Environmental Box 2.0
Spring 2025 ME Executive Summary

Design Team

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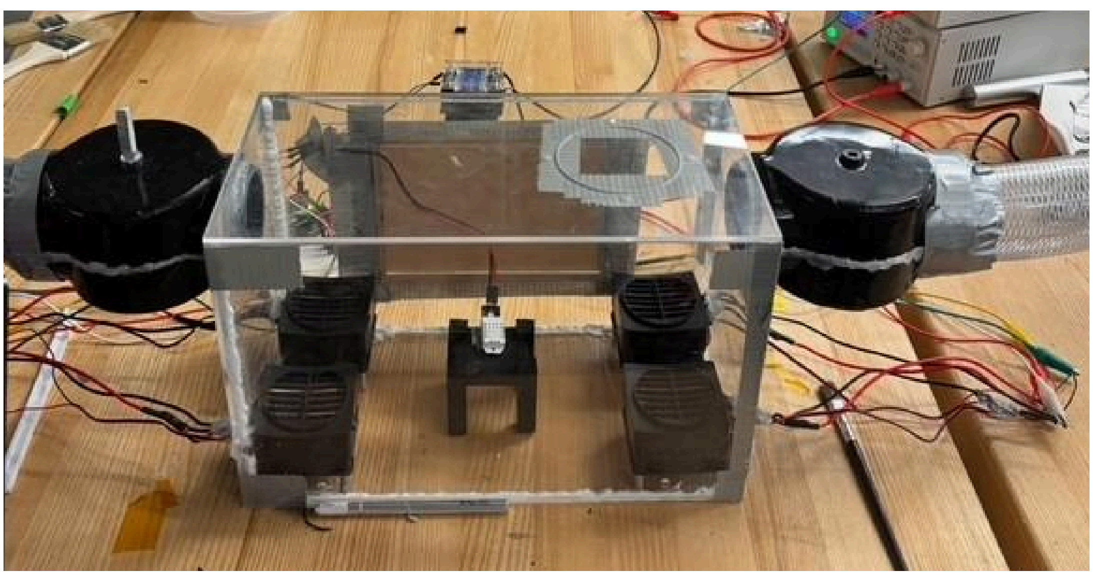
Abstract

The Multiphase Transport Research Lab at Northeastern University, led by Dr. Xiaoyu Tang, seeks a way to perform droplet experiments under different environmental conditions, where even minor fluctuations in temperature and humidity compromise reproducibility. Commercial chambers impose prohibitive costs and neglect specific research needs, and Environmental Box 1.0 failed to sustain conditions beyond five minutes because of improper sealing of components and control protocols that were not fully built out. Our Environmental Box 2.0 Team, a Northeastern Mechanical Engineering Capstone team, aimed to address these issues by grounding the design in thermodynamic and psychrometric principles, evaluating PID and PWM control strategies, and analyzing airflow and gradient behavior through simulation, building on lessons from the shortcomings of the 1.0 prototype. The resulting design integrates a sealed acrylic enclosure with 4 corner-mounted PTC heaters, ultrasonic humidification, and modular desiccant dehumidification, coordinated through Arduino-based control and custom 3D-printed valves that actively manage airflow while preserving a sealed environment. Testing demonstrated stability within ±2.5 °C and ±5% RH for over 30 minutes, enabling reproducible droplet experimentation. By delivering comparable performance to commercial systems that cost more than $18,000 while keeping the build cost under $1,000, Environmental Box 2.0 provides a robust, adaptable research instrument that advances laboratory environmental control.



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Need

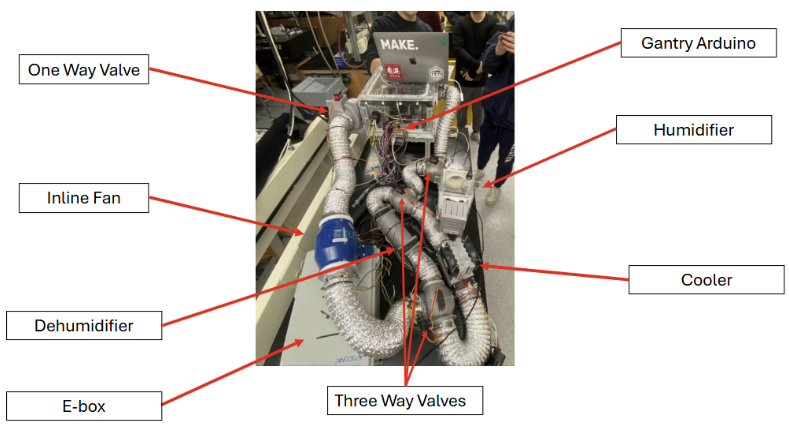
Within Professor Xiaoyu Tang's laboratory at Northeastern University, researchers study the evaporation and crystallization of microscopic droplets to understand how temperature and humidity influence phase changes. Professor Xiaoyu Tang identified the need for a compact, controllable environmental chamber tailored to her laboratory's ongoing droplet-evaporation studies. The system must maintain stable temperature and humidity setpoints for thirty minute durations while minimizing internal airflow to preserve stable conditions. In response to this request, the Environmental Box 2.0 project was conceived to bridge the gap between costly commercial solutions and research-specific precision tools.

Background and Significant Prior Work

Environmental Box 2.0 draws on prior capstone work, core thermodynamic principles, and commercial chamber designs to tackle the challenge of precise environmental control in droplet experimentation. Recognizing the limitations of Environmental Box 1.0 and insights from broader research on temperature–humidity interactions guided the development of our new system. By studying the shortcomings of Version 1.0, reviewing psychrometric and control-system literature, and comparing commercial approaches, we pinpointed key gaps in reproducibility and stability.

