DESIGN DOCUMENT:
Environmental Enclosure for a Single-Cell Inkjet Printer

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PREFACE

Due to restrictions imposed as a result of the COVID-19 pandemic, we were not able to complete all elements of the project. The following document reflects the intended design, with all elements fully assembled. The actual prototype is not fully integrated due to shipping and manufacturing delays , as well as an inability to access vital equipment.

CHANGELOG

Version	Date	Editor	Change
1.0	24/09/19	All	Document created.
1.1	11/11/19	LH	Added to High-Level Design; added to FEU section; created new Appendix for the original TCU.
1.2	11/18/19	LH, AY	LH: Rewrote section introductions; added to FEU and ECU section; added new Appendices for materials properties and definitions. AY: Added to HCU section; created Appendix for humidity calculations.
1.3	11/22/19	All	Filled out in the TCU, HCU, and ECU sections.
1.4	08/02/20	All	SW, NL: Made the TCU section more concise. LH: Updated FEU section; moved all electronics/controls to ECU. AY, WZ: Updated HCU section.
1.5	04/01/21	All	Updated all sections.

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LIST OF ACRONYMS AND ABBREVIATIONS

ABS	Acrylonitrile Butadiene Styrene
AC	Alternating Current
ANSI	American National Standards Institute
BioMEMS	Bio-Medical Micro Devices[1]
BSP	British Standard Pipe
Cx.x	Constraint x.x
DC	Direct Current
ECU	Electronics Control Unit
FDM	Fused Deposition Modeling
FEU	Filtration and Enclosure Unit
FSM	Finite State Machine
Fx.x	Functional Requirement x.x
G1/4”	G Quarter Inch
HCU	Humidity Control Unit
H_2O	Hydrogen Oxide (Water)
LCD	Liquid Crystal Display
NFx.x	Non-Functional Requirement x.x
PA	Polyamide
PC	Polycarbonate
PETG	Polyethylene Terephthalate
PID	Proportional-Integral-Derivative
PMMA	Polyacrylate (acrylic)
PP	Polypropylene
PSU	Power Supply Unit
PTC	Positive Temperature Coefficient

[1] This abbreviation is defined by the laboratory of the client. The colloquial definition of BioMEMS is “Biomedical Micro-Electrical-Mechanical Systems”

PVC	Polyvinyl Chloride
PWM	Pulse Width Modulation
RAMPS	Reprap Arduino Mega Pololu Shield
RH	Relative Humidity
SLS	Selective Laser Sintering
SLA	Stereolithography
TCU	Temperature Control Unit
TECH	Thermo-Electric Cooler and Heater
TR	Temperature Regulation
WDM	Weighted Decision Matrix
WS	Weighted Score
µC	Microcontroller

1 INTRODUCTION

This document aims to describe the design of the environmental enclosure for a single cell inkjet printer. Decisions for the various design aspects of the product are outlined, along with accompanying justifications. Multiple appendices are included that explore different design aspects in more detail. For further information on specific terminology, refer to Appendix A. For information on how the WDMs were created, refer to Appendix B.

2 HIGH-LEVEL DESIGN

The high-level design of the environmental enclosure is depicted in Figure 1. The enclosure is broken down into four main subsystems: (1) TCU , (2) HCU, (3) FEU, and (4) ECU.

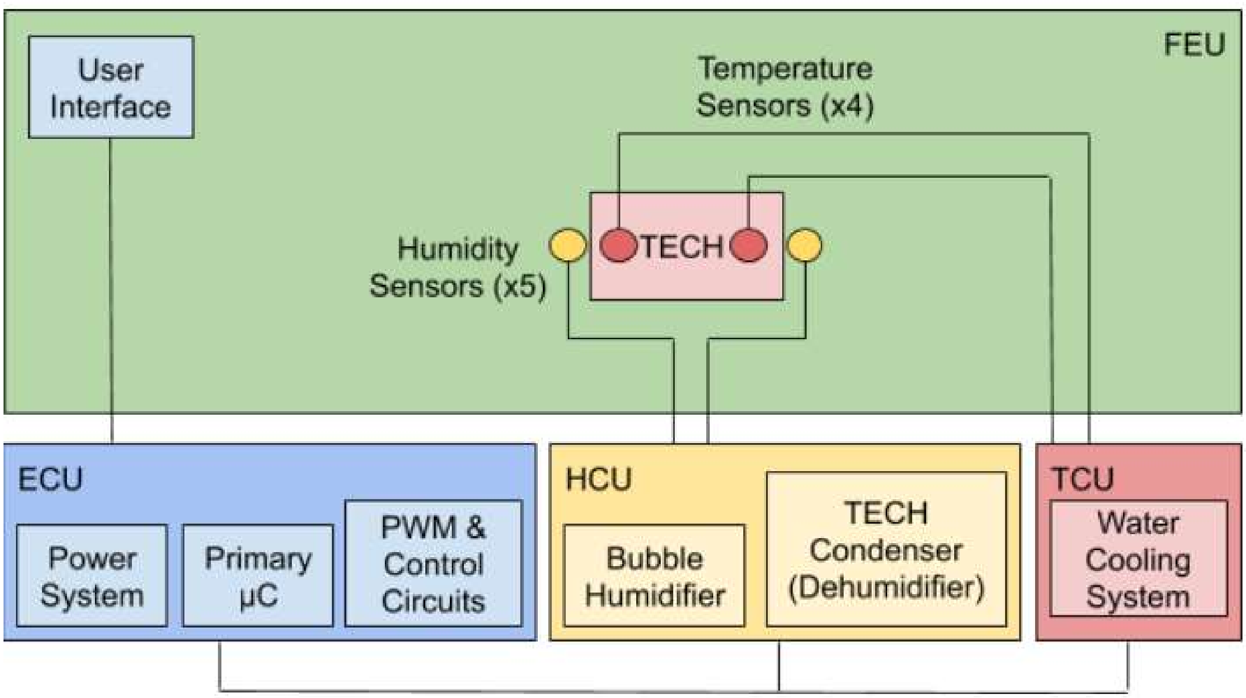


Figure 1: High-level design of system

1. Temperature Control Unit (TCU):

Refers to the printing platform that holds the well plate and maintains a highly regulated local temperature. This subsystem consists of a TECH element to both heat and cool the well-plates, accompanied by a water-cooling system for heat dispersion. Thermistors embedded within the platform provide real-time temperature information, which feeds back to a PWM circuit to regulate the temperature in a closed loop.

2. Humidity Control Unit (HCU):

Refers to the element that produces and maintains humidity within the main chamber of the FEU. The RH is regulated by feedback from humidity and ambient temperature sensors. Humidity is produced using a bubble humidifying mechanism. The system is dehumidified by flowing air past a heatsink cooled by a TECH element. This subsystem minimizes evaporation of the samples and prevents condensation on the well plates to avoid contamination.

3. Filtration and Enclosure Unit (FEU):

Refers to the sealed chamber that houses the single cell inkjet printer. The enclosure provides a stable environment for which the subsystems can be dynamically controlled and adjusted. The frame of the FEU is composed of aluminum extrusions, while the panels are made of polypropylene. Components from the other subsystems are placed externally to the FEU to minimize disturbance to the inkjet printing system.

4. Electronics Control Unit (ECU):

Includes the power system for the various subsystems as well as the primary microcontroller circuit and user interface. The power system consists of a 450W 120 VAC to 12VDC/5VDC PSU, a RAMPS controller board, and a current regulator. The microcontroller circuit integrates and monitors the various control systems (HCU and TCU) and connects to the user interface to provide user-selectable controls.

Simplified diagrams of the integrated environmental enclosure and its main features are shown in Figure 2 and Figure 3 below:

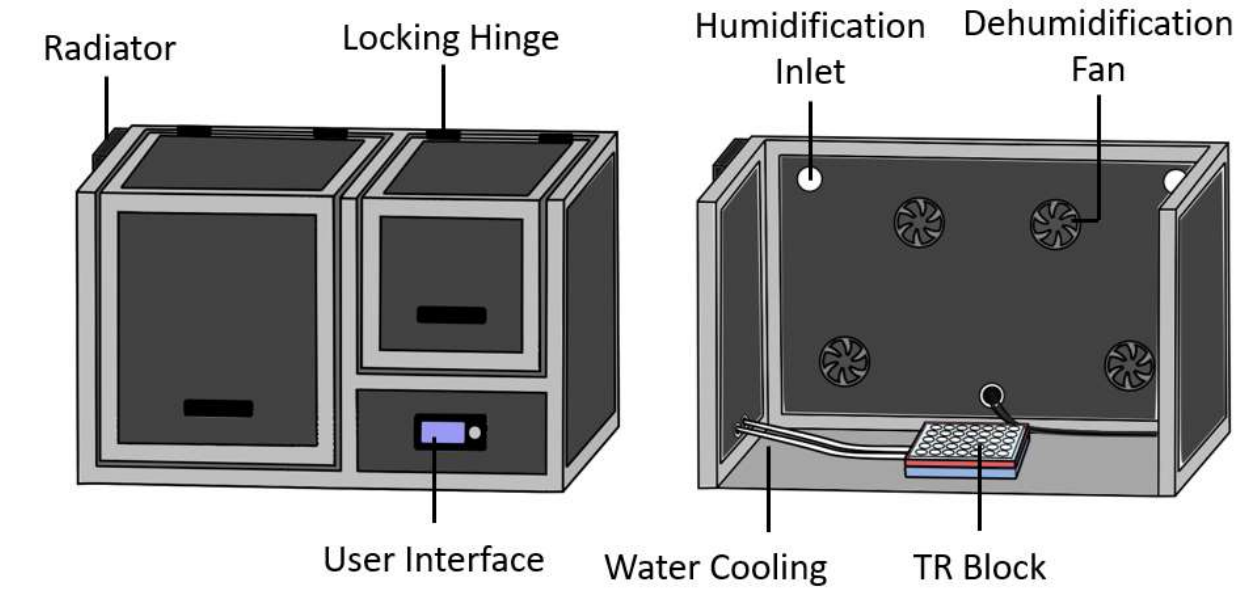


Figure 2: Front Side of Environmental Enclosure

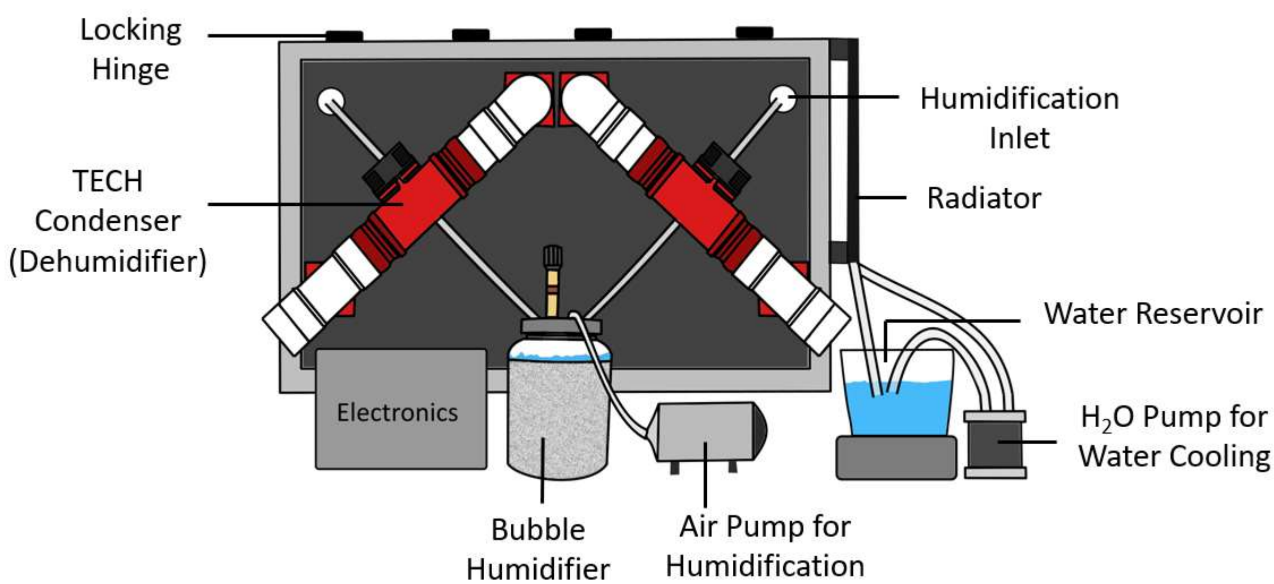


Figure 3: Back Side of Environmental Enclosure

3 TEMPERATURE CONTROL UNIT (TCU)

The temperature control unit serves to regulate temperature locally at the well plate. As opposed to ambient control, local control ensures that the temperature of the printing substrate is regulated directly, reducing the complexity and power consumption of the TCU. The design of the TCU can be further broken down into the following components:

- TR Block
  - Substrate adaptor
  - TECH adaptor and sensor array
  - Aluminum water cooling block
  - Thermistor
  - TECH
- Water cooling system
  - 12V DC water pump
  - Fittings and tubing
  - 360 mm radiator and 3x120 mm fans

3.1 TR Block

The TR block adapts to both the nanowell plate and the 96-well plate according to requirements NF2.1 and NF2.2.

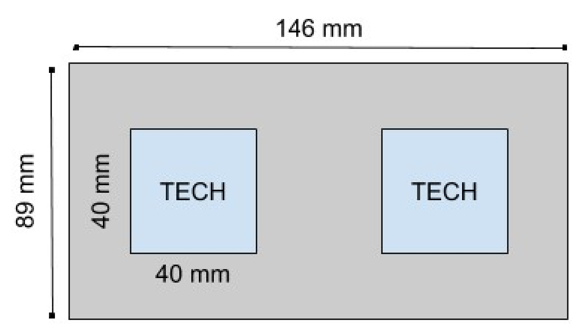


Figure 4: Thermal footprint of the TR block (top-down)

Figure 5 below highlights some of the key characteristics of the TR Block as seen through an exploded view.

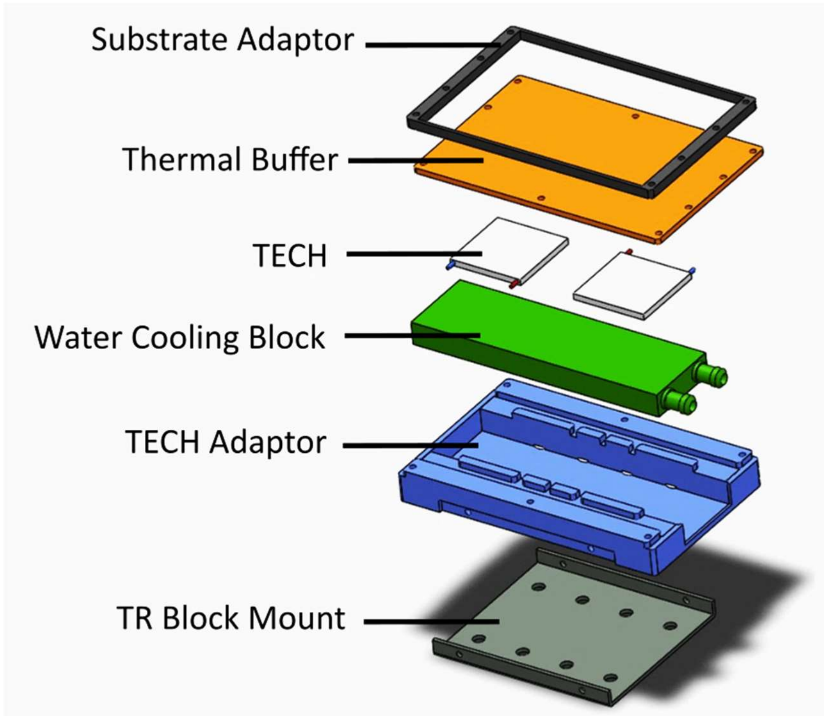


Figure 5: Exploded view of the TR block

3.1.1 Substrate Adaptor

The substrate adaptor is the topmost layer of the TR block. It houses the mounting mechanisms to allow for the installation of both the nano and microwell plates.

