SMART PASSIVE AMBIENT CONTROL FOR INDOOR VERTICAL FARMING BY SIMULATION AND EMPIRICAL STUDY

by

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Rafiqul Islam

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ABSTRACT

The objective of this research is to design and develop a smart passive temperature control system for indoor vertical farming by simulation and empirical study. Passive temperature control is defined as the process of controlling or manipulating the temperature of a system with natural heat transfer like conduction, convection, and radiation, etc and the purpose is to reduce energy consumption. And indoor vertical farming (IVF) can be defined as the practice of growing produce stacked one above another in a closed and controlled environment. With many benefits of IVF like saving space, unaffected by adverse weather, minimize water usage, fresh food production, reducing transportation cost, etc., it also has some challenges like temperature and humidity, air circulation, equipment setup due to limited space, energy consumption due to artificial lights, etc. Among all the challenges, the high temperature of air and water inside the closed environment is a big issue and it can be mitigated by passive temperature control. This research will focus on how the temperature of the water for growing plants can be controlled using passive temperature control.

The IVF in EverGreen lab in the Freeman Center, San Marcos, TX is considered as the case study to implement passive temperature control (PTC) system. First, the theoretical calculation of the energy required to cool down the system make it favorable for the plants is estimated and compared with the energy consumption after adding PTC and found that the energy consumption for cooling down the system can be reduced by using passive temperature control combining with the active cooling system. Then a computational fluid dynamics (CFD) model is developed to simulate the effect of outside temperature on the indoor air and water and the model is validated with experimental data. The purpose of CFD model is to simulate the temperature of indoor air and water and any given time of the day and year which will save time and equipment required for actual data collection and also find the optimum time period for transferring water from inside to outside as a PTC process and found that, with the combination of material or methods for conduction, convection & radiation can help to balance the indoor temperature from the external ambient temperature. Later, an empirical study is done based on observation and measurement of temperature data of air and water both from inside and outside of the shipping container in order to validate the simulation and use the water or growing solution as heat storage material which can be transferred from outside to inside for controlling temperature naturally. Finally, an integrative system is developed with the design of experiments by combining all the passive cooling systems that can reduce energy consumption and keep the environment livable to plants.

1. INTRODUCTION

Whether it is a factory or home or any building, air conditioning and water cooling are the most energy-consuming system. It is consistent, and it is necessary for both human comfort and some types of machinery. In earlier days, the necessity of air conditioning was only limited to those kinds of the sector. Lately, indoor vertical farming (IVF) is growing, and it is becoming popular as a new method of growing fresh produce in a controlled environment. Controlling air temperature, humidity, and water temperature, etc. are some of the key parameters for indoor vertical farming technology. But the main problem of temperature control of the indoor air and water is that the process is highly energy-intensive. High energy consumption increases the overall cost of the IVF system and they become financially an infeasible option. Therefore, any effort that can control the ambient with less or no energy consumption will be vital in the IVF industry. Smart and passive ambient control are among the methods that have been utilized in industrial and residential buildings [1]. This study will investigate the possibility of passive, smart, and other low-cost ambient control methods for IVF applications.

1.1 Literature Review

Indoor Vertical Farming

Indoor vertical farming can be defined as the practice of growing produce stacked one above another in a closed and controlled environment [1]. By using growing shelves mounted vertically, it significantly reduces the amount of land space needed to grow plants compared to traditional farming methods [2]. This type of growth is often associated with the city and urban farming because of its ability to thrive in limited space. Vertical farms are unique in that some setups don't require soil for plants to grow [3].

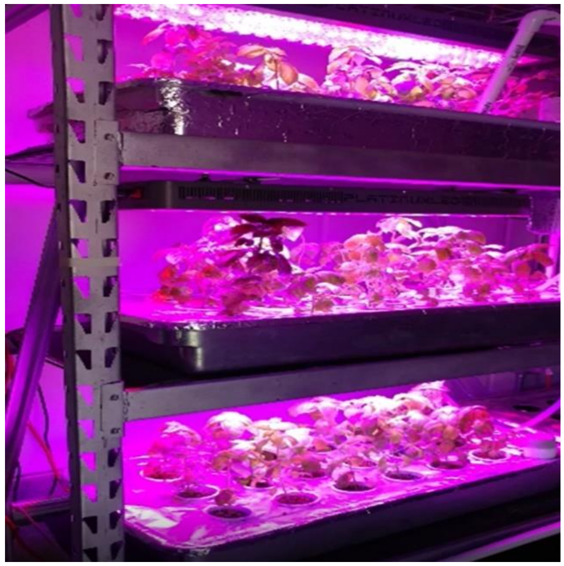


Figure 1: Indoor Vertical Farming with a hydroponic system [4].

Most are either hydroponic, where vegetables are grown in a nutrient-dense bowl of water, or aeroponic, where the plant roots are systematically sprayed with water and nutrients [5]. Artificial grow lights are used in indoor vertical farming.

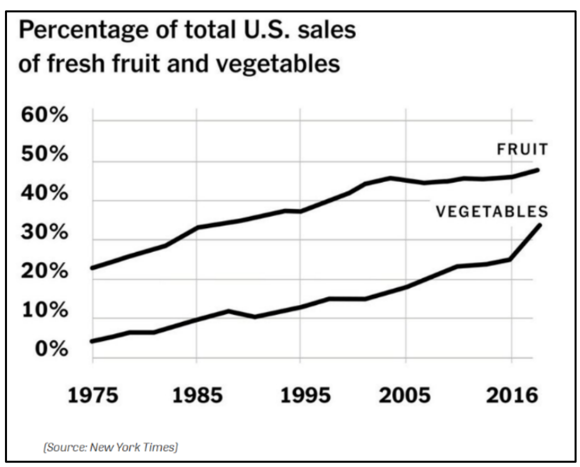


Figure 2: Historical growth of fresh product sales in the US [6].

Currently, the United States imports 35% of produce and travels an average of 2,000 miles, taking roughly 2 weeks before hitting the grocery store shelves. Since indoor vertical farming is largely local, vegetables grown in these vertical farms are much more appealing and edible for a longer period. With an extensive list of benefits, indoor vertical farming has the potential to vastly improve the modern agricultural landscape [1, 6].

1.1.1 Problems with indoor vertical farming:

- **Temperature and humidity:** The first climate management challenge that vertical farmers must overcome is figuring out how much cooling, dehumidification, and heating is required to manage the temperature and humidity of the grow space. In a VF, lighting contributes the greatest source of heat, followed by motors used to operate fans, pumps, and automation. Because VFs are often well-insulated and designed to operate day and night throughout the year, cooling is usually required 24/7 and year-round to remove the heat generated inside the space. Dehumidification is also constantly required to remove the moisture added to the air via evapotranspiration from the plants and irrigation system. The rate and quantity of evapotranspiration depend on several variables, including light intensity, air temperature, and humidity, etc. Heating systems in the VF are rarely required, due to all the heat generated inside the space by lights [7].
- **Air circulation:** The second biggest challenge is figuring out how to deliver the conditioned air everywhere within the vertical farm to create a (hopefully) uniform growing environment. When racks are spaced tightly together both vertically and horizontally it is difficult to create uniform conditions everywhere. In the horizontal direction, the plants and lights obstruct the flow of air from Point

A to Point B, often resulting in temperature, humidity, and air speed differences from one end of the rack to the other. Several strategies can be applied to facilitate air movement in the VF. The use of small circulating fans, installing them at incremental positions within the racking system and above the plants can help boost airflow from one end to the other. Air movement can also be enhanced by considering where conditioned air is introduced into the space and where it is then removed after loading up with heat and moisture [7].

- **Cooling equipment location:** Another big challenge is to place the cooling equipment like heat exchangers, exhaust fans, phase change materials, etc. because they usually take a lot of space to install. In the case of vertical farming in a container, the space allocation issue becomes more problematic [8].
- **Cost for high energy consumption:** Vertical farming uses quite a lot of energy because of using artificial lights all the time, pumps, and motors for the circulation of the water and nutrients, and of course for the cooling system. So, minimizing the cost for these parameters is one of the biggest challenges [8].

1.1.2 Science and Theory Related to Ambient Control

Heat Transfer

Heat is transferred from one area to another by four different methods: conduction, convection, thermal radiation, and evaporative cooling:

- **Convection:** Convection is heat transfer by mass motion of a fluid such as air or water when the heated fluid is caused to move away from the source of heat, carrying energy with it. Convection above a hot surface occurs because hot air expands, becomes less dense, and rises. For the vertical farming system, convection heat transfer can be an efficient way to control the temperature of the fluid which is a vital part in this case [9].

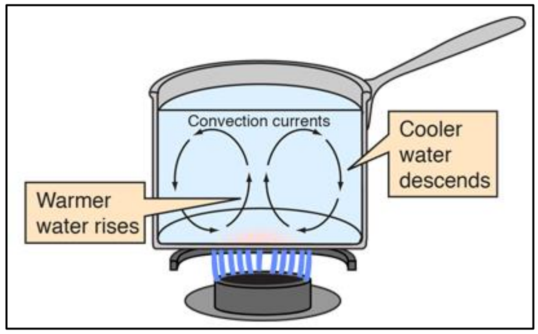


Figure 3: Convection heat transfer in a boiling pot [9].

- **Conduction:** Conduction is the transfer of heat between substances that are in direct contact with each other. The better the conductor, the more rapidly heat will be transferred. Metal is a good conduction of heat. Conduction occurs when a substance is heated, particles will gain more energy, and vibrate more. In this case, conduction heat transfer through the wall is a parameter for the heat transfer from outside to inside. So proper selection of heat conducting material can be beneficial in order to control indoor temperature.

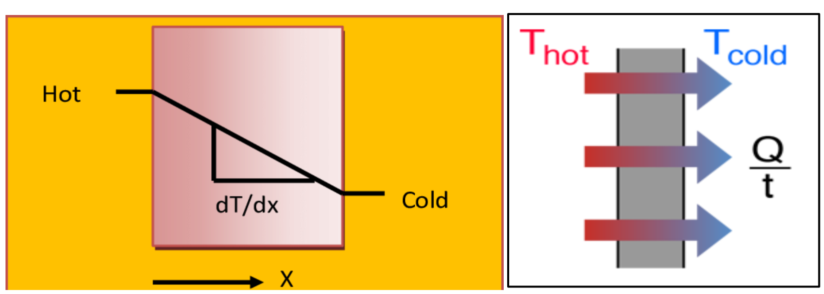


Figure 4: Conduction Heat Transfer [9].

For heat transfer between two plane surfaces, such as heat loss through the wall of a house, the rate of conduction heat transfer is:

$$\frac{Q}{t} = \frac{kA(T_{hot} - T_{cold})}{d} \quad \ldots\ldots\ldots\ldots\text{(1)} \quad [9]$$

Where,

$Q = heat\ transferred\ in\ time\ t$

$k = thermal\ conductivity\ of\ the\ barrier$

$A = area$

$T = temperature$

$d = thickness\ of\ barrier$

- **Radiation:** Heat transfer due to the emission of electromagnetic waves is known as thermal radiation. Heat transfer through radiation takes place in form of electromagnetic waves mainly in the infrared region. In indoor vertical farming, radiation heat transfer also has an effect [10, 11].

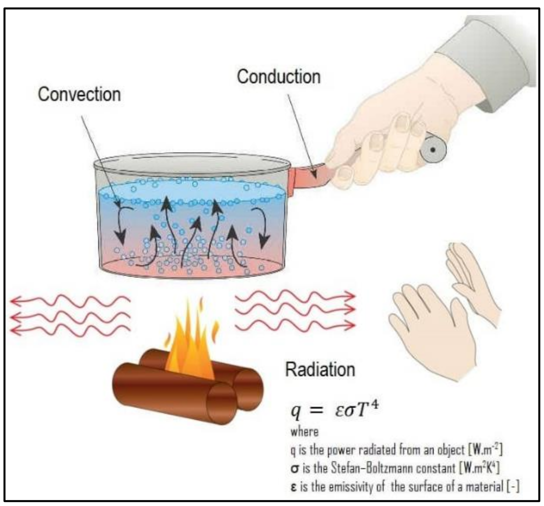


Figure 5: Radiation Heat Transfer [10].

Radiation heat transfer rate, q [W/m2], from a body to its surroundings is proportional to the fourth power of the absolute temperature and can be expressed by the following equation:

$\boldsymbol{q = \varepsilon\sigma T4}$ ………. (2)

where σ is a fundamental physical constant called the Stefan–Boltzmann constant, which is equal to 5.6697×10^{-8} W/m^2K^4 [12].

- **Evaporation:** Evaporation is the process by which water changes from a liquid to a gas or vapor. During the evaporation, process liquid takes away the heat with it. There are many practical applications of evaporative cooling for residential buildings. So, this can be a good way to control the indoor temperature [13].

  The rate of heat loss by evaporation can be calculated with the following formula,

  $\boldsymbol{Q_e = F_e * L_t}$ ………. (3)

  $F_e \text{ is the rate of evaporation of water in } \frac{kg}{m^2 s}$

  $L_t \text{ is the latent heat of evaporation in } kJ$

  $\text{For pure water,} \quad L_t = \frac{(2494 - 2.2t)kJ}{kg}; \quad t \rightarrow \text{water temperature.}$

  $F_e = -K_e * \frac{de}{dz};$

  $K_e \text{ is diffusion coefficient for water vapor and}$

  $\frac{de}{dz} \text{ is the gradient of water vapor concentration}$ [14].

Calculation of the Change in Temperature

The formula for heat energy required to produce a certain change in temperature is:

$\boldsymbol{Q = mc\Delta T}$ ………. (4)

Where,

m = the mass of the object/material,

c = the specific heat capacity of the material it’s made from and

ΔT = the change in temperature

Time taken (t) is given by:

$\boldsymbol{t = \frac{Q}{P}}$ ………. (5) Where, Q is the heat energy, and P is the power in watts (W, i.e., joules per second) [15].

1.1.3 Current Materials, Technologies, and Methods in Passive Ambient Control

High Potential Materials

Materials for convection

PCM: PCM stands for Phase Change Material. These are materials whose phase change, from solid to liquid, and liquid to solid, is used to store and release heat. In PCM's, energy is stored for use at a later time [16] [17].

