VALIDATION 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 requirements are intended for the fully assembled design, however, at this point the actual prototype is not fully integrated due to shipping and manufacturing delays , as well as an inability to access vital equipment. As a result, the following document includes both incomplete and complete experiments. A summary is included at the beginning to indicate the status of each validation experiment.

CHANGELOG

Version	Date	Editor	Change
1.0	24/09/19	All	Document created.
1.1	24/11/19	WZ	Added validation experiment for HCU.
1.2	08/02/20	All	Added validation for HCU and TCU.
1.3	06/04/20	All	Updated validation experiments in all sections.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS AND ABBREVIATIONS

BIOME	Biological Metabolism Maintaining Environmental Enclosure[1]
ECU	Electronics Control Unit
EFU	Enclosure and Filtration Unit
FEU	Filtration and Enclosure Unit
FSM	Finite State Machine
HCU	Humidity Control Unit
N.D.	No Data
PID	Proportional Integral Derivative
RH	Relative Humidity
TCU	Temperature Control Unit
TEC	Thermo-Electric Cooler
WDM	Weighted Decision Matrix

[1] BIOME is the product name of the Environmental Enclosure, chosen by the Capstone team

1 OVERVIEW

1.1 Purpose

The validation document is prepared to demonstrate the performance of the product. The purpose of this document is to:

- Provide details of testing done to assess its validity
- Verify whether the design conforms to the functional and non-functional requirements
- Identify any design deficiencies

Table 2, Table 3, and Table 4 summarize the validation experiments included in this document, as well as their completion status. If necessary, please refer to Appendix B for further information on experimental equipment.

Complete – Experiment was completed; no further testing required	**Complete –** Experiment was completed with previous test prototype; further testing is required to validate current system	**Incomplete –** Experiment could not be completed

Table 1: Validation Test Status Colour Coding

Section	Test	Description	Additional Notes	Status
2.1	TCU Temperature Setpoints - Proof of Concepts	Test the viability of the TECH	N/A	Complete
2.2	TCU Temperature Setpoints	Test the TCU's capability to reach and maintain the setpoints	Testing was done using the TCU test prototype 1. Further validation on the updated TCU is required	Complete - TCU test prototype 1
2.3	TCU Precision	Test the TCU's sensor precision	N/A	Complete

Table 2: TCU - Summary of Tests

Section	Test	Description	Additional Notes	Status
3.1	Humidification System - Proof of Concept	Validate that bubble humidifying method	Bubble humidification is proved to be a feasible method for the requirements	Complete
3.2	Dehumidification System - Proof of Concept	Test to ensure HCU dehumidification can dehumidify system	N/A	Complete
3.3	Humidification System - Water Temperature and Air Flow Rate	Determine the influence of the water temperature and inlet air flow rate on the performance of the humidification system	System performance is improved with an increase in water temperature. In a high inlet air flow rate range (>50 L/min), the system performance is decreased with an increase in air flow rate.	Complete
3.4	Humidification System - Air Flow Rate	Determine the optimum inlet air flow rate for the humidification system	At a low inlet air flow rate range (10-25L/min), the performance of the bubble humidification system is improved with an increase in inlet air flow rate	Complete
3.5	Humidification System - Prototype Testing	Determine the performance of the current Bubble humidifier prototype	The humidification system prototype provides stable and reliable performance	Complete

Table 3: HCU - Summary of Tests, Complete

Section	Test	Description	Additional Notes	Status
3.6	Dehumidification System - Dehumidification Speed	Testing HCU's ability to reach dehumidification requirements	This test requires an assembled BIOME which was not available	Incomplete - COVID-19
3.7	Dehumidification System Modelling	Getting a model for the HCU dehumidification system	This test requires an assembled BIOME which was not available	Incomplete - COVID-19
3.8	Dehumidification System Control	Validation that HCU dehumidification matches expected model	This test requires an assembled BIOME which was not available	Incomplete - COVID-19

Table 4: HCU - Summary of Tests, Incomplete

2 TEMPERATURE CONTROL UNIT (TCU)

2.1 TCU Temperature Setpoints – Proof of Concepts

2.1.1 Scope of Test

The temperature at the surface of the TCU must reach a set temperature in the range of 2.0 °C - 80.0 °C. This test is performed to measure the performance of the chosen TECH unit, power supply and the water-cooling system.

2.1.2 Equipment

- Calibrated temperature sensor (NTC 10K Thermistor)
- TECH element
- 12V 10A Power supply
- Arduino Uno
- 5mL Arctic Silver 5 Thermal paste
- 5cm Electrical Tape

2.1.3 Procedure

1. Setup and calibrate the thermistor
2. Apply thermal paste on top of the TECH unit
3. Place the thermistor on top of the thermal paste and secure with tape
4. Connect the thermistor to the Arduino Uno (Design Document[20], Section 6.3.1.3)
5. Connect the TECH unit to the power supply
6. Turn on the power supply and start the logging program
7. Stop logging after the temperature past 0°C or 90°C

8. Turn off the power supply
9. Wait until the TECH returns to room temperature
10. Switch the polarity of the TECH unit on the power supply
11. Repeat steps 6 to 8

2.1.4 Findings

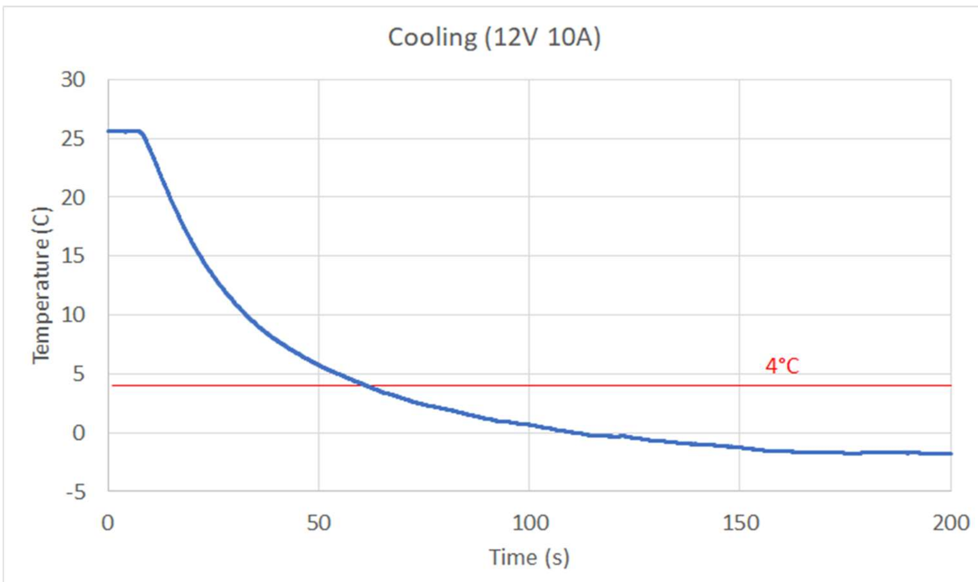

Figure 1: Temperature on top of the TECH unit over time (cooling)

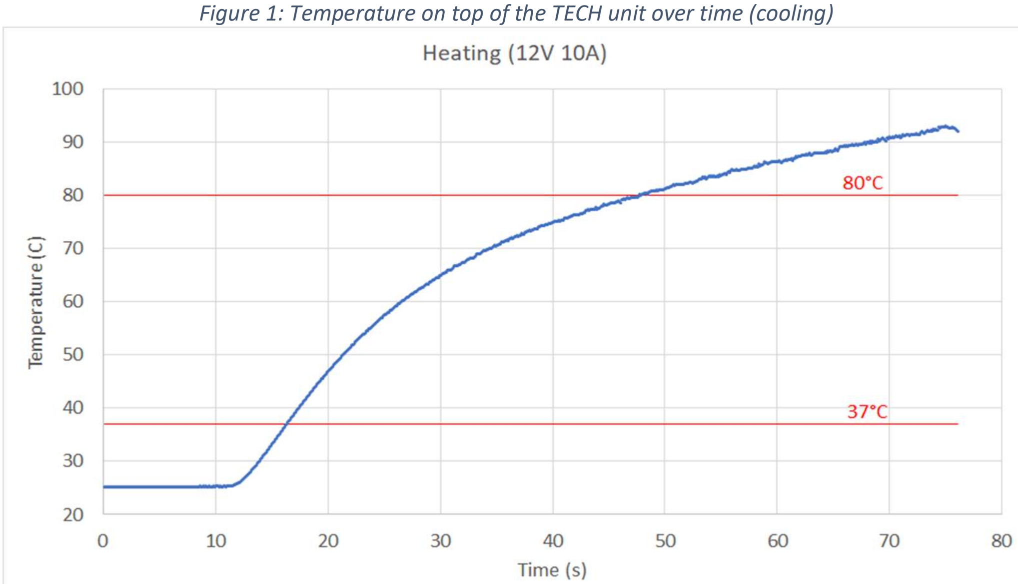

Figure 2: Temperature on top of the TECH unit over time (heating)

As shown in Figure 1 and Figure 2, the TECH was able to cool down to 2°C in about 90 seconds and heat up to 80°C in about 40 seconds from room temperature.

2.1.5 Conclusion

Setpoint temperature	Requirement satisfied
2-4°C	F1.0
37°C	F1.1
80°C	F1.2

Table 5: Test result

From the test result, both the TECH unit and the chosen power supply with the help of water cooling were able to reach all the temperature setpoints as per specifications F1.0, F1.1, and F1.2.

2.1.6 Documentation

Date of testing: January 17, 2020

Testing performed by: Natkamol Limapichat

2.2 TCU Precision Temperature Setpoints

2.2.1 Scope of Test

The purpose of this test is to measure the performance of the chosen component, as well as the control schemes. The temperature at the surface of the TCU must reach a set temperature in the range of 2.0 °C - 80.0 °C at a rate greater than 5 °C per minute. The temperature must be maintained with a stability of 0.5 °C for all three setpoints: (1) 2.0 °C - 4.0 °C, (2) 37.0 °C, and (3) 80.0 °C. The TCU must work for both the 5184 Nanowell plate and 96-Well plate.