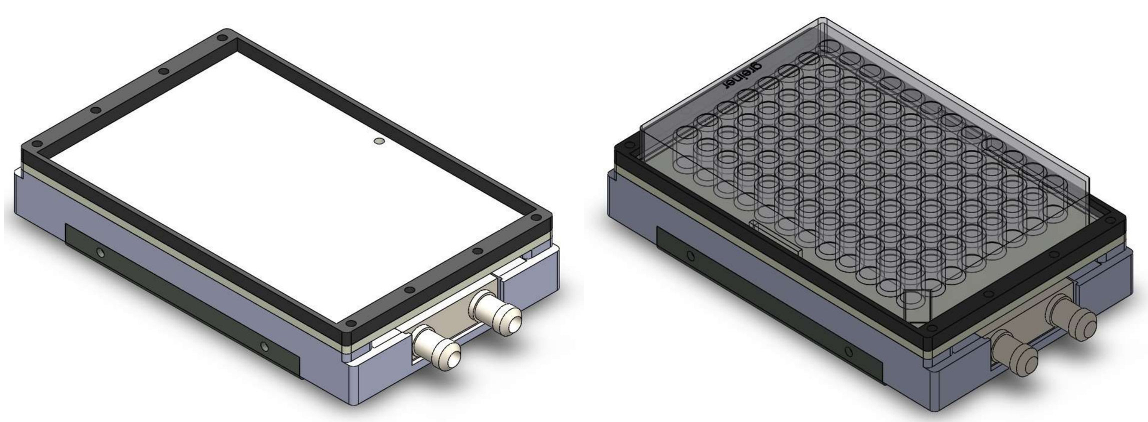


Figure 6: TR block with substrate adaptor (a) without well-plate (b) with well-plate

The adaptor is manufactured using SLS 3D printing due to its ability to print at high precision, using a variety of engineering resins with different material properties. The adaptor must be able to cycle through temperatures of 2-4 °C, 37 °C and 80 °C to meet requirements F1, F1.1, and F1.2 respectively. The resin of choice for this application is the high temperature resin seen in Table 1.

Criteria	Weight (%)	TCU Water Cooling Block									
		High Temp Resin		ABS FDM		PETG FDM		Clear Resin		PC FDM	
		Score	WS	Score	WS	Score	WS	Score	WS	Score	WS
Manufacturer time	20	100	20	75	15	75	15	100	15	75	15
UV Light Resistance	10	25	2.5	25	2.5	100	10	25	2.5	75	7.5
Low Cost	10	25	2.5	80	8	100	10	25	2.5	40	4
Thermal tolerance	30	100	30	80	24	40	12	40	12	70	21
Thermal Resistivity	10	100	10	100	10	75	7.5	75	7.5	25	2.5
Sterilizable by ethanol	10	100	10	50	5	50	5	100	10	100	10
Low Water Absorption	10	100	10	25	2.5	75	7.5	100	10	75	7.5
TOTAL (%)		**95**		67		67		54.5		67.5	

Table 1: WDM for substrate adaptor and liquid cooling block

The add-on for the adaptor is a friction-fit piece that sits in the adaptor cavity (Figure 7). This allows for the installation of up to two nanowell plates optimally above the TECH elements.

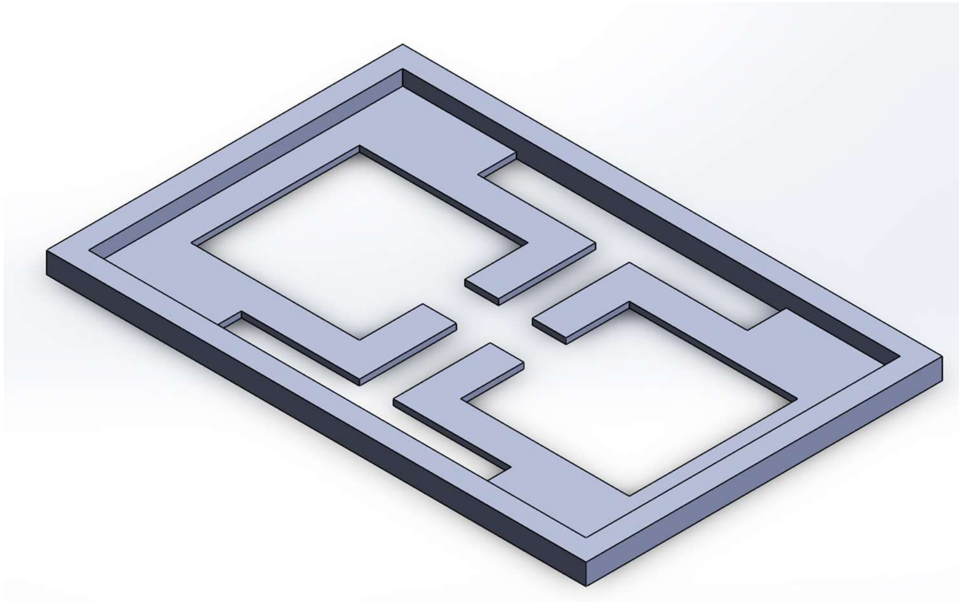


Figure 7: Add-on for substrate adaptor for nanowell plate

3.1.2 TECH Adaptor and Sensor Array

The TECH adaptor houses the TECH elements and sensors. It consists of the thermal buffer, TECH brace, TECH elements, thermistor array and water-cooling block as seen in the Figure 5 exploded view.

The TECH modules are surrounded by braces, which are built into the adaptor (Figure 8). The braces are 0.2mm taller than the TECHs they surround and are made of thermally insulating, compressible resin which is chosen for the reasons outlined in Table 2. The braces allow for a tight fit between the TECHs and the aluminum plates, reducing the likelihood of damaging the TECHs. The TECHs have thermal paste applied to their faces to further increase the surface area of thermal contact with the aluminum plates. Gaps in the brace material provide passage for the thermistor wiring.

Criteria	Weight (%)	Brace Material									
		Flexible Resin		TPU FDM		Nylon FDM		Clear Resin		Rubber High Temp	
		Score	WS	Score	WS	Score	WS	Score	WS	Score	WS
Manufacturer time	20	100	20	75	15	75	15	100	20	25	5
Strain	30	100	30	100	30	50	15	0	0	100	30
Low Cost	10	25	2.5	80	8	100	10	25	2.5	0	0
Thermal tolerance	30	100	30	40	12	100	30	40	12	100	30
Precision	10	100	10	50	5	50	5	100	10	50	5
TOTAL (%)		**97.5**		70		75		44.5		70	

Table 2: WDM for brace material

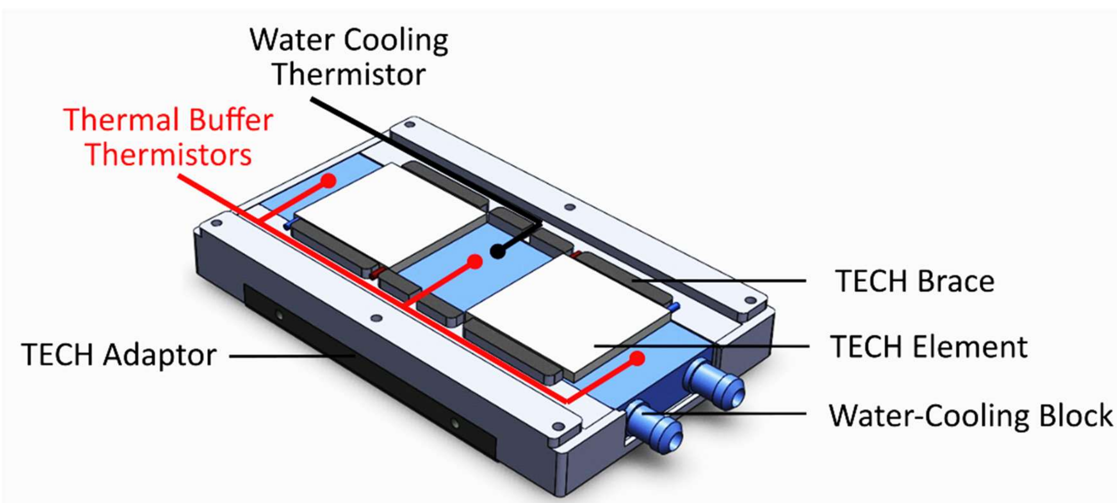


Figure 8: TECH Adaptor without Thermal Buffer

Three thermistors are placed in the configuration shown in red in Figure 8, on the topside of the thermal buffer (not shown). The thermistors nearest to the well plate ensure system accuracy, while the thermistors close to the TECHs aid in system stability. An additional thermistor is placed on the aluminum water-cooling block to ensure the temperature difference does not exceed 68°C, preventing system failure.

3.1.3 Thermistor

The quality of the temperature sensor used directly impacts the system precision and accuracy requirements (F1.3, F1.4), as well as the performance of the PID controls.

The WDM in Table 3 compares several temperature sensor types. The thermistor is selected due to its precision and response time.

Criteria	Weight (%)	Temperature Sensors					
		Resistance Temperature Detectors (749-1057-1-ND)		Thermistor (RL0503-5820-97-MS)		(Type T)Thermocouple (1TC-24-TT-36-T-3)	
		Score	WS	Score	WS	Score	WS
Precision	45	100	45	88	39.6	0	0
Response time	40	0	0	100	40	97	38.8
Cost	15	85	12.75	100	15	0	0
TOTAL (%)		55.75		**94.6**		38.8	

Table 3: WDM for temperature sensors

3.1.4 Thermo-Electric Cooler Heater (TECH)

A TECH unit is used due to its unique ability to both heat and cool a substrate at high rates. To achieve requirements F1.2 and F1.5, the design incorporates the use of two 10A TECH elements. For the microwell plate, both TECH elements are used to reach the setpoint, while one is used to maintain it. For a single nanowell plate, only one element is used.

The TECH is chosen to fulfill the underlying requirement of heating and cooling (F1.0, F1.1, F1.2). The following attributes make a TECH unit ideal for the application:

- ***Size:***
  - Must have a thin profile to meet dimensional constraints (C3.0, C3.1).
- ***Temperature Range***:
  - Must provide both cooling and heating functions in a single unit.

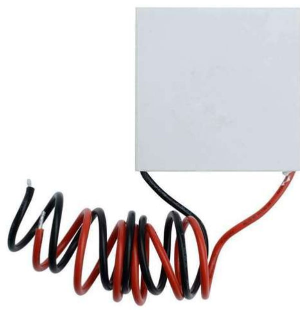


Figure 9: TEC1-12730 TECH Unit [1]

3.1.5 Aluminum Water-Cooling Block

The water-cooling block is used to maximize the cooling of the hot side of the TECHs. A custom water channel is not implemented due to limited manufacturing capabilities. This system does not require gaskets or waterproofing, simplifying the design and improving reliability. Furthermore, the cooling blocks are readily available, inexpensive and easy to replace.

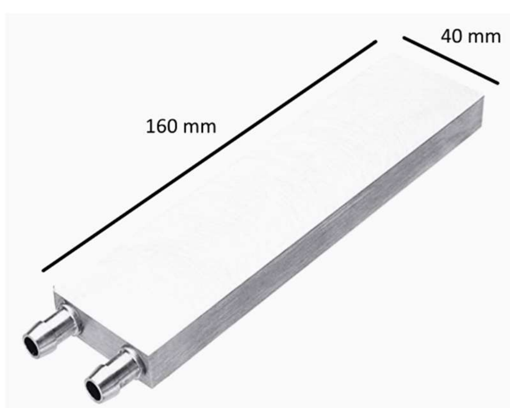


Figure 10: Zitainn Aluminum Liquid-Water Cooling Block [2]

The input and output channels are threaded for G1/4” BSP fittings which are the standard in water-cooling for commercial electronics. The channels have an inner diameter of 10mm which is matched by the cooling channel width to maintain flowrate and pressure from the pump.

3.2 Water Cooling System

The water-cooling system comprises the pump, tubing, fittings, radiator and aluminum water-cooling block described in section 3.1.5. The closed loop system is annotated in Figure 11 below.

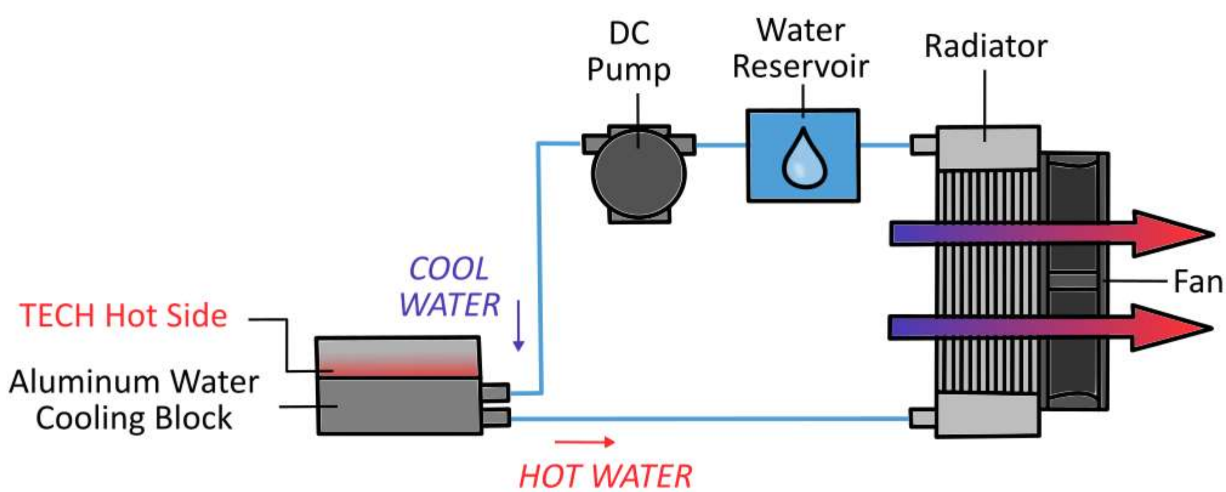


Figure 11: Water-cooling system

3.2.1 Water Pump

The pump selected for the system is a 12V DC centrifugal EK-DCP 2.2 pump. It was chosen based on the following criteria:

- Cheap and easy to source from retailers (i.e. Amazon)
- Intended for water cooling systems
- Has threadings compatible with the G1/4” fittings
- High flow rate of 400L/h

When compared to high pressure peristaltic pumps, the DC pump performs better for this application due it is high flow rate and cheap price (50% cheaper). Furthermore, data gathered from the Validation Document [26], Section 2.1 shows significant performance increase after switching to the DC pump. With a peristaltic pump, the system was not able to meet temperature setpoint requirements .

