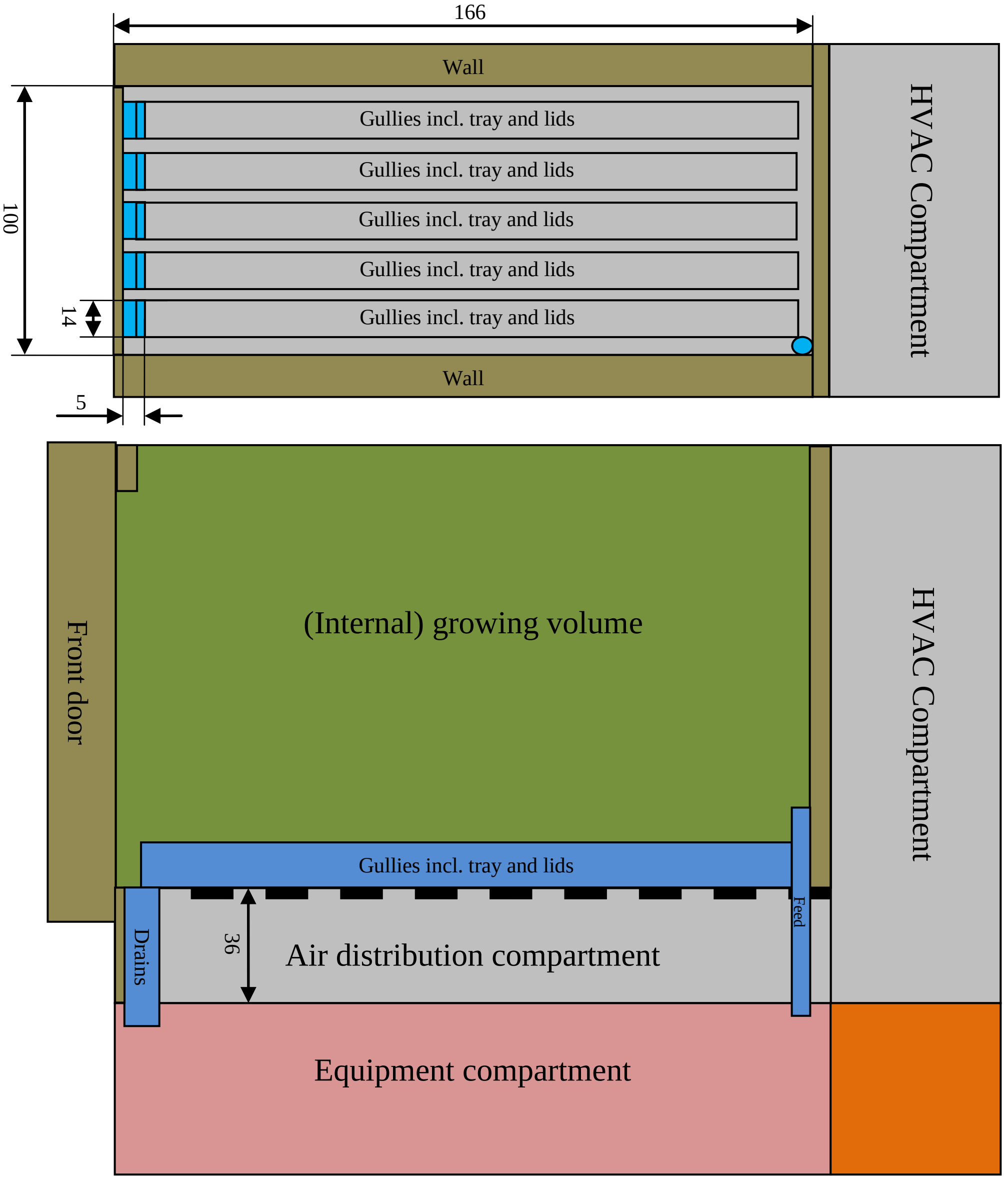



**Fig. 5** Schematic of the air distribution compartment (top and side view)

The ground plate separating the air distribution compartment from the equipment compartment is not taken into account in the dimensions (36 cm) of the air distribution compartment. This is accounted for in the equipment compartment volume envelope.

### *2.1.4 Equipment compartment*

The equipment compartment is limited in height by the air distribution compartment. The wall between these two compartments is part of the equipment compartment volume envelope. Depending on the delivery strategy, the space below the HVAC compartment (orange in Fig. 1) can be added to the equipment compartment. If the size of the chamber is limited in depth for transportation in the UGent elevator, this space must be empty or separable from the main equipment compartment. In that case it could for example be used for removable equipment such as gas analyzers or $CO_2$ bottles. The equipment compartment contains the following elements:

- Nutrient solution tank. The Electrical Conductivity (EC) and pH stock solution tanks are stored externally from the PCU subunits. All three subunits use the same stock solution tanks.
- Hydroponic system pumps and valves.
- Main parts of the nutrient solution delivery system.
- Main parts of the nutrient solution recovery system.
- The plate separating the air distribution compartment from the equipment compartment is part of the equipment compartment volume envelope.

### 2.1.5 *Front door*

The front door will be side hinged and seals off tightly. A schematic of the door layout is given in Fig. 6. Exact dimensions and positioning of the door are subjects of the design phase.

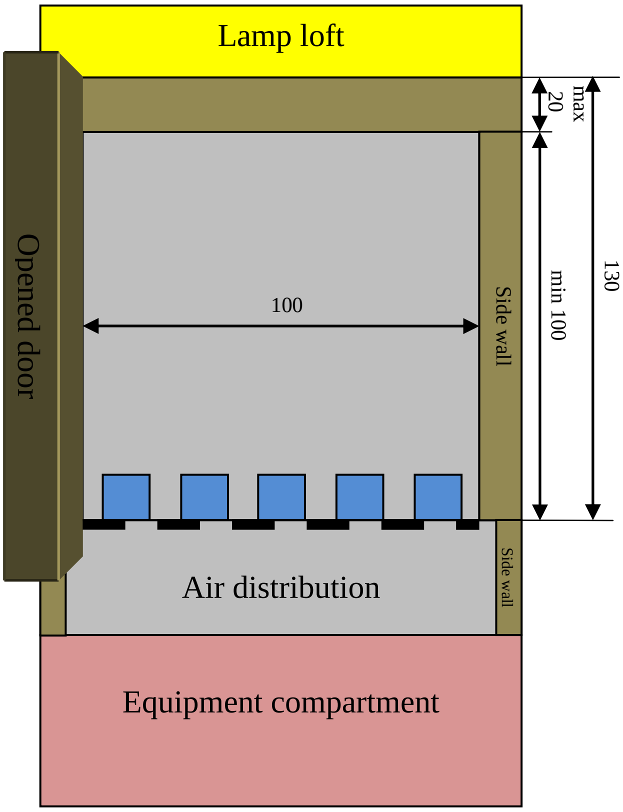



**Fig. 6** Front view with opened door and view into air distribution compartment

### 2.1.6 Lamp loft

The lower part of the lamp loft (glass and its supporting frame) is permanently fixed to the growth chamber for reasons of air tightness. The thickness of the glass roof and its frame must be taken into account for the total height for delivery.
The lamp loft comprises the following elements:

- Loft structure
- Lamps and reflectors
- Fans

The fans are located on the rear side of the chamber and suck air out of the loft. The air inlet is located on the front side of the loft. The outgoing airstream passes over the adjacent ballasts for cooling.

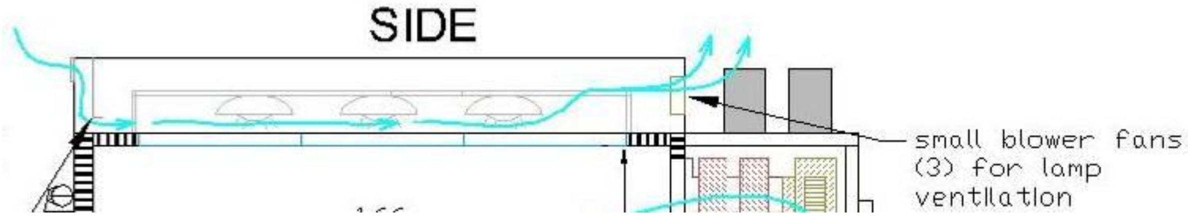



**Fig. 7** Lamp loft air handling

The design of the opening mechanism of the lamp loft will have to take into account height limitations of the room at UGent as specified in Fig. 3.

### 2.1.7 Lamp electronics

The lamp electronics (ballasts and power distribution panels) are located on top of the HVAC compartment. Positioning and sizing is flexible as long as the overall dimensions of the PCU subunit stay the same.

## 2.2 Interface specifications

### *2.2.1 Liquid interfaces*

#### *2.2.1.1 Heating/cooling water ports*

The following table sums the interface requirements to the heating and cooling water ports as specified in Ref 2:

**Tab. 2** Summary of heating and cooling water supply I/F requirements

| | |
|---|---|
| Pressure range of supplied heating and cooling water | 2-10 bars |
| Selectable temperature range for heater (1°C increments) | 40-80°C |
| Temperature range of cooling water (not user selectable) | 5-8°C |
| Maximal oscillation of heating and cooling water | 0.2°C per hour |

Flow rates are controlled at chamber level (3-way proportional valve for both hot and cold water with bypasses). The maximal flow rates needed are calculated assuming that the PCU is an adiabatic volume. The calculation is based on the following values:

- 3000 W heat load due to the lamps as described in 3.3.2.
- The dissipation of other pieces of equipment (pumps, blower etc) is collectively represented by a heat load of 150 W as a worst case estimate.
- The heat required for condensation of the transpired water of the plants at maximal size is used (850W; see chapter 3.3.2).
- The coldest atmosphere temperature setpoint of 15°C is used as a reference together with the warmest cooling water temperature (8°C).

The flow rate is calculated based on the heat load on the chamber and the cooling water in and output temperature. The following values are used:

- Specific heat capacity of water: 4186 J/kg K
- Heat exchanger inlet temperature: 8°C
- Heat exchanger outlet temperature: 12°C (a 3°C ΔT to the 15°C minimal atmosphere temperature is kept).

With these values a water flowrate of **14 l/min** is obtained to constantly remove **4000W**. Since these calculations are based on several assumptions, this value is only to be used as a guideline.
Heating water supply will have much lower requirements. Under nominal conditions the chamber will always need cooling power to counterbalance the radiative heat load. Heating is basically just needed to reheat air after cooling down for condensation. Furthermore the ΔT is higher and the total heat to be delivered lower. Calculation of the exact flow rates needed is not possible at this stage.

### 2.2.2 *Gas interfaces*

As specified in Ref 2, the HVAC ducting design must provide the possibility of having a gas input port for $CO_2$ addition and two gas sampling ports. Furthermore four spare ports are required for later expansion if needed. These ports shall be useable for sampling or injection of gas.

According to Ref 4 the $CO_2$ uptake rate generally ranges between 40-300 $g/m^2day$ for typical crops. For the following calculation the upper value is used. The bench tests at UGuelph described in Ref 3 obtained an uptake rate of 57 $g/m^2day$ on a 16 hour light cycle. Thus the $300g/m^216h$ is a clear upper limit.

With a specific volume of 557 ml/g for $CO_2$ at 23°C and 1 bar, a total of **17 L/h (283 ml/min)** results to meet the 300 $g/m^216h$ on a 1.66 $m^2$ growing surface.

# 3 Subsystem specifications

## 3.1 Hydroponic subsystem

### *3.1.1 Sealed hydroponic system*

Following several discussions and scientific requirements (see Ref 2), the PCU hydroponic system should be sealed off from the chamber atmosphere to allow more precise mass balances and to avoid interactions between the root zone and the aerial zone. A sealed off system however implies several complex problems to be solved from a technical point of view. Further research and development is needed to address these problems. In the near future, experiments will be performed with opened gullies as it has been done in FC1 bench tests. But the system is designed with a retrofitting in mind and will keep sufficient flexibility to perform tests and research on this issue and to implement a sealed hydroponic system at later stages.

The following critical design issues have been identified:

<u>Baseline evaporation:</u>
At the beginning of a cultivation, when the plant transpiration is insignificant, problems with chamber humidity could occur (once plants have reached a certain size, transpiration will be sufficient to keep the chamber RH balanced).
With an open gully system (as used in all FC1 bench tests) a dedicated humidification system is not needed to keep the chamber atmosphere humidity at the required levels. Sufficient water evaporates from the gullies themselves (baseline evaporation). Adequate humidity control is possible by condensation (water removal) on the HVAC cold heat exchanger only.
Sealing off the gully completely from the chamber atmosphere might lead to too dry air at the beginning of a cultivation. Thus a humidifier might have to be added to the HVAC system if the hydroponic system is completely sealed. The water management system of the hydroponic system might also require revision as the condensate is recovered to the nutrient solution tank. Addition of an external water source (humidifier) could jeopardize nutrient solution levels and control depending on the quantities added. The real necessity of an external humidifier will depend on the temperature and RH regimes to be attained (test profile)
A semi sealed hydroponic system as proposed in chapter 4.1.6 of Ref 2 would mitigate the problem of low humidity at the beginning of a cultivation by flushing the gullies and thereby providing a constant baseline evaporation. The mass transfer of water, $O_2$ (and $CO_2$) can be quantified by measuring the difference between the in and outflow of the gas phase. Thus mass transfer is quantifiable but not blocked (the parameters of the root and shoot zone remain interdependent). This reliability of this solution in terms of measurement precision is still unknown as the measurable differences will certainly be very low.

