Optimizing Forced-Air Evaporative Cooling Chambers for Vegetable Preservation

by

Gabriela Alvarez Perez

Submitted to the
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ABSTRACT

Forced air evaporative cooling is a developing approach to help with post-harvest fruit and vegetable storage and preservation. The rapid cooling of produce harvested has been shown to reduce food waste substantially making it a promising area for food waste reduction. This technology will be used by farmers in regions of the world that live in hot arid regions off the grid and would benefit from a cooling chamber that can run off minimal energy and will cool produce quickly. To advance understanding of the technology, a test chamber of the forced air evaporative cooler has been designed and built. This chamber will be used to test key design parameters so that their impacts on the cooling will be best understood so that they can inform the design of full-scale chambers that can be used to cool produce soon after harvest. This thesis follows the rationale for the test chamber design as well as information on the application of the test chamber and the testing areas of interest.

Thesis Supervisor: Eric Verploegen
Tile: Research Engineer at MIT D-Lab

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I would like to give many thanks to Eric Verploegen for all the assistance and advice that was critical in keeping this project going and providing insurmountable amount of useful background and perspective into the evaporative cooling chambers. Many thanks to Joyce Tang, for all of her assistance in the design and construction of the chamber and many hours of hard work getting the chamber put together. To Jack Whipple, thank you for all the assistance with shop materials and knowledge on how to build cool things well. Finally, all the members of D-Lab who helped out with this project and were supportive of its development, a special thanks to Ghassan Aljawi for being my shop buddy.

TABLE OF CONTENT

LIST OF FIGURES

1. INTRODUCTION

With around 1.3 billion tons of food being wasted or lost annually according to the Food and Agriculture Organization, it becomes clear that solutions should be deployed to help bring this number down especially as food sources are stressed because of both population and increased weather variability [1]. Reducing food loss would result in increased food security around the world and will also alleviate concerns with rising food prices due to increased demand. There would also be improvements in the livelihood of many communities around the world whose income comes from crop production and who lose money when food losses occur [2].

While food security concerns have been the overall motivator, solutions explored have more often relied on increasing food productivity, with 95% of research investments in the past 30 years focusing on this aspect, rather than reducing food loss, which account for the remaining 5% of investments [3][4]. However, increased food productivity does not address the many negative externalities that food waste has, including greenhouse gas production, cost of waste management, and more [5]. Food loss should be addressed and greatly reduced, especially as estimates to the extent of food waste put it at around 30-50% of global production [6].

This project aims to develop an experimental setup to study various key parameters and use insights from these studies to optimize forced evaporative cooling chambers designed to improve vegetable storage in low-income rural communities. This is motivated by the high demand that exists for improving food storage to reduce food waste, especially in regions of the world where obtaining and maintaining refrigeration to keep produce cool and fresh is challenging. The use of forced evaporative cooling makes it such that the produce can be stored in a cooler and more humid environment which will reduce food loss and enable farmers to have more autonomy over what time of day they will sell their produce, which will help ensure that they get the best prices for their products [7].

2. BACKGROUND

2.1 FORCED AIR EVAPORATIVE COOLING

A key step of postharvest is the cooling of the produce, especially since a temperature reduction leads to a reduced respiration rate resulting in an extended shelf life and protected quality due to reduced water loss [8]. There exist a series of different approaches to pre-cool harvests, where the term pre-cool refers to the first cooling steps that occur as soon as possible after harvesting. Some methods that work best in areas that do not have a ready supply of electricity, meaning that the use of mechanical refrigeration systems is not possible, include room cooling, hydrocooling, forced-air cooling, vacuum cooling, and using ice.

Of interest to this work is the utilization of forced evaporative cooling, paired with increasing the relative humidity, as it is the approach that is being used to lower the temperature of produce. Motivations for this approach being chosen include the short time frame needed to reach the cool temperatures, often in the order of a couple of hours, while remaining a portable and cost efficient [8]. Additionally, forced air cooling also offers the advantage of being able to cool off large volumes of produce, to the scale of room coolers, effectively without wetting the produce or resulting in a lot more handling of fresh produce [9].

The way evaporative cooling works is through the evaporation of a liquid into surrounding air, thus cooling other objects it encounters, an image showing this process is shown below in figure 1. An evaporative cooler works by forcing hot, dry air through wetted pads using a fan, which results in the water evaporating into the air flowing through the pad. When the water evaporates, the air loses heat, The overarching process that explains the cooling is from the heat exchange that occurs as the hot air flows through the wetted surface, and the latent heat of evaporation is used since water evaporation requires vast amounts of heat, so the air that goes through the wetted surface comes out cooler and more humid [10]. A metric that offers insight to the evaporative cooling potential comes from comparing the air's dry-bulb temperature, meaning the temperature taken by a thermometer freely exposed to the elements, relative to the wet-bulb temperature, which occurs when equilibrium is reached by the water surface when the rate of heat transfer by convection equals the rate of mass transfer away from the surface. The wet-bulb temperature can also be described as the lowest temperature that air can be cooled to by the evaporation of water into air at a constant pressure [11].

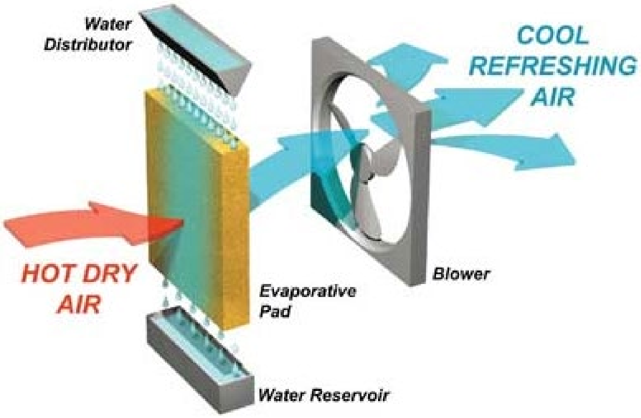

FIGURE 1: Evaporative Cooling Diagram [12]

By harnessing the evaporative cooling through the now colder and more humid air, produce can be maintained at a much better temperature soon after harvest. This helps a lot with the issues of food waste, as cooling the produce soon after harvest is one of the most effective tactics that can keep products fresh. This is important because keeping produce fresh longer can not only empower farmers by giving them more control over when they sell their crops, but also increases their income as less food will be wasted since produce will last longer giving them more time to sell at optimal times in nearby markets.

2.2 PREVIOUS WORK

D-Lab has been exploring the use of forced-air evaporative cooling in low-income rural communities to keep fresh produce cool. Currently, D-Lab is deploying a solution based on retrofitting a shipping container as a room-sized coolers in both Kenya and India, with a full-sized set up also constructed at D-Lab. The approach uses retrofitted shipping containers, that have been insulated and store crates of produce. The shipping container uses a fan to push hot air through wetted pads, thus producing cool and humid air. This air is then directed through the crates of produce before exiting through exhaust vents. This way the vegetables are cooled by the humid air. Figure 2 below shows this airflow within the shipping container configuration. For the system to work, there is a pumping system that distributes water through the cooling pads, which are made of corrugated cellulose, and any excess water that is not picked up by the pads gets collected through some channels at the bottom of the cooling pads and brought back to the reservoir. Since both the fan and pump require electricity, there is also a photovoltaic system to help power the system even in off the grid applications.