Figure 12: EK-DCP 2.2 Pump [3]

3.2.2 Fittings and Tubing

The tubing delivers the coolant between the water-cooling block and the radiator, effectively transferring heat away from the hot side of the TECH unit.

Criteria	Weight (%)	Tubing Material					
		PVC		Silicone		Polyurethane	
		Score	WS	Score	WS	Score	WS
Max Continuous Temperature	40	0	0	100	40	0	0
Flexibility	30	0	0	100	30	50	15
Kink Resistance	15	80	12	0	0	100	15
Stickiness	15	100	15	100	15	0	0
TOTAL (%)		27		**85**		30	

Table 4: WDM for tubing material

As seen from the WDM in Table 4, silicone is best suited for the design because its flexibility does not impede the movement of the TCU and it has a high operating temperature.

3.2.3 Radiator

The radiator and fan unit cool the warm water from the TR block, which is then pumped back into the system as cool water. The TCU can produce 200W of heat during operation, requiring a large radiator with sufficient airflow.

Figure 13: 360mm radiator with 120mm fans [4]

A 360mm radiator with three 120mm fans as seen in Figure 13 above creates a closed loop system for the water, reducing maintenance time and increasing operation time. The system uses G1/4" fittings for compatibility with the TR block.

4 HUMIDITY CONTROL UNIT (HCU)

The humidity control system is designed to maintain precise control of the humidity within the inkjet printing compartment of the FEU. It produces a high RH level to prevent sample evaporation and contamination (through condensation). The main design considerations are listed below:

- Humidification system
  - Water Heating
  - HCU Sterilization
  - Pressure Relief Valve
  - Pump
- Dehumidification system
  - Dehumidification Method (TECH Condenser)
  - Tubing
  - Adaptor
- HCU Sensors
- Integration with Enclosure

4.1 Humidification System

The WDM in Table 5 compares different humidification methods, with bubble humidification receiving the highest overall score. Bubble humidification satisfies all design requirements, including F2.0, F2.1, F2.4, C1.2, and C1. It is one of the few humidification methods that produce water vapours instead of the larger, contamination-prone water aerosols that are generated by more common methods.

Criteria	Weight (%)	Humidification System									
		Bubble		Steam		Ultrasonic		Wick		Impeller	
		Score	WS	Score	WS	Score	WS	Score	WS	Score	WS
Creates small-sized water vapor	30	100	30	75	22.5	0	0	100	30	0	0
Does not bring in contaminants	30	100	30	100	30	0	0	75	22.5	0	0
Required time to reach the desired RH	20	100	20	25	5	75	15	0	0	50	10
Low Power Consumption	20	75	15	0	0	50	10	100	20	25	5
TOTAL (%)		**95.0**		58.0		25.0		72.5		15.0	

Table 5: WDM for humidification system selection

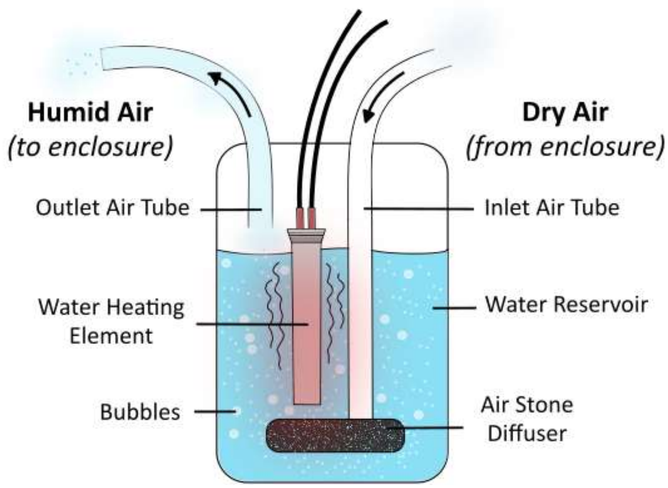


Figure 14: Humidification system with bubble humidifying mechanism

Several factors that constrain the performance of the bubble humidification system include:

1. Inlet air flow rate
2. Size of the air bubble produced
3. Water temperature inside the reservoir
4. Height of the water level

The inlet air of the humidification system is generated with an air pump. The time for the humidification system to reach 95% RH is reduced with a higher inlet air flow rate. To improve the performance, the air bubble size should be minimized to obtain a higher surface area-to-volume ratio for each air bubble[5].

Furthermore, a higher reservoir water temperature increases the RH level of the outlet air entering the FEU. A water temperature control unit moderates the temperature of the water (see section 4.1.1). A higher water level inside the reservoir also increases the RH level of the outlet air because it allows a longer contact duration between the air bubbles and the water molecules.

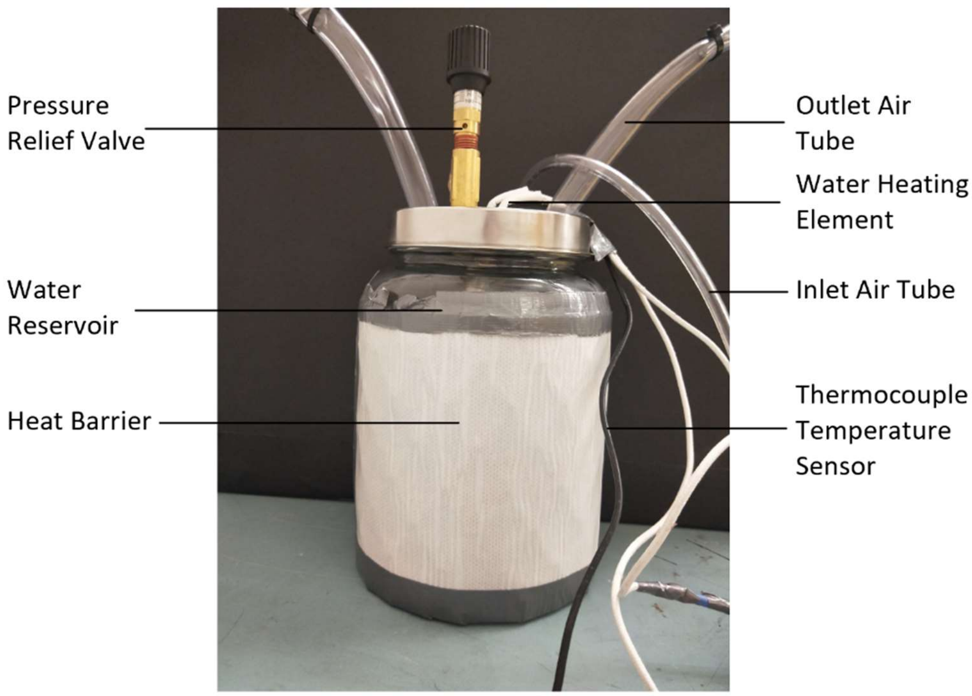


Figure 15: Bubble Humidification System Components

4.1.1 Water Heating

An immersion water heater is chosen to modulate the temperature of water inside the humidification reservoir to satisfy requirement F3.4. The WDM in Table 6 provides justification for this design choice.

Criteria	Weight (%)	Water Temperature Control									
		Electric Heat Pad		PTC Heating Element		Heat pipe		Immersion Water Heater		Peltier	
		Score	WS	Score	WS	Score	WSl	Score	WS	Score	WS
Heat Exchange Area	30	100	30	25	7.5	0	0	75	22.5	25	7.5
Ability to Heat Water	30	0	0	75	22.5	0	0	100	30	75	22.5
Low Cost	15	100	15	50	7.5	25	3.75	75	11.25	0	0
Ease of Control	15	0	0	75	11.25	25	3.75	100	15	0	0
Safety	10	100	10	75	7.5	0	0	50	5	75	7.5
TOTAL (%)		55.0		56.25		7.5		**83.75**		37.5	

Table 6: WDM for water temperature control method

Figure 16: (a) Immersion water heater DNCA1501154 [6] (b) Heat barrier Thermo-Tec 13575 [7]

(c) Pressure relief valve CR25-100 [8]

The water heater is controlled through a relay and provides uniform heating. Further details are described in Section 6.3.2.2

A waterproof thermocouple temperature sensor DS18S20 measures the real-time water temperature for control purposes. The heat barrier pad serves as a thermal shield, isolating the cylindrical wall of the reservoir from the surrounding air to reduce heat loss. A pressure relief valve is implemented to avoid pressure build up inside the reservoir as dry air is introduced.

4.1.2 Water Sterilization

The water reservoir used in the humidification system is sterilized by UV light and is filled with deionized water to satisfy constraint C1.3. The WDM Table 7 identifies the reasons this method is chosen.

Criteria	Weight (%)	Sterilization Method									
		UV Light		Boiling		Iodine Solution		Chlorine Drops		Water Filter	
		Score	WS	Score	WS	Score	WS	Score	WS	Score	WS
Does Not Change Water State	20	100	20	0	0	100	20	100	20	100	20
Does Not Need to be Frequently Replaced	40	75	30	100	40	0	0	25	10	50	20
Easily Controllable	40	100	40	75	30	0	0	0	0	0	0
TOTAL (%)		**90**		70		20		30		40	

Table 7: WDM for water sterilization method

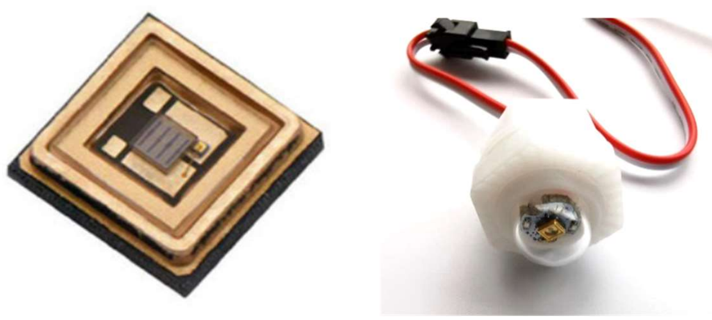


Figure 17: (a) Deep UV-C LED 265nm LW-265S35C (b) Quartz glass protector [9]

UV-C light is selected for sterilization as it can be enabled and disabled easily with a microcontroller and has a longer lifespan than alternative methods. 265nm wavelength is chosen for germicidal purposes, as it is the optimum wavelength for water disinfection. A quartz glass protection tube is used to protect the LEDs from water while still facilitating the propagation of UV light. The UV light runs for 30 seconds prior to humidification to eliminate bacteria within the water reservoir.

4.1.3 Air Pump

Based on the experimental results from the Validation Document [26], section 3.3.4 and 3.4.4, two air pumps with a total air flow rate of 36L/min are chosen as the inlet air source. Together, the air pumps satisfy the flow rate requirements of the humidification system. Other commercial air pumps available either do not satisfy the flow rate requirements of the system or are not used for gas flow specifically.

Figure 18: Air pump B078H92695 [10]

4.2 Dehumidification System

The dehumidification system eliminates oversaturation and condensation of water vapours inside the FEU, satisfying C1.1. Air is moved over a cooled heatsink which condenses the water vapours, removing them from the enclosure air. The TECH condenser dehumidification system is depicted in Figure 19 and Figure 20. Two of these systems are used in the FEU and attach to the back wall of the enclosure as seen in Figure 3**.**

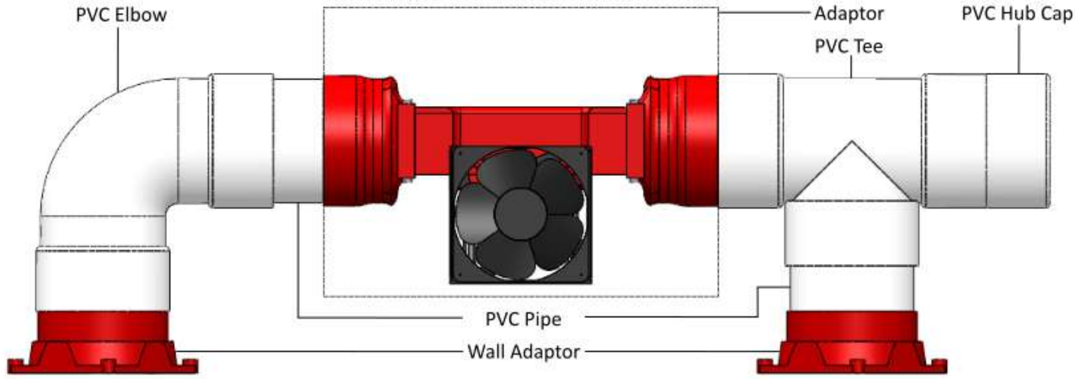


Figure 19: Complete system modelled in SolidWorks

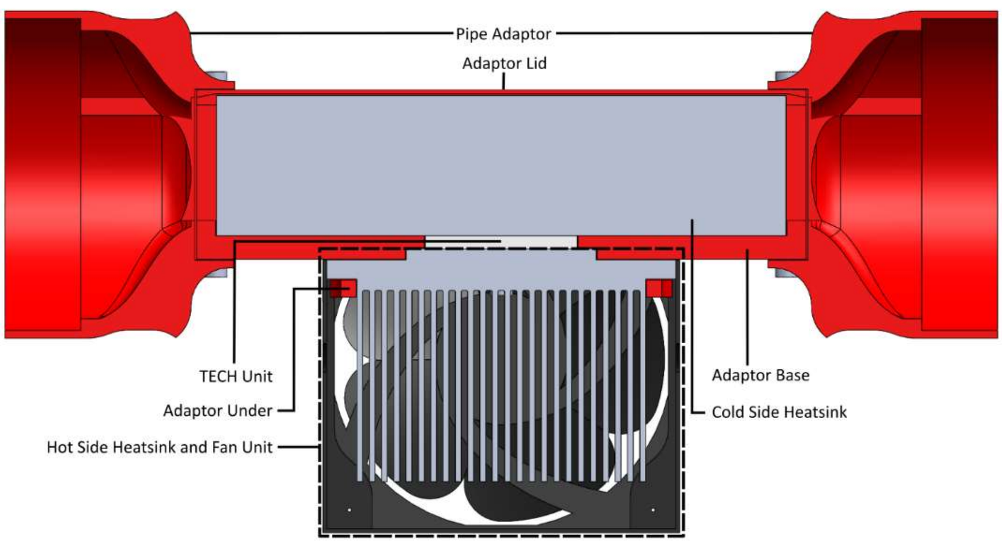


Figure 20: Cross-sectional view of adaptor in SolidWorks

4.2.1 Dehumidification Method

The TECH cooling mechanism is chosen for the dehumidification system. The WDM in Table 8 compares different dehumidification methods, with TECH dehumidification receiving the highest overall score. The product selected is identical to that seen in Section 3.1.4.

Criteria	Weight (%)	Dehumidification System							
		TECH		Desiccant Rotor		Refrigeration		Ionic Membrane	
		Score	WS	Score	WS	Score	WS	Score	WS
Does Not bring in contaminants	30	100	30	50	15	100	30	0	0
Required time to reach the desired RH	30	100	30	25	7.5	75	22.5	0	0
Low Power Consumption	15	50	7.5	100	15	0	0	100	15
Ease of Control	15	100	15	25	3.75	50	7.5	0	0
Safety	10	50	5	100	10	0	0	100	10
TOTAL (%)		**87.5**		51.25		60		25	

Table 8: WDM for dehumidification system selection

4.2.2 Piping

As depicted in Figure 19, pipes are used to move air through the dehumidification system and back into the enclosure. The selected PVC pipes are 3 inches in diameter to match the heatsink width. The reason for this material selection is found in Table 9.