Air tight interface with plant stems: Sealing off growing plants at the stem level is difficult. First of all, the plant must not be damaged. Secondly, the seal must be flexible enough to allow growth while keeping the interface tight at all times.

Ventilation of the nutrient solution: The nutrient solution must be oxygenized and ventilated to ensure proper root growth and functioning. The advantage of a NFT system is a constant solution aeration due to the thin liquid film in the gully and the thereby inherent large contact area between liquid and gas. Sealing off the gullies from the atmosphere will however create a stagnation zone in the gullies gas phase. Therefore a certain level of mass exchange with either the chamber atmosphere or an external source is necessary.
The aeration strategy will largely depend on the overall sealing design. A completely sealed-off design will require an external oxygen source. A semi sealed hydroponic system as proposed in chapter 4.1.6 of Ref 2 will use chamber air for gully flushing.

Pressure gradients: in case of a completely separated hydroponic system, pressure differences between the gullies interior and the chamber atmosphere could lead to leaks or influences on plant growth. Therefore equal pressure must be ensured at all times.

### *3.1.2 Gullies*

The gullies are based on a stainless steel design as employed in the UGuelph hypobaric and SEC2 chambers. The advantage of stainless steel as a construction material lays in its durability, outgassing neutral properties and ease of manufacturing for a (complex) sealed design. The following modifications are needed:

- Threaded boreholes on both ends for gas tube fittings. The fittings should be of large diameter to reduce pressure losses. In the first design no tubes are connected to the fittings, leaving the gully system open. Thereby the problems of air humidification at the beginning of cultivation are mitigated. Once the PCUs are installed, different strategies of gully flushing can be tested to determine the optimal solution.
- The lid must be sealed. This can be achieved by adding a gasket between the lid and the gully and clamps to keep the lid in position. Other solutions such as one-way sealing with (outgassing proof) silicone might also be possible.
- The open flow nutrient solution feed as currently used in the hypobaric chambers must be modified to allow a sealed of connection with the lid. This could be done with a tube fitting and a flexible tube.
- A nutrient solution collection system at the exit of each gully which is sealed from the atmosphere and which routes back the gully overflow to the nutrient tank.
- An open system for the plant interface. For the first design, slotted gully covers will be designed. Subsequent sealing designs will be deduced through experimentation and built in later design iterations.

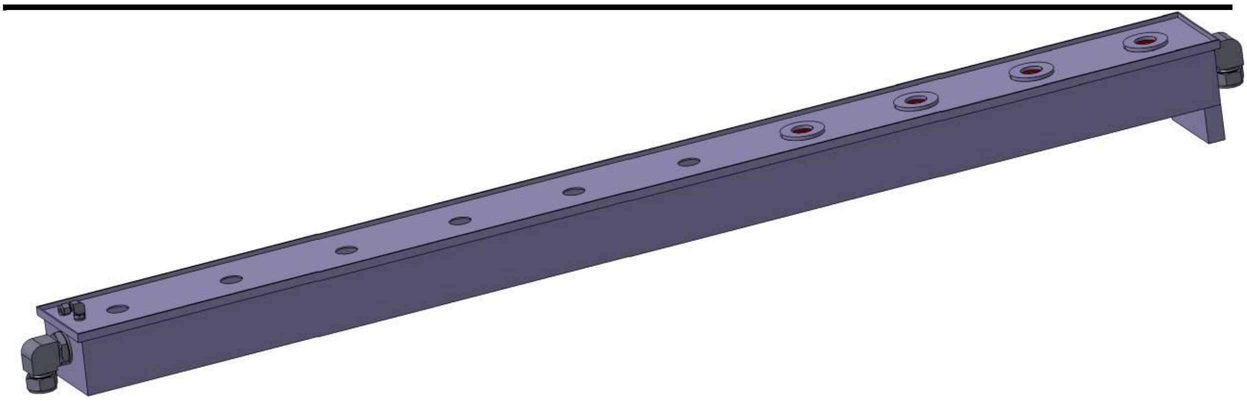


**Fig. 8** Sealed gully concept assembly view

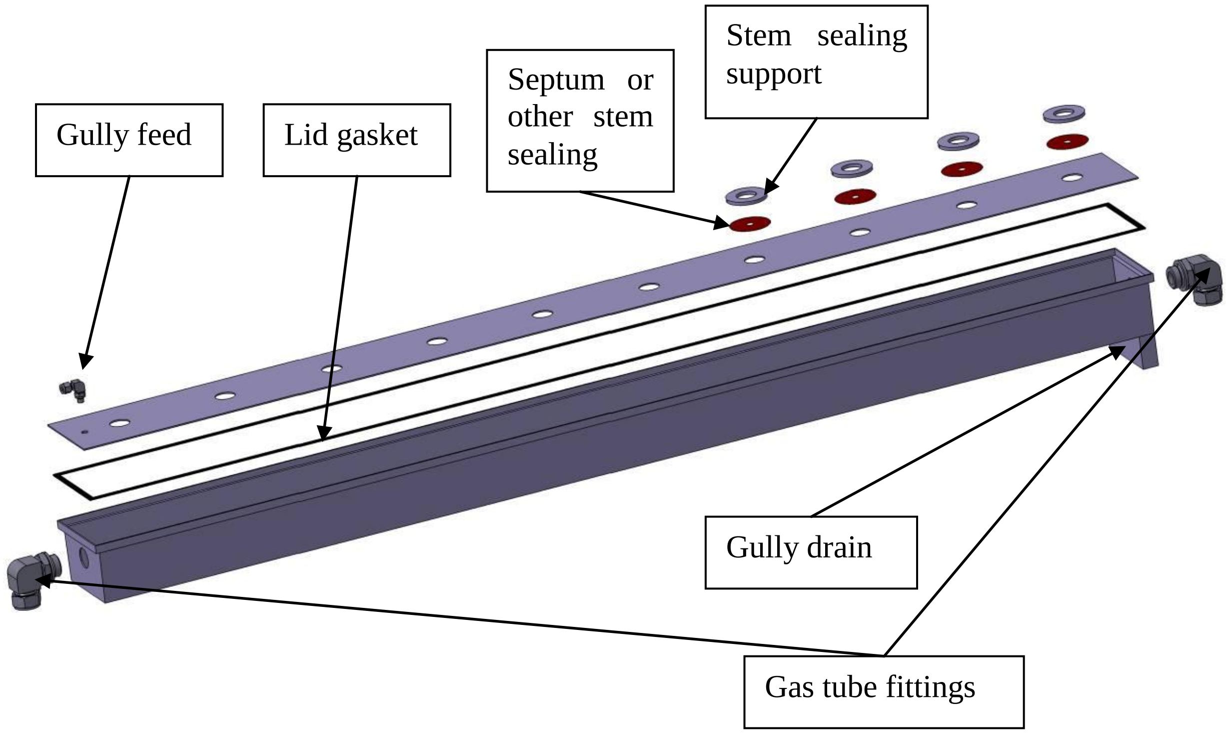



**Fig. 9** Sealed gully concept exploded view

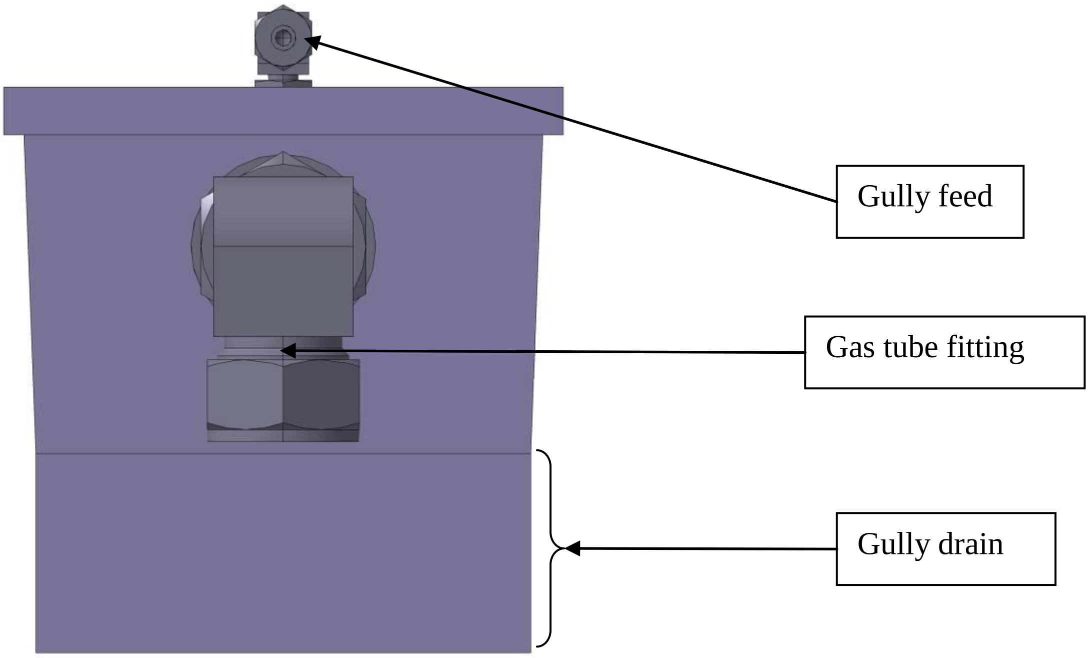



**Fig. 10** Sealed gully concept front view

This concept leaves all options open for future development:

- A fully sealed hydroponic system is possible by routing the two gas tubes connected at both ends of each gully out of the chamber. This might turn out to be difficult if pressure gradients are present between the chamber atmosphere and the hydroponic system. Furthermore, the water evaporated from the gullies is lost (but quantifiable) if not routed back to the main nutrient tank as it is the case for HVAC condensate. This has to be taken into account for the nutrient tank sizing or replenishment strategy. Furthermore, a humidification system may have to be added for the first weeks of a cultivation.
- Half open systems using the chamber air to flush the gullies can also be implemented. In that case, connection ports for gas retrieval and recirculation are needed in the chamber shell. The advantage of such a half open system is that the above mentioned humidity problems at the beginning of a cultivation (small plants) are avoided. A half open system allows the establishment of mass balances of all transfers between root and shoot zone and thereby a detailed quantification of source and sinks in both compartments. The mass transfer between both compartments is however not completely eliminated.

### *3.1.3 Gully temperature*

For the setup of CFD simulation boundary conditions, it is important to estimate the gully surface temperature.
As the gullies will be shaded by plants during the largest part of a cultivation, IR radiation does not play an important role in the thermal balance of the gullies. The major factors are the (warmer) surrounding air flow and the (colder) internal liquid flow. In most experimental setups the nutrient solution temperature is set a few degrees below the air temperature. In the simulated scenarios the air temperature provided by the HVAC system is set to 21°C.
Preliminary simulations (without a defined gully surface temperature) showed that at gully level this temperature is evenly achieved as the flow pattern is bottom up and the largest fraction of the heat is introduced to the chamber in the volume occupied by plants above the gullies (IR from lamps and convection from the warmer lamp loft glass). Thus the air passing the gullies has the setpoint temperature provided by the HVAC system.
Taking into account the constant (cooler) liquid flow, the gully surface temperature can be estimated to be 19°C. This value will be used together with the material properties of stainless steel 316 in CFD simulations discussed in WP 8400.

### *3.1.4 Nutrient solution delivery*

According to previous projects (MPP), calibration of each feed line to obtain an even distribution of nutrient solution to all gullies is important as the pressure drop along the main feed tube leads to unequal flow rates at the gully feeds. Active flow distribution control (i.e. flow sensors and flow control valves for each gully) are complex, clog easily and are cost intensive. The total flow rate will be controlled at subunit level. Meaning that one flow sensor at the main feed line is used to control the pump via a variable frequency drive (VFD). At gully level only equal flow is needed, active control between each gully is not necessary. The design of the nutrient solution delivery system will be based on the following concept:
One pump provides (flow controlled) nutrient solution for all gullies through a main feed pipe. A possible distribution system utilizes elbowed fittings that distribute the solution to each gully (see Fig. 11). By rotating (manually) the elbows at the main delivery pipe the level (see Fig. 12) the hydrostatic pressure at the feed exit is changed and thus the flow can be adapted. The system will require a manual calibration before an experiment measuring the flow rate in each gully and adapting the elbow angle.