There are several types of PCM. The most common types are:

- Water-based: These PCM's contain mostly water. Cold storage systems or ice storage systems are mainly used in the air conditioning or process industry.
- Salt hydrates: Paraffin or wax is a derivative of petroleum. The latent melting heat is reasonable, and they do not have any problems with supercooling.
- Plant-based: These are organic PCM's because they come from plant oil or animal fat. The range of melting temperatures is wide and lie between -30 °C and 150 °C [17].

The figure below shows how phase change material incorporated wall can maintain temperature [18].

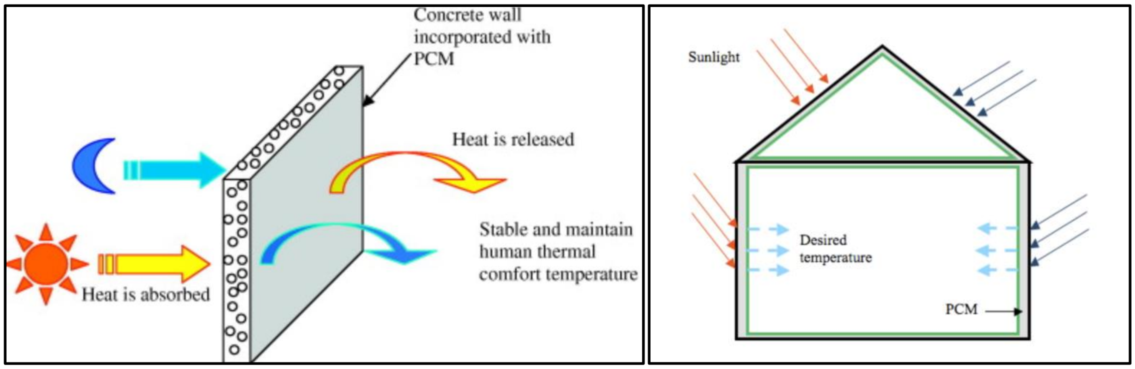


Figure 6: Phase change material incorporated wall. [18]

Materials for conduction

Metal heat sink: A metal heat sink is a passive heat exchanger that transfers the heat generated by an electronic or a mechanical device to a fluid medium [19]. The most common heat sink materials are aluminum alloys. Aluminum alloy 1050A has one of the higher thermal conductivity values at 229 W/m.K. [20]. All heat sinks can be broken down into two major categories:

- Active heat sinks: These generally have a fan or blower of some kind. The most common type is a ball bearing motor fan. These provide excellent performance, but they consist of moving parts and are on the expensive side.
- Passive heat sinks: These have no mechanical components. They only use the convection process to dissipate thermal energy. Because they have no moving parts, they are more reliable. But they should still have continuous air flow across their fins [21].

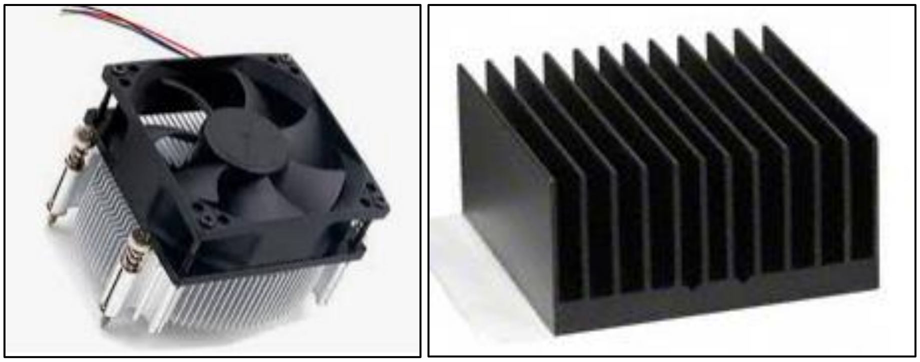


Figure 7: Active (left) and passive (right) heat sink [21].

Heat sinks are usually made from aluminum or copper. Each has its own advantages. Aluminum is the most common material for heat sinks. In particular, extruded aluminum heat sinks fit the needs of most projects. The metal is lightweight and has relatively good thermal conductivity. Copper has even better thermal conductivity than aluminum. Its drawbacks, though, are weight and cost. The metal is sometimes used where the importance of thermal conductivity outweighs weight savings [21].

Materials for radiation

Radiant barrier: A radiant barrier is a type of shiny, reflective building material that reflects thermal radiation and reduces heat transfer. A radiant barrier reflects heat radiation (radiant heat), preventing transfer from one side of the barrier to another due to a reflective, low emittance surface. The most common radiation reflective material is aluminum foil. It has a reflectance of around 80–85%. High quality white paints are also reflective and offer reflectivity in the same range [22].

Sigma and other leading companies have developed a variety of other types of heat reflective fabric [23]:

- Aluminum foil - fabric laminates
- Metalized thin film - fabric laminates

- Direct-metallized fabrics (non-laminates)

Figure 8: Sigma's ThermFlux 3100 Series radiant barrier fabric for residential and commercial insulation applications [22, 23].

Transparent glass: Transparent glass is the most common and cheaper way to use solar energy as a transmitting material. The basic principle is that at daytime, smaller wavelength radiation can go through the glass but at night, due to some heat absorption by the indoor material, the wavelength becomes larger and cannot escape. As a result, the indoor stay warmer in winter. It is called the greenhouse effect [24].

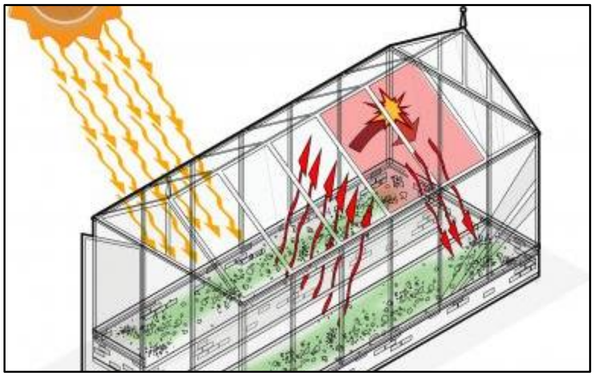


Figure 9: Glass as transmitting material used in the greenhouse [24].

There are some other smart transparent shields that allow useful wavelength of lights in and prevents UV wavelengths. Researchers at Harvard University have invented a way to make building on Mars by placing sheets of silica aerogel on the planet's surface, which would warm it up to make it suitable for growing plants. The shields would be made from silica aerogel, transparent material with low thermal conductivity. Spreading them across the planet's surface would mimic the greenhouse effect by trapping heat that would warm the ground below. This approach requires "less infrastructure or maintenance" than others. The system could be used in hostile environments on Earth [25].

Heat storage materials

Water: Water is one of the best storage media for low-temperature applications. Its operating temperature range is between 25–90 °C. Its advantages are high specific heat, non-toxicity, cheap cost, and easy availability. But it has few drawbacks like high vapor pressure and corrosiveness. Water is best used for house space heating and hot water supply type of applications [26, 27].

PCM: Latent heat storage materials also called phase change materials (PCM) absorb heat energy as their “latent heat of fusion” during the melting process. During the heat energy absorption process there is a phase change happening and the temperature swing is very small. The thermal energy stored in phase change material can be expressed as,

$Q=m.L$; where m is the mass (kg) and L is the latent heat of fusion (kJ /kg) [26].

1.1.4 Current Application of Passive Temperature Control

Table 1: Comparison of works done by others with the work goal of this research.

Article title / Application	Author	Convection	Conduction	Radiation	Heat storage
Use of phase change materials for thermal energy storage in concrete: An overview,"[18]	Ling et al, (2013)	✓	✗	✗	✓
Occupant Comfort and Indoor Temperature Reduction by Using Passive Air Conditioning System with Solar Chimney Concept in Hot Arid Climate [28]	A. S. Hassan Abdallah, (2017)	✓	✗	✗	✗
Synthetic clay as an alternative backing material for passive temperature control of photovoltaic cells [29]	A. H. Alami, (2016)	✓	✓	✗	✗
Passive alternatives to the mechanical air conditioning of the building [30]	D.G. Leo Samuel et al, (2013)	✓	✓	✓	✗
Evaluation of airflow and thermal comfort in buildings ventilated with wind catchers: Simulation of conditions in Yazd City, Iran [31]	S.H. Hosseini et al, (2016)	✓	✗	✗	✗
Texas State University Green House [32]	Texas State University	✓	✗	✗	✗
Smart Passive Ambient Control for Indoor Vertical Farming by Simulation and Empirical Study	Rafiqul Islam	✓	✓	✓	✓

Applications

Solar cell cooling: Passive cooling with synthetic clay-like aluminum-clay is used to cool the solar cell and the benefits of porous clay help maintain solar cell module temperature at levels that would keep power output and efficiency at the desired level. Conduction heat transfer plays the role in here.

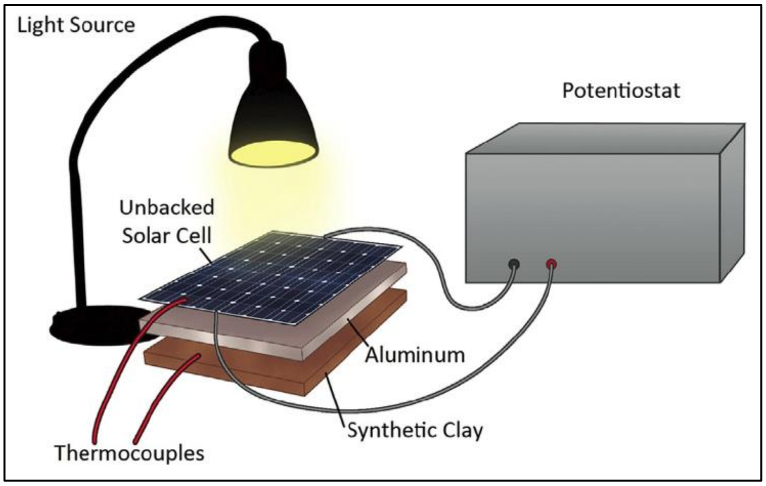


Figure 10: Passive cooling of solar cell with synthetic clay [29].

Radiators: A radiator is a type of heat exchanger. It is designed to transfer heat from the hot coolant that flows through it to the air blown through it by the fan.[33] Radiators can be many types depending on their application like a single panel radiator, double panel radiator, column type, etc. [34]. But two main types of radiators which are used in household temperature control are:

- Steam Radiator: This is an old type of radiator and the steam generated by the boiler goes through the radiator's fins and turns back into the water by releasing heat. The cycle continues to provide continuous heat in the household.
- Hot Water Radiator: This type of radiator works the same way as the steam type except without all the pressure created by the steam and with a more active

approach to moving the heat around. Every radiator in a hot water system has an inlet and outlet. The inlet is to take hot water in, and the outlet is to let the water back out [35].

Figure 11: Radiator used in the household in winter. [35]

Some other radiators have an application in cars and personal computers. The below picture shows a radiator for pc which prevents computers from overheating by liquid CPU cooler. A micro-fine copper cold plate removes heat quickly, and the advanced fan design reduces noise for quiet operation [36].

Figure 12: CORSAIR - Hydro Series 120mm Radiator CPU Liquid Cooling System [36].

Texas State University greenhouse: Heat exchanger on the wall in implemented to control the ambient temperature at Texas State University Green House. Here, hot air from the outside goes through this heat exchanger and becomes cold on the inside. Water is circulated in the heat exchanger from a reservoir. Convection heat transfer plays the role in here. There are 4 exhaust fans on the opposite side of the wall to suck the indoor air which helps to maintain airflow through the exchanger [32].

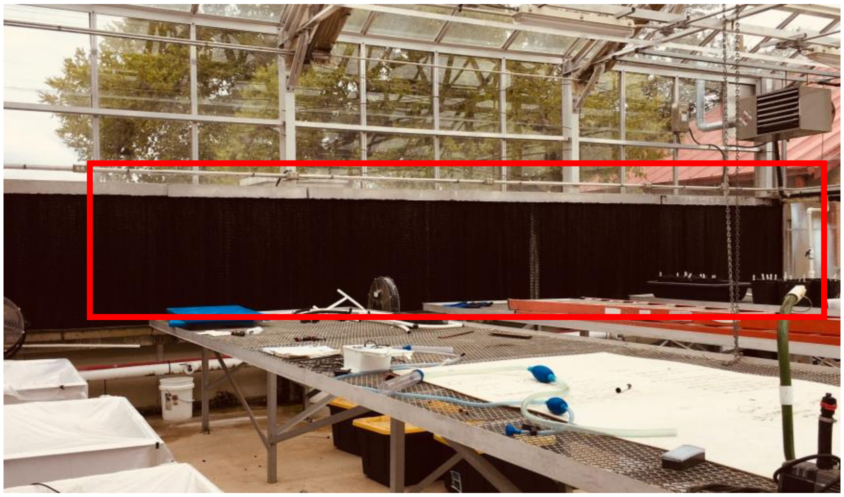


Figure 13: Heat Exchanger in Green House at Texas State University [32].

Cellulose pad heat exchanger for household cooling: A wet cellulose pad heat exchanger is made from expanded paper. It is wetted by a water pipe running on the top of the pads. The excess water from the pad is collected at the bottom of a water reservoir. A small water pump is used to recirculate water through the pad [28].