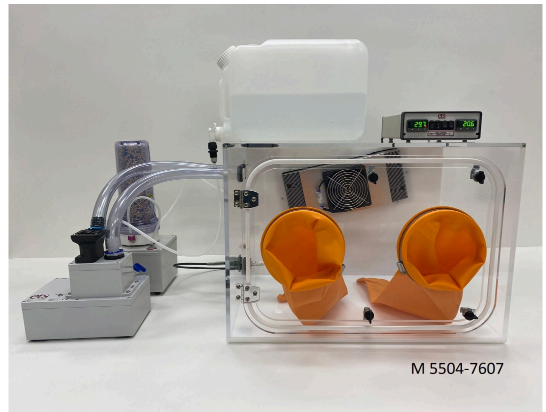
Environmental Box 1.0

Environmental Box 2.0 builds directly on the foundation of Environmental Box 1.0, a previous Northeastern capstone project that demonstrated the feasibility of a compact, low-cost environmental chamber for droplet studies. Version 1.0 successfully integrated, a closed airflow network, and basic humidification/dehumidification, but it also revealed several critical shortcomings: uninsulated tubing that caused temperature leakage, ambient-air intrusion through the humidifier intake, bang-bang humidity control that produced drift, and a droplet gantry that could not operate while maintaining thermal stability [3]. These limitations directly informed our starting point for Environmental Box 2.0, shaping the need for improved insulation, a fully closed flowpath, continuous feedback control, and a redesigned dispensing system.



Foundations and Research

To understand the need for tighter control, a reader must know the basic thermodynamic and psychrometric principles that govern temperature/humidity interactions. Dry-bulb temperature sets the air's moisture-holding capacity, while relative humidity reflects the ratio of vapor to saturation. Using Dalton's law and the ideal gas law, the vapor mass in a closed chamber can be calculated directly from temperature and RH, which is essential for predicting humidifier and dehumidifier load requirements [1], [6]. To prevent condensation, which distorts optical measurements in droplet experiments, the Magnus dew-point relation is used within the PID control system to ensure that all system setpoints remain above the dew-point threshold during operation. These principles frame how environmental chambers maintain stable internal conditions [1].



Existing solutions in research and industry rely on a variety of approaches. Commercial chambers, such as the Electro-Tech Systems M 5504 glovebox, achieve wide temperature and humidity ranges using thermoelectric heating/cooling and integrated moisture-control subsystems [4], [5]. However, these systems cost over $18,000 and are not optimized for micro-scale droplet research, lacking optical access, compact form factor, or droplet-placement capability. Academic work consistently supports the use of PID feedback control for regulating temperature and humidity, showing strong stability and adaptability in environmental and HVAC systems [2]. Studies such as Qu et al. (2020) demonstrate how even small fluctuations in humidity and temperature significantly alter evaporation rates and crystallization behavior, underscoring the necessity of tightly controlled, low-noise chambers for reproducible droplet experiments [8].

Environmental Box 1.0 utilized ultrasonic humidification, which research identified as the most efficient method of humidification. Ultrasonic humidifiers generate humidity by vibrating a piezoelectric transducer at high frequency to atomize water into fine mist droplets. They consume only 25–35 W of power, up to 90% less energy than steam-based systems, and deliver rapid, quiet, and responsive humidity control. Because they rely on mechanical vibration rather than heat, they avoid thermal disturbances inside sensitive chambers and provide near-instant mist generation that supports stable experimental conditions. The shortcomings of 1.0 arose from the sealing and execution of the humidifier subsystem, not the base technology [9].

Similarly, Version 1.0 employed desiccant-based dehumidification, the best method for the project's needs, but suffered from design execution issues. Desiccant dehumidifiers remove moisture by adsorbing water vapor onto a silica gel wheel and regenerating the desiccant with heated air. They achieve extremely low humidity levels, with dew points as low as –62 ℃ and single-digit relative humidities, without the risk of coil freeze or condensate re-entrainment. This deep-drying capability makes them ideal for experiments that demand strict moisture suppression, even though they operate at lower exergy efficiency compared to refrigerant-based systems [10].

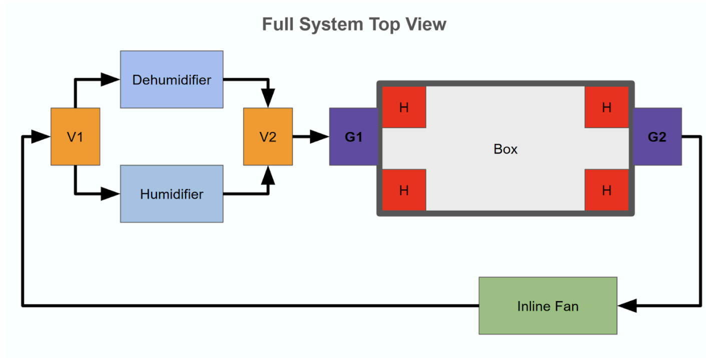
<u>*Summary*</u>

Environmental Box 2.0 builds on thermodynamic principles, prior capstone findings, commercial system limitations, and recent research on droplet behavior. Together, these factors guided every design decision, resulting in a compact, modular, research-grade chamber tailored for micro-scale evaporation studies. The project continues the ongoing work in Professor Tang's laboratory at Northeastern University, where precise environmental control is essential for droplet evaporation and beneficial for related fields like material-science research. By refining Environmental Box 1.0 and integrating advanced control strategies, Environmental Box 2.0 provides an affordable, precise, and reliable chamber that supports consistent, reproducible experimentation.

Design Solution

We engineered Environmental Box 2.0 to provide precise and reliable control of both temperature and humidity within a controlled test environment. The system achieves this through a series of integrated mechanical subsystems, including the test chamber, humidifier, dehumidifier, and inline fan. These components work together to maintain stable and adjustable environmental conditions.

The system manages airflow using two three-way valves that direct air through either the humidifier or the dehumidifier, along with gate valves that control the entry of conditioned air into the test chamber. This configuration allows the system to deliver either high-humidity (saturated) air or low-humidity air, depending on the target conditions. The inline fan promotes thorough mixing and ensures consistent delivery to the test chamber.