2.2.2 Equipment

- TCU Test Prototype 1 (See Design Document [20], Appendix C)
- Calibrated temperature sensor (NTC 10K Thermistor)
- 12V 10A power supply
- Arduino Uno
- 5mL Arctic Silver 5 Thermal paste
- 5cm Electrical Tape
- 63 cm x 63 cm x 68 cm Testing chamber

2.2.3 Procedure

1. Apply thermal paste on top of the TCU
2. Place the temperature sensor on the thermal paste and secure with tape
3. Place the TCU inside the testing chamber
4. Connect the TCU to the Arduino Uno and the power supply as referenced in design document (6.3.1.3 TCU Control Circuit)
5. Set the power supply to 12V 2.5A
6. Set the setpoint temperature using the Arduino Uno
7. Start the logging program
8. Turn on the power supply
9. Let the test run until the temperature stops fluctuating more than ± 0.5°C for more than 20 seconds
10. Stop the logging program
11. Turn off the power supply
12. Repeat steps 6-11 with different temperature setpoints

2.2.4 Findings

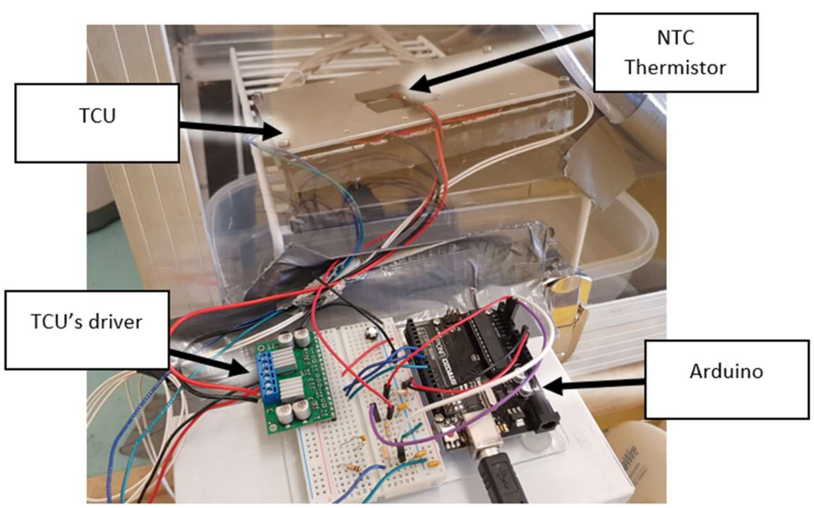

Figure 3: Test setup

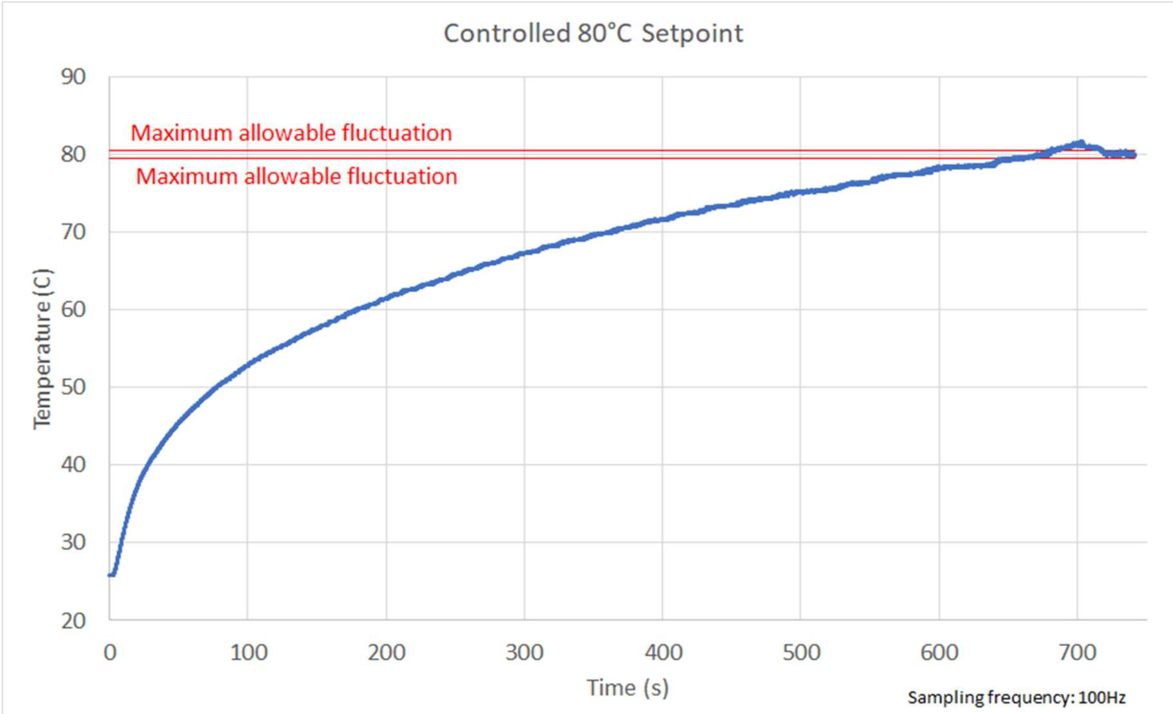

Figure 4: Surface temperature of TCU over time (80°C setpoint)

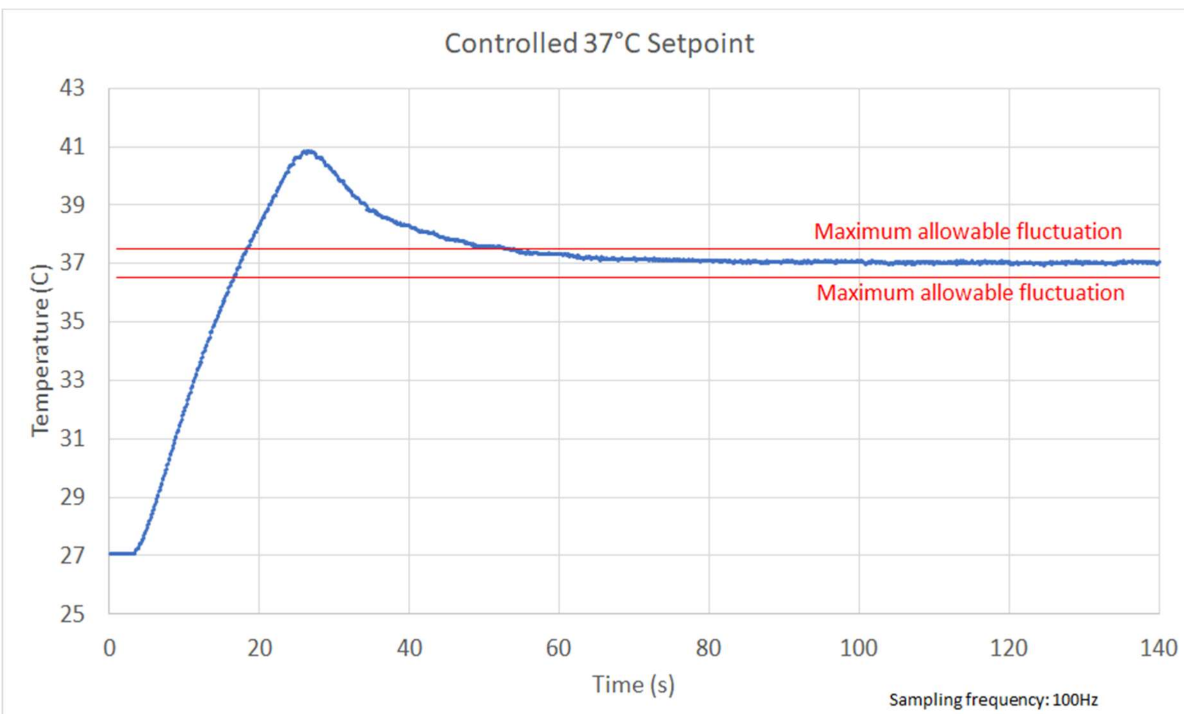

Figure 5: Surface temperature of TCU over time (37°C setpoint)

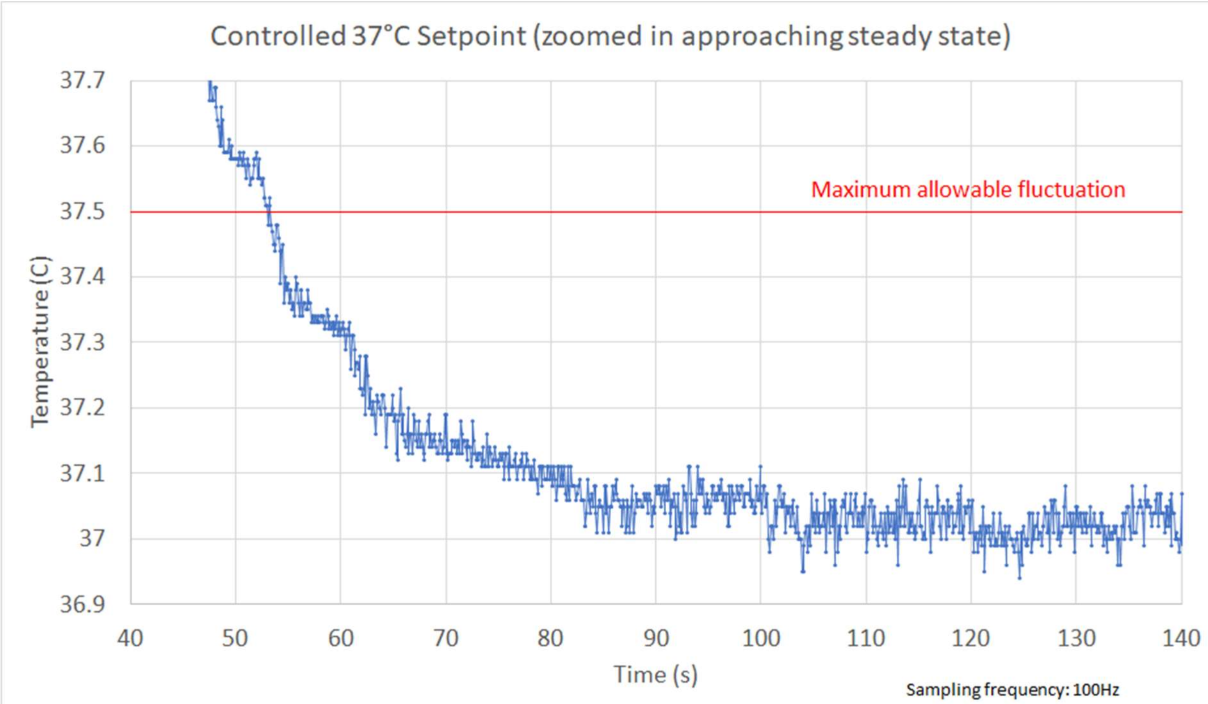

Figure 6: Surface temperature of TCU over time zoomed in (37°C setpoint)