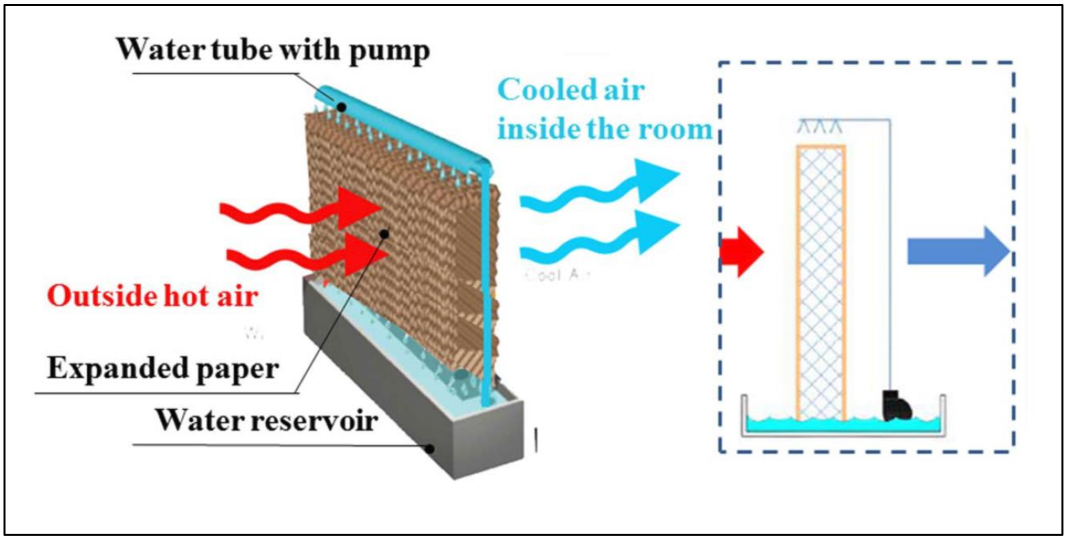


Figure 14: Wet cellulose pad heat exchanger. [28]

Windcatchers in Iran: Windcatchers are traditional tower-like structures projected through the top of roofs of buildings with openings toward the favorable prevailing wind to catch the warm wind, cool it down by evaporating water, and transmit it to interior space to provide thermal comfort for occupants. Figure 15 shows the windcatcher used in Iran [37].

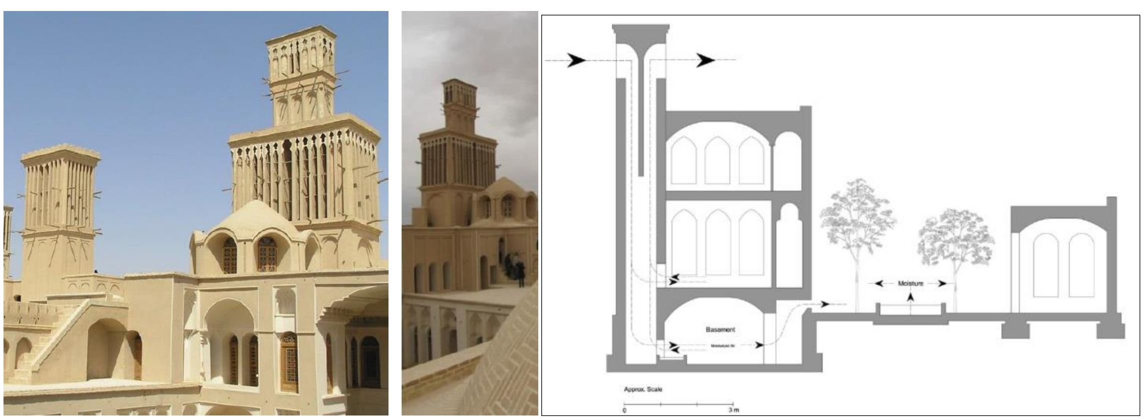


Figure 15: Transferring and evaporating air by means of windcatchers in hot-arid regions in Iran [37].

1.2 Simulation & Modeling: Computational Fluid Dynamics (CFD)

CFD is a branch of fluid mechanics that uses numerical analysis and data structures to analyze and solve problems that involve fluid flows. Computers are used to perform the calculations required to simulate the free-stream flow of the fluid, and the interaction of the fluid (liquids and gases) with surfaces defined by boundary conditions [38].

The basic workflow of CFD can be shown as the following figure:

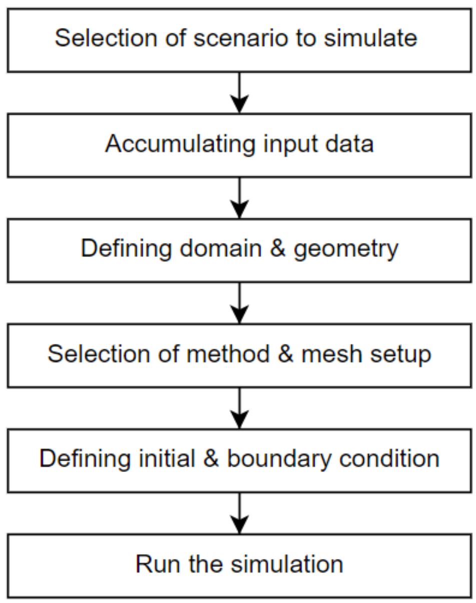


Figure 16: Flowchart of the methodology of CFD [39].

Examples of CFD:

Car industry: CFD technology helps carmakers to improve their model's aerodynamic performances which leads to better fuel economy. The figure below shows how & where the wind speed can have an effect on the car body in CFD and from this analysis manufacturers figure out the optimum design for better aerodynamic and fuel economy [40].

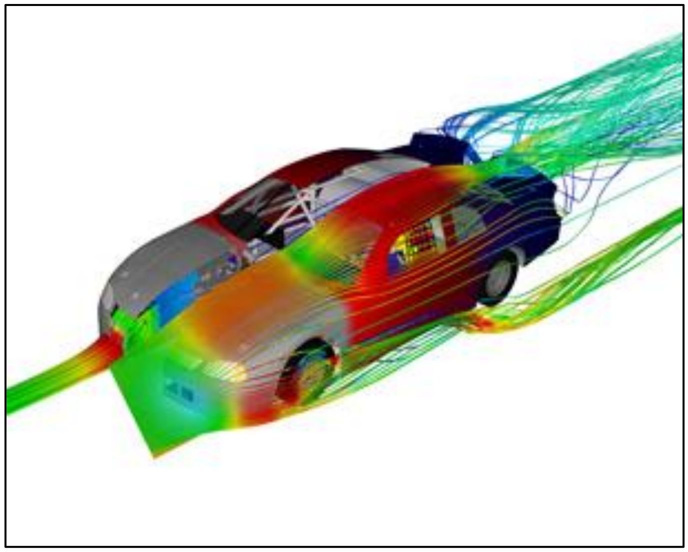


Figure 17: CFD analysis of a car against wind speed [40].

Computer CPU cooling fan: Another major application of CFD is in computer cooling fan design which in other words is called an active heat sink. It is very important to design the cooling fan in such a way that it cools the CPU as required and at the same time does not make much noise. CFD simulations can analyze the thermal and flow fields within a commercial desktop PC enclosure and the effect of various parameters such as power dissipation of the processor, fan speed, ambient air temperature, and the air intake area on the CPU case temperature, etc. can be measured which will lead to the perfect design [41].

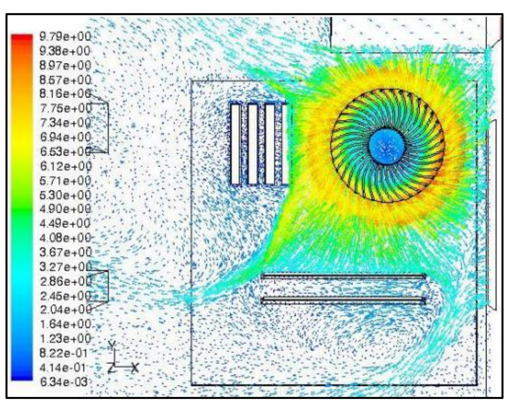


Figure 18: Plot of velocity vectors by CPU fan on the computer motherboard [41].

In buildings, heat transfer takes place in its all modes i.e., conduction, convection, and radiation. To reduce heat losses from buildings, CFD analysis can be done for the optimum configuration for composite walls, roof, and floor [42].

In buildings, the heat transfer analysis can be done for all parts of buildings (walls, roof, and floor) in the following two ways

- Steady-State Thermal Analysis
- Transient Thermal Analysis [42].

1.3 EverGreen IVF Research Lab

EverGreen Research Lab at Texas State University has indoor vertical farming, and its goal is to find innovative solutions for the global food-water-energy. This lab has IVF with a hydroponic system and as the name implies, one of the main goals of this research lab is to implement passive temperature control to save energy and utilizing the resources in a more smart way [4]. Despite well-insulated buildings (40 ft Reefer shipping container) and installed AC and fan units, EverGreen is facing overheating problems similar to other IVF systems, especially in the summertime. This lab will be used as a testbed for this research for validation, experimentation, and optimization of the findings in this research.

Figure 19: Indoor Vertical Farming in EverGreen Lab at Texas State University [4].

1.4 Research Motivation

High ambient temperature and high energy consumption have been significant problems for IVF systems. This study will investigate, model, and assess all relevant passive and smart methods, materials, technologies that can control the indoor temperature in a passive or low energy method. Theoretical study, Modeling/simulation, and Empirical studies will be utilized when necessary.

1.5 Hypotheses

To achieve the goals of this study, the following hypotheses will be assessed. Each hypothesis and its relevant method and result will form one of the chapters of the report of this thesis:

1) For indoor vertical farming, energy consumption for cooling down the system can be reduced by using passive temperature control combining with the active cooling system.
2) Passive Temperature Control using a combination of materials/methods/planning for conduction/convection/radiation can help to balance the indoor temperature from the external ambient temperature.
3) For indoor vertical farming, the growing solution can be used as heat storage and temperature can be controlled by transferring the water from inside to outside and vice versa and along with transferring different positions in the container.
4) Designing an integrative system to combine all the passive cooling systems can significantly reduce the energy cost and can keep the environment livable to plants.

2. THEORETICAL CALCULATIONS OF ENERGY

2.1 Statement of Problem and Hypothesis

This chapter describes the design, development, and assessment for hypothesis 1 which is for indoor vertical farming, energy consumption for cooling down the system can be reduced by using passive temperature control combining with the active cooling system.

2.2 Methods and Materials

The methods and materials for this section consist of mainly the theoretical calculation of energy consumption of the container for indoor vertical farming. To assess the hypothesis, basic physics (e.g., mass, heat capacity, heat transfer) for the shipping container, the normal temperature inside and outside in different operating hours/seasons, are considered and calculated and the energy required to maintain the indoor temperature favorable for plants are estimated. Then the total energy consumption is found by adding the existing energy consuming equipment (e.g., light, fan, cooler, etc.) with the theoretically estimated energy consumed by an active cooling system.

2.2.1 Existing Electrical Equipment

The shipping container for indoor vertical farming needs some essential electrical equipment like lights, pumps, etc. for running the system.

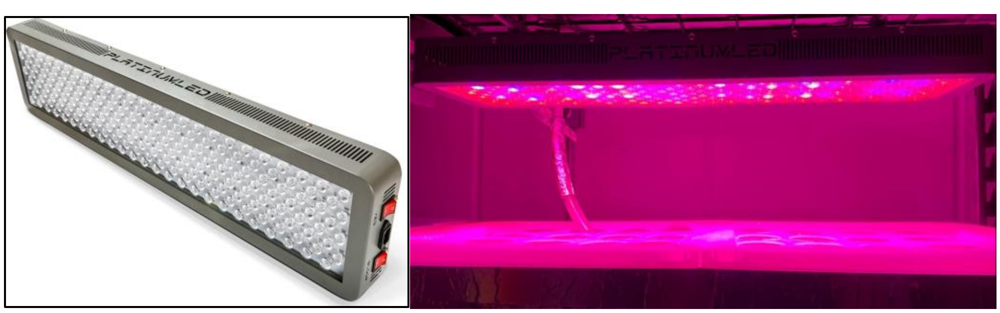


Figure 20: LED rack light used in EverGreen Lab.

Figure 20 shows the LED lights used in EverGreen Lab for growing plants. Table 2 shows the power consumed by the existing electrical equipment in the shipping container of EverGreen Lab. From the table, we can see that the lights consume the highest amount of power, and it also produces the highest amount of heat in the container.

Table 2: Electrical equipment and their power consumption

	Equipment	Per unit consumption (W)	Units	Total power consumption (W)
1	Rack lights	184	48	8832
2	Exhaust fan	200	1	200
3	Pumps	50	16	800
4	Cooler	900	1	900
			Subtotal =	**10732**

So, the total energy consumed in 24 hours, $= \frac{10732 \times 24}{1000} = \mathbf{257}\ kWh$

2.2.2 Cooling Load Estimation

To mitigate the heat produced by grow lights and heat gained from outside through the walls by conduction, the more cooling unit is required and hence more energy. To find out the electrical power required for that cooler, we need to calculate the thermal load of the container. Thermal load calculation is divided into two parts which are thermal load from walls and thermal loads from light sources.

a. Thermal load from walls

The formula for calculating the thermal load from walls is:

$Q_{wall} = UA\Delta T = UA(t_o - t_i)$ … … … … … … … … … … … … … … … … … … (2) [43]

$where,$

$U = Overall\ coefficient\ of\ heat\ transmission\ of\ the\ wall$

$A = Area\ of\ the\ wall$

$t_0 = Outside\ air\ temperature$

$t_i = Inside\ air\ temperature$

Now we need to find out the value of U. When the wall is made up of layers of different materials as shown in Figure 21, the formula for U is,

$$U = \frac{1}{\frac{1}{f_0}+\frac{x_1}{k_1}+\frac{x_2}{k_2}+\frac{x_3}{k_3}+\frac{1}{f_i}} \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots (3)\ [43]$$

$where,$

$f_0 = Outside\ film/surface\ conductance$

$f_i = Inside\ film/surface\ conductance$

$k = Thermal\ conductivity\ for\ the\ material\ of\ the\ wall$

$x = Thickness\ of\ the\ wall$

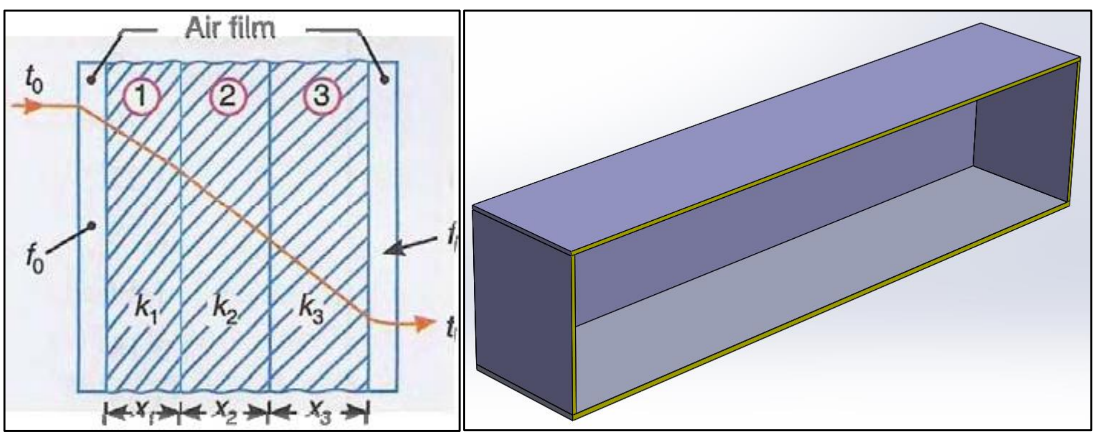


Figure 21: Container wall with three layers of material

The container wall of EverGreen lab is made up of three layers of materials with aluminum on the outer side and polyurethane inside.