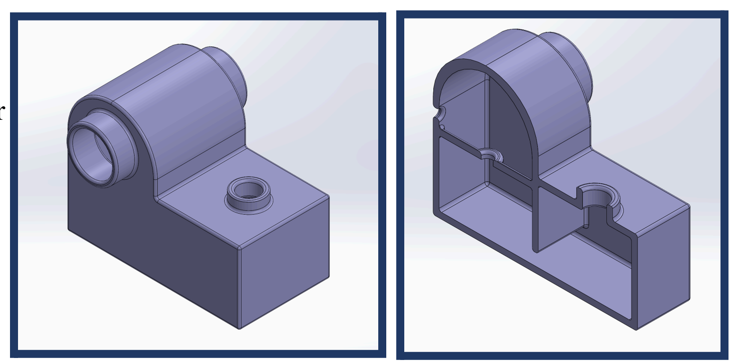


The system controls temperature independently of airflow. Four PTC heaters, which we positioned at the corners of the test chamber, provide even heating and maintain a consistent thermal environment. This placement minimizes temperature gradients and allows the system to sustain stable thermal conditions without relying on air circulation.

By integrating sensors, electronic components, and Arduino-based control logic, the system continuously monitors and adjusts environmental conditions. These subsystems operate in coordination to maintain a precisely controlled environment with independently adjustable temperature and humidity. The system responds dynamically to changes and ensures stable, repeatable conditions for testing and experimentation.

Humidifier

Environmental Box 2.0, like its predecessor, uses a piezoelectric transducer to achieve ultrasonic humidification. The design team restructured the humidifier to resolve sealing issues and inefficiencies present in the earlier version. The transducer generates ultrasonic waves within a water reservoir, producing mist and saturating the air inside the subsystem.



To contain all vapor, the water reservoir is divided with a baffle that leaves a small gap at the bottom below the water level. This configuration separates the effective reservoir from the fill reservoir. The transducer sits on one side of the baffle, and the fill entry sits on the other. The bottom opening allows both reservoirs to equilibrate. As users replenish the fill reservoir, the effective reservoir rises accordingly, enabling simultaneous refilling and operation without releasing mist from the closed system.
The design also includes a cylindrical chamber aligned with the system tubing. This chamber guides the saturated air into the flow path and maximizes the delivery of humidified air to the test chamber

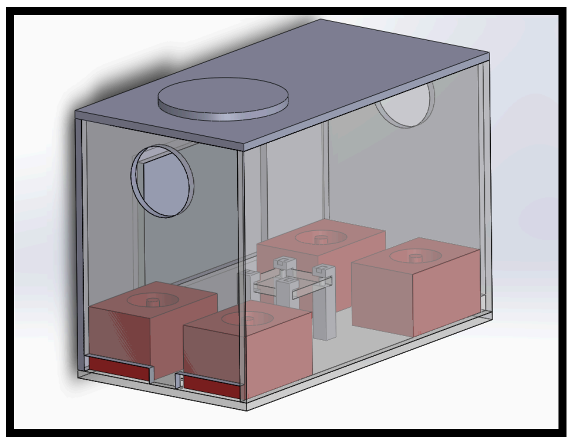
Dehumidifier

Environmental Box 2.0, like its predecessor and most existing humidity control chambers, uses a desiccant-based dehumidifier that relies on silica gel. This approach effectively maintains relative humidity levels between 5% and 95%. However, the desiccant's fixed capacity requires periodic reactivation to sustain continuous operation. To streamline this process, the system employs a screw-on cap design with interchangeable caps for filling and use. Users can easily replace or reactivate the desiccant by sliding and press-fitting the container into a dedicated holding fixture, no tools required. This modular setup simplifies maintenance, reduces downtime, and enables quick return to operation after servicing.

The subsystem includes enough desiccant to support over ten consecutive tests without any measurable drop in performance. By combining modularity, ease of handling, and generous capacity, Environmental Box 2.0 delivers reliable, efficient dehumidification while minimizing user effort and turnaround time.

Test Box

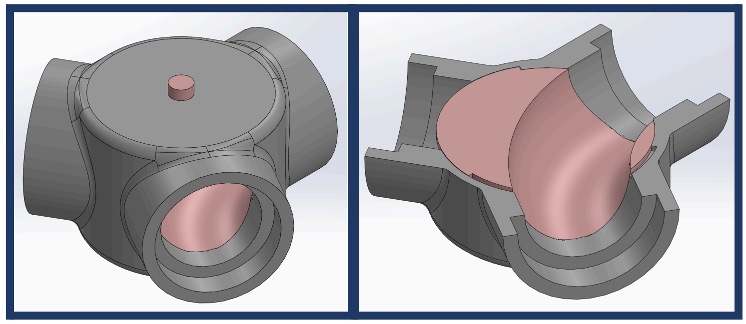
The test box functions as the primary control target and analytical focus of the Environmental Box 2.0 system. During development, we analyzed temperature and humidity gradients within the chamber and identified optimal methods for introducing inputs while preserving a stable, uniform environment. Constructed from acrylic and measuring 12 × 8 × 6 inches, the box includes a central elevated test platform for experiments, a door for specimen placement, inlet and outlet airflow ports, and integrated heaters for temperature regulation. These dimensions minimize volume while accommodating all components and providing adequate space for droplet experimentation.



To maintain symmetry and ensure balanced thermal distribution, the design places four PTC heaters at the box corners. Each heater combines a resistive element with an integrated fan that directs air through the element to promote convective heat transfer. Analysis confirmed that low-level airflow is essential for achieving uniform temperature and humidity. Operating at 24 volts and drawing roughly 10 amperes each, the heaters consume significantly less power than alternatives. By capping voltage at 24 volts, the system improves electrical safety, simplifies integration, and supports reliable operation from a single power source.

The system achieves successful environmental control by balancing two key objectives: minimizing airflow velocity in the test area and reducing temperature and humidity gradients throughout the chamber. Without airflow, heat accumulates near the top while humidity concentrates near the bottom due to warmer air's higher moisture capacity. To counteract this, the control algorithm runs heater fans at low speed, generating gentle airflow that softens gradients without disturbing the test area. Although some vertical variation persists, the elevated test platform places experiments in the most thermally uniform zone. This central configuration also channels convection currents around the test area, creating a low-velocity region ideal for maintaining stable droplet conditions during experimentation.
experimentation.