**Fig. 11** Concept of the nutrient solution distribution system as used at UGuelph

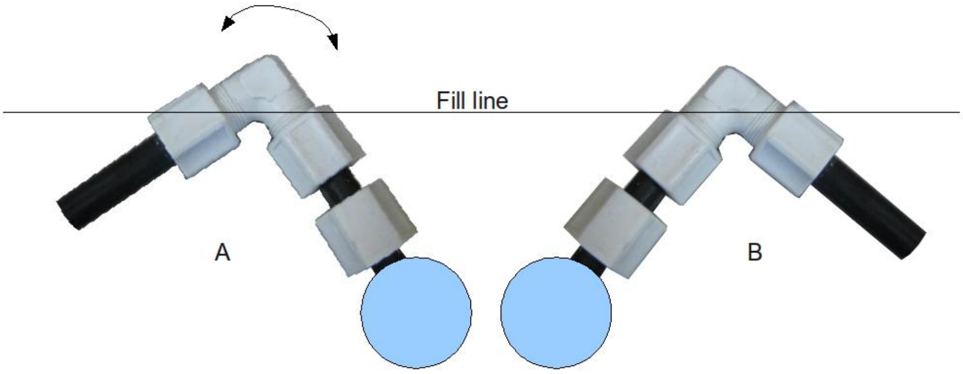



**Fig. 12** Rotating elbows to adapt the flow rate of each feed port

### *3.1.5 Nutrient solution recovery*

The design of the drainage system is not yet defined. A clogging-resistant system has to be designed. To keep sufficient design flexibility, five volume envelopes with the width of one gully are kept free over the whole height of the air distribution compartment (See Fig. 5). For example drainage ducts of up to 14 x 5 $cm^2$ can be used underneath each gully to collect the nutrient solution. In the equipment compartment these ducts can be combined in one lateral gutter. The system will be compliant with sealing requirements to allow future research and implementation of a sealed gully system.

### *3.1.6 Pumps*

One main irrigation pump with a bypass loop for tank mixing and sensors will be used. The pump will have an electronic control (Variable Frequency Drive, VFD) which will be controlled via a flow sensor in the main nutrient solution delivery line and user defined flowrate setpoints.

## 3.2 Illumination subsystem

### *3.2.1 Lamps*

6 HPS/MH mounts will be available in each PCU subunit. The system will be capable of using MH or HPS bulbs at each lamp position. As the lamp loft is separate from the remaining PCU system, adaptation to other systems (e.g. LEDs or radiofrequency lamps) will structurally be possible at later stages. Installed lamps and ballasts can easily be unmounted and a new system installed.

### *3.2.2 Ballasts*

The ballasts used will provide up to 1000 W for each lamp (6 x 1000W = 6000W in total). Each ballast is capable of using a MH or HPS lamp providing moderate flexibility in the spectral composition of the illumination system.

### *3.2.3 Cooling*

The lamp loft is separate from the main growing volume and aerated by fans to remove convective heat. IR radiation is mainly passing through the lamp loft glass and needs to be compensated by the HVAC system. The cooling air will be drawn from the surrounding atmosphere and will be returned back into the laboratory. The largest part of the convective lamp heat will be rejected by the warmer air exiting the loft. Due to the increased temperature of the loft air, some heat is also transferred to the loft glass which will warm up and in turn transmit some convective heat to the growing volume.
For the CFD simulation this effect has to be quantified by specifying the temperature present inside the lamp loft. Measurements in hardware with very similar properties (UGuelph hypobaric chambers with same surface area, loft airflow and lamp heat load) result in an average loft temperature of 35°C. This representative value will be used in the CFD analyses.

## 3.3 HVAC subsystem

The HVAC subsystem is comprised of the volume behind the growth compartment (green in Fig. 13) in which the heat exchangers (CW 12 & HC 12) and the blower are positioned. This is referred to as the HVAC compartment. It also comprises the air distribution compartment underneath the growing tray where the ducting and air distribution pipes are located. The volume envelope of the complete HVAC subsystem is outlined in red in Fig. 13. The ducting is not shown as it is subject of the design process.
The blower position is flexible within the volume envelope of the HVAC subsystem. The position in Fig. 13 is purely indicative. The centrifugal blower chosen has two inlets on both sides of the rotor and one outlet.
The air outlet of the chamber shall be positioned horizontally centered and as high as possible in the growth compartment to obtain a homogeneous flow.

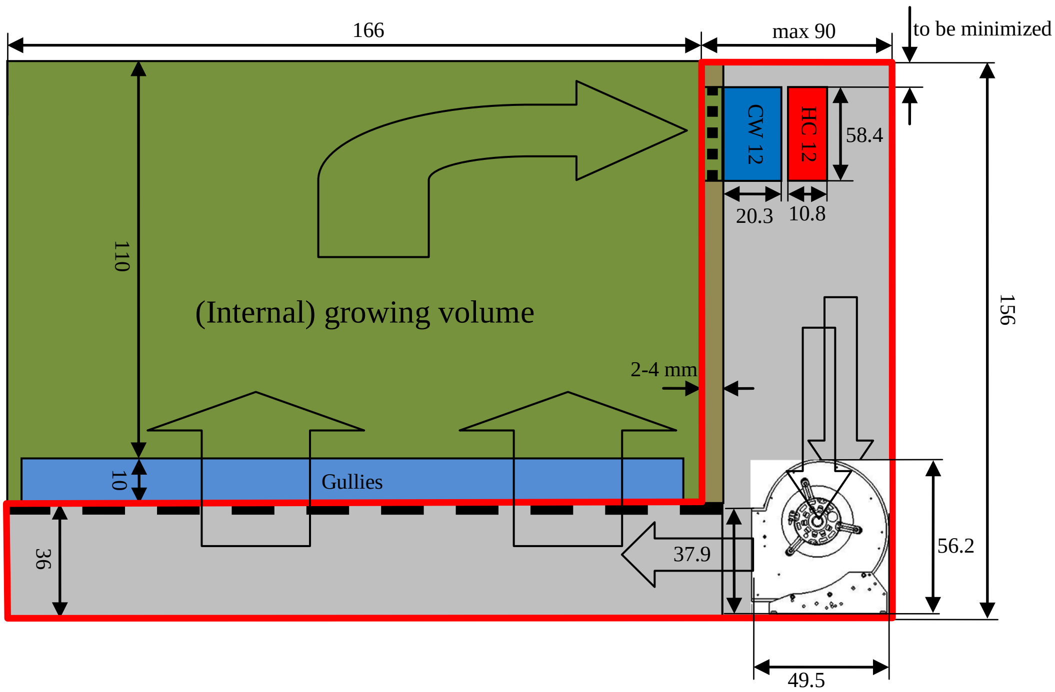



**Fig. 13** Schematic of the HVAC subsystem arrangement

### 3.3.1 *HVAC blower*

Two different approaches are used to estimate the required blower performance. All calculations are done with SI-units. The flow rates are then converted to imperial units as a Canadian manufacturer was chosen for the blowers and all specifications are based on imperial units.

First the blower flow rate is calculated for two extreme air velocity scenarios (maximum and minimum air velocity). Thereby the following assumptions are used:

- An equal flow through the whole growing surface with the required (maximum and minimum) air velocities is given. This means, that no objects are assumed to be present in the chamber (e.g. plants) which reduce the effective cross sectional area of the chamber.
- The air behaves like an ideal gas at constant pressure and temperature conditions (constant density).
- For the minimal flow rate the first setpoint above 0 m/s is used.
- For the maximal flow rate 0.4 m/s is used. The requirement is to stay below 1 m/s to avoid stress on plants. A value of 1 m/s would however require at least 10,000 L/min for a growing surface area of 1.66m$^2$ (not taking into account pressure losses). 0.4 m/s is estimated to be sufficient for cooling purposes (based on experience with similar chambers and based on the calculations in Tab. 4). Higher values would require unrealistically large blowers.

**Tab. 3** Required flow ranges calculated by air velocity

| | | |
|---|---|---|
| Growing surface area | 1.66 m$^2$ | |
| Minimal air velocity | 0.1 m/s | |
| Nominal air velocity | 0.2 m/s | |
| Maximal air velocity | 0.4 m/s | |
| **Minimal flow rate** | **9960 L/min** | **352 foot$^3$/min** |
| Nominal air velocity | 19920 L/min | 703 foot$^3$/min |
| **Maximal flow rate** | **39840 L/min** | **1407 foot$^3$/min** |

Taking into account a margin of 10% for pressure losses, the following values result:

**Minimal flowrate: 8964 L/min (317 foot$^3$/min)**
**Maximal flowrate: 43824 L/min (1548 foot$^3$/min)**

These flow rates have to be provided considering the pressure drop of the whole HVAC system (heat exchangers, air grilles etc.). In most experiments an air velocity around 0.3 m/s will be used. Running a blower at its maximum rating for prolonged periods will reduce life expectancy. However the highest velocities are not used continuously. Thus the blower is chosen to provide the maximal flow rate at full load.

A second approach has been chosen to complement the flow rate results of the above calculations:

Instead of specifying a certain air velocity, the flow rate needed to obtain a certain cooling effect is calculated based on a predefined temperature difference between the inlet and the outlet. For these calculations, latent heat of humidity is taken into account. For a worst case scenario with no evaporation, the total amount of water is kept constant to represent the lack of evaporation. Since the RH value changes with the temperature, the humidity ratio in kg water per kg air is used. The calculation sheets also allow calculating the flow rate requirements including the latent heat of evaporation by adapting the humidity ratios between in- and outlet . The calculations show that low temperatures combined with low humidity setpoints and small temperature gradients are not possible. A temperature setpoint of 15°C with a ΔT of 2°C combined with an initial RH setpoint of 12% would require a flow rate of at least 3300 $foot^3$/min. This would lead to too high air velocities. With the same temperature setpoint but a ΔT of 5°C, the required flow rate is just 1400 $foot^3$/min. The RH drops from 12% to 9 % due to the increase in temperature. In this scenario, a large temperature gradient is only present during the beginning of the experiment. Once the plants have grown, evaporation will increase and thereby the temperature gradient in the chamber will drop. The calculations in Tab. 4 represent a typical cultivation at 20°C with an allowed ΔT of 4°C inside the chamber. A plant evaporative load of 10 L per day (16 hours light) is taken into account (rise of humidity ratio from 0.0074 to 0.0076 kg/kg).

**Tab. 4** Required flow rates calculated by temperature difference

| | | | |
|---|---|---|---|
| General | heat load | 4000 | W |
| | atmospheric pressure | 1000 | mbar |
| | specific heat capacity of dry air | 1.006 | kJ/kg K |
| | specific heat capacity of water vapor | 1.864 | kJ/kg K |
| | evaporation heat of water | 2270 | kJ/kg |
| Chamber inlet HVAC outlet | T at inlet | 20 | C |
| | RH of air at inlet | 50 | % |
| | vapor partial pressure at inlet | 11.74 | mbar |
| | saturation vapor partial pressure at inlet | 23.49 | mbar |
| | humidity ratio at inlet | **0.0074** | **kg/kg** |
| | specific enthalpy of air at inlet | 37.17 | kJ/kg |
| | density of air at inlet | 1.18 | kg/m3 |
| Chamber outlet HVAC inlet | T at outlet | 24 | C |
| | RH of air at outlet | 40 | % |
| | vapor partial pressure at outlet | 12.04 | mbar |
| | saturation vapor partial pressure at outlet | 30.09 | mbar |
| | humidity ratio at outlet | **0.0076** | **kg/kg** |
| | specific enthalpy of air at outlet | 41.69 | kJ/kg |
| | density of air at outlet | 1.17 | kg/m3 |
| | **flow rate to be provided by blower** | **0.89** | **kg/s** |
| | | **0.75** | **m3/s** |
| | | **1587** | **foot$^3$/min** |
| | | **44926.8** | **L/min** |

The calculation presented in Tab. 3 shows that a maximal flowrate capacity of~ 1600 foot$^3$/min is needed to reach an average air velocity of 0.4 m/s. As shown in Tab. 4 the same flow rate will provide a temperature gradient of maximally 4°C including a plant evaporative load of 10 L/day.

**The selected blower shall therefore deliver at least 1600 foot$^3$/min.**

The preliminary selected hardware providing up to 1700 foot$^3$/min is given in the appendix, chapter 5.1.2 (*Delhi Industries G12-9DD*). The geometry and performance curves of this blower will be used for further CFD simulations.
These thermodynamic calculations represent a simplified view on the system and can only give an estimation of inlet and outlet temperatures. The actual temperature distribution inside the chamber and the exact temperature gradient locations will have to be determined either by CFD simulation or by mapping of the real chamber hardware.

### 3.3.2 *HVAC cooler*

The cooler has to provide two functions:

- Counterbalancing the heat of the lamps and the equipment dissipation by keeping the temperature setpoint according to the experimental protocol.
- Control of air water content. If a high VPD is requested by the experimental protocol, a chilling to lower temperature than the atmosphere temperature setpoint can be necessary. In this case the air needs to be reheated to the correct temperature after condensation on the cooler.

The heat load of the lamps is estimated based on the conversion factor from the total power consumption of the lamps to IR radiation. A worst case estimate of 50% is used. Tab. 5 shows a summary of different heat radiation factors. With a total power consumption of up to 6000 W, a constant heat load of 3000 W results. The lamping loft is separate from the chamber volume and is cooled independently. Thus only the IR radiation is entering the chamber volume. Convective heat is removed by the loft internal cooling system.

