SRP EVAP

Final Design Report

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DISCLAIMER

This report was prepared by students as part of a university course requirement. While considerable effort has been put into the project, it is not the work of licensed engineers and has not undergone the extensive verification that is common in the profession. The information, data, conclusions, and content of this report should not be relied on or utilized without thorough, independent testing and verification. University faculty members may have been associated with this project as advisors, sponsors, or course instructors, but as such they are not responsible for the accuracy of results or conclusions.

EXECUTIVE SUMMARY

Problem Statement & Project Objective

In regions such as Arizona, significant water losses occur in open canal systems due to evaporation. The deployment of solar panels over canals has been proposed as a potential dual benefit solution for reducing evaporation while generating renewable energy. However, the lack of experimental data on how canal water evaporation is influenced by parameters such as surface temperature, relative humidity, wind speed, and overhead panel coverage limits the ability to validate this solution. Without controlled experimentation, it is difficult to quantify the evaporation rate and provide recommendations that are both scientifically rigorous and relevant to real world canal management.

The objective of this project is to design and operate a controlled apparatus that models canal conditions under turbulent free convection to measure and analyze evaporation rates. After confirming turbulent free convection with a flow visualization test, we will conduct three iterations of the experiment:

1. The effect of water surface temperatures on evaporation.
2. The effect of relative humidity on evaporation.
3. The impact of overhead panel coverage on evaporation under natural convection.

If all results from previous experiments are satisfactory, and time permits, we will expand the experimentation to include forced convection. Through these tests, the experiment aims to generate clear, quantitative data that can validate theoretical mass transfer models and supports SRP's ongoing assessment of solar over canal systems.

Research

The main focus of our research has involved understanding the physical and thermodynamic mechanisms of evaporation from a water surface, particularly through forced convection. At our client's request, we have been working towards understanding the mass transfer equation that is readily found in heat transfer textbooks. This equation has a few main parameters that we will be focusing on throughout our study. The first is the convective mass transfer coefficient, which is dependent on the Sherwood number, the diffusivity of water vapor, and a characteristic geometric length. The driving force of the mass transfer equation is the concentration gradient present on the water surface. This gradient is characterized as the difference in pressures from the atmosphere to the saturated vapor pressure on the surface of the water. Additionally, we will be employing the analogy between heat and mass transfer to extract a solvable mathematical model which we can then apply to the parameters in our experiment.

Design

Because our goal in this project is to investigate some of the basic parameters involved in evaporation from a water delivery canal, we have been working with our client to keep both our apparatus and our experiments as simple as possible. Incorporating a few main parameters into our design will ensure that our results will be concise and useful for SRP's extended research. Through our mathematical research, we have established three main parameters that we will use in our experimentation. Relative humidity, air temperature, and water temperature.

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1 BACKGROUND

This section provides an overview of the project, outlining its objectives, scope, deliverables, and success metrics. Initially, the project involved designing a solar roof over a canal to reduce evaporation and generate renewable energy, but due to the complexity, the focus shifted to analyzing evaporation rates. The ultimate success of this project will be measured by the accuracy and reliability of the evaporation data collected and its usefulness to SRP and ASU's research teams. The results will contribute to a larger research effort investigating the feasibility of solar panels over canals as a water conservation strategy, ensuring that the project has a meaningful impact on sustainability efforts in the region.

1.1 Project Description

Originally, the project given to the team was extremely complicated and detail oriented. The project required the team to create a solar roof over a canal that reduced evaporation while simultaneously generating power from the sun. The project would have required the team to not only calculate evaporation with accuracy but also account for building and testing the solar roof's efficiency. Due to the detailed nature of the project, as well as considering the time and experience the team must need and apply to the goal, the team's client, Dr. Tom Acker, decided to give the team a more realistic goal. The client gave the team a goal of solely calculating the evaporation of the canal. With the new goal it has allowed the team to focus and devote all our time towards this section of the project.

SRP has given the team a budget of $5,000 to use on this project. The budget will be used for two primary goals. The first goal is to take a trip down to Phoenix to visit the ASU team which were also given the same project in the previous semester. The ASU team have built an evaporation testing apparatus that directly tests the conditions in which our team needs to test for. Although the ASU team has this apparatus, their primary target was to test the solar aspect of this project, which left their data a bit scattered. The second goal for the budget is to create an apparatus of our own. This apparatus will have all the sensors needed to test for all variables that might affect evaporation. As well as an abundance of sensors, the experiment will be closed off and have a controlled atmosphere. Due to the project's requirements, given to the team by the client, a prototype isn't necessary for the goal, instead the client prefers for our team to focus on figuring out the evaporation issue.

On top of the $5,000 budget, our team is required to fundraise a portion of the budget as part of capstone requirements. A total of 10% or $500 needs to be fundraised to go towards the project budget. Our team decided that it would be best to start a go fund me with all the project information to inform people about our goal. After the go fund me was created, it was posted so that more people could view the project. Currently our team has raised a total of $765 reaching the goal that was set.

This project is important because clean water is a massive, limited resource in Phoenix. Naturally saving any amount of water from being wasted during transportation would help with this problem immensely. If done successfully the project helps Phoenix not only save water but also utilizes unused space for solar panels without taking up too much space.

1.2 Deliverables

The team has an abundance of deliverables that need to be completed for both the client and for the course. The following is a list of the deliverables the team needs to complete for the course as well as any extra research the client requested completion on at the end of the list. Each deliverable will have a short description of what it entails as well as the date completed.

1) Weekly Timecard (Due: Every Monday)
    - Every week each member of the team needs to log any hours spent on the project leading to a total minimum hour count of at least 9 hours in any given week. Each member needs to log the hours spent on each day with specific times, as well as the location where the work was done. Each member will then need to describe the work that was done during those hours in a detailed oriented manner.
2) Project Management (Due: 9/2/2025)
    - This document outlines the requirements for a project-management report that reflects last semester's performance, identifies areas for improvement, and establishes clear action items for Capstone 2. It also requires updated Gantt charts, a top-level budget, a detailed purchasing plan, and a manufacturing plan to ensure the team is prepared for upcoming hardware milestones. Optional sections allow analytical or competition-based teams to tailor the deliverables to their project needs.
3) Engineering Calculations Summary (Due: 9/8/2025)

- This assignment requires teams to produce a concise engineering model summary that proves their design will work in the real world by compiling all relevant standards, equations, analyses, safety factors, diagrams, and updated subsystems. It emphasizes clearly organized load cases, subsystem-specific calculations, evidence of analysis, and how each result informed design choices. The document concludes with a forward-looking plan identifying remaining calculations and engineering work needed to fully validate the final design.

4) Hardware Status Update 33% build (Due: 9/22/2025)

    - This first Hardware Status Update outlines the requirements for a short in-class presentation demonstrating your team's design progress, purchasing status, manufacturing progress, and early hardware functionality. Teams must show updated CAD, budgets, BOM excerpts, manufactured components, and at least 33% of their physical build, along with a brief Gantt chart update and discussion of any roadblocks. The goal is to verify that design work is complete, and that fabrication and procurement are well underway heading into the next project phase.

5) Hardware Status Update 67% build (Due: 10/13/2025)

    - This second Hardware Status Update requires a 10–12 minute presentation demonstrating that the project has progressed to at least 67% completion in purchasing, manufacturing, and hardware assembly. Teams must show finalized design work, updated budgets and BOMs, major manufactured components, and a substantial portion of functional hardware, along with a brief update on schedule status and roadblocks. The goal is to verify that the build is well underway and on track for final integration and testing.

6) Finalized Testing Plan (Due: 10/27/2025)

    - The Finalized Testing Plan outlines the full sequence of tests the team will run, including procedures, sensor setups, and environmental conditions. It serves as the roadmap for how data will be collected and ensures the team is ready for consistent, repeatable experimentation.

7) Hardware Status Update 100% build (Due: 11/3/2025)

    - This presentation demonstrates that the physical system has been fully built and assembled. It confirms that all components mechanical, electrical, and measurement related are complete and ready for full testing

8) Initial Testing Results (Due: 11/17/2025)

    - The Initial Testing Results summarize the first outcomes from the evaporation apparatus. This deliverable demonstrates that the system is functional, sensors are logging correctly, and early trends can be seen in the data and where changes are needed

9) Final Cad Packet (Due: 11/17/2025)

    - The Final CAD Packet includes fully updated models, drawings, and design details for the apparatus. It captures the final mechanical design configuration and communicates manufacturing details for future reference.

10) Final testing results (Due: 11/24/2025)

    - The Final Testing Results compile all completed test runs, showing clean, validated datasets and final correlations. This deliverable demonstrates that the experiment met its objectives and produced reliable evaporation measurements.

11) Final Poster (Due: 11/23/2025)

    - The Final Poster presents the entire project in a visual, concise format for showcase and review. It highlights the design, methods, testing, analysis, and key findings for a broad audience.

12) Final Presentation (Due: 11/23/2025)

    - The Final Presentation summarizes the project's design, testing process, and results. It demonstrates the team's understanding of their system and communicates the project's impact clearly and professionally.

13) Operation/Assembly Manual (Due: 12/1/2025)

    - This manual provides complete instructions for assembling, operating, and maintaining the evaporation apparatus. It ensures that future teams or clients can rebuild and use the system without additional guidance.

14) Final Report (Due: 12/1/2025)

- The Final Report is the complete written documentation of the project, covering design decisions, analysis, testing, results, and conclusions. It serves as the official engineering record for the entire system.

15) Client Handoff (Due: 12/8/2025)

- The Client Handoff transfers all project materials, data, manuals, and final documents to SRP and ASU. It ensures the client can use, maintain, and expand upon the system after the project ends.

16) Client Deliverables

- The client's goal for the team is to have the team fully understand curtain chapters from the heat transfer books that directly help the team's understanding of evaporation. The client wants each team member to practice examples from the book so that each member is knowledgeable about the heat transfer equations.

1.3 Success Metrics

Since the nature of our project is a research based study, we are not preparing a product to sell or compete with. This means that our success metrics are solely dependent on whether our apparatus produces useful results for our research partners at ASU and SRP. To do this successfully, we need to conduct state-of-the art research so we can build the best apparatus that we can. If our apparatus produces useful results that we can corroborate with our mathematical modelling, then we will be able to deem this project a success. We are planning for at least three iterations of testing for each parameter over the course of the next seven to eight months, to account for possible errors in our apparatus design as well as unforeseen setbacks that will most likely arise throughout the experimentation process. We will be working closely with our client to ensure that the results we obtain will be useful for SRP's research team. To quantify this usefulness, we will be referencing our mathematical model between heat transfer and mass transfer equations. Past our mathematical model and approval from our client, the success of our results, and therefore our project is open-ended. Once we do create our apparatus, run our tests, gather data and present this data in report form to SRP's research team, we might not have confirmation that our contributions were of significant help until months later, if ever. This is because our project is one piece of an ongoing and extensive research effort being conducted by not only SRP and their research teams but also among other utility companies and universities across the Western U.S. and even the world. Although this bigger picture is worth noting, we have every intention of focusing on our specific task and producing results that can contribute meaningfully to the overall research on the subject of solar panels mounted over canals. Additionally, we wish to do well in capstone and receive good grades in class. This will be easily quantifiable because our grade books will track the progress of the quality of our work on individual and group assignments. We plan on achieving this by working hard and giving our best effort over the entire course of our capstone project.

2 REQUIREMENTS

The requirements for the SRP evaporation analysis were developed to ensure that the system accurately models the canal evaporation under controlled natural turbulent conditions. These requirements are categorized into (2.1) Customer Requirements (CRs), which show the functional needs and constraints defined by SRP and project stakeholders, and (2.2) Engineering Requirements (ERs), which translates the customer needs into measurable and technical specifications. These criteria will ensure that the project's objectives align with SRP's goals and industry best practices.

2.1 Customer Requirements (CRs)

Our team has identified seven key customer requirements to guide the design and testing of our experimental apparatus. The first customer need begin the ability to control/maintain air temperature, the apparatus should hold a setpoint the reproduces the canal temperature difference, staying within plus or minus .01 to .5 degrees °C over multi hour runs with continuous logging. Second, we must control/ maintain water surface temperature at multiple surface locations, because the air/water temperature difference drives buoyancy and evaporation. Third, we must control/maintain relative humidity, condition the apparatus to target values within our range and logging at the same cadence as temperatures. Fourth, we must measure relative humidity accurately using sensors that meet the accuracy with calibration checks and foxed recording intervals. Fifth, we must maintain a convective flow regime, so the Grashof and Schmidt product matches the canal within an agreed band of about 50% confirmed by calculations and smoke flow visualization. Sixth, we must stay within budget by tracking the bill of materials against the cost target with an owner for each line item and primary/backup vendors. Finally, we must maintain water tightness, the tank should pass a 24-hour static fill test with no visible leaks and with any leak loss less than a small fraction of the expected daily evaporation loss.

CR-1: Ability to Control and Maintain Air Temperature

The apparatus must reproduce air temperatures representative of Phoenix canal conditions, allowing the system to maintain steady-state temperature differences between the water surface and the surrounding air. For this requirement, an internal air conditioning system and proper insulation would help insure temperature setpoints are held for the duration of testing.

CR-2: Ability to Control and Maintain Water Temperature

With evaporation driven by the buoyant forces, the ability to properly maintain the water temperature is a requirement. The apparatus must sustain precise and repeatable water temperatures, and drives the need for a precise water heater and multiple thermocouples correctly placed for accurate data to be returned. Water temperatures must stay stable throughout the entire testing process.

CR3: Ability to Control and Maintain Relative Humidity (RH)

The evaporation rate depends on the vapor concentration gradient directly above the water surface. The apparatus must be capable of setting and maintaining a target RH value that directly correspond to Phoenix conditions. This requirement motivates the use dehumidification with tools such as desiccant packages, dehumidifiers and an overall airtight insulation to prevent the buildup of water vapor in the testing apparatus.

CR-4: Ability to Control and Maintain Air Temperature

The system must integrate the use of calibrated humidity sensors with sufficient accuracy and stability to capture the transient and steady state relative humidity values. Since the difference in humidity drives mass transfer, inaccurate readings would directly affect the Sherwood numbers. The sensors must remain stable over long durations of testing and be readable at fixed time intervals with automated data collection.

CR-5: Ability to Maintain a Convective Flow Regime Representative of the Grand Canal

The apparatus must operate within the turbulent free-convection regime ($Gr \cdot Sc > 2x10^7$), confirmed through a flow visualization test and dimensionless analysis. This ensures that the experimental Sherwood- Rayliegh relationships are physically meaningful and scalable to the canal conditions. This requirement guarantees that buoyancy governs the evaporation mass flux and not forced airflow.

CR-6: Project Must Stay Within Budget

All design decisions including the water tank, climate system, sensors, insulation, and data-acquisition hardware, must fall within the predetermined budget constraints. The components bought must be cost effective while still meeting the accuracy, durability, and precision needs necessary for scientific validity.

CR-7: Maintain Water tightness and Structural Integrity

The apparatus must operate leak-free over the extended test periods. The water tank, siphon, and surrounding frame must withstand multiple days of exposure without seepage or structural degradation. A 24 hour leak test must confirm that there is no unexpected water loss.

2.2 Engineering Requirements (ERs)

To ensure that our design meets the goals of precise evaporation measurement and environment control, we developed a set of engineering requirements aligned with our customer needs. These include precision of data collection, accuracy of sensors, material durability and longevity, geometric similarity, scalability of Rayleigh number, economic feasibility and practical implementation, and lastly adhere to scientific standards/ principles. Building on that, we set concrete targets and checks for data precision. Our goal is to record water surface temps, ambient air temps, relative humidity, and water loss due to evaporation. We want to ensure that our sensors are accurately calibrated to achieve correct readable data. Each engineering requirement ties directly to those measurements and has a verification method addressed in the technical requirements targets.

ER-1: Precision of Data Collection

All logged data must be captured at consistent intervals with minimal noise to accurately collect the data for mathematical calculations. Sampling rates and data logging must remain constant to allow accurate calculations of the vapor density gradients, convective coefficients, and non-dimensional parameters.

ER-2: Sensor Accuracy and Calibration

Temperature sensors must be pre-calibrated or calibrated at multiple reference temperatures (boiling, ambient, and freezing) to achieve a minimum of ± 0.5°C accuracy. The humidity sensor must remain within ± 2% RH of known humidity. These accuracy thresholds ensure that the measured gradients are representative of the intended inputs and not sensor error.

ER-3: Material Durability and Longevity

The apparatus must endure repeated thermal cycles, elevated temperatures, and dry air environments without structural degradation. Materials such as plywood, spray foam insulation, PVC pool liner, and framing must maintain at least a six month operation window. During the testing period the apparatus must be able to pass thermal degradation checks and have a load bearing factor of safety of at least 2.

ER-4: Geometric Similarity to the Grand Canal

The apparatus must maintain geometric and boundary condition similarity to Phoenix's Grand Canal. While scaled down, surface area representation and characteristic length must reflect the scaling factor that keeps the dimensionless parameters like the Rayliegh and Sherwood numbers.

ER-5: Rayliegh/Grashof Number Scalability

The system must operate within the correct turbulent natural convection regime, producing Grashof numbers within the order 0f 10^9 to 10^10, which is what is expected with the scaled conditions. This requirement ensures that the Sherwood correlation collected from the apparatus remain physically representative of canal evaporation.

ER-6: Economic Feasibility

Material selection, required sensors, components, and construction must meet the cost target stated in the QFD. The cost must stay under $5765, including travel and transport of the apparatus for testing in Phoenix condition. Low cost but accurate sensors must be balanced with performance and precision to utilize the budget without under preforming.

ER-7: Adhere to Scientific Standards and Proper Experiment Methodology

All tests must follow accepted mass transfer practices, including steady-state verification, variable isolation, repeated trials, dimensionless value analysis, and verification of the flow regime. Data collection methods must reduce bias and that the dependent variables respond solely to the controlled changes of air temperature, water temperature, and humidity.

2.3 House of Quality (HoQ)

The Quality Function Deployment (QFD) is structured to translate customer needs into clear and measurable technical requirements. This is to ensure that the systems design decisions meet the expectations of both the client and the research team. In this QFD, each customer requirement was weighed on a scale of 0 to 9, where 0 shows little importance and 9 indicates the maximum importance. This is to show how strongly each engineering feature contributes to the customer's expectations. These results produced technical ratings with Precision of data collection, and similarity of Rayleigh number ranking first (51 points), and the least important factor being material durability and longevity (27 points). Competition ratings were also introduced with a scale of 1 to 5, to compare this design to existing systems and tests. This will provide context for how the SRP system performs relative to similar benchmarks. Overall, the QFD serves as a structured tool for prioritizing the most crucial functions of the evaporation recording apparatus, while maintaining measurable targets.

Project: Captsone SRP QFD
Date: 9/4/2025

(Between 1 and 5, lowest rating to highest rating)
(0=N/A) (3 = weak) (6 = moderate) (9 = strong)

System QFD

		Technical Requirements (0,3,9)							Competition (1-5)				
Customer Needs	**Customer Weights**	Precision of data collection	Accuarracy of sensors	Material Durability & Longevity	Geometric Similarity	Similarity of Rayleigh number	Economic Feasibility & Practicial Implementation	Adhere to scientific experimentation principles	*Casa Blanca Canal Solar Project*	*Project Nexus*	*Gujarat Canal Solar Project*		
Ability to control/maintain air temp.	9	9	9	3	6	9	6	9	1	1	1		
Ability control/maintain water surface temp.	9	9	9	3	6	9	6	9	1	1	1		
Ability control/maintain relative humidity	9	9	9	3	6	9	6	9	1	1	1		
Ability to measure relative humidity	9	9	9	0	6	9	3	9	2	2	1		
Ability to maintain convective flow regime	9	6	9	3	9	9	9	9	1	1	1		
Project stays within budget	9	0	3	6	0	6	9	0	3	3	3		
Maintain water tightness	9	9	0	9	3	0	6	3	5	5	5		
Technical Requirement Units		in/day	°C, RH%	Years	N/A	N/A	$	N/A					
Technical Requirement Targets		0.58 in/day	±1 °C, ±3% RH, ±0.02g	6 months	100%	3.18*10^8	$5,740	90%					
Absolute Technical Importance		51	48	27	36	51	36	48					
Relative Technical Importance		1st	3rd	7th	5th	2nd	6th	4th					

Figure 1: QFD

3 Research Within Your Design Space

3.1 Benchmarking

Casa Blanca Canal Solar Project

The Casa Blanca Canal Solar Project is an ongoing project located within the Gila River Indian Community, south of Phoenix, Arizona. This project is being developed by the Pima-Maricopa Irrigation Project (P-MIP) with funding support from the U.S. Bureau of Reclamation. The design is patented by Tectonicus, with George Cairo Engineering as the main engineer, and Straight-Arrow Contracting, a native-owned construction company, leading the on-site construction [6].

This project aims to cover canals with solar panels to serve a dual purpose, which is generating renewable energy while reducing water loss from evaporation. The first phase of construction focusses on a 1.3 MW nameplate capacity, with future expansions planned to extend coverage over the entire 16-mile canal system, resulting in a total project size of 33 MWdc.

For our capstone project, the Case Blanca Canal Solar Project serves as an important benchmark in exploring evaporation strategies as there are not many benchmarking ideas out there. By studying its design and projected benefits, we can assess whether similar shading structures could be adapted to our apparatus. Furthermore, understanding the technical challenges of this project allows us to evaluate new approaches that may be more beneficial and cost-effective.

Project Nexus

Project Nexus is the first of its kind being conducted by the Turlock Irrigation District (TID) in California. Designed as a Proof of Concept, the project aims to explores the feasibility of installing solar panel canopies over irrigation canals and evaluate their co-benefits in terms of water conservation, renewable energy production, and environmental improvements. Funded by the State of California, Project Nexus is a collaborative effort between TID, the California Department of Water Resources (DWR), UC Merced and Solar AquaGrid. The project is currently under construction and is expected to be fully commissioned by 2025 [7].

The project consists of two primary canal locations, a 20-foot-wide section, where construction is currently in progress with solar panels already mounted, and a 110-foot-wide section, which will begin after the TID irrigation season concludes in November. UC Merced has positioned research equipment at both locations to collect baseline data and assess the project's impact on evaporation rates, water quality, and renewable energy generation.

Project Nexus is particularly significant because of its potential for large scale implementation. California has approximately 4,000 miles of public water delivery canals, and if the solar-over-canal concept proves successful, it could lead to statewide adoption, maximizing both renewable energy production and water conservation efforts. One key advantage of installing solar panels over canals is the cooling effect of water, which can increase solar panel efficiency by preventing overheating. Additionally, it can maximize the use of existing structures, making it a more efficient solution.

For our project, Project Nexus provides a comprehensive study on integrating solar technology with water conservation efforts. Unlike other solar over canal studies, Project Nexus specifically aims to evaluate the technical, economic, and environmental trade-oofs associated with large scale solar shading in an irrigation district. This is relevant to our research as it allows us to examine how structural design, solar panel efficiency, and hydrological effects interact in a real-world setting. By understanding how Project Nexus quantifies these factors, we can refine our own data collection approach and ensure that our experimental design somewhat algins with other industries. Furthermore, the scalability considerations explored in this project provide a useful framework for assessing the long-term feasibility of canal shading solutions in Arizona's climate.