Valves and Gates



The valves and gates define the airflow path and regulate humidity inputs and outputs within the system. A pair of three-way valves directs cyclic airflow through either the humidifier or the dehumidifier, while a pair of gate valves enables or disables flow circulation as needed.

For prototyping, we designed the valves with cylindrical geometry to support reliable DC motor actuation and ensure structural robustness during additive manufacturing. They used custom 3D printing, as no commercially available, cost-effective valves fit the 2-inch tubing required to meet the target mass flow rate. Both valve types include internal mechanical stops that constrain rotation to designated end positions. These built-in limits eliminate the need for high-precision motor control by mechanically restricting excess rotation, which improves reliability and simplifies actuation.

Electronics

We ensured proper selection and integration of electronic components and schematics to protect user safety and prevent malfunction. With the help of electronics expert Kevin McCue, We identified all components requiring electrical power, evaluated their power requirements, and determined how to integrate and operate them safely within the system. We selected PTC heaters because they offered superior efficiency compared to all evaluated alternatives and operated at a low voltage of 24 volts. These heaters account for more than 70 percent of the system's total power consumption.

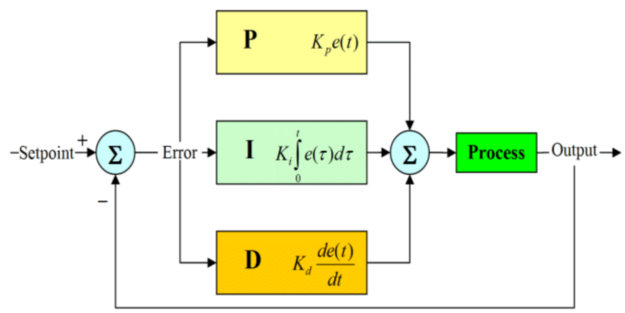
Each group of components requiring control, including heating elements, heater fans, gates, valves, and the humidifier, are connected to solid-state relays that switch at approximately 10 millisecond intervals. By using solid-state relays instead of mechanical ones, they eliminated delay concerns within the control algorithm. They also selected a single high-rated relay to control all heaters, which ensured uniform and symmetrical power delivery.

SHT40 Temperature and Humidity Sensor Modules measure environmental conditions with a temperature accuracy of ±0.2 degrees Celsius and a relative humidity accuracy of ±2.0 percent. These sensors exceed the project's precision requirements by more than a factor of two and operate over a range substantially greater than required. The sensors transmit rapid and reliable measurements to the Arduino Uno, which processes the data and applies it within the control algorithms to regulate system operation.

Control Logic and Algorithms

Temperature and humidity operate under independent control algorithms, coordinated by supervisory logic that determines their timing and capacity. The system regulates temperature using PID control of pulse-width modulated (PWM) power to the heaters, and manages humidity through a gate-closing algorithm that predicts overshoot and stabilizes conditions.

PWM enables scalable heater control by adjusting the duty cycle of a signal delivered via a solid-state relay, which switches states every 10 milliseconds. The Arduino Uno generates this signal, ensuring safe, cost-effective power modulation with electrical isolation.



The PID controller continuously calculates the error e(t)=SP-PV and produces a control signal u(t) with proportional, integral, and derivative components. It responds to current error, compensates for past deviations, and anticipates future trends. Although the heater's response does not follow a strictly linear pattern, its consistent and time-invariant behavior allows the PID algorithm to regulate temperature effectively. By integrating this robust temperature control with predictive humidity logic, the system maintains precise, stable, and repeatable environmental conditions across a wide range of operating scenarios.

Summary

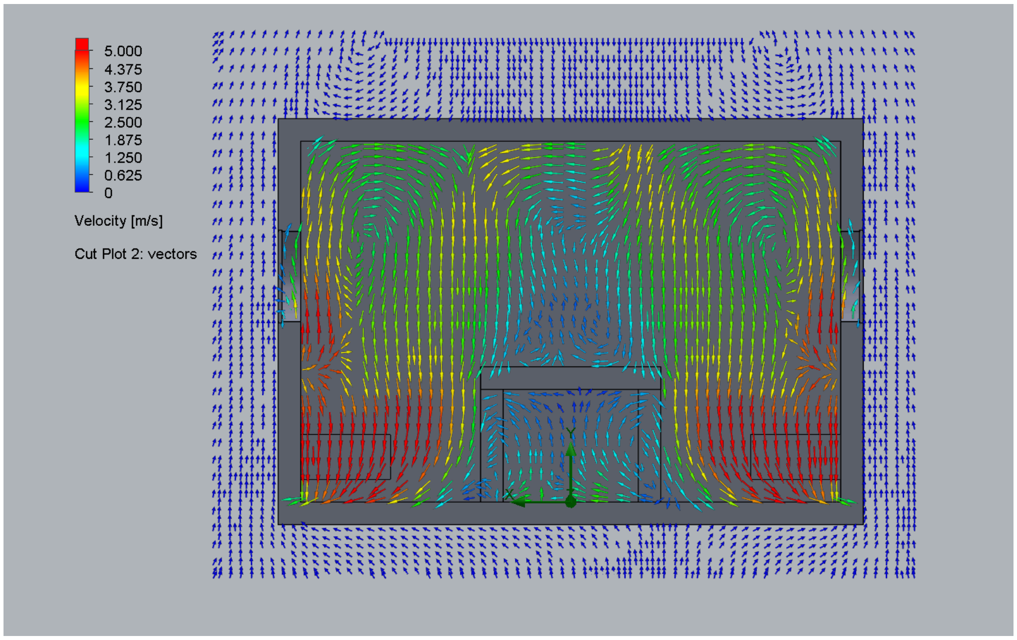
Environmental Box 2.0 unifies its mechanical, electrical, and control subsystems into a coherent design that achieves precise regulation of temperature and humidity. The sealed acrylic chamber, corner-mounted PTC heaters, ultrasonic humidifier, and modular desiccant dehumidifier are arranged to minimize gradients and maintain uniform conditions. Custom 3D-printed valves and gates direct airflow through the system, while Arduino-based PID and PWM control continuously adjusts heater output and humidity inputs to sustain stability. By coordinating these elements, the design delivers a controlled environment that balances low airflow velocity with consistent thermal and moisture distribution, ensuring reproducible conditions for droplet experimentation.