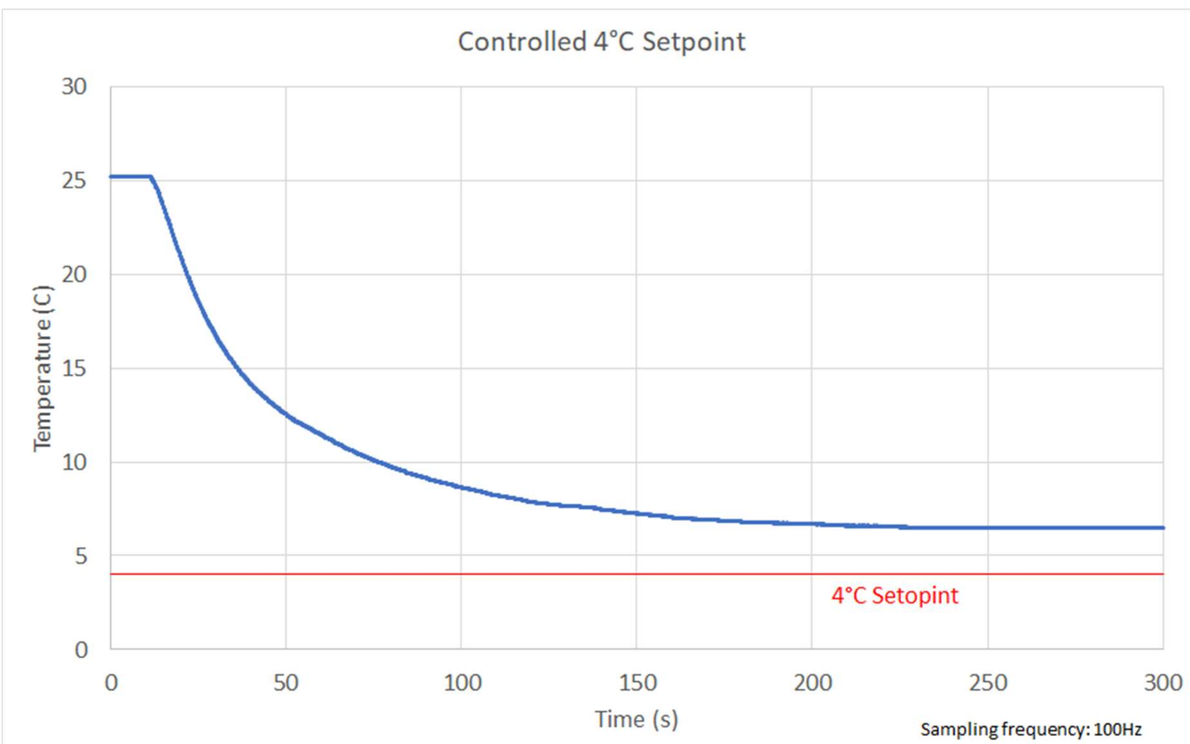

Figure 7: Surface temperature of TCU over time (4°C setpoint)

In Figure 4 and Figure 5 , the two red lines show the maximum allowed fluctuation of temperature at steady state per requirement F1.4. The testing for the 80°C setpoint was stopped due to overheating of the TCU motor driver. Nonetheless, the plot indicates that the TCU was able to reach the setpoint and was about to enter steady state. The current iteration of the TCU was able to reach the 80°C setpoint after about 10 minute.

The 37°C setpoint was achieved in about 55 second from room temperature, with the steady state stability at ±0.1°C. The 4°C setpoint was not achieved.

2.2.5 Conclusion

Setpoint temperature	Time to reach setpoint	Maximum temperature fluctuation at setpoint	Requirement satisfied
4°C	*N.D.*	*N.D.*	--
37°C	75 seconds	± 0.1°C	F1.1, F1.4, F1.5
80°C	700 seconds	*N.D.*	--

Table 6: Setpoint temperature test result

From the test, the TCU was able to meet specification F1.1. The TCU could not achieve satisfactory results for the other setpoints. However, the proof of concept test (test 2.1) shows that the TECH can reach all the setpoint temperatures. A suggested improvement is to replace the TCU's driver with one able to supply 10A. A more robust control could also reduce the overshoot seen in the 37°C setpoint.

2.2.6 Documentation

Date of testing: February 7, 2020

Testing performed by: Natkamol Limapichat

2.3 TCU Precision

2.3.1 Scope of Test

The purpose of this test is to determine whether the temperature reading is precise to within ±0.2 °C as per specification F1.3

2.3.2 Equipment

- Arduino UNO
- FLUKE 2175A Digital Thermometer
- NTC 10K Thermistor
- 150 mL of Tap Water
- Ice (Made from Tap Water)
- 250 mL Container
- 1000W Electric Kettle

2.3.3 Procedure

1. Setup the thermometer, thermistor, and Arduino UNO as specified in the Design Document [20] (Section 6.3.1.3)
2. Fill the container with ice water with a 50:50 water to ice ratio.
3. Place the thermometer and thermistor probe in the container next to each other for 30 seconds.
4. Record the reading of the thermometer and thermistor.
5. Use the electric kettle to change the water temperature and repeat the procedure

2.3.4 Findings

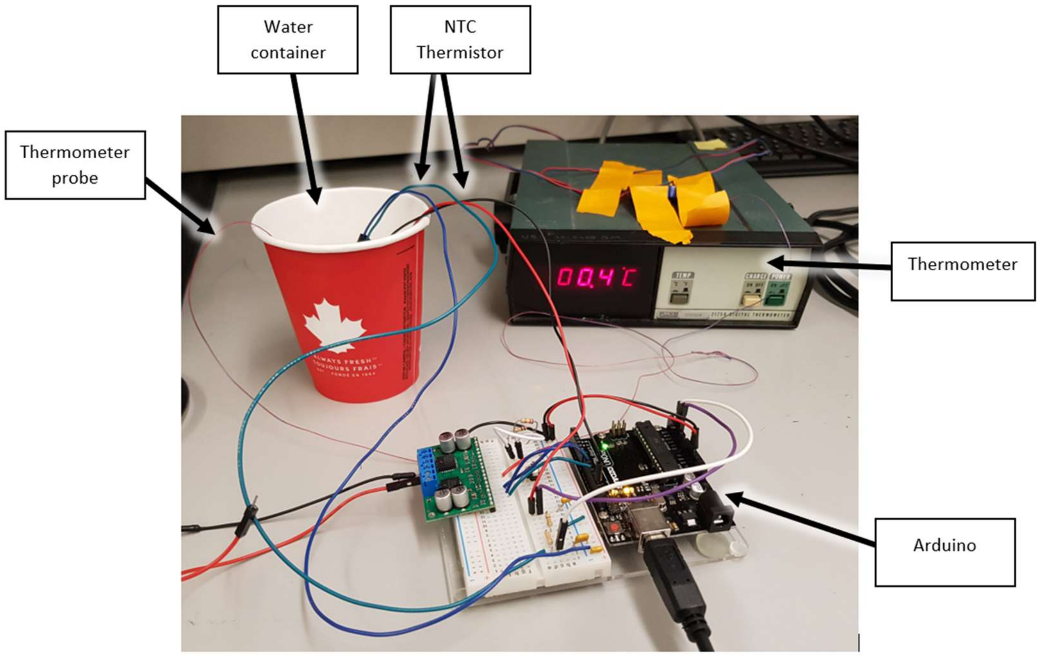

Figure 8: Experiment setup for testing sensor precision

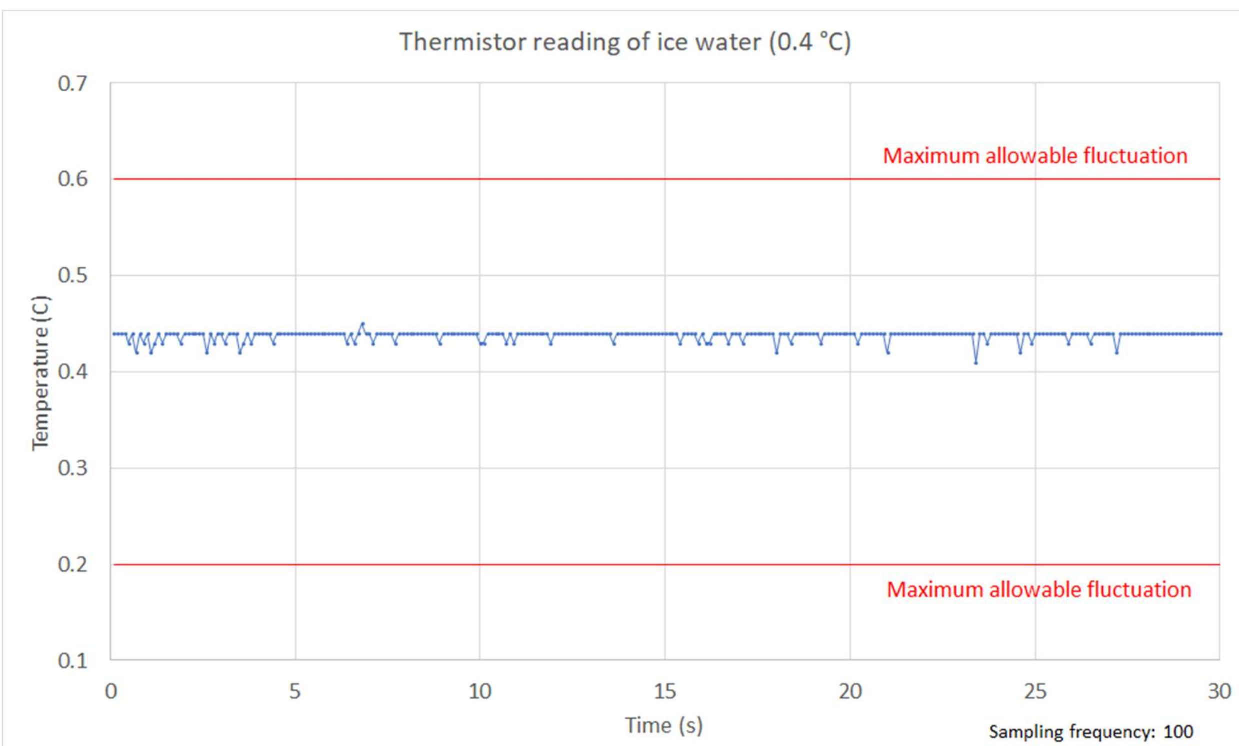

Figure 9: Thermistor reading over time (0.4°C)