Gujarat Canal Solar Project

The Gujarat Canal Solar Project is a project that combines solar power generation with water conservation. Launched in 2012, this project was the first large scale deployment of solar panels over irrigation canals to prevent water loss due to evaporation while simultaneously generating renewable energy. The initiative was led by the local government of Gujarat in partnership with SunEdison, a US based renewable energy company, which constructed an initial 1 MW pilot installation over half a mile of canal at a cost of $2.6 million USD. After proving successful, the project expanded to a 10 MW system by 2015, covering more canal sections and serving as a model for other Indian states interested in similar solar over canal solutions [8].

This project effectively addresses energy generation and water conservation by installing solar panels over canals, reducing evaporation by an estimated two billion litters annually while also enhancing solar panel efficiency by 7-15% due to water cooling effects. By utilizing infrastructure, it eliminates the need for additional land, making it a scalable and replicable model that has inspired similar initiative in other regions. However, the project comes with high initial cost, with the 10 MW expansion costing $18.3 million USD and a payback period of 13 years. Despite these challenges, the project's long-term benefits in water conservation, energy production, and sustainability highlight its potential as an innovative solution for canal networks worldwide.

The Gujarat Canal Solar project provides an important benchmark for our project by demonstrating the real-world impact of shading strategies on evaporation mitigation. The project's large-scale data on water savings and increased solar efficiency gives us a key performance indicator that we can compare with our experimental findings. Additionally, analyzing the cost-benefits of this project will help us evaluate the economic feasibility of applying solar shading or alternative evaporation control methods to Arizona's canal system. Finally, the engineering challenges faced by the Gujarat Canal Solar Project such as structural stability, panel maintenance, and energy integration will provide insights into potential design constraints and optimization strategies for our testing apparatus.

3.2 Literature Review

3.2.1 Lilliana Hadik-Barkoczy

[31] Michael T. Pauken 1 1 et al., "An experimental investigation of combined turbulent free and forced evaporation," Experimental Thermal and Fluid Science, https://www.sciencedirect.com/science/article/abs/pii/S0894177798100389 (accessed Apr. 22, 2025).

This paper was an evaporation experiment conducted in a wind tunnel. Both natural convection and forced convection under low velocity wind speeds were investigated. The water surface was a class A evaporation pan, and a total of 48 tests were run, collecting data at 10-minute intervals. Sherwood correlations were established for Grashof number ranges of 1.2×10^9 to 5.5×10^9. This paper helped me to study another mass transfer evaporation experiment that has been done by actual experts in the field. I also took our siphon design for mass transfer data collection from this experiment. Additionally, the Sherwood correlation for turbulent free convection was used in some of my theoretical calculations, as well as the equations for the other dimensionless numbers such as Grashof and Schmidt.

[30] Pauken, “Experimental investigation of water evaporation into low-velocity air currents,” ASHRAE transactions., no. 1, pp. 90–96, 1995, doi: info:doi/.

This paper is another version of the previously listed source and was presented by the authors in a conference and the ASHRAE journal in 1995. The overall content of the experiment is the same, but this paper provided more details on the experimental set up used, as well as some additional graphs that were used ion creating the correlations.

[32] R. J. Goldstein, E. M. Sparrow, and D. C. Jones, “Natural convection mass transfer adjacent to horizontal plates,” International Journal of Heat and Mass Transfer, vol. 16, no. 5, pp. 1025–1035, May 1973, doi: https://doi.org/10.1016/0017-9310(73)90041-0.

This research paper was used when I switched from using the Grashof number as the main dimensionless parameter, to using the Rayleigh number, which is just the Grashof number multiplied by the Schmidt number. Although this paper was on an experiment of sublimation mass transfer rather than evaporation mass transfer, the flow regime was still turbulent natural convection, so it was relevant and helpful to our experimental research. Additionally, this paper detailed the numerical effects of using a different characteristic length for the geometry of the experiment, in which the surface area of the evaporating surface is divided over the perimeter of the surface to obtain the characteristic length. I had been investigating this other characteristic length in the textbooks and was considering switching over to using it for mathematical modelling, and so this paper detailed the merits of doing so and informed me on the topic. I also investigated the Sherwood correlations that were produced by this experiment and compared their relevancy to the other Sherwood correlations from other experiments.

[33] J. R. Lloyd and W. R. Moran, “Natural Convection Adjacent to Horizontal Surface of Various Planforms,” Journal of heat transfer, vol. 96, no. 4, pp. 443–447, 1974, doi: 10.1115/1.3450224.

This was another sublimation mass transfer experiment but has turbulent free convection as a flow regime. Additionally, the range of Rayleigh numbers that data was collected over for this experiment was 2.2×10^4 to 1.6×10^9, which our Rayleigh number perfectly fit into. Because of this, I used the Sherwood correlation from this research paper for our final Sherwood number and

evaporation rate predictions. This experiment also used the other characteristic length in their mathematical modelling, and referenced the previous paper while doing so, which was a good addition to my calculations in terms of consistency.

[23] R. W. Fox and J. W. Mitchell, *Fox and McDonald's introduction to fluid mechanics*. Hoboken: Wiley, 2019.

The chapter from this textbook that I used as a source is chapter 7, Dimensional Analysis and Similitude. Although this textbook focuses on applications of fluid dynamics, this chapter, and particularly section 7.4, Flow similarities and model studies, gives a good introduction on dimensionless parameters using methods such as the Buckingham Pi theorem, and the requirements that prototypes and models must have in order to be effectively scaled to actual size. This is relevant for our research because one of the main objectives in our project is too dimensionless parts of the heat and mass transfer equations to establish parameters which will accurately reproduce the conditions of a canal covered in solar panels to observe the effects on evaporation.

[24] Leonid Ivanovich Sedov, *Similarity and Dimensional Methods in Mechanics*. Elsevier, 1959.

Although it is a much older source, this book provides a good introduction on how to set up an experiment with the proper non-dimensionalized parameters in order to accurately describe the natural phenomena in question. This source leads off of the first one in providing proficient background in setting up proper experimentation procedures for accurate modelling, as well as going into detail on how to go about this. This is going to be crucial for our project as we need to replicate the evaporation from the canal accurately in order to produce useful results.

[25] B. McKuin *et al.*, "Energy and water co-benefits from covering canals with solar panels," *Nature Sustainability*, Mar. 2021, doi: https://doi.org/10.1038/s41893-021-00693-8.

This paper was written by researchers from Sierra Nevada Research Insitute, University of California, Merced, and the Environmental Studies Department, University of Santa Cruz. This is a valuable paper for our research because it is one of the few studies that has been published so far directly on the co-benefits of canals covered by solar panels. The research was completed for the Nexus project, which is being developed in California. Some modeling for evaporation rate reduction was included in the study, which makes it a good reference for our background research.

[26] A. Albalasmeh, O. Mohawesh, D. Zeadeh, and K. Unami, “Robust optimization of shading types to control the performance of water reservoirs,” *Journal of Cleaner Production*, vol. 415, p. 137730, Jun. 2023, doi: https://doi.org/10.1016/j.jclepro.2023.137730.

This paper is based on a study done out of Agricultural Research Station of Mutah University in Jordan. The study provides some good references for experimental methods, as well as valuable background information on forced convection evaporation. Some of the mathematical modelling used in this study is relevant to our specific application, making it a good source for our initial research. This study also provided some information on possible measurement devices for an evaporation study.

[27] Çengel Y. A. and A. J. Ghajar, *Heat and mass transfer: fundamentals & applications*, 5th ed. New York, Ny: Mcgraw Hill Education, 2015. Chapters 6, 7, 9, 10, 14.

This book has been one of the main sources for my research, especially chapter six and fourteen. Chapter six provides an introduction to convection, which is the main focus of study in this project. It covers boundary layers, laminar and turbulent flow, as well as forced and natural convection. The non-dimensional conservation equations for heat and mass transfer are also introduced in this chapter, which we will be using to find our non-dimensional numbers such as the Reynolds and Sherwood numbers. In chapter fourteen, the analogy between heat and mass transfer is described, which is a large part of our conceptual research. Overall, the conceptual lessons from this textbook and the equations are very important when it comes to solving our particular problem, and per our client's request, I have been using this textbook extensively for my research.

[28] T. L. Bergman and E. Al, *Fundamentals of heat and mass transfer*, 8th ed. Hoboken: J. Wiley & Sons, Cop, 2011. Chapters 6, 7, 9, 14.

As with the previous source, this book is very valuable to our research because it also has a chapter dedicated to the analogy between heat and mass transfer which is a significant portion of the subject of our study. Additionally, chapter six in this book covers convection which provides an introduction to some relevant non-dimensional numbers that we will be using in our project. These include the Reynolds number, Prandtl number, and Sherwood number. There is also

information on characteristic lengths, and non-dimensional partial differential conservation equations which we will be using to find the previously mentioned numbers.

[29] M. J. Moran, H. N. Shapiro, D. D. Boettner, and M. B. Bailey, *Fundamentals of engineering thermodynamics*. Hoboken, Nj: Wiley, 2014. Chapter 12.

Lastly, this textbook is valuable for our research because it covers the fundamental principles of the process of evaporation from an engineering standpoint. There are many different fields that cover the study of evaporation for countless applications, such as agricultural and hydrological as well as meteorological, therefor many different equations have been developed to describe the process in order to fit the needs of the subject of study. Because our project is focused on studying the rates of evaporation from an engineering perspective, this book provides relevant information for our specific applications. This includes information on relative humidity and the pressure gradient that occurs during evaporation, as well as values for the saturated water vapor pressure at different temperatures.

3.2.2 Garet Bowels

[11] Y. M. Ghazaw, "Design and analysis of a canal section for minimum water loss," *Alexandria Engineering Journal*, vol. 50, no. 4, pp. 337–344, Dec. 2011. doi:10.1016/j.aej.2011.12.002

This source helped us understand how canal design plays a crucial role in reducing water loss. It explained how adjusting the geometry of a canal can minimize both evaporation and seepage, which directly influenced how we approach surface area optimization in our project. By refining the shape and dimensions of a canal, water exposure to wind and heat can be reduced, slowing down evaporation rates. This insight helped us consider structural design elements that support water conservation while maintaining efficient flow.

[12] (PDF) water losses from irrigation canals and their Modern Sustainable Solutions -A review, https://www.researchgate.net/publication/368915088_Water_Losses_from_Irrigation_Canals_and_their_Modern_Sustainable_Solutions_-A_Review (accessed Feb. 8, 2025).

This review provided a broad look at different strategies for reducing water loss, including covering methods and evaporation suppression techniques. It reinforced the importance of environmental control mechanisms, helping us design a system that directly targets water conservation. By analyzing various sustainable approaches, we were able to refine our system to

incorporate modern, effective water-saving techniques. This source helped guide our decision-making process, ensuring we used tested and successful solutions to meet our conservation goals.

[13] S. E. Baradei and M. A. Sadeq, "Effect of solar canals on evaporation, water quality, and power production: An optimization study," MDPI, https://www.mdpi.com/2073-4441/12/8/2103 (accessed Mar. 9, 2025).

This research identified the key factors that contribute to water loss in canals, such as temperature, wind speed, and surface exposure. It reinforced the need for environmental monitoring, helping us design a system that tracks climatic conditions affecting evaporation. Their findings validated our focus on precision measurement, allowing us to develop targeted strategies for reducing water loss. By using proven conservation methods, we can ensure our system is scientifically sound and effective in real-world applications.

[14] S. El Baradei and M. Alsadeq, "Impact of covering irrigation canals on evaporation rates in arid areas," *Proceedings of International Structural Engineering and Construction*, vol. 5, no. 1, Jul. 2018. doi:10.14455/isec.res.2018.30

This study highlighted the benefits of covering canals to reduce evaporation, especially in hot, arid climates like Arizona. It provided strong evidence that solar panels can serve a dual purpose by both conserving water and generating renewable energy. The research helped us justify our design choices, showing that canal coverings significantly slow evaporation rates. This source strengthened our argument for implementing solar panels as an effective and sustainable conservation method.

[15] M. Mutema and K. Dhavu, "Review of factors affecting canal water losses based on a meta-analysis of Worldwide Data," *Irrigation and Drainage*, vol. 71, no. 3, pp. 559–573, Feb. 2022. doi:10.1002/ird.2689

This study compiled data from various global sources to highlight the most significant contributors to water loss in canals. By analyzing evaporation trends across different climates, it helped us determine which evaporation reduction methods are most effective. It reinforced why precise evaporation measurement and control are critical to our project's success. The findings guided us in developing accurate monitoring systems and refining our approach to suppressing evaporation in a way that is both efficient and practical.

[16] B. W. Atkinson, E. C. Penning-Rowsell, and D. J. Parker, *Weather and Water*. Oxford, England: Pergamon Press Ltd, 1986.

This book provided a detailed understanding of how weather impacts water loss, focusing on temperature, humidity, and wind speed. It reinforced why environmental condition monitoring is essential, helping us predict how changing weather patterns affect evaporation rates. With this knowledge, we refined our approach to tracking and mitigating water loss in real time. This source played a key role in shaping our climate-adaptive strategies for reducing evaporation.

[17] A. W. Castleman, R. S. Berry, and H. Haberland, *Water in Confining Geometries*. Berlin/Heidelberg: Springer Berlin Heidelberg, 2003.

This source provided a scientific perspective on water behavior in confined spaces, particularly how evaporation occurs at a molecular level. It helped us understand how solar panels and canal coverings can limit water exposure, directly influencing our evaporation suppression strategies. By applying this knowledge, we were able to refine our design approach to minimize evaporation more effectively. This resource gave us a strong theoretical foundation for how physical barriers impact evaporation rates, allowing us to develop a more precise and efficient solution.

[18] "Sensors," Adafruit Learning System, https://learn.adafruit.com/category/sensors (accessed Sep. 6, 2025).

This source provided practical, hands-on guidance for wiring and integrating the sensors used in our system, including humidity, temperature, water probes, and load cells. The detailed diagrams and calibration tips helped us build circuits that remained stable over long test durations, even with multiple devices operating on shared communication lines. By following Adafruit's validated examples, we ensured that our sensor configurations were reliable, safe, and optimized for accurate environmental data collection.

[19] Arduino Workshop: A hands-on introduction with 65 projects by John Boxall - PDF drive, https://www.pdfdrive.com/arduino-workshop-a-hands-on-introduction-with-65-projects-e157647939.html (accessed Sep. 5, 2025).

This project-based text helped us understand how to structure Arduino code and hardware layouts through progressively more complex examples. It reinforced essential concepts such as digital communication, analog input handling, and building modular code, which directly influenced how we organized our data-logging system. The book's practical approach supported our ability to prototype quickly and translate small circuits into a fully integrated environmental monitoring apparatus.

[20] “Programming arduino: Getting started with sketches 2nd edition - ebook pdf download,” Scribd, https://www.scribd.com/document/898957168/Programming-Arduino-Getting-Started-with-Sketches-2nd-Edition-eBook-PDF-download (accessed Sep. 22, 2025).

This source strengthened our understanding of Arduino programming fundamentals and intermediate techniques needed for multi-sensor applications. It helped us incorporate cleaner coding practices, error handling, and timing control into the final sketch, improving reliability during our test experiments. By following its guidance on functions and libraries, we were able to create a more stable software framework for the system.

[21] Practical Electronics for Inventors, https://neuron.eng.wayne.edu/ECE330/Practical_Electronics_for_Inventors.pdf (accessed Sep. 10, 2025).

This reference strengthened our understanding of the electronics behind our system, especially when it came to solving noise, grounding, and interference issues. When we struggled with unstable load cell readings or long I²C runs, this book explained the underlying circuitry and why those problems were occurring. Using its guidance, we were able to redesign parts of our wiring to make the entire system more dependable.

[22] M. Margolis, “Arduino cookbook, 2nd edition,” O’Reilly Online Learning, https://www.oreilly.com/library/view/arduino-cookbook-2nd/9781449321185/ (accessed Sep. 16, 2025).

The Arduino Cookbook became our go-to reference whenever we got stuck or needed a proven example to build from. It covers everything from sensor communication to data logging, which helped us piece together a complex system without getting lost in the details. Its practical

solutions and sample code made it much easier to integrate all our components into one fully working and efficient data-collection program.

3.2.3 Trey Bushling

[35] 13.6: Humidity, Evaporation, and Boiling," *Physics LibreTexts*, Nov. 01, 2015.

Humidity, evaporation, and boiling describe how water transitions between phases based on temperature and pressure. Humidity measures water vapor in the air, with relative humidity comparing actual moisture to the air's capacity at a given temperature. High humidity slows evaporation, making heat feel more intense, while low humidity increases evaporation, causing dryness. The dew point is when air reaches full saturation, leading to condensation. Boiling occurs when a liquid's vapor pressure matches atmospheric pressure, allowing bubbles to form throughout. These principles explain weather patterns, temperature changes, and industrial processes like freeze-drying, where reducing pressure speeds evaporation.

[36] Y. Waheeb Youssef and A. Khodzinskaya, "A Review of Evaporation Reduction Methods from Water Surfaces," *E3S Web of Conferences*, vol. 97, p. 05044, 2019, doi:

The paper reviews evaporation reduction methods for water conservation, categorizing them into physical, chemical, and biological approaches. Physical methods, like floating covers and solar panels, are the most effective, reducing evaporation by 70–95%. Chemical methods, such as monolayer films, offer 20–40% reduction. Biological methods, including floating plants and windbreaks, help but have environmental limitations. Air bubble injection lowers surface temperatures in deep reservoirs to slow evaporation. Physical methods provide the best results, while chemical and biological techniques offer additional benefits.

[37] Seginer, Ido. "Wind Effect on the Evaporation Rate." *Journal of Applied Meteorology (19621982)*, vol. 10, no. 2, 1971, pp. 215–220. *JSTOR*, www.jstor.org/stable/26174903,

The paper "Wind Effect on the Evaporation Rate" by Ido Seginer examines how wind influences evaporation based on a resistance model. It identifies that evaporation depends on the interaction between surface temperature, atmospheric resistance, and internal vapor resistance. For wet

surfaces, evaporation increases with wind speed, while for dry surfaces, the effect varies depending on internal resistance and humidity. The study highlights a critical resistance threshold where evaporation shifts behavior, potentially leading to sudden increases or decreases. The findings are important for understanding evaporation in agriculture, water conservation, and climate studies, particularly in the design of windbreaks to control water loss

[38] Wang, Chunzai, et al. "Effects of the Wind Speed–Evaporation–SST Feedback on the El Niño–Southern Oscillation." *Journal of the Atmospheric Sciences*, vol. 56, no. 10, May 1999, pp. 1391–1403

The paper examines how wind speed, evaporation, and sea surface temperature (SST) interact to influence ENSO dynamics. It introduces feedback where wind speed affects evaporation, cooling SST, which then alters wind patterns, creating irregular oscillations and phase-locking ENSO to seasonal cycles. This thermodynamic feedback differs from traditional momentum-based models and may contribute to decadal variability. The study highlights the importance of both oceanic dynamics and thermodynamics in shaping ENSO behavior.

[39] Uri Stiubiener, et al. "PV to Reduce Evaporative Losses in the Channels of the São Francisco's River Water Transposition Project." *Scientific Reports*, vol. 14, no. 1, 21 Mar. 2024,

The paper explores the use of photovoltaic (PV) panels to reduce evaporation losses from open water channels in the São Francisco River Integration Project (PISF) in Brazil. These channels, crucial for supplying water to arid regions, experience significant water loss due to solar radiation. The proposed solution involves covering the channels with solar panels, which would reduce evaporation and simultaneously generate clean energy to power water pumps. Findings suggest that this approach could save up to 25,000 cubic meters of water per day and produce 1,200 gigawatt-hours of electricity annually, improving water security and energy efficiency in the region. The study highlights the potential global application of this method for sustainable water management.

[40] "Evaporation and its Methods of Measurement," *The Constructor*, Oct. 06, 2010.

Evaporation is the process by which liquid water changes into water vapor, transferring energy from the water body. It occurs when energy is supplied to the liquid, causing water molecules at the surface to escape into the atmosphere. Factors like air and water temperature, wind speed, atmospheric pressure, and the surface area of the water body influence the rate of evaporation. In nature, evaporation works alongside transpiration from plants, together forming evapotranspiration (ET), which is a crucial part of the water cycle. This process reduces the amount of water available as surface runoff, contributing to water loss in a given area. The rate of evaporation can be measured using various techniques, such as evaporation pans or empirical equations, though these methods have limitations and require adjustments to account for differences between pans and larger bodies of water.

[41] I. Le Bras, "Lecture 12: Scaling and Nondemensionalization 12.1 Learning Objectives," 2015.

The paper discusses scaling and nondimensionalization as mathematical techniques to simplify equations and analyze dominant forces in a system. It covers how to scale variables, nondimensionalize differential equations, and derive nondimensional numbers such as the Reynolds and Froude numbers which help describe fluid dynamics. Examples include applying these methods to Navier-Stokes equations, a 1D diffusion model demonstrating how nondimensionalization clarifies system behavior and shows key parameters affecting stability and dynamics

[42] "Chapter 3 Nondimensionalisation."

The chapter discusses nondimensionalization, a key technique in analyzing differential equations. It involves scaling variables using reference values to simplify equations and identify dimensionless groups that control solution behavior. This process helps compare term sizes, highlight dominant forces, and reduce the number of parameters. Examples include applications in radioactive decay, damped pendulums, heat transfer, and fluid dynamics, demonstrating how nondimensionalization aids in understanding physical systems. The Buckingham Pi theorem is introduced as a formal method for identifying dimensionless quantities, showing its importance in simplifying complex problems.

[43] Introduction to Fluid Mechanics

This reference provides the fundamental principles of fluid motion that shows natural-

convection behavior in the apparatus. Concepts such as buoyancy-driven flow, boundary layers, and thermal stratification directly support how temperature and humidity gradients form above the water surface. These fundamentals help justify the use of Rayleigh-number based correlations and explain the physical mechanisms driving evaporation in both shaded and unshaded conditions.

[44] SOLIDWORKS 2023 Reference Guide

The SOLIDWORKS reference guide supports the mechanical design aspect of the project by providing the modeling standards, features, and drafting tools needed to create accurate 3D representations of the apparatus. It ensures that the frame, lid, side-box, and sensor mounts are modeled with correct dimensions and tolerances, enabling clear communication of design intent and reliable fabrication.

3.2.4 Jorge Cesin

[58] S. E. Baradei and M. A. Sadeq, “Effect of solar canals on evaporation, water quality, and power production: An optimization study,” Water, vol. 12, no. 8, p. 2103, Jul. 2020. doi:10.3390/w12082103

This study goes in depth on the very topic this project is about, solar canals. The article talks about how their team studied solar canals and goes over the information that was gathered. It talks about the positives and the negatives of having these channels and some of the research done on these channels. It talks about the need for these canals in order to save money and resources and how these canals are a good way of making used space more efficient.

[59] H. Chanson, Hydraulics of Open Channel Flow. Burlington: Elsevier, 2004.