Design Process

The design process was taken step by step, with four major stages cleared for most of the sub-systems. Separating the 2.0 into five major sub-systems helped us divide work amongst group members, and allowed testing of each system individually once prototypes were created. Another reason we decided to divide the overall project into sub-systems was that each one required different design processes, although they all followed the same general four step process. The design process started with research, then moved to necessary calculations and simulations. After we confirmed our ideas had efficacy, we moved onto the design of parts in SolidWorks, with these mainly being housing units for purchased components added to finalize the sub-system. Any minor parts not easily placed under any specific sub-system were given to one member of the group to complete, an example being the three-way valves.

Heating Array

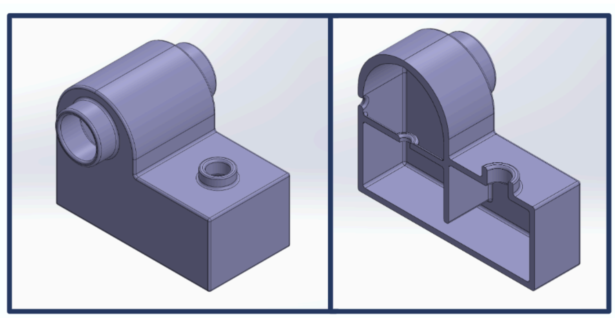
One of the key aspects of this Capstone project is raising the temperature of the testing environment and then maintaining that temperature. Many heating element designs fit our specifications (20–60 °C (±1 °C)), so research became a major component of this sub-system design. We considered resistive heaters, circulation heaters, PTC heaters, and strip heaters. As with all sub-systems, we examined Environmental Box 1.0, which used one large 900 Watt strip heater. This design choice posed multiple issues, chief among them safety, because the 900 Watt heater required over 100 Volts for operation. After meeting with the capstone electronics expert Kevin, we set 24 Volts as a safe operating voltage. This decision made performing large numbers of tests easier once we completed the prototype heating setup, since no supervision was required. After researching and incorporating the 24 Volt limit, one option stood out: the PTC heater. These heaters produce hundreds of watts of heating at low voltage, making them an ideal choice.



After we selected PTC heaters, one of our group members ran a simulation in SolidWorks Flow Sim to model both temperature and humidity gradients, as well as flow velocity inside the chamber. Professor Tang emphasized early in the design process that minimizing convection in the testing area is vital, because convection can significantly impact the evaporative process. PTC heaters require fans for operation, but simulations with four PTC heaters in each corner demonstrated that we could create a relatively low velocity area around the testing plate.

We also generated temperature and humidity plots for various heater outputs and fan speeds. The main takeaway from these simulations showed that fans prevent temperature and humidity gradients.With fans operating at sufficient capacity, we drastically reduced the temperature and humidity gradients. The relative humidity plots inversely correlated with temperature gradients: relative humidity decreased from the bottom of the chamber to the top, opposing the temperature profile

Humidification System



The humidification system proved to be the smoothest design process overall. The design specifications for the humidifier remained broad, with price and size as the main limiting factors. Environmental Box 1.0’s humidifier system produced a sufficient amount of mist with a piezoelectric transducer. However, a few issues arose, including residue buildup and improper sealing. We resolved these issues by 3D printing a housing with 100% infill to reduce water leakage, then applying an acrylic sealant to the inside of the housing to completely prevent water from escaping. We quickly printed and assembled our first design, and humidity tests confirmed full saturation of air passed through the subsystem.

Dehumidification

Creating a dehumidification system required the longest iterative process to develop an optimal prototype. Initially, we debated between a refrigerant and desiccant dehumidifier, with desiccant as our final choice given its higher efficiency at lower relative humidities compared to a refrigerant system. The amount of heat transfer introduced to the system remained much smaller with desiccant absorption, since refrigerant-based dehumidifiers required the air temperature to drop past the dew point to remove moisture. Desiccant absorption generated heat, but the generation was far smaller than the removal of heat required by a refrigerant system.

One design challenge we faced with desiccant dehumidification was that absorption rates declined over time as the material became saturated with moisture. We resolved this issue by designing a "hot-swap" system, where saturated desiccant could be quickly replaced. This design simplified reactivation, since we removed moisture from the desiccant during tests without pausing dehumidification.

For desiccant placement, we built two test setups: one completely filled with desiccant (V2) and another with an open airway surrounded by desiccant (V1). We tested both systems to determine which would dehumidify at a faster rate. The resultant data plot appears in the results section, but the end result demonstrated that version 2 achieved significantly higher dehumidification rates, with a smaller loss of absorption over time due to the increased amount of silica gel inside the container.

Electronic Control

Our control system methodology evolved significantly during the design process. Environmental Box 1.0 relied on a dedicated PID unit for temperature regulation, which provided precise control but struggled with stability due to inadequate chamber sealing. Initially, we planned to adopt the same PID-only approach. However, after further research and consultation with a Thermal Systems Analysis and Controls professor, we determined that a dual strategy, combining PID control with PWM modulation, would better suit our application by improving temperature reliability.

For humidity regulation, proper sealing ensures consistent moisture retention throughout testing. To achieve target humidity levels, we implemented a predictive approach: by analyzing humidification and dehumidification dynamics, we can estimate the time required to reach the desired condition. Once achieved, the chamber is sealed, effectively trapping the moisture for the duration of the experiment

Summary

We approached the development of Environmental Box 2.0 with a clear, step‑by‑step methodology. We divided the project into five subsystems: heating, humidification, dehumidification, airflow control, and electronics. We assigned responsibilities to ensure steady progress and carried out research and calculations to establish safe operating limits. We used SolidWorks simulations to predict gradients and airflow behavior, then designed and fabricated components through CAD modeling and 3D printing. We refined prototypes until each subsystem met performance requirements, tested them individually, and confirmed their functionality. Finally, we integrated all subsystems into a cohesive chamber. By moving through research, simulation, design, and testing in sequence, we created a reliable system that maintains controlled temperature and humidity for droplet experimentation.