**Tab. 5** Heat radiation factors for different lamp types as specified in Ref 4

| Lamp Type | PAR 400-700 nm [%] | Invisible radiation [%] | Conduction/ Convection [%] | Ballast loss [%] |
|---|---|---|---|---|
| Incandescent | 7 | 83 | 10 | N/A |
| Cool white fluorescent | 20 | 37 | 39 | 4 |
| HPS | 25 | 47 | 13 | 13 |
| MH | 22 | 52 | 13 | 13 |
| LPS | 27 | 25 | 26 | 22 |

The heat dissipation of other pieces of equipment is estimated to 150 W. The heat to be rejected for condensation of the water transpired by the plants is calculated in Tab. 6. For this calculation the maximum water consumption of the UGuelph durum wheat bench tests are used. In these bench tests durum wheat had the highest water consumption of all crops. The calculations in Tab. 4 use a lower evaporation rate of 10 L/day as here the aim is to show the performance results under average conditions.

**Tab. 6** Cooling capacity required for condensation

| | |
|---|---|
| Enthalpy of vaporization (@25°C) | 44 kJ/mol |
| Maximal evaporation rate of plants | 20 L/16h |
| Molar mass of water | 18 g/mol |
| **Maximal cooling capacity required** | **849 W** |

**Tab. 7** Total cooling capacity required

| | |
|---|---|
| Condensation | 850 W |
| Secondary equipment | 150 W |
| Heat radiation | 3000 W |
| **Total cooling capacity** | **4000 W** |

In these calculations the response time requirements defined in Ref 2 of the chamber have not been considered. The cooler design must also take into account that the condensed water needs to be quantified. The cooler shall be the only location within the chamber where condensation takes place (except the compensation bag, where chamber humidity might condense if external temperatures drop below the dew point).
Furthermore sensor locations must be provided to position temperature sensors in the heating and cooling water inlet and outlet streams of the heat exchangers.

**The cold heat exchanger chosen for the PCU shall have a total cooling capacity of at least 4000W in combination with the selected associated equipments (blower and cold water supply).**

To be able to conduct CFD simulations, the *Delhi Industries CW-12* heat exchanger is preliminarily chosen. The manufacturer specification sheet is given in the appendix (5.1.1). The geometry and specifications will be used to define the CFD model.
This cooler has an integrated condensate recovery system. A system for condensate quantification has to be added.

Applicable requirements:

| | |
|---|---|
| SYS-PERF-CON-1: | Condensation shall only take place in dedicated A/C equipment. <br>Rank 1 |
| SYS-FUNC-PM-2: | The amount of water condensed from the atmosphere shall be logged with its volume and time point (e.g. tipping bucket). The overall measurement precision shall be at least 5% from the total mass flow. <br>Rank 1 |

### *3.3.3 HVAC heater*

The heater has to provide sufficient heat to raise the air temperature after cooling and dehumidification on the cold heat exchanger. To provide air with 35°C and 50% RH (0.18 kg/kg humidity ratio), the air has to be cooled down to 23°C on the cold heat exchanger to provide sufficiently dry air (assuming that the air exiting the cold heat exchanger is saturated with water (100% RH). To heat up the humid air to the correct temperature (35°C), 12 kW is needed for a maximum air flow rate (~1600 foot$^3$/min) as calculated in chapter 3.3.1.

**The hot heat exchanger chosen for the PCU shall have a total heating capacity of at least 12 kW (41 MBH) for an air flow rate of 1600 foot$^3$/min and a heating water temperature of 60°C (140 F).**

To be able to conduct CFD simulations, the *Delhi Industries HC-12* heat exchanger is preliminarily chosen. The manufacturer specification sheet is given in the appendix (5.1.1).

This heater interfaces with the cooler as it is from the same manufacturer and the same model range. With a 1600 foot$^3$/min air flow rate at an inlet temperature of 21°C and a water flow rate of 22.7 L/min (6 US gpm) at 60°C, the heater provides a heating capacity of 18 kW (62 MBH). The reference air temperature value given in the manufacturer sheet (21°C) is lower than the 23°C calculated above (which in principle leads to a higher heat transfer) but the resulting heating capacity has more than adequate margin for the PCU requirements (18 kW compared to the required 12 kW). At low air flow rates (700 foot$^3$/min = lower total heat transfer, worst case scenario) and otherwise same parameters the heat exchanger will still provide a heating capacity of 11.5 kW (39.5 MBH) which is deemed sufficient for the PCU design.

### *3.3.4 $CO_2$ control*

$CO_2$ levels will be controlled by measurement of the chamber internal level and addition of pure $CO_2$. $CO_2$ control will only be possible by addition. $CO_2$ removal is only achieved through photosynthesis or system venting. No active $CO_2$ stripping technology is envisaged to compensate for the $CO_2$ production during dark periods.

### *3.3.5 Oxygen and ethylene removal*

$O_2$ and Ethylene removal is an important consideration for further development. Currently no applicable technology is in view. Therefore this subject is discussed in TN 98.8.3, the analysis of critical subsystems.

## 3.4 Chamber shell subsystem

The internal parts of the shell are made of stainless steel 316. The chamber is clad with insulation to minimize the influence of external temperature variations. Further information on the overall chamber structure is available in chapter 2.1.

## 3.5 Control subsystem

The PCU is composed of 3 subunits with each 5/3 $m^2$ of growing surface area. As each subunit is to be controlled individually and the requirements are the same for each subunit, only one subunit is considered in this document for the elaboration of the specifications. The CS will however be capable of controlling at least 3 subunits.

In the following the PCU system is divided into these subsystems:

- Chamber access subsystem
- Illumination (lighting control) subsystem
- Atmospheric (air control) subsystem
- Hydroponic subsystem

The atmospheric subsystem includes control of temperature and humidity inside the chamber and quality of the air ($O_2$/$CO_2$/ethylene).
Only the requirements, part of the TN 98.7 in relation with control specifications are taken into account in this document.
For the air subsystem, and from the identified disturbances and specifications, a specification for a dynamical and physical model is given.

### *3.5.1 Chamber Access*

#### *3.5.1.1 Requirements*

SYS-OPER-OP-1: The PCU shall have one access door to the main chamber volume.

SYS-PERF-RESP-2: The chamber shall be capable of stabilizing the chamber internal environmental parameters to its previous values within 30 minutes after (short <30 min) user interventions.

#### *3.5.1.2 Analysis*

There is no equipment to ensure the tightness of the door when closed.
There is no alarm for the “Open Door” state.

#### *3.5.1.3 Control specifications*

There is no associated control for the chamber access. The door will be secured by several latches. Accidental opening is not possible.

#### *3.5.1.4 Other involved Control loop*

An opened door induces disturbances to the atmospheric control of the chamber due to mixing with exterior air:

- ➔ Disturbance for the temperature and RH control
- ➔ Disturbance for the $O_2$/$CO_2$ control of the chamber

The opening of the chamber will be considered as a non-measured **disturbance**, whose parameters have to be determined for the testing of the control model of the temperature and humidity of the chamber.

Remark: the room temperature is not considered as a disturbance for the atmospheric control, when the door is closed, as its variation is considered as very slow and is compensated by the T/RH control with the cool and heat exchanger.
There will be no automatic change of the HVAC system operation mode when the door is opened as there is no sensor to determine the door opening state. When the door is opened the user should turn of the $CO_2$ control first. Keeping the T/RH control on is recommended when the lights are on even with an opened door. The procedure to open the door will be documented in the user manual.

#### *3.5.1.5 Requirement/Specification matrix*

| Requirement | Technological or controller solution | Associated specifications for simulation and validation |
|---|---|---|
| **SYS-OPER-OP-1**<br>The PCU shall have one access door to the main chamber volume | One door is designed | |
| **SYS-OPER-OP-2**<br>The chamber shall be capable of stabilizing the chamber internal environmental parameters to its previous values within 30 minutes after (short <30 min) user interventions | | Opening of the chamber will be considered as a **disturbance** for the atmospheric control (T/RH/CO2/O2). |

### *3.5.2 Illumination subsystem*

#### *3.5.2.1 Requirements*

SYS-FUNC-GRO-8: The PCU shall be capable of keeping all illumination parameters constant (intensity and spectrum) within the boundaries and the homogeneity defined in chapters 4.2 (of Ref 2).

SYS-OPER-MOD-3: The PCU illumination shall be automatically switched off (or dimmed if possible with illumination system) if temperature inside the chamber at plant level exceeds the setpoint temperature by 10 degrees.

#### *3.5.2.2 Associated equipments*

Specific Equipments of the control loop:

The lighting system is situated in a separate "lamp loft":
LAMP-BLST-01 to LAMP-BLST-06: 6 Lamps. 2 lamps operated by one relay
LAMP-Tloft-01: Temperature in the loft
LAMP-FAN-01: 3 fans for cooling the lamps
LAMP-AIRFLW-01: 1 air flow sensor

In the chamber:
LAMP-PAR-01: 1 PAR sensor

Associated equipments:

HVAC-T-01 and 02: 2 temperature measurements (at this stage of the design) in the main PCU air volume

#### *3.5.2.3 Control specifications*

Two control loops must be considered linked to the illumination: One for the control of the lighting inside the growing chamber to fulfil the requirements and the other one in the lamp loft to maintain the temperature under a safety limit.

##### *3.5.2.3.1 Light intensity control*

**Function**

Lighting is operated with 3 relays, each of them switching on/off the dedicated lamps.

**Control Strategy**

Programmable day/night cycle, linked to the growing requirement of the crop will switch on/off the lights (1, 2 or 3 2-lamp arrays).
3 modes are considered:

- OFF : all lights are off
- AUTOMATIC mode :
  - The operator can define the starting and stopping hour for the illumination
  - The operator can choose the array configuration (3 arrays, each of 2 lamps)
- MANU : the operator defines the array(s) to be lighted instantaneously

For safety reasons, the automatic mode can only be set if:

- The blower (HVAC-BLWR-01) is started
- No very high alarm temperature in the growing chamber

**Alarms**
Depending on the selected lamp configuration:
- If PAR measurement is lower or greater than a defined range, an alarm is set to warn personnel.

**Remark**
The illumination will induce disturbance to the control of temperature in the growing chamber as it is a (potentially variable) source of heat and is therefore considered as a control disturbance.

#### *3.5.2.3.2 Lighting loft temperature control*

**Function**
In order to remove the heat produced by the light, and to prevent any temperature increase in the chamber, the lamp loft is equipped with 3 fans, one flow switch and one temperature probe. During the day cycle, if the loft temperature reaches a user defined high value (42°C for instance), the first alarm is set to alert the operator. If the temperature continues to increase until a (user defined) very high temperature (45°C for instance), a second alarm is triggered, then immediately after, the lights are switched OFF and the fans are maintained until a (user defined) lower threshold is reached (43 °C for instance) to remove heat outside the loft.

**Control Strategy**
The control loop can be managed by three modes:
- OFF: All equipments are OFF
- AUTO: All equipments are ON if only one array is ON
- MANUAL: The operator decides to switch equipment ON or OFF

**Alarms**
Temperature:
- In case of high value, an alarm is set.
- In case of very high value, an alarm is set and the lights are stopped. Lamp fans are maintained to ensure the heat load evacuation from the loft.

Flow sensor:
- If the fans are on and the flow sensor is not switched, an alarm is set.

It is not necessary to stop the lights, as the temperature alarm will do it if necessary.

### 3.5.2.4 *Requirement/specification matrix*

| Requirement | Technological or controller solution | Associated specifications for simulation and validation |
|---|---|---|
| **SYS-FUNC-GRO-8** The PCU shall be capable of keeping all illumination parameters constant (intensity and spectrum) within the boundaries and the homogeneity defined in chapter 4.2 | Design of the illumination | Validation by the design of the lights |
| **SYS-OPER-MOD-3** The PCU illumination shall be automatically switched off (or dimmed if possible with illumination system) if temperature inside the chamber at plant level exceeds the setpoint temperature by 10 degrees. | This requirement is fulfilled by the control strategy | |

Note: If necessary the final design of the CS will also be adapted to turn off the lights when the nutrient solution flow rate is below a certain setpoint to protect the plants from drying out.

### ***3.5.3 Atmospheric subsystem***

#### *3.5.3.1 Requirements*

**Pressure**

SUB-CATM-PRS-1: The static pressure inside the plant growth chamber main growing volume shall be equal to ±2 kPa to the lab atmospheric pressure at all times.

SUB-CATM-PRS-4: Pressure relief valves shall secure the system from over and under pressure in case of anomalous behavior. The pressure relief valves shall be set to maximum 2 kPa over/under pressure.

**Atmosphere Temperature**

SUB-CATM-TMP-1: The chamber atmosphere temperature shall be settable between 15°C and 35°C with 1°C increments for light and dark phases.

SUB-CATM-TMP-2: Up to 30 min after a switch from dark to light phases and vice versa, the temperature stability shall be ±5°C until a stable state is reached.