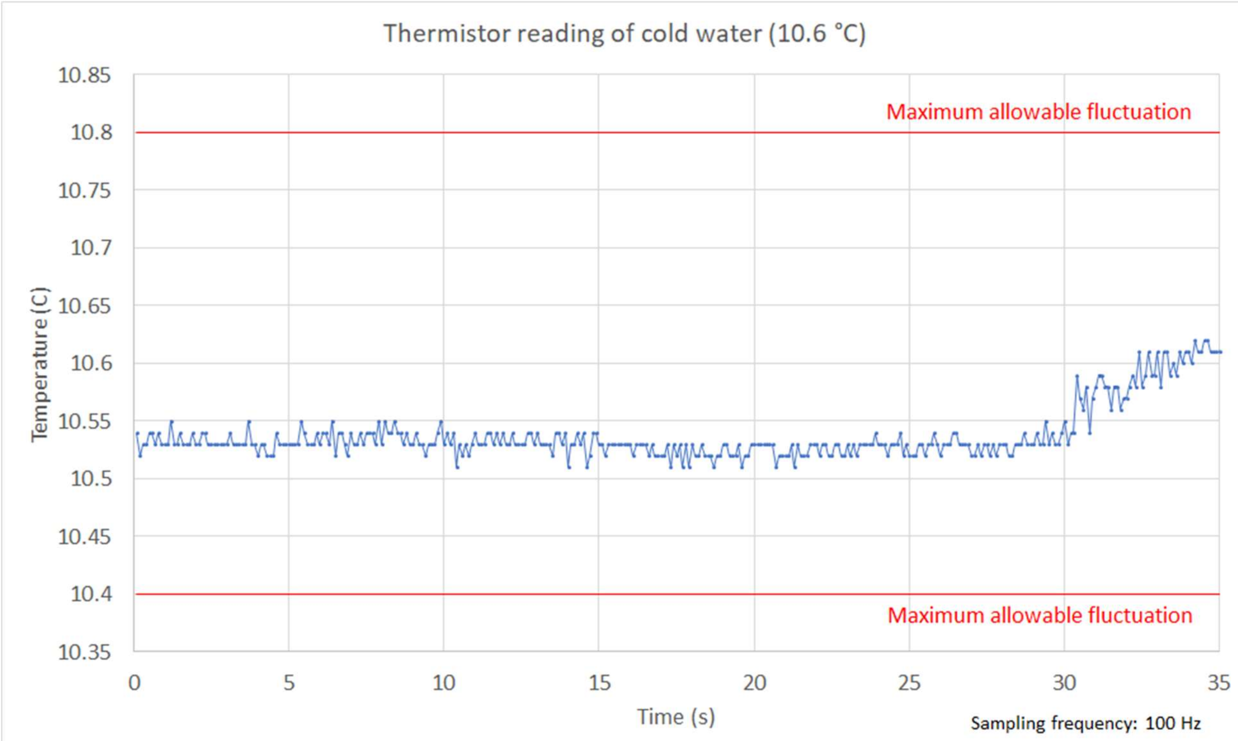

Figure 10: Thermistor reading over time (10.6°C)

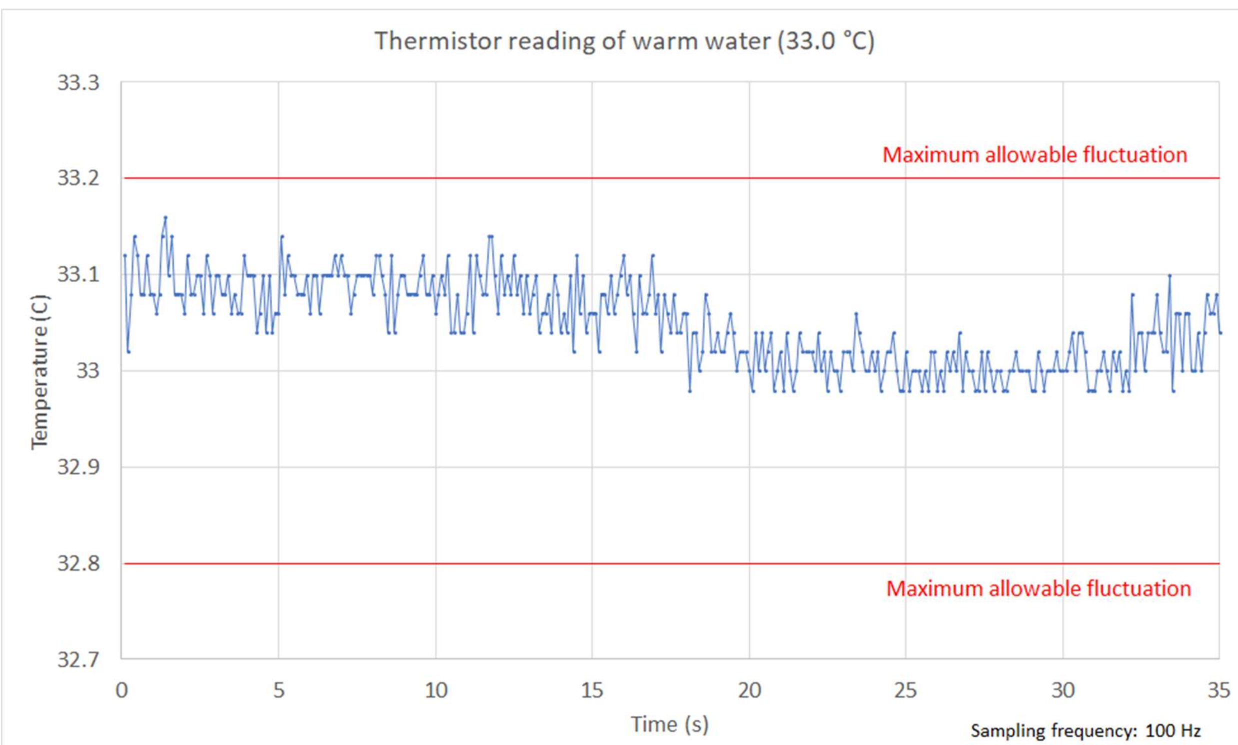

Figure 11: Thermistor reading over time (33°C)

From the figures above (Figure 9 to Figure 11), all the sensor readings show some fluctuation, but they do not deviate more than about 0.02°C of the average reading. The red lines show the maximum allowable error in the readings. With the fluctuations, the sensor was able to maintain reading well within the precision requirement F1.3.

2.3.5 Conclusion

Reading from the temperature probe	**Reading from by the sensor (thermistor)**	**Maximum absolute differences**	**Requirement satisfied**
0.4°C	0.41°C - 0.45°C	0.05°C	F1.3
10.6°C	10.5°C - 10.55°C	0.1°C	F1.3
33.0°C	32.97°C - 33.15°C	0.15°C	F1.3

Table 7: Temperature reading precision test result

Based on the test result, the TCU can satisfy requirement F1.3. Please note that testing can be further improved by testing the overall range from 0°C - 100°C, providing a more complete dataset. Note that the test requires a thermometer with data logging function, and a hotplate to heat up the water over time. The temperature reported by the thermometer and the thermistor can be compared over time.

1.1.1 Documentation

Date of testing: February 5, 2020

Testing performed by: Natkamol Limapichat

3 HUMIDITY CONTROL UNIT (HCU)

3.1 Humidification System - Proof of Concept

3.1.1 Scope of Test

The purpose of this experiment is to validate that bubble humidifying method can be used as the humidification system in the HCU.

3.1.2 Equipment

- 1 testing chamber with 63cm x 63cm x 68cm dimension (Appendix B1)
- 1 mechanical air pump with 2.5W power (Appendix B.2)
- 1 air inlet tube with ¼ inch inner diameter
- 1 air outlet tube with ¼ inch inner diameter
- 1 cylindrical water reservoir with 10cm diameter (Appendix B.3)
- 1 piece of cling film with 20cm x 20cm dimension
- 500mL of warm water (40°C)
- 1 DHT11 humidity and temperature sensor (Appendix B.4)
- 1 Arduino UNO

3.1.3 Procedure

1. Construct a basic bubble humidifier with an air inlet tube, an air outlet tube, a cylindrical reservoir, cling film, and 500mL of warm water
2. Measure the height of the water level inside the reservoir
3. Measure the temperature of the water inside the reservoir

4. Connect the air inlet tube with the mechanical air pump
5. Place the bubble humidifier and the air pump inside the testing chamber
6. Connect the DHT11 sensor with Arduino and place them inside the testing chamber
7. Close and seal the entrance of the testing chamber
8. Turn the air pump on and record the ambient RH inside the testing chamber every 0.1 second for 25 minutes
9. Turn off the air pump
10. Take out all components from the testing chamber
11. Measure the height of the water level inside the reservoir
12. Measure the temperature of the water inside the reservoir

3.1.4 Findings

The setup of this experiment is shown below:

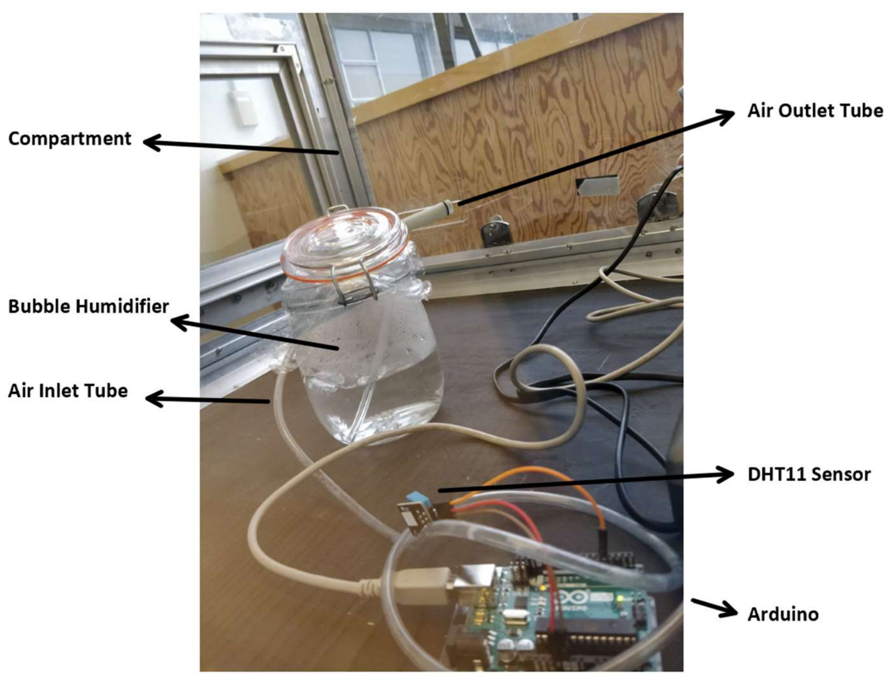

Figure 12: Experimental setup of homemade inside the test chamber

		Water Level (cm)	RH (%)	Water Temperature (°C)
Time (min)	0	5.8	56	46
	25	5.5	63	32