Criteria	Weight (%)	Tube Material			
		PVC		ABS	
		Score	WS	Score	WS
Sterilizable with Ethanol	30	75	22.5	100	30
High Tensile Strength	55	100	55	50	27.5
Low Cost	15	75	11.25	100	15
TOTAL (%)		**88.75**		72.5	

Table 9: WDM for Pipe Material Selection

4.2.3 Pipe Adaptor

The 3D printed portions of the dehumidification system are shown in the figures from Section 4.2; they are essential for separating the hot and cold sides of the TECH element and for keeping the enclosure air isolated from the external air. The WDM in Table 11 shows why PETG is selected for the 3D printed components.

Criteria	Weight (%)	3D Printing Material							
		PLA		ABS		PETG		Nylon	
		Score	WS	Score	WS	Score	WS	Score	WS
Does Not React to disinfectants	20	100	20	50	10	100	20	100	20
Low Cost	10	100	10	50	5	75	7.5	25	2.5
Temperature resistance	30	25	7.5	100	30	75	22.5	75	22.5
Easy to Print	20	100	20	25	5	100	20	25	5
Reaction to high RH	20	75	15	100	20	75	15	25	5
TOTAL (%)		72.5		70		**85**		55	

Table 10: WDM for Selecting 3D Printing Material

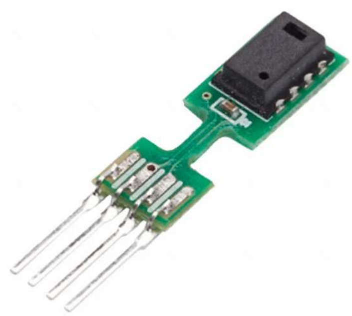
4.3 HCU Sensors

The sensor of choice is a CC2D23-SIP which meets F3.1 and F3.2. Table 11 shows the criteria used to make this selection.

Criteria	Weight (%)	Humidity Sensor					
		DHT-11		DHT-22		CC2D23-SIP	
		Score	WS	Score	WS	Score	WS
High Precision	30	0	0	100	30	100	30
High Accuracy	30	0	0	100	30	100	30
High Sampling Rate	30	50	15	0	0	100	30
Low Cost	10	100	30	50	5	0	0
TOTAL (%)		45		65		**90**	

Table 11: WDM for humidity sensor selection

This sensor also has temperature detection which is used to measure the temperature of the ambient air. The CC2D23-SIP is used due to its high precision and accuracy measurements in addition to the high sampling rate.



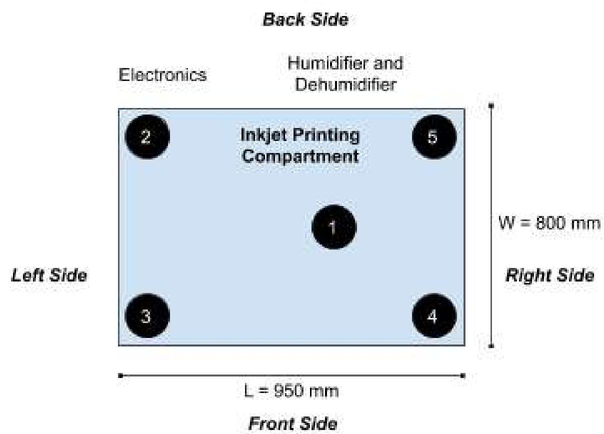


Figure 21: (a) CC2D23-SIP humidity/ temperature sensor [11] (b) Placement within enclosure

There are five humidity sensors placed throughout the enclosure. CC2D23-SIP is placed next to the sample and acts as the main sensor for ambient temperature and humidity control. Four DHT22 sensors are used to ensure ambient temperature and RH are relatively stable throughout the entire space. They are stationed in the corners of the enclosure, as see in Figure 21.

5 FILTRATION AND ENCLOSURE UNIT (FEU)

The filtration and enclosure unit provides a stable environment for the cell isolation process. The inkjet printer is housed within the main chamber of the FEU, while electronics and humidifier components are mounted externally. The main design aspects of the FEU are listed below:

- Paneling materials and thickness
- Frame
- Structure
    - Conduits and conduit placement
    - Door gasket and seal mechanism

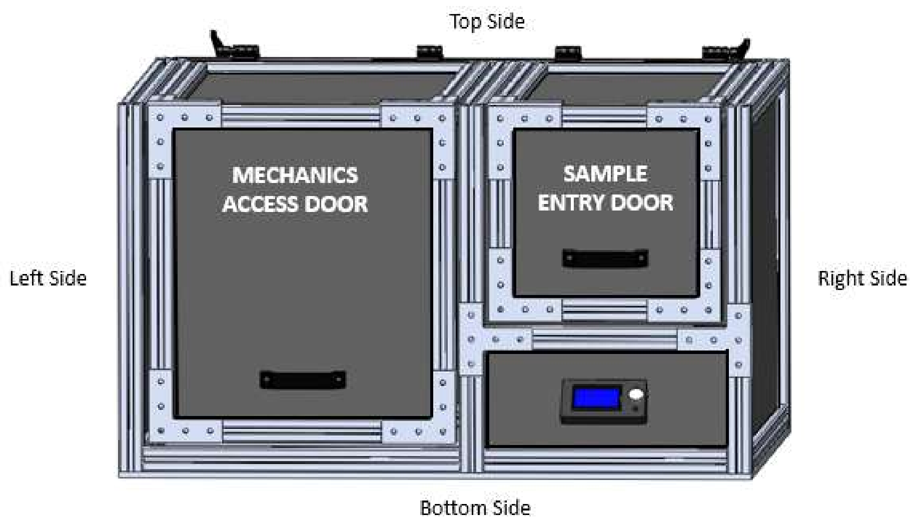


Figure 22: 3D CAD model of enclosure

5.1 Paneling Materials

Opaque polypropylene panels are used for the walls for the enclosure; the following section provides justification for this design choice.

NF4.0 to NF4.3 specify that certain materials are unsuitable for the project. Table 12 outlines the faults of different paneling options and why they are inappropriate for this application.

Material	Problems with the Material	
	Problem	Description
Metals	Conflicts NF4.2	● May oxidize or rust in the presence of humidity ● Metals that do not rust are more expensive
	Not thermally insulative	● Thermal insulation is a preference for the humidity control system
Wood	Conflicts NF4.2	● May warp, crack, or shrink in the presence of humidity
	Conflicts NF4.1	● May mold in the presence of humidity ● Sawdust may contaminate environment
	Not sterilizable	● Porous nature prevents the material from being properly cleaned
Foam	Not mechanically robust	● Can break with relatively small forces
	Not sterilizable	● Porous nature prevents the material from being properly cleaned
Glass	Not mechanically robust	● Brittle, low impact resistance
	Minimally thermally insulative	● 4 times less thermally insulative than common plastics
	Heavier than common plastics	● 2 times heavier than acrylic ● To achieve the same insulation, multiple panels would be required and thus the resultant weight would be quite unreasonable (see NF4.3)
Ceramic	Not mechanically robust	● Brittle, low impact resistance ● May crumble at cut edges therefore dimensional tolerance is difficult to control during processing
	Not sterilizable	● Porous nature prevents the material from being properly cleaned

Table 12: Challenges with common building materials

Plastics are concluded to be the best option for enclosure paneling. Table 13 compares the relevant materials properties of different plastics, where a score of 100 indicates the highest affinity for an attribute relative to the available options. See Appendix E for further details on materials properties.

Criteria	Weight (%)	Paneling Material Option									
		PA		ABS		PMMA		PP		PC	
		Score	WS	Score	WS	Score	WS	Score	WS	Score	WS
Available Through ECE	2.5	0	0	0	0	100	2.5	0	0	100	2.5
UV Light Resistance	7.5	75	5.6	25	1.9	100	7.5	75	5.6	75	5.6
Low Cost	10	25	2.5	25	2.5	50	5	100	10	0	0
Dimensional Stability	10	0	0	25	2.5	100	10	100	10	100	10
Thermal Resistivity	10	0	0	100	10	75	7.5	75	7.5	25	2.5
Sterilizable by ethanol	30	100	30	50	15	50	15	100	30	100	30
Low Water Absorption	30	0	0	25	7.5	75	22.5	100	30	75	22.5
TOTAL (%)		38.1		39.4		70.0		**93.1**		73.1	

Table 13: WDM for paneling material selection

Overall, polypropylene is the best option for the enclosure paneling, receiving a WDM score of 93%. Polypropylene is appropriate due to its high thermal, mechanical, and chemical robustness, as well as high resistance to water absorption.

A paneling thickness of 6mm is chosen to minimize the heat loss during HCU ambient temperature control without incurring significant additional cost. Since ambient temperature control is not implemented for this version of the project, heat loss is not a primary concern. See Appendix E for further information on paneling thickness and heat loss calculations.

5.2 Frame

The frame of the enclosure comprises 4040 series aluminum t-slot extrusions. Aluminum is ideal because it is lightweight, mechanically robust, corrosion resistant, and sterilizable. Unlike wood and plastics, it is less likely to warp or deform under loads and in higher moisture or temperature conditions.

Figure 23: 4040 aluminum t-slot extrusion [12]

T-slot extrusions are chosen because they are highly modular and flexible as opposed to welded steel, allowing structures to be modified and re-assembled as needed.

Figure 24: (a) 40-4481 "L" flat plate fastener [13] (b) 40-4488 locking zinc hinge [14]

The extrusions are fastened together using "L" flat plates from the 40 series catalog. Zinc locking hinges are used to facilitate movement of the doors. The hinges feature a ratcheting and locking mechanism, allowing the doors to be propped open without additional support (satisfying NF1.2 and NF1.3).

5.3 Structure

The structure of the enclosure is designed to maximize the use of space and provide ease of operation. Two 90-degree angled doors provide full-access to the inside of the enclosure; the smaller door allows sample entry and retrieval with minimal disturbance to the inner environment, while the larger door provides greater access to the printer mechanics. The dimensions of the doors are chosen to satisfy NF1.0

Figure 25: Example of a 90-degree door [15]

The enclosure structure includes a main inkjet printing compartment, with mounts off the back panel for HCU, TCU, and ECU components.

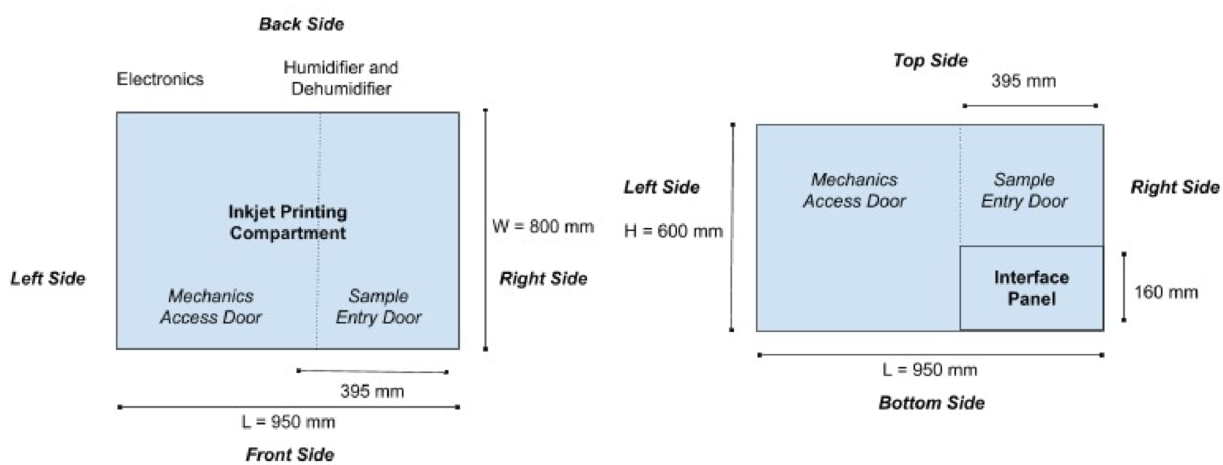


Figure 26: FEU compartmentalization (a) Top view of (b) Front view

5.3.1 Conduits and Conduit Placement

Cable glands provide passage of cables between FEU compartments. The cable glands fit tightly into holes cut through the polypropylene panels. Compression rings within the cable glands act as a seal, preventing external contaminants from entering the inkjet printing compartment and humid air from affecting the electronics.

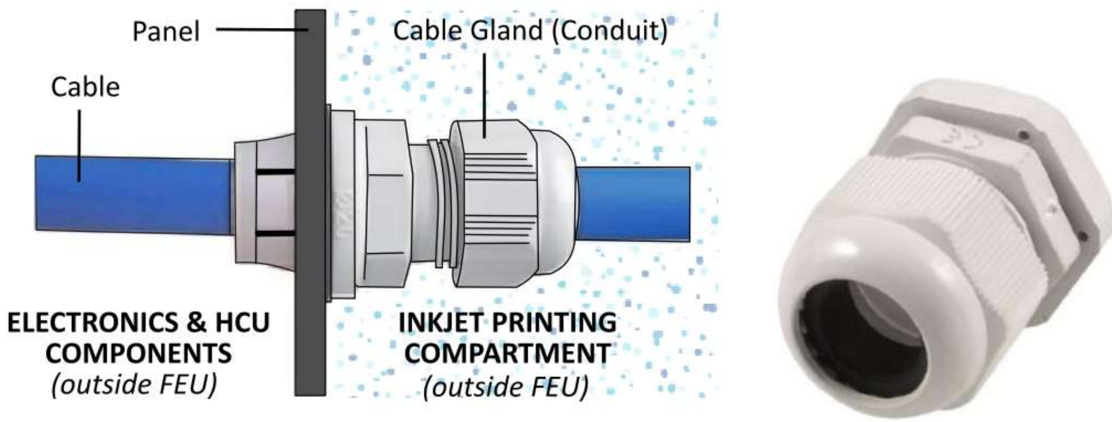


Figure 27: (a) Cable gland (b) Fitting waterproof PG-21 white, Lee's Electronics [16]

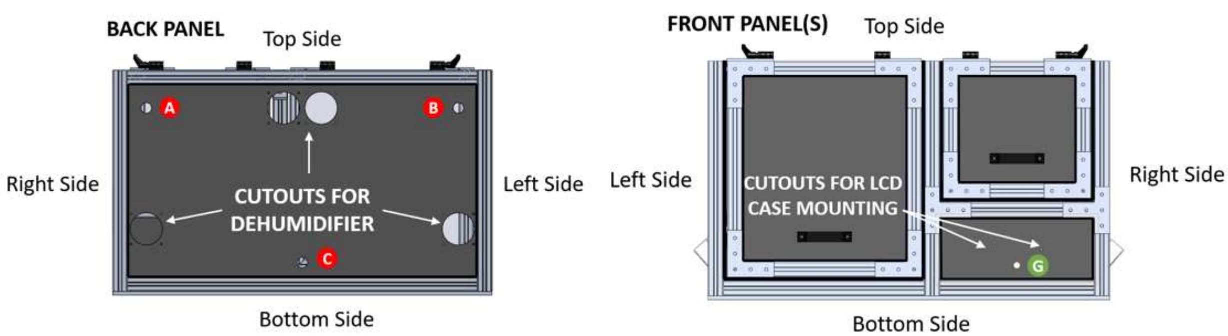


Figure 27: Conduit placement (a) Back panel (b) Front panel(s)