This book is like other engineering books as it has chapters biased on the equations of various concepts. The chapters in this book vary from open channel hydraulics to the transport of sediment in canals. The book provides examples and solvable problems to give the reader a good understanding of the material. This book could prove useful as it has an abundance of equations and concepts that could help the team with canal flow and overall canal water movement. It also presents other challenges for the team like sediment, something that was previously not considered.

[60] A. ONEILL, "Quarterly Journal of the royal meteorological society," Quarterly Journal of the Royal Meteorological Society, vol. 106, no. 450, pp. 659–690, Oct. 1980. doi:10.1256/smsqj.45001

The journal examines evaporation processes, linking meteorological parameters like wind speed, humidity, and boundary-layer turbulence to loss of water from canals. Although the journal does not go into depth about canals, it does mention irrigation and evapotranspiration which is something the team can use to link to canal evaporation. Overall, this journal would be useful for addressing weather for this project. Since weather is a massive part of evaporation, this journal is a good source to have.

[61] S.Assouline a et al., "Evaporation from three water bodies of different sizes and climates: Measurements and scaling analysis," Advances in Water Resources, https://www.sciencedirect.com/science/article/abs/pii/S0309170807001248?fr=RR-2&ref=pdf_download&rr=90ef6bc928d2f8d3.

This article reviews the data collected from 3 bodies of different sizes and climates and studies the evaporation from each of the bodies of water. The article studies surface hydrology, micrometeorology, as well as countless other topics relating to the evaporation of water. This article is especially useful as it tests different climates and how those climates affect evaporation. Each climate presents its own variables which is something the team can use to gather the variables from the climate that needs to be tested for the project.

[62] Flow of water in irrigation and similar canals, https://il.water.usgs.gov/proj/nvalues/supplementary/Flow_of_Water_in_Irrigation_and_Similar_Canals.pdf.

Although this book is rather short and old, it contains equations and concepts that are still being used today. The book talks about wetted surface area and hydraulic radius which are still variables that are used today. The book also contains solved equations with quantitative values as well as graphs that give the values a visible line to follow. Something especially useful is how it goes over different canal shapes and gives data on each of the shapes. Overall, it's a pretty good source to use for this project and could be useful for the team.

[63] “Evaporation rates, condensation rates, and relative humidity,” Evaporation Rates, Condensation Rates, and Relative Humidity | METEO 3: Introductory Meteorology, https://www.e-education.psu.edu/meteo3/l4_p4.html

This is a chapter from the Department of Meteorology and Atmospheric Science talks about evaporation rates, condensation rates, and relative humidity. All 3 of these topics directly relate to the project in some way. Below there is an equation for relative humidity that relates to this project. This chapter has an experiment that can be done to test the relative humidity in a small container. It talks about the experiment having 2 phases, the first phase is when the water is added, which has a high evaporation rate, the second phase is when the water has evaporated after time and the evaporation rate is the same as the condensation rate balancing everything out.

[64] W. Wang et al., “Estimating evaporation from irrigation canals in the midstream areas of the Heihe River basin by a double-deck surface air layer (DSAL) model,” MDPI, https://www.mdpi.com/2073-4441/11/9/1788#B18-water-11-01788

This research has been the most useful piece of information that I have currently found. This research directly talks about evaporation over solar canals specifically. My mathematical modeling below uses the equations that the research uses to test for evaporation over canals. This piece of literature provides a way of testing for evaporation by splitting the air above the flowing water into 2 parts. Although this formula won't be used in this project, it's a nice equation to compare our research with another team's research.

[65] “G. Brunner, “Heat transfer,” Supercritical Fluid Science and Technology, https://www.sciencedirect.com/science/article/pii/B9780444594136000042

This article basically goes over how water is used to move heat around in power plants, especially in nuclear ones. It breaks down how water acts in different states like gas, liquid, or somewhere in between and what happens when it gets super-hot and pressurized. It also talks about how heat moves through pipes and what changes when other stuff is mixed in with the water. This article can help with how heat transfers in water and the different states of water.

[66] D. Shi and K.-T. Lee, “Experimental and computational study of enhanced forced convection heat transfer in novel slotted wavy-plate-fin channels,” *Journal of Heat Transfer*, vol. 145, no. 4, p. 041801, 2023.

This article was quite useful for what the team needs as it relates to my designated individual section. The article is about forced convection, and with wind being a large part of our project, it's important to do research on this topic. The article is interesting and even includes an experiment that they conducted to test for forced convection. The article includes their experimental apparatus as well as the method they used to test everything and their results.

[67] T. Poós and E. Varju, “Mass transfer coefficient for water evaporation by theoretical and empirical correlations,” *International Journal of Heat and Mass Transfer*, vol. 153, p. 119500, 2020, doi: 10.1016/j.ijheatmasstransfer.2020.119500.

This was a very useful article that gave equations, experiments, methods, and results. These will all come in handy as a lot of the mass transfer in the books that we’ve been looking at have only been a section of 1 chapter. The article is about evaporation, which also relates to our project. The opening page gives a list of the variables and what they mean, giving the reader something to reference when unknown symbols show up. Overall, it's a strong article for the team and can prove to be useful.

3.2.5 Brendan Steele

[48] A. G. Olabi, *Renewable Energy. Volume 1, Solar, Wind, and Hydropower: Definitions, Developments, Applications, Case Studies, and Modelling and Simulation*. London: Academic Press, an imprint of Elsevier, 2023.

This book written by Olabi, was utilized for the calculations, providing formulas for the radiation intensity directly from the sun. It offered equations like the Hour angle equation and how to find the solar hour which is directly relevant to calculating the intensity over Phoenix during peak summer months. While this book wasn’t used for much it provided a brief understanding as to why each variable was used and how it relates to the equation.

[49] T. L. Bergman and A. S. Levine, *Fundamentals of Heat and Mass Transfer “12.3.2 Radiation Intensity and Its Relation to Emission.”* Hoboken, NJ: John Wiley & Sons, Inc, 2019.

The textbook *Fundamentals of Heat and Mass Transfer* has been a great help with chapter 6 going over convection of free body's, has also been a great help for understanding radiative properties of heat. Section 12.2.3 provides a detailed summary of emission of electromagnetic waves produced by the solar properties of the sun. When developing the mathematical model for the intensity of radiation through PV panels, this section allowed me to understand surrounding variables. This whole chapter of the textbook provided great insight on the understanding of longwave heat transfer that directly affects the temperature over water and describing factors such as absorptivity and how the stefan-boltzman equation will factor into our final calculations.

[50] D. D. Rooij, "Calculation of solar insolation," Manage risks and maximize ROI for your PV and energy storage projects, https://sinovoltaics.com/learning-center/basics/calculation-of-solar-insolation/#:~:text=Solar%20insolation%20(I)%20can%20be,formula:%20I%20=%20S%20cosZ. (accessed Mar. 8, 2025).

This article was utilized to find the solar insolation that transfers through the PV panels PVDF back sheet. While there isn't a lot of direct information it was extremely helpful for explaining the variables. The information on this breakdown provided enough detail to help calculate the intensity of solar radiation emitted from the PV panels per unit area over the canal.

[51] "Reducing urban temperatures," Canal & River Trust, https://canalrivertrust.org.uk/things-to-do/canal-and-river-wildlife/nine-ways-canals-can-fight-climate-change/reducing-urban-temperatures (accessed Mar. 8, 2025).

The link talks about how canals can play a role in fighting climate change, especially by cooling down cities. Canals naturally soak up heat and release coolness through evaporation, which helps lower the temperature in urban areas. This is super helpful in cities, where concrete and buildings often trap heat, making things hotter. By taking care of canals and using them wisely, cities can stay cooler and more comfortable. This information doesn't directly help the research but provides insight on the effect canals have on their surroundings.

[52] S. W. Brazel and R. C. B. Jr., "Temporal analysis of long-term atmospheric moisture levels in Phoenix, Arizona," AMETSOC, https://journals.ametsoc.org/view/journals/apme/25/2/1520-0450_1986_025_0112_taolta_2_0_co_2.xml?tab_body=pdf (accessed Mar. 8, 2025).

This article discusses the atmospheric moisture levels in Phoenix providing data like the average temperature and humidity in immense detail. The values are super helpful when it comes to solving the evaporation rate of canals. As this document is over 40 years old the information is still relevant today. With data for several periods in the prior years to this publishing being on them allows us to see how the climate will change annually and what to expect during different seasons. This information will be great when we move our research to the next step of testing evaporation rates throughout the whole year.

[53] J. Hao and E. Lu, "Variation of relative humidity as seen through linking water vapor to air temperature: An assessment of interannual variations in the near-surface atmosphere," MDPI, https://www.mdpi.com/2073-4433/13/8/1171 (accessed Mar. 8, 2025).

This Article goes into detail of how atmospheric water vaper increases due to higher evaporation. Using the Clausius-Clapeyron (C-C) equation with relative humidity staying stable, the equation allows the rate of evaporation to be calculated. This article goes into detail how relative humidity has a greater effect on evaporation rates than one may assume. However, this isn't true in every case because this equation is highly dependent on elevation, as the higher it's tested, the less significant relative humidity has on the evaporation rate.

[54] K. Heck, E. Coltman, R. Helmig, and J. Schnieder, Influence of radiation on evaporation rates: A numerical analysis - heck - 2020 - water resources research - wiley online library, https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2020WR027332 (accessed Mar. 9, 2025).

This article is a research journal where a team used a soil atmosphere model to test how radiation effects evaporation. Although their data won't correlate to our research it provides insight into how the radiation varies under shaded regions. That specific information helps our team make assumptions about how the temperature may vary underneath a PV panel. As our team continues to move forward with our research, this data will help with assessing the radiation aspect of evaporation. This data will help us assess how shading directly affects the energy and water balance.

[55] F. Moraes, "HTML for beginners The easy way: Start learning html & css Today »," HTML, https://html.com/ (accessed Apr. 10, 2025).

This website was helpful in teaching how to hard code a website in HTML to build a clean professional website for the SRP research team. The guide broke down the design in simple and practical steps making it easy to create a foundation for our website. It also clearly explained to format the code and include simple styles from CSS. This helped drastically creating a clean final product that is user friendly without sacrificing any of the collected information that needs to be on the website like the design, data, and results.

[56] "W3schools CSS," W3Schools Online Web Tutorials, https://www.w3schools.com/css/ (accessed Apr. 20, 2025).

Like the source above, this website went deeper into the styles implemented in the website. CCS styles allow for more in depth structures, giving the designer more control for the formatting of the website. The "Try it Yourself" editor made it easy to experiment with code and see the changes without posting the code. This site helped create a presentable design with custom visual designs making it look more polished and professional.

[57] "Welcome to the SOLIDWORKS web help," 3D SOLIDWORKS, https://help.solidworks.com/2025/english/SolidWorks/sldworks/c_Assemblies_first_map_topic.htm?id=7 (accessed Sep. 23, 2025).

This source helped with providing resources to properly design our experimental apparatus for the SRP project. By walking through the help page I was able to properly define each aspect for an early stage design prototype and implement each part in an assembly. Ultimately the tutorials helped refresh my skills that were previously learned for modeling and design, while learning more efficient ways to use each tool in SOLIDWORKS. This source strengthened my ability to design by giving step by step assistance throughout the modeling process.

3.2.6 Samantha Synk

[1] "Matlab tutorials," MATLAB Tutorials - MATLAB & Simulink, https://www.mathworks.com/support/learn-with-matlab-tutorials.html?ef_id=EAIaIQobChMI1sm1pcmOkQMVLiBECB0RTjQwEAAYASAAEgKjLfD_BwE%3AG%3As&s_kwcid=AL%218664%213%21%21%21%21x%21%21&s_eid=PDL_33478&g

ad_source=1&gad_campaignid=21666610448&gbraid=0AAAAAD0FmXLDf9H-rCxFgLv5ADbtXPu4s&gclid=EAIaIQobChMI1sm1pcmOkQMVLiBECB0RTjQwEAAYASAAEgKjLfD_BwE (accessed Nov. 25, 2025).

This MATLAB Tutorials resource was used extensively throughout the development of this project. These tutorials provided guidance on structuring efficient MATLAB scripts, working with function files, and organizing code into modular sections. The tutorials also supported the implementation of vectorized operations, nested parameter sweeps, and visualization tools. Which allowed the team to rapidly test thousands of combinations of air temperatures, water temperatures, humidity, and apparatus length, Additionally, the tutorials helped reinforce proper use of anonymous functions, custom function handles and debugging workflows used while validating the mass transfer correlations. Overall, this source improved the accuracy, efficiency, and readability of all MATLAB analysis performed for this capstone.

[2] "SCATTER3," 3-D scatter plot - MATLAB, https://www.mathworks.com/help/matlab/ref/scatter3.html (accessed Nov. 25, 2025).

This source scatter3 documentation was used to create the three-dimensional visualization tools that supported the analysis of our apparatus. This function allowed me to plot combinations of ambient air temperature, relative humidity, and apparatus length while color coding the resulting Sherwood numbers. By using scatter3, I was able to visually identify clusters of operating conditions that most closely matched the buoyancy-driven flow regime of the Grand Canal. The documentation provided essential guidance on formatting markers, applying color maps, labeling axes, and attaching data-driven color bars. Which improved the clarity of the plots.

[3] "Array indexing," MATLAB & Simulink, https://www.mathworks.com/help/matlab/learn_matlab/array-indexing.html (accessed Nov. 25, 2025).

This source, Array Indexing documentation, played an important role in organizing the large datasets generated during testing. Our Sherwood script evaluates thousands of combinations of water temperatures, air temperatures, relative humidity, and apparatus lengths. Resulting in multidimensional arrays that require precise indexing to sort, filter, and extract meaningful results. The tutorials clarified how to efficiently access specific rows and columns, use logical indexing to isolate exact matches to target loops. This improved not only runtime performance but also the clarity of the code. Using this resource ensured that our parameter sweeps were handled accurately and that complex arrays remained well structed throughout our analysis.

[4] "Heat transfer with MATLAB curriculum materials courseware," Heat Transfer with MATLAB Curriculum Materials Courseware - MATLAB & Simulink, https://www.mathworks.com/academia/courseware/heat-transfer.html (accessed Nov. 25, 2025).

This source helped support my ability to integrate engineering heat transfer principles directly into our computational analysis. This resource reinforces core concepts such as natural convection, thermal boundary layers, and temperature-dependent fluid properties. The courseware examples demonstrated how to structure MATLAB functions, apply property correlations, and visualize heat transfer behavior using plotted results. These instructional materials helped bridge the gap between textbooks and MATLAB implementation. Allowing me to confidently compute temperature-dependent air viscosity, saturation vapor pressures, and buoyancy-driven density differences. Ultimately, this resource improved both the physical accuracy and computational structure, strengthening the reliability of the design.

[5] D. Venturi, B. Pulvirenti, and S. Salvigni, "DIRECT NUMERICAL SIMULATION OF NATURAL CONVECTIONOVER HORIZONTAL PLATES," XXIII Congresso Nazionale UIT sulla Trasmissione del Calore Parma, pp. 20–22, 2005.

This paper by Venturi, Pulvirenti, and Salvigni on direct numerical simulation of natural convection over horizontal plates provided grounding for understanding our smoke flow visualization test. Their simulations show how horizontal heated surfaces generate distinct natural convection structures. Including rising plumes, cellular patterns, and transitional oscillations. Which are controlled by the Rayleigh numbers. The temperature field images and mode analysis in their paper provided clear benchmarks for what convection should look like at different buoyancy strengths. These visual cues helped us determine the exact flow features that our smoke visualization should detect. Which was upward thermal plumes and lateral return flow near the surface. By comparing our incense smoke observations to the plume structures and stability transitions documented in this paper, we were able to evaluate whether our apparatus truly operated within a free connection regime consistent with canal scale behavior.

[9] El Baradei S.A. Alsadeq M. and El Baradei S.A. Alsadeq M., "Combined effect of wind speed and covering irrigation canals on water quality parameters," Business Administration School, https://ba.nu.edu.eg/publications/combined-effect-wind-speed-and-covering-irrigation-canals-water-quality-parameters (accessed Feb. 3, 2025).

This article examines how wind speed impacts evaporation rates in irrigation canals. It provides experimental data showing that as wind speed increases, evaporation losses also rise due to increased water air interactions. This study is relevant to our project because one of our key parameters is wind speed, and we need to evaluate how different wind conditions affect evaporation in open versus covered canal sections. Understanding this relationship will help in designing wind mitigation strategies, such as barriers or floating covers.

[10] Study of the effect of wind speed on evaporation from soil through integrated modeling of the atmospheric boundary layer and shallow subsurface - davarzani - 2014 - water resources research - wiley online library, https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2013WR013952 (accessed Feb. 3, 2025).

This study provides valuable insights into how wind speed influences evaporation through atmospheric boundary layer modeling. The research employs mathematical models to predict evaporation rates under various wind conditions. Applying these modeling techniques to our project will allow us to refine our predictions for Arizona canals. By adapting the study's methodologies, we can compare open water evaporation rates to those in covered or shaded canal conditions, helping to validate our experimental results.

[45] MIT, https://people.csail.mit.edu/jaffer/convect/thermo.pdf (accessed Apr. 11, 2025).

This MIT resource on natural convection over horizontal surfaces was used to support both our theoretical modeling and our smoke flow visualization test. It explains how temperature gradients generate buoyant plumes and cellular convection structures. Which directly informed what patterns we expected to observe during test 0. The document also reinforces the use of Rayleigh, Grashof, and Prandtl numbers and clarifies how to choose a characteristic length for boundary layer calculations, guiding our similarity analysis for matching canal conditions. Overall, this source helped validate that our apparatus should exhibit free convection behavior and provide the theoretical benchmarks needed to interpret our smoke visualization results.

[46] P. H. Oosthuizen and A. Y. Kalendar, "Natural convective heat transfer from horizontal and near

horizontal surfaces," SpringerLink, https://link.springer.com/book/10.1007/978-3-319-78750-3 (accessed Apr. 12, 2025).

This book offers a comprehensive review of natural convection heat transfer from horizontal and near horizontal surfaces, an area that closely reflects the thermal behavior of canal water surfaces in our capstone research. Unlike traditional models, the text addresses more complex geometries and real-world configurations, such as inclined surfaces or surfaces covered by shading structures like solar panels. These considerations are vital to our work, as we aim to evaluate how panel coverage affects convective heat transfer and evaporation rates. The book also presents improved predictive models that account for laminar to turbulent transitions in natural convection, helping us refine our calculations of heat transfer coefficients. Its insights into characteristic length scales and surface-to-air heat exchange will directly inform our boundary layer analysis and help us better model evaporation under varying temperature gradients and airflow conditions.

[47] (PDF) a review of evaporation reduction methods from water surfaces, https://www.researchgate.net/publication/333463999_A_Review_of_Evaporation_Reduction_Methods_from_Water_Surfaces (accessed Apr. 12, 2025).

This article provides a review of global methods developed to reduce water evaporation, which is directly relevant to the goals of our capstone project. The study examines physical, chemical, and biological approaches for evaporation reduction over a 14-year period, highlighting their efficiency, benefits, and limitations. For our project, the most applicable insight is the use of physical methods such as floating or suspended covers, which have demonstrated water savings between 70% and 95%. Although our team is not using floating photovoltaic systems, this article expands our understanding of alternative mitigation strategies, such as shading techniques or surface barriers, that may be integrated into future iterations of our experimental design. The review also introduces other less conventional approaches like thermal mixing, chemical suppressants like Water Surface, and biological interventions such as windbreaks and vegetation, which we can reference when exploring alternative or hybrid solutions for Arizona's canal systems.

3.3 Mathematical Modeling

Nomenclature

T_s Water Surface Temperature
T_∞ Ambient Air Temperature
T_f Film Temperature (Avg.)

A_s Surface Area

P Perimeter of surface area

L_c Characteristic length

ϕ Relative humidity

D_{AB} Diffusivity constant of water into air

v Kinematic viscosity

R_m Mass transfer Rayleigh number

$R_{m,GC}$ Mass transfer Rayleigh number at the Grand Canal

$R_{m,appar}$ Mass transfer Rayleigh number at the apparatus

Sh Sherwood number

h_m Convective mass transfer coefficient

$\dot{m}_v$ Rate of mass transfer of water vapor from evaporating surface

P_{atm} Atmospheric pressure in Pheonix or Flagstaff

$P_{v,s}$ Water vapor pressure at the saturated surface

$P_{a,s}$ Dry air pressure at the saturated surface

$P_{v,\infty}$ Water vapor pressure in the ambient air

$P_{a,\infty}$ Dry air pressure in the ambient air

P_{satT_∞} Saturation pressure for water at the ambient air temperature

$\rho_{v,s}$ Water vapor density at the saturated surface

$\rho_{a,s}$ Dry air density at the saturated surface

ρ_s Density of water vapor and dry air mixture at the saturated surface

$\rho_{v,\infty}$ Water vapor density in the ambient air

$\rho_{a,\infty}$ Dry air density in the ambient air

ρ_∞ Density of water vapor and dry air mixture in the ambient air

R_v Specific gas constant on water vapor

R_a Specific gas constant of dry air

3.3.1 Dimensionless Numbers Calculated from Phoenix Grand Canal – Lilliana Hadik-Barkoczy & Samantha Synk

From the data collected by SRP, average values were extracted from statistical distributions. These are the conditions that are present on the Grand Canal in Pheonix for the month of April 2025.

$T_\infty = 21.5°\text{C}(294.65K)$ - *Temperature of the ambient air (70.7°F) at the free stream wind velocity located 2m above the water surface*

$T_s = 17.5°\text{C}(290.65K)$ - *Temperature at the saturated water surface (63.5°F)*

$T_f = 19.5°\text{C}(292.65K)$ - *Film temperature within the concentration boundary layer*

$\phi = 20.2\%$ - *Relative Humidity in air 2m above water surface*

$D_{AB} = 2.41 \times 10^{-5}\,\frac{m^2}{s}$ - *Diffusivity of water vapor in air, evaluated at film temp.*

$v = 15.236 \times 10^{-6}\,\frac{m^2}{s}$ - *Kinematic viscosity of air, evaluated at film temp.*

$L = 13.716m(45ft)$ - *Length of the canal from bank to bank*

$W = 2.743m(9ft)$ - *Width of sample section of canal*

The characteristic length is evaluated using the surface area and perimeter ratio.

$$L_c = \frac{A_s}{P} = \frac{37.626m^2}{32.918m} = 1.143m$$

Before calculating the Rayleigh number, the concentration of water vapor and air vapor mixture densities need to be found.