Table 8: Initial and final values of the water level, RH, and water temperature

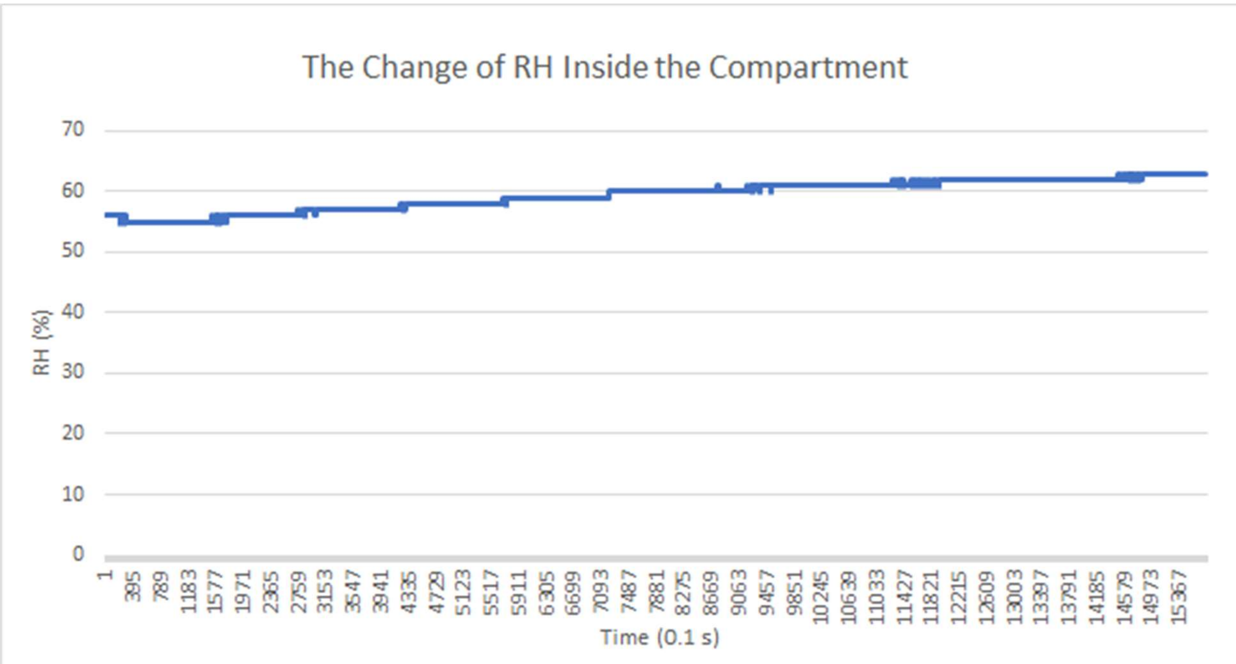

Figure 13: Change in RH within the testing chamber over time

Based on the data collected, the height of the water level inside the testing chamber decreased from 5.8cm to 5.5cm during the humidification process. Given a reservoir diameter of 10cm, about 23.5mL of water was removed from the reservoir and dispersed into the ambient air within the 0.27m^3 testing chamber.

The RH inside the testing chamber increased steadily by 7% within 25 minutes from 56% to 63% as shown in Figure 13. The increase of the measured RH validates the feasibility of this method.

Without the implementation of a thermal isolation shield, the water temperature inside the reservoir dropped from 46 °C to 32 °C in 25 minutes (see Figure 13). The rate of increase in RH within the testing chamber dropped as the temperature decreased. This proves that a higher water temperature inside the reservoir leads to a better performance of the bubble humidifier.

3.1.5 Conclusion

The homemade bubble humidifier increases the RH inside the testing chamber by 7% in 25 minutes, which validates the feasibility of this method. Further experiments should be conducted for improvements of this mechanism.

3.1.6 Documentation

Date of testing: Nov 17th, 2019

Testing performed by: Andrew Yan, Wendy Zhou

3.2 Dehumidification System – Proof of Concept

3.2.1 Scope of Test

The purpose of this experiment is to validate that the dehumidification system can remove water from an enclosed space.

3.2.2 Equipment

- 1 testing chamber with 63cm x 63cm x 68cm dimension
- 1 80 mm x 80 mm DC fan
- 2 ABS Elbow Fittings
- 4 ABS Pipes (3” Diameter) (1x each of 7mm, 10mm, 20mm, and 34mm)
- 1 CC2D23-SIP Humidity and Temperature Sensor attached to an RH Cable Board
- 1 PLA 3D Printed Pipe Adaptor
- 1 Lenovo Heatsink Assembly
- 1 Small Heatsink (150x69x37 mm)
- 1 TECH Element (12V)
- 1 12V 10A Power Supply
- 1 36V 4A Lab Power Supply
- 1 Arduino MEGA
- 1 Breadboard
- 2 3.9 Kiloohm Resistors
- 1 220 Nanofarad Capacitor
- 1 Laptop with PuTTY installed

3.2.3 Procedure

1. Place the CC2D23-SIP Humidity and Temperature Sensor inside the testing chamber
2. Connect the wires of the cable board to the correct places on the Arduino using the circuit schematic in Section 6.3.2.4 of the Design Document.
3. Assemble the adaptor based on the exploded model shown in section ??? of the design document which includes both heatsinks, the 90 mm x 90 mm fan and the TECH element
4. Connect the 20 mm ABS pipe to one end of the adaptor
5. Attach the 80 mm x 80 mm fan to the 20 mm ABS pipe using duct tape, with the airflow towards the pipe adaptor
6. Connect the 7 mm ABS pipe to the other end of the adaptor
7. Attach one elbow fitting to the 7 mm ABS pipe
8. Attach the 10 mm ABS pipe to the elbow fitting
9. Attach another elbow fitting to the 10 mm ABS pipe
10. Attach the 34 mm ABS pipe to the elbow fitting
11. Close off any gaps for air to escape using duct tape
12. Place both ends of the tube inside the testing chamber
13. Completely seal the testing chamber using duct tape
14. Connect the TECH element to the 12V 10A power supply, do not plug the power supply in yet
15. Connect the fan to the 36V 4A laboratory power supply with settings at 12V, 0.5A. The power supply should remain turned off at this stage.
16. Connect the Arduino to the laptop and prepare to record data using PuTTY (setup Serial COM port and file where data will be saved)
17. Simultaneously turn on the power supplies and start recording data in PuTTY
18. Let the experiment run for 60 minutes
19. Stop the recording
20. Power off all devices

3.2.4 Findings

The setup of this experiment is shown below:

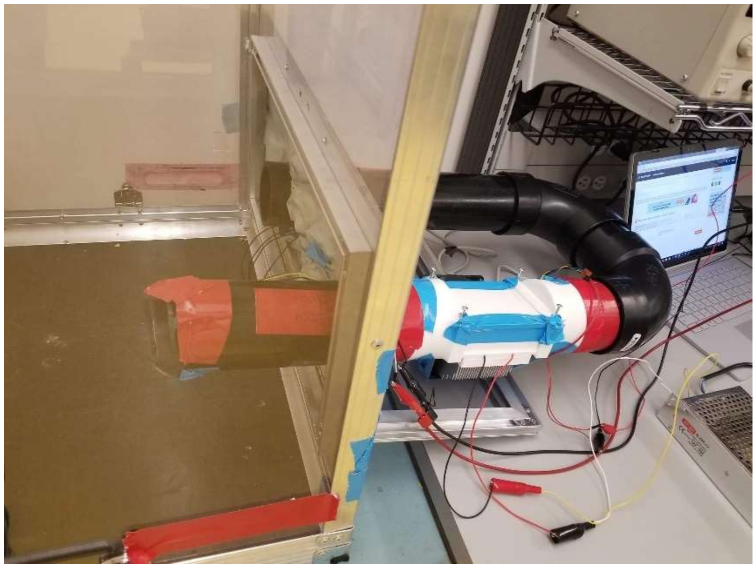

Figure 14: Experimental setup of dehumidifying system in testing chamber

The raw results from the experiment are shown in Figure 15:

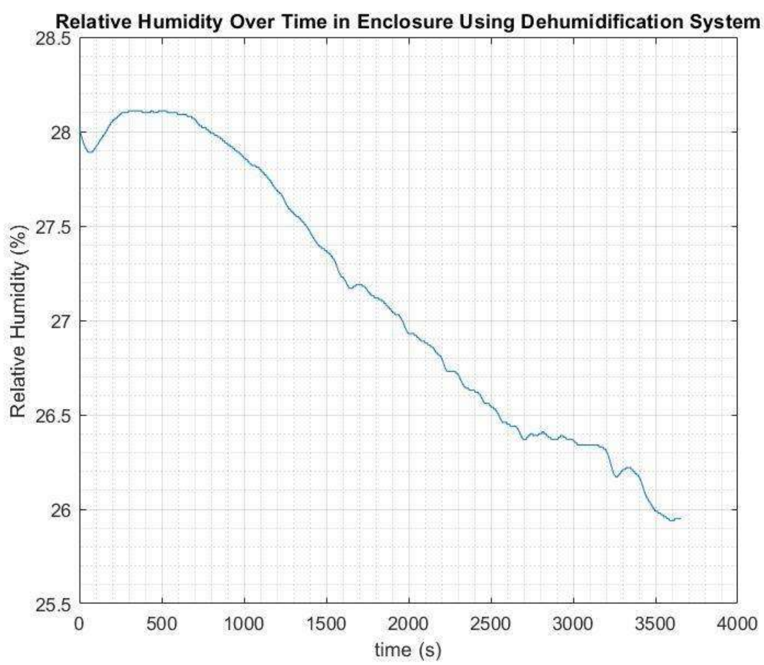

Figure 15: Change in RH within the testing chamber over time

As seen in the graph, the RH dropped over the 60-minute period as expected. However, this raw data is dependent on temperature, which fluctuated over the 60-minute period. The data is converted into an absolute humidity (kg of water per kg of air) which gives quantitative information about the change in dissolved water mass (Figure 16).