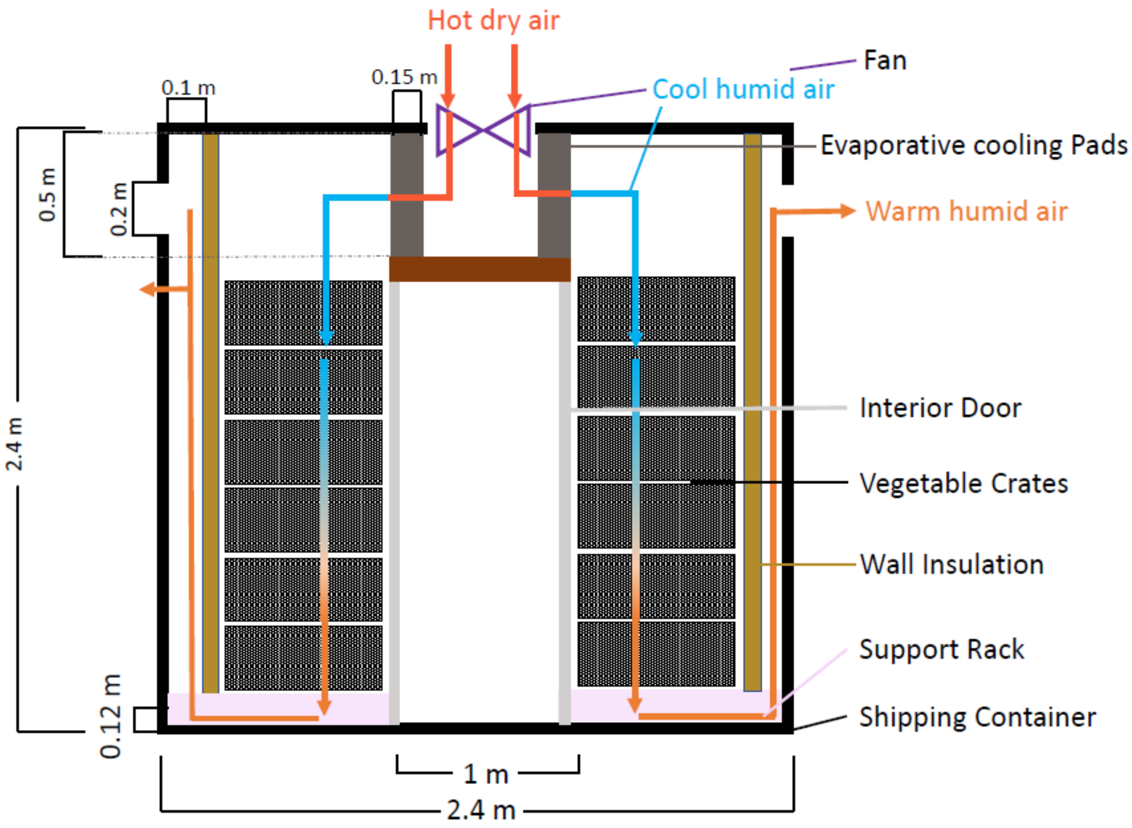

FIGURE 2: Diagram of Full-Scale Shipping Container

The arrangement of the vegetable crates within the shipping container can be seen in a top-down view in figure 3 below. There is produce arranged on either side of a central aisle, which is located below where the fan is. The width of the aisle is such that a person can go in and rearrange the crates comfortably, designed as such for easy user management. The crates can be accessed by moving the sliding interior door, although this door design might be modified in future iterations of the system. There is evaporative cooling that runs the entire chamber's length so that the cool, humid air is evenly distributed. For the cooling to best work the entire system must be airtight so that the flow of air is as expected and flowing through all the different vegetable crates. The warm humid air, which is the air after it has flown through the vegetable crates, exhausts through a small exhaust gap that is accessed from below the vegetable crates through the support crate, which is either welded metal or uses wooden shipping pallets, relying on the pressure of the fan blowing it in that direction and then out through cut holes on the side of the shipping container.

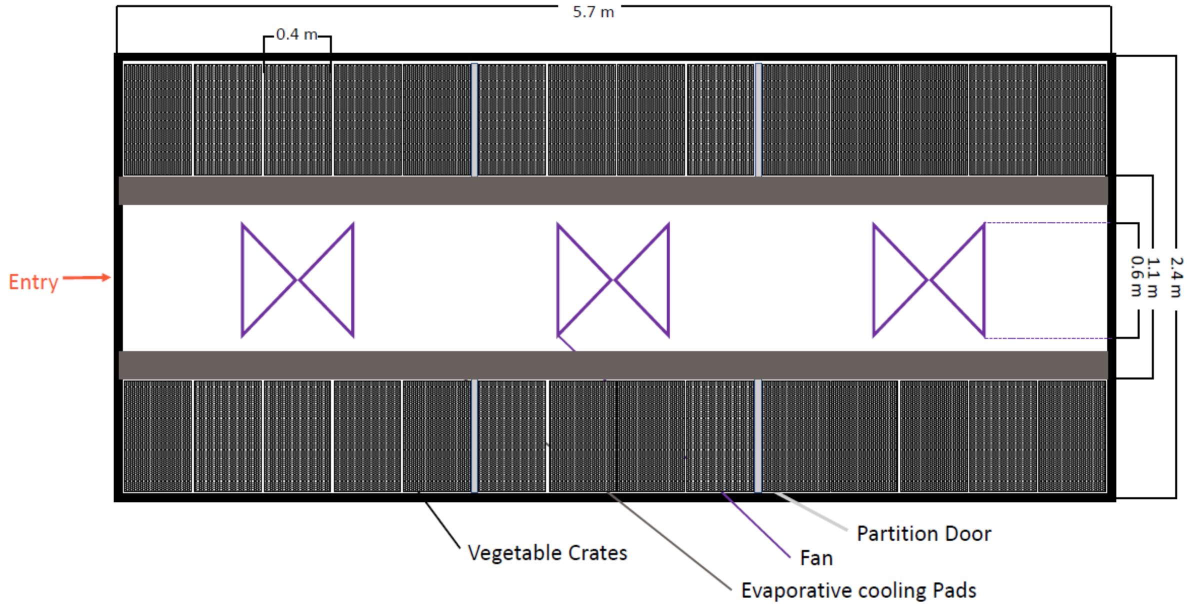

FIGURE 3: Overhead Diagram of Full-Scale Shipping Container

This system was chosen because of some key advantages it offers over a lot of traditional cooling systems. For one this system offers fast cooling, allowing for around 3,000 kg of produce to be cooled 8°C in under 6 hours inside of a 20' shipping container, which is a great reduction from the typical 10-15 hours needed to achieve such a drop using typical cold rooms[13]. There is a slight downside in that this approach cannot reach temperatures below 20°C, which typical cold rooms can achieve, but produce storage does not need to be that low for most fruits and vegetables. Replacing a cold room with evaporative cooling of this design has also been shown to have a lower cost and lower energy consumption, both of which are immensely helpful to the communities that are going to benefit from this device. This approach also has a much lower water consumption than more passive evaporative cooling approaches, such as the charcoal coolers shown in figure 4.