SUB-CATM-TMP-3: The temperature stability after the transition phases from dark to light and vice versa shall be ±0.5°C.

**Atmosphere Relative Humidity (or VPD)**

SUB-CATM-RH-1: The chamber atmosphere VPD shall be settable between 0.2 and 1.5 kPa with 0.1 kPa increments during dark and light phases.

SUB-CATM-RH-2: The RH stability shall be ±5% during continuous working.

SUB-CATM-RH-3: During the first 30 minutes after the switching from light to dark phases (and vice versa) the RH stability shall be ±20%.

**Atmosphere Composition**

The requirements about $O_2$ and ethylene control were all rated 2 respectively 3 in Ref 2 which means that they might not be implemented in the initial PCU design. Currently no applicable technologies for $O_2$ and ethylene removal are available. Thus the PCU hardware as well as the CS must be capable to be upgraded to include these functionalities once the technology becomes available.

**$CO_2$**

SUB-CATM-CMP-1: The PCU shall be capable of controlling the $CO_2$ level in the chamber by addition of pure $CO_2$.

**$O_2$**

SUB-CATM-CMP-3: The PCU shall be capable of keeping $O_2$ level in the chamber permanently below 25%.

**Ethylene**

SUB-CATM-CMP-5: The PCU shall be capable of keeping ethylene level in the chamber permanently under user defined limits. The limits shall be settable between 10 ppb and 10 ppm with increments of 1 ppb.

**Air flow**

SUB-CATM-FLO-1: The blower of the HVAC system shall be capable of providing sufficient air velocity (respectively recirculation) to counterbalance the lamps heat load and to provide sufficient mass exchange in the foliage.

SUB-CATM-FLO-2: The average air velocity in the growth compartment shall be below 1 m/s to avoid stress effects on plants.

SUB-CATM-FLO-3: The flow pattern shall be bottom up.

SUB-CATM-FLO-4: The design of the air flow shall avoid any dead zones in the whole chamber atmosphere (homogeneous gas distribution and proper mixing).

**Atmosphere homogeneity**

SUB-CATM-HOM-1: The temperature in the volume occupied by the plants shall be homogeneous to ±2°C.

SUB-CATM-HOM-2: The RH in the volume occupied by the plants shall be homogeneous to ±5%.

SUB-CATM-HOM-3: The flow speed in the volume occupied by the plants shall be homogeneous in its magnitude to ±0.1m/s.

SUB-CATM-DYN-1: The temperature control shall be capable of running user defined scenarios of temperature changes within the temperature ranges defined in SUB-CATM-TMP-1 with maximal temperature changes of 0.1°C/min by keeping all other environmental variables constant.

SUB-CATM-DYN-2: The RH control shall be capable of running user defined scenarios of RH changes within the RH ranges defined in SUB-CATM-RH-1 with maximal RH changes of 0.1%/min by keeping all other environmental variables constant.

#### *3.5.3.2 Associated equipment*

The following control loops are distinguished for the equipment allocation:

Pressure

- One pressure sensor HVAC-kPa-01
- Pressure relief valve HVAC-PRV-01
- Pressure compensation bag HVAC-PBAG-01

T/RH

- 2 temperature and RH sensors (exact number to be validated)
- Temperature sensors for:
    - cold inlet coil, cold outlet coil, cold inlet, cold outlet, cold utility temp
    - hot inlet coil, hot outlet coil, hot inlet, hot outlet, hot utility temp
- 2 valves and 2 pumps (hot and cold)

Flow sensor

- 1 flow sensor for the hot water supply to the heat exchanger
- 1 flow sensor for the chilled water supply to the heat exchanger

Note: Flow sensors on the heating and cooling fluid lines are not absolutely necessary. Low flow rates are indirectly seen when T and RH setpoints cannot be maintained. These sensors are only used to increase the safety level of the system and to warn the operator.

Condensate

- Connected tipping bucket

Air Blower

- Centrifugal blower
- Air flow sensor

$CO_2$/$O_2$

- $CO_2$/$O_2$ analyser
- Mass flow controller for $CO_2$ injection and associated valve

#### *3.5.3.3 Control specifications*

##### *3.5.3.3.1 Pressure*

Pressure is passively controlled with a pressure compensation bag (HVAC-PBAG-01).
In case of high pressure, a passive safety relief valve is activated.

**Alarms**
If the pressure is beyond a user specified high or a low limit, an alarm is displayed

##### *3.5.3.3.2 Temperature and RH control*

**Function**
The aim is the control of the temperature and humidity in the chamber to fulfil the requirements.

The heat exchanger system is divided in two different parts.

- The cold exchanger
- The hot exchanger

Each part has a proportional valve (HVAC-3VLV-01, HVAC-3VLV-02), a gear pump (HVAC-PUMPhot-01, HVAC-PUMPcold-02), utility input temperature probe (HVAC-Tloop-01, HVAC-Tloop-02), input exchanger temperature probe (HVAC-Tin-01, HVAC-Tin-02), output exchanger temperature probe (HVAC-Tout-01, HVAC-Tout-02) and two exchanger output air temperature probes (HVAC-Tcoil-01 - HVAC-Tcoil-04).

Furthermore there are two T/RH probes to directly measure the chamber conditions (HVAC-TRH-01, HVAC-TRH-02). As the temperature and RH had to fulfil the specified requirements in the growing volume, the positioning and number of probes will be tested and validated through dedicated simulation of the HVAC system: reduced dynamic model.
The controllability will be demonstrated with the reduced model and associated controllers.

**Control Strategy**

Wherever the position of the sensors and the way to average them, a temperature (called $T_{chamber}$) and a relative humidity (called $RH_{chamber}$) have to be controlled with the following strategy.

Three modes are available:

- OFF: the pumps and valves of both heat exchanger are OFF (pump stopped and valve closed)
- AUTOMATIC: the operator defines a setpoint for:
  - -day humidity
  - -night humidity
  - -day temperature
  - -night temperature

  The operator can start the automatic mode if the blower HVAC-BLWR-01 is ON. In case of blower failure, the automatic mode will be triggered in OFF mode.

  The automatic mode also triggers the nutrient and condensate level control loop in automatic mode.
- MANUAL: the operator decides to start or stop the pump and decides the % of opening of both heat exchanger valves.

Temperature and humidity are controlled by the 2 valves of utilities (hot and cold).

Blower speed will be controlled via an air flow sensor in the air distribution compartment. The flow rate will be user definable

Identified disturbances for the control:

- Air blower speed variation during a crop test
- Evapotranspiration (water loss) of the crop (addition of water)
- Lights switched on and off for the day cycle
- Opening of the door

These disturbances will be tested for the validation of the closed loop model in TN 98.8.4.

**Alarms**

In case of low, high, very low, very high value in the chamber for temperature and /or humidity, an alarm is displayed to the user.
In case of temperature very high (to be adjusted depending on the crop), the lights are stopped.

#### *3.5.3.3.3 Condensate*

There is no associated control strategy as the condensate is evacuated to the nutrient tank through a tipping bucket.
Knowing the capacity of the tipping bucket, the condensate volume of water will be measured by logging of the signals.

#### *3.5.3.3.4 Air blower*

**Function**

The blower provides the air circulation inside the chamber. This function is coupled with temperature and humidity control to provide air flow through the cold and hot exchanger. An air flow sensor provides the monitoring of the blower.

**Control Strategy**

Three modes are available.

- OFF: Blower is Stopped
- AUTOMATIC: Blower is started
- MANUAL: the operator chooses to start or stop the blower.

The blower speed is controlled via a flow controller in the air distribution compartment and a VFD for the blower motor.

**Alarms**

A flow measurement is installed to ensure air velocity in the chamber.

In case of blower ON and a flow measurement lower than a threshold, it is considered that the blower is not ensuring the necessary flow for the chamber.

In consequence, the lighting, temperature and humidity controllers are stopped. Without circulating air, it is not possible to effectively control temperature or humidity. Lights will increase the temperature in the chamber without the possibility to mitigate the heat load.

*3.5.3.3.5 $CO_2/O_2$*

**Function**

For a better plant growth, the closed atmosphere of the chamber is maintained at a specified concentration of $CO_2$. The chamber is equipped with a $CO_2/O_2$ analyser, a mass flow controller and a valve, in order to control the $CO_2$ concentration.

Instrumentation to remove $O_2$ from the chamber is not foreseen at this stage in the design but will be added later when technology becomes available. The CS will keep upgrade capabilities open.

**Control Strategy**

Three modes are available:

- OFF: the valve is closed and the setpoint sent to the controller is set to 0.
- AUTOMATIC: $CO_2$ is added to maintain the measurement to the setpoint.
- MANUAL: the operator enters a flow setpoint in the flow controller.

The quantity of $CO_2$ added to the chamber is calculated by integrating the flow rate over time (in manual and automatic mode). In automatic mode the $CO_2$ flow rate will be adjusted by the controller and the added amount automatically calculated by integrating the (variable) flow rate over time. In manual mode the added amount is simply calculated by integrating the constant flow rate over time.

Disturbances:

- Opening of the door: the chamber is in contact with the atmospheric air at ambient $CO_2$ concentrations.
- $CO_2$ production by the plants during the night and consumption during the day (nominal mode)

**Alarms**

$CO_2$ high level and very high level, compared to the setpoint, during the day are displayed
$CO_2$ low level and very low level, compared to the set point are displayed. Alarm action will be user notification only. There is no method of $CO_2$ removal for high alarms and a low alarm indicates analyzer malfunction or a lack of bottled $CO_2$. Both states require user intervention to verify the cause of the alarm.
Absolute high and very high level of $O_2$ are displayed as alarms for the user

*3.5.3.3.6 Ethylene*

No associated equipment to remove ethylene will be included in the first design but will be added once appropriate technology becomes available. Ethylene removal strategies will be assessed in detail in WP 8300.
No associated control loop is present at the moment but will be added when required.

### *3.5.3.4 Requirement/specification matrix*

| Requirement | Technological or Controller solution | Associated specifications for simulation and validation |
|---|---|---|
| **SUB-CATM-PRS-1** The static pressure inside the plant growth chamber main growing volume shall be equal to ±2 kPa to the lab atmospheric pressure at all times. | Pressure compensation with HVAC-PBAG-01 | |
| **SUB-CATM-PRS-4** Pressure relief valves shall secure the system from over and under pressure in case of anomalous behaviour. The pressure relief valves shall be set to maximum 2 kPa over/under pressure. | Relief valve HVAC-PRV-01 | |
| **SUB-CATM-TMP-1** The chamber atmosphere temperature shall be settable between 15°C and 35°C with 1°C increments for light and dark phases. | | Control test for the reduced physical model |
| **SUB-CATM-TMP-2** Up to 30 min after a switch from dark to light phases and vice versa, the temperature stability shall be ±5°C until a stable state is reached | | Control test for the reduced physical model |

| Requirement | Technological or Controller solution | Associated specifications for simulation and validation |
|---|---|---|
| **SUB-CATM-TMP-3** The temperature stability after the transition phases from dark to light and vice versa shall be ±0.5°C | | Control test for the reduced physical model |
| **SUB-CATM-RH-1** The chamber atmosphere VPD shall be settable between 0.2 and 1.5 kPa with 0.1 kPa increments during dark and light phases | | Control test for the reduced physical model (for RH) |
| **SUB-CATM-RH-2** The RH stability shall be ±5% during continuous working | | Control test for the reduced physical model |
| **SUB-CATM-RH-3** During the first 30 minutes after the switching from light to dark phases (and vice versa) the RH stability shall be ±20%. | | Control test for the reduced physical model |
| **SUB-CATM-CMP-1** The PCU shall be capable of controlling the $CO_2$ level in the chamber by addition of pure $CO_2$ | CO2 supply with mass flow controller.<br>Remark : CO2 can be controlled only by addition during the day | |
| **SUB-CATM-CMP-3** The PCU shall be capable of keeping O2 level in the chamber permanently below 25% | No associated equipment to ensure the function | |

| Requirement | Technological or Controller solution | Associated specifications for simulation and validation |
|---|---|---|
| **SUB-CATM-CMP-5** The PCU shall be capable of keeping ethylene level in the chamber permanently under user defined limits. The limits shall be settable between 10 ppb and 10 ppm with increments of 1 ppb | No associated equipment to ensure the function | |
| **SUB-CATM-FLO-1** The blower of the HVAC system shall be capable of providing sufficient air velocity (respectively recirculation) to counterbalance the lamps heat load and to provide sufficient mass exchange in the foliage | HVAC design to fulfil the requirement | Light heat load considered as a disturbance for the T/RH controller |
| **SUB-CATM-FLO-2** The average air velocity in the growth compartment shall be below 1 m/s to avoid stress effects on plants | | CFD simulations |
| **SUB-CATM-FLO-3** The flow pattern shall be bottom up | Designed for this requirement | |
| **SUB-CATM-FLO-4** The design of the air flow shall avoid any dead zones in the whole chamber atmosphere (homogeneous gas distribution and proper mixing) | | CFD simulations |

| Requirement | Technological or Controller solution | Associated specifications for simulation and validation |
|---|---|---|
| **SUB-CATM-HOM-1** The temperature in the volume occupied by the plants shall be homogeneous to ±2°C | | Reduced physical model with T/RH control. Will be simulated in reduced volume (6 zones) |
| **SUB-CATM-HOM-2** The RH in the volume occupied by the plants shall be homogeneous to ±5% | | Reduced physical model with T/RH control. Will be simulated in TN 98.8.4 |
| **SUB-CATM-HOM-3** The flow speed in the volume occupied by the plants shall be homogeneous in its magnitude to ±0.1m/s | | CFD simulations |
| **SUB-CATM-DYN-1** The temperature control shall be capable of running user defined scenarios of temperature changes within the temperature ranges defined in SUB-CATM-TMP-1 with maximal temperature changes of 0.1°C/min by keeping all other environmental variables constant | | To be tested in the reduced model with T/RH controller. |
| **SUB-CATM-DYN-2** The RH control shall be capable of running user defined scenarios of RH changes within the RH ranges defined in SUB-CATM-VPD-1 with maximal RH changes of 0.1%/min by keeping all other environmental variables constant | | To be tested in the reduced model with T/RH controller. |

### 3.5.4 Hydroponic subsystem

#### 3.5.4.1 Requirements

**Irrigations System**

SUB-HYDR-NUT-1: The volumetric flow of the nutrient delivery shall be adjustable between 0 and 10 l/min for the whole system (5 gullies).