So, in this case,

$x_1 = x_3$ = thickness of aluminum = **0.002** m

x_2 = thickness of polyurethane = **0.073** m

$k_1 = k_3$ =thermal conductivity of aluminum = **205** W/m*K

k_2 = thermal conductivity of polyurethane = **0.025** W/m*K

f_o = surface conductance of outside air film = **22.7** W/m^2*K

f_i = surface conductance of inside air film = **8.3** W/m^2*K

Hence, putting these values to equation (3), we get,

$$U = \frac{1}{\frac{1}{22.7} + \frac{0.002}{205} + \frac{0.073}{0.025} + \frac{0.002}{205} + \frac{1}{8.3}}$$

$= 0.32\ W/m^2K$ ……………………………………………….(4)

The temperature difference of inside and outside of the container is assumed to be 20 degrees. And the total wall surface area is $112\ m^2$.

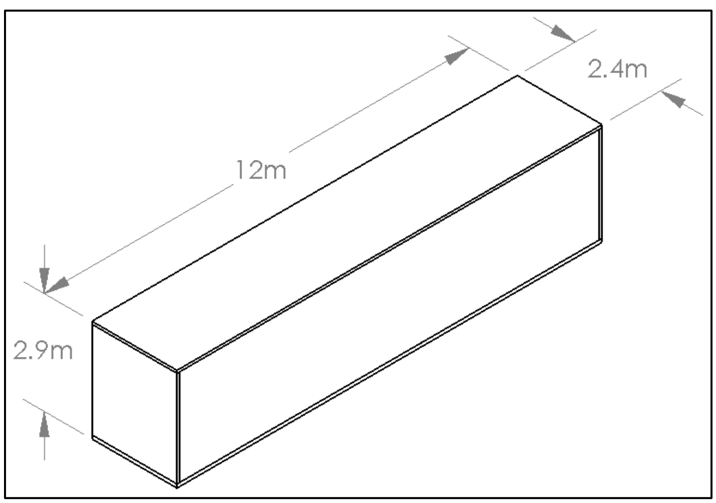


Figure 22: Container dimension

Now from equation (2), the thermal load from the wall is,

$$Q_{wall} = UA\Delta T = UA(t_o - t_i)$$

$= 0.32 \times 112 \times 20$

$= 716\, W$ ………………………………………(5)

b. Thermal load from light sources

From Table 2 we get that the total input power for all the lights is 8832 W.

So, the thermal load from the lights $Q_{lights} = 8832\, W$ ………………………(6)

Now, adding the equation (5) & (6), we get the total thermal load of the shipping container,

$Q = Q_{wall} + Q_{lights} = (716 + 8832)$

$= 9548\, W = 9548 \times 3.41\, BTU/h = 32558\, BTU/h$ …………………….(7)

2.3 Result and Analysis

The container requires an AC unit of capacity 32558 BTU/h to maintain desirable temperature which consumes about 3000 watts of electrical power or $3000 \times \frac{24}{1000} = 72\, KWh$ energy. This means if a portable air conditioner has a cooling capacity of 6000 BTU/h, then we need 5 of them to maintain the desired temperature when all the electric components of the container are running. Figure 23 shows 5 units of the required air conditioner.

Figure 23: Air conditioner units required to cool down the system.

The existing cooler consumes $900 \times \frac{24}{1000} = 22\ KWh$ energy which means (72-22) = 50 KWh more energy is necessary.

But this energy consumption can be reduced by incorporating passive temperature control like adding more exhaust fans which will balance the inside air temperature of the container and the water temperature can be controlled by transferring from inside to outside or outside to inside at a certain time of the day. Figure 24 shows the possible elimination of air conditioners after implementing passive temperature control.

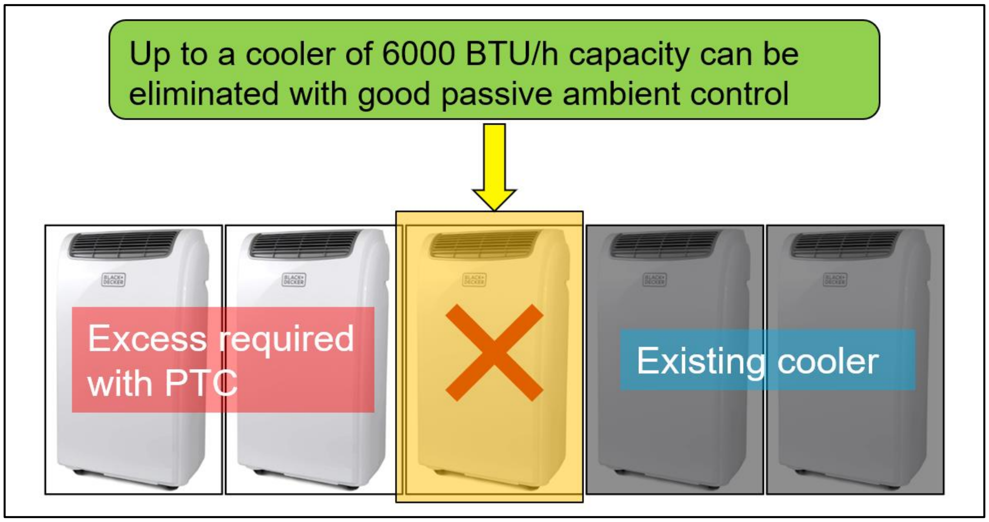


Figure 24: Elimination of AC units with passive temperature control.

According to hypothesis 1, energy consumption for cooling down the system can be reduced by using passive temperature control combining with the active cooling system. From Figure 24, we can see that less energy is required with the implementation of passive temperature control. So we fail to reject the hypothesis which means, hypothesis 1 is accepted.

The subsequent chapters will focus on controlling water temperature by both simulation and empirical study.

3. SIMULATIONS

3.1 Statement of Problem and Hypothesis

This chapter describes the design, development, and assessment for hypothesis 2 which is Passive Temperature Control using a combination of materials/methods/planning for conduction/convection/radiation can help to balance the indoor temperature from the external ambient temperature. To assess this hypothesis, CFD is used to simulate the effect of outside temperature on the indoor air and water through air (forced convection) container wall (conduction), and through solar radiation. The purpose of this simulation is to find the temperature of inside water throughout the day and use the water as a medium of passive temperature control by transferring the water from inside to outside or outside to inside.

3.2 Methods and Materials

The heat transfer process from the outside ambient temperature and solar radiation to the shipping container and the air and water inside is modeled with COMSOL Multiphysics software. The flow chart of the design process is shown in Figure 25. The first part of the flow chart is on simulation which will be discussed here in this chapter and the second portion is on the design of experiments from the data collected from the simulation which will be discussed in Chapter 5.

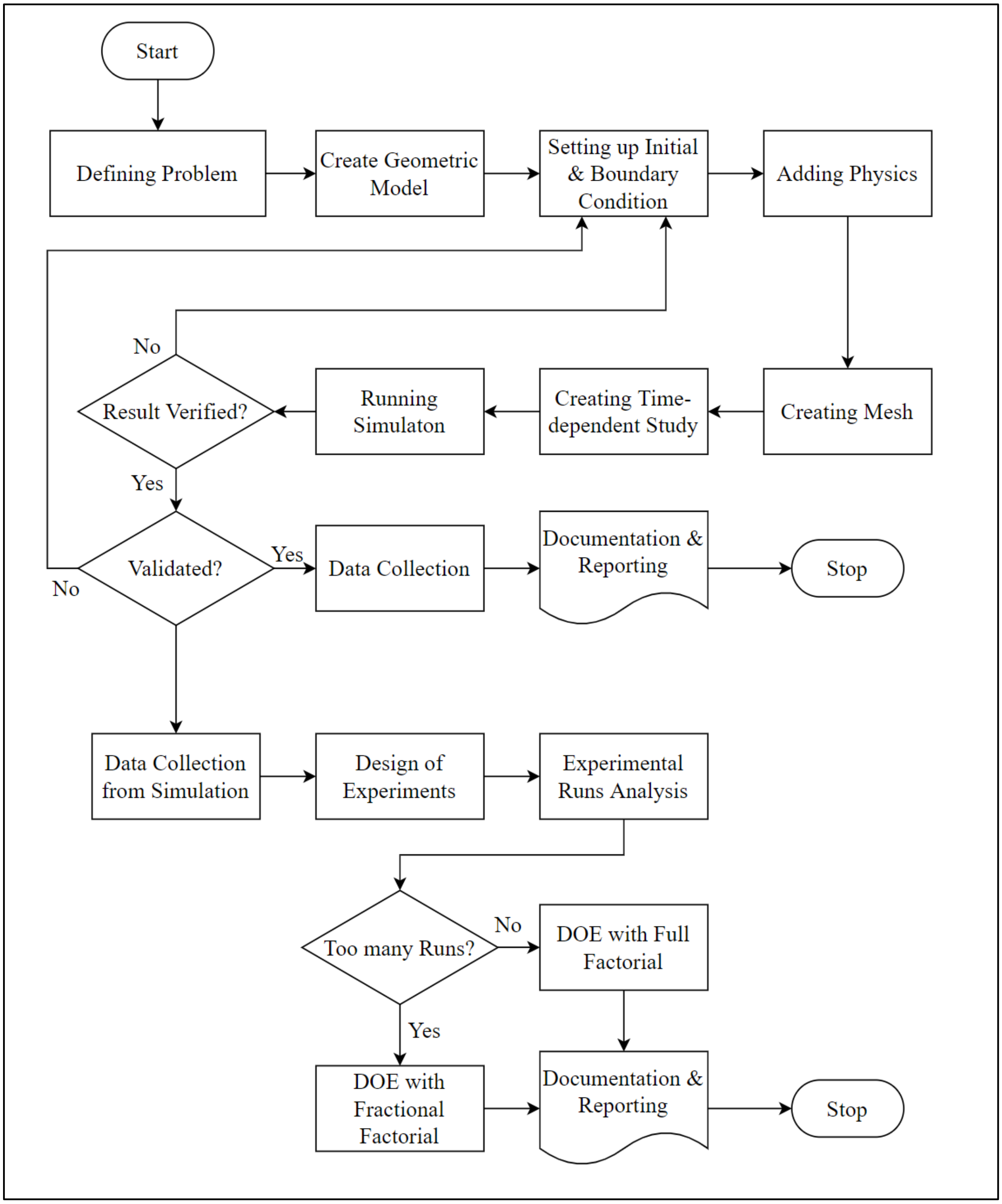


Figure 25: Simulation and design of experiment flow chart

From the flowchart shown in Figure 25, the simulation steps can be described as follows:

1. Drawing and setting up the geometry of container, inside air, water reservoir, and water.

2. Setting up the initial and boundary conditions.
    a. Adding ambient properties.
    b. Adding physics to the model (heat flux for natural forced convection on the wall and conduction through the wall, surface to surface radiation for solar radiation).
    c. Adding Multiphysics to link all the heat transfer phenomena.
3. Creating and building mesh.
4. Creating time-dependent study with Multiphysics.
5. Running the simulation.
6. Analyzing the result.

3.2.1 Geometry

The geometry was created with four main components: container wall, air domain inside the container, water reservoir, and water. Figure 26 shows the whole geometry of the container and the water reservoir.

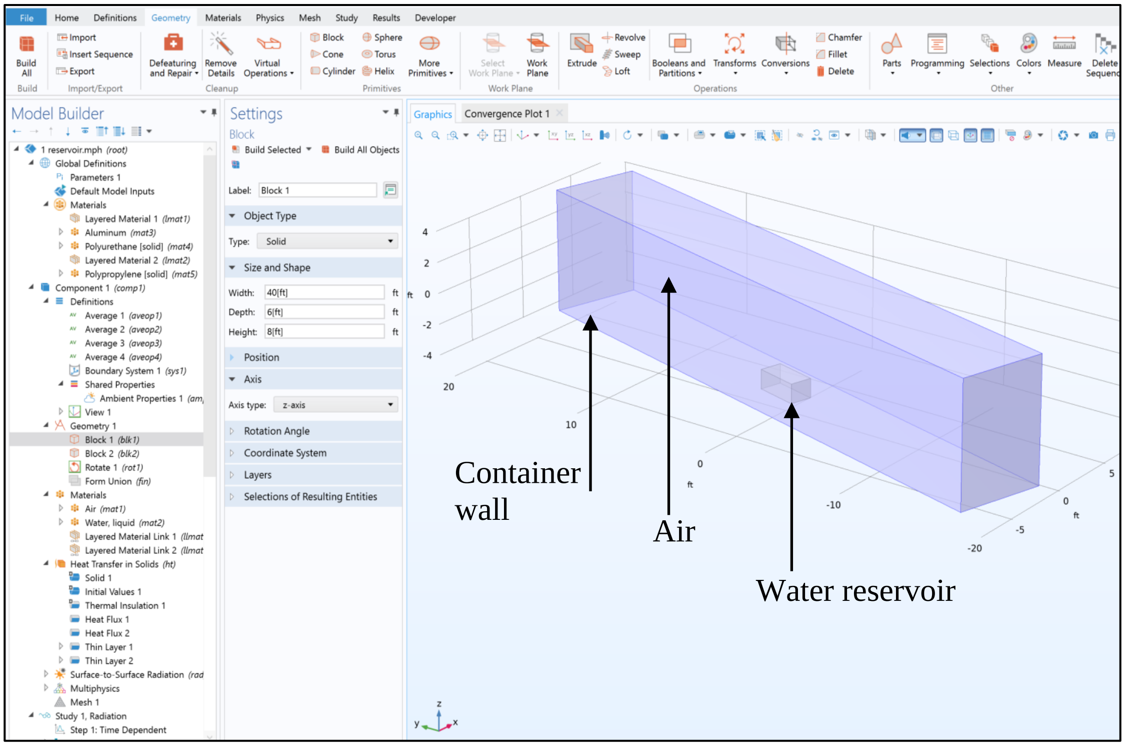


Figure 26: Shipping container geometry in COMSOL.