FIGURE 4: Charcoal Cold Rooms for Passive Evaporative Cooling

This forced evaporative cooling solution was developed by D-Lab through a long process of lab testing and implemented experiments with full scale evaporative cooling chambers in Kenya. This solution involved close collaborations with researchers in the University of Nairobi who have experience working with the farming cooperatives that this technology hopes to assist along with experience working on different kinds of cooling chambers, there have also been a number of visits to the region to get deeper understandings of the needs of the communities as well as feedback from the World Vegetable Center and the Hunnarshala Foundation, who also have extensive experience and knowledge on this subject. There is currently a full-scale version of the shipping container cooler that has been built at D-Lab as well as 2 current deployments of the pilot of the technology, reference appendix A for further information about these full-scale chambers. The pilot programs of this technology are of 20’ shipping containers that are being retrofitted into evaporative cooling chambers in collaboration to partners in Kenya and in India.

3. TEST CHAMBER

With a high demand for improving food storage to reduce food waste, and promising community partner feedback on the feasibility of implementing forced air evaporative cooling as a real solution to combat the cooling problem that compromises the lifetime of produce. To optimize the performance of this technology a smaller chamber will be built with certain components intentionally made such that they are variable, allowing for further research of how alterations to some parameters of the chamber may affect the cooling potential of the technology.

Specifically, this thesis aims to design and construct an indoor representative version of the forced-air evaporative cooling chamber being built in shipping containers such that experiments can be run to investigate the heat and mass transfer behavior and optimize the system.

3.1. DESIGN

The deciding feature in the dimensional planning of the chamber came down to the choice to build the chamber such that two crate stacks would be cooled. This set the width of the chamber. The additional decision to only include one of the side aisles of cooling instead of the symmetrical two rows of crate approach established the other dimension of the chamber. Figure 4 shows the layout and critical dimensions of the indoor chamber that has been constructed.

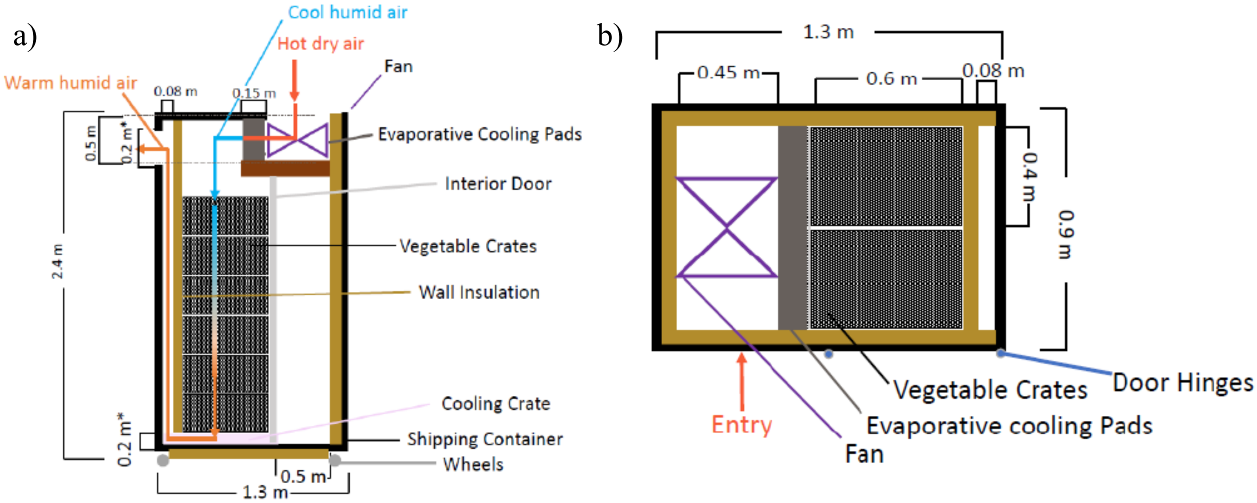

FIGURE 5: Testing Chamber Layout. a) Side view of the test chamber; b) top-down view of the test chamber.

A key part of ensuring even cooling in the chamber is the implementation of symmetry and adiabatic layers so that heat transfer is well understood within the chamber. The use of insulation was intentionally decided so that such symmetry can occur. This can be seen in the insulation on the far right of the chamber, which is meant to make it so that the as transfer occurs by the crates on the left, the resistance through the crate is comparable to the thermal resistance happening through the far right. The insulation added to both the hinged door and its opposing wall also is such that there is symmetry between those two planes. Additionally, the implementation of insulation on both the top and bottom of the chamber was such that the heat loss from the top and bottom would also be symmetrical.

The need for bottom insulation came about with the decision to make the box mobile. By elevating the entire chamber on some castor wheels, the entire chamber can be moved throughout the research space. Another design feature that was made based on the available space was the choice to use a double hinged elbow door. This design was made so that accessing both the aisle and the vegetable crates could easily be done from the outside without having the door block too much space in the shared research space. By using the elbow joint, the door can be tucked back and around the box when opened, providing much access to all the areas of interest. Figure 5 shows the elbow joint door in the chamber and how it opens along with its latching system to set the door in place when closed.

FIGURE 6: Elbow hinged door pictures. a) Door closed and latched into place; b) door open at the hinge; c) fully opened hinge door, with the door tucked to the side.

A goal of the construction of this box is to use it to run experiments on the cooling capabilities of the technology to optimize its operation. To achieve this some components of the chamber were designed to be modifiable. The exhaust vent was cut out to be a larger than usual space so that it could be covered up to run tests on how the exhaust vent size might affect the cooling of the chamber. The support crate was also made to be a minimum height off the ground and could be elevated further using blocks to test varying height set ups for the vegetable crates. To set the vegetable crates such that the air gap by the exhaust wall could be achieved, the support crate was made using square metal tubing welded as shown in figure 7. The air gap between the bottom of the chamber and the start of the insulation offset from the exhaust wall was also designed to be the largest of interest such that it could be covered up to test smaller gap configurations.

FIGURE 7: Welded Support Crate

3.2. FAN

Being able to circulate air throughout the test chamber through a variety of different speeds would allow for the test chamber to gather data about the effects of varying air inputs. As such it was a priority in the decision-making process for the fan to get an appropriately powerful fan that would be able to be controlled to different speed configurations. A critical consideration also came from estimating what would be the desired flow rate of the chamber utilizing the known flow rate of the full-scale shipping 20’ container chamber. To calculate this a ratio relation of the flow rate to volume of the two chambers was as follows: flow $Q_{20}/V_{20'}= Q_{mini}/V_{mini}$, where Q is flow rate and V is the volume of the chamber. Using that $Q_{20}=6458.3$ CFM and $V_{20}=33.2\ m^3$ and calculating that $V_{mini}\approx 3.5m^3$, the desired flow rate would be around 700CFM. The fan chosen was able to meet this requirement by a significant margin which would give the experimental freedom to try a series of different configurations for the speed. Further details on the fan chosen can be found in the materials list in Appendix B and more information on the process of configuring the fan will be discussed in the following section.

To install the fan selected, a switch was ordered along with the fan so that its speed could be modified. This meant that some wiring had to be done to get the fan up and running. Figure 8 below shows the wiring that set up the fan, with the different colors being representative of the wire colors used in the installation, following the general convention that green wiring is ground, blue is neutral and brown is live.