$P_{atm} = 967.84\ hPa = 96.784kPa$ - *An atmospheric pressure that is commonly recorded in Pheonix*

$T_f = 292.65K$- *Film temperature in concentration gradient*

$$\rho = \frac{P_{atm}}{R_a \cdot T_{avg}} = \frac{96.784\ kPa}{0.287\ \frac{kPa \cdot m^3}{kg \cdot K} \cdot 292.65K} = 1.1523\ \frac{kg}{m^3}$$

Table 1: Density calculations at water surface

$P_{v,s} = 2.02205\ kPa$	*Vapor pressure at saturated surface taken from table A-9*
$P_{a,s} = P_{atm} - P_{v,s} = 96.784\ kPa - 2.02205\ kPa = 94.762\ kPa$	*Pressure of air at saturated surface*
$T_s = 17.5°C (290.65K)$	*Temperature of Water Surface*
$R_a = 0.287\ \frac{kPa \cdot m^3}{kg \cdot K}$	*Specific gas constant of dry air*
$R_v = 0.4615\ \frac{kPa \cdot m^3}{kg \cdot K}$	*Specific gas constant of water vapor*
$\rho_{a,s} = \frac{P_{a,s}}{R_a \cdot T_s} = \frac{94.762\ kPa}{\left(0.287 \frac{kPa \cdot m^3}{kg \cdot K}\right)(290.65\ K)} = 1.136\ \frac{kg}{m^3}$	*Density of dry air at saturated surface*

$\rho_{v,s} = \frac{P_{v,s}}{R_v \cdot T_s} = \frac{2.02205\ kPa}{\left(0.4615\ \frac{kPa \cdot m^3}{kg \cdot K}\right)(290.65\ K)} = 0.015 \frac{kg}{m^3}$	*Density of water vapor at saturated surface*
$\rho_s = \rho_{a,s} + \rho_{v,s} = 1.136\ \frac{kg}{m^3} + 0.015 \frac{kg}{m^3} = 1.151 \frac{kg}{m^3}$	*Density of water vapor and dry air mixture at water-air interface*

Table 2: Density calculations in Ambient Air

$P_{v,\infty} = \phi P \cdot_{satT_\infty} = 0.202(2.588kPa) = 0.5228kPa$	*Pressure of water vapor in air 2m above water surface*
$P_{a,\infty} = P_{atm} - P_{v,\infty} = 96.784\ kPa - 0.5228\ kPa = 96.261\ kPa$	*Pressure of dry air 2m above water surface*
$T_\infty = 21.5°C(294.65K)$	*Temperature of air 2m above water surface*
$\rho_{a,\infty} = \frac{P_{a,\infty}}{R_a T_\infty} = \frac{96.261\ kPa}{\left(0.287 \frac{kPa \cdot m^3}{kg \cdot K}\right)(294.65K)} = 1.138 \frac{kg}{m^3}$	*Density of dry air 2m above water*
$\rho_{v,\infty} = \frac{P_{v,\infty}}{R_v T_\infty} = \frac{0.5228kPa}{\left(0.4615 \frac{kPa \cdot m^3}{kg \cdot K}\right)(294.65K)} = 0.003845 \frac{kg}{m^3}$	*Density of water vapor in air*
$\rho_\infty = \rho_{a,\infty} + \rho_{v,\infty} = 1.138 \frac{kg}{m^3} + 0.003845 \frac{kg}{m^3} = 1.142 \frac{kg}{m^3}$	*Density of water vapor and dry air mixture 2m above water surface*

Both (2) and the equations used in tables 1 and 2 are from chapter 14 of Çengel Y. A. and A. J. Ghajar [27].

The three densities calculated provide information about the concentration gradient present in the mass transfer of water from the canal into the atmosphere. Now the mass transfer Rayleigh number can be calculated using these values. The Rayleigh number is a dimensionless number that characterizes the ratio of buoyant and viscous forces in natural convection.

$$Ra_m = \left[\frac{g(\rho_s - \rho_\infty)L_c^3}{\rho_\infty \cdot v}\right] \cdot \frac{v}{D_{AB}} \tag{3}$$

$$Ra_{m,GC} = \left[\frac{9.81\frac{m}{s^2}\left(\left|1.151\frac{kg}{m^3} - 1.142\frac{kg}{m^3}\right|\right) \cdot (1.143m)^3}{1.142\frac{kg}{m^3} \cdot \left(15.236 \times 10^{-6}\frac{m^2}{s}\right)^2}\right] \cdot \left(\frac{15.235 \times 10^{-6}\frac{m^2}{s}}{2.41 \times 10^{-5}\frac{m^2}{s}}\right) = 3.143 \times 10^8$$

A predicted Sherwood number can be calculated using the Lloyd and Moran experimentally derived Sherwood correlation [33].

$$\overline{Sh} = 0.15(Ra_m)^{\frac{1}{3}}, \ (8 \times 10^6 \leq Ra_m \leq 1.6 \times 10^9) \tag{4}$$

3.3.2 Scaled Dimensionless Numbers for Apparatus – Lilliana Hadik-Barkoczy & Samantha Synk

For our apparatus, the same method was used to calculate (3) and (4). Starting with the scaled conditions necessary to produce a Rayleigh number as close to the canal as possible given the geometry scale of our apparatus.

$$T_s = 32.2℃(305.37K)$$

$$T_\infty = 37.2℃(280.37K)$$

$$\phi = 0.02$$

$$T_f = 292.87K$$

$$L = 3.05m(10ft)$$

$$W = 0.6096m(2ft)$$

Evaluated at the film temperature:

$$D_{AB} = 2.41 \times 10^{-5}\frac{m^2}{s}$$

$$v = 15.255 \times 10^{-6}\frac{m^2}{s}$$

The characteristic length is calculated from (1). Both the sample area from the Grand Canal and the water tank in the apparatus are 1:5 rectangles for consistency in the evaporation surface geometry.

$$L_c = \frac{1.858m^2}{7.315m} = 0.254m$$

The densities of the dry air and water vapor mixtures were calculated using the same methods as in tables 1 and 2. The mass transfer Rayleigh number for the apparatus is then calculated from (3).

$$Ra_{m,appar} = \left[\frac{9.81\frac{m}{s^2}\left(\left|1.138\frac{kg}{m^3}-1.262\frac{kg}{m^3}\right|\right)(0.254m)^3}{1.262\frac{kg}{m^3}\cdot\left(15.255\times10^{-6}\frac{m^2}{s}\right)^2}\right]\cdot\frac{15.255\times10^{-6}\frac{m^2}{s}}{2.41\times10^{-5}\frac{m^2}{s}} = 4.31 \times 10^7$$

The same Sherwood correlation, (4), is used to calculate a predicted Sherwood number for the apparatus.

$$\overline{Sh} = 0.15(4.31 \times 10^7)^{\frac{1}{3}} = 52.6$$

3.3.3 Convective Mass transfer coefficient, & Rate of Evaporation – Lilliana Hadik-Barkoczy

Now that we have a predicted Sherwood number for both the Grand Canal and the apparatus, we can calculate the respective mass transfer coefficients (5). Consequently, we can use the convective mass transfer coefficients to calculate an expected rate of evaporation over the surfaces of the canal and the apparatus (6).

$$\overline{h}_m = \frac{Sh \cdot D_{AB}}{L_c} \tag{5}$$

$$\dot{m}_v = \overline{h}_m \cdot A_s(\rho_{v,s} - \rho_{v,\infty}) \tag{6}$$

For the canal sample area:

$$\overline{h}_m = \frac{101.986 \cdot 2.41 \times 10^{-5} \frac{m^2}{s}}{1.143m} = 0.00215 \frac{m}{s}$$

$$\dot{m}_v = 0.00215 \frac{m}{s} \cdot 37.626m^2 \left(0.015 \frac{kg}{m^3} - 0.00385 \frac{kg}{m^3}\right)\left(\frac{1000g}{1kg}\right) = 0.902 \frac{g}{s}$$

This is about 0.082 inches of water evaporating from the canal sample area surface per day.

For the apparatus water tank:

$$\overline{h}_m = \frac{52.6 \cdot 2.41 \times 10^{-5} \frac{m^2}{s}}{0.254m} = 0.005 \frac{m}{s}$$

$$\dot{m}_v = 0.005 \frac{m}{s} \cdot 1.858m^2 \left(0.0344 \frac{kg}{m^3} - 0.000159 \frac{kg}{m^3}\right)\left(\frac{1000g}{1kg}\right) = 0.318 \frac{g}{s}$$

This is about 0.582 inches per day of water evaporation from the apparatus surface if the scaled conditions were constantly maintained.

3.3.4 Error Propagation – Brendan Steele

Root-Sum-Square

When determining the overall accuracy of the evaporation experiment, the measured uncertainties associated with each sensor and instrument used must be combined. The experiment setup includes a load cell, two thermocouples, two humidity sensors, and two temperature sensors. Because the uncertainties come from independent sources, their combined effect on the overall accuracy can be estimated with the root-sum-square (RSS) method. This provides a statistically valid way to correlate the errors, and for consistency the individual sensors uncertainties will be expressed in percent errors. This allows for the overall accuracy to be reported as a final percent uncertainty, derived from the RSS method.

Load Cell Uncertainty

Stated by the spec sheet provided, the YZC-133 load cell has a nonlinearity accuracy of 0.0005% Full-Scale Output (FSO), 0.0003% Linearity Error, and 0.0003% repeatability. With the FSO being 1000 grams, the accuracy is calculated below.

To calculate it:

$$\sqrt{0.0005^2 + 0.0003^2 + 0.0003^2} = 0.000656\ \%$$

$$0.00000656\ x\ 1000\ grams = \pm 0.00656\ grams$$

Then to remove the units for a final percent, the accuracy will be divided by the expected average range of data the sensor will collect. In this case the expected evaporation will be around 0.1 grams per experiment.

Final percent from Load Cell:

$$\sigma_{Lc} \frac{0.00656\ grams}{0.01\ grams} = 0.0656\ x\ 100 = \pm 65.6\%$$

Thermocouple Uncertainty

Stated by the spec sheet provided, the Ds18b20 thermocouples have a stated accuracy of ±0.5°C. That stated final percent can be found with average temperature being 33°C

Final percent per Thermocouple:

$$\frac{0.5°C}{33°C} = 0.0151\ x\ 100 = \pm 1.52\%$$

Then accounting for the two thermocouples:

$$\sigma_{tc} = \sqrt{1.52^2 + 1.52^2} = \pm 2.15\%$$

Humidity Sensor Uncertainty

Stated by the spec sheet provided, the Sht31d humidity sensors have a stated accuracy of ±2%.

That stated final percent can be found with average relative humidity around 50%

Final percent per Humidity Sensor:

$$\frac{2\%}{50\%} = 0.04\ x\ 100 = \pm 4\%$$

Then accounting for the two sensors:

$$\sigma_{hs} = \sqrt{4^2 + 4^2} = \pm 5.66\%$$

Temperature Sensor Uncertainty

Stated by the spec sheet provided, the Sht31d temperature sensors have a stated accuracy of ±0.3°C. That stated final percent can be found with average relative humidity around 33°C.

Final percent per temperature Sensor:

$$\frac{0.3°C}{33°C} = 0.009\ x\ 100 = \pm 0.91\%$$

Then accounting for the two sensors:

$$\sigma_{ts} = \sqrt{0.91^2 + 0.91^2} = \pm 1.29\%$$

Final h_m Uncertainty

From the calculated uncertainties above, the final heat transfer coefficient uncertainty can be found. With this uncertainty, all results can now be quantified with a percent of accuracy. With the error propagation being on equation 6.

$$\bar{h}_m = \frac{\dot{m}}{A_s[\rho_{v,s} - \rho_{v,\infty}]}$$

The given data can be found in the tables from section 3.3.1 and is provided with units.

$$\dot{m}_v = 0.318\frac{g}{s} = 0.000318\ kg/s$$

Where $u_{\dot{m}_v} = 0.00000656\frac{kg}{s}$

For A_s L = 10 ft = 3.048 m & W = 2 ft = 0.6096 m

Where $u_L = u_W = \frac{1}{16}\ in = 0.0015875\ m$

For the vapor partial pressures $P_{v,z} = 2.02205\ kPa,\ P_{v,\infty} = 0.5228\ kPa$

Where $u_{P_v} = 0.001\ kPa$ for each

For the temperatures $T_s = 17.9\ °C = 291.05\ K, T_\infty = 21.5°C = 294.65\ K$
Where $u_{T_s} = u_{T_\infty} = 0.5\ K$

1. Area and its uncertainty can be found as:

$$A_s = LW = 3.048\ x\ 0.6096 = 1.85806\ m^2$$

Propagating $u_A = \sqrt{(0.6096 \cdot 0.0015875)^2 + (3.048 \cdot 0.0015875)^2} = 4.94\ x\ 10^{-3}\ m^2$

With the relative area uncertainty being

$$\frac{u_A}{A_s} = \frac{4.94\ x\ 10^{-3}}{1.85806} = 0.00266\ (0.266\%)$$

2. Vapor Densities & their Uncertainties

Using ideal gas for the vapor:

$$\rho_v = \frac{P_v}{R_v T}$$

For the surface vapor

$$\rho_{v,s} = \frac{2.02205}{0.4615 \times 291.05} = 0.015055\ kg/m^3$$

Then the partials for uncertainty

$$\frac{\partial \rho}{\partial P_v} = \frac{1}{R_v T} = \frac{1}{0.4615 \cdot 291.05} = 0.007446 \frac{kg}{m^3 \cdot kPa}$$

$$\frac{\partial \rho}{\partial T} = -\frac{P_v}{R_v T^2} = -\frac{\rho}{T} = \frac{0.015055}{291.05} = -5.17\ x\ 10^{-5} \frac{kg}{m^3 \cdot K}$$

Then

$$u_{\rho_{v,s}} = \sqrt{(0.007446 \cdot 0.001)^2 + (5.17\ x\ 10^{-5} \cdot 0.5)^2} = 2.69\ x\ 10^{-5}\ \frac{kg}{m}$$

Ambient Vapor

$$\rho_{v,\infty} = \frac{0.5228}{0.4615\ x\ 294.65} = 0.003846 \frac{kg}{m^3}$$

Then the partials for uncertainty

$$\frac{\partial \rho}{\partial P_v} = \frac{1}{R_v T} = \frac{1}{0.4615 \cdot 294.65} = 0.007354 \frac{kg}{m^3 \cdot kPa}$$

$$\frac{\partial \rho}{\partial T} = -\frac{P_v}{R_v T^2} = -\frac{\rho}{T} = \frac{0.003846}{294.65} = -1.31\ x\ 10^{-5} \frac{kg}{m^3 \cdot K}$$

Then the uncertainty is

$$u_{\rho_{v,\infty}} = \sqrt{(0.007354 \cdot 0.001)^2 + (1.31\ x\ 10^{-5} \cdot 0.5)^2} = 9.83\ x\ 10^{-6}\ \frac{kg}{m}$$

The density difference and its uncertainty:

$$\Delta\rho_v = \rho_{v,s} - \ \rho_{v,\infty} = 0.015055 - 0.003846 = 0.011209\ \frac{kg}{m^3}$$

$$u\Delta_{\rho_v} = \sqrt{u_{\rho_v}^2 + u_{\rho_v}^2} = \sqrt{(2.69\ x\ 10^{-5})^2 + (9.83\ x\ 10^{-5})^2} = 2.87\ x\ 10^{-5} \frac{kg}{m^3}$$

With the relative uncertainty

$$\frac{u\Delta_{\rho_v}}{\Delta_{\rho_v}} = \frac{2.87\ x\ 10^{-5}}{0.011209} = 0.00256\ (0.256\%)$$

Computed $\bar{h}_m$ and its propagated uncertainty

$$\bar{h}_m = \frac{\dot{m}}{A_s \Delta_{\rho_v}} = \frac{0.000318}{1.8508\ x\ 0.011209} = \ 0.005 \frac{m}{s}$$

$$\frac{u_h}{h} = \sqrt{0.00727^2 + 0.00266^2 + 0.00256^2} = 0.00815$$

$$u_h = 0.00815\ x\ 0.005 = \ 4.075\ x\ 10^{-4} \frac{m}{s}$$

So for a 95% confidence interval

$$t_{95} = 1.96\ u_h = \pm 7.9\ x\ 10^{-4}\ \frac{m}{s}$$

Where

$$\bar{h}_m = 0.005\frac{m}{s} \pm 0.0007987\frac{m}{s}\ (= \ \pm 15.97\%)$$

4 Design Concepts

4.1 Functional Decomposition

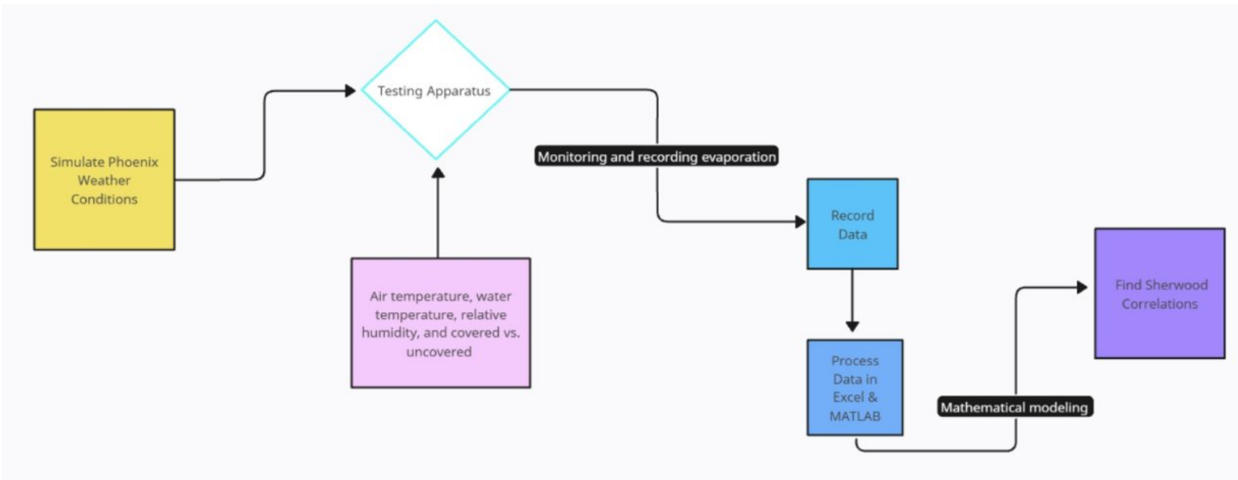


Figure 2: Flow Chart

Figure 2 illustrates our team's functional model, which is essential for understanding and organizing the key processes our project must accomplish. The model breaks down the critical steps needed to measure and analyze evaporation rates in canals under different conditions. Each function in the diagram represents an essential operation needed to collect accurate data and perform meaningful analysis.

The process begins by simulating Phoenix weather conditions, which involves selecting representative combinations of air temperature, water temperature, and relative humidity. These environmental inputs are then applied to our testing apparatus, where controlled experiments are run under both covered and uncovered conditions. The apparatus continuously monitors and records evaporation, capturing the key variables that govern natural convection and mass transfer.

All measurements are recorded and stored, forming the dataset used for further analysis. The collected data is then processed in Excel and MATLAB, where we perform calculations such as mass loss, air temperature, water temperature, and relative humidity. These processed results feed into our mathematical modeling workflow. Which evaluates how well each experimental condition aligns with known natural convection behavior.

Finally, the processed data and model outputs are used to determine Sherwood correlations, allowing us to quantify the mass transfer coefficient under different environmental and cover configurations. This final step provides the analytical link between our physical testing and the scaled evaporation mechanisms that SRP is interested in.

4.2 Concept Generation Spring 2025 (Forced Convection)

At the beginning of the project in Spring 2025, our team started by framing the problem around a forced-convection setup. We expected that by creating controlled airflow across the water surface, we could better manage the boundary conditions and measure evaporation in a repeatable way. With that goal in mind, our early concept generation focused on four main components: how large the apparatus needed to be, how we would measure temperature, how we would measure humidity, and how we would capture wind speed at several locations along the canal. All of these factors were essential for defining the thermal and velocity boundary layers needed to calculate the convective heat-transfer coefficient for forced convection, so we spent considerable time evaluating how each part would integrate into the overall system.

To explore these ideas, we looked at a wide range of possible scales—from smaller setups that would be easier to move and prototype to larger, greenhouse-style builds that could more realistically represent canal geometry. At the same time, we researched and compared different sensing options such as thermistors, digital temperature probes, ultrasonic and vane anemometers, and various humidity sensors. Each configuration had different strengths in terms of accuracy, durability, and data-collection capability, which helped us generate several potential system layouts. During this stage, wind-speed measurement was one of our main design drivers, since maintaining a reliable forced-convection flow was central to our initial approach. As we refined these concepts and learned more about how each subsystem behaved, we began to recognize practical and scientific limitations that ultimately pushed us to reconsider forced convection as our primary method moving forward.

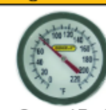
Concept	Option 1	Option 2	Option 3	Option 4
Humidity	Hydrometer	Hygrometer*	Gravimetric Humidity Sensor	Psychrometer
Scientific methods of recording the humidity within the test apparatus at multiple locations.	Cole-Parmer	 Fine Tools	 Livington Janice JABE	 Fine Art America
Temperature	Thermocouple*	Electric Thermometer	Analog Thermometer	
Methods of recording the temperature at multiple locations such as in the water above the water and the general apparatus.	 RAM-Sensors	 SP-Bell Art	 General Tools	
Wind	Digital Anemometer*	Robinson Anemometer		
Scientific methods of recording the wind speed directly over the surface of the water reservior.	 WinTact	 METEO OMINIUM		

Figure 3: Morphological Matrix

From Figure # Starting with humidity from left to right then temperature and finally wind speed the pros and cons will be listed below in bullet points.