SUB-HYDR-LIQ-3: The volume of the stock solutions inside the tanks shall be monitored.

SUB-HYDR-LIQ-5: The liquid level in the nutrient solution tank shall be monitored.

**pH and EC**

SUB-HYDR-LIQ-8: The nutrient solution composition (pH, EC) shall be controlled automatically by addition of stock solutions.

SUB-HYDR-LIQ-9: The pH setpoint shall be definable from 4 to 8 with increments of 0.1.

SUB-HYDR-LIQ-10: The accuracy of pH control shall be at least ±0.5.

SUB-HYDR-LIQ-11: The EC setpoint shall be definable from 0 to 3000µS/cm with increments of 1µS/cm.

SUB-HYDR-LIQ-12: The accuracy of EC control shall be at least ±100µS/cm.

SUB-HYDR-LIQ-13: The nutrient solution temperature shall be settable from 15 to 30°C with increments of 0.1°C and an accuracy of at least ±1.0°C.

#### 3.5.4.2 Associated equipments

The following control loops are distinguished for the equipment allocation.

Irrigation system
- Irrigation pump (HYDRO-PUMP-01)
- Irrigation flow sensor (HYDRO-Tfeed-01)
- High level switch in the nutrient Tank (HYDRO-LVL-05)
- Low level switch in the nutrient Tank (HYDRO-LVL-06)

Nutrient temperature
- Temperature in the nutrient loop (HYDRO-Tloop-01)
- Temperature at the entrance of the gullies (HYDRO-Tfeed-01)
- Nutrient cooling valve (HYDRO-SVLV-05)

pH

- 2 pH sensors (HYDRO-pH-01 and HYDRO-pH-02) connected to CS via one transmitter (HYDRO-XMIT-01)
- Acid and base injection valves (HYDRO-SVLV-01, HYDRO-SVLV-02)
- Acid and base level switch (HYDRO-LVL-01 and HYDRO-LVL-02)

EC

- 2 EC sensors (HYDRO-EC-01 and HYDRO-EC-02) connected to CS via one transmitter (HYDRO-XMIT-02)
- Tank A and B injection valves (HYDRO-SVLV-03, HYDRO-SVLV-04)
- Tank A and B level switch (HYDRO-LVL-03 and HYDRO-LVL-04)

#### *3.5.4.3 Control specifications*

##### *3.5.4.3.1 Irrigation system*

**Function**

The plants are irrigated by a hydroponic system. The liquid is driven via a pump and valves to trays for feeding the plants. The stream returns directly to the nutrient tank by gravity. The nutrient tank is also alimented with the condensate. The irrigation pump circulates the liquid and a dedicated loop coming back to the nutrient tank is equipped with pH and EC sensors. The flow rate is controlled by a VFD on the irrigation pump and a flow controller in the main gully feed line. The flow setpoint is manually set. pH and EC stock solutions are introduced into the nutrient tank by the 4 injection valves when needed.
A liquid flow sensor monitors if the flow is sufficient at the entrance of the gully tray. There are 4 levels of flow alarm (high, very high, low and very low).

**Control Strategy**

The control loop can be managed by three modes:

- OFF: All nutrient delivery system equipment OFF
- AUTO: The pump is ON

  In order to protect the plants, the pump is turned OFF, if:
  - the pH value is very high or low
  - the EC value is very high
  - the low level switch of the nutrient tank is not triggered.
  - the flow rate is very high or very low.
- MANUAL: The operator decides to switch the pump ON or OFF

**Alarms**

In case of a low solution level in the nutrient tank, an alarm is set and the pump is stopped. In the case of high solution, an alarm is set to notify the user that intervention is required.
In case of very high or very low flow, an alarm is set and the pH/EC control is stopped (while the pump is kept active to keep the root zone watered).
In case of no flow (for a user defined duration) an alarm is set and the lights are turned off to avoid drying out of plants.

*3.5.4.3.2 Nutrient temperature*

**Function**

Temperature of the tank is controlled (cooling only) with a chilled water loop.

**Control Strategy**

The control loop can be managed by three modes:

- OFF: All equipments are OFF (the cooling valve)
- AUTO: The temperature is controlled with the cooling valve.
  The control mode can be set if the low level switch is not activated.
- MANUAL : the cooling valve can be opened/closed by the operator

**Alarms**

In case of very high temperature, an alarm is set

*3.5.4.3.3 pH*

**Function**

The pH needs to be monitored and controlled for optimal plant growth. Only valves are managed. The acid solution and the base solution are added to the nutrient tank by gravity when one of the two valves is opened.

**Control strategy**

Three modes are available.

- OFF: valves are closed.
- AUTOMATIC: The controller adjusts the pH value depending on the setpoint and the dead zone entered by the operator.
  If the irrigation flow is in a very high or very low flow state, the control loop will automatically be triggered to OFF mode and an alarm state will be issued for user intervention.
- MANUAL: the operator selects valves and opening time (in seconds).

**Alarms**

In case of a low acid or base tank level an alarm is set.
An alarm is set in case of low or high pH values.
An alarm is set and the irrigation is stopped in case of very high or very low pH values.

*3.5.4.3.4 EC*

**Function**

The EC needs to be monitored and controlled for optimal plant growth. Only valves are managed. The solution A and the solution B are added to the nutrient tank by gravity when valves are opened. There is no equipment to decrease the EC. Only plant consumption can do it.

**Control Strategy**
Three modes are available.

- OFF: valves are closed.
- AUTOMATIC: The controller adjusts the EC value depending on the setpoint and the dead zone entered by the operator.
  The automatic mode can be set if
  - The flow is not in very low or very high alarm. If not, the control loop will automatically be triggered to OFF mode.
- MANUAL: the operator selects valves and opening time (in seconds).

**Alarms**
In case of tank low level (A or B) an alarm is set.
An alarm is set in case of low or high EC values to initiate system inspection by personnel.
An alarm is set and the irrigation is stopped in case of very high or very low EC values.

*3.5.4.4 Requirements/specification Matrix*

| Requirement | Technological or Controller solution | Associated specifications for simulation and validation |
|---|---|---|
| **SUB-HYDR-NUT-1**<br>The volumetric flow of the nutrient delivery shall be adjustable between 0 and 10 l/min for the whole system (5 gullies) | Design | |
| **SUB-HYDR-LIQ-3**<br>The volume of the stock solutions inside the tanks shall be monitored | A low level switch will alert in case of low level in the stock solutions | |
| **SUB-HYDR-LIQ-5**<br>The liquid level in the nutrient solution tank shall be monitored | A low level switch will alert in case of low level in the stock solutions | |
| **SUB-HYDR-LIQ-8**<br>The nutrient solution composition (pH, EC) shall be controlled automatically by addition of stock solutions | | pH controller will ensure pH setpoint<br>EC controller will ensure EC setpoint. It is only possible to increase EC by stock addition |
| **SUB-HYDR-LIQ-9**<br>The pH setpoint shall be definable from 4 to 8 with increments of 0.1 | | pH setpoint can be set by the user in this range |

| Requirement | Technological or Controller solution | Associated specifications for simulation and validation |
|---|---|---|
| **SUB-HYDR-LIQ-10** The accuracy of pH control shall be at least ±0.5 | | From MPP experience, it should be the case. |
| **SUB-HYDR-LIQ-11** The EC setpoint shall be definable from 0 to 3000µS/cm with increments of 1µS/cm | | EC setpoint can be set by the user in this range |
| **SUB-HYDR-LIQ-12** The accuracy of EC control shall be at least ±100µS/cm | | From MPP experience, it should be the case. Nevertheless, it is not possible to decrease EC by addition of nutrient solution |
| **SUB-HYDR-LIQ-13** The nutrient solution temperature shall be settable from 15 to 30°C with increments of 0.1°C and an accuracy of at least ±1.0°C | Cooling line | Only cooling is available. The nutrient solution will heat up automatically due to the chamber internal dissipation if cooling is stopped. |

### 3.5.5 Specification of dynamical and physical simulation model

Here are the specifications of the dynamical and physical model needed for the validation of the specifications.
It is developed for the purpose of the atmospheric control (temperature and humidity, air flow) as it is the most critical point for the design of the HVAC system.

To validate the specifications on the T/RH control, it is necessary to represent the behaviour of the air system during operational mode.

- Fixed value of the HVAC blower (value proposed by UGuelph and used for the CFD model, one scenario with maximum flow rate and one with minimal flow rate)
- Just necessary representation of the T/RH distribution in the growing chamber
  - It is fixed at 6 volumes :
    - 3 in the length
    - 2 in the height
- Air flow distribution from the CFD model
- Calculation of T/RH/p/air flow at each node of the model:
  - Each of the 6 volumes
  - Average over inlet/outlet of the exchangers
  - average over the outlet of the fan
- Addition of a water source (representing the plant evapotranspiration)
- Addition of heat load, due to the lights, day/night cycle

Identified disturbances

- Opening of the door → non measured disturbance on temperature and RH
- Water source: plant evapotranspiration (water loss): disturbance for T/RH controller
- Lighting heat load: disturbance for the temperature control.
- Speed variation of the blower

Simulation test:

- Test will be performed over one day/night cycle
- Test will be performed at different level of crop evapotranspiration.

Closed loop test:

- To be representative, it will be simulated over several days with an increasing water source addition.
- Temperature and RH setpoints can be different during the day and the night

# 4 Conclusion

This document provides the general specifications for a PCU design. This includes the general compartmentalization and geometrical dimensions, preliminary calculations for the HVAC dimensioning (and deduced therefrom a preliminary hardware choice to be able to perform the CFD simulations required for the preliminary design). Furthermore specifications for fluid interfaces have been defined and the specifications of each subsystem (hydroponics, illumination, HVAC, chamber shell and control system) assessed individually. Along with this, some preliminary solutions and strategies for further development have been presented. The preliminary design (WP 8200) is based on the specifications and conclusions presented in this document.

Critical points have been clearly identified. At system level these comprise the installation in the UGent laboratories, interfacing with already available hardware (UGuelph heating and cooling water supplies) and performance of local laboratory air conditioning (cooling). The critical aspects of these points have been elaborated and explained in this document. Critical points were also identified at subsystem level. These comprise sealing of the hydroponic system, environmental homogeneity (atmosphere as well nutrient solution) and atmosphere composition ($O_2$ and ethylene contents). These points will be carefully addressed in the following TNs.