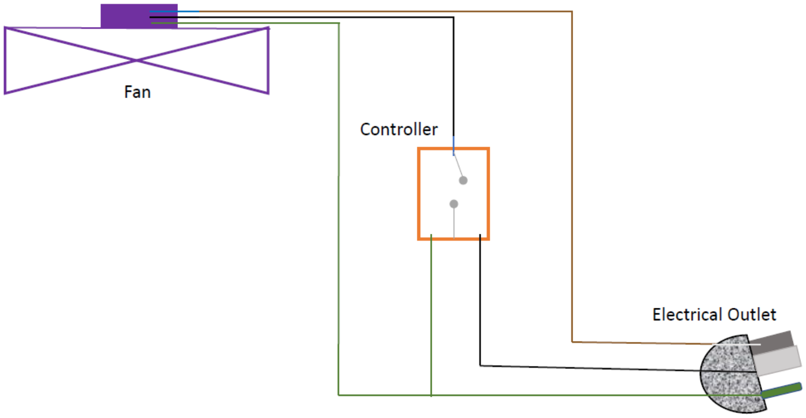

FIGURE 8: Fan Components and Wiring Diagram

Unlike the off the grid shipping containers that will require solar panels for the fan and other electrical components to run, this chamber can be directly plugged into the wall, which is why the figure above features a wall plug along with the switch and the fan.

3.3 PLUMBING

A key detail of the evaporative cooling is the use of cooling pads to get the forced air cooler so that the vegetables in the crates. To get the hot air to lose heat through the pads, the pads need to be wetted. This is done using a reservoir and pump system in both the full-scale system and in this experimental chamber. The general approach can be seen in figure 9 below, detailing the overall plumbing structure used in the testing chamber, which is only slightly adapted from the full-scale system. The main differences in the system come from the scale of the reservoirs, the testing chamber is much smaller so less water will need to be circulating. The testing chamber also uses PVC piping for harnessing the evaporative cooling pad system rather than running metallic u brackets, more information on the metal harness in the full-scale chamber may be found in Appendix A. The change in harness in the testing chamber was partly due to the reduced weight capacity that the harness would have to hold due to reduced pad coverage distance in the much smaller testing chamber. Another benefit of this approach is that this harnessing approach will hopefully be the easiest to do rapid replacements of in testing scenarios where different cooling pad layouts may be desired.

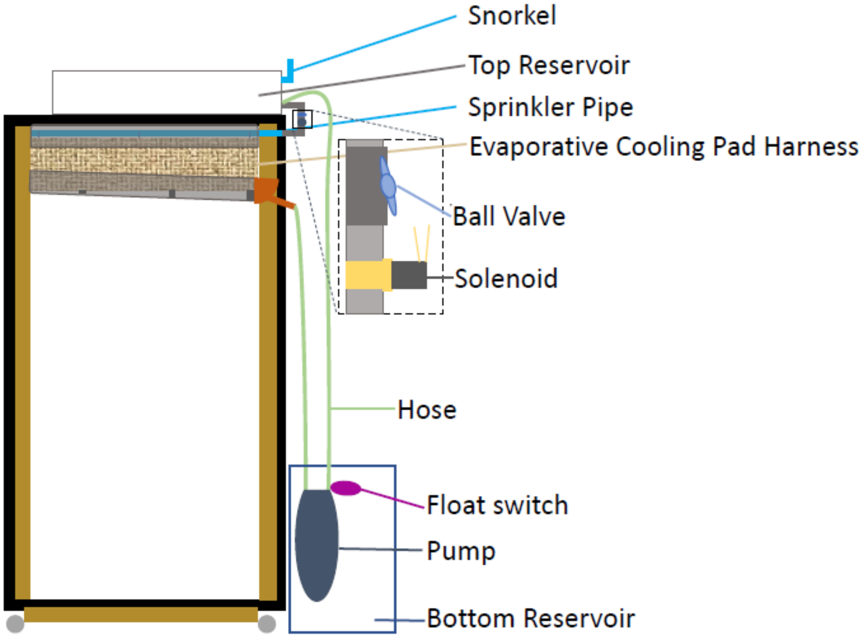

FIGURE 9: Diagram of Plumbing in the Testing Chamber

The following sections follows the testing and prototyping steps taken in the installation of the plumbing for the testing chamber.

3.3.1 LIQUID FLOW RATE TESTING

To test the needed height difference between the top reservoir and the watering on the cooling pad system a tabletop test was run using PVC piping drilled with small holes. Holding this set up in an aquarium and holding the piping level to simulate the top of the cooling pad mechanism, a sufficient height is needed to acquire sufficient pressure such that the water flows all the way through the piping properly wetting the pads throughout. Figure 10 below shows this experimental set up.

FIGURE 10: Aquarium Testing for Water Flow Rate

This experiment also helped guide the size and number of perforations that should occur in the pipe. As such for the 80cm test chamber size of piping needed to water the evaporative cooling pad set up, from now on referred to as the ‘sprinkler’ piping, 30 1mm holes were drilled in, with some spacing, around 3cm on either end, budgeted for the edges of the pads. Once the sprinkler piping was done, it was tested with the cooling pads using an evaporative cooling harness, as can be seen in figure 11. The methodology for the design and manufacture of this harness will be covered in the following section.

FIGURE 11: Testing Harness with Evaporative Cooling Pads in an Aquarium Test

3.3.2 EVAPORATIVE COOLING HARNESS

To hold the evaporative cooling in the chamber together, the following must be true: the sprinkler piping, described in the previous section, must be held securely sandwiched to the evaporative cooling pads, and the whole set up should remain securely attached to the ceiling of the chamber. This was achieved in this test chamber by using 3” PVC piping along with some thin steel bars.

To encourage the drainage on the bottom of the supports, a small tilt was designed into the holder, as shown in figure 12. The bars were installed in a cross shape to best support the two pads needed to cover the width of the test chamber. Figure 13 shows the assembled evaporative cooling harness with all its components, a breakdown of them can be found in the materials list in Appendix B.

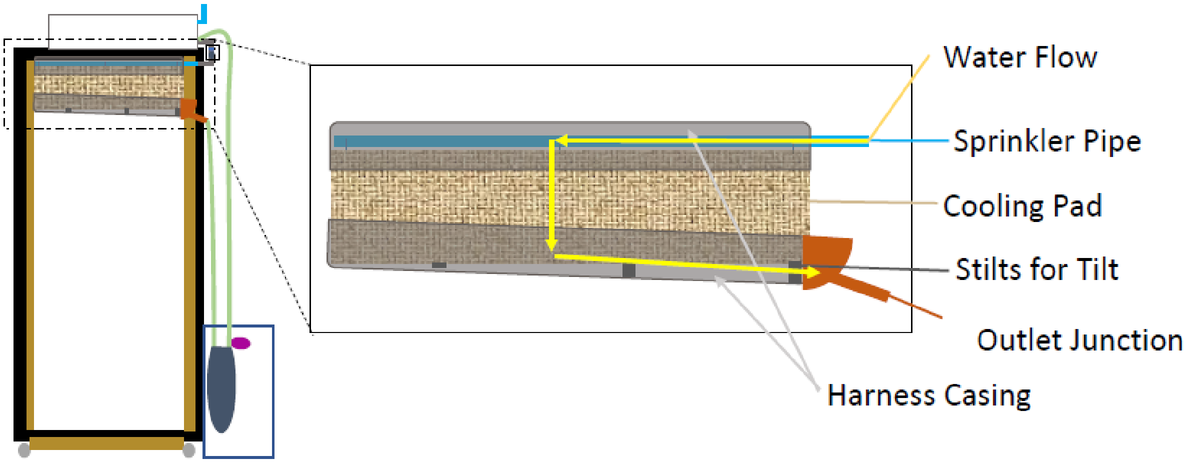

FIGURE 12: Evaporative Cooling Bottom Harness Tilting Diagram

FIGURE 13: Evaporative Cooling Assembled Harness

3.3.3 SENSORS IMPLEMENTED

The plumbing system requires a few different controls, which will be further described in the controls section of this work. The inclusion of these controls occurs primarily using a pump which was originally shown in figure 7. By implementing a pump in the bottom reservoir, when water is sent to the top reservoir for use by the evaporative cooler described in previous sections can be controlled. This pump is in the bottom reservoir and uses a float switch to track how close to emptying out that reservoir is. The switch can turn the pump off if the bottom reservoir is close to bottoming out, the pump and float switch used in this test chamber can be seen in figure 14, with further information on materials in Appendix B. The bottom reservoir is one of four failure modes that were cause of concern for this plumbing system.