Humidity:

- Hydrometer – A scientific tool to collect the density of water in the air
- Pros:
  - Inexpensive
  - Portable
  - No power needed
- Cons:
  - Limited precision
  - Affected by heat
  - Manual reading
- Hygrometer – A scientific tool to collect the relative humidity of environment
- Pros:
  - Accuracy

        - Portable
        - Minimal set up once calibrated
    - Cons:
        - Some maintenance required
        - Cost
- Gravimetric Sensor – A scientific tool to collect humidity in a computational setting
    - Pros:
        - High Accuracy
        - Direct measurement
    - Cons:
        - Bulky
        - Extremely expensive
        - Not real time
        - Intensive Maintenance required
- Psychrometer – A scientific tool to measure dry bulb temperature and wet bulb temperature
    - Pros:
        - Accuracy for Wet and dry bulb temperatures
        - Inexpensive
    - Cons:
        - Requires hand math for humidity levels
        - Not digital

Temperature:

- Thermocouple – A scientific tool to collect the exact temperature at precise locations

- Pros:
  - Wide temperature ranger
  - Durable
  - Fast response time
  - Exact temperature at specific location
- Cons:
  - Requires calibration
  - Non-linear output
  - Sensitive to noise

- Electric thermostat – A scientific tool to collect the ambient temperature
- Pros:
  - Provides digital reading of temperature
- Cons:
  - Only collects ambient without probe
  - Rudimentary

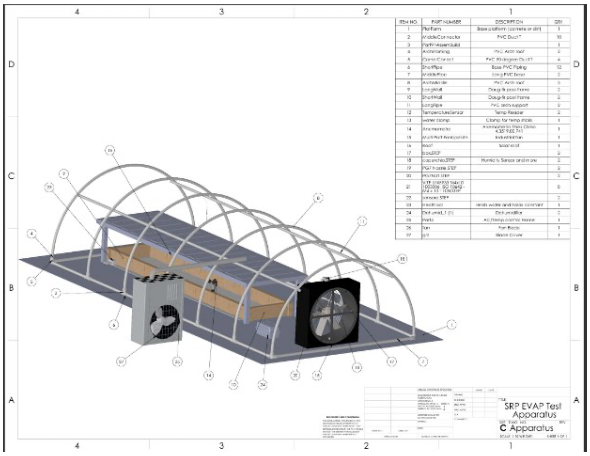
- Analog Thermostat – A scientific tool to collect the ambient temperature
- Pros:
  - No recalibration needed
- Cons:
  - Requires readout
  - Rudimentary
  - Not accurate after time

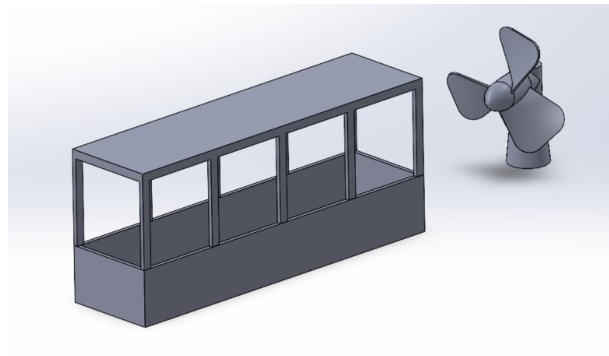
Wind Speed:

- Digital Anemometer– A scientific tool to measure the wind speed
  - Pros:
    - High Accuracy
    - Multifunctional
    - Real time data collection
  - Cons:
    - Fragile electronics
    - Expensive
- Robinson Anemometer – A scientific tool to measure the wind speed
  - Pros:
    - Simple
    - Weather Resistant
    - Low cost
    - Cons:
    - Less precise
    - Limited functionality
    - Slow response time for measurements

Using the above criteria the team came up with three early-stage test apparatus ideas. The first consisting of a climate-controlled tent with ventilation, the second being a handmade apparatus sealed completely with minimal visual on what's going on inside, and the third being a full-scale green house with a larger replica of a canal. Below is Figure 4 showing each concept drawn out.

Design 1 **Design 2**





Design 3

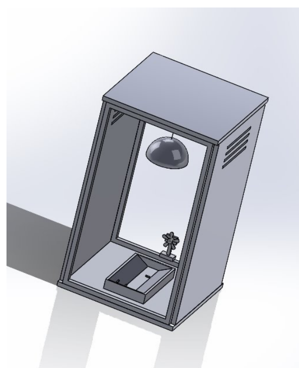


Figure 4: Concept generation Drawings

4.3 Selection Criteria Spring 2025

When we built our selection criteria for Spring 2025, we relied heavily on the engineering and customer requirements outlined in our first QFD. Those priorities pushed us toward designing a system capable of making very accurate measurements of the variables that matter most to evaporation. At the top of the list were evaporation rate precision, the ability to monitor environmental conditions consistently, and overall scientific accuracy. Because these factors were so central to the project, we focused on choosing equipment with accuracies within about ±5% of the true value. Cost wasn't a major constraint during this phase thanks to a budget of $5,750 that gave us enough flexibility within this project. Another important factor was monitorability: whatever sensors we selected needed to provide continuous digital output without requiring us to physically open the apparatus and disturb the controlled environment inside.

As we layered in other practical constraints, such as fitting the apparatus in the Solar Shed or through campus doorways, ensuring the system was movable, and keeping total power use under the standard 1800-watt limit, we gradually formed a set of criteria that initially supported a fairly complex forced-convection setup. This included multiple fans, airflow controllers, wind-speed sensors, and a more robust enclosure. For a while, these requirements aligned well with our early vision for the apparatus. But as we continued refining the design toward the end of the semester, we began to see clear drawbacks with the forced-convection approach. The added airflow complicated the very conditions we were trying to measure, and maintaining a stable forced-convection regime proved more disruptive than helpful. These limitations ultimately made it clear that we needed to reconsider our direction moving into the next semester.

4.4 Concept Selection Spring 2025

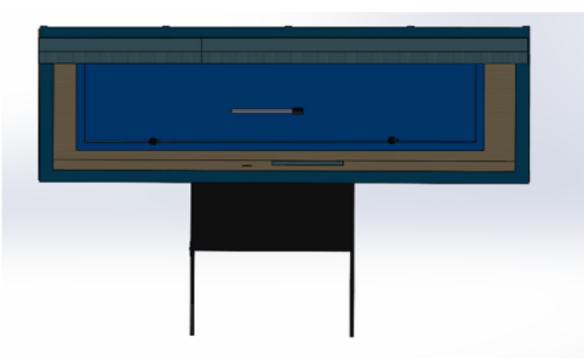
PUGH Chart - SRP Evaporation				
		Concept		
		1	2	3
Criteria	Cost	-	+	-
	Power	+	0	0
	Mobility	+	-	-
	Aparatus Seal	+	-	0
	Size Smaller= better	+	0	-
	Temp Higher=better	+	+	-
	Accesible	-	-	+
	Monitorability	+	-	+
Sum of +		6	2	2
Sum of 0		0	2	2
Sum of -		2	4	4
Total		4	-2	-2

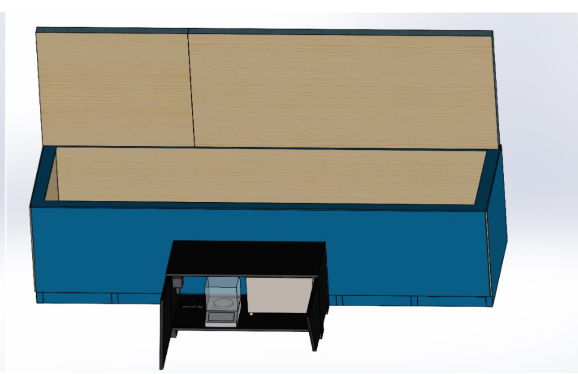
Figure 5: Pugh Chart

This Pugh chart was created to highlight the most important functions that are required solely for the apparatus to be most efficient and accessible for monitorability and control of our designated variables. Cost was determined by the prices of the exterior walls surrounding the controlled canal. Power was based off how much estimated wattage would be required to run all equipment to have all apparatus systems functioning. Mobility was designated to if the team could easily move the apparatus for presentation. Size being similar to mobility, as the space provided for our research is limited to the solar shed southwest of the engineering building. Temperature was rated off how well insulated the apparatus could be to fully control the interior climate. Finally for Accessibility and monitorability, these were described as how well the team could change the elements inside if needed, and how quickly we could gather all data collected by our sensors.

4.5 Concept Selection Fall 2025 (Natural Convection)

As the project transitioned from Spring (forced convection focus) to Fall (natural convection focus), the design approach shifted toward achieving controllable buoyancy driven flow rather than mechanically induced airflow. Early concepts involving fans and wind tunnels were removed to avoid disturbing the boundary layer that drives evaporation. Instead, the team redesigned the apparatus to emphasize insulation, passive temperature control, humidity regulation, and canal like geometry to replicate Rayleigh scaling. This led to the selection of a sealed wooden frame with integrated heating/cooling, dehumidification, and a sensor network that could operate for multiple hours without external disturbances. The Fall concept prioritizes scientific accuracy, stability, and simplicity over complexity or portability.





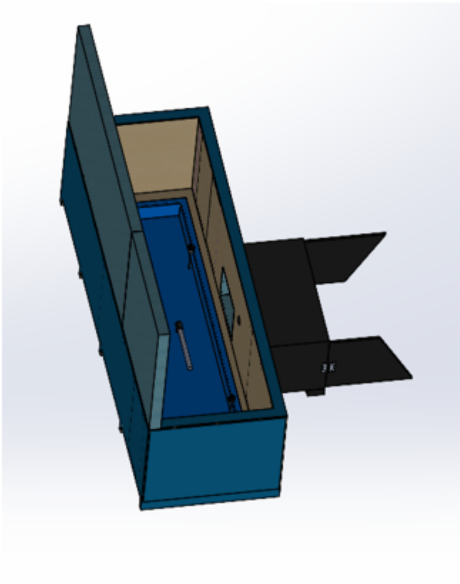


Figure 6: Final CAD

4.5.1 Wooden Frame

The wooden frame provides a rigid structure capable of supporting insulation, the vinyl pool liner, and the hinged lid without deformation during multi-hour tests. Its construction emphasizes airtightness, minimizing unintended airflow that could shift the convection regime. Corner braces and spray-foam sealing strengthen the enclosure, while wheels allow limited mobility without compromising structural integrity.

Figure 7: Wooden Frame of Apparatus

4.5.2 Water Heater

A 1500 W immersion heater maintains the water surface temperature necessary to drive buoyancy forces and achieve the target Rayleigh number. Its high-power output enables fast warm-up while thermostat control prevents overheating. The heater is mounted in a region to avoid disrupting flow patterns on the water surface.

Figure 8: Hot Tube Heater used for Water Tank

4.5.3 Dehumidifier

The compact dehumidifier provides rapid humidity reduction needed to set initial boundary conditions prior to testing. It operates at the lowest fan setting to avoid introducing unwanted forced convection. Once RH reaches the target value, the dehumidifier is turned off and the system transitions to passive control using silica desiccant packs.

Figure 9: Dehumidifier

4.5.4 Arduino Circuit & Sensors

The Arduino acts as the main controller of our entire measurement system, tying together all the sensors that make the evaporation apparatus actually function. Its job is to power and read each device, keep everything synchronized, and record clean data throughout every test. Through the Arduino we run our SHT31-D air temperature and humidity sensors, the DS18B20 water temperature probes, the SD card module, a Real-Time-Clock module, and the HX711-based load cell that tracks mass loss in the graduated cylinder. By constantly collecting these signals, timestamping them, and saving them to the SD card, the Arduino turns the physical setup into a fully automated data-logging tool. This subsystem is essential because it allows us to capture the full picture of the environment inside the chamber and measure evaporation without needing to manually intervene, making the entire experiment consistent, repeatable, and easy to analyze.

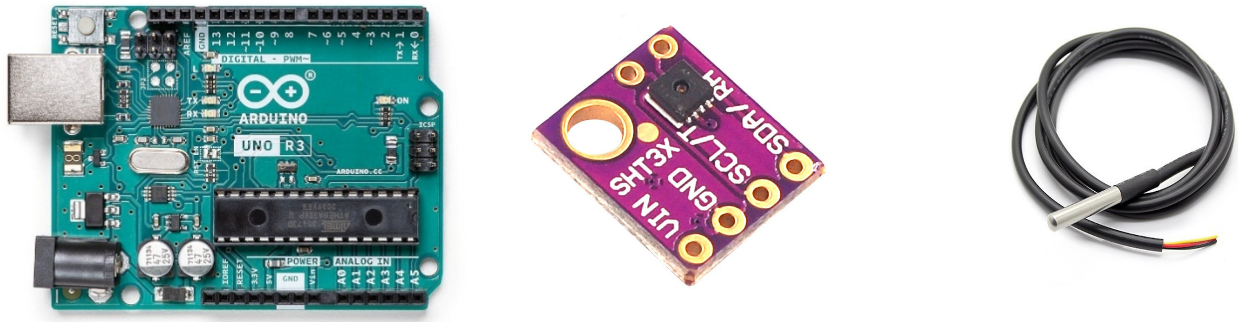


Figure10: Arduino Uno R3, SHT31D, & DS18B20

4.5.5 Siphon

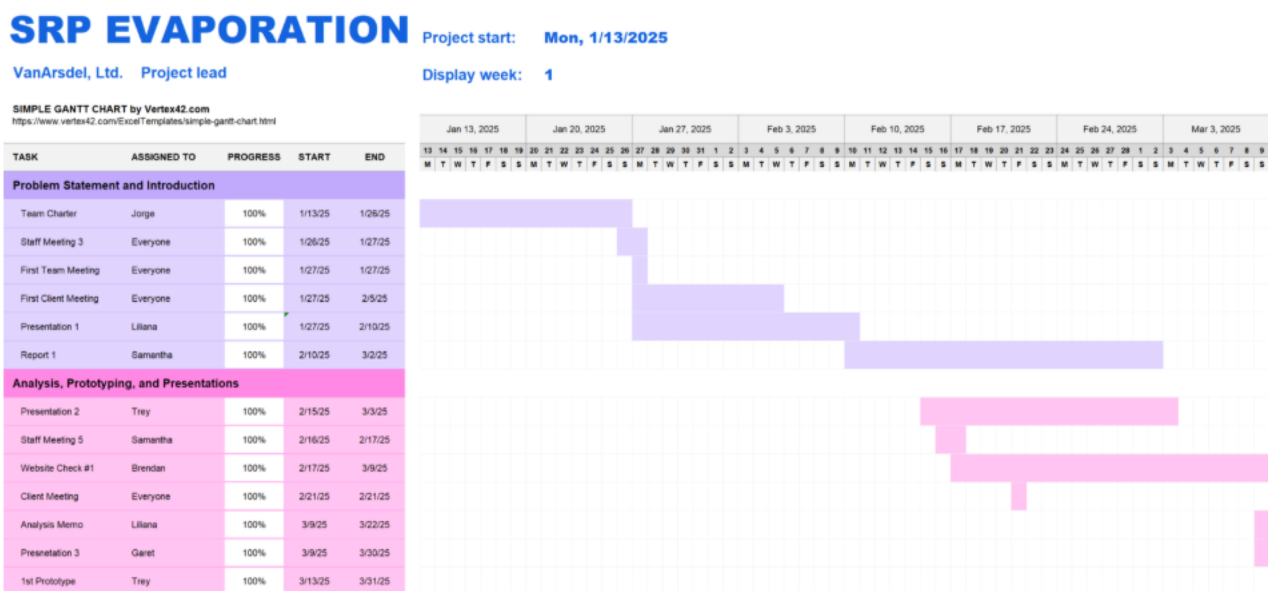
The siphon system transfers water from the tank into an external graduated cylinder placed on a load cell. This enables continuous measurement of mass loss without disturbing the internal environment. As well as having a sperate tube inside the water to reduce oscillating water levels.

Figure 11: Picture of Siphon

5 Schedule and Budget

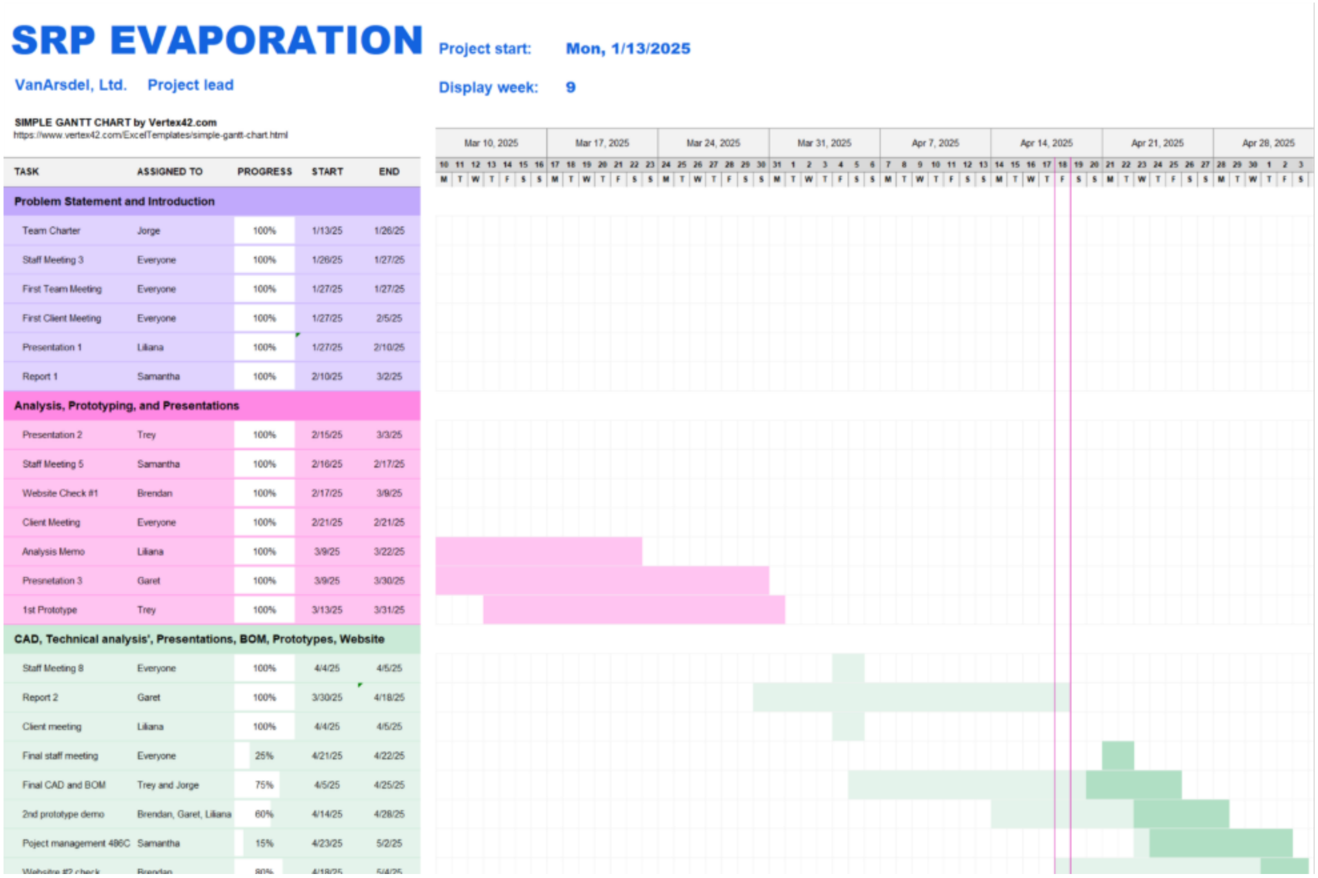
5.1 Schedule

The Gantt charts shown below highlights the teams assignments, presentations, and other deliverables done for each semester. The chart shows the date that the assignments were started as well as the dates that the assignments were completed and submitted. Each semester was broken down into 2 parts, leading to a total of 4 Gantt charts as seen below:



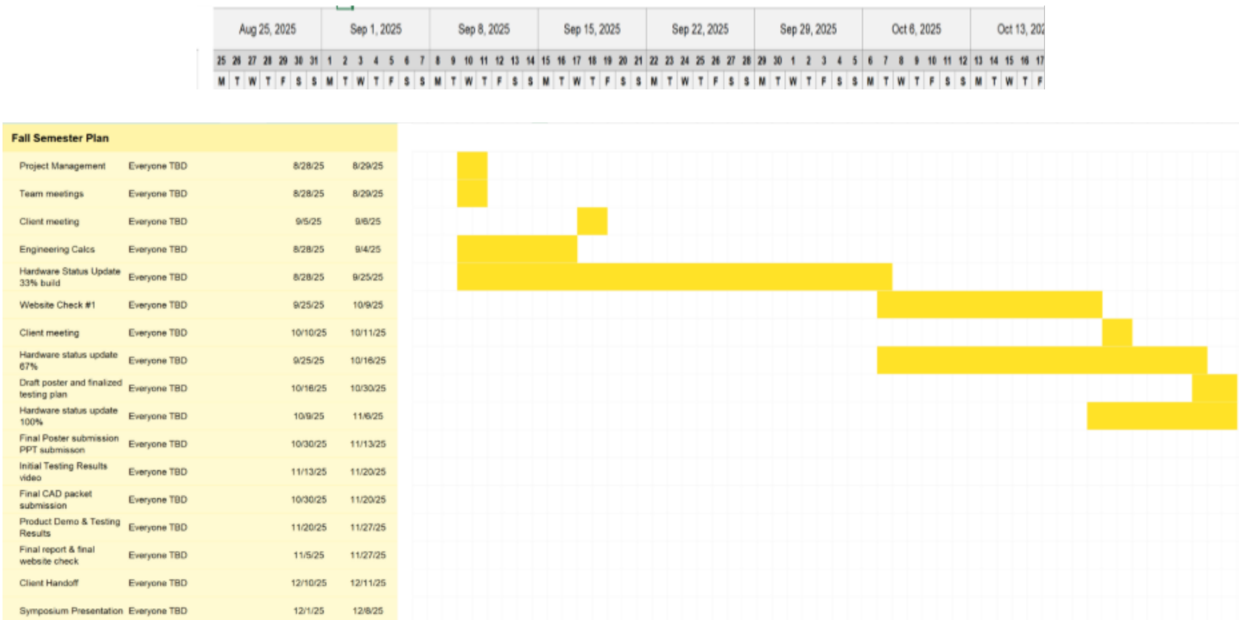
TASK	ASSIGNED TO	PROGRESS	START	END
Problem Statement and Introduction				
Team Charter	Jorge	100%	1/13/25	1/26/25
Staff Meeting 3	Everyone	100%	1/26/25	1/27/25
First Team Meeting	Everyone	100%	1/27/25	1/27/25
First Client Meeting	Everyone	100%	1/27/25	2/5/25
Presentation 1	Liliana	100%	1/27/25	2/10/25
Report 1	Samantha	100%	2/10/25	3/2/25
Analysis, Prototyping, and Presentations				
Presentation 2	Trey	100%	2/15/25	3/3/25
Staff Meeting 5	Samantha	100%	2/16/25	2/17/25
Website Check #1	Brendan	100%	2/17/25	3/9/25
Client Meeting	Everyone	100%	2/21/25	2/21/25
Analysis Memo	Liliana	100%	3/9/25	3/22/25
Presnetation 3	Garet	100%	3/9/25	3/30/25
1st Prototype	Trey	100%	3/13/25	3/31/25

Figure 12: Spring Semester Gantt Chart (1/13/2025 – 3/9/2025)