The dimension of the shipping container was set to 40 ft x 6 ft x 8ft (length x width x height). The material of the wall of the container was made with a three-layer sandwich-type with 2mm aluminum on the outer side and 73mm polyurethane on the middle. And the water reservoir was made of 8.7mm polypropylene. Figure 27 shows the layer material used in the geometry in COMSOL.

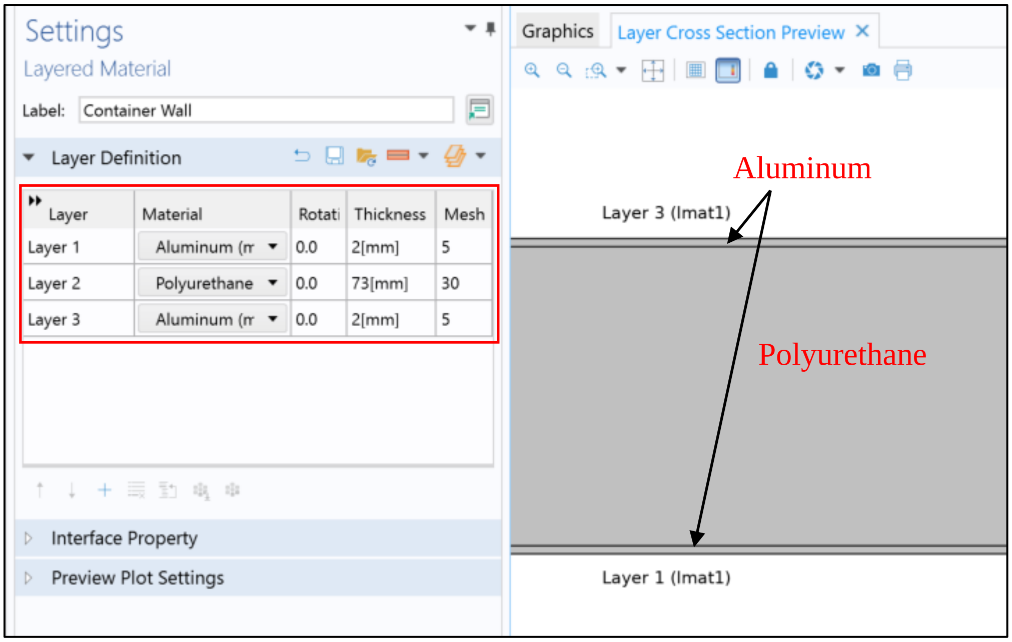


Figure 27: Container wall material and thickness

After building the container wall and water reservoir with respective materials, the inside air and water domain was defined.

3.2.2 Initial and Boundary Conditions

Ambient properties:

To define the outside ambient condition for temperature, air velocity, atmospheric pressure, solar radiation, sun direction, etc. COMSOL Multiphysics software's ability to link meteorological data for specific location, date, and time to the simulation model was utilized. The time and date of the study were set to April 24, 2021, at 1:00 pm and the study was run for 72 hours. The location was set to San Marcos, Texas, USA.

The azimuthal of the shipping container was measured using a compass and was found to be 105° East and was set this value to the software to get the accurate effect of solar radiation from sunlight. Figure 28 shows the ambient properties and azimuthal of the shipping container.

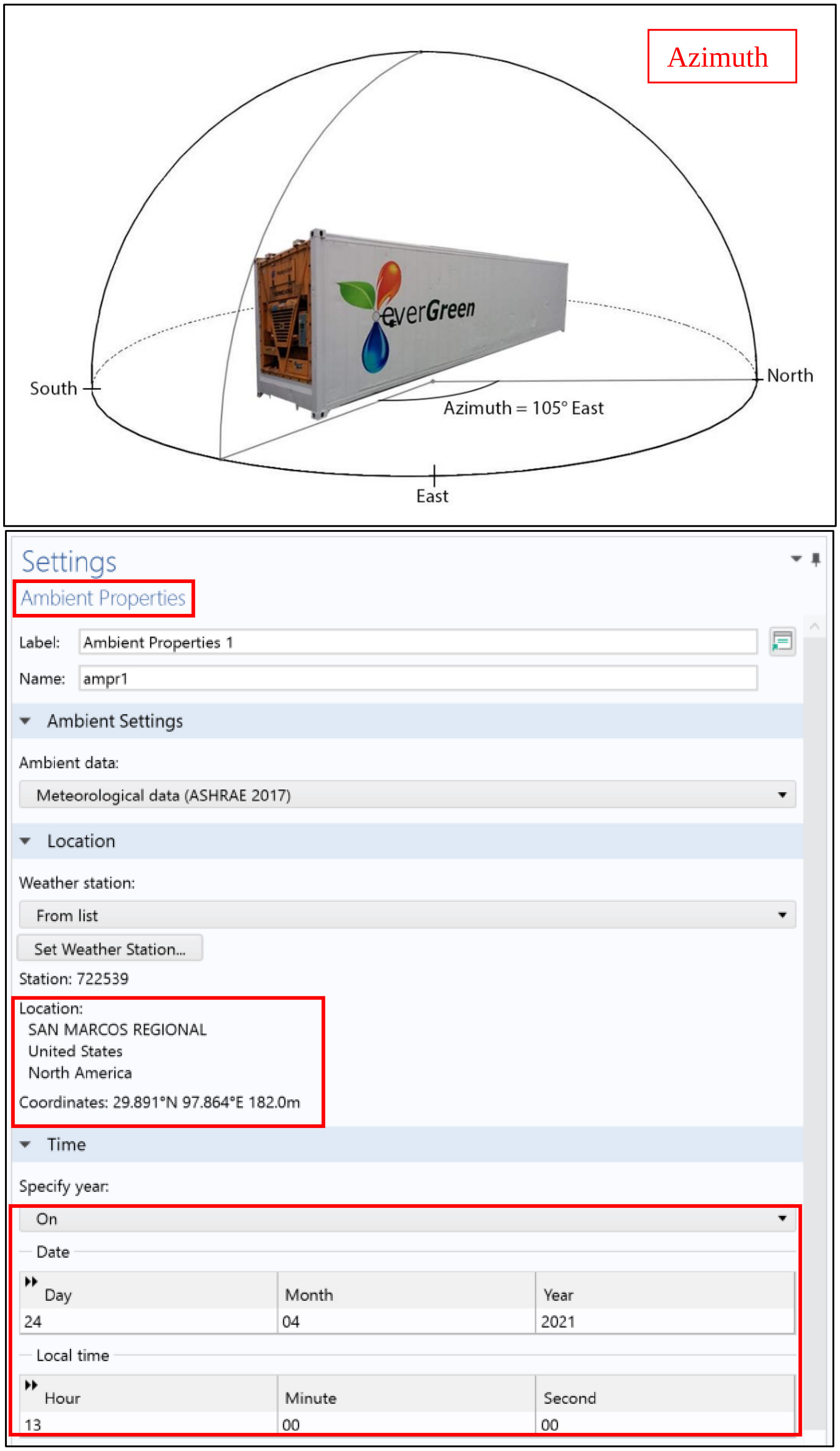


Figure 28: Ambient properties and azimuthal of the shipping container.

Adding Physics and Multiphysics

For this study, two physics were added to the simulation model.

1. Heat flux to consider heat transfer with convection and conduction.
2. Surface to surface radiation to consider solar radiative heat transfer.

Heat transfer from the ambient to the inside air & water happens in three steps:

a) Natural forced convection from outside ambient to the container wall surface

b) Conduction heat transfer from outside to inside through wall material

c) Natural convection from the inside wall surface to the air and water

Then Multiphysics was added to link heat flux and surface to surface radiation. Figure 29 shows heat flux and radiation properties in the software.

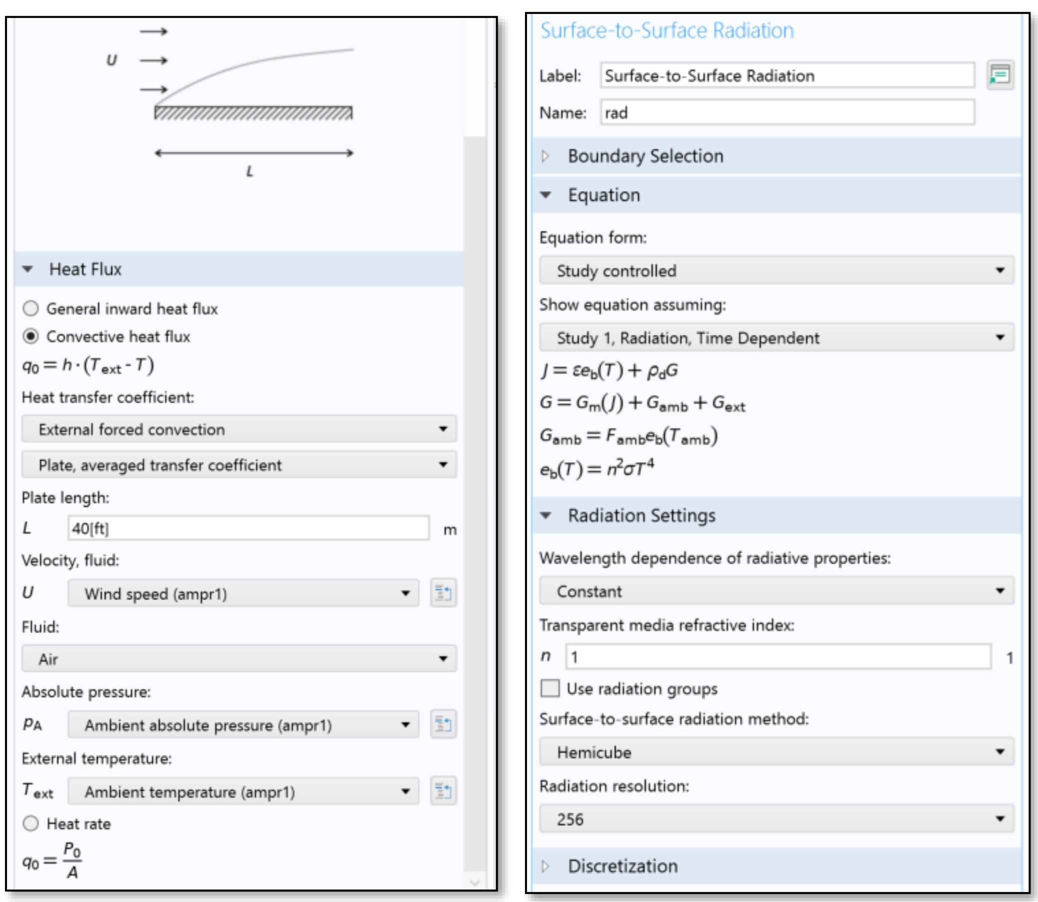


Figure 29: Heat flux and surface to surface radiation added to the model.

3.2.3 Adding Mesh

After adding boundary conditions, the mesh was added. The purpose of adding mesh is to break down the geometry into thousand shapes to properly define the physical shape of the objects. The more detailed the mesh, the more accurate the 3D model is, and more time is required to compute the study and more accurate results. In this study, the mesh was set to extra fine as shown in figure 30.

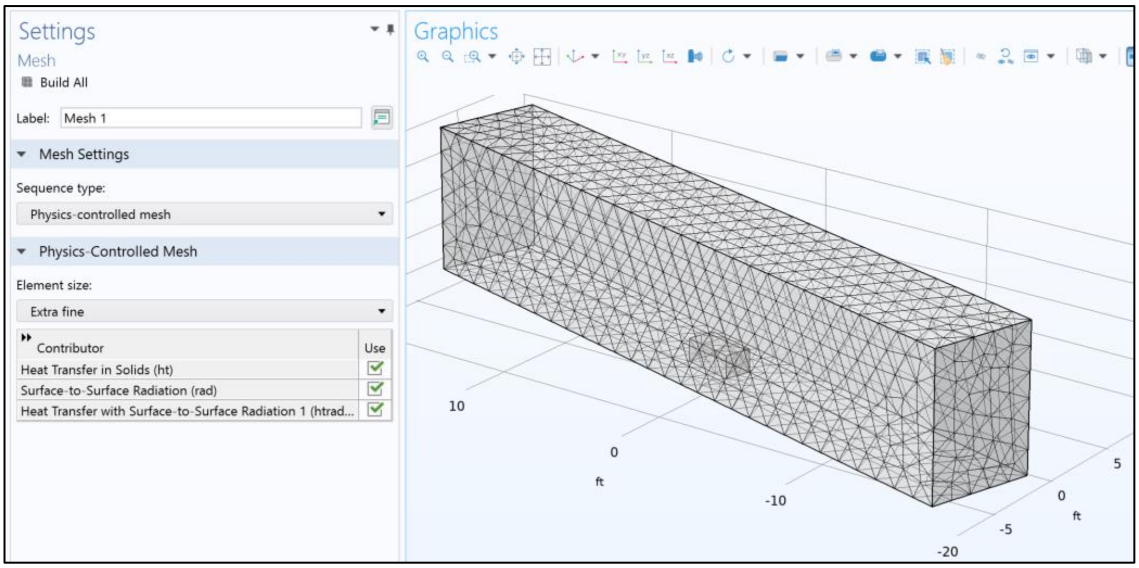


Figure 30: Mesh setup.

3.2.4 Adding Study & Running the Simulation

A time-dependent study was added to compute the temperature changes with the change of time. In this time-dependent study, the step parameter was set to 1 hour which means the software will compute the results with a 1-hour interval. The total study was set to simulate for 72 hours. Natural heat transfer and surface to surface radiation were checked along with the Multiphysics coupling as shown in Figure 31. Then the simulation model was computed, and it took about 15 minutes to run the computation.