FIGURE 14: Pump and Float Switch

Another failure concern was the bottom reservoir overflowing, which will simply be resolved by using the volume of the lower reservoir to dictate the initial water volume used in the system. Since this system is located indoors, no additional water should enter the system as is the case in the full-scale models that are exposed to weather elements like rain.

The other failure modes considered were related to the top reservoir. A concern over potential pressure builds up or potential overflow led to the inclusion of a snorkeler to the top reservoir to encourage equalizing the fluid inside the reservoir with ambient conditions. Worries over overfilling the top reservoir also led to inserting a snorkel into the top reservoir, which figure 15 shows. Another potential failure mode for the top reservoir came from the top reservoir emptying too much, which is one of the motivations for the use of a solenoid valve to control the outflow of water from the top reservoir into the evaporative cooling harness. Figure 16 shows this solenoid valve, but the controls that dictate its operation will be further discussed in a future section.

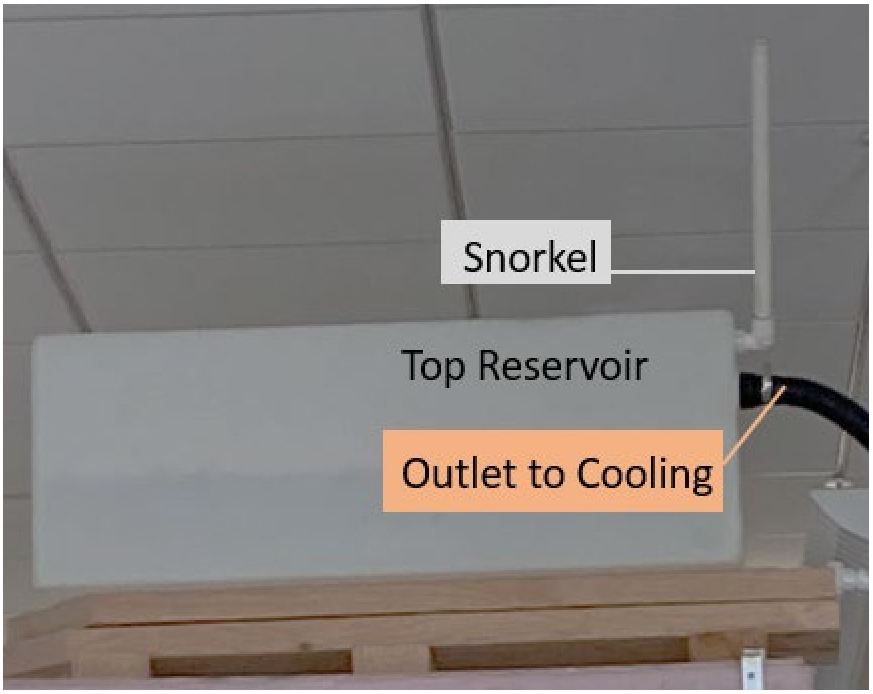

FIGURE 15: Top Reservoir Overflow Snorkel

FIGURE 16: Solenoid Valve

3.3.4 OVERVIEW

The assembled plumbing used for this test chamber was constructed in the configuration that can be seen in figure 17. Different PVC components are attached using either coupling joints, elbow joints, and unions that use more interchangeable screw on pieces. The couplings and elbows were adhered using PVC cement while screw terminals that did not feature a waterproof O-ring seal were attached using nylon tape.

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FIGURE 17: Assembled Plumbing Hardware. a) Top reservoir to cooling harness; b) full system.

3.4 CONTROL SYSTEM

3.4.1 OVERVIEW

A key aspect of this system is the controls components. This is run by a Particle Argon control board for this lab set up, with Boron kits being used for more remote locations where Wi-Fi is not readily available and instead cellular signal can be used. The board set up is such that 8 BME sensors, which record pressure, humidity, and temperature The sensor is selected due to its low power requirements making it key for this application. There are also 12 temperature probes scattered throughout the chamber collecting real time data on the conditions of different areas of interest. To get information on how well the evaporative cooling is working, some water moisture sensors will be mounted by the pads and will be providing live data on the conditions of them. There is also an anemometer that will be mounted near the exhaust to give insight as to the wind speed at the outlet. The fan power will also be controlled, as is described in the upcoming ventilation section. Figure 18 shows the general sensor location for the entire test chamber, in future sections the value of these sensor locations will be further discussed.

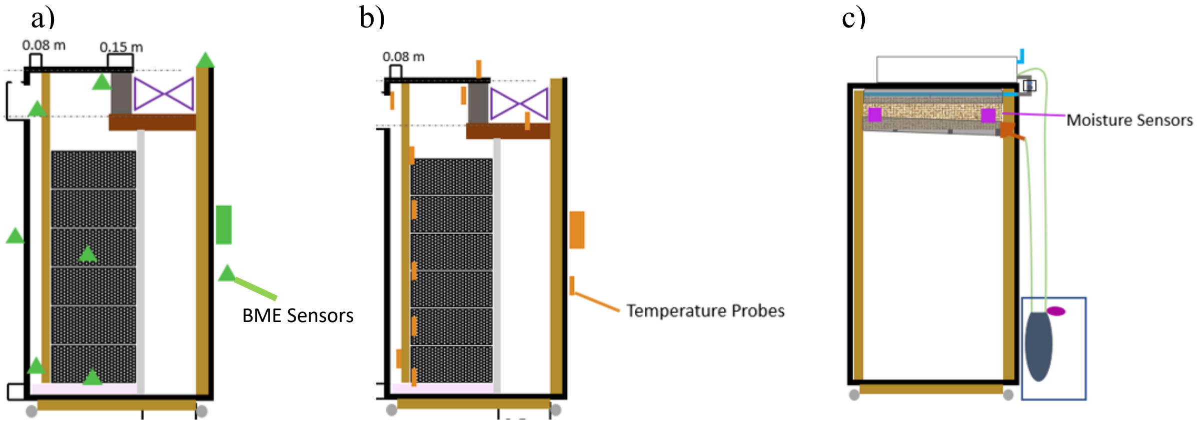

FIGURE 18: Test Chamber Sensor Locations. a) Shows the locations where the BME sensors will be located; b) shows temperature probe; c) shows the water moisture sensors that will be used for insight to the state of the cooling pads.