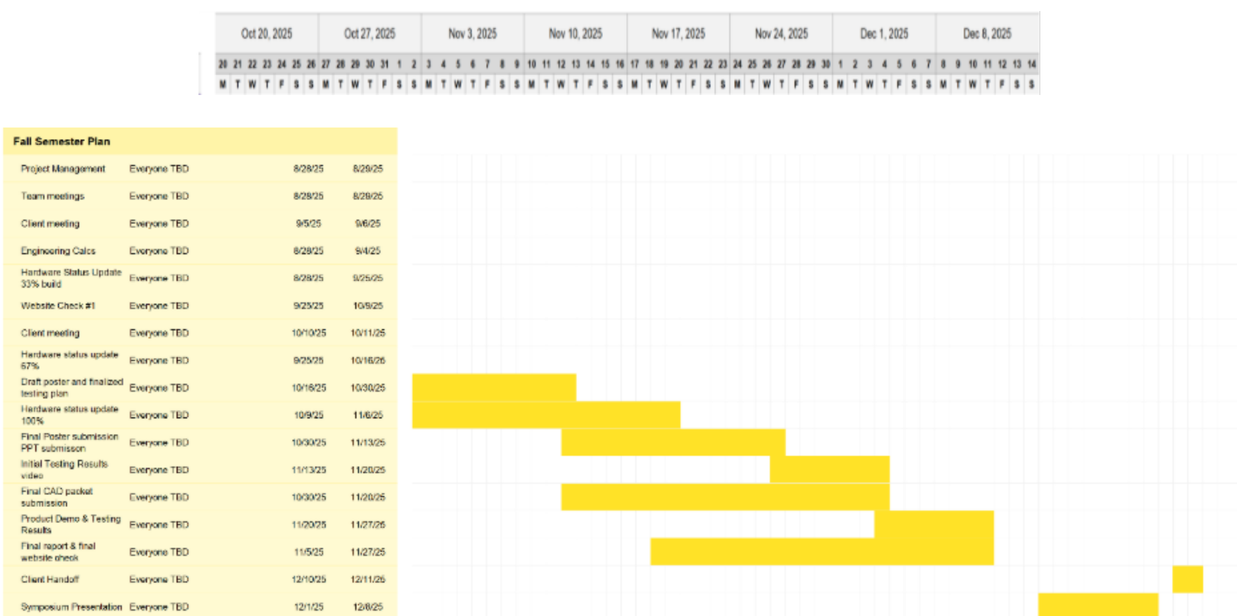
TASK	ASSIGNED TO	PROGRESS	START	END
Problem Statement and Introduction				
Team Charter	Jorge	100%	1/13/25	1/26/25
Staff Meeting 3	Everyone	100%	1/26/25	1/27/25
First Team Meeting	Everyone	100%	1/27/25	1/27/25
First Client Meeting	Everyone	100%	1/27/25	2/5/25
Presentation 1	Liliana	100%	1/27/25	2/10/25
Report 1	Samantha	100%	2/10/25	3/2/25
Analysis, Prototyping, and Presentations				
Presentation 2	Trey	100%	2/15/25	3/3/25
Staff Meeting 5	Samantha	100%	2/16/25	2/17/25
Website Check #1	Brendan	100%	2/17/25	3/9/25
Client Meeting	Everyone	100%	2/21/25	2/21/25
Analysis Memo	Liliana	100%	3/9/25	3/22/25
Presnetation 3	Garet	100%	3/9/25	3/30/25
1st Prototype	Trey	100%	3/13/25	3/31/25
CAD, Technical analysis', Presentations, BOM, Prototypes, Website				
Staff Meeting 8	Everyone	100%	4/4/25	4/5/25
Report 2	Garet	100%	3/30/25	4/18/25
Client meeting	Liliana	100%	4/4/25	4/5/25
Final staff meeting	Everyone	25%	4/21/25	4/22/25
Final CAD and BOM	Trey and Jorge	75%	4/5/25	4/25/25
2nd prototype demo	Brendan, Garet, Liliana	60%	4/14/25	4/28/25
Poject management 486C	Samantha	15%	4/23/25	5/2/25
Websitre #2 check	Brendan	80%	4/18/25	5/4/25

Figure 13: Spring Semester Gantt Chart (3/10/2025 – 5/4/2025)



Fall Semester Plan			
Project Management	Everyone TBD	8/28/25	8/29/25
Team meetings	Everyone TBD	8/28/25	8/29/25
Client meeting	Everyone TBD	9/5/25	9/6/25
Engineering Calcs	Everyone TBD	8/28/25	9/4/25
Hardware Status Update 33% build	Everyone TBD	8/28/25	9/25/25
Website Check #1	Everyone TBD	9/25/25	10/9/25
Client meeting	Everyone TBD	10/10/25	10/11/25
Hardware status update 67%	Everyone TBD	9/25/25	10/16/25
Draft poster and finalized testing plan	Everyone TBD	10/16/25	10/30/25
Hardware status update 100%	Everyone TBD	10/9/25	11/6/25
Final Poster submission PPT submission	Everyone TBD	10/30/25	11/13/25
Initial Testing Results video	Everyone TBD	11/13/25	11/20/25
Final CAD packet submission	Everyone TBD	10/30/25	11/20/25
Product Demo & Testing Results	Everyone TBD	11/20/25	11/27/25
Final report & final website check	Everyone TBD	11/5/25	11/27/25
Client Handoff	Everyone TBD	12/10/25	12/11/25
Symposium Presentation	Everyone TBD	12/1/25	12/8/25

Figure 14: Fall Semester Gantt Chart (8/25/2025 – 10/19/2025)



Fall Semester Plan			
Project Management	Everyone TBD	8/28/25	8/29/25
Team meetings	Everyone TBD	8/28/25	8/29/25
Client meeting	Everyone TBD	9/5/25	9/6/25
Engineering Calcs	Everyone TBD	8/28/25	9/4/25
Hardware Status Update 33% build	Everyone TBD	8/28/25	9/25/25
Website Check #1	Everyone TBD	9/25/25	10/9/25
Client meeting	Everyone TBD	10/10/25	10/11/25
Hardware status update 67%	Everyone TBD	9/25/25	10/16/25
Draft poster and finalized testing plan	Everyone TBD	10/16/25	10/30/25
Hardware status update 100%	Everyone TBD	10/9/25	11/6/25
Final Poster submission PPT submission	Everyone TBD	10/30/25	11/13/25
Initial Testing Results video	Everyone TBD	11/13/25	11/20/25
Final CAD packet submission	Everyone TBD	10/30/25	11/20/25
Product Demo & Testing Results	Everyone TBD	11/20/25	11/27/25
Final report & final website check	Everyone TBD	11/5/25	11/27/25
Client Handoff	Everyone TBD	12/10/25	12/11/25
Symposium Presentation	Everyone TBD	12/1/25	12/8/25

Figure 15: Fall Semester Gantt Chart (10/19/2025 – 12/14/2025)

- Team Charter – Establishes our shared goals, expectations, and responsibilities so the team starts aligned.

- Presentation 1 – Communicates our initial findings and proposed direction to get feedback and build momentum.
- Report 1 – Documents early project progress, key decisions, and technical background.
- Presentation 2 – Shares updates on progress, pivots, and next steps in a clear, visual format.
- Website Check #1 – First review of our project website to ensure it accurately reflects our progress and design.
- Analysis Memo – Summarizes our technical evaluations or simulations and justifies design decisions.
- Presentation 3 – A refined overview of our design and prototype work, preparing for client and faculty input.
- 1st Prototype – The first physical build of our system, used to test design assumptions and gather feedback.
- Report 2 – A second comprehensive document updating all technical progress and outcomes since the first report.
- Final CAD and BOM – Complete 3D models and the bill of materials needed for final production or evaluation.
- 2nd Prototype Demo – Demonstration of the improved version of our system, highlighting changes and results.
- Project Management 486C – Administrative and planning documentation to meet course-specific requirements.
- Website #2 Check – Final review of our website to ensure it's complete and professional for public or sponsor viewing.
- Project Management – Ongoing coordination of tasks, deadlines, documentation, and team communication.
- Engineering Calcs – Detailed calculations validating the design's performance, efficiency, or safety.
- Hardware Status Update 33% Build – Shows that we've completed one-third of our physical

system build.

- Hardware Status Update 67% – Indicates that we're over halfway finished with hardware and ready to begin integration.
- Draft Poster and Finalized Testing Plan – Creates a visual summary of our project and outlines how we'll validate its performance.
- Hardware Status Update 100% – Marks that the system build is complete and ready for full testing or handoff.
- Final Poster Submission & PPT – Submits our final visual presentation materials for the symposium or project showcase.
- Initial Testing Results Video – Documents how our prototype performs and helps communicate it to stakeholders.
- Final CAD Packet Submission – A full technical package of our design including drawings and references for future use.
- Product Demo & Testing Results – Showcases how well the system works and explains any limitations or discoveries.
- Final Report & Final Website Check – Wraps up the entire project into one polished document and verifies the website's final state.
- Client Handoff – Transfers all relevant materials and documentation to the client or sponsor, ensuring they can continue independently.
- Symposium Presentation – Publicly presents the project in a final showcase to peers, faculty, and possibly industry professionals.

5.2 Budget

The initial team budget given to the team by SRP and by NAU was $5000, with the requirement that 10% of the total budget is fundraised on top of the given budget. To meet this requirement, the team decided that opening a GoFundMe which reached the goal of $765 meeting the required 10% mark. GoFundMe takes a small fee of $25, putting the total budget at $5740. Due to the heavy research conditions of this project, as well as the guidance from the team's client, there was not much spent the first semester. The only physical prototyping done in the first semester was a simple shading test to test the evaporation of two water tanks with one of the tanks covered by solar panels and one left in open conditions. This simple experiment cost the team less than $50 to conduct. As the team entered the second semester, it was time to start using the budget to construct the apparatus. The apparatus cost the team around $3500 to construct and to buy the necessary sensors and equipment to run the test. The remaining $1500 was used to transport the team and the apparatus down to Pheonix to run tests at the ASU solar lab. Additionally, the team spent around $200 on the fund raiser for gas.

5.3 Bill of Materials (BoM)

The following table shows the team's full bill of materials including the vendor and quantity of each item. Both the unit price and the total price is listed as well as the order status. The following bill of materials shows each part used to construct the apparatus, as well as any expenses spent on the trip to Phoenix. The table shows where every portion of the budget was spent.

Table 3: BOM

Part	Vendor	Quantity	Unit Price ($)	Total Price ($)	Order Status
Plywood	Home Depot	15	14.98	224.7	Arrived
Wood Beams	Home Depot	35	2.98	104.3	Arrived
#8 2in Flat head Philips exterior screws (5lb pk of 6720)	Home Depot	1	33.39	33.39	Arrived
2" Corner Brace Zinc 20pk	Home Depot	5	14.97	74.85	Arrived
#6 3/4in Flat Head Philips metal to wood screws (50 pk)	Home Depot	4	5.98	23.92	Arrived
Waterproof floor putty	Home Depot	1	6.97	6.97	Arrived
5" x 5" Zinc T-Plate	Home Depot	12	2.86	34.32	Arrived
Insulation	Home Depot	2	20.67	41.34	Arrived
Reptile Humidity & Thermometer	Pet Smart	2	6.99	13.98	Arrived

Digital Water Thermometer	Pet Smart	2	11.99	23.98	Arrived
Plastic Water Container	Target	3	4	12	Arrived
Hot Glue Sticks	Micheals	2	3	6	Arrived
1500W Water Heater	Briidea	1	104.5	104.5	Arrived
LED Detachable Tripod Light	Home Depot	3	24.88	74.64	Arrived
Wall & Cavity Foam	Home Depot	1	199.98	199.98	Arrived
Wide Spray Foam Sealant	Home Depot	4	39.98	159.92	Arrived
Arduino	Amazon	1	0	0	Arrived
Vinyl Pool liner	Home Depot	1	104.97	104.97	Arrived
Hinges	Home Depot	3	10.47	31.41	Arrived
Silicone Caulk	Home Depot	5	6.89	34.45	Arrived
Caulk Gun	Home Depot	1	11.98	11.98	Arrived
Construction Mask	Home Depot	6	2	12	Arrived
4mm Rubber Gloves (200 count)	Uline	2	13	26	Arrived
GFCI Outlet box	Home Depot	3	10.48	31.44	Arrived
Desiccant	Uline	1	215	215	Arrived
Gap Sealant	Home Depot	1	173.92	173.92	Arrived
Scientific Balance	US Solid	1	157	157	Arrived
Rubber Siphon Tube	Home Depot	1	0	0	Arrived
GFCI Outlet	Home Depot	3	15.51	46.53	Arrived
Insulation Spray Foam Adhesive Guru	Home Depot	1	169.99	169.99	Arrived
Arduino Sensors	Amazon	6	10.93	46.53	Arrived
Electrical Box for Arduino	Amazon	1	12.99	12.99	Arrived
Flat Brackets	Home Depot	10	4.72	46.53	Arrived
Rubber Fridge Liner	Amazon	1	19.99	19.99	Arrived
Heavy Duty Tarp	Home Depot	1	77.97	77.97	Arrived
Weatherproof Coating	Home Depot	1	22.5	22.5	Arrived
Paint Brush	Home Depot	3	1.87	5.61	Arrived

Paint Holder	Home Depot	2	0.98	1.96	Arrived
Dehumidifier	Airecoler	1	393	393	Arrived
Arduino Loading Cells	Amazon	4	15.99	15.99	Arrived
Weatherproof Paint	Shermin Williams	2	0	79.06	Arrived
PVC Glue	Home Depot	1	5.85	5.85	Arrived
PVC Male Adapter	Home Depot	1	2.7	2.7	Arrived
PVC Bushing	Home Depot	1	4.17	4.17	Arrived
PVC Spigot	Home Depot	1	10.65	10.65	Arrived
PVC Sealant Tape	Home Depot	1	0.98	0.98	Arrived
Syphon Pump	Home Depot	1	17.5	17.5	Arrived
10T Bucket	Home Depot	1	2.5	2.5	Arrived
Grommets	Harbor Freight	1	4.99	4.99	Arrived
Rubber Tires	Harbor Freight	6	21.95	131.7	Arrived
Tire Stop	Harbor Freight	1	5.5	5.5	Arrived
Door Wedge	Harbor Freight	1	6	6	Arrived
Vinyl Tube	Home Depot	1	16	16	Arrived
Clamp	Home Depot	1	2	2	Arrived
Syphon Tube (Skinny)	Home Depot	1	10.93	10.93	Arrived
Door Hinges(small)	Home Depot	3	3.64	14.56	Arrived
Grove Pliers	Home Depot	1	23.97	23.97	Arrived
Mixing Buckets	Home Depot	2	5.15	10.3	Arrived
Hotel	NAU	3	246.98	740.94	Arrived
Transport	NAU	1	950	950	Arrived

Gas	SRP EVAP Group	2	300	300	Arrived
			Total Spent ($):	5,245.88	

6 Design Validation and Initial Prototyping

6.1 Failure Modes and Effects Analysis (FMEA)

Product Name: EvapBox 1.0		Development Team: SRP-EVAP25				Page No 1 of 1			
System Name: Evaporation Apparatus SRP						FMEA Number: 1			
Subsystem Name: EVP						Date: 12/05/2025			
Component Name	: Scale Canal								
Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurence (O)	Current Design Controls Test	Detection (D)	RPN	Recommended Action
1.Scaled Roof Covering of Canal Vessel	Error in Scalability or ratio	Distorts radiation input; affects evaporation simulation	7	Incorrect geometric scaling or not matching thermal properties	5	Visual Inspection; energy input simulation	4	140	Use IR lamps or heaters to replicate solar; perform thermal matching test, heat flux sensor
2. Scaled Canal Vessel	Error in Scalability or ratio	Misrepresentation of measurements	5	Incorrect fluid depth, surface area ratio, or boundary conditions	5	Dimensional verification through are calculations	3	75	Apply scaling analysis (Re, Sh, Sc) to ensure dynamic similarity, CFD simulation
4. Vented Wall (Sealed Container)	Improper Sealing or leaking	Alters pressure and humidity balance; hinders boundary layer	8	Clogged vents or improper sealing method	6	Leak test; humidity stability test	5	240	Hydrophobic filters, check valves, multi-layer seals, RT humidity sensor
5. Standard Wall (Sealed Container)	Air Leakage or wall condensation	Alters internal properties; skews evaporation rate	7	Seal failure or thermal gradient across walls	4	Seal integrity test; IR camera for condensation	5	140	Thermal insulation, Transparent materials with low thermal cond.
6. Temperautre Controller	Drift or response lag	Inaccurate water/air temp; invalid evaporation rate	8	Faulty sensor, lag, or calibration error	4	Thermocouple cross-check	6	192	Digital feedback, software-based calibration checks
7. Humidity Controller	Poor regulation or sensor inaccuracy	Relative humidity error; mass flux error	9	Senor degradation; delay in humidity response	4	RH logging and error analysis	5	180	High resolution and fast RH sensor, calibration checks

Figure 16: FMEA

A Failure Modes and Effects Analysis (FMEA) was conducted to evaluate the major risks associated with the apparatus and their potential impacts on evaporation measurements. Several high items were identified, particularly those related to geometric scaling, sealing, and environmental control. Errors in the scaled roof and canal vessel (RPN = 140 and 75) could distort radiation input or misrepresent the water air interface that will lead to inaccurate evaporation behavior. To mitigate this risk, dimensional verification was performed during construction, and similarity analyses using Rayleigh, Sherwood, and Nusselt's numbers were applied to ensure dynamic consistency with canal conditions.

The sealed container and vented wall presented some of the highest overall risk, with improper sealing producing an RPN of 240. Any leakage or condensation within the enclosure could alter humidity balance, disturb boundary layers, or shift the convection regime away from natural convection. The team mitigated these issues by reinforcing all seams with silicone sealant and conducted extended stability tests prior to data collection.

Temperature and humidity controllers also carried elevated RPN values (192 and 180), as drift or sensor inaccuracy would directly affect evaporation driving forces. These risks were reduced by implementing multiple sensors, performing calibration checks before each test, and validating sensor response through cross comparison.

6.2 Initial Prototyping

For the team's initial prototype, it was a very simple water evaporation experiment. The team wanted to know just how much shading a body of water would affect the evaporation. The test was simple; 2 equal containers were filled with water and weighed. First the weight was taken of each of the containers then zeroed out. The containers were then filled with water and weighted; the tanks were then left on the floor in the sun in the solar shack. One tank was left as is, while the other was covered via solar panel a couple inches above the water. Every hour, using the weather app, the wind speed, relative humidity, and temperature were taken and recorded. The results of the experiment show that the shaded tank kept a good portion more than the water left in the sun. This experiment allowed us to confirm the fact that shading reduces evaporation. This allowed the team to then continue to build the final apparatus.

6.3 Other Engineering Calculations

The siphon holds much less water than the evaporation tank, so when the water level in the siphon drops, much less water is leaving the siphon than is leaving the water tank. A correlation between the two surface areas was used to convert the decrease in water level from the siphon (inlet) to the corresponding decrease in water level in the tank (outlet).

$$\dot{m_{outlet}} = \dot{m_{inlet}}\left(\frac{A_{outlet}+A_{inlet}}{A_{inlet}}\right) \tag{7}$$

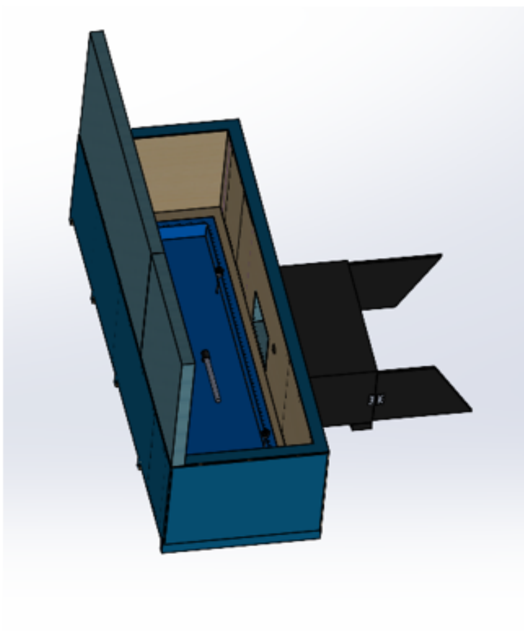
Because the surface areas remain constant, (7) was represented in the MATLAB code as (8).

$$m_{v2} = m_{v1}(2087.96) \tag{8}$$

7 Final Hardware

7.1 Final Physical Design

The following images show the final CAD model as well as the final physical prototype. The apparatus is primarily constructed of 2in x 3in x 96in wooden beams as well as 48in x 96in x .5in plywood sheets. Inside of each wall, the roof, and the base, is a layer of spray insulation to keep the conditions within the box consistent. The tank is made of the same beams and plywood cut to the needed lengths, then covered by a layer of pool liner to keep the water in. In the tank is the water heater. The box connected to the main apparatus contains the loadcell, water heater GUI, dehumidifier, and Arduino. The final component in the apparatus is the desiccant packets.



8 Final Testing

8.1 Top level testing summary table

The following table provides a consolidated overview of all experiments conducted for the project and specific design requirements for each teste addresses. This top level testing summary highlights how our testing sequence was structured to validate the functionality, accuracy, and physical realism of the apparatus before performing trials. Each experiment targets a different aspect of system performance from confirming natural convection to evaluating humidity control, and evaporation measurements in both Flagstaff and Phoenix conditions. By outlining the purpose, this table serves as a roadmap for the project's experimental methodology and how each stage contributes to meeting the customer and engineering requirements.

Table 4: Top Level Testing Summary

Experiment	Relevant DR	Testing Equipment Needed	Other Resources
EXP 1– Flow Visualization	CR5: Natural Convection CR2: Heated Water CR1: Air Temperature Control	Outdoor incense Black backdrop Camera/Tripod Water Heater	Good weather (low wind)
EXP 2- Measurement & Precision of Collected Data with Arduino	ER1: Accurately Collect Data ER2: Sensor Accuracy	Arduino/breadboard Thermocouples Humidity sensors Load cells SD card	Excel access Power source
EXP 3- Relative Humidity	ER3: Closed lid CR1: Air Temperature Control CR2: Heated Water CR3: Accurately Control RH% ER2: Sensors reading	Dehumidifier Desiccant Arduino/breadboard SD card Water Heater	Power source
EXP 4- Siphon Functionality	CR8: Water Tightness ER1: Data Collection ER2: Sensor Accuracy	Graduated cylinder Vinyl tube Camera Tape measurer	N/A

EXP 5- Ambient Open Test (Flagstaff)	CR4: Accurately Measure RH% CR5: Natural Convection CR7: Accurately Measure Water ER1: Data Collection ER5: Scalability of Rayleigh ER7: Scientific principals	Apparatus Arduino/Breadboard/sensors Siphon/Scale SD Card Desiccants	Good weather conditions
EXP 6- Ideal Scaled Conditions (Flagstaff)	CR1: Air Temperature Control CR2&3: Accurately Control H20 Temp and RH% CR4: Accurately Measure RH% and Temp CR5: Natural Convection CR7: Accurately Measure Water Loss ER1: Data Collection ER5: Scalability of Rayleigh ER6: Practicality ER7: Scientific principals	Apparatus Arduino/Breadboard/sensors Siphon/Scale SD Card Water tank heater Desiccants	Air temperature outside 45F Low humidity outside
EXP 7- Ambient Open Test (Phoenix)	CR4: Accurately Measure RH% CR5: Natural Convection CR7: Accurately Measure Water ER1&2: Data Collection ER5: Scalability of Rayleigh ER7: Scientific principals	Apparatus Arduino/Breadboard/sensors Siphon/Scale SD Card Desiccants	Good weather conditions

8.2 Detailed Testing Plan

8.2.1 Test 1: Smoke Flow Visualization (Free Convection Confirmation)

Design Requirements (DRs):

DR-A: Ability to achieve and hold target $\Delta T = T_w - T_a$ and RH setpoints.

DR-B: Operation in intended free convection regime with canal like $Gr \cdot Sc$.

DR-C: Ability to show evaporation rate in mm/day equivalent.

DR-D: Baseline characterization of mass transfer coefficient and comparison to correlations.

Test/Experiment Summary:

The purpose of this test is to determine whether our apparatus successfully achieves a stable natural convection regime characterized by visible plume or cell structures over the water surface. This test supports design requirement B which ensures that the apparatus accurately represents canal like free convection conditions. We will use outdoor incense as the source of smoke to visualize the airflow. The incense smoke provides a controllable, neutrally buoyant tracer that makes convection patterns visible in natural outdoor conditions. This method is particularly suitable for open air testing as it avoids the need for powered foggers and creates a continuous, visible stream of smoke that clearly indicates airflow direction and strength.