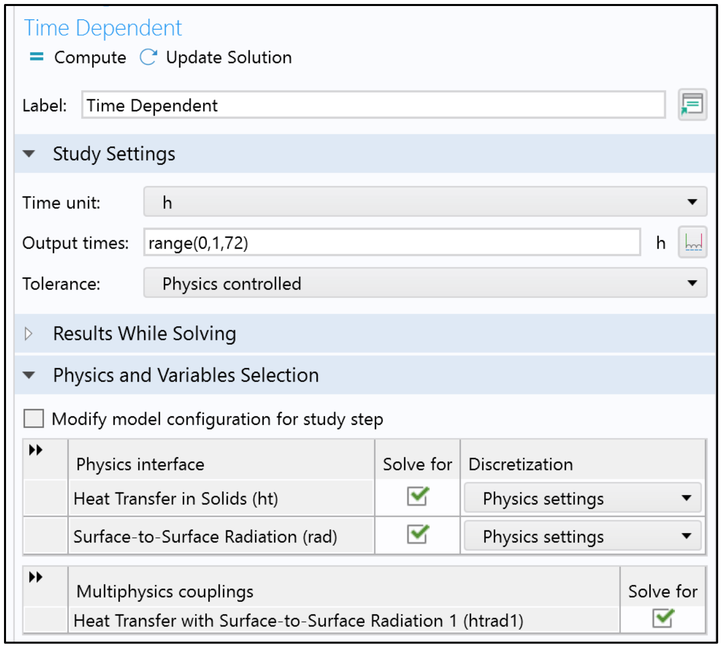
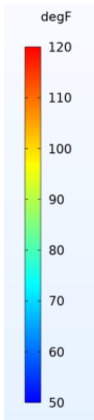
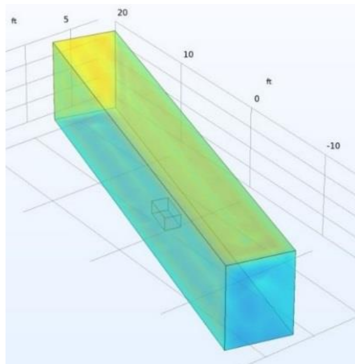
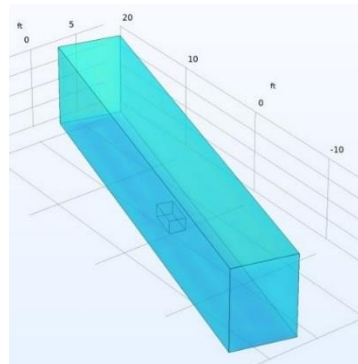
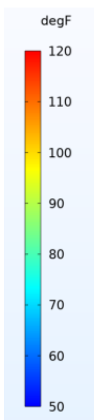
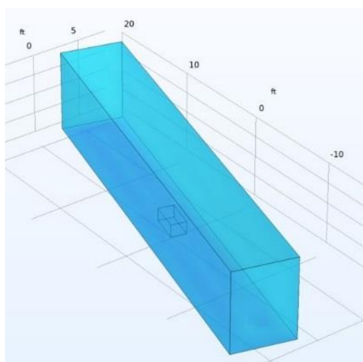
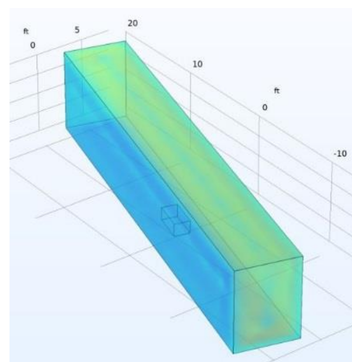
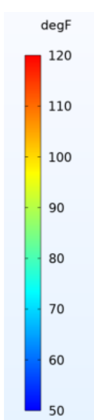
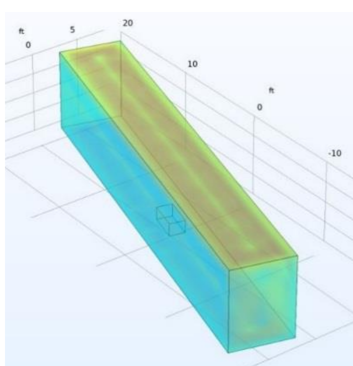
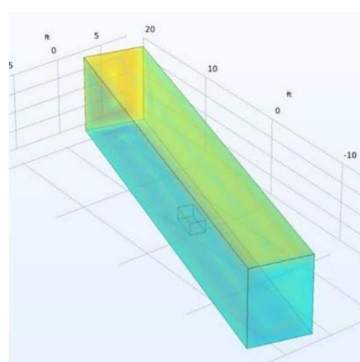


Figure 31: Time-dependent study setup.

3.2.5 Result and Analysis

After completing the CFD simulation, the result was produced, and to better visualize the temperature data found, the temperature profile was plotted at a different time of the day. The Table below is the temperature profiles of the container at different hours of the simulation. Simulation start time was 1 pm on April 24 and the first image is shown IN table 3 is at 6 pm, April 24.

Table 3: Temperature profile of the container.

	6 pm, 04.24.2021 	12 am, 04.25.2021 
	6 am, 04.25.2021 	9 am, 04.25.2021 
	12 pm, 04.25.2021 	6 pm, 04.25.2021 

From the above table, we can see that how the ambient temperature affects the container surface, air, and water. For example, in the afternoon (6 pm), the roof and the west surface are hotter and at nighttime, all the domains are cooler.

To have a better understanding of the temperature of the domains (air, water, etc.), and the ambient temperature, a temperature vs time graph is shown in Figure 32.

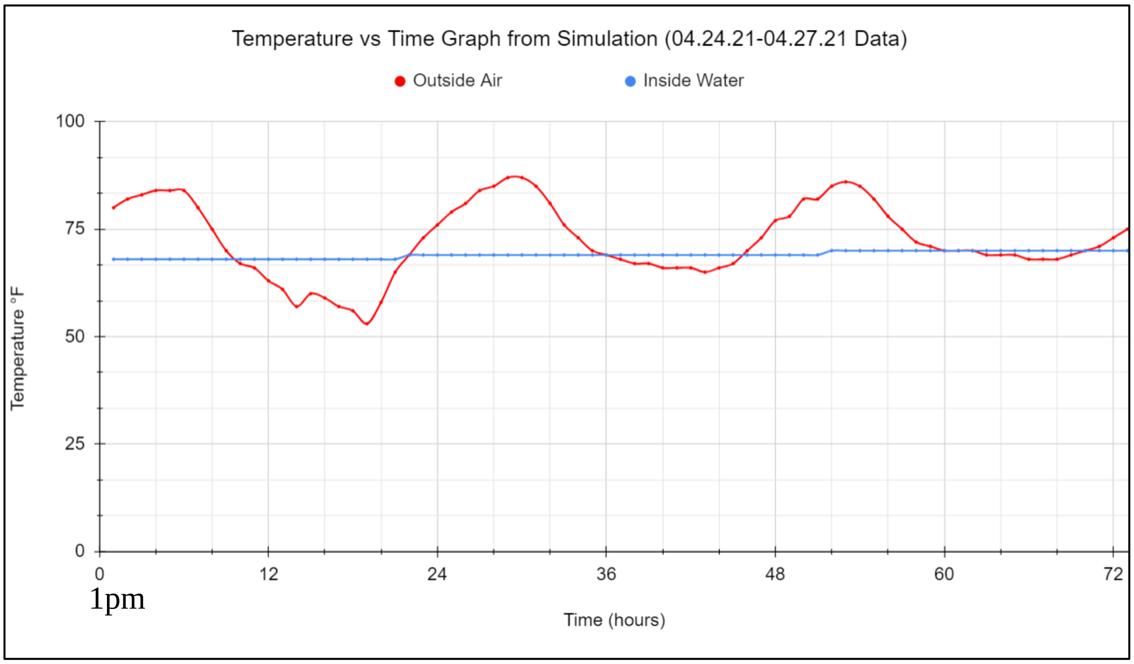


Figure 32: Temperature vs Time Graph from Simulation (04.24.21-04.27.21 Data)

From the graph in figure 32, we can see that inside air temperature is influenced by the outside air temperature with a lag because it takes some time to disperse the heat to inside air through the wall. But there is very little change in water temperature because there was no external heating source (lights) in the system, and it needs a significant amount of heat to change the temperature of 150 liters of water.

3.3 Validation

To validate the result from the simulation, the water temperature data obtained from the simulation are compared with the actual data with a similar condition like the date and time of the temperature recording, size of the water, container, etc. The comparison of the temperature is shown in Figure 33.

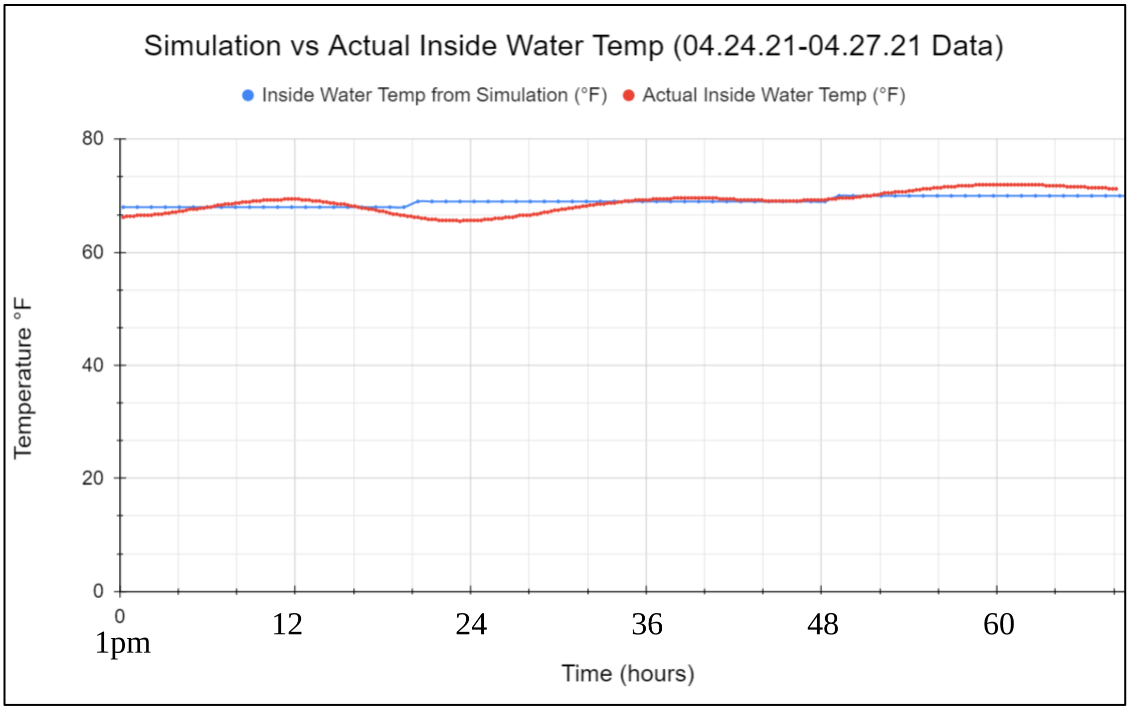


Figure 33: Simulation vs Actual Inside Water Temp (04.24.21-04.27.21 Data)

From Figure 33, we can see that the temperature data from the simulation and the actual data are almost matches with each other except at times where there is a very little deviation.

To validate this model statistically, a paired t-test with 95% confidence interval (CI) is done in "Minitab". Figure 34 shows the paired t-test of the simulated and actual temperature data.

Paired T-Test and CI: Wate...

PAIRED T-TEST

Paired T-Test and CI: Water Temp From Simulaiton (°F), Actual Water Temp (°F)

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
Water Temp From Simulaiton (°F)	71	68.986	0.765	0.091
Actual Water Temp (°F)	71	68.923	1.900	0.225

Estimation for Paired Difference

Mean	StDev	SE Mean	95% CI for μ_difference
0.063	1.513	0.180	(-0.295, 0.421)

μ_difference: population mean of (Water Temp From Simulaiton (°F) - Actual Water Temp (°F))

Test

Null hypothesis H₀: μ_difference = 0
Alternative hypothesis H₁: μ_difference ≠ 0

T-Value	P-Value
0.35	0.726

Figure 34: Paired t-test and confidence interval of simulated & actual data.

From Figure 34, we can see that zero is included in the confidence interval of [-0.3, 0.4]. That means that statistically there is no significant difference between the temperature data from the simulation and actual data. Hence the model is valid.

From the validated simulation model, a variety of scenarios can be designed and tested without actual implementation of them. For example, we can determine the temperature of the water inside on any given date and time which will help to decide water transfer from outside to inside. In this simulation model, all the heat transfer mode like conduction, convection, and radiation are considered and water is used as the heat storage material for passive temperature control which proves hypothesis 2 which is passive temperature control using a combination of materials / methods / planning for conduction / convection / radiation can help to balance the indoor temperature from the external ambient temperature. So we accept hypothesis 2.

4. EMPIRICAL STUDY

4.1 Statement of Problem and Hypothesis

This chapter describes the design, development, and assessment for hypothesis 3 which is, for indoor vertical farming, the growing solution can be used as heat storage and temperature can be controlled by transferring the water from inside to outside and vice versa and along with transferring different position in the container. To assess this hypothesis, an empirical study has been carried out based on observation and measurement of temperature data of air and water both from inside and outside of the shipping container.

4.2 Methods and Materials

To conduct the experiment of the measurement of temperature data of air and water, a water reservoir with 135 liters of water was placed inside the container and a similar reservoir of water was also placed outside the container. Figure 35 shows the water reservoirs.

Figure 35: Water reservoirs placed inside (left) and outside (right) of the container

To take the temperature data, a temperature data logger (Elitech GSP-6G) shown in figure 36, was used which was bought from amazon. This logger can measure and store the temperature of air and water every 15 minutes and it can record up to 16000 records. It has a wide temperature measurement range from -40°F to 185°F, max with accuracy up to ±0.5°F. After taking the desired amount of data, the readings can be exported to a computer using a USB cable.

Figure 36: Elitech GSP-6G temperature data logger.

The experiment of taking temperature data was conducted several times in different weather conditions. Table 4 shows the list of experiments done. The notation used in the table is I-inside, O-outside, A-air, W-water, and EG-EverGreen.