The boards used by this system to connect all the needed sensors can be seen in figure 19 and 20 below. There are two main boards being used, one with a multiplexor that contains all the connectors to the sensors directly, and a separate board that features the Argon chip as well as all main power connections for the boards and sensors.

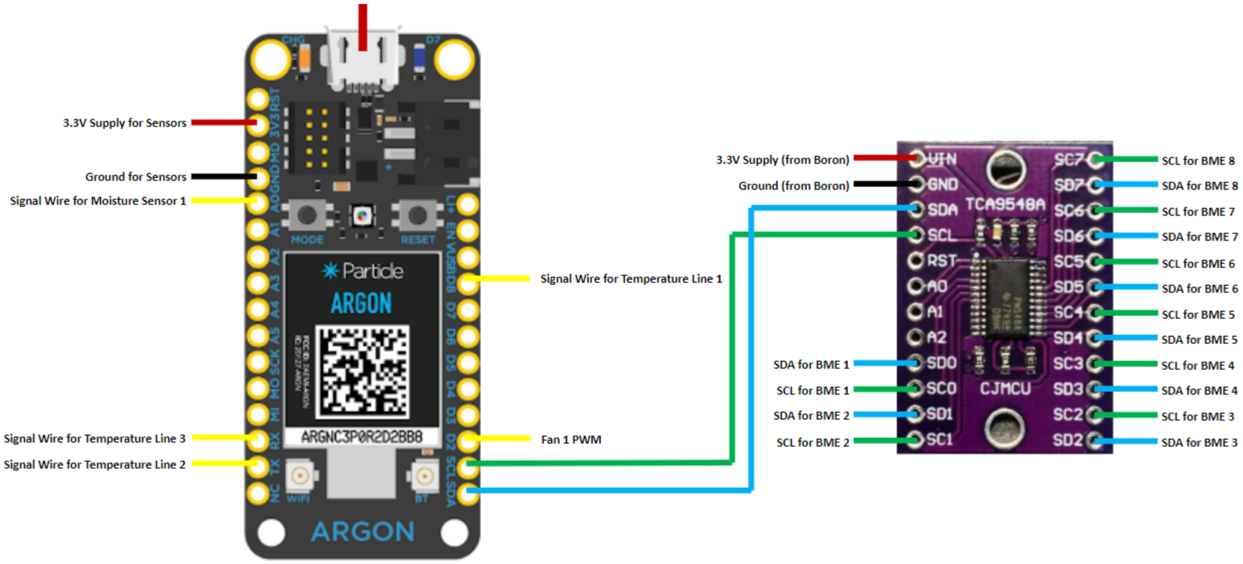

FIGURE 19: Electronic Diagram

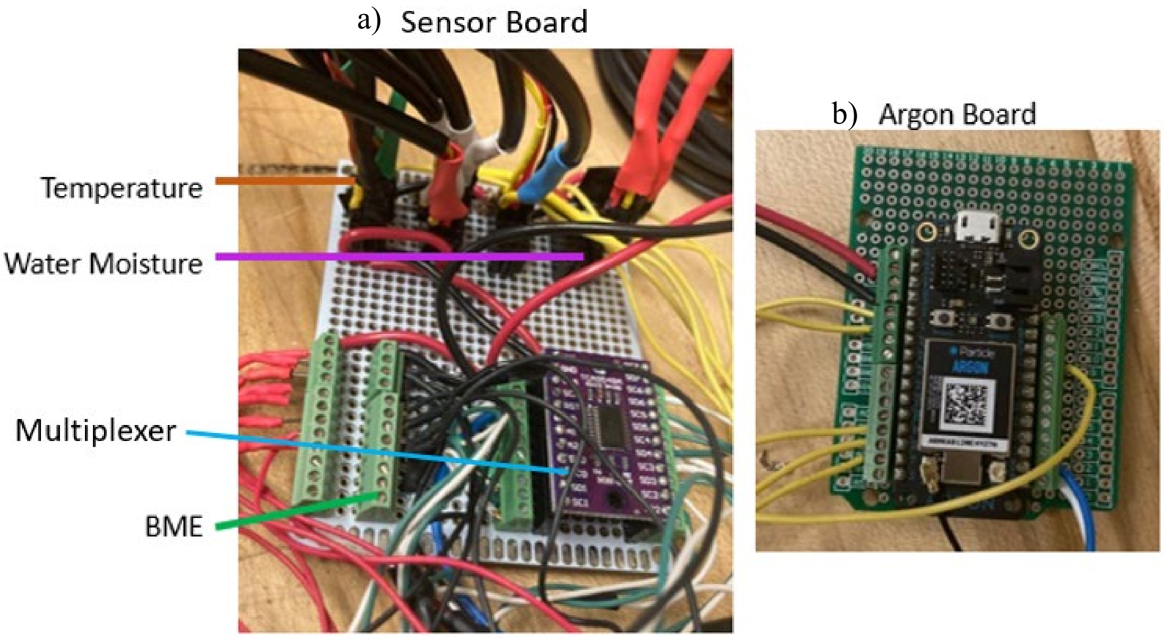

FIGURE 20: Wired Up Boards. a) Sensor board with wired sensors; b) Particle Argon board.

3.4.2 PUMPING CONTROLS

The pumping system is a critical component of this system as it ensures the evaporative cooling pads remain wet thus allowing the cooling to occur. The pumping comes from the bottom reservoir, where there is a pump connected to a float switch that pushes the water up to the top reservoir. The top reservoir then gets filled up through the bottom pump. A failure mode accounted for in the top reservoir is accidental overflow or pressure build up, which is why there is a snorkel installed in the top reservoir that will equalize the pressure of the water in the tank with ambient pressure.
From the top reservoir there is an outlet from which the water can flow out that leads to the sprinkler piping in the evaporative cooling harness. To control for the flow of water that pours out of the top reservoir, there are two valves limiting the flow of water, a ball valve and solenoid. The ball valve's primary task is a physical obstruction to the flow setting the flow rate for the water and can be adjusted to be either open during pump operation or closed if no testing is occurring. The solenoid is the electronically controlled valve used to control the flow of water into the pads. The way a solenoid valve works is that a plunger keeps the valve closed preventing any fluid flow until the solenoid coil is powered, which results in a magnetic field that then raises the plunger allowing fluid flow. The power for the solenoid can be hand controlled with an installed switch, primarily for failsafe reasons, but will also be controlled through the Argon board. The solenoid valve will operate on a timer, such that it is operational on a cycle, around 5 seconds on and 5 seconds off.

From the valves, the next step is to have the water travel through the evaporative cooling harness. This occurs by having the water flow down the sprinkler pipe, which is installed into the chamber, level, and thus get the evaporative cooling pads wet all the way across the chamber, which in this case covers 80cm of cooling pads. There are 7cm in both ends of the sprinkler pipe that are not drilled, such that they do not sprinkle the very edge of the cooling pad, helping ensure that there are no leaks. From the cooling pads the flow goes next to the bottom of the evaporative cooling harness, which is tilted down to drive the flow downward. The tilt was achieved using stilts for tilts, as can be seen in figure 12, which in the testing chamber were small pieces of PVC tubing cut to a 5° tilt. From there the water flows through a homemade cap outlet junction into the hosing that connects it to the bottom reservoir, thus completing the cycle.