The equipment required for this test includes incense sticks, a holder or fixes piping configuration to ensure consistent smoke release, a high-resolution camera, and adjustable lighting sources to enhance visibility. We will use a dark or neutral background to provide contrast, ensuring that the smoke is clearly visible on camera. Based on best practices from airflow visualization studies, several important considerations will guide this test. First, the smoke setup must be configured correctly. The incense will be positioned so that smoke enters at the beginning of the airflow source, ensuring that convection currents can interact with the smoke immediately. The incense will be mounted securely to avoid disturbances from operator movement that could interfere with the airflow. Second, we will select incense with a moderate burn rate and visible smoke. This ensures that the smoke accurately represents the airs motion without bias. Third, smoke will be introduced perpendicular to the airflow where possible to best visualize the upward and lateral motion of connective cells. Injecting smoke in the same direction as the airflow will be avoided to prevent distortion of the observed pattern. Finally, we will use optimized lighting and good camera angles in at least two camera angles positioned at different sides of the tank. [5]

The key variables observed in this test will be qualitative: plume formation, the vertical rise of smoke, lateral return flows, and any oscillating or cellular behavior indicative of turbulent free convection. Supporting quantitative data will include recorded air temperature, water temperature, relative humidity, and timestamps throughout the observation period. From this data, we will calculate the Rayleigh number to classify the convective flow regime. Flow patterns will also be categorized qualitatively as laminar cellular, transitional, or unstable based on smoke visualization.

Procedure:

The procedure for this test begins by filling the water tank and allowing the environment to stabilize. Once the air and water temperature boundary conditions are reached, incense sticks will be lit and placed at several fixed locations along the water surface edge. The smoke will be allowed to interact naturally with the buoyant air currents, and recording will begin once the flow stabilizes. Videos will be captured for two to three minutes from multiple angles. This procedure will be repeated for three different temperature differences at a constant relative humidity, and again at varying humidity levels. All temperature and humidity data will be continuously logged.

Results:

The expected results include visible upward motion of smoke plumes and cellular flow structures forming above the water surface. Stronger convection cells and more pronounced vertical plumes are anticipated at higher temperature gradients, while higher relative humidity may reduce visibility but will not eliminate cellular flow. The calculated Rayleigh number values are expected to range between $10^7$and 10^8, aligning with our target for canal scale similarity.

Conclusion:

The test will be considered successful if consistent plume patterns or convective cells are clearly visible across multiple orientations and if the computed Rayleigh number remains within the canal reference value order of magnitudes. Failure to observe distinct motion or significant deviation from the expected Ra number range will indicate the need for modifications, such as adjusting incense positioning, improving shielding from outdoor wind, or recalibrating environmental control settings. This smoke visualization test will provide clear confirmation of the natural convection environment critical for validating subsequent evaporation experiments.

8.2.2 Test 2: Measurement & Precision of Collected Data

Design Requirements (DRs):

DR-A: Ability to collect synchronized data across all sensors in time intervals of two seconds.
DR-B: Ability to maintain RH measurement accuracy within ±5 % RH
DR-C: Ability to quantify and document measurement uncertainty for each sensor type, including standard deviation and drift rate over time.
DR-D: Ability to maintain/control air–water temperature stability within ±0.5 °C during expected testing

Test/Experiment Summary:

This experiment verifies the precision, repeatability, and data reliability of the Arduino-based measurement system used to record air temperature, relative humidity, and water surface temperature. The goal is to confirm that the sensors and data-logging process can accurately capture environmental trends needed to compute the evaporation rate in g/s or mm/day. The design requirements being tested include data synchronization across all sensors, consistent precision in environmental measurements, and quantification of drift over time. Equipment includes the Arduino Uno data-logging circuit, SHT31 and DS18B20 sensors, RTC module, SD card module, and a test apparatus partially filled with water to allow natural evaporation. The variables directly measured are air temperature (°C), relative humidity (%RH), and water temperature (°C). From these, the evaporation rate will be calculated using steps shown in Test 1.

Procedure:

For this test, the Arduino data-logging system will be assembled with the SHT31 and DS18B20 sensors connected to measure relative humidity, air temperature, and water surface temperature, with timestamps recorded through the DS3231 real-time clock module. The sensors will operate based on their manufacturer pre-calibration data, which has been verified through published performance and error curves in their respective datasheets. We will trust these factory calibrations as our baseline accuracy for both temperature and humidity, but will further evaluate each sensor's precision, standard deviation, and drift rate during extended testing to validate their real-world performance. Temperature probes will still undergo a two-point verification in ice and warm water baths to confirm their calibration alignment with the sensor specifications. Once assembled, the Arduino will continuously log data at a fixed interval of $\Delta t = 2$ s for a series of respected test ranging from fifteen minutes to an hour long under stable ambient conditions, while simultaneously recording all readings to a CSV file on the SD card. After the test, the CSV file will be imported into Excel or MATLAB, where data will be filtered and statistically analyzed. The mean, standard deviation, and drift rate for each variable will be calculated and plotted over time to assess sensor repeatability and stability. Finally, using the logged air temperature and relative humidity data, the evaporation rate will be calculated using similar test found in Test 1 above. The processed data will be displayed graphically to visualize the relationship between temperature, relative humidity, and evaporation rate, allowing us to confirm the sensitivity and synchronization of all sensors in the system.

Results:

From this test, we expect to see clear relationships between air temperature, relative humidity, and the evaporation rate (which will be calculated in Test 1). As the air warms, it can hold more water vapor, which increases the vapor pressure difference between the water surface and the surrounding air, causing evaporation to speed up. On the other hand, when humidity rises, the air becomes more saturated, that difference shrinks, and the evaporation rate slows down. Because of this, we anticipate a positive relationship between temperature and evaporation rate and a negative relationship between relative humidity and evaporation rate. The first example graph (Figure 1) shows that pattern clearly: as temperature increases from around 10 °C to 50 °C, the blue curve shows evaporation climbing steadily, while the dashed black line shows relative humidity dropping off. The second example (Figure 2) shows the same trend with real data; higher humidity levels line up with lower evaporation rates, and warmer temperatures (shown in orange and red) push evaporation higher across all humidity ranges.

When we analyze our Arduino data, we expect to see those same patterns appear. Once the logged temperature and humidity data are plotted, we'll be able to generate scatter plots and trendlines that show Evaporation Rate vs. Relative Humidity and Evaporation Rate vs. Temperature, along with color maps that tie the variables together visually. The data should mirror what's shown in the figures: evaporation rates drop as humidity rises and increasing steadily with temperature. Seeing those trends will help confirm that our measurement setup is capturing the physics of evaporation accurately and that our sensors are working in sync the way they should.

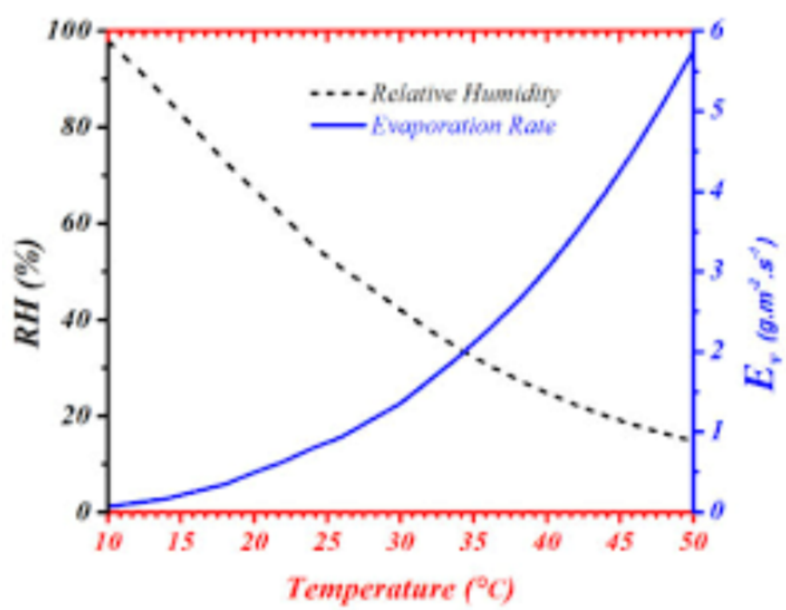


Figure 17: Relative Humidity vs Temperature Dash-line Curve

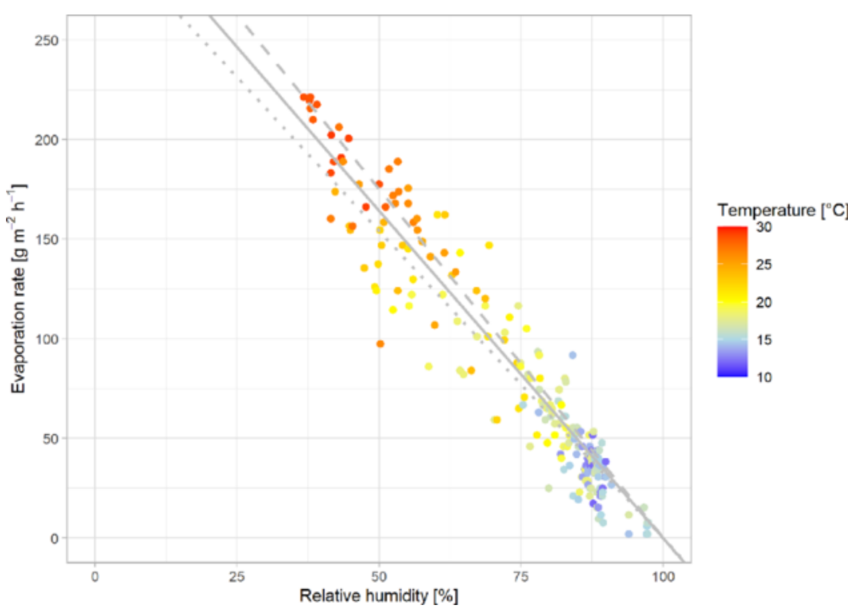


Figure 18: Evaporation Rate as a Function of RH and Temperature

Conclusion:

This experiment shows how well our data collection system performs and whether it can measure environmental conditions with accuracy and consistency. By relying on the factory calibration of the SHT31 sensors and verifying our temperature probes with ice and warm water baths, we can trust that our Arduino setup will record reliable and synchronized data. We expect to see evaporation increase as temperature rises and decrease as humidity goes up, which will confirm that the system is capturing real environmental behavior. Seeing these patterns in our results will give us confidence that our sensors are working properly and that our setup meets our design goals for precision, accuracy, and documenting uncertainty. This will set a strong foundation for the evaporation rate calculations and analysis that will follow in future tests.

Post-calibration residuals are targeted at ≤ ±0.2 °C (T) and ≤ ±1.5 %RH, with drift over four hours ≤ 0.1 °C and ≤ 0.5 %RH. The combined standard uncertainty is propagated to h_m and $\dot{m}_v$ via first-order Taylor expansion and will be reported alongside 95% confidence intervals. Passing Ex3 certifies the instrumentation for use in Ex4–Ex7.

8.2.3 Test 3: Accuracy of Relative humidity

Design Requirements (DRs):

DR-A: Ability to maintain and hold target relative humidity (RH) setpoints while simultaneously recording synchronized air and water temperature data.

DR-B: Ability to achieve rapid humidity adjustment using both the active dehumidifier and passive silica desiccant, reaching target RH values within ±2 %.

DR-C: Ability to quantify humidity stability through steady-state error, overshoot, and drift analysis over multi-hour runs.

DR-D: Ability to maintain air-to-water temperature stability within ±0.5 °C during humidity control testing to prevent interference with evaporative mass transfer.

Test/Experiment Summary:

This test is focused on making sure the team can reliably control and hold the humidity inside the enclosure. Since relative humidity directly affects the evaporation rate, it's important that both the active system (the dehumidifier) and the passive system (silica packets) can reach the desired humidity levels without adding extra airflow or temperature changes. The test is broken into two parts. The first part uses the electric dehumidifier to quickly pull the RH down to a low value, around 10%, and hold it there. The second part uses only silica desiccant packets to keep the humidity steady after the dehumidifier is turned off. Both phases help show how much control we really have over RH, and how much drift happens naturally when the system is left on its own. Temperature and RH are logged every 60 seconds during both phases so we can track the transient response and stability over time.

Procedure:

Before starting, the apparatus is set up with water and the pool heater running to get the surface water temperature stable. The roof is closed to limit external airflow and to make sure the test focuses only on humidity control. All RH sensors are checked with quick calibration to make sure they're reading accurately. Once the temperatures and humidity are stable, a 15-minute baseline is recorded with no dehumidifier or desiccant running, just to see how fast the humidity naturally changes.

For the first part of the test, the dehumidifier is turned on at the lowest fan setting, so it removes moisture but doesn't create a strong air current. The target RH is around 10%, but if the system can't reach that due to ambient conditions, we use the lowest achievable stable RH and record that value as the new target. Data logging continues throughout, and the team watches how fast the humidity drops and when it stabilizes. The main goals are to measure the time it takes to reach the setpoint, any overshot, and how well the system stays within ±2% of that target once it settles. Once the humidity is steady, the system lasts for about an hour so we can analyze steady-state errors and noise in the readings.

In the second part of the test, the dehumidifier is turned off completely, and several pre-weighed silica desiccant packets are placed evenly around the enclosure on small stands to avoid direct contact with the water. These packets absorb moisture slowly and should maintain the RH close to the setpoint without any fan movement. This phase lasts around 90 minutes, or until the RH drifts out of the ±2% band for more than ten minutes. If the humidity starts to rise, another small set of packets is added, and that time and mass are recorded so we can estimate how much moisture the silica can absorb. At the end, the packets are removed, weighed again, and their moisture gain is recorded. Throughout the whole test, the air and water temperatures are monitored to confirm that they stay within ±0.5°C of each other.

Results/Conclusion:

Data from the RH sensors are corrected using calibration values, and then absolute humidity is calculated based on air temperature and relative humidity readings. For the dehumidifier phase, the RH response is analyzed like a standard step response in controls we find the time to reach the target, any overshoot, and the settling time (defined as when the RH stays within ±2% for 20 minutes straight). The steady-state error is found by averaging the final 30 minutes of data and comparing it to the setpoint. If air temperature changes by more than 0.5°C during this time, that run is discarded and repeated with less dehumidifier power.

For the silica desiccant phase, the focus is on how stable the RH stays and how quickly it starts to drift. A simple linear fit is used to get the drift rate (%RH/hour), and the total moisture absorbed by the silica is compared to the predicted moisture removal based on the enclosure's air volume. The test is considered successful if the dehumidifier can reach and hold within ±2% RH with a settling time under 20 minutes, and if the silica packets can maintain that humidity within the same ±2% band for at least 30 minutes to a hour with less than 0.2% RH/hour drift. Meeting these results confirms that the team can both achieve and maintain controlled humidity conditions in two different ways, which is essential for accurate evaporation measurements later.

8.2.4 Test 4: Siphon accuracy

Design Requirements (DRs)

DR-A: Ability to establish and maintain a stable siphon flow between two water reservoirs without the introduction of air bubbles or loss of prime during steady operation.

DR-B: Ability to measure and record volumetric flow rate, pressure head difference, and water-level change over time to verify theoretical siphon behavior.

DR-C: Ability to document the relationship between elevation difference, tube diameter, and discharge rate while accounting for minor losses and viscous effects.

Test/Experiment Summary:

This experiment is intended to verify that the siphon mechanism used in the evaporation apparatus functions as expected under controlled and ambient test. The siphon is responsible for transferring water between the scale and the water tank with continuous flow without the use of pumps or outside help. By maintaining similar heights to each container. As evaporation lowers the tank's water level, the head difference naturally increases, and the siphon draws just enough water to keep the two sides trending back toward equilibrium. If the connection is tight and bubble-free, the rate of mass decrease of the source container equals the evaporation rate of the tank (to within leakage and tiny splashing losses). This gives a continuous, pump-free mass-loss signal that matches the logging cadence for temperature and humidity.

Procedure:

The U-tube is pre-filled with degassed water to remove trapped air. Both ends are kept submerged during handling, so the siphon stays primed. The small source container (clean, dry, known tare) is placed centered on the precision scale. Its outlet end of the U-tube is fixed 2–3 cm below the source free surface; the tank end is set at the same submergence below the tank free surface. The source is positioned, so its free surface is a few centimeters higher than the tank to guarantee initial flow into the tank. The scale is tared with the filled source container in place; time zero is when you release the line clamps and confirm a steady siphon strand entering the tank. From that moment, the scale logs mass every 30–60s. Avoid bumping the table or dragging the tube; even small movements can introduce bubbles or fake weight readings.

During the run, you visually check the siphon for micro-bubbles, kinks, or any outlet that rises above the free surface (which would break prime). If bubbles appear, gently flick the tube to dislodge them while keeping both ends submerged. If the prime is lost, re-prime and note the timestamp (you'll omit those data from the slope fit). Let the system run at least 90–120 minutes so the evaporation signal is clearly above noise. At the end, cap the tube ends underwater to preserve prime for the next run, record final masses and levels, and save the synchronized logs.

Results/Conclusion:

The mass data collected from the smaller source container on the scale is used to determine the rate of evaporation from the uncovered tank. As water evaporates, the siphon draws in replacement water from the source, and the corresponding decrease in source mass directly represents the evaporation occurring in the main tank. The evaporation rate is calculated using the negative slope of the source container's mass over time, expressed in grams per second

$$\dot{m_{evap}} = -\frac{dm}{dt}$$

To express this result as an evaporation depth, the mass rate is converted using the surface area of the uncovered tank (As) and the density of water (ρw) at the measured temperature:

$$\frac{mmH2O}{hour} = \frac{\dot{m}}{\rho_w A_s} \times 3.6 \times 10^6$$

This calculation provides a continuous measure of evaporation based solely on the change in mass of the smaller container. A stable, linear decrease in mass over time indicates consistent evaporation conditions and confirms that the siphon equalizer system is functioning correctly. The test is considered successful when the mass data shows a smooth linear trend with minimal fluctuations, demonstrating that the siphon-maintained equilibrium and accurately reflected the rate of water loss due to evaporation.

8.2.5 Test 5: Data Set for Ideal Scaled Conditions to Model the Grand Canal

Design Requirements (DRs):

DR-A: Ability to achieve and hold target ΔT = T_w − T_a and RH setpoints.

DR-B: Operation in intended free convection regime with canal like Ra

DR-C: Collection of evaporative mass transfer in g/s

DR-D: Baseline characterization of mass transfer coefficient and comparison to correlations.

Test/Experiment Summary:

In this experiment, we will be collecting data under the conditions that we have obtained from scaling the sample area of the Grand Canal that has been selected as a model for the experiment. The average temperature and relative humidity conditions present at the Grand Canal were used to calculate a Rayleigh number. We then designed our apparatus to be able to produce conditions that matched this Rayleigh number as closely as possible. The data from this test will be correlated and used to create a mass transfer coefficient to describe the evaporation rate in the Grand Canal.

Procedure:

The water temperature will be maintained at 90°F, and we will collect data at night when the ambient air temperature outside is 45°F. We will run the dehumidifier to reduce the relative humidity as much as possible and then collect data until a significant amount of mass transfer has occurred. This may only take 10 minutes, but we will only know once we are collecting the data.

Results:

Assuming that the boundary conditions for the test are met, we have established a theoretical rate of evaporation. The calculations for the expected evaporative mass transfer are shown below.

$T_s = 90°\mathrm{F}(305.37K)$- W*ater surface temperature*

$T_\infty = 45°\mathrm{F}(280.37K)$- *Ambient air temperature*

$\emptyset = 2\%$ - *Relative humidity*

$T_f = 67.5°\mathrm{F}(292.87K)$- *Film temperature, avg temperature inside boundary layer*

$D_{AB} = 2.41 \times 10^{-5}\,\frac{m^2}{s}$- *Water into air diffusivity constant evaluated at film temperature*

$v = 15.255 \times 10^{-6}\,\frac{m^2}{s}$- *Kinematic viscosity evaluated at the film temperature*

$Lc = \frac{As}{P} = \frac{1.86m^2}{7.32m} = 0.254m$- *Characteristic length evaluated as the surface area divided by the* *perimeter of the 1:5 rectangle in apparatus*

$Sc = \frac{15.255\times10^{-6}\frac{m^2}{s}}{2.41\times10^{-5}\frac{m^2}{s}} = 0.633$- *Schmidt number*

$Ra_m = \frac{9.81\frac{m}{s^2}\left(\left|1.13787\frac{kg}{m^3}-1.26231\frac{kg}{m^3}\right|\right)(0.254m)^3}{\left(1.26231\frac{kg}{m^3}\right)\left(15.255\times10^{-6}\frac{m^2}{s}\right)^2} \times 0.633 = 4.31 \times 10^7$- *Mass transfer Rayleigh number*

[33]$\overline{Sh} = 0.15(Ra_m)^{\frac{1}{3}} = 0.15(4.31 \times 10^7)^{\frac{1}{3}} = 52.59$- *Average Sherwood number for apparatus*

$\bar{h}_m = \frac{\overline{Sh}\times D_{AB}}{Lc} = 0.005\frac{m}{s}$- *Average convective mass transfer coefficient for apparatus*

$$\dot{m_v} = \bar{h}_m \times A_s(\rho_{v,s} - \rho_{v,\infty}) = 0.005\frac{m}{s} \times 1.86m^2\left(0.015\frac{kg}{m^3} - 0.000159\frac{kg}{s}\right)\left(\frac{1000g}{1kg}\right)$$

$\dot{m_v} = 0.318\frac{g}{s}$- *Target evaporation rate to mimic Grand Canal conditions*

$$\dot{m_v} = \frac{0.4969\frac{kg}{hr} \times 24\frac{hr}{day} \times \frac{1mm}{1kg\cdot m^{-2}}}{1.85806m^2} = 6.42\frac{mm}{day}$$

As shown above, the expected rate of evaporation is 0.318 grams per second under the scaled conditions. When converted to units of millimeters per day, the theoretical evaporation rate out of the apparatus tank is 6.42 mm/day, which is around a quarter of an inch. This seems reasonable considering the high water temperature and low air temperature that we will be running the test under.

Conclusion:

With this test, we hope to establish data sets to replicate the conditions at the Grand Canal. Through dimensionless scaling, we have identified the boundary conditions that produce the closest Rayleigh numbers between the canal and our apparatus. Due to time and budget constraints, these Rayleigh numbers are not equal, but the data collected from this test will be informative on the rates of evaporation in the Pheonix canals none the less.

8.2.6 Test 6: Ambient Open Test (Flagstaff)

Design Requirements (DRs):

DR-A: Ability to collect synchronized air temperature, water temperature, and humidity data under natural ambient conditions without active control.

DR-B: Ability to measure and document the effects of fluctuating humidity on evaporation rate and air-water temperature difference ($\Delta T = T\_w - T\_a$).

DR-C: Ability to determine whether the apparatus can still maintain free convection conditions when exposed to uncontrolled external air.