Table 4: List of experiments of temperature measurement

No.	Condition	Data from	Date & Time	Duration (Days)
1.	Empty container, no light, no water flow	IW, IA, OA	4.11.21 2pm-4.14.21 6pm	3
2.	Empty container, no light, no water flow	IW, OW, OA	4.17.21 6pm-4.21.21 6am	4
3.	Empty container, no light, no water flow	IW, OW, IA, OA	4.24.21 2pm-4.27.21 12pm	3
4.	EG container, 1 light, water flow ON	IW, OW, IA, OA	5.8.21 3pm-5.11.21 3pm	3
5.	EG container, 2 light, water flow ON	IW, OW, IA, OA	5.11.21 4pm-5.14.21 4pm	3
6.	EG container, no light, water flow ON	IW, OW, IA, OA	5.17.21 6pm-5.20.21 6pm	3

4.3 Result and Analysis

After the experiments, the temperature data were visualized with a graph to have a better understanding of when there is a difference between inside and outside temperature of air and water, and from these data, it will be easier to decide when the water should be transferred from/to outside/inside.

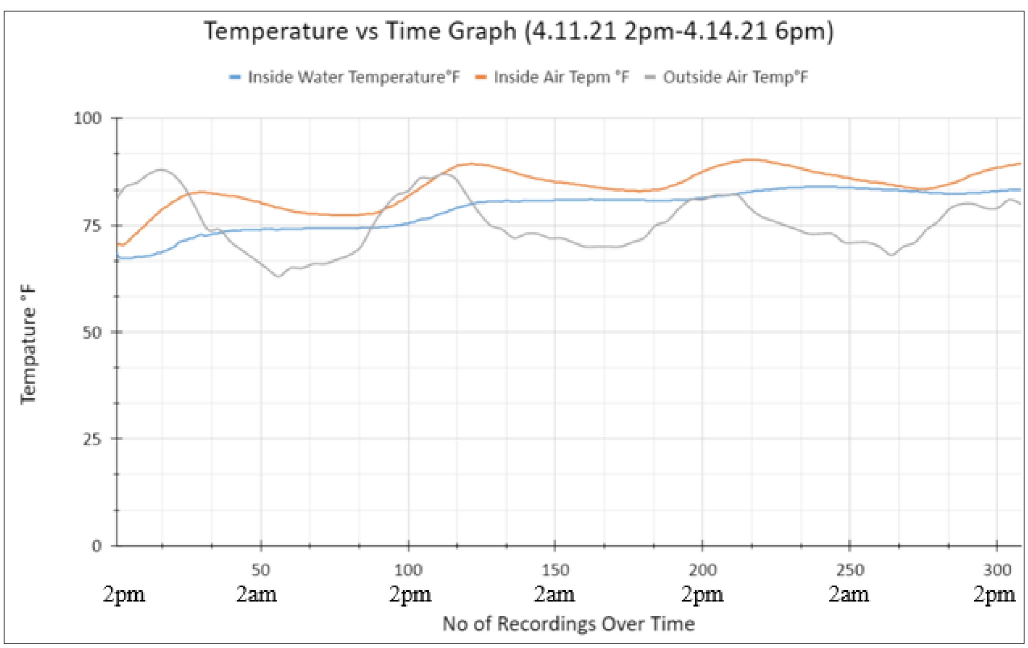


Figure 37: Temperature vs time graph with no light and no water flow (4.11.21).

Figure 37 shows the temperature vs time graph with no light inside the container and no water flow in the water reservoir. The data (Appendix, Table A-1) was taken in an empty container and temperature measurement was taken from inside water, inside air, and outside air. The outside air temperature was obtained from a weather station located 100 feet away from the container. Along the x-axis, every 100 recordings represent 24 hours of the time interval. As the experiment was started at 2 pm, so 50 on the x-axis represents 2 am the next day, 100 represents 2 pm the next day, and so on. From the graph, we can see that inside air and water follow the temperature change of outside air but with a lag because it takes some time to transfer the heat from outside air to inside air and water through the wall. From the pattern in the graph we can see that the water temperature keeps rising from 2 pm to 2 am and stays steady for about 10 hours and then rises again from 2 pm for another 8 hours and then stays steady for about 12 hours. This is because of the variation of the outside temperature from day to day.

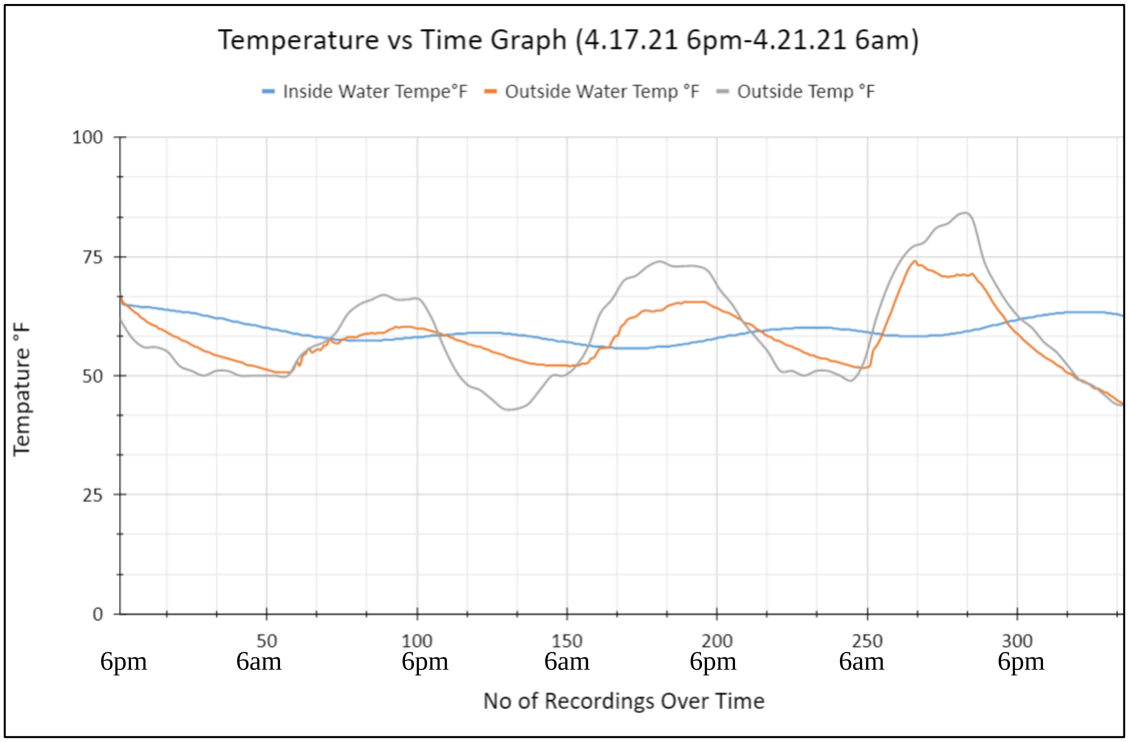


Figure 38: Temperature vs time graph with no light and no water flow (4.17-4.21).

Figure 38 shows the temperature vs time graph where data was taken from 4.17.21 6 pm to 4.21.21 6 am. The outside temperature was different from the previous graph, hence the inside water temperature was also different. But the similarity is that the water temperature starts to drop at night time and it rises at day time with a delay from the outside temperature.

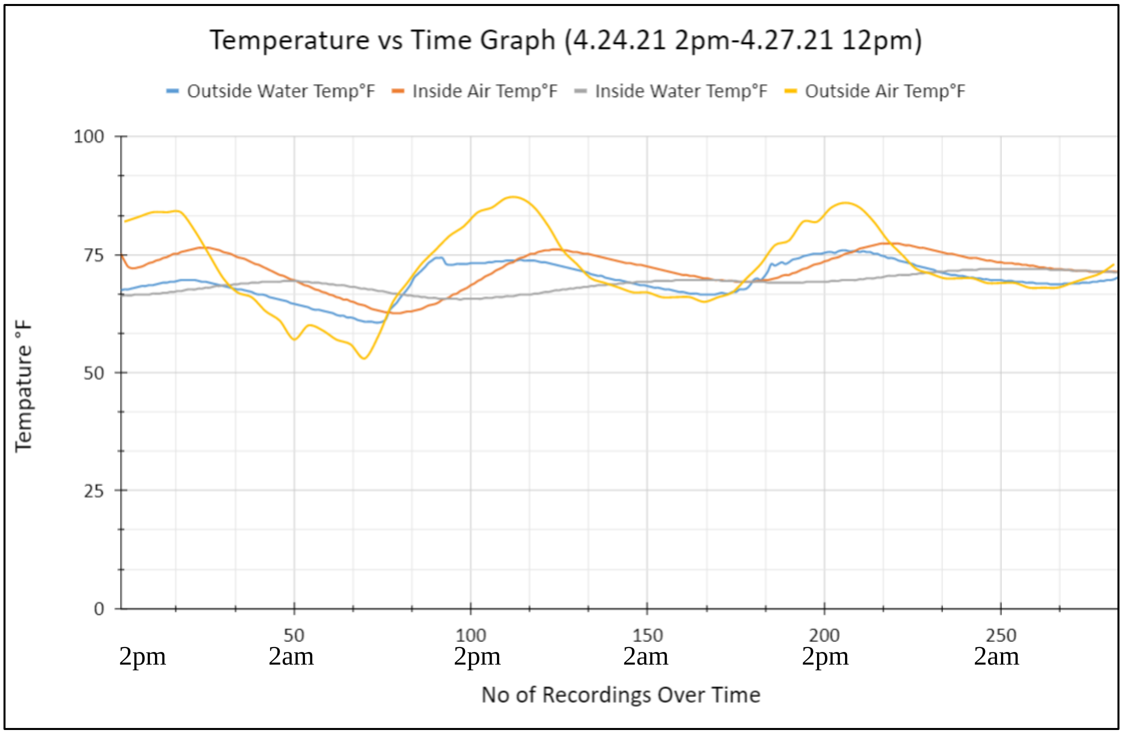


Figure 39: Temperature vs time graph with no light and no water flow (4.24.21).

In Figure 39, the outside water temperature was also taken along with inside water, inside air, and outside air (Appendix, Table A-2). Here we can see that outside water temperature is lower from 10 pm to 8 am than the inside water temperature and higher in the next 12 hours and this cycle goes on. So, if we replace the inside water with outside water at night time, the temperature can be controlled without adding any water cooler which means passive temperature control.

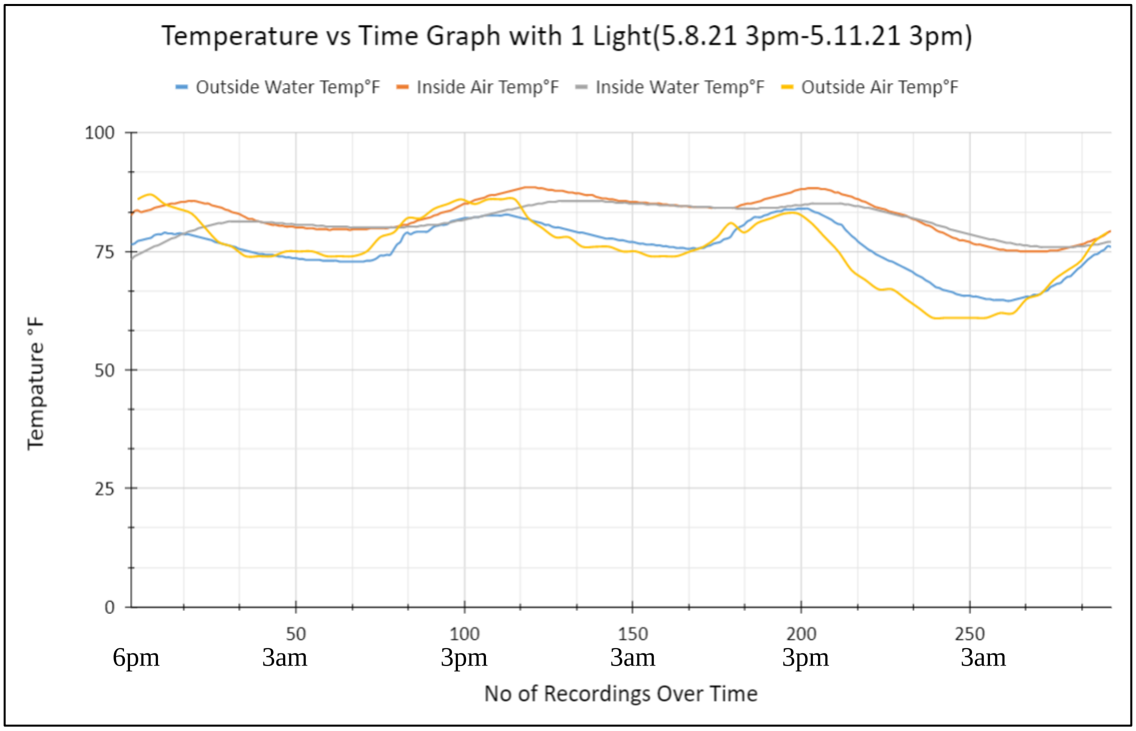


Figure 40: Temperature vs time graph with 1 light and no water flow (5.8.21).

After adding 1 light in the system, the temperature difference between outside and inside is shown in figure 40. Here outside temperature is lower than the inside water almost all the time except few hours in the daytime. This means, adding light increases inside water temperature and the inside water temperature can be controlled most of the time just by replacing it with outside water.