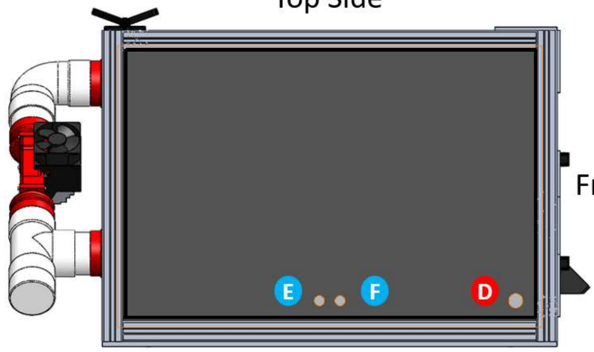


Figure 27: Conduit placement on left panel

Label	Location	Cables/Tubes Passing Through | Purpose		Conduit Type
A	Back panel, top left	1 x 19.05 mm tube	Humidifier	PG-21
B	Back panel, top right	1 x 19.05 mm tube	Humidifier	PG-21
C	Back panel, bottom center	4 x 1.3208mm wire 16 x 1.524 mm wire 15 x 1.524 mm wire 1 x 6.5 mm cable 1 x 7.7 mm cable	Dehumidifier Dehumidifier TCU Control Inkjet Printer Inkjet Printer	PG-21
D	Left panel, bottom right	2 x 5.5 mm cable 1 x 5 mm cable 2 x 1.5 mm wire	Inkjet Printer Inkjet Printer Inkjet Printer	PG-21
E	Left panel, bottom center	1 x 11 mm tube	TCU Water Cooling	PG-13.5
F	Left panel, bottom center	1 x 11 mm tube	TCU Water Cooling	PG-13.5
G	Front panel, center	10 x 1.3208mm wire	LCD Wiring	PG-9

Figure 28: Conduit placement and specifications

5.3.2 Door Gasket and Seal Mechanism

4040 series polypropylene gaskets are inserted within the t-slot grooves to improve the seal of the FEU. The gaskets compress against the polypropylene panels to minimize any gaps and prevent leakage through the wall. This ensures that the sterile, humid air is entrapped within the inkjet printing compartment, while the contaminated air is kept external to the FEU. 4040 series rubber door seals are also used to line the door frame.

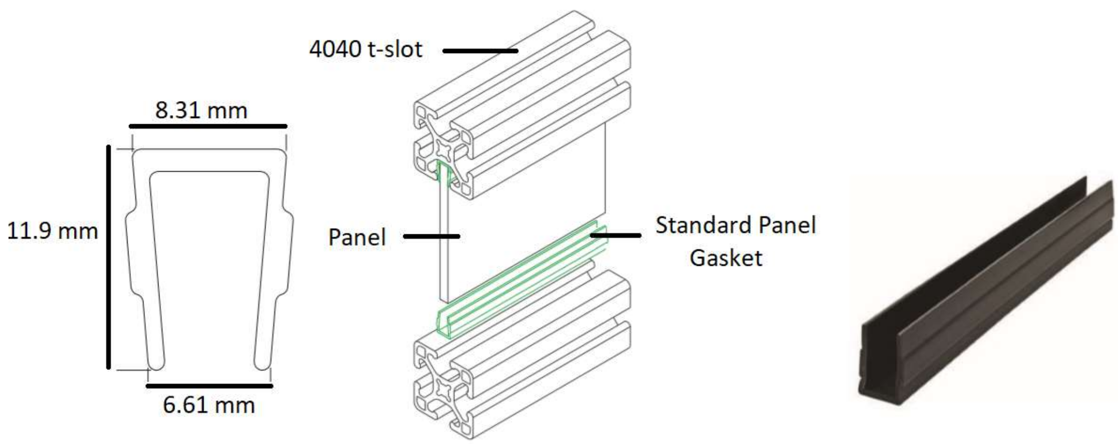


Figure 29: 40-2120 panel gasket (a) Cross-section (b) Insertion schematic (c) Photo [17]

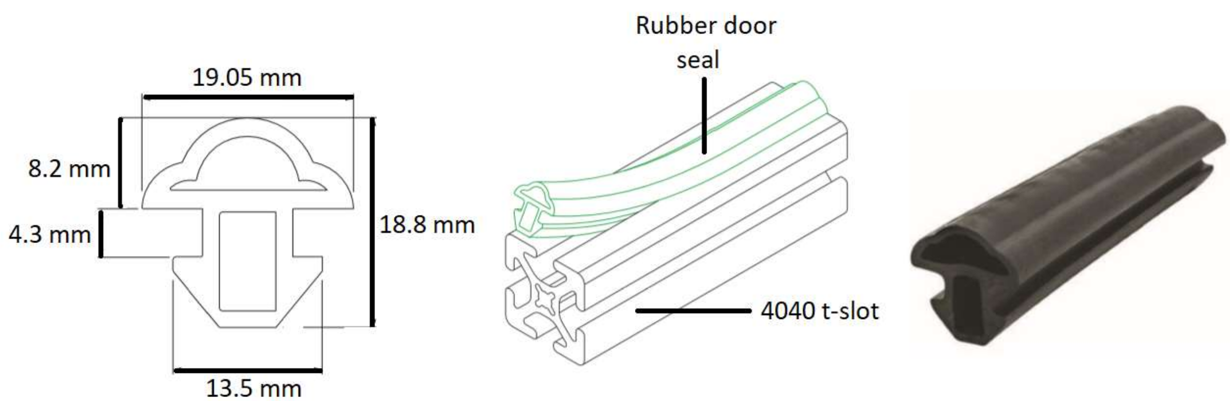


Figure 30: 2829 rubber door seal (a) Cross-section (b) Insertion schematic (c) Photo [18]

6 ELECTRONICS CONTROL UNIT (ECU)

The ECU integrates and controls the HCU, TCU and FEU; it is responsible for executing commands, recording, analyzing, and processing data, ensuring that setpoints are reached in an optimal manner. The ECU also includes the power system and user interface. The primary design aspects of the ECU are:

- Power system
- Primary microcontroller
- Sensor integration and System control
- User Interface and FSM

6.1 Power System

The power system supplies power to both the HCU and TCU; it consists of the following elements:

- 450 W 120 VAC to 12VDC/5VDC PSU
- RAMPS 1.4 Controller Board
- LM2596S Current Regulator Board

1. 450W PSU

The 450W PSU meets the power needs of the various subsystem components. It adapts the AC wall-outlet power to DC voltage (satisfying NF3.0), allowing it to be used by the various DC electronic components in the system.

2. RAMPS 1.4 Controller

The RAMPS is an attachment for the Arduino MEGA that provides supplementary circuitry for power and control. On its own, the Arduino MEGA cannot provide enough current to drive the LCD, UV lights, and additional components; the RAMPS solves this by interfacing between the Arduino and subcomponents, amplifying signals as needed.

3. Current Regulator

The UV lights required for sterilization of the bubble humidifier are very sensitive to fluctuations in current, thus a current regulator is required. The current regulator ensures that the current does not exceed 40mA for each UV light.

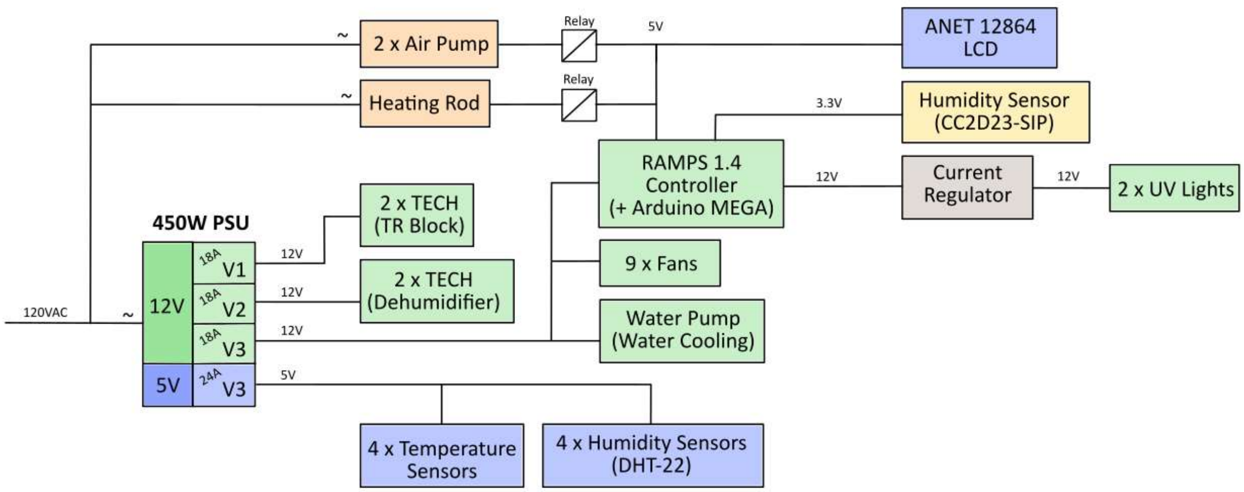


Figure 31: Simplified power system layout

6.2 Primary Microcontroller

The primary microcontroller is an Arduino Mega 2560; it controls the HCU and TCU, integrating feedback from the temperature and humidity sensors to provide precise and dynamic regulation of the internal FEU conditions. The primary microcontroller also controls the user interface.

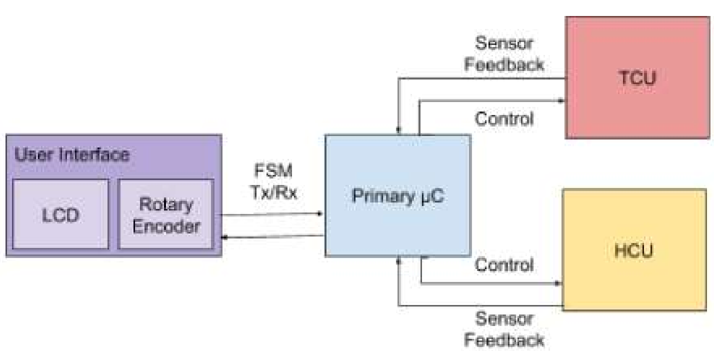


Figure 32: Simplified flow diagram of primary microcontroller system

Data detected from the TCU and HCU is processed and converted into user-interpretable values within the primary microcontroller. The processed data is then utilized within the main control system, with control signals feeding back to the TCU and HCU to ensure setpoints are maintained appropriately. The processed data is also transmitted to the user interface and displayed on the LCD so that users receive real-time information about the internal conditions of the FEU.

6.3 Sensor Integration and System Control

The following section describes the control processes for each subsystem.

6.3.1 TCU Control System

The TCU control system can be broken down into three components as seen in Figure 33.

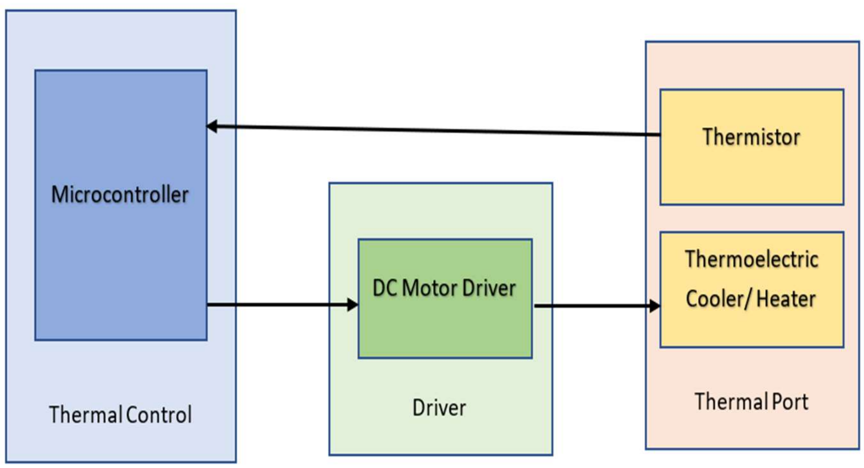


Figure 33: TCU system diagram

1. ***Thermal Control:*** main function is to perform calculations to determine the appropriate PWM signal to send to the driver unit. The calculations are performed using the user-defined setpoints and the temperature readings from the thermistor using a PID control loop.

2. ***Motor Driver:*** primary function is to process the input signal from the controller unit and output the correct current to power the thermal port.

3. ***Thermal Port:*** receives power from the driver unit and powers the thermoelectric cooler. The TECH unit also sends the temperature reading from the thermistor back to the controller unit.

6.3.1.1 Temperature Control Logic

An Arduino microcontroller (see Appendix F) sends PWM and direction signals to the driver unit; the PID feedback control loop allows selection and maintenance of various temperature setpoints, per F1.0, F1.1, F1.2. Other control methods such as open loop control would not allow for a precise real-time response, thus they are not considered for this design aspect.

Figure 34 shows the logic for the temperature control per one instance of operation. The key concept is using the ambient temperature as a heat source and sink. Naturally, the heat will transfer in and out of the system to reach the equilibrium ambient temperature. This system utilizes said phenomenon in the 'Do nothing' operation. By letting the system heat or cool naturally, the driver does not need to switch polarity actively, reducing strain on the TECH and the driver.

In terms of control, the system compares the setpoint temperature with the ambient temperature to select the mode to operate in. It then compares the setpoint temperature with the sensor readings and the setpoint. It either does nothing or sends power to the TECH to increase or decrease the temperature to reach the setpoint. The Arduino's PID function [19] is used to calculate the magnitude of increment and decrement of temperature. Refer to Appendix H for further information on TCU Modeling.