# 5 Appendix

## 5.1 Manufacturer datasheets

### *5.1.1 Heat exchangers*

## Heating Coil Capacities

**Based on 70 deg. F Air in Temp.**

### Model HC-07

**Based on 2 U.S. gpm - Pressure drop - 3.3 ft wg**

| CFM / SP - in. wg | 300 / 0.03 | 375 / 0.05 | 450 / 0.07 | 525 / 0.09 | 600 / 0.11 | 675 / 0.14 | 750 / 0.16 |
|---|---|---|---|---|---|---|---|
| Water Temp. DEG F | Heating Capacity - MBH | | | | | | |
| 140 | 16.3 | 18.9 | 21.1 | 22.3 | 24.0 | 25.5 | 26.8 |
| 160 | 21.0 | 24.5 | 27.1 | 29.2 | 30.8 | 32.9 | 34.4 |
| 180 | 25.6 | 29.6 | 33.1 | 35.7 | 37.7 | 40.2 | 42.1 |

### Model HC-09

**Based on 4 U.S. gpm - Pressure drop - 2.5 ft wg**

| CFM / SP - in. wg | 400 / 0.04 | 500 / 0.05 | 600 / 0.07 | 700 / 0.10 | 800 / 0.12 | 900 / 0.15 | 1000 / 0.18 |
|---|---|---|---|---|---|---|---|
| Water Temp. DEG F | Heating Capacity - MBH | | | | | | |
| 140 | 21.9 | 25.5 | 28.6 | 31.0 | 33.1 | 35.2 | 36.9 |
| 160 | 28.2 | 32.7 | 36.8 | 39.9 | 42.5 | 45.2 | 47.5 |
| 180 | 34.4 | 40.0 | 44.9 | 48.8 | 51.0 | 55.3 | 58.0 |

### Model HC-10

**Based on 5 U.S. gpm - Pressure drop - 2.8 ft wg**

| CFM / SP - in. wg | 500 / 0.04 | 600 / 0.05 | 700 / 0.07 | 800 / 0.09 | 900 / 0.11 | 1000 / 0.13 | 1100 / 0.15 |
|---|---|---|---|---|---|---|---|
| Water Temp. DEG F | Heating Capacity - MBH | | | | | | |
| 140 | 27.1 | 30.7 | 33.9 | 36.5 | 38.8 | 40.8 | 42.8 |
| 160 | 34.9 | 39.4 | 43.6 | 46.9 | 49.8 | 52.4 | 55.1 |
| 180 | 42.6 | 48.2 | 53.3 | 57.3 | 60.9 | 64.0 | 67.3 |

### Model HC-12

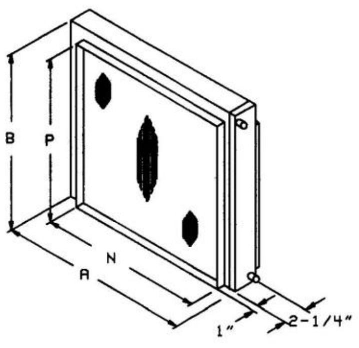
**Based on 6 U.S. gpm - Pressure drop - 2.8 ft wg**

| CFM / SP - in. wg | 700 / 0.04 | 850 / 0.05 | 1000 / 0.07 | 1150 / 0.09 | 1300 / 0.11 | 1450 / 0.13 | 1600 / 0.15 |
|---|---|---|---|---|---|---|---|
| Water Temp. DEG F | Heating Capacity - MBH | | | | | | |
| 140 | 39.3 | 44.9 | 49.8 | 53.6 | 57.0 | 60.2 | 62.9 |
| 160 | 50.5 | 57.7 | 64.0 | 68.9 | 73.3 | 77.5 | 80.9 |
| 180 | 61.8 | 70.6 | 78.2 | 84.2 | 89.6 | 94.7 | 98.9 |

### Model HC-15

**Based on 8 U.S. gpm - Pressure drop - 3.1 ft wg**

| CFM / SP - in. wg | 1500 / 0.07 | 1600 / 0.07 | 1700 / 0.08 | 1800 / 0.09 | 1900 / 0.10 | 2000 / 0.11 | 2100 / 0.12 |
|---|---|---|---|---|---|---|---|
| Water Temp. DEG F | Heating Capacity - MBH | | | | | | |
| 140 | 71.4 | 73.9 | 76.4 | 78.7 | 80.8 | 82.9 | 84.7 |
| 160 | 91.8 | 95.0 | 98.2 | 101.2 | 103.9 | 106.5 | 108.9 |
| 180 | 112.2 | 116.2 | 120.0 | 123.6 | 127.0 | 130.2 | 133.1 |




**Dimensions - in.**

| Model | "A" | "B" | "N" | "P" |
|---|---|---|---|---|
| HC-07 | 17-3/4 | 15-3/8 | 16 | 13-1/2 |
| HC-09 | 21 | 18 | 19-1/8 | 16-1/8 |
| HC-10 | 22-1/4 | 20 | 20-3/8 | 18-1/8 |
| HC-12 | 27 | 23 | 25-1/8 | 21-1/8 |
| HC-15 | 32-1/2 | 26-3/4 | 30-5/8 | 25-1/8 |

**OD - in.**

| Model | Inlet | Outlet | wt - lbs |
|---|---|---|---|
| HC-07 | 5/8 | 5/8 | 10 |
| HC-09 | 5/8 | 5/8 | 14 |
| HC-10 | 5/8 | 5/8 | 17 |
| HC-12 | 3/4 | 3/4 | 23 |
| HC-15 | 3/4 | 3/4 | 32 |

## Cooling Coil Capacities

Based on 80 deg. F DB / 67 deg. F WB Air in Temp.

### Model CW-07

Based on 4 U.S. gpm - Pressure drop - 3.0 Ft w.g.

| CFM<br>SP - in. wg | 300<br>0.09 | 375<br>0.13 | 450<br>0.17 | 525<br>0.22 | 600<br>0.28 | 675<br>0.34 | 750<br>0.41 |
|---|---|---|---|---|---|---|---|
| Water Temp.<br>DEG F | Total Cooling Capacity (Sensible) - MBH | | | | | | |
| 42 | 14.2 (9.4) | 16.2 (11.0) | 17.9 (12.4) | 19.5 (13.8) | 20.8 (15.1) | 21.9 (16.3) | 22.8 (17.4) |
| 45 | 12.6 (8.7) | 14.4 (10.2) | 15.8 (11.6) | 17.3 (13.0) | 18.5 (14.2) | 19.4 (15.3) | 20.3 (16.4) |
| 48 | 11.0 (8.0) | 12.6 (9.5) | 13.8 (10.8) | 15.1 (12.1) | 16.1 (13.3) | 17.0 (14.4) | 17.7 (15.5) |

### Model CW-09

Based on 5 U.S. gpm - Pressure drop - 2.6 Ft w.g.

| CFM<br>SP - in. wg | 400<br>0.09 | 500<br>0.13 | 600<br>0.17 | 700<br>0.22 | 800<br>0.28 | 900<br>0.34 | 1000<br>0.41 |
|---|---|---|---|---|---|---|---|
| Water Temp.<br>DEG F | Total Cooling Capacity (Sensible) - MBH | | | | | | |
| 42 | 18.9 (12.5) | 21.6 (14.6) | 18.6 (14.4) | 26.0 (18.5) | 27.7 (20.2) | 29.2 (21.7) | 30.4 (23.2) |
| 45 | 16.8 (11.6) | 19.2 (13.6) | 21.2 (15.5) | 23.1 (17.3) | 24.6 (18.4) | 25.9 (20.5) | 27.0 (21.9) |
| 48 | 14.7 (10.7) | 16.8 (12.6) | 18.5 (14.4) | 20.2 (16.2) | 21.5 (17.7) | 22.6 (19.2) | 23.6 (20.6) |

### Model CW-10

Based on 6 U.S. gpm - Pressure drop - 2.8 Ft w.g.

| CFM<br>SP - in. wg | 500<br>0.09 | 600<br>0.12 | 700<br>0.16 | 800<br>0.20 | 900<br>0.25 | 1000<br>0.30 | 1100<br>0.35 |
|---|---|---|---|---|---|---|---|
| Water Temp.<br>DEG F | Total Cooling Capacity (Sensible) - MBH | | | | | | |
| 42 | 23.5 (15.5) | 26.2 (17.6) | 28.5 (19.6) | 30.8 (21.6) | 32.6 (23.3) | 34.2 (25.0) | 35.7 (26.5) |
| 45 | 20.9 (14.4) | 23.2 (16.4) | 25.3 (18.3) | 27.4 (20.2) | 29.0 (21.9) | 30.4 (23.5) | 31.7 (25.0) |
| 48 | 18.2 (13.3) | 20.3 (15.2) | 22.1 (19.0) | 23.9 (18.8) | 25.3 (20.5) | 26.5 (22.0) | 26.7 (23.5) |

### Model CW-12

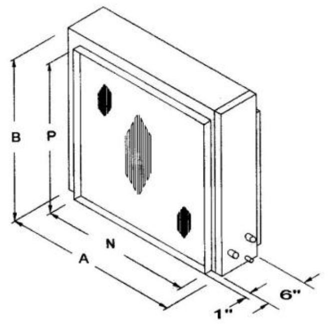
Based on 7 U.S. gpm - Pressure drop - 3.6 Ft w.g.

| CFM<br>SP - in. wg | 700<br>0.08 | 850<br>0.12 | 1000<br>0.15 | 1150<br>0.19 | 1300<br>0.24 | 1450<br>0.29 | 1600<br>0.34 |
|---|---|---|---|---|---|---|---|
| Water Temp.<br>DEG F | Total Cooling Capacity (Sensible) - MBH | | | | | | |
| 42 | 32.8 (21.7) | 37.0 (25.0) | 40.7 (28.0) | 43.4 (30.7) | 45.8 (33.2) | 47.9 (35.6) | 49.7 (37.8) |
| 45 | 29.1 (20.1) | 32.9 (33.3) | 36.1 (26.2) | 38.6 (28.8) | 40.7 (31.2) | 42.5 (33.5) | 44.0 (35.6) |
| 48 | 25.4 (18.6) | 28.7 (21.6) | 31.6 (24.4) | 33.7 (36.8) | 33.6 (29.2) | 37.1 (31.4) | 38.5 (33.5) |

### Model CW-15

Based on 8 U.S. gpm - Pressure drop - 5.0 Ft w.g.

| CFM<br>SP - in. wg | 1500<br>0.14 | 1600<br>0.15 | 1700<br>0.17 | 1800<br>0.19 | 1900<br>0.21 | 2000<br>0.22 | 2100<br>0.24 |
|---|---|---|---|---|---|---|---|
| Water Temp.<br>DEG F | Total Cooling Capacity (Sensible) - MBH | | | | | | |
| 42 | 59.0 (41.3) | 60.6 (43.0) | 62.0 (44.6) | 63.2 (46.2) | 64.4 (47.7) | 65.5 (49.2) | 66.5 (50.6) |
| 45 | 52.4 (38.6) | 53.8 (40.2) | 55.0 (41.8) | 56.1 (43.4) | 57.2 (44.9) | 58.2 (46.3) | 59.0 (47.7) |
| 48 | 45.8 (36.0) | 47.0 (37.6) | 48.1 (39.1) | 49.1 (40.6) | 50.0 (42.1) | 50.8 (43.5) | 51.6 (45.0) |




Dimensions - in.

| Model | "A" | "B" | "N" | "P" |
|---|---|---|---|---|
| CW-07 | 17-3/4 | 15-3/8 | 16 | 13-1/2 |
| CW-09 | 21 | 18 | 19-1/8 | 16-1/8 |
| CW-10 | 22-1/2 | 20 | 20-3/8 | 18-1/8 |
| CW-12 | 27 | 23 | 25-1/8 | 21-1/8 |
| CW-15 | 33-1/2 | 28 | 30-5/8 | 25-1/8 |

OD - in.

| Model | Inlet | Outlet | Drain | wt - lbs |
|---|---|---|---|---|
| CW-07 | 5/8 | 5/8 | 5/8 | 22 |
| CW-09 | 7/8 | 7/8 | 5/8 | 29 |
| CW-10 | 7/8 | 7/8 | 5/8 | 36 |
| CW-12 | 7/8 | 7/8 | 5/8 | 42 |
| CW-15 | 7/8 | 7/8 | 5/8 | 61 |

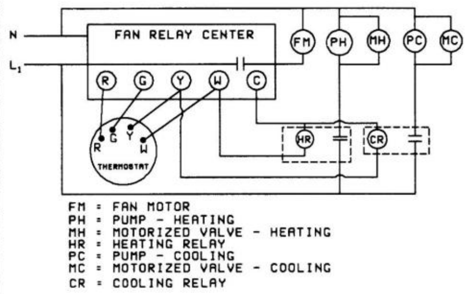
### Heating Coil Capacity
### Air Temperature Correction Factor

| Air Temp Deg. F. | Water Temp. deg. F 140 | 160 | 180 |
|---|---|---|---|
| 80 | 0.86 | 0.89 | 0.91 |
| 70 | 1.00 | 1.00 | 1.00 |
| 60 | 1.14 | 1.11 | 1.09 |
| 50 | 1.29 | 1.22 | 1.18 |

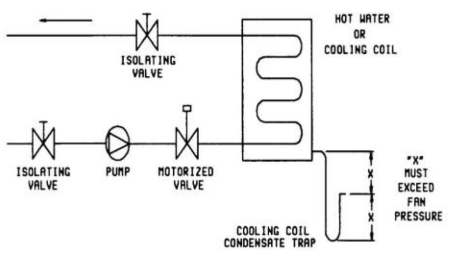
### Useful Formula

Air Temp. Rise = $\frac{\text{Mbh} \times 1000}{\text{cfm} \times 1.08}$

Water Temp. Drop = $\frac{\text{Mbh} \times 1000}{\text{gpm} \times 500}$




Typical Wiring Diagram (by others)




Typical Plumbing Diagram (by others)

### Typical Selection Example

**Requirement**
An application requires 40 Mbh heating and 26 Mbh of cooling.
Hot water temperature is 160 deg. F. Chilled water is 45 deg. F.