DR-D: Ability to analyze data variability and quantify uncertainty caused by environmental fluctuations in Flagstaff ambient testing.

Test/Experiment Summary:

This test is designed to observe how the system behaves when it's completely exposed to Flagstaff's natural weather without any humidity or temperature control. In the previous test, humidity was actively set using a dehumidifier or silica packets; here, the goal is to measure how much relative humidity naturally varies over time and how that variation affects the measured evaporation rate. Since Flagstaff's climate tends to be dry and variable, this test will help determine how sensitive our evaporation data is to environmental changes like sudden increases in ambient humidity or drops in air temperature. This is an important baseline for understanding what kind of corrections or shielding we might need when we move the experiment to outdoor conditions in Phoenix later.

Procedure:

To begin the test, both the roofs of the apparatus are removed or opened to allow direct contact between the air above the water and the ambient atmosphere. No dehumidifier, heater, or silica desiccant packets are used during this run. The goal is to let the ambient air temperature and humidity fluctuate naturally and monitor the system's passive response.

Before data collection starts, the relative humidity and temperature sensors are verified with the same calibration factors from the previous humidity control test (Ex-RH). Once verified, logging begins and continues uninterrupted for a minimum of few hours, or long enough to capture at least one full diurnal humidity trend if possible. During the test, the team periodically records outside weather data (from a handheld hygrometer or nearby weather station) to compare external ambient RH with the values measured inside the enclosure. The difference helps estimate how open air coupling affects the moisture field over the water surface.

Air temperature, water surface temperature, and RH are logged every 60 seconds. Water mass is measured either continuously with a scale or manually by weighing the container at hourly intervals to determine the rate of evaporation. Throughout the test, no active interventions are made with no fans, doors, or roof adjustments so that the readings purely represent natural Flagstaff ambient conditions. The final step is to save all logged data, annotate the run with external conditions (such as time of day, wind strength, and cloud cover), and take a few smoke tracer videos to visualize the airflow patterns above the water during different humidity levels.

Results/Conclusion:

The basis of this test is to create a standard so when one variable is controlled it is now able to be compared to the standard to see how the evaporation rate is affected. Assuming this is done with Flagstaff weather data that is recorded at the time of the test, we cannot predict what the evaporation rate may be. Once weather data is recorded, we can use the same mathematical process as test 4 to produce a theoretical evaporation rate which will also help us to validate our previous evaporation modelling.

Once the test is complete, the data will be processed to evaluate how much humidity fluctuated and how those changes influenced evaporation. A time series of RH, T_a, T_w, and ΔT is plotted to show how ambient conditions evolved over the test period. Evaporation rate ($\dot{m}_v$) is computed using the gravimetric mass loss method and compared to theoretical predictions using the instantaneous values of air and water properties. From these data, a correlation between evaporation rate and relative humidity can be estimated even without active control.

The expected outcome is that the relative humidity will vary significantly throughout the test—typically between 10% and 40% depending on the time of day—and that evaporation rate will inversely follow these changes. During lower relative humidity periods, mass loss should increase, while during higher RH, it should decrease. The Rayleigh number (Ra_m) and Sherwood number (Sh) can still be calculated for several time intervals to check if the free convection regime remains consistent. The test will be considered successful if the apparatus records smooth, synchronized data across all sensors, the calculated Ra_m values stay in the same order of magnitude (10^7–10^8) as in controlled tests, and the qualitative relationships between relative humidity and evaporation rate match theoretical expectations.

This uncontrolled humidity test gives the team a realistic understanding of how environmental fluctuations affect evaporation and whether the system is robust enough for outdoor or field testing. The results also help define what level of control precision is needed in future tests, especially before transporting the setup to Phoenix.

8.2.7 Test 7: Controlled Variables Test (Flagstaff)

Design Requirements (DRs):

DR-A: Ability to hold a constant water surface temperature (T_w) and air temperature (T_a) difference (ΔT) within ±0.5°C while maintaining a fixed relative humidity (RH) level.

DR-B: Ability to achieve steady-state humidity conditions using both the dehumidifier and silica desiccant control systems.

DR-C: Ability to collect synchronized temperature, humidity, and mass-loss data to determine the evaporation rate under fully controlled conditions.

DR-D: Ability to calculate theoretical and experimental evaporation rates (ṁ_v) and validate them against expected mass transfer correlations (Sherwood and Rayleigh number relationships).

Test/Experiment Summary:

This experiment focuses on obtaining high-quality, steady-state evaporation data under individually controlled conditions. The main goal is to evaluate how evaporation behaves when only one variable is changed at a time.

During this test there will be three iterations, the first being controlled air temperature where there is no dehumidifier and no water heater. This test will demonstrate how much the surrounding air has an effect on the rate of which evaporation will occur. It is expected that with out the extreme dehumidification process, that if this test runs for too long the air will get too saturated and stop the evaporation.

$$T_\infty = 45°\text{F}(280.37K) - Ambient\ air\ temp$$

The second iteration will be to only control the temperature of the water with the water heater. This will be too test if having a higher ΔT increases the rate of evaporation. It is expected that with the larger ΔT, evaporation will happen at a quicker rate similar to a common household example of a steamy shower. Similarly to iteration one, this test will have to be kept short to lower the chance of fully saturating the surrounding air and stopping the evaporation process completely inside the apparatus.

$$T_s = 90°\text{F}(305.37K) - Water\ surface\ temp$$

For the final iteration of the controlled variables test, the relative humidity within the apparatus will be set as low as possible with thermal equilibrium met for the water and air temperature. This is to isolate the effects of having as little possible moisture in the air at all times for the entire duration of the test, and from here a consistent evaporation rate can be found.

$$\emptyset = 2\% - Relative\ humidity$$

This allows the team to directly compare measured evaporation rates with theoretical predictions from the mass transfer analogy and determine how accurately the apparatus represents canal-like behavior. With each component tested separately, a chart can be created to show the impact of each variable.

Procedure:

Before the test, all sensors (temperature, relative humidity, and mass) are calibrated as described in earlier tests to make sure readings are consistent and traceable.

The first iteration will be completed by running the test at night where we can reach ambient air temperatures of 45 °F with all other conditions at the natural weather in Flagstaff. The box will remain sealed until the outside air matches 45°F. At that time the roof will be removed to allow the air to reach the body of water. Data will be collected here.

For iteration two, the water container heater is turned on to bring the water to the target temperature usually around 90°F (305 K) to simulate a hot canal surface. The enclosure's air temperature is allowed to stabilize near ambient with the roof off before putting roof back on, which creates strong free convection over the surface. Data will be collected here.

Once thermal equilibrium is reached, the dehumidifier is turned on to lower the relative humidity to the desired level, below 10%. After the setpoint is reached, silica desiccant packets are added to maintain the humidity level with minimal airflow, allowing the dehumidifier to cycle off intermittently. The enclosure is kept sealed throughout the test to maintain stability, and the water surface is monitored visually to confirm that no external airflow is disturbing it.

All variables T_w, T_a, relative humidity, and mass are logged every 60 seconds for a couple of hours to ensure the system reaches and stays at steady state. If the humidity drifts more than ±2% or the temperature difference ΔT changes more than ±0.5°C, the test is paused and restarted after corrections are made. At the end of the run, the total water mass loss is recorded, and the rate of evaporation ($\dot{m}$) is calculated using the slope of mass versus time. Theoretical values are also computed based on the measured conditions using standard mass transfer equations.

Results/Conclusion:

Once the test is complete, the data are processed to evaluate how much humidity fluctuated and how those changes influenced evaporation. A time series of relative humidity, T_a, T_w, and ΔT is plotted to show how ambient conditions evolved over the test period. Evaporation rate (ṁ_v) is computed using the siphon method and compared to theoretical predictions using the instantaneous values of air and water properties. From these data, a correlation between evaporation rate and relative humidity can be estimated even without active control.

The expected outcome is that the evaporation rates will vary significantly throughout the test in each iteration. The Rayleigh number (Ra_m) and Sherwood number (Sh) will be calculated for several time intervals to check if the free convection regime remains consistent. The test will be considered successful if the apparatus records smooth, synchronized data across all sensors, the calculated Ra_m values stay in the same order of magnitude (10^7–10^8) as in controlled tests, and the qualitative relationships between RH and evaporation rate match theoretical expectations.

The results of this test will allow the team to acquire results as close as possible to the conditions in Phoenix. Although the environment within the box does not simulate the exact conditions in Phoenix, the results should show different evaporation rates as each variable changes. Although the number is different from the numbers that would be gathered in Phoenix due to the vastly different environment, it will still return values that the client can use.

8.2.8 Test 8: Ambient Open Test (Pheonix)

Design Requirements (DRs):

DR-A: Ability to collect synchronized air temperature, water temperature, and humidity data under natural ambient conditions without active control.
DR-B: Ability to measure and document the effects of fluctuating humidity on evaporation rate and air-water temperature difference (ΔT = T_w − T_a).
DR-C: Ability to determine whether the apparatus can still maintain free convection conditions when exposed to uncontrolled external air.
DR-D: Ability to analyze data variability and quantify uncertainty caused by environmental fluctuations in Phoenix ambient testing.

Test/Experiment Summary:

This test is designed to observe how the system behaves when it's completely exposed to Phoenix's natural weather without any humidity or temperature control. In previous tests, humidity was actively set using a dehumidifier or silica packets; here, the goal is to measure how much RH naturally varies over time and how that variation affects the measured evaporation rate. Since Phoenix is the stated problem statement, the climate will be directly related to where the physical canal is located. This test will help determine how sensitive our evaporation data is to environmental changes like sudden increases in ambient humidity or drops in air temperature.

Procedure:

To begin the test, both the roofs of the apparatus are removed or opened to allow direct contact between the air above the water and the ambient atmosphere. No dehumidifier, heater, or silica desiccant packets are used during this run. The goal is to let the ambient air temperature and humidity fluctuate naturally and monitor the system's passive response.

Before data collection starts, the relative humidity and temperature sensors are verified with the same calibration factors from the previous humidity control test (Ex-RH). Once verified, logging begins and continues uninterrupted for a minimum of few hours, or long enough to capture at least one full diurnal humidity trend if possible. During the test, the team periodically records outside weather data (from a handheld hygrometer or nearby weather station) to compare external ambient relative humidity with the values measured inside the enclosure. The difference helps estimate how open air coupling affects the moisture field over the water surface.

Air temperature, water surface temperature, and relative humidity are logged every 60 seconds. Water mass is measured either continuously with a scale or manually by weighing the container at hourly intervals to determine the rate of evaporation. Throughout the test, no active interventions are made: no fans, doors, or roof adjustments, so that the readings purely represent natural Phoenix ambient conditions. The final step is to save all logged data, annotate the run with external conditions (such as time of day, wind strength, and cloud cover), and take a few smoke tracer videos to visualize the airflow patterns above the water during different humidity levels.

Results/Conclusion:

Once the test is complete, the data are processed to evaluate how much humidity fluctuated and how those changes influenced evaporation. A time series of relative humidity, T_a, T_w, and ΔT is plotted to show how ambient conditions evolved over the test period. Evaporation rate ($\dot{m}_v$) is recorded using the siphon method and compared to theoretical predictions using the instantaneous values of air and water properties. From these data, a correlation between evaporation rate and relative humidity can be estimated even without active control.

The expected outcome is that the relative humidity will vary significantly throughout the test typically between 10% and 30% depending on time of day and that evaporation rate will inversely follow these changes. During lower relative humidity periods, mass loss should increase, while during higher relative humidity, it should decrease. The Rayleigh number (Ra_m) and Sherwood number (Sh) can still be calculated for several time intervals to check if the free convection regime remains consistent. The test will be considered successful if the apparatus records smooth, synchronized data across all sensors, the calculated Ra_m values stay in the same order of magnitude (10^7–10^8) as in controlled tests, and the qualitative relationships between RH and evaporation rate match theoretical expectations.

After completing the last test for the experiment, the collected data is analyzed to quantify how each element of the evaporation process has an influence on the total evaporation rate. The evaporation rate (m_v) will be calculated using the equations from test 4, and it is expected that the evaporation rate will change with the relative humidity near the apparatus. The results from this test will provide a realistic basis for scaling the Flagstaff data to the hotter Phoenix conditions, enabling an accurate evaluation of the evaporation rates from the data collected in Flagstaff.

8.3 Testing Results

8.3.1 Results from Uncovered Tests

The uncovered tests gave us our first real look at how the system behaved without any shading or environmental control. These runs were useful for understanding general trends in the environment, but they quickly showed how unpredictable the environment can be when everything is open to the atmosphere. Small gusts of wind, sudden changes in sunlight, and even passing clouds caused swings in temperature, humidity, and wind speed. Because these conditions were constantly shifting, the evaporation rate moved a lot. Even though we could see the basic pattern of evaporation increase when the air was dry and slowed down when humidity crept up. The data was never stable enough to rely on for any kind of solid correlation.

Another problem with the uncovered tests was how sensitive our setup was to tiny mass changes. Since the evaporation in the open atmosphere was sometimes only a few hundredths of a gram, the load cell noise made it hard to tell whether we were measuring actual evaporation or just sensor error. You could physically see the trends happening with more heat meant more evaporation. But the numbers on the data/graph jumped around too much to trust them for anything precise.

The uncovered tests helped confirm that our apparatus worked and that the physics made sense, but they also showed that we needed a much more controlled environment before we could extract meaningful results. The uncovered tests acted more like a "proof of concept" rather than something we could collect precise correlations from. They showed us what was going on, but they also showed us how much the environment could ruin the data. That's ultimately why the shaded (covered) tests ended up being so important to our correlations. They eliminated the environmental chaos that made the uncovered tests nearly impossible to analyze.

8.3.2 Results from Covered Tests

Once we added the scaled cover over the tank everything about the testing became more controlled and predictable. The air above the water stayed more consistent the humidity rose in a smoother pattern, and we no longer had random wind gusts ruining the readings. Because of that stability, the evaporation rate decrease which is exactly what you expect when water is shaded. More importantly, the data finally formed trends that made sense.

Average mass transfer coefficient and Sherwood numbers for 10.1 inches covered tests:

$$\overline{h_m} = 0.23096 \text{ m/s}$$

$$\overline{Sh} = 2311.83$$

Average rate of evaporation from covered tests:

$$\dot{m}_v = 0.0056 \frac{g}{s} = 0.01 \frac{inches}{day}$$

These results are physically consistent with mass transfer theory.

Sherwood correlation for tests with a 10.1 inch scaled cover over specific Rayleigh number range:

$$Sh = 1.63 \times 10^{-6}\ Ra_m^{1.372}$$

$$R^2 = 0.974$$

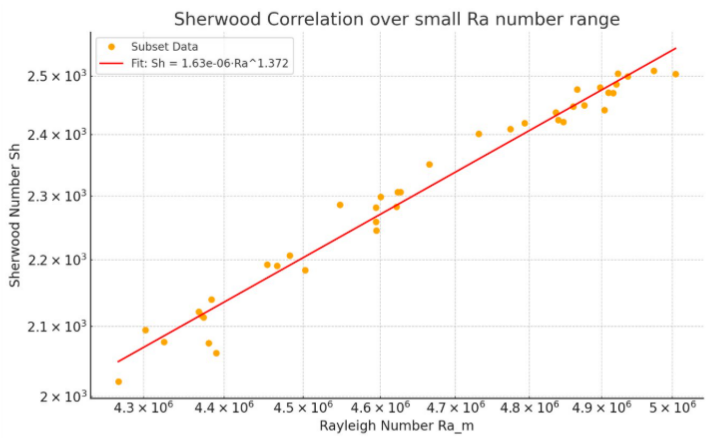
R^2 value of 0.97 means that 97% of the Sherwood number's behavior is explained by the Rayleigh number.

This correlation is only valid over the range:

$$4.3 \times 10^6 \leq Ra_m \leq 5.0 \times 10^6$$

These averages and correlations were the first sign that the covered tests were giving us meaningful information. The mass transfer coefficient wasn't bouncing all over like before, and the Sherwood number settled into a range that stayed consistent from test to test. This alone made the covered tests better than what we collected before. the biggest improvement came when we plotted Sherwood vs. Rayleigh on a log-log scale. The points didn't scatter all over the place instead, they followed a clean, upward sloping trend to get a solids correlation.

Log-log plot of covered tests Sherwood correlation:



$$Sh = 1.63 \times 10^{-6}\ Ra_m^{1.372}$$

$$4.3 \times 10^6 \leq Ra_m \leq 5.0 \times 10^6$$

The line of best fit showed an incredibly strong match between the Sherwood number and the Rayleigh number. Having an R^2 of about 0.97. That means the Rayleigh number basically explains everything happening in the Sherwood number within this testing range. It was the kind of clean correlation we never could have gotten in the uncovered setup because there was way too many things changing in the background. It's important to note that this correlation only holds across that small Rayleigh range. Outside that range, the humidity buildup under the cover starts to flatten the driving force, so things level out. But within that range, the data shows exactly how the system behaves under shading, and the results line up smoothly. The covered tests are where the project really came together. They gave us usable evaporation rates, stable Sherwood numbers, and a correlation that actually behaves the way it should. Without this controlled setup, we never would have gotten the clean, consistent relationship between Rayleigh and Sherwood.

9 Future work

Over the course of this capstone project, significant progress has been made in researching the mechanics of mass transfer evaporation under a natural convection flow regime. Additionally, an apparatus was built to test how water evaporates in the Phoenix Grand Canal. This was achieved by scaling the conditions present at the Grand Canal through dimensionless numbers such as the Rayleigh number and the Sherwood number. The ASU research team that is made up of solar panel experts and graduate student hydrologists, have been our associates throughout the course of this capstone project. They have been researching this topic through the lenses of their respective disciplines for multiple years, and plan to continue this research in the future. Because of this, the nature of this capstone project can be viewed as one piece of a much larger effort to investigate water evaporation in the Phoenix canals, and the co-benefits of solar panel covers. We were tasked with researching the topic from a mechanical engineering lense, before building an apparatus to implement our research and gather data to further inform the experimentation that the main research team at ASU has been conducting. Preliminary tests were completed that provided this capstone project with initial results. However, there is considerable room for improvement in regard to this research project becoming fully successful.

Firstly, because the Grand Canal is quite large in size, the apparatus design would also need to be quite large. The 10ft by 2ft water tank was suitable for our time constraints and budget, but an apparatus at least twice this size would be much more effective in accurately representing the 45ft wide and hundreds of miles long Phoenix canals. Our associates at ASU are planning on building a water tank that is around 23ft long. This will aid in the scaling of the rest of the parameters involved in evaporation, such as the air and water temperatures, and most importantly, the relative humidity. Because our water tank was shorter in length, the relative humidity had to be scaled down to 2% to maintain a similar Rayleigh number. This is a very low relative humidity percentage that does not occur naturally in the local region, which proved to be a big setback when it came to implementing the design of our apparatus. Additionally, the air and water temperatures will be able to sit at much more moderate range than our air temperature of 45°F and water temperature of 90°F. We are confident that ASU's longer design for the water tank will effectively mitigate these issues that we came across with our design.

Secondly, a significant factor of water evaporation in the Phoenix canals is the presence of wind, also known as forced convection. Because of our time constraint of one year, our team was advised by our client to focus on the simplest environmental circumstances as a foundation that we could then build upon later. For our application, this meant that we would investigate the effects of solely natural convection on water evaporation. Unfortunately, time did not permit us to introduce forced convection into our experimentation. Fortunately, the ASU researchers are planning on including forced convection in their larger apparatus design. They will have fans that can be adjusted to different speeds, which will greatly improve the quality of this research project.

The third aspect of this project that requires future work is the range of Rayleigh numbers that data is collected over. As a team, our focus was on recreating the conditions of the Grand Canal in a scaled down apparatus. These conditions were recorded in weather data taken by SRP that was supplied to our team to use for theoretical calculations on the evaporation phenomenon. During this investigation into the average Rayleigh number present at the Grand Canal, the necessity for gathering data over a large range of Rayleigh numbers was overlooked. When mass transfer experiments are conducted, data is typically collected over a range of multiple magnitudes, for example 10^1 up to 10^6 [32]. This allows for a greater trend to arise from the evaporation data; that can then be described by a Sherwood correlation. The data taken for this project ranged from 10^5 to 10^7. Although some correlations were established, it would be advantageous to gather data from a wider range of Rayleigh numbers to establish more encompassing Sherwood correlations for all possible conditions at the Phoenix canals.

Lastly, an aspect of this project that our team had difficulties with was the data collection of the rate of mass transfer of water from the evaporating surface. Our design implemented a graduated cylinder that was placed on a scientific balance or a load cell, which was connected to the evaporating water tank through a siphon. Through the properties of fluid dynamics, the changing water level in the water tank was reflected in the water level of the graduated cylinder. This design for data collection was taken from a previous mass transfer evaporation experiment [30] [31]. While this method was adequate for our preliminary research, a much more precise and reliable method of mass transfer data collection would greatly benefit this project. Our associates at ASU are utilizing a high-precision automated evaporation gauge which has a price range of $5,000 - $15,000. These instruments integrate mass-loss sensing, environmental shielding, and automated data logging, and are commonly used in professional hydrologic evaporation studies. This gauge eliminates all uncertainties and guess work for collecting evaporation data, which will greatly improve the error propagations in their results compared to ours.

10 CONCLUSIONS

Our project has successfully established the foundation for accurately measuring and modeling evaporation under controlled natural convection conditions. Over the course of the project, we have designed and refined an experimental apparatus capable of testing evaporation. By integrating calibrated sensors, a data logging system, and heat pump, we have been able to meet the majority of the customer and engineering requirements needed to produce reliable data.

A major milestone of the project was confirming that the apparatus operates within the intended free convection regime. Through the smoke visualization test, we verified the presence of buoyant plume behavior consistent with theoretical Rayliegh number predictions. This validation ensured that subsequent measurements of evaporation and Sherwood correlations are physically meaningful and scalable to canal behavior.

On the analytical side, MATLAB modeling and dimensional analysis played a critical role in guiding both design decisions and data interpretation. The team developed scripts to identify temperature and humidity combinations that reproduce canal scale Rayleigh similarity. These tools allowed the team to evaluate design tradeoffs early, predict flow regime transitions, and assess whether the apparatus could reach dimensionless targets before hardware was fully constructed. Combined with literature based Sherwood correlations, the modeling framework created a solid foundation for future comparison between theoretical predictions and measured mass loss.

This project also established a clear multi-phase testing methodology, including dedicated experiments for the flow visualization, collection of data with Arduino, relative humidity test, siphon functionality test, ambient open test for Flagstaff, ideal scaled conditioned test for Flagstaff, and ambient open test for Phoenix. These tests will allow SRP and ASU to quantitatively evaluate how solar over canal systems influence evaporation under controlled conditions and whether shading consistently reduces mass transfer rates.

Overall, this project aimed to design, validate, and prepare a robust experimental system for measuring evaporation under natural convection. The work completed over the past two semesters provided the technical foundation and validated methodology needed to generate meaningful evaporation data for SRP and the ASU teams. The apparatus has developed a strong starting point for future evaporation studies and will contribute to the broader effort to reduce water loss in Arizona’s canals.

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