Results

Testing of Environmental Box 2.0 demonstrated reliable temperature and humidity control within the enclosed chamber. The PTC heater array raised the temperature from ambient to 60 °C and beyond within [time] and maintained stability within ±2.5 °C (as of the writing of this report).

Measurements inside the chamber indicated that thermal and humidity gradients were existent but manageable for the purposes of droplet experimentation, confirming that the distributed heater placement and low-speed internal airflow created a stable and uniform environment. The ultrasonic humidifier and desiccant-based dehumidifier altered humidity between ~5% and above 95% RH with less than ±5% variation.

Airflow regulation through the 3D-printed valves provided balanced circulation without noticeable leakage. Tests with integrated electronics confirmed consistent communication between sensors, relays, and control algorithms, with no electrical failures or overheating observed. The chamber successfully maintained independent temperature and humidity control - an improvement on the previous design, which was unable to maintain a stable humidity for longer than a few minutes. Overall, Environmental Box 2.0 achieved the project's goal of creating a compact, low-cost, and precise testing environment, marking a clear improvement over Environmental Box 1.0 in both performance and reliability.

Summary and Impact

Environmental Box 2.0 now functions as a reconfigurable research instrument that researchers can update and improve over time. As a mechanical and electronic device, it supports enhancement through reprogramming, material upgrades, and software improvements, allowing researchers to adapt it to evolving experimental needs. Professor Xiaoyu Tang's laboratory plans to use this system to advance droplet-evaporation experiments by enabling faster setup, improving environmental consistency, and increasing data accuracy.

The redesigned chamber maintains stable temperature and humidity for over 30 minutes within ±2.5 °C and ±5% relative humidity. This performance marks a significant improvement over Environmental Box 1.0, which maintained stability for only about five minutes. The device features six clear acrylic walls that provide full visibility and a sealed enclosure that minimizes airflow, ensuring the clarity and precision required for delicate droplet behavior studies. With a build cost under $1,000, the system achieves accuracy comparable to commercial alternatives priced above $18,000. It also simplifies construction and maintenance by incorporating PTC heaters, an ultrasonic humidifier, a desiccant dehumidifier, and PID control.

Through the process of integrating mechanical, electrical, and software systems, we developed a systematic and collaborative approach to solving complex engineering challenges. Beyond its role in Professor Tang's lab, Environmental Box 2.0 serves as a replicable, open-source blueprint that expands access to precision environmental control. This project demonstrates how thoughtful engineering can make advanced experimentation both affordable and widely achievable.

References

[1] M. J. Moran and H. N. Shapiro, *Fundamentals of Engineering Thermodynamics*, 9th ed. Wiley, 2025.

[2] J.-N. Lee, T.-M. Lin, and C.-C. Chen, "Modeling Validation and Control Analysis for Controlled Temperature and Humidity of Air Conditioning System," *Sci. World J.*, vol. 2014, p. 903032, 2014.

[3] E. Cervantes, W. Dionne, R. Huang, D. Kokoros, A. Luk, and M. Sarbessa, "Climate Controlled Box," Dept. Mech. Eng., Northeastern Univ., Boston, MA, USA, 2023.

[4] Electro-Tech Systems, Inc., *M 5504 Compact Temperature and Humidity Glovebox*, 2025.

[5] Cole-Parmer, *Electro-Tech 5504 Series Temperature and Humidity Glove Box Chambers*, 2025.

[6] University of Kentucky, "Relationship Between Temperature and Moisture," *Animal & Food Sciences*, 2025. [Online]. Available: https://afs.ca.uky.edu/poultry/chapter-7-relationship-between-temperature-and-moisture

[7] AIDOT, "Getting to Know Different Types of Humidifiers." Accessed: Nov. 16, 2025. [Online]. Available: https://www.aidot.com/blog/post/types-of-humidifiers

[8] J. Qu, L. Escobar, J. Li, Z. Rao, and B. Xu, "Experimental Study of Evaporation and Crystallization of Brine Droplets Under Different Temperatures and Humidity Levels," *Int. Commun. Heat Mass Transf.*, vol. 110, p. 104427, 2020.

[9] A. Coppola, A. Annunziata, and G. Fiorentino, "Heated Humidification Devices," in Humidification in the Intensive Care Unit: The Essentials, A. M. Esquinas, Ed., Cham: Springer International Publishing, 2023, pp. 3–9. doi: 10.1007/978-3-031-23953-3_1.

[10] F. Ge and C. Wang, "Exergy analysis of dehumidification systems: A comparison between the condensing dehumidification and the desiccant wheel dehumidification," Energy Convers. Manag., vol. 224, p. 113343, Nov. 2020, doi: 10.1016/j.enconman.2020.113343.

Appendix: Engineering Analysis

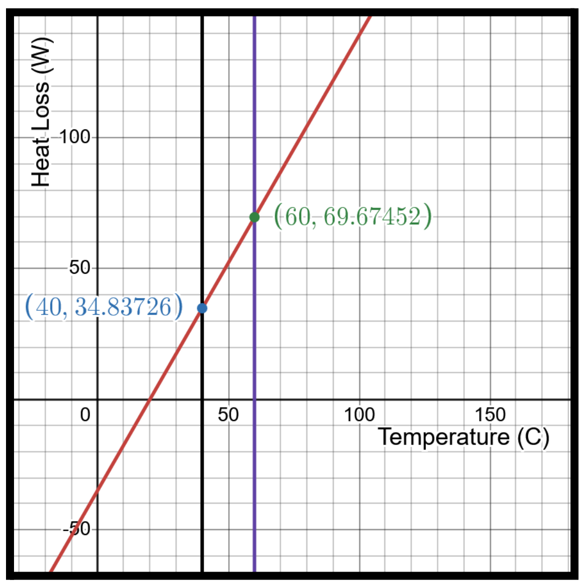
Introduction

The heating of the box is a critical design element in the Environmental Box 2.0 - as such, several rounds of tests were performed with the heating elements to confirm they would be of sufficient strength to be able to heat the box once it was constructed in its final form. In addition to the tests, analysis was performed in order to select a heater which provided sufficient heat wattage to the system in the first place. In the end, we found that four 120W PTC heaters were more than enough to heat up our system.