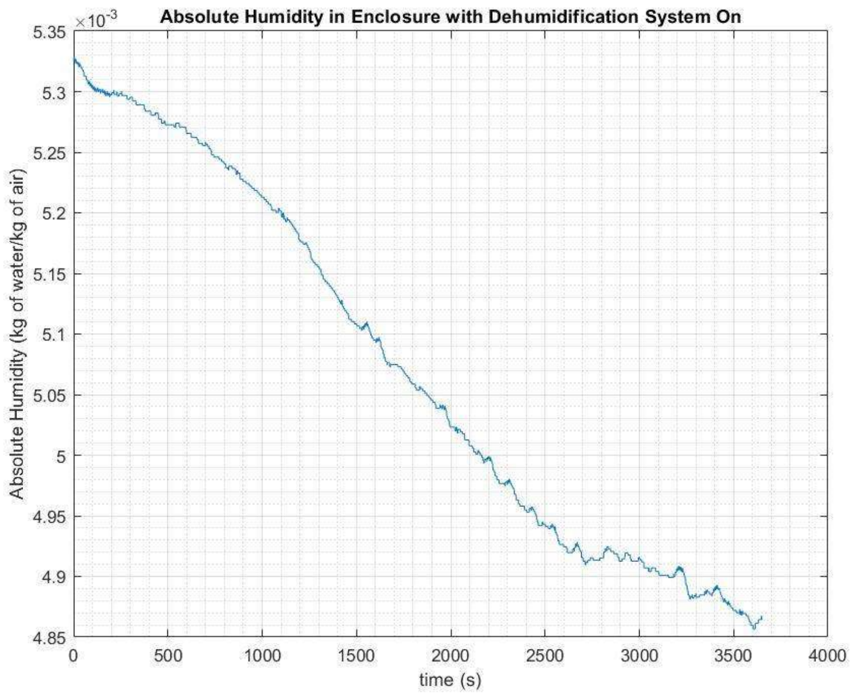

Figure 16: Change in Absolute Humidity within the Sealed Testing Chamber Over Time

The absolute humidity can also be converted to a RH at 4 degrees Celsius, which can be extrapolated to determine how the system would perform when trying to reach requirement F2.0 (Figure 17).

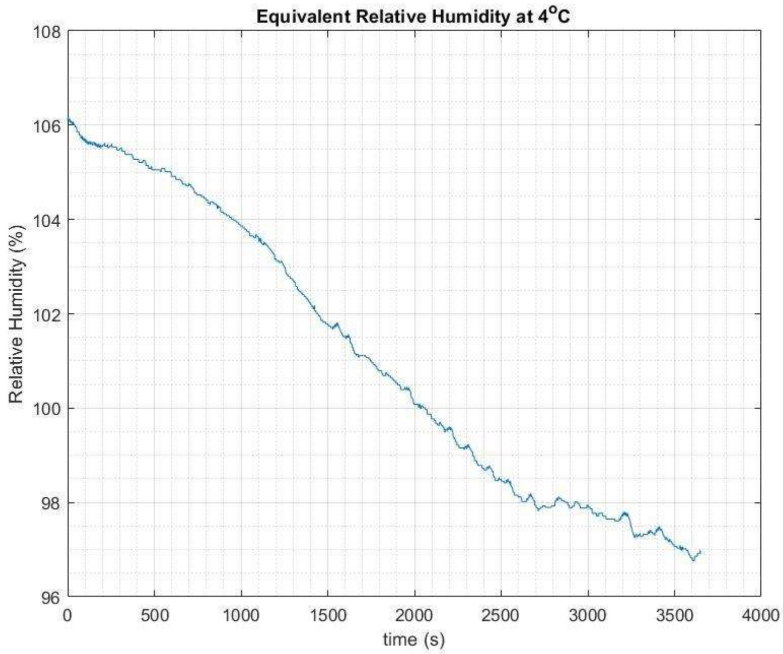

Figure 17: Equivalent Change in RH within the Sealed Testing Chamber if it were at 4°C

3.2.5 Conclusion

In conclusion, the dehumidifier was able to decrease the RH of the testing chamber by approximately 2% at room temperature, which is approximately equivalent to a 9% RH drop at 4 °C. This experiment validates the feasibility of this design, but further improvements must be made in order to allow the system to meet the requirements F2.0.

3.2.6 Documentation

Date of testing: Feb 2nd, 2020

Testing performed by: Andrew Yan, Sadan Wani

3.3 Humidification System - Water Temperature & Air Flow Rate

3.3.1 Scope of Test

There are 4 major factors that affect the performance of bubble humidification system: water temperature inside the reservoir, inlet air flow rate, size of the bubble generated in the reservoir, and height of water level inside the reservoir. System performance is improved with higher water temperature, water level, and smaller bubble size. The humidity level of the outlet air is increased with slower inlet air flow, but the time required for the entire enclosure to reach 95% RH level is increased concurrently (Design Document [20], Section 4.1). The purpose of this experiment is to determine the influence of the water temperature and inlet air flow rate on the performance of the humidification system.

3.3.2 Equipment

- 1 testing chamber with 63cm x 63cm x 68cm dimension (Appendix B.1)
- 1 air inlet tube with ¼ inch inner diameter
- 1 air outlet tube with ¼ inch inner diameter
- 1 cylindrical water reservoir with 10cm diameter (Appendix B.3)
- 1 water heating plate (Appendix B.6)
- 1 DHT11 humidity and temperature sensor (Appendix B.4)
- 1 Arduino UNO
- 1 laboratory air compressor
- 1 air stone diffuser with 2.4-inch diameter (Appendix B.7)

3.3.3 Procedure

1. Construct a basic bubble humidifier with an air inlet tube, an air outlet tube, a cylindrical reservoir, an air stone diffuser, and 500mL of water
2. Measure the height of the water level inside the reservoir
3. Measure the temperature of the water inside the reservoir
4. Heat the water to desired temperature with the heating plate
5. Connect the air inlet tube with the air compressor
6. Place the humidity sensor DHT11 inside the testing chamber
7. Connect the DHT11 sensor with Arduino
8. Close and seal all entrances of the testing chamber
9. Turn on the air compressor on to desired flow rate and record the ambient RH level inside the testing chamber
10. Turn off the humidification system
11. Take out all components from the testing chamber

3.3.4 Findings

The setup of this experiment is shown below:

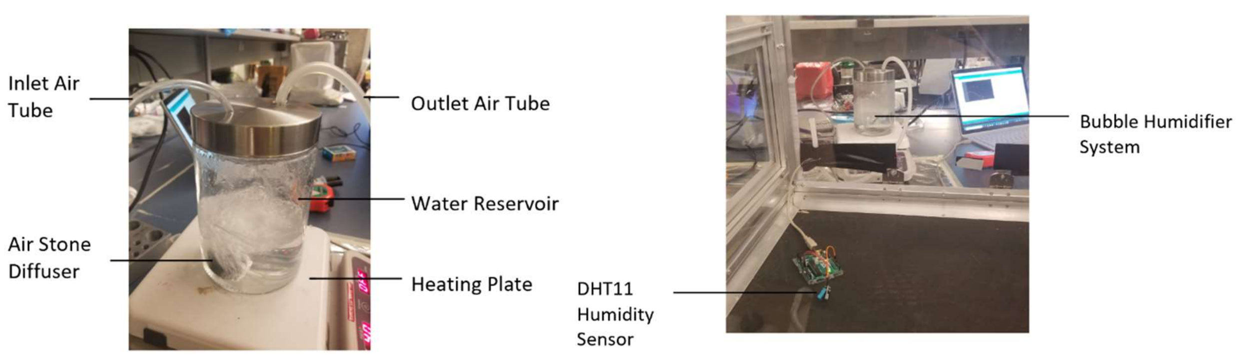

Figure 18: Experimental setup of bubble humidifier (a) Humidifier (b) Testing Chamber

	Water Temperature (°C)	Flow Rate(L/min)	Time to reach 90% RH (sec)
Test 1	40	50	405
Test 2	80	50	388
Test 3	80	80	N.D.

Figure 19: Input parameters setup and corresponding time required to reach 90% RH

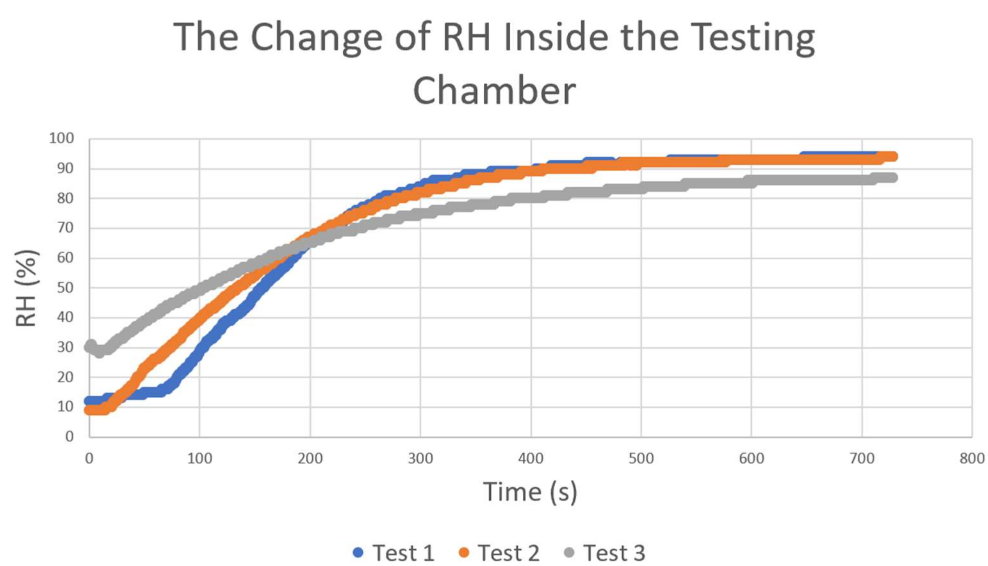

Figure 20: Change in RH within the testing chamber over time

In test 2, the initial water temperature was higher, resulting in a higher rate of change in RH when compared to test 1.The rate of change in RH for Test 2 slowed down at around 200 seconds and gradually reached a plateau at around 400 seconds. Test 2 arrived at 90% RH 17 seconds earlier than Test 1. The heating plate could be a factor that constrained the performance in Test 2. The heating plate was insufficient at holding the water temperature at 80 °C which potentially led to the decay in RH change rate.

The initial RH in Test 3 was higher compared to that of Test 2. However, the performance of Test 3 was worse as shown in Figure 4. With a higher flow rate, the amount of humid air transmitted into the testing chamber was increased. However, a higher flow rate reduced the contact time between air bubbles and water, resulting in lower RH level in outlet air of the system.

3.3.5 Conclusion

The performance of the bubble humidification system is improved with an increase in water temperature inside the reservoir. At a high inlet air flow rate range, the performance of the bubble humidification system is worsened with an increase in inlet air flow rate. Further experiment is needed to identify the optimum air flow rate for the enclosure system.

3.3.6 Documentation

Date of testing: Nov 27th, 2019

Testing performed by: Wendy Zhou, Andrew Yan

3.4 Humidification System - Air Flow Rate

3.4.1 Scope of Test

The purpose of this experiment is to determine the optimum inlet air flow rate for the humidification system.