3.4.3 VENTILATION CONTROLS

The ventilation controls for this system consist entirely of controlling when the fan turns on and the speed at which it is operating. The main components are the fan, switch, and plug as shown in figure 8. The switch is also pictured in figure 21, showing the fan's ability to work at a range of speeds that are selected using a dial. The dial will establish the speed at which the fan will spin when turned on, but it is a relay switch on the plug that will control when the fan is turned on. The details of the relay along with other controls needed over electrical power will be discussed in the following power controls section.

FIGURE 21: Fan's Control Switch

The controls for the fans rely on feedback from various parts of the system. Specifically, the crate temperatures are compared with the ambient temperature, outside of the chamber, to decide whether the fan is engaged. If the crate temperature is lower than the ambient temperature, the fan will be turned off. If the crate temperature is higher than the ambient temperature then the fan will be turned on unless the difference in temperature between the crate temperature readings and the wet bulb, which is the temperature read by a thermometer covered by a soaked cloth, reading the temperature for the most humid air possible. Another metric compared is whether the ratio between the crate temperature and the wetted bulb temperature is within 70%.

3.4.4 POWER CONTROLS

Since the test chamber will be operated exclusively in a lab setting, it allows for greater flexibility in the power consumption of the overall system. Components like the fan or pump were not chosen primarily in metrics of energy efficiency since reliance in intermittent energy sources like solar power do not apply to this model. Since implementations of the results of this testing chamber will be implemented in other locations where such requirements are needed, having a good understanding of the power use at different configurations will also prove to be key. To track the power use, all wall plugs will be plugged in through a kill a watt, shown in figure 22, which measured the kW drawn through the outlet.

FIGURE 22: Kill a Watt

Additionally, to measure the power consumption, the actual power control of different components that we care to turn on and off also get plugged in using a relay. Figure 23 shows the relays used in the test chamber electronics. Relays work by converting electrical currents from varying voltages to ensure that the equipment connected is operating under specific operational controls [14]. The relays used are normally closed, meaning that the default operation, when a signal is not being received, is to cut power. This helps ensure safety in case of electrical failure as it ensures that the pumping though the chamber is paused and the fan also ceases operation. The specific components that use these switches control are the fan and the solenoid and they will be operated through the settings described in the ventilation and plumbing control sections, respectively. they will require turning on or off relative to the data collected from the sensors. Further details on the rationale to when the fan or solenoid valve are turned on can be found in the ventilation and plumbing sections above, respectively. The other electronic components, like the Argon and the pump are plugged into a source of electricity consistently. This is because the pump's power draw is separately controlled by the float switch thus it will not require additional controls. Additionally, the argon is always powered to ensure consistent data collection and control throughout operation.

FIGURE 23: Current Relay Switch

3.4.5 SAFETY OVERDRIVE SWITCHES

As previously mentioned, most components that could potentially pose a risk for either the chamber structure or general safety have had a kill switch incorporated. These switches all allow for the component to be turned off safely and reliably.

The pump in the bottom reservoir will have its power input cut off by the float switch when that is triggered. The float switch works by having an object float on the water with a sensor inside that will notify when the switch gets triggered when there is insufficient water in the container. If the object floating on the water tilts down, it shuts off the power since the tilt down indicates insufficient water. This switch could also be triggered by hand if the floating object simply gets submerged so that it tilts down.

The solenoid also has a switch wired into it so that it could be turned on or off externally beyond the typical control used during chamber operation. The ball valve by the solenoid also works as a failsafe as it can also be switched such that no flow occurs through that piping.

Additionally, critical components that are getting operational signals from the Argon are also connected to power through a relay, allowing for another way to ensure that power will be cut off if needed.

4. FUTURE WORK

4.1 EXPERIMENTATION PLAN

As was introduced in the Design section of the paper, this chamber was made such that different parameters can be modified such that further information can be known about the impacts of variation of them on the cooling capabilities of the chamber. These variations will motivate the future experimentation plan.

The most pressing parameter to explore with this chamber is the air flow. By running multiple tests with the fan dial at different settings, the air speeds at which the evaporative cooling will be most efficient could be experimentally found. Additionally, varying the evaporative cooling pad thicknesses will also be tested to find out how having increased thicknesses of pads may influence the cooling effects of the system.

Beyond the airflow, the testing chamber will also be used to explore the impact that different crate configurations have on the performance of this system. Since the chamber is designed such that 2 stacks of up to 7 crates can be stored, there are several permutations that can be explored with the testing chamber. Additionally, the support crate can be elevated to explore varying gaps beneath the crates and the impacts they have on the chamber. The items stored in the crate can also be varied to test the different effects that different crops may have. For the testing, small water bottles will initially be used while the chamber's configurations are initially explored, but eventually this is going to be varied to test things that are more similar in shape to actual fruits and vegetables before eventually running with vegetables stored to best simulate the intended action.

Additionally, the gap between the offset exhaust wall insulation and the floor can be modified by reducing the size of the gap through a barricade addition. The exhaust hole to the outside of the chamber is also currently designed to be larger than the exhaust in the full-scale chambers so different gap sizes can be attempted by selectively blocking sections of the exhaust.

4.2 CHAMBER IMPROVEMENTS

While at the time of writing the chamber is operational in its most critical components, it is not yet at a final state, and therefore certain improvements are going to be needed, with varying degrees of urgency. The most urgent of modifications is the finalization of insulation attachment as well as improved airproofing of sections of the chamber. This is urgent since it impacts the effectiveness of the cooling if symmetry is not achieved, or if air flow is not controlled within the chamber with minimal losses. Another urgent task is modifying the plumbing such that the top reservoir is shifted, allowing for the chamber to reside in its intended spot in the lab since right now it has limited mobility due to its height with the snorkeler attached.

A future addition to the chamber involves the addition of two more sensors to the top reservoir, to be used to avoid both overfill and bottoming out of the top reservoir. To avoid overfilling this top reservoir there is a water level sensor rigged up to the top, as was shown in figure 16, that is set to stop the flow of the bottom pump once that level is reached. A second sensor, also shown in the figure, will be placed lower in the reservoir, and is intended to alert of a too-empty top reservoir. These sensors could then be used to inform the solenoid's phase, meaning whether it was open or closed, ensuring that the system runs smoothly.

5. CONCLUSIONS

The goal of this work was to design and construct a test chamber that would simulate the forced evaporative cooling that is needed to advance the approach as a solution for fruit and vegetable preservation post-harvest. This was successfully accomplished through the test chamber made, which has all the critical design components described in previous sections. The sensor system is up and running and collecting information about the chamber qualities which will be used to check in on the quality of chamber operation and the impacts that variations may have. The continued use of this chamber will be important for exploring the areas of interest described in the testing plan in the Future Works section. The knowledge gained from using this test chamber will educate design decisions and priorities for both current and future implementations of this technology.

6. APPENDIX

6.1 APPENDIX A: FULL SCALE EVAPORATIVE COOLING CHAMBER

The full-scale evaporative cooling chambers use a retrofitted shipping container in order to have two sections of stacked produce crates on either side of a center aisle that can be accessed to facilitate management and movement of the crates. The shipping containers used in all 3 pilots of the technology (India, Kenya and the chamber in Cambridge at MIT's D-Lab) use a 20' shipping container that has been set up in a similar fashion to the testing chamber. The purpose of this appendix is to provide further background to the finer details of these full-scale chambers as they have been key in determining the design of the testing chamber. Figure A1 below shows the status of the full-scale chamber in India.