Description of Tools/Methodology

To accomplish our goal of heater acquisition/testing, we used hand calculations, simulations, and physical test boxes with sensor data. The simulations were performed in Solidworks with the built in simulation software package. The first test box was not technically accurate to the final dimensions of our design, but nonetheless provided important and useful data. The boxes used ¼" clear acrylic (same as used in our final design) and instead of the door that is present in the actual Environmental Box 2.0, the electronics/heaters were simply slipped under after the box was raised. From there, DHT11 temperature sensors were placed in the test box and routed to an arduino. The data collected from those sensors was then analyzed in Python.

Results and Discussion



To start, we determined the minimum heat output of our heaters by calculating the heat lost by the system at maximum temperature (60 °C). From that information a safety factor was added, which both provides a buffer against insufficient heat production while also allowing for faster times to get up to temperature (due to the increased heat wattage). Heat loss due to radiation was deemed to be negligible. Given this, Equation 1 below was used, where q_{loss} is the heat loss

$q_{loss} = \Delta T/(2/hA+L/kA)$
[Equation 1] Heat loss

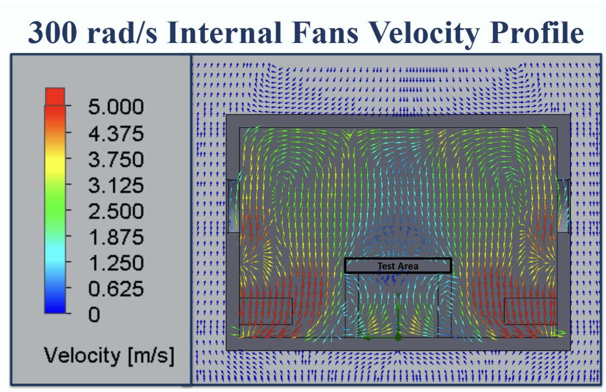
via convection and conduction through the acrylic walls, ΔT is the difference in temperature from the box interior to the ambient air outside, h is the convective coefficient, A is the surface area, L is the thickness of the acrylic, k is the conduction coefficient. From the given values of our test box, Equation 2 below was used to make the graph in Figure X to the right.

qloss =1.742(T-20)
[Equation 2] New heat loss with our variables put in

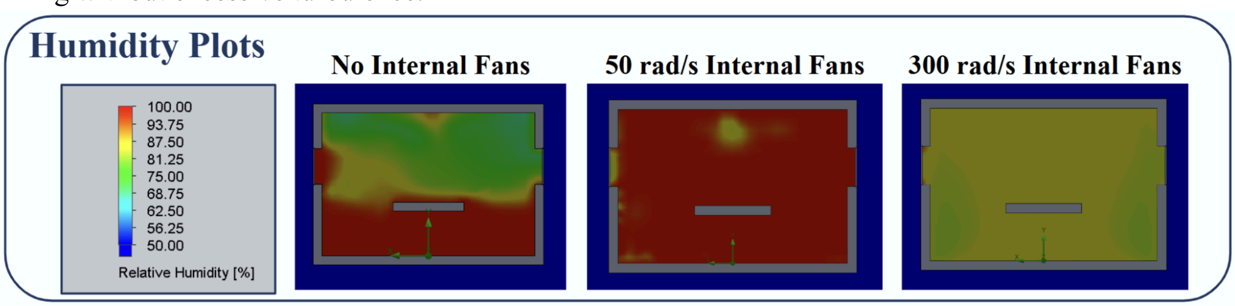
Figure X illuminates that at 60 °C the heat power being lost to the environment is around 70W. This information helped us to decide on our heaters.

However, it is important to bear in mind this is the heat wattage input/output - any inefficiencies in bringing the electrical wattage input into heat wattage output is not included here. In addition, this analysis assumes steady state, however when the box is getting up to temperature it is in a transient state where the air in the box is absorbing heat and not passing all of it along (thus increasing in temperature). For this reason this analysis is not necessarily applicable in figuring out how long it would take to reach the proper temperature. As there was no strict time requirement provided by the customer (Professor Tang), the required transient "heating up time" was assumed to be acceptable by adding more heat wattage than necessary.

Simulations



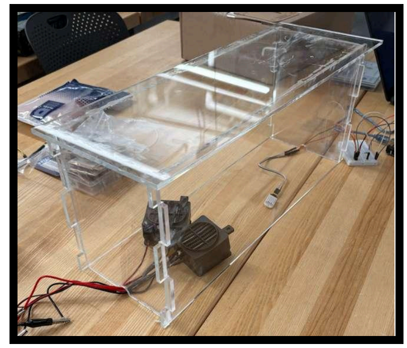
To evaluate airflow and environmental gradients within the test chamber, the design team conducted transient simulations using SolidWorks Flow Simulation. Each simulation ran for two minutes, allowing the system to reach steady-state behavior and reveal dynamic interactions between airflow, temperature, and humidity. The model incorporated four PTC heaters positioned at the chamber corners, delivering a combined thermal output of 500 watts. Fans were defined by their velocity and pressure differential, enabling precise control over mixing intensity and airflow distribution. Air entered and exited the system at a flow rate of 14.17 in^3/s, calculated to achieve full circulation of the chamber's internal volume once per minute, ensuring thorough mixing without excessive turbulence.



Simulation results confirmed that this configuration successfully balances environmental uniformity with low air velocity in the test region. The model produced a stable low-velocity pocket at the center of the chamber, preserving droplet behavior while maintaining consistent temperature and humidity gradients throughout the enclosure. This outcome validates the design's ability to support sensitive droplet-scale experimentation without compromising environmental control.