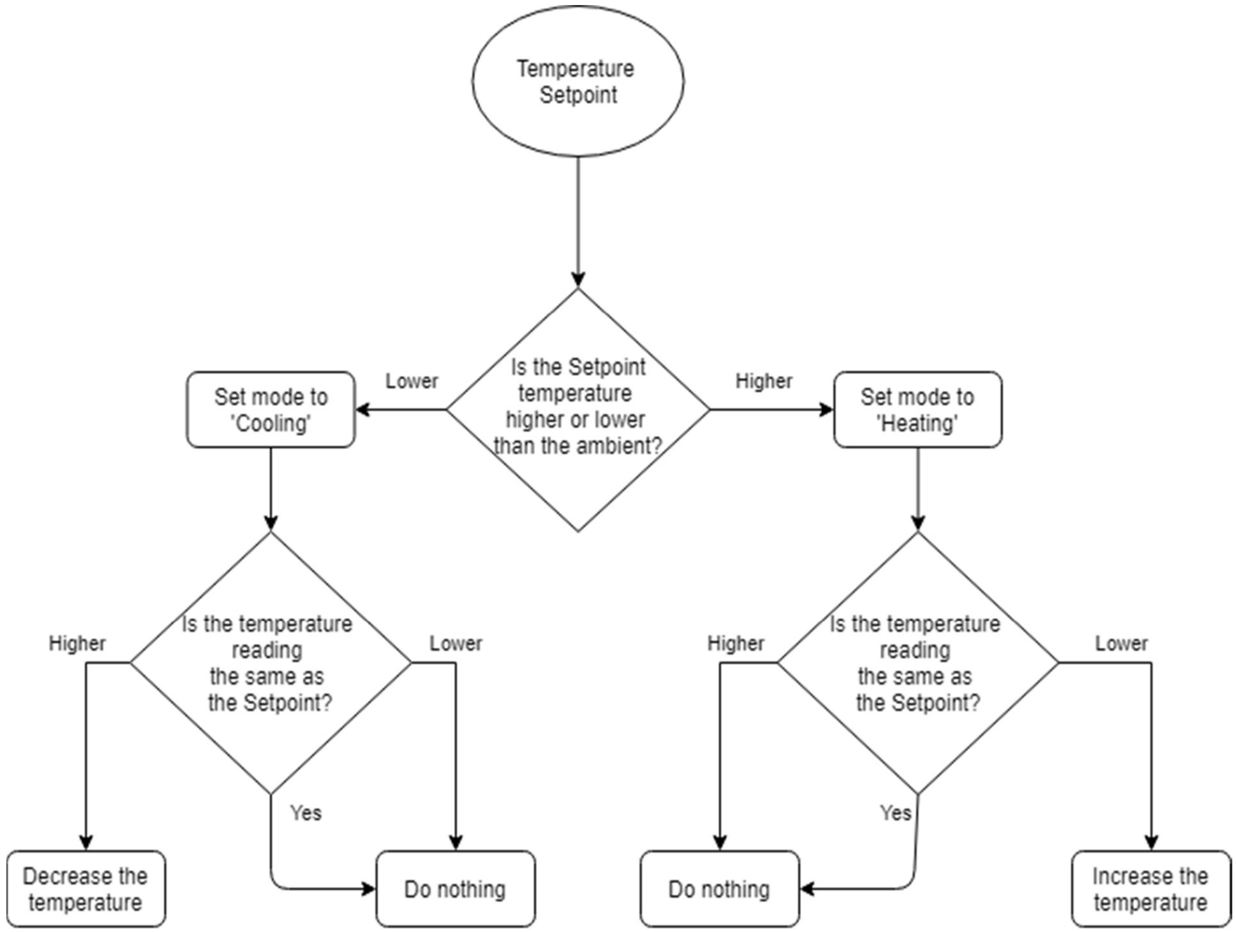


Figure 34: Flow Diagram for Temperature Control

6.3.1.2 DC Motor Driver

The DC motor driver modulates the power sent to the TECH unit based on the input signal from the controller. The key functionality of the driver includes:

- ***Variable Current Output***:
  - Allows the TECH to adjust the rate of heating and cooling.
- ***Switching Polarity***:
  - Allows the TECH to switch between heating and cooling mode.

The DC motor driver is selected based on the WDM in Table 14:

Criteria	Weight (%)	Motor Driver					
		L298		BTS7960		MDD10A	
		Score	WS	Score	WS	Score	WS
Current Rating	40	0	0	100	40	100	40
Voltage Rating	10	100	10	100	10	100	10
Cost	20	100	20	0	0	20	4
Output Frequency	10	0	0	100	10	100	10
Compatibility	20	100	20	0	0	100	20
Total (%)		50		60		**84**	

Table 14: WDM for motor driver

The MDD10A is selected, scoring the highest within the WDM. The main attraction of this module is its current output combined with its compatibility with other system components.

Figure 35: Dual MDD10A motor driver [20]

6.3.1.3 TCU Control Circuit

The following circuit schematic shows how the sensor and driver is connected to the Arduino pins.

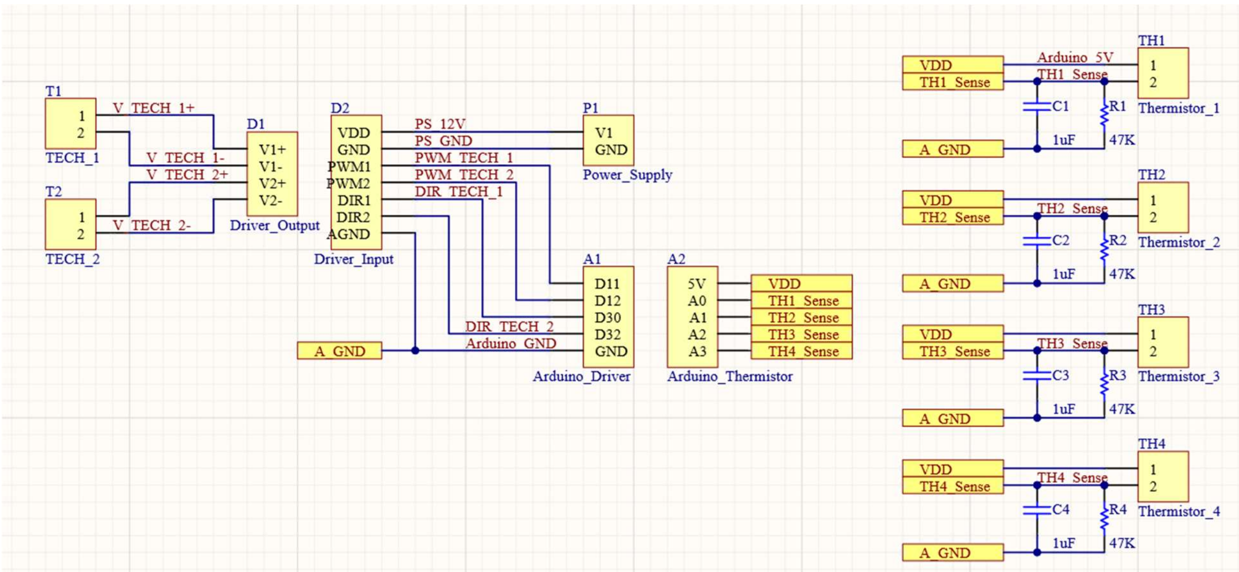


Figure 36: Schematic of TCU control circuit

6.3.2 HCU Control System

The system control for the HCU responds to different well plate setpoints and is highlighted within the flowchart in Figure 37. The system control ensures that the HCU satisfies requirement F2.0. This is controlled by an Arduino microcontroller (see Appendix F). The system control is based on readings from the CC2D23-SIP humidity and temperature sensor selected in Section 4.3.

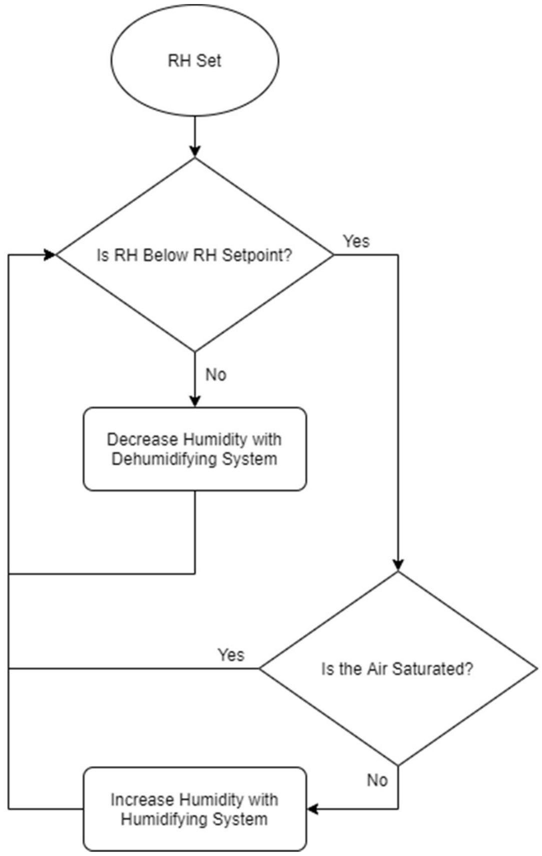


Figure 37: Flow diagram for humidity control

6.3.2.1 HCU Sensor Circuit

The following circuit schematic shows how the sensor is connected to the Arduino pins.

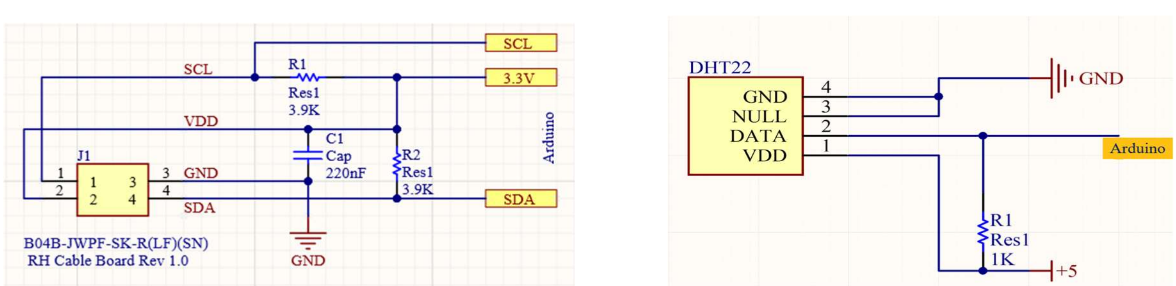


Figure 38: Humidity Sensor to Arduino Schematic (a) CC2D23-SIP (b) DHT22

6.3.2.2 Humidification System Circuit

The schematic shown in Figure 39 illustrates the circuitry of the humidification system to Arduino.

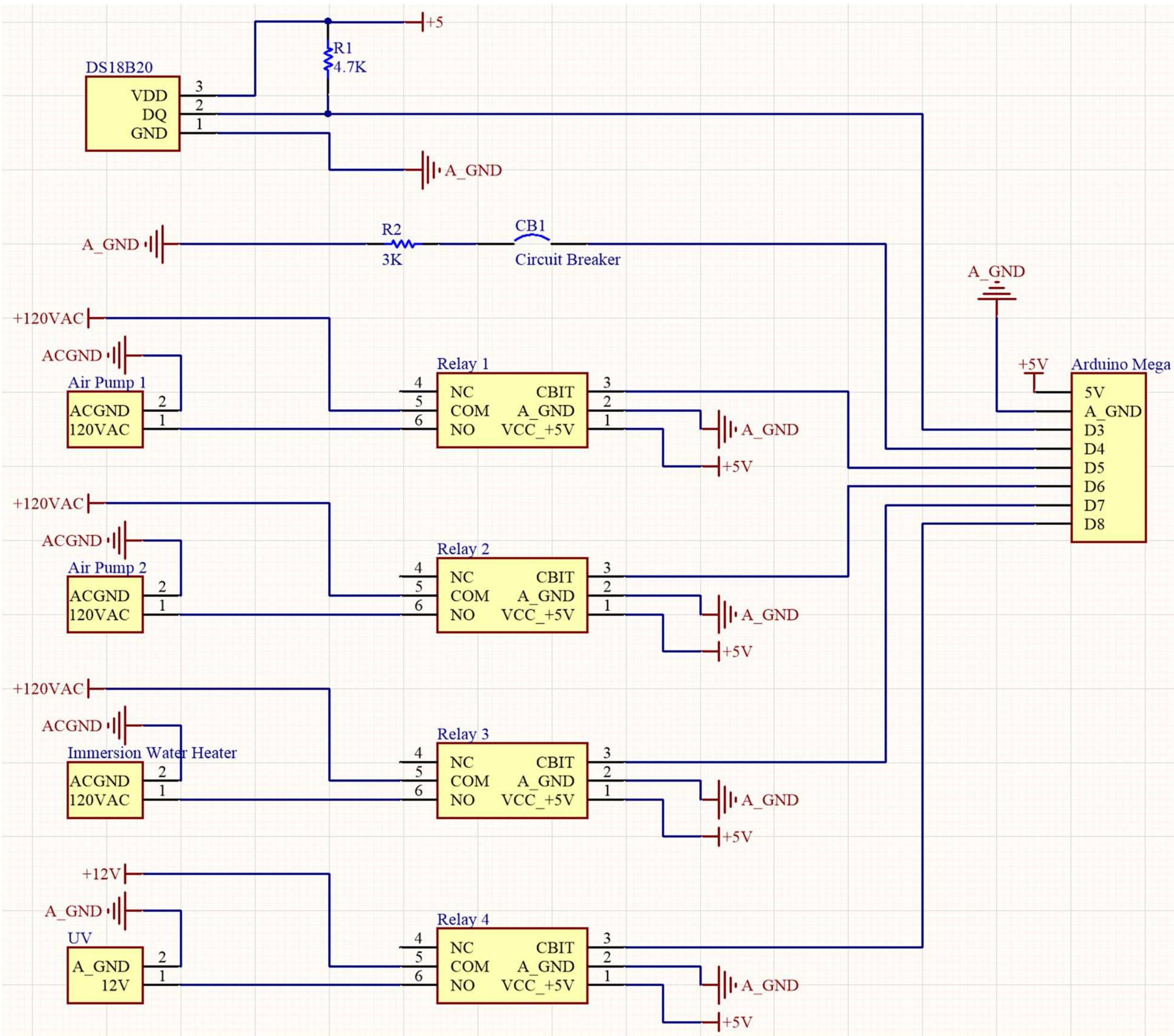


Figure 39: Humidification System to Arduino Schematic

6.3.2.3 Dehumidification System Circuit

The diagram seen in Figure 40 displays how the dehumidification system is connected to both the Arduino and the main power supply.

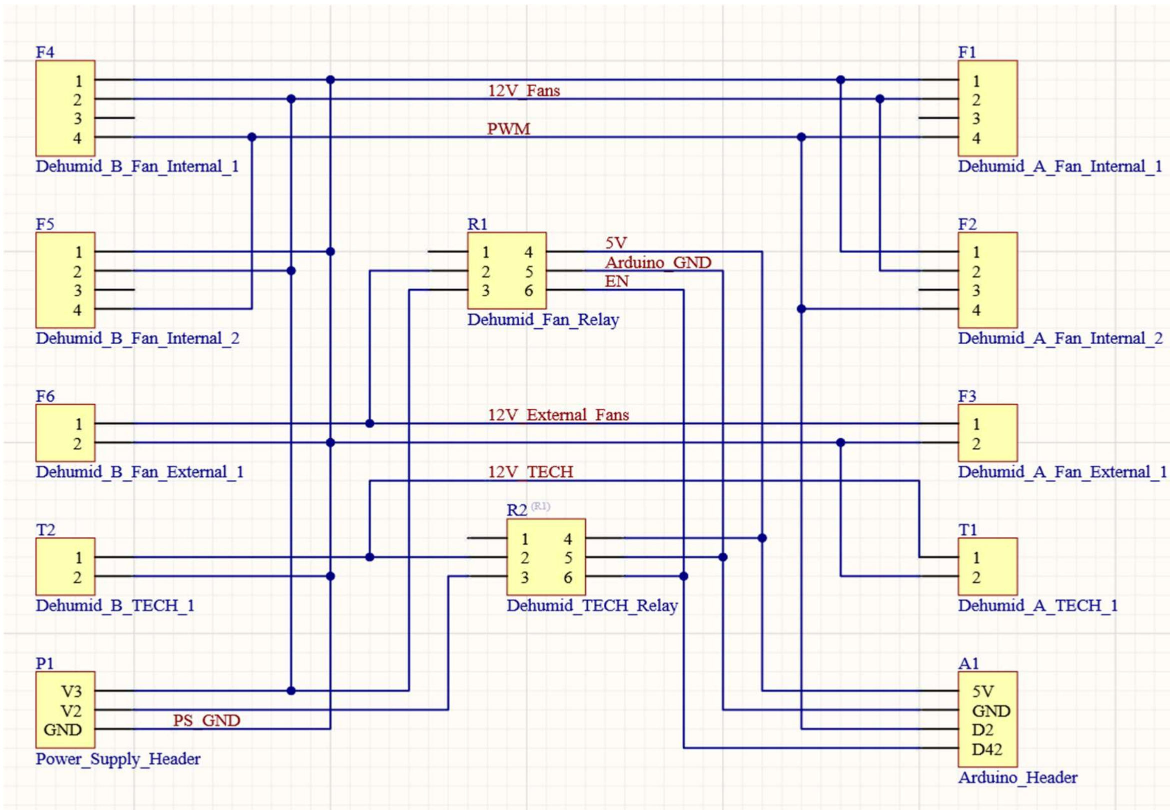


Figure 40: Dehumidification System to Arduino and Power Supply Schematic

6.4 User Interface and FSM

The user interface is designed to satisfy N5.0, N5.1, and N5.2. An Anet 12864 LCD Smart Display Controller module is used to toggle through the various options and display live data. Software within the primary microcontroller iterates through an FSM based on the user-selected inputs. The FSM is summarized in the Figure 42 flow-chart .