Figure A-1: India Full-Scale Chamber

As can be seen from figure A-1 above there are a series of exhaust vents cut out on either side of the container all the way through the end. While only one side can be seen in the image, the other side is a reflection since symmetry is utilized about the center aisle of the chamber to ensure equal cooling throughout. These exhaust vents are the output of the air that has been blown in by the fans, which can be seen underneath the tent at the top of the chamber in figure A-1. After the fans blow in the air, the air flows through the evaporative cooling pads, which can be seen in the top center of the container in image A-1 but are shown more closely in figure A-2 below. From the cooling pads the now much cooler air is forced through the vegetable crates, cooling them before flowing through the support crate, the metal support in the bottom right of the shipping container in figure A-1, and through to the exhaust, refer to figure 2 for a diagram of the flow since it is not shown in the image due to obstruction by the insulation.

FIGURE A-2: Pad Support and Fan Installation in Full-Scale

The plumbing of the system, which is responsible for ensuring the cooling pads remain moist thus facilitating the humidifying and cooling of the air, can consist of either a 1 tank or 2 tank system. The India pilot is currently utilizing a 2-tank system while the D-Lab chamber is using a 1 tank system. Both will be discussed further below.

The figure below shows the 2-tank system currently being used in India. Much like the test chamber constructed, it consists of a top and bottom reservoir. Where the top reservoir feeds into the evaporative cooling pads and the bottom reservoir is used to catch the water that flows through the cooling pads. Figure A-3 below shows the tank set-up in the chamber being constructed in India.

FIGURE A-3: 2 Tank System in India.

The alternative pumping approach, which is utilized in the chamber that was built at D-Lab uses only a single bottom reservoir that pumps up to the top of the evaporative cooling pads and then gathers the runoff from the pads. Since this chamber is designed to be a test set up, this reservoir was placed inside of the cooler in the place of where the crate storage would be across the aisle from the installed crate section figure A-4 shows this system, with the recycling bin being used as the water reservoir.

FIGURE A-4: 1 Tank system in D-Lab.

The crate set up for the full-scale shipping container can be seen in Figure 3, this shows how the full length of the container allows for sections of 2 stacks of vegetable crates that run along both sides of the center aisle. The full-scale chamber at D-Lab is shown in the figure below and highlights a few different features around the compartmentalization of the produce crates. Part A of figure A-5 below shows the insulation that is used to separate the different sections between the two crate stacks. Meanwhile part B shows the sliding door that was chosen due to its ability to allow for complete access to all the crates in the section which allows for the user to easily configure the crates. Part B also shows the configuration of the crate compartment relative to the evaporative cooling pads, which are within the wooden structure at the top of the image. The air flows through the pads and is fed directly to the crate stacks through the opening at the top of the crate section. This section is air sealed from the middle corridor to ensure that all the cooling is going through the crates and out the exhaust and not getting wasted through the corridors.

FIGURE A-5: Vegetable Crate Storage Compartment. a) vegetable crates insulated behind sliding door; b) vegetable crates seen with open sliding door.

6.2 APPENDIX B: LIST OF MATERIALS

The following table breaks down the materials used to construct the test chamber alongside quantities needed.

Item Description	System	Quantity
3/8” plywood sheets 4’x8’	Structure	7
¼” plywood sheet	Structure (roof)	1
8’ 2x4 wood	Structure	6
Caster Wheels	Structure (mobility)	4
R10 2” Insulation Sheets 4’x8’	Structure	6
Hinges	Structure	3
Latches	Structure	3
Fan (DXP400-4AC-11 - DXP Motorized Axial AC Fans - Continental Fan Manufacturing Inc. (cfmfans.com))	Ventilation	1
Fan Speed Control Switch (same link as fan)	Ventilation(control)	1
Pump (https://www.amazon.com/Superior-Pump-92250-Thermoplastic-Submersible/dp/B000IJR5F6)	Plumbing	1
Hose (pump drainage kit)	Plumbing	1
Solenoid Valve (https://www.amazon.com/Electric-Solenoid-Normally-Closed-diesel/dp/B007N0J98E)	Plumbing (control)	1
Ball Valve (https://www.zoro.com/zoro-select-34-socket-pvc-ball-valve-inline-107-634-np/i/G2134465/)	Plumbing (control)	1
Top Reservoir 20 gal (Amazon.com: Class A Customs | T-2000-BPK| 20 Gallon Fresh Water Tank & Plumbing Kit RV Concession : Automotive)	Plumbing	1
Bottom Reservoir 30gal (trashcan used atm)	Plumbing	1
3” PVC tubing	Plumbing (evaporative cooling harness)	80cm, cut in half lengthwise
3” PVC endcap	Plumbing (evaporative cooling harness)	1
¾” PVC tubing	Plumbing (evaporative cooling harness and general connections)	Miscellaneous lengths used
PVC tubing connectors (unions, elbow joints and collars, miscellaneous fittings)	Plumbing (connections)	Varying quantities for

		different components, refer to image_ for idea on how it was connected
Argon Particle control board https://store.particle.io/products/argon?gclid=Cj0KCQjwyMiTBhDKARIsAAJ-9VusqDvPSfKWkIof1OOB8j1pLkXgYAX_gqsCJYtnDJnfA4mNil-Tu1MaAkWJEALw_wcB	Electronics	1
Multiplexer https://www.amazon.com/AITRIP-PCSTCA9548A-Multiplexer-Breakout-Expansion/dp/B08JGSMRF9/	Electronics	1
Protoboards: (https://www.amazon.com/DEYUE-Double-sided-Prototyping-Solder-able-Protoboards/dp/B07FFDFLZ3/)	Electronics	2
Screw terminals (https://www.amazon.com/SamIdea-10Pieces-2-54mm-Terminal-Assorted/dp/B07FTJSNN7/) and Header pins (https://www.amazon.com/HiLetgo-20pcs-2-54mm-Single-Header/dp/B07R5QDL8D/)	Electronics	Miscellaneous quantities, refer to figure _
BME sensors (https://www.amazon.com/Onyehn-Temperature-Humidity-Barometric-Pressure/dp/B07KR24P6P/)	Electronics	8
Temperature Sensors DS18B20 (https://www.amazon.com/Gikfun-DS18B20-Temperature-Waterproof-EK1083x3/dp/B012C597T0/)	Electronics	12 used; 25 max
Humidity Sensors (https://www.amazon.com/CENTAURUS-Capacitive-Corrosion-Resistant-Detection/dp/B09JNJ3B2X/)	Electronics	2
Water Level Sensors (https://www.amazon.com/Taidacent-Contact-Liquid-Sensor-Controller/dp/B07FC5RGC7/)	Electronics	2 needed in future

Anemometer (https://www.amazon.com/HOLDPEAK-Anemometer-Measuring-Temperature-Backlight/dp/B00ZHKWCP4/)	Electronics	1
Kill-a-watt (https://www.amazon.com/Electricity-Monitor-Voltage-Overload-Protection/dp/B07DPJ3RGB/)	Electronics	2
Relay Controller What we are using now: https://www.globaltestsupply.com/product/scs-770069-power-relay The ones that will be migrated to this summer: https://www.amazon.com/HiLetgo-Channel-Isolation-Support-Trigger/dp/B00LW15D1M/	Electronics	2

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FIGURE SOURCES