**Selection**
An HC-09 will provide 42.5 Mbh @ 160 deg F water temp with an air flow of 800 CFM. The matching Cooling Coil, CW-09, needs 900 CFM to deliver the 26 Mbh cooling load which will determine the design CFM. The system SP, excluding the coils and filter section, has been calculated as 0.4 in. wg based on the 900 CFM.

**sp Estimate**

| Component | sp - in. wg |
|---|---|
| System | 0.40 |
| CW-09 Cooling Coil | 0.34 |
| HC-09 Heating Coil | 0.15 |
| F209A Filter | 0.04 |
| **Total sp** | **0.93** |

**Blower Selection**

Select Model 209 or 9209 duct blower to match HC-09 & CW-09 dimensions

**Motor Selection**

From Duct Blower CAT. #SS-31, page 7, models 209 & 9209 performance data, at 900 CFM & 1" SP requires .28 BHP @ 1125 RPM
Select a 1/3 BHP motor

**For Duct Blower details request Delhi Catalogue #SS-31**
**"Forward Curved Inline Duct Blowers"**

**DELHI Industries Inc.**
**523 James Street, Delhi, Ontario, Canada N4B 2Z3**

**TEL: (519)582-2440**
**FAX: (519)582-0581**

**www.delhi-industries.com**
**email: sales@delhi-industries.com**

**CAT. #SS-38-4 MAY 2002**

Printed in Canada

### *5.1.2 Blower*

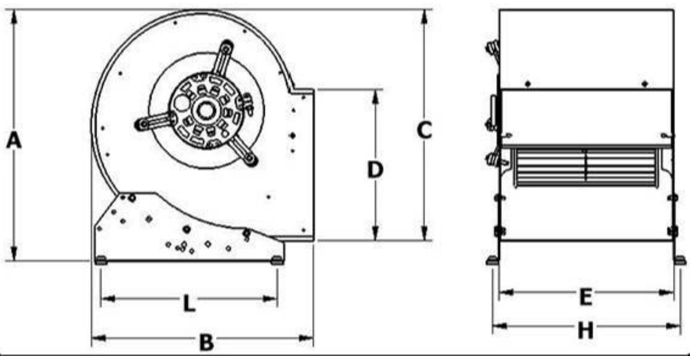
DELHI INDUSTRIES INC.

**Centrifugal**
**Forward Curved**
**Direct Drive Blowers**
**With**
**3 speed PSC Motor**

# G-DD Series - Centrifugal, Forward Curved, Direct Drive Blowers

**Features**

- 3 speed, 115V, PSC motor
- Corrosion resistant G90 galvanized housing
- Universal base for 4 position discharge

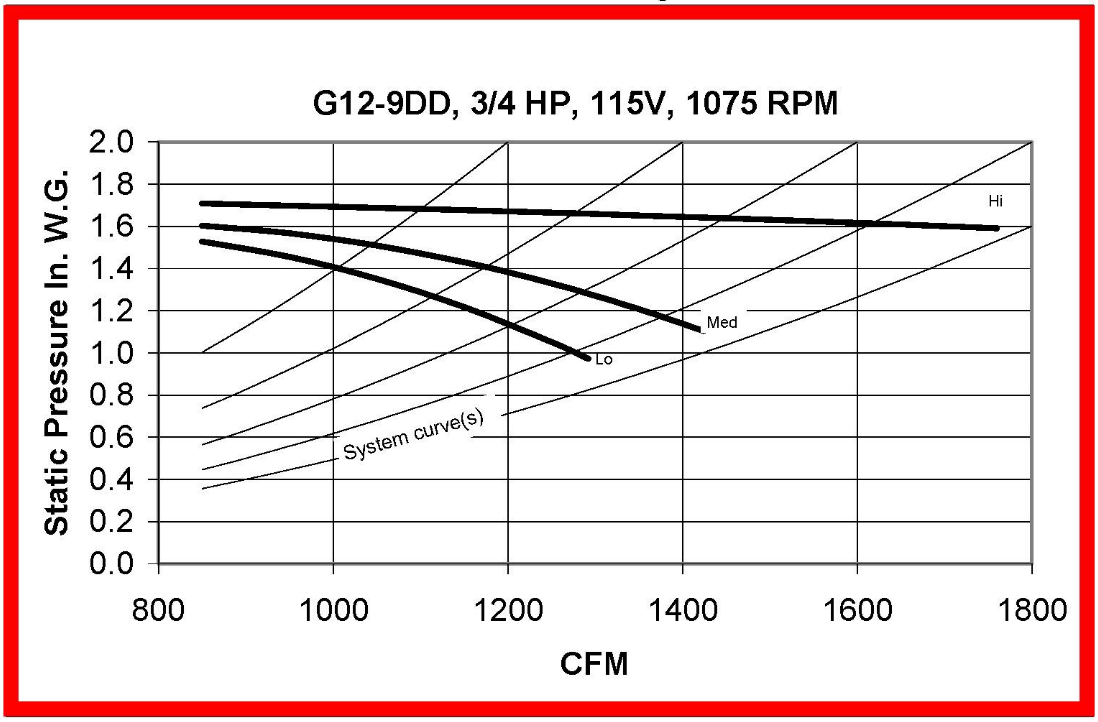


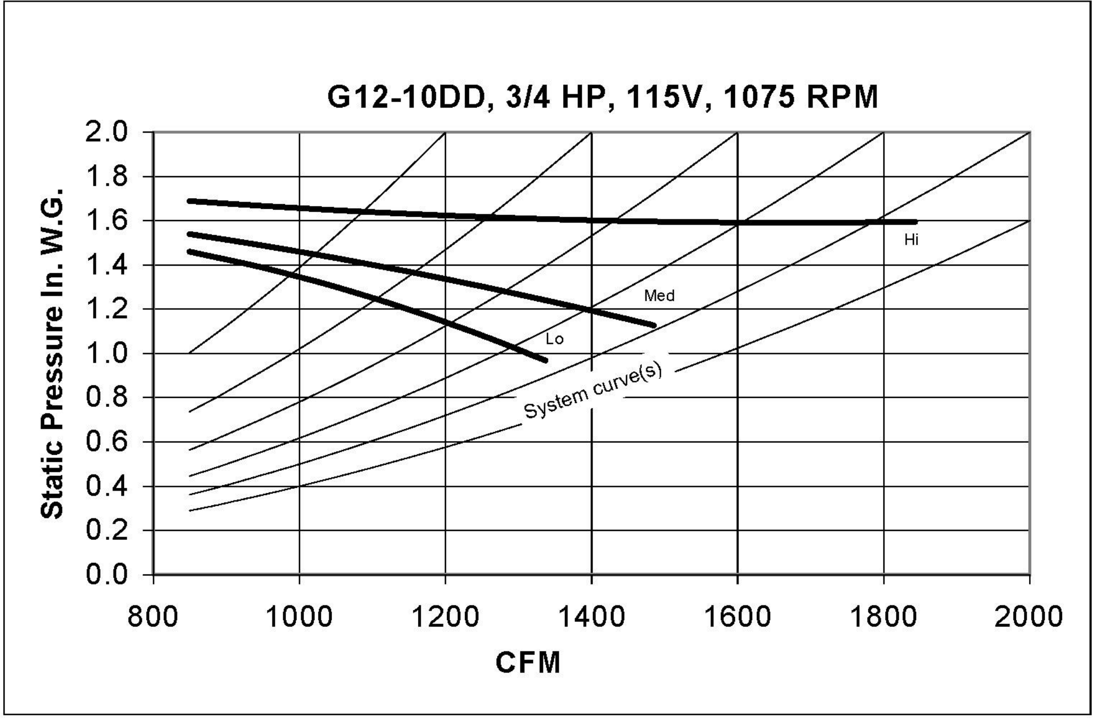

Heavy Duty
Resilient Mount
Motor Mounting Bracket

| Model -HP | Dimensions | | | | | | | Static Pressure- IN W.G. | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 | 1.2 | 1.4 | 1.6 |
| | A | B | C | D | E | H | L | CFM @ Med Speed - (see curves for Hi & Lo speed performance) | | | | | | | | |
| G9-7-DD-1/3 | 16-15/16 | 15-1/16 | 15-9/16 | 10-1/4 | 9-3/16 | 10-3/16 | 11-3/4 | - | - | 1148 | 1041 | 841 | - | - | - | - |
| G9-7-DD-1/2 | | | | | | | | 1363 | 1270 | 1170 | 1045 | 865 | - | - | - | - |
| G9-DD-1/3 | 16-15/16 | 15-1/16 | 15-9/16 | 10-1/4 | 11-13/16 | 12-13/16 | 11-3/4 | - | - | 1213 | 1025 | 742 | - | - | - | - |
| G9-DD-1/2 | | | | | | | | - | 1444 | 1316 | 1172 | 979 | - | - | - | - |
| G10-8-DD-1/2 | 19 | 16-3/4 | 17-3/8 | 11-3/8 | 10-1/2 | 11-1/2 | 13-3/8 | - | - | - | - | 1372 | 1238 | - | - | - |
| G10-8DD-3/4 | | | | | | | | - | - | - | - | - | 1535 | 800 | - | - |
| G10-DD-1/2 | 19 | 16-3/4 | 17-3/8 | 11-3/8 | 13-1/8 | 14-1/8 | 13-3/8 | - | - | - | 1514 | 1335 | 1115 | - | - | - |
| G10-DD-3/4 | | | | | | | | - | - | 1665 | 1581 | 1486 | 1379 | 1000 | - | - |
| G12-9-DD-3/4 | 22-1/8 | 19-1/2 | 20-5/8 | 13-7/16 | 12-1/4 | 13-1/4 | 16-1/8 | - | - | - | - | - | - | 1358 | 1174 | 870 |
| G12-10-DD-3/4 | 22-1/8 | 19-1/2 | 20-5/8 | 13-7/16 | 13-1/8 | 14-1/8 | 16-1/8 | - | - | - | - | - | - | 1393 | 1102 | - |

Page 2

See back cover for selection guidelines

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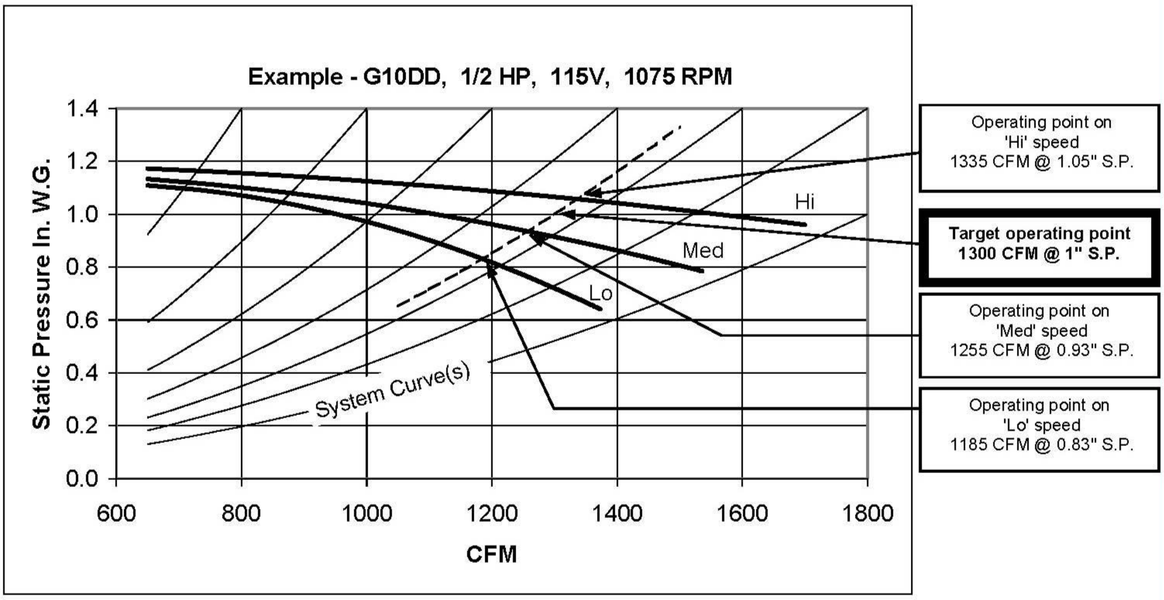


**Example:** An application requires 1300 CFM @ 1" S.P.

1 - Locate the desired operating point on the Fan curve.

2 - Draw the system curve (dotted line) through the 1300 CFM @ 1" S.P. operating point.

3 - The intersection of the system curve with the "Hi" , "Med" & "Lo " fan curves identify the actual operating point at each of the 3 motor speeds shown in the table below.

| Motor Speed | CFM | S.P. in W.G. |
|---|---|---|
| "Hi" | 1335 | 1.05" |
| "Med" | 1255 | .93" |
| "Lo" | 1185 | .83" |

**Warranty**

Delhi Air Moving Products are guaranteed for a period of one year against manufacturing defect in material and workmanship when operating under normal conditions. Liability is limited to the replacement of defective parts. Labour and transportation costs are not included.

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REPRESENTED BY:

**CAT. #SS-53-1 SEPTEMBER 2005**