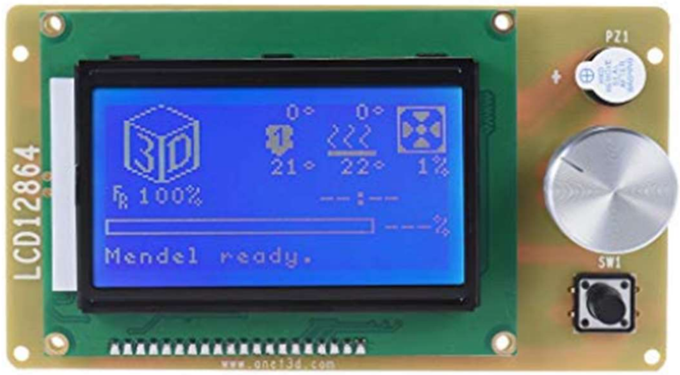


Figure 41: Anet 12864 LCD Smart Display Controller Module [21]

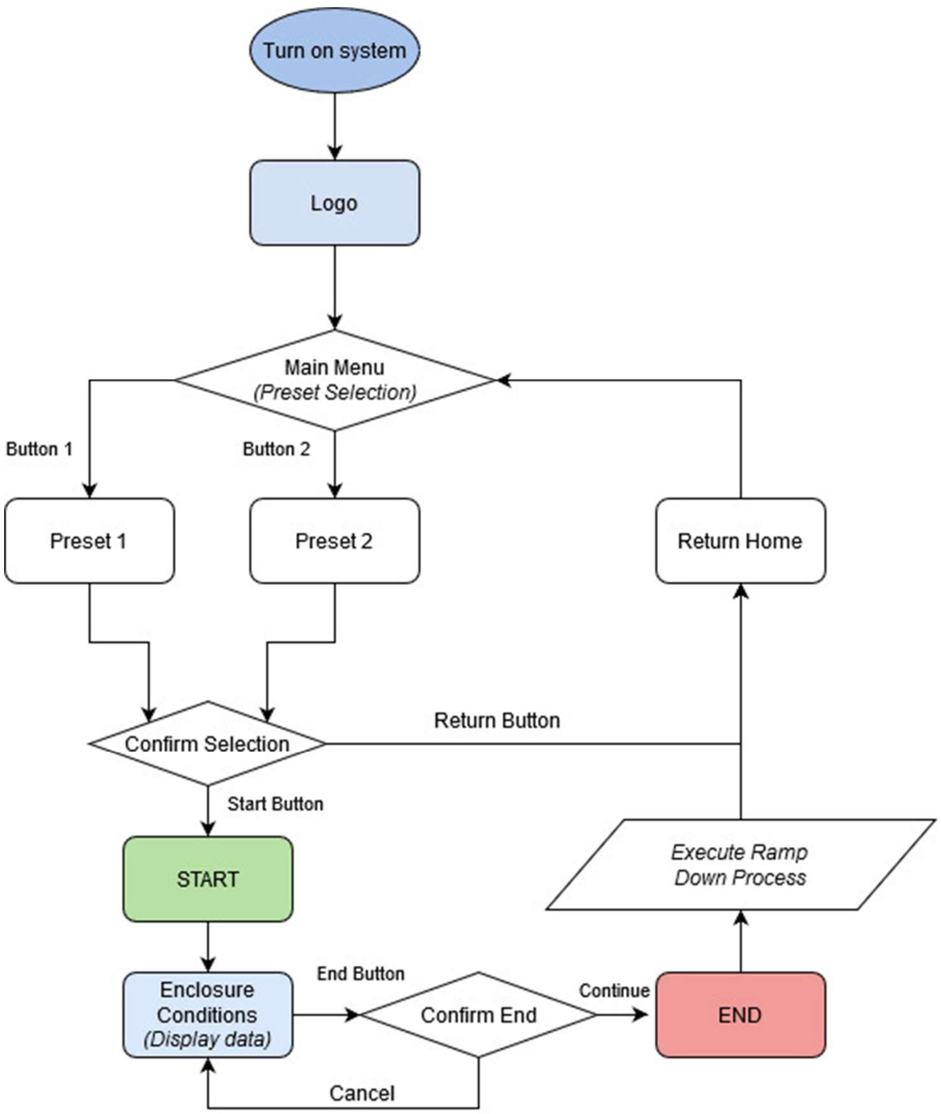


Figure 42: Simplified FSM flow diagram

The corresponding display screens for the FSM are depicted as follows. The user must first select the desired internal conditions (either Preset 1 or Preset 2). The user then confirms their selection and clicks START to initiate the environmental control sequence. To end the sequence, the user must select END; this will initiate a “ramp-down” process for the TCU and HCU, returning the FEU to an idle state. The ramp down process ensures all subsystems are turned off in an appropriate and safe manner. The user navigates through the different options using the rotary encoder.

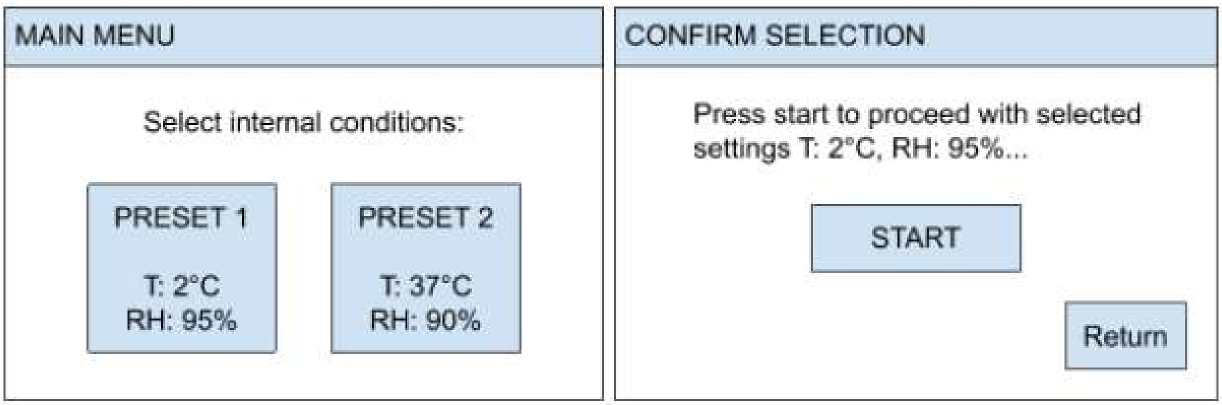


Figure 43: (a) Main Menu with preset selection (b) Confirm Selection display

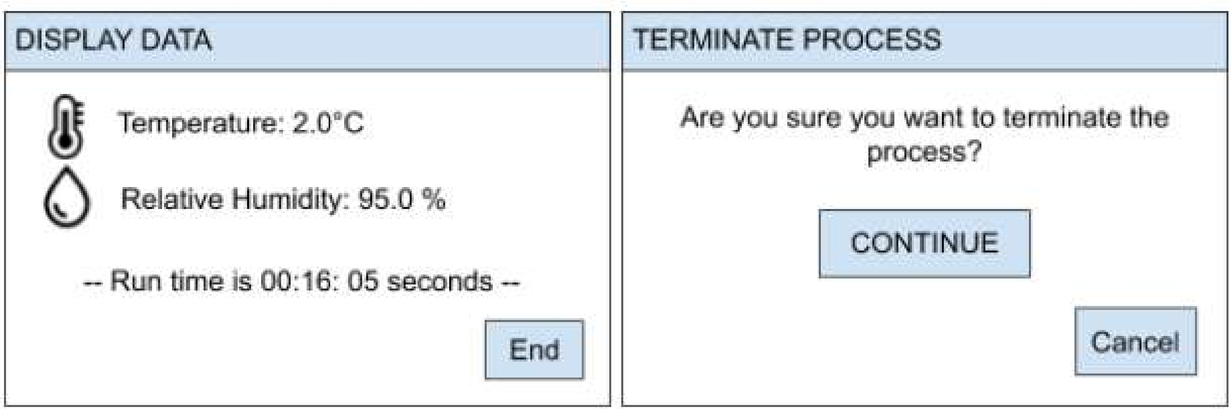


Figure 44: (a) Display Data screen (b) Terminate Process

APPENDIX A: DEFINITIONS

Chemical Property: Acetone @ 100%, 20°C	the chemical resistance of plastics to Acetone @ 100%, 20°C(ability to keep properties when exposed to this reagent)
Chemical Property: Ethanol @ 96%, 20°C	the chemical resistance of plastics to Ethanol @ 96%, 20°C(ability to keep properties when exposed to this reagent)
Coefficient of Linear Thermal Expansion	a material property which characterizes the ability of a plastic to expand under the effect of temperature elevation
Fire Resistance (LOI)	an index used to assess the burning capability or flammability of polymer
Glass Transition Temperature	the temperature at which amorphous polymer takes on characteristic glassy-state properties like brittleness, stiffness and rigidity (upon cooling)
Max Continuous Service Temperature	the maximum acceptable temperature above which mechanical properties (tensile strength, impact strength) or electrical properties (dielectric strength, linked to insulation properties) of a plastic part are significantly degrading
Min Continuous Service Temperature	the minimum acceptable temperature above which mechanical properties (tensile strength, impact strength) or electrical properties (dielectric strength, linked to insulation properties) of a plastic part are significantly degrading
Relative Humidity	the amount of water vapor present in air expressed as a percentage of the amount needed for saturation at the same temperature
Sterilization Resistance (Repeated)	the ability of polymers to endure repeated sterilization cycles (chemical, steam or gamma radiation sterilization…) without significant damage.

Surface area-to-volume ratio the ratio is the surface area divided by the volume; indicates how much surface area is available compared to how big the cell is

Thermal Resistivity the ability of a material to resist the flow of heat

UV Light Resistance how well a material resists photodegradation by UV light

Water Absorption 24 hours the capacity of a plastic or a polymer to absorb moisture from its environment

Young Modulus the ratio of the stress applied to the material to the deformation or strain, measured on that same axis

APPENDIX B: WDM DEVELOPMENT

The WDM is used to compare design alternatives and determine which alternative is best suited for the product. Design options are first scored relative to different criteria. Options that best match a given design criteria are awarded the highest score (i.e. 100 %), while options that fail to meet the criteria receive the lowest score (i.e. 0 %). The scores are then weighted relative to the importance of each design criteria, resulting in a weighted score (WS). For example, in Table 15, Option #1 receives a score of 25% for Criteria #1; since the weight of criteria #1 is 10%, the resultant weighted score for Option #1 is 2.5%. The weighted scores in each column are summed to produce the total weighted score. The total with the highest score is bolded, indicating the most favourable option.

Criteria	Weight (%)	Design Option					
		Option #1		Option #2		Option #3	
		Score	WS	Score	WS	Score	WS
Criteria #1	10	25	2.5	50	5	75	7.5
Criteria #2	20	25	5	50	10	75	15
Criteria #3	30	75	22.5	0	0	100	30
Criteria #4	40	50	20	25	10	75	30
TOTAL (%)		50		25		**82.5**	

Table 15: Template for WDM

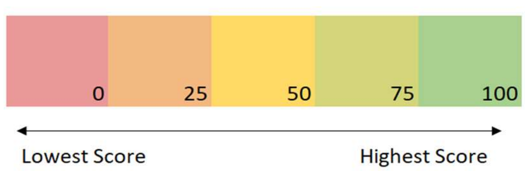


Figure 45: Colour scheme for WDM

Table 15 depicts the style of WDM used for this project. Each result is colour-coded according to the colour scheme in Figure 45, where red corresponds to the lowest score and bright green corresponds to the highest score.

APPENDIX C: TCU TEST PROTOTYPE 1

This section describes the previous prototype of the TCU, which was designed and built for testing and validating the performance. The overall top-level design is the same as the one depicted in Section 3.

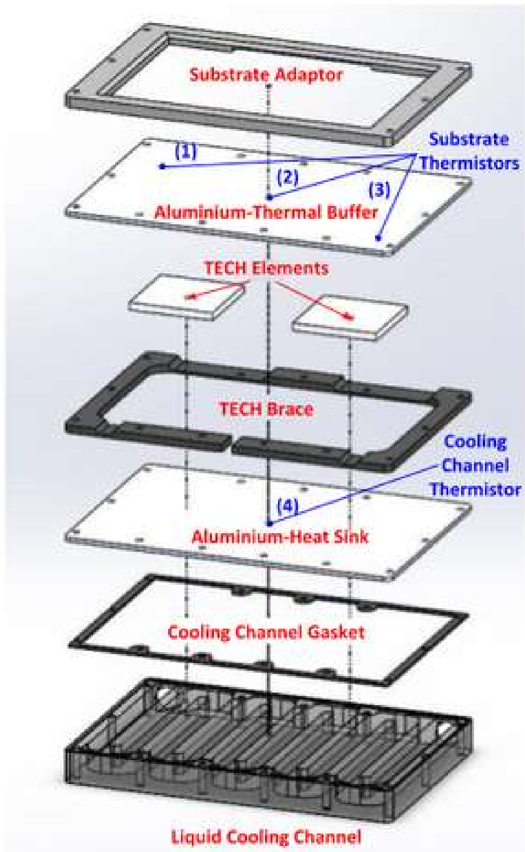


Figure 46: TCU Prototype 1 Exploded View

As shown in Figure 46, the major change to the TR block is the replacement of the custom printed liquid cooling channel (including the gasket and heat sink) with an commercial aluminum water-cooling block. The change simplified the maintenance of the TCU as the test prototype was susceptible to leaks. The previous prototype also used a less powerful motor driver, the dual MC33926, which limited the maximum temperature that could be maintained by the TCU control system. This was updated to the dual MDD10A motor driver to ensure the TCU could meet all temperature setpoints.