3.4.2 Equipment

- 1 testing chamber with 63cm x 63cm x 68cm dimension (Appendix B.1)
- 1 air inlet tube with ⅜ inch inner diameter
- 2 air outlet tubes with ¾ inch inner diameter
- 1 cylindrical water reservoir with 20cm diameter (Appendix B.8)
- 1 immersion water heater (Appendix B.9)
- 1 CC2D23-SIP humidity and temperature sensor (Appendix B.10)
- 1 DHT22 humidity and temperature sensor (Appendix B.11)
- 1 Arduino Mega
- 1 laboratory air compressor
- 1 pressure relief valve (Appendix B.13)
- 1 thermocouple temperature sensor (Appendix B.14)
- 1 air stone diffuser with 4-inch diameter (Appendix B.15)
- 1 heat barrier (Appendix B.16)
- 1 flow rate meter (Appendix B.17)
- 3 resistors (1x each of 1K, 3K, 4.7K)
- 1 circuit breaker
- 1 relay module (Appendix B.18)

3.4.3 Procedure

1. Construct the humidification system with an air inlet tube, two air outlet tubes, a cylindrical reservoir, an air stone diffuser, a water heating element, 2 humidity sensors, a pressure relief valve, a thermocouple temperature sensor, and a heat barrier
2. Construct the humidification control circuit with 1K, 3K, and 4.7K resistors, a circuit breaker, a relay module, and an Arduino Mega microcontroller
3. fill the reservoir with 2L water
4. Connect the air inlet tube with the air compressor
5. Place the humidity sensor CC2D23-SIP in the middle of the testing chamber
6. Place the humidity sensor DHT22 at the corner of the testing chamber
7. Close and seal all entrances of the testing chamber
8. Turn on air compressor; calibrate inlet flow rate to desired level with flow rate meter
9. Record the ambient RH level
10. Record the temperature of the water inside the reservoir
11. Turn off the humidification system
12. Take out all components from the testing chamber

3.4.4 Findings

The setup of this experiment is shown below:

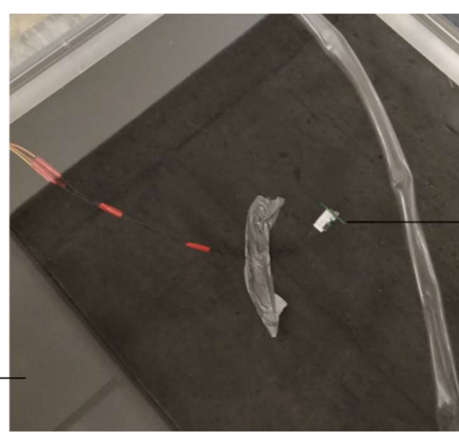

Figure 21: Experimental setup of the humidification system, part (a)

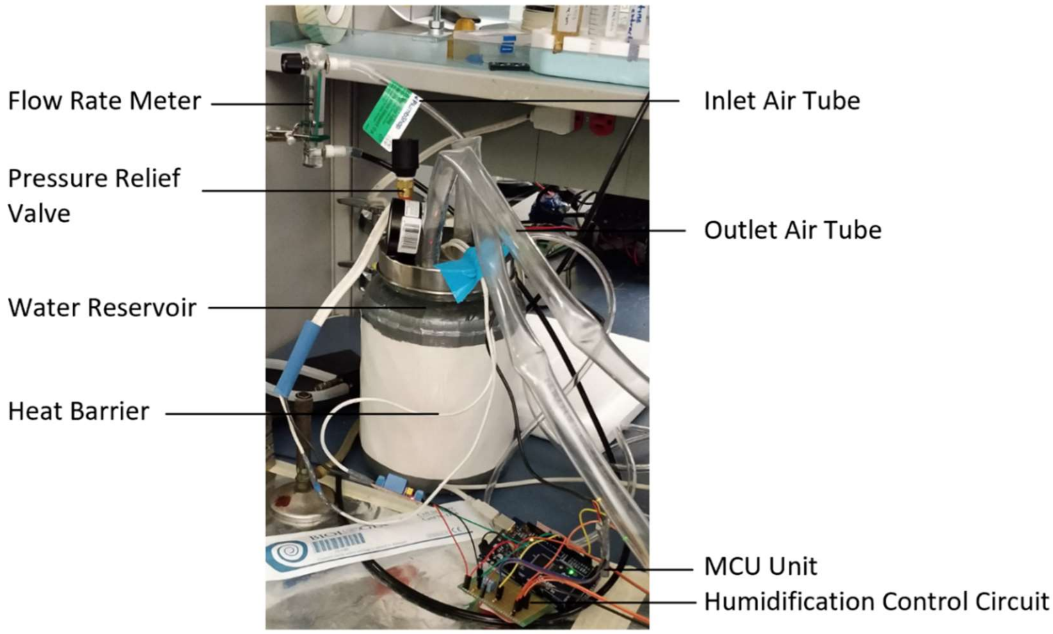

Figure 22: Experimental setup of the humidification system, part (b)

	Flow Rate(L/min)	Time to reach 90% RH (sec)
Test 1	10	N.D.
Test 2	20	2076
Test 3	25	2193

Table 9: Input parameters setup and corresponding time required to reach 90% RH

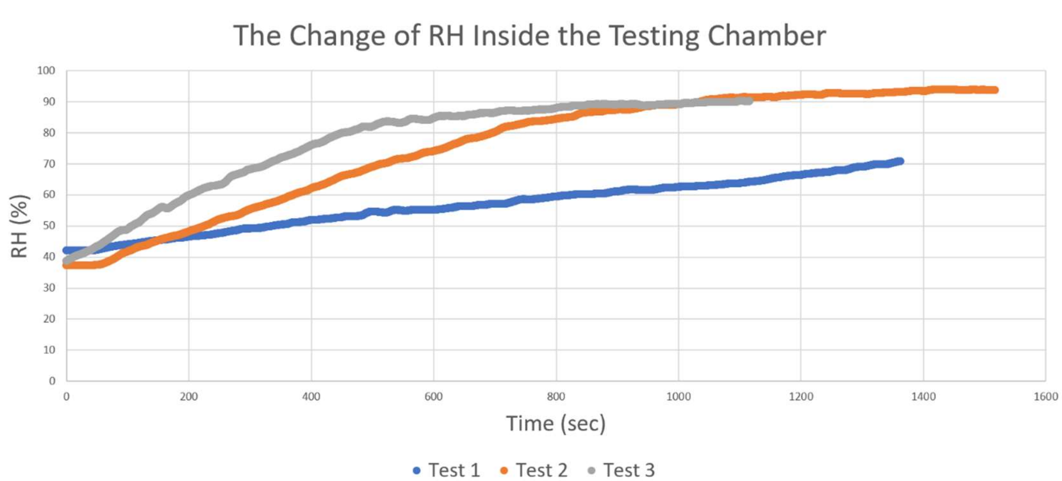

Figure 23: Change in RH within the testing chamber over time

Based on the result from Test 1 and Test 2, as the inlet air flow rate increased from 10L/min to 20L/min, the performance of the humidification system improved dramatically. The initial rate of increase in RH for Test 3 exceeded that of Test 2. However, the rate of change slowed down at around 500 seconds. During the experiment, it was observed that some water inside the reservoir was pushed into the air outlet tubes in Test 3 due to high inlet air flow rate. One outlet tube was completely blocked at around 500 seconds. This could potentially affect the system performance in Test 3 and lead to the RH rate of change decreasing.

3.4.5 Conclusion

At a low inlet air flow rate range, the performance of the bubble humidification system is improved with an increase in inlet air flow rate.

3.4.6 Documentation

Date of testing: Feb 8th, 2020

Testing performed by: Wendy Zhou, Andrew Yan

3.5 Humidification System – Prototype Testing

3.5.1 Scope of Test

The purpose of this experiment is to determine the performance of the 2nd version prototype of the Bubble humidifier. Note that two air pumps are implemented as the inlet air source instead of the air compressor.

3.5.2 Equipment

- 1 testing chamber with 63cm x 63cm x 68cm dimension (Appendix B.1)
- 2 air inlet tubes with ⅜ inch inner diameter
- 2 air outlet tubes with ¾ inch inner diameter
- 1 cylindrical water reservoir with 20cm diameter (Appendix B.8)
- 1 immersion water heater (Appendix B.9)
- 1 air flow rate meter (Appendix B.17)
- 1 CC2D23-SIP humidity and temperature sensor (Appendix B.10)
- 1 DHT22 humidity and temperature sensor (Appendix B.11)
- 1 Arduino Mega
- 2 air pumps (Appendix B.19)
- 1 pressure relief valve (Appendix B.13)
- 1 thermocouple temperature sensor (Appendix B.14)
- 1 air stone diffuser with 4-inch diameter (Appendix B.15)
- 1 air stone diffuser with 2.4-inch diameter (Appendix B.7)
- 1 heat barrier (Appendix B.16)
- 3 resistors (1x each of 1K, 3K, 4.7K)
- 1 circuit breaker
- 1 relay module (Appendix B.17)

3.5.3 Procedure

1. Construct the humidification system with two air inlet tubes, two air outlet tubes, a cylindrical reservoir, two air pumps, two air stone diffusers, an immersion water heater, two humidity sensors, a pressure relief valve, a thermocouple temperature sensor, and a heat barrier
2. Construct the humidification control circuit with 1K, 3K, and 4.7K resistors, a circuit breaker, a relay module, and an Arduino Mega microcontroller
3. fill the reservoir with 2L water
4. Connect the air inlet tubes with the air pumps
5. Place the humidity sensor CC2D23-SIP in the middle of the testing chamber
6. Place the humidity sensor DHT22 at the corner of the testing chamber
7. Close and seal all entrances of the testing chamber
8. Measure the air flow rate of each pump with an air flow meter
9. Activate the humidification system and turn on the 2 air pumps
10. Record the ambient RH level
11. Record the temperature of the water inside the reservoir
12. Turn off the humidification system once the ambient RH level inside the testing chamber has reached 95%
13. Take out all components from the testing chamber

3.5.4 Findings

The result of this experiment is shown below:

Test #	Flow rate (L/min)	Time to reach 95% RH (sec)
1	36	1142
2	36	1092

Table 10: Time required to reach 95% RH for 2 test slots

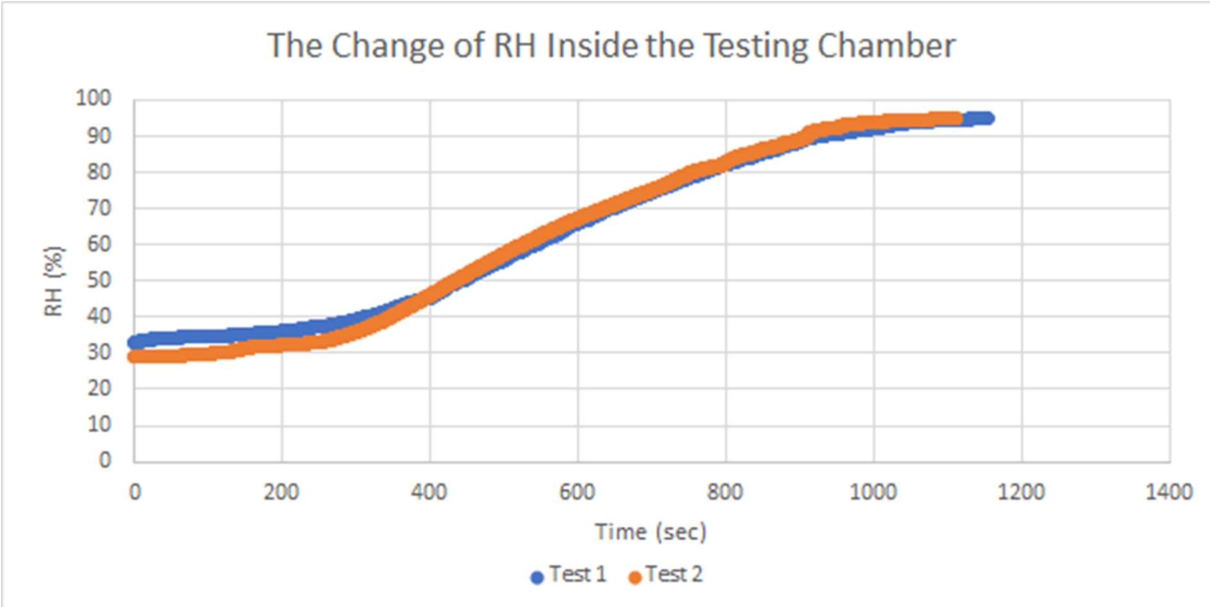

Figure 24: Change in RH within the testing chamber over time

Based on the measurements shown in Table 10, the air flow rate of the pump was 18L/min each and 36L/min in total. This inlet air flow rate fell within the optimal range as discussed in Sections 3.3.4 and 3.4.4.Test 1 and Test shared identical input parameters and setup. As shown in Figure 24, the performance of the system was relatively stable throughout the 2 test slots. The desired 95% RH setpoint in the testing chamber could be reached in approximately 18 minutes for both tests. The result of this validation experiment suggested that the current prototype of the bubble humidification system is stable and reliable and can be further implemented as the final version of the system.

It was observed that there existed some degree of water leakage at the lid of the reservoir during the experiment. This is undesired and potentially harmful to the ECU of the system and to the user. This potential hazard can be eliminated with a suitable sealing gasket.

3.5.5 Conclusion

With the current prototype of the humidification system, the RH level inside the testing chamber can be raised from room RH level to 95% in approximately 18 minutes. Further improvements to the system may include adding the Water Sterilization System (Design Document[20], Section 4.1.2) and a sealing gasket to the reservoir.

3.5.6 Documentation

Date of testing: Mar 10th, 2020

Testing performed by: Wendy Zhou

3.6 Dehumidification System – Dehumidification Speed

3.6.1 Scope of Test

The purpose of this experiment is to validate that the dehumidification system can remove water from an enclosed space to meet requirement F2.3.

3.6.2 Equipment

- 1 assembled BIOME enclosure (Design Document [20], Section 2)
- 1 Laptop with MATLAB, PuTTY and Arduino IDE installed

3.6.3 Procedure

1. Open the Arduino IDE
2. Modify Arduino code to output humidity readings, setpoints and timestamps to the serial monitor
3. Flash the modified code onto the Arduino
4. Connect the Arduino to the laptop and prepare to record data using PuTTY (setup Serial COM port and file where data will be saved)
5. Start the dehumidification process using the LCD screen
6. Upload the data to Excel
7. Plot the data using Scatterplot
8. Record the stop time as the point at which the data stays within 0.1% of the setpoint for 5 minutes
9. Subtract 5 minutes from the total time and record

3.6.4 Findings

Unfortunately, this test could not be completed due to the COVID-19 pandemic.

3.7 Dehumidification System Modeling

3.7.1 Scope of Test

The purpose of this experiment is to get a model of the system that can be controlled using PID.

3.7.2 Equipment

- 1 assembled BIOME enclosure (Design Document [20], Section 2)
- 1 Laptop with MATLAB, PuTTY and Arduino IDE installed

3.7.3 Procedure

1. Open the Arduino IDE
2. Modify Arduino code to output humidity readings, setpoints and timestamps to the serial monitor
3. Modify Arduino code to output a 100% PWM to the dehumidification fans (255)
4. Flash the modified code onto the Arduino
5. Connect the Arduino to the laptop and prepare to record data using PuTTY (setup Serial COM port and file where data will be saved)
6. Start the dehumidification process using the LCD screen
7. Upload the data to MATLAB
8. Use the System Identification Toolbox to approximate the plant model of the system

3.7.4 Findings

Unfortunately, this test could not be completed due to the COVID-19 pandemic.

3.8 Dehumidification System Control

3.8.1 Scope of Test

The purpose of this experiment is to validate that the dehumidification system correctly implements PID control that matches initial modelling, limits overshoot and reaches the correct steady state value.

3.8.2 Equipment

- 1 assembled BIOME enclosure (Design Document [20], Section 2)
- 1 Laptop with MATLAB, Simulink, PuTTY and Arduino IDE installed

3.8.3 Procedure

1. Open the Arduino IDE
2. Modify Arduino code to output humidity readings, setpoints and timestamps to the serial monitor
3. Flash the modified code onto the Arduino
4. Connect the Arduino to the laptop and prepare to record data using PuTTY (setup Serial COM port and file where data will be saved)
5. Start the dehumidification process using the LCD screen
6. Load the data into MATLAB
7. Plot the data against the expected response (given the ideal plant model)
8. Record overshoot, settle time, steady state value and rise time for both the expected response and the actual response
9. Calculate the percentage error for all the values in step 8

3.8.4 Findings

Unfortunately, this test could not be completed due to the COVID-19 pandemic.

APPENDIX A: DEFINITIONS

Dewpoint	the temperature at which the air is fully saturated (100% RH). Condensation will form if the temperature is lower further, or more water vapour is added.
Relative Humidity (RH)	a measure of the amount of water vapour in the air at a given temperature in a given volume.

APPENDIX B: EXPERIMENTAL EQUIPMENT

1. Enclosed compartment

Figure 25: 63 cm x 63 cm x 68 cm enclosed compartment

2. 2.5W power mechanical air pump

Figure 26: 2.5W air pump B06XS9TVNG [1]

3. Cylindrical water reservoir with 10cm diameter

Figure 27: Water reservoir with 10mm diameter [2]

4. DHT11 humidity and temperature sensor

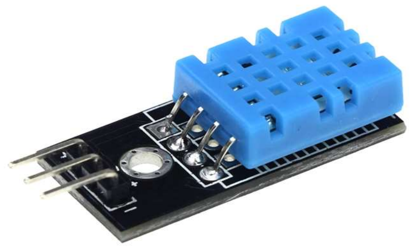

Figure 28: DHT11 sensor [3]

5. Arduino UNO

Figure 29: Arduino UNO [4]

6. Water heating plate

Figure 30: Water heating plate [5]

7. Air stone diffuser with 2.4-inch diameter

Figure 31: 2.4-inch air stone diffuser [6]

8. Cylindrical water reservoir with 20cm diameter

Figure 32: Water reservoir with 20mm diameter [7]

9. Immersion water heater

Figure 33: Immersion water heater DNCA1501154 [8]

10. CC2D23-SIP humidity and temperature sensor

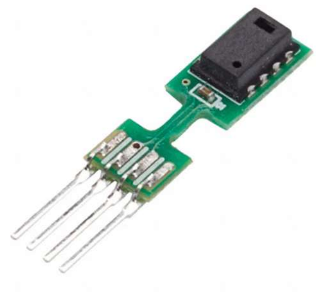

Figure 34: CC2D23-SIP sensor [9]

11. DHT22 humidity and temperature sensor

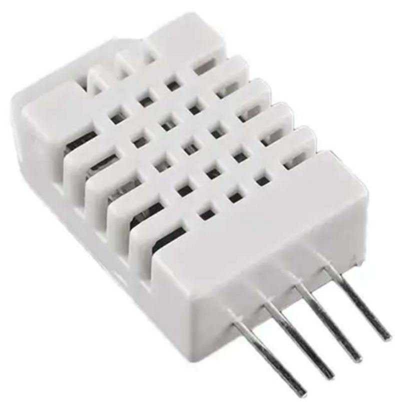

Figure 35: DHT22 sensor [10]

12. Arduino Mega

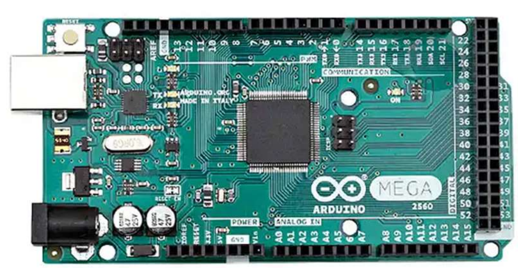

Figure 36: Arduino Mega2560 [11]

13. Pressure relief valve

Figure 37: Pressure relief valve [12]

14. Thermocouple temperature sensor

Figure 38: Waterproof thermocouple temperature sensor DS18S20 [13]

15. Air stone diffuser with 4-inch diameter

Figure 39: 4-inch air stone diffuser [14]

16. Heat barrier

Figure 40: Aluminum heat barrier [15]

17. Flow rate meter

Figure 41: Laboratory flow rate meter [16]

18. Relay module

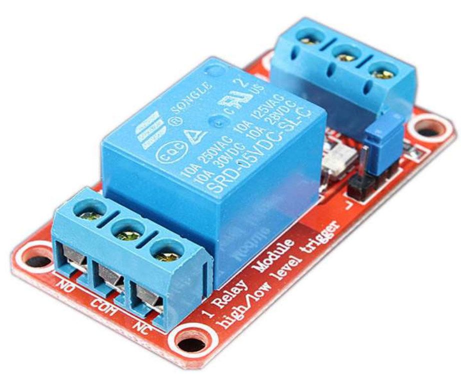

Figure 42: 5VDC relay module [17]

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