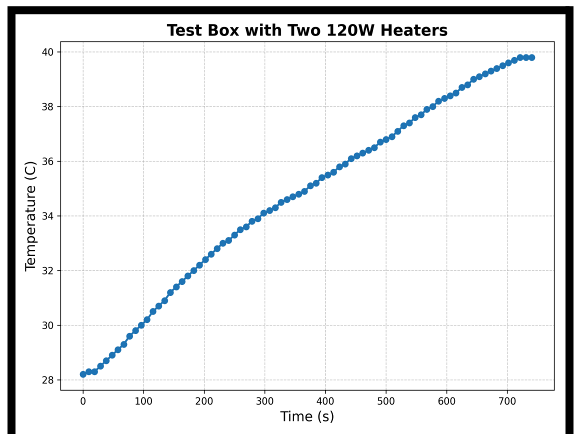
Further analysis revealed that humidity gradients are largely governed by temperature gradients. As temperature increases vertically, relative humidity decreases due to the air's increased moisture capacity. This thermodynamic relationship reinforces the importance of uniform thermal distribution in maintaining consistent humidity levels across the test area.

Physical Tests

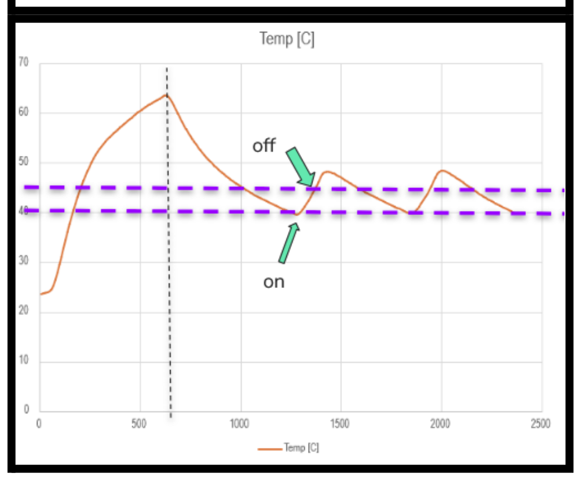


To confirm our heating system works as intended, it was necessary to perform physical tests. To this end we created a test box with more or less the same dimensions (the first box did not have the same dimensions as the final design because of a change in design in the intervening time from when it was built) as the final design.With ¼" clear acrylic being used for the walls, those walls were then lasercut and superglued together to make the first prototype box. The first prototype box is shown in Figure X to the right.

To facilitate the data collection, DHT11 sensor(s) were wired up and connected to an Arduino Uno where it could be printed to the serial monitor. From there, that temperature information was collected and various Excel and Python's Pyplot libraries were used to analyze the data and produce figures.



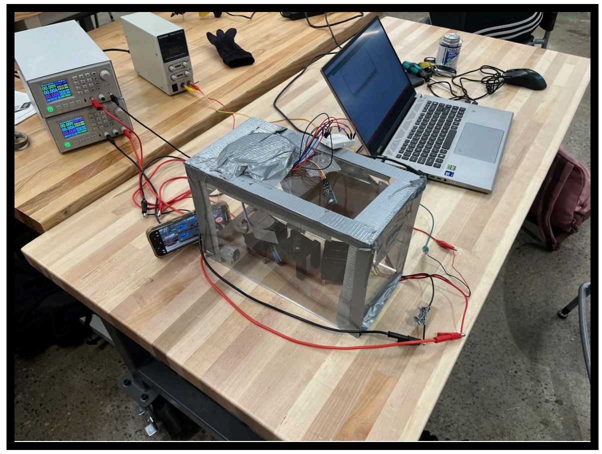
The first relevant test was done with this initial test box and two 120W heaters. The purpose of this test was to determine the efficacy of the test apparatus itself - prior to this test, it was unclear if the temperature sensor even worked, for example. The testing was stopped after the sensor outputted the same temperature three times in a row. In all, the two 120W heaters took the box from room temperature of around 40 °C in 12 minutes, which seemed to suggest that longer tests with more powerful heaters were necessary.



The next relevant test was done with a single, more powerful 300W heater. Broadly, the test was meant to shed some light on how difficult actively controlling the temperature in the box would be. However, the test also incidentally proved that a 300W heater could bring the box to 60 °C on its own. In this test, the temperature was "controlled" after reaching its peak temperature of 60 °C by manually turning the heaters off when the temperature sensor read greater than 45 °C, and on again when the sensors read less than 40 °C (in the final product a PID controller was used, rather than the user manually switching the heaters on and off.

The outcome of this test is depicted in Figure X to the right. From the ±2.5 °C control range labeled with the purple dashed lines, it can be observed that while turning the heaters on relatively quickly brought the temperature back up, turning the heaters off produced a kind of "skidding" effect, where the temperature continued increasing for some time even as the heaters were not actively receiving power. This overshoot is likely a result of a combination between the heater's inability to instantly cool off once the electrical power is no longer being supplied and the heat power lost being lesser in magnitude compared to the heat power input from the 300W heater. Overall, however, it can be observed that stable oscillations were produced from this test, which boded well for the successful use of our PID controller later down the line (PID controllers require time invariance in output response).

The last critical test utilized the second prototype box, shown in Figure X to the left. The second prototype improved on the initial prototype box mainly by being more accurate to the dimensions and features of the final design. Where the first prototype was essentially just a couple acrylic pieces super glued together, the second prototype included features like the door and the vent holes which allowed for more accurate tests (as well as humidifier and dehumidifier tests, though this is not relevant to the heater testing). Duct tape was used here instead of super glue because the laser cutting device was not functioning properly, making jagged cuts in the acrylic. These jagged cuts made it difficult to super glue/acrylic weld the pieces together (as would be used in the final design) - as such, duct tape was used to make up for this.



This last critical test tracked the temperature in the box with multiple sensors placed in different locations within the box. The idea behind this was to get a better idea of what the temperature gradient looked like within the box, as this would have implications for the necessary heater fan speed as well as later drop evaporation analysis. Our results (Figure X) how a significant temperature gradient primarily based around the height of the sensors, with the ceiling temperature sensor getting much hotter than the two sensors located closer to the bottom of the box. This result probably derives from the fact that hot air is less dense than cold air, and as such this hot air naturally displaces the cold air and rises to the top (and vice versa for cold air).