APPENDIX D: HUMIDITY CALCULATIONS

Saturation Mass of Water per Kilogram of Air

The saturation mass of water per kilogram of air is calculated from the saturation water vapour partial pressure, and the pressure of air (101.325 kPa). The formulas are taken from the Engineering Toolbox [23].

$$x(kg\ of\ H_2O)/(kg\ of\ Air) = 0.62198 \times \frac{p_{ws}}{p_a - p_{ws}}$$

The saturation water vapour partial pressure is calculated using the following equation, which is dependent on temperature.

$$p_{ws} = e^{(a+bT+\quad /T)}/T^d$$

$$a = 77.3450, b = 0.0057, c = 7235, d = 8.2$$

Substituting the equation for saturation water partial pressure into the first equation gives an expression for the saturation mass of water per kilogram of air dependent on temperature. This is graphed and displayed in the figure below with the setpoint temperatures highlighted.

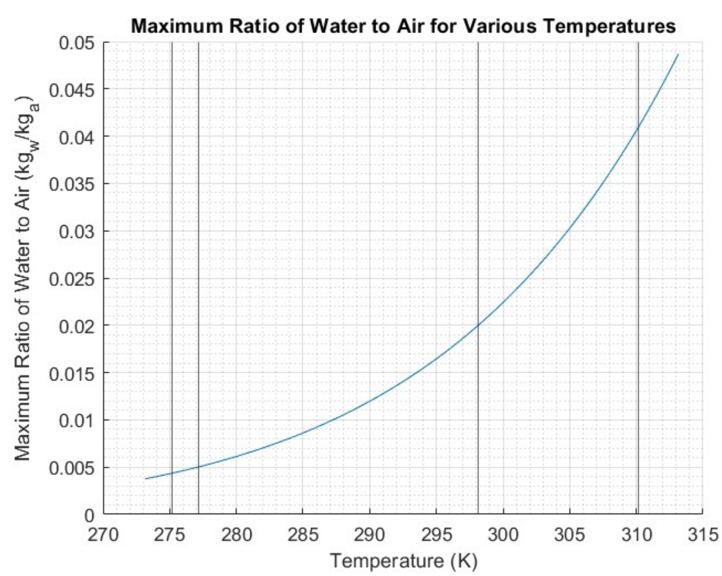


Figure 47: Maximum ratio of water to air for various temperatures

APPENDIX E: MATERIAL PROPERTIES

The following table outlines material property information in further detail; this information was used to select the appropriate material for the enclosure panels [23].

Characteristic		Material		
		PA	ABS	PVC
Available through ECE?		No	?	No
Bulk Cost (UScent / lb)		150—154	154—159	119-123
Type		Semi-crystalline Engineering Thermoplastic	Amorphous Commodity Thermoplastic	Amorphous Commodity Thermoplastic
Physical and Chemical Properties	Coefficient of Linear Thermal Expansion	5 - 12 x 10-5 /°C	7 - 15 x 10-5 /°C	5 - 18 x 10-5 /°C
	Water Absorption 24 hours	1.6 - 1.9 %	0.05-1.8%	0.04-0.4%
	Fire Resistance (LOI)	23 - 26 %	19%	40-45%
	Young Modulus	0.8 - 2GPa	1.79-3.2GPa	2.4-4GPa
	UV Light Resistance	Fair	Poor	Fair
	Glass Transition Temperature	60 °C	90-102°C	60-100°C
	Max Continuous Service Temperature	80-120 °C	86-89°C	50-80°C
	Min Continuous Service Temperature	-40 to -20 °C	60-80°C	-10-1°C
	Sterilization Resistance (Repeated)	Poor	Poor	-
	Thermal Conductivity	0.24 W/m.K	0.13-0.19W/m.K	0.16W/m.K
	Acetone @ 100%, 20°C	Satisfactory	Non-Satisfactory	Non-Satisfactory
	Ethanol @ 96%, 20°C	Satisfactory	Limited	Satisfactory

Characteristic		Material		
		PMMA	PP	PC
		Acrylic, Polyacrylate	Polypropylene	Polycarbonate
Available through ECE?		Yes	No	Yes
Bulk Cost (UScent / lb)		125-130	71.5—73.5	173—201
Type		Amorphous Commodity Thermoplastic	Semicrystalline Commodity Thermoplastic	Amorphous Engineering Thermoplastic
Physical and Chemical Properties	Coefficient of Linear Thermal Expansion	5 - 9 x 10-5 /°C	6 - 17 x 10-5 /°C	7 - 9 x 10-5 /°C
	Water Absorption 24 hours	0.1 - 0.4 %	0.01 - 0.1%	0.1-0.2%
	Fire Resistance (LOI)	19 - 20 %	17 - 18%	24-35%
	Young Modulus	2.5 - 3.5 GPa	1.1 - 1.6 GPa	2.2-2.5GPa
	UV Light Resistance	Good	Fair	Fair
	Glass Transition Temperature	90 - 110 °C	-10°C	160-200°C
	Max Continuous Service Temperature	70 - 90 °C	100 - 130°C	100-140°C
	Min Continuous Service Temperature	-	-20 to -10°C	-
	Sterilization Resistance (Repeated)	Poor	Poor	Fair
	Thermal Conductivity	0.15 - 0.25 W/m.K	0.15 - 0.21 W/m.K	0.21W/m.K
	Acetone @ 100%, 20°C	Non-Satisfactory	Satisfactory	Non-Satisfactory
	Ethanol @ 96%, 20°C	Limited	Satisfactory	Satisfactory

Table 16: Materials Properties of different plastics

APPENDIX F: ARDUINO MICROCONTROLLER

The Arduino microcontroller is selected based on the following:

- ***Ease of use***: Arduino documentation and support is extensive.
- ***Compatibility***: Arduino supports many different libraries, for numerous applications. There are also a wide range of electronics that are specifically designed for use with Arduino microcontrollers.
- ***Wide availability***: Arduino products are very accessible, from many different platforms. This allows the controller to be easily replaced, simplifying maintenance for the end-user.

Figure 48: Arduino Mega 2560 microcontroller [24]

APPENDIX G: AMBIENT TEMPERATURE CONTROL

A future improvement that could be made to the system is to control the RH levels for 37°C. As explained in the Ambient Temperature Theory section below, ambient air temperature must be raised in order to reach RH requirements for temperatures greater than room temperature. The ambient air temperature of the FEU can be raised using a PTC elements, seen to be the better option from the WDM in Table 17:

Criteria	Weight (%)	Heating Method									
		Ceramic Heat Lamp		Nichrome Wire		Heating Pad		TECH Element		PTC Heating Element	
		Score	WS	Score	WS	Score	WS	Score	WS	Score	WS
Low Cost	5	0	0	90.79	4.54	37.08	1.85	44.75	2.24	37.98	1.90
Ease of Control	30	25	7.50	75	22.5	50	15	50	15	100	30
Safety	30	100	30	0	0	75	22.5	75	22.5	75	22.5
No Light Production	5	100	5	50	2.5	100	5	100	5	100	5
Ability to Heat Air	30	75	22.5	50	15	25	7.5	50	15	100	30
TOTAL (%)		65		44.54		51.85		59.74		**89.4**	

Table 17: WDM for ambient air heating element

An image of the product is shown below. The heating rate is regulated by the 60 mm by 60 mm fans which move air through the PTC elements.

Figure 49: PTC heating element for ambient air [26]

Ambient Temperature Theory

As mentioned in requirements F2.0, the enclosure must be kept at 95.0% RH for the 2-4°C setpoint. However, RH regulation for higher temperatures is ideal and may be implemented in future versions of the design. Using the formulas found in Appendix D, the maximum dissolvable water mass per kilogram of air is determined for different temperatures. The temperatures of interest are listed in the table below.

Temperature (°C)	Max. Dissolvable Water Mass per kg of Air (g)
2	4.35
23	17.68
37	40.94

Table 18: Maximum dissolvable water mass per kilogram of air for different temperatures

The first model in Figure 50 outlines the scenario in which ambient temperature is not controlled for any setpoint.

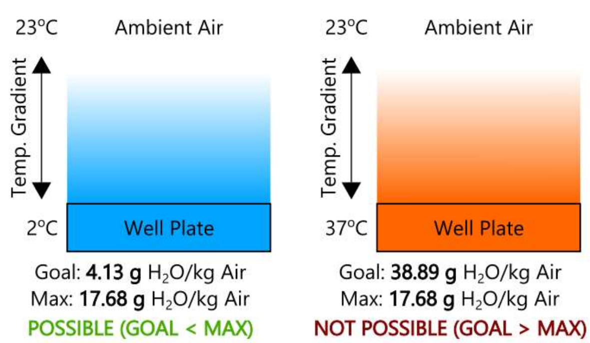


Figure 50: Impact of temperature gradient on ability to reach higher temperature setpoints

As the air nears the well plate, its temperature will be closer to that of the well plate, creating a temperature gradient. This is not a concern for the 2 - 4°C setpoint as the saturation water mass for these temperatures is below the saturation water mass for room temperature. This allows the system to meet requirement F2.0 without any additional modifications. Note that even though the ambient air is saturated in 37oC setpoint, the air closest to the well plate is at 45.5% RH which is not acceptable.

Since the humidity specification is achievable for the 2 - 4°C setpoint without ambient temperature control, it will only need to be implemented for higher temperature setpoints. This is demonstrated in the second model, where the ambient air temperature is raised to the well plate temperature.

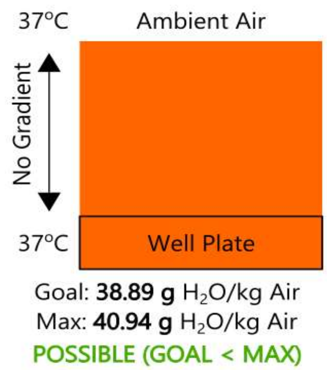


Figure 51: Impact of heating the ambient air on ability to reach higher temperature setpoints

Power Required for Ambient Air Heating

Assuming no heat loss, the energy required to heat the ambient air in the enclosure is given by the equation below.

$$Q = mc\Delta T$$

The mass of the air in the enclosure is calculated using the volume of air in the enclosure. The enclosure dimensions are 950 mm by 850 mm by 600 mm. This gives a total volume of 0.4845m^3. Air density is approximated to be 1.225 kg/m^3, giving a total of 0.5935 kg of air. The specific heat capacity (c) is approximated to 1.006 kJ/(kgK) and therefore the net energy required to raise the enclosure from room temperature (23ºC) to 37ºC using the formula above is 8.359 kJ. The minimum power is calculated using F3.4, which states humidity must be reached within 5 minutes (300 seconds), or 27.86 W.

For future design work, heat loss will need to be included in the calculation.

APPENDIX H: TCU MODELLING AND PID TUNING

The thermal characteristics of the TCU are estimated using MATLAB's system identification tool. Experimental data of the temperature output as compared to the PWM input was then used to construct a black-box model. Note that the temperature output is measured relative to both sides of the TECH element, thus control is based on the change in the temperature difference between the hot side and the cool side. Using the estimated model, PID tuning was done using the MATLAB's PID Tuner tool.

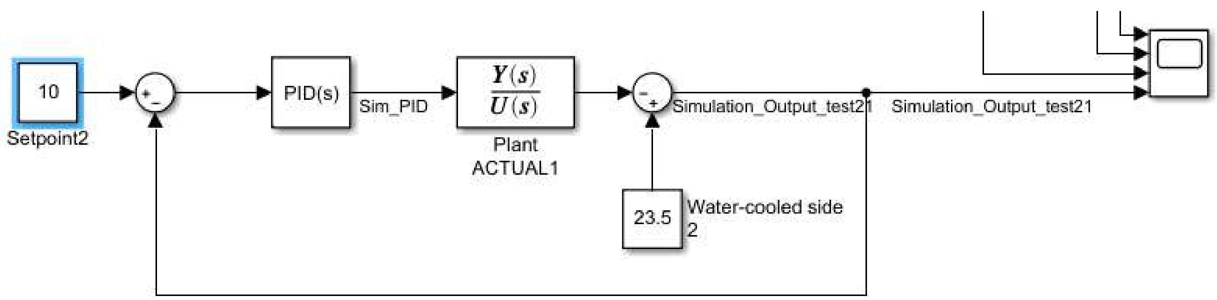


Figure 52: TCU model block diagram

The model was then simulated using Simulink as per the diagram above. The plant transfer function is a model of the TECH element inside the TR. The plant transfers heat on the interface side with the well plate attached to it to the side with the water-cooling block attached to it, effectively cooling or heating the interface side. The output of the plant in the block diagram is the temperature on the interface side. The water-cooling system is efficient enough to keep the heat sink side relatively stable, hence it is modelled as a constant here. Note that a separate model is also built for the heating operation of the TCU, as the TECH element has a different temperature profile for cooling verses heating.

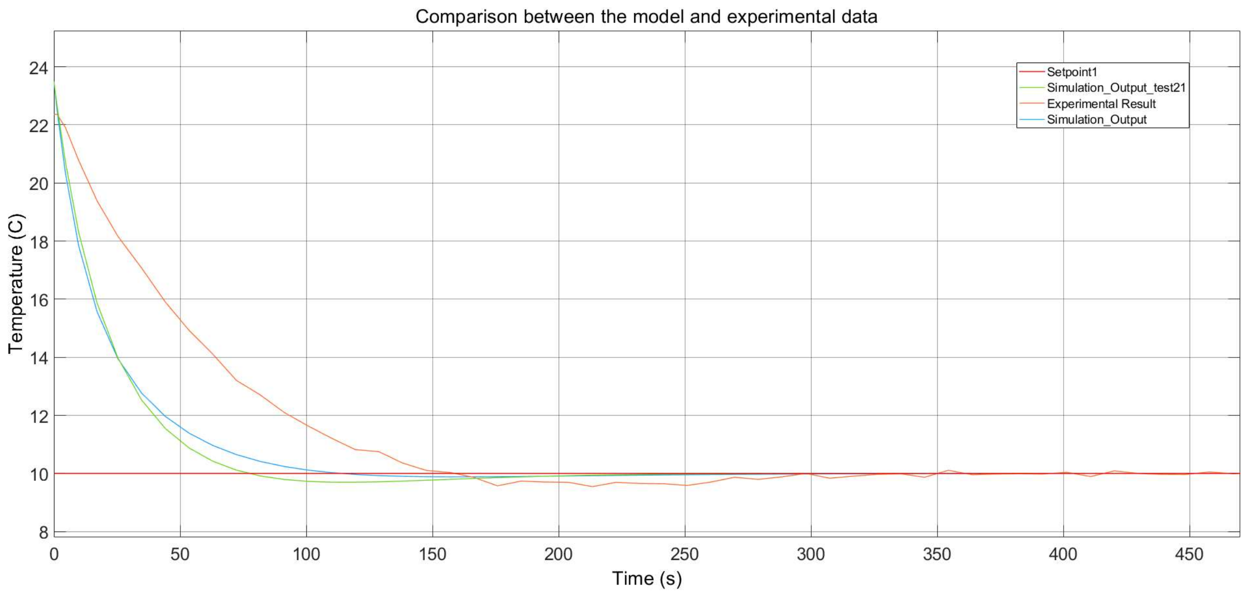


Figure 53: TCU Control System - Comparison between model and experimental data

The plot above shows the comparison between two of the estimated models with the actual system response when applying the PID values. In this test, the setpoint was set to 10°C. As seen in the plot, there is a gap between the time response of the model and the actual system. Further tuning is required on the actual system to achieve the desired response. This discrepancy can be attributed to use of a linear model for the PID, since testing shows that the system exhibits nonlinear behavior in some conditions. Further improvement to the modelling can be done by using a linear approximation of a nonlinear system or modelling the system as a hybrid system.

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