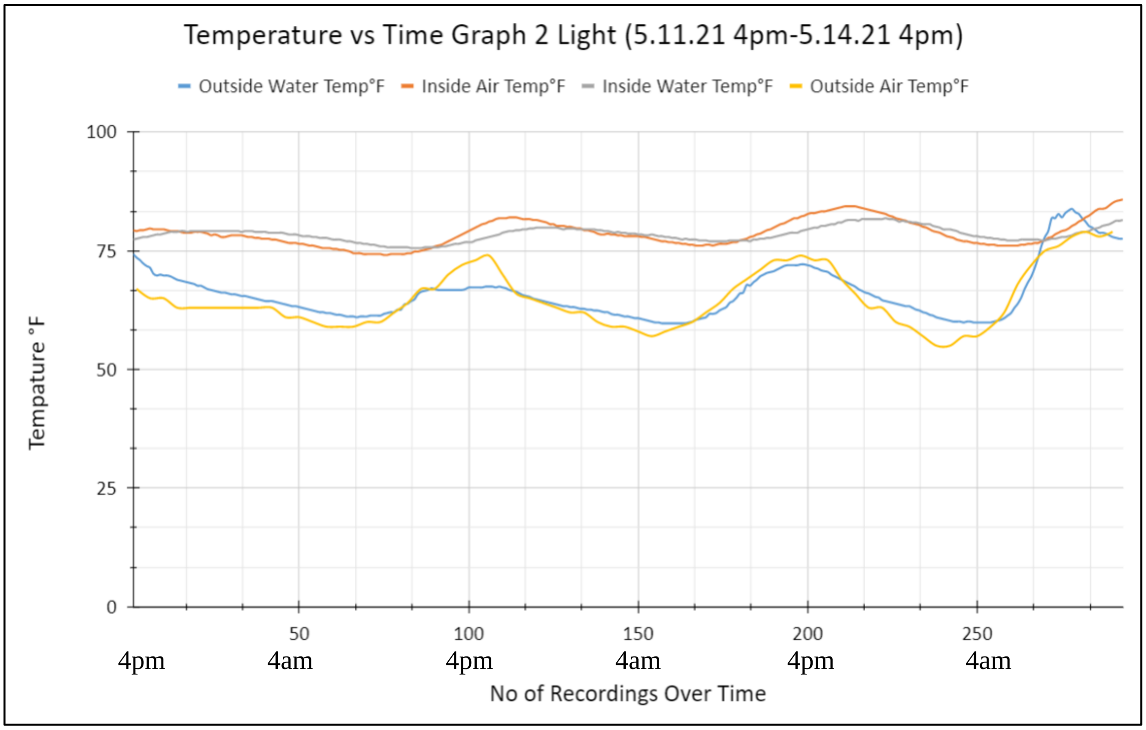


Figure 41: Temperature vs time graph with 2 light and no water flow (5.11.21).

After adding 2 lights to the system, the temperature difference between outside and inside is shown in figure 41 (Appendix, Table A-3). Here outside temperature is significantly lower than the inside water all the time. This means, adding more light increases inside water temperature drastically and the inside water temperature can be controlled anytime just by replacing it with outside water.

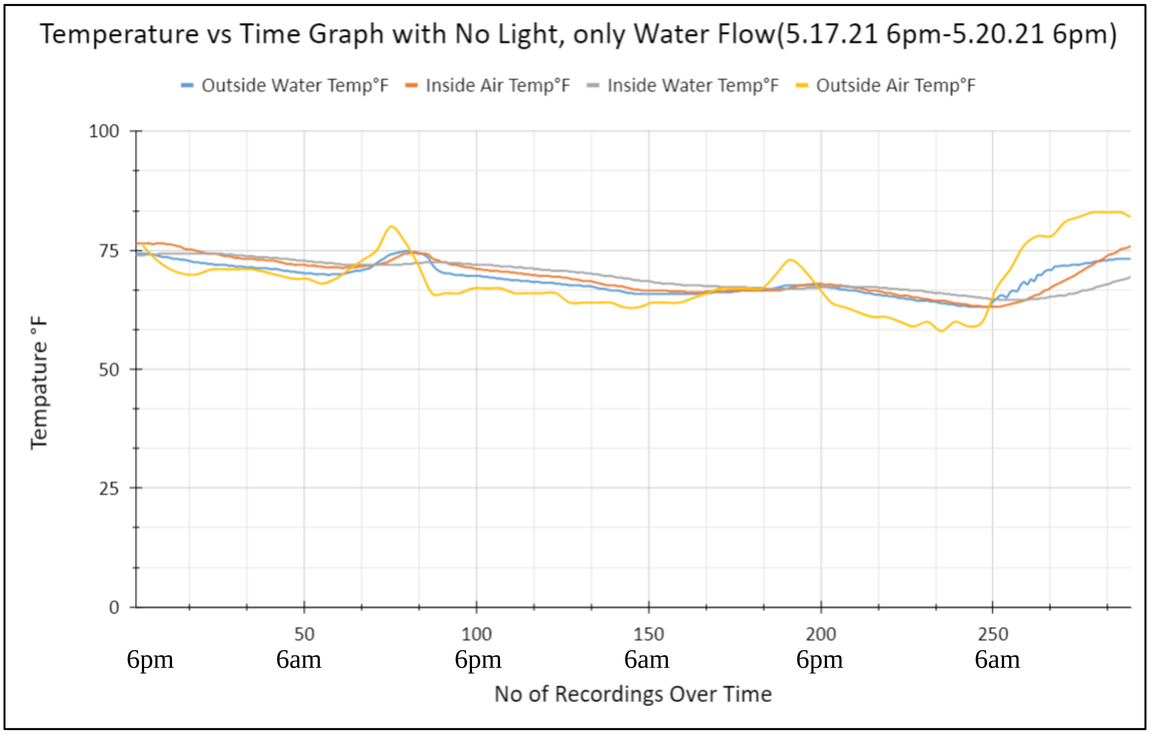


Figure 42: Temperature vs time graph with no light and with water flow (5.17.21).

The final experiment was done by turning off all the lights and adding water flow in the inside water reservoir. Here in Figure 42, we can see that the difference between inside air and water temperature shrinks as the inside water gets more affected by the air temperature for water flow. So it can be concluded that if the lights are turned on, the inside air temperature will go higher and so will the water, hence there will be more different in temperature between inside and outside water.

From the analysis of figure 36 to figure 41, we can conclude that the growing solution or water can be used as heat storage material and temperature can be controlled by transferring the water from inside to outside which is hypothesis 3. So we accept hypothesis 3.

5. DESIGN OF EXPERIMENTS

5.1 Statement of Problem and Hypothesis

This chapter describes the design, development, and assessment for hypothesis 4 which is designing an integrative system to combine all the passive cooling system can significantly reduce the energy cost and can keep the environment livable to plants. To assess this hypothesis, the design of experiments is done with the data found from the simulation.

Design of Experiments (DOE):

Design of experiments is defined as a series of tests in which purposeful changes are made to the controllable input factors of the process so that we may observe and identify the corresponding changes in the output response. The concept of DOE can be visualized with Figure 43:

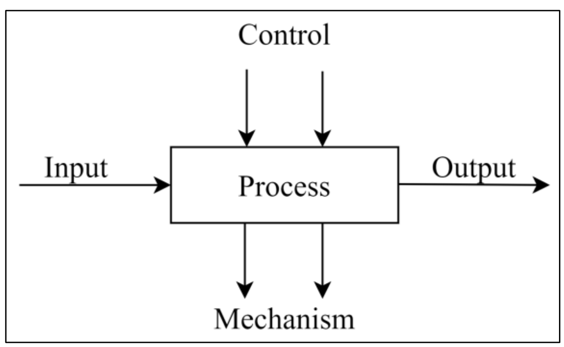


Figure 43: Design of experiment process.

The purpose of DOE is to compare different design alternatives and configurations and determine the key parameters that impact the performance and finally finding the optimum design parameters. The types of DOE is as follows:

- *1 Factor design*: When there is only 1 factor with different levels

- *Factorial design*: When there are multiple factors with multiple levels. Factorial design is then divided into different types. The most common two types are:
    - Full factorial design: When there are few factors (e.g., 1-3) with few levels (e.g., 1-3 levels)
    - Fractional factorial design: When there are multiple factors and levels, and experiments are time-consuming and/or expensive.
- *Response surface method (RSM) design*: These are special designs that are used to determine the settings of the factors to achieve an optimum value of the response [44].

5.2 Methods and Materials

To design an optimum system of passive temperature control, a factorial design of experiments was made. The flow chart of the design of experiments is shown in Figure 44. This is the second portion of the flow chart shown in figure 25 in chapter 3.

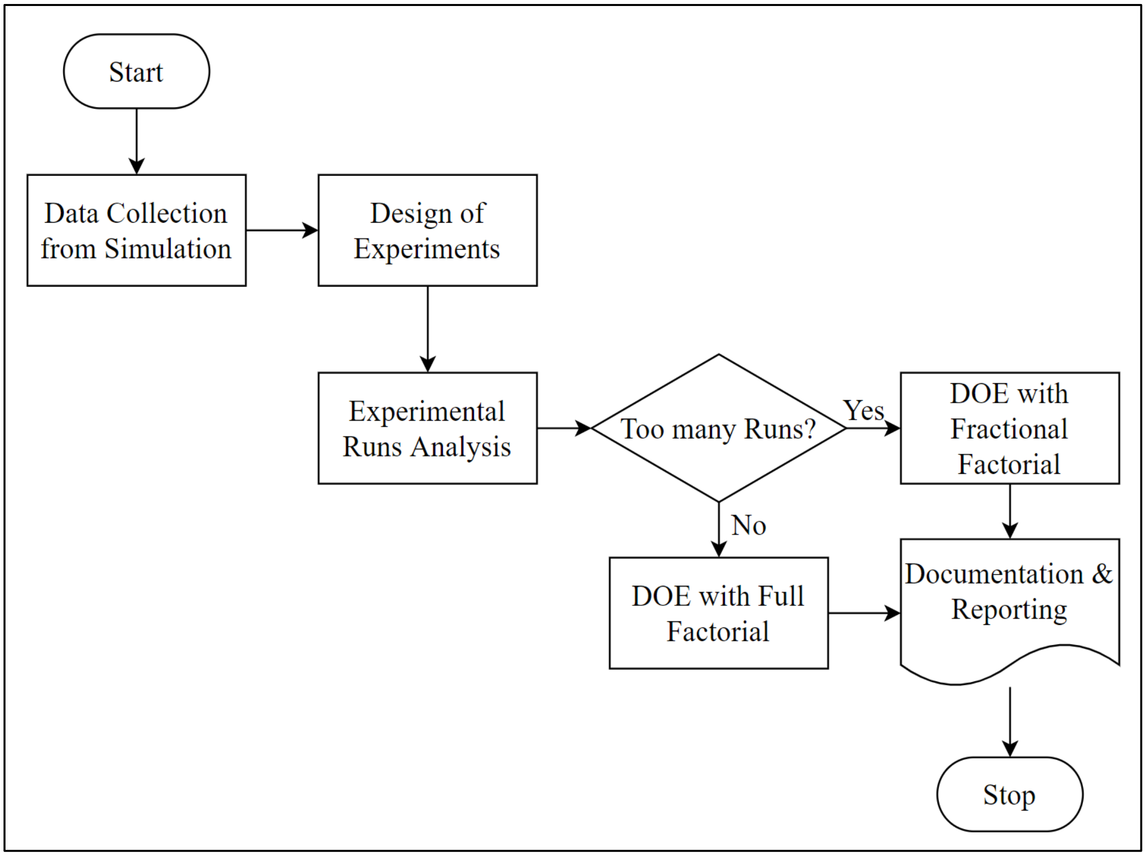


Figure 44: Flow chart of the design of experiment.

From the flowchart shown in Figure 44, the simulation steps can be described as follows:

- Identify the design points or the levels.
- Running experiment (simulation) and energy & cost estimation
- Analysis of the results
- Selecting the type of DOE and
- Interpret the result and come to an optimum solution.

In this case, three factors with three levels were considered. The factors or independent variables are the amount of water that needs to be transferred, the duration between the transfers, and the start-stop times of the transfer. The average temperature of the outside water, the energy consumed for the transfer, and the reservoir cost are the dependent variables or results. Table 5 shows the values of independent variables considered.

Table 5: Independent variables and levels for the DOE factorial design

Levels	**Factors**		
	A: Water (Gallons)	**B: Duration (hours)**	**C: Start Time**
1	50	4	12pm
2	200	8	8pm
3	400	12	4am

Since there are three factors with each has three levels, the full factorial design with 3 factors and 3 levels will have $3 \times 3 \times 3 = 27$ runs which is very large. So, a fractional factorial design is considered with the "Taguchi Design Method" in "Minitab" shown in figure 44 with 9 runs. Then the simulation is done as shown in figure 46 considering each combination found from the "Taguchi Design Method" shown in Figure 45

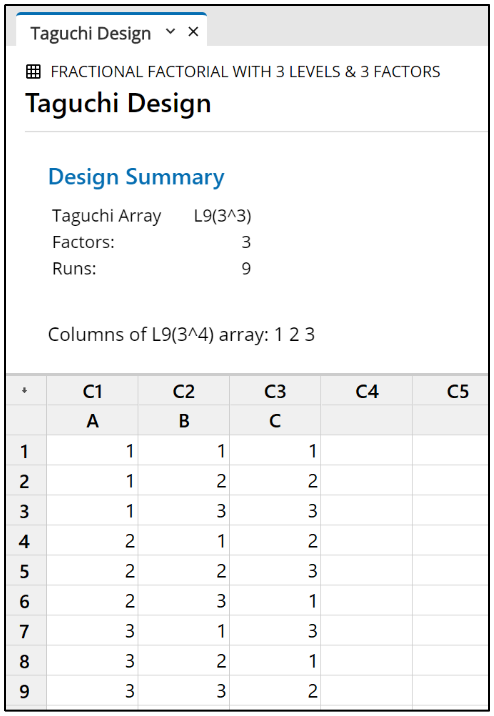


Figure 45: Taguchi Design in Minitab

Table 6: Results of the responses for the fractional factorial design

Runs	**A Water (Gallons)**	**B Duration (hours)**	**C Start Time**	**Avg Temperature Outside - Inside (°F)**	**Pump Energy (Wh)**
1	50	4	12 pm	71.7-69.1=2.5	5
2	50	8	8 pm	66.1-68.7= -2.6	5
3	50	12	4 am	69.9-68.7=1.2	5
4	200	4	8 pm	67.7-68.8= -1.1	20
5	200	8	4 am	65.1-67.2= -2.1	20
6	200	12	12 pm	71.8-69.2=2.5	20
7	400	4	4 am	62.6-68.3= -5.7	40
8	400	8	12 pm	72.2-69.3=2.8	40
9	400	12	8 pm	65.2-68.6= -3.4	40

Table 6 shows the fractional factorial design of experiments obtained from the Taguchi Method in Minitab with results from simulation. The submersible pump shown in figure 47 has a flow rate capacity of 550 gallons per hours, which means to transfer 50 gallons of water, it needs $\frac{50}{550} = 0.1$ hour. The power rating of this pump is 50 watt. So, energy consumed to transfer 50 gallons water = 50 watt × 0.1 hour = 5 Wh. The reservoir shown in figure 47 needs to be replaced every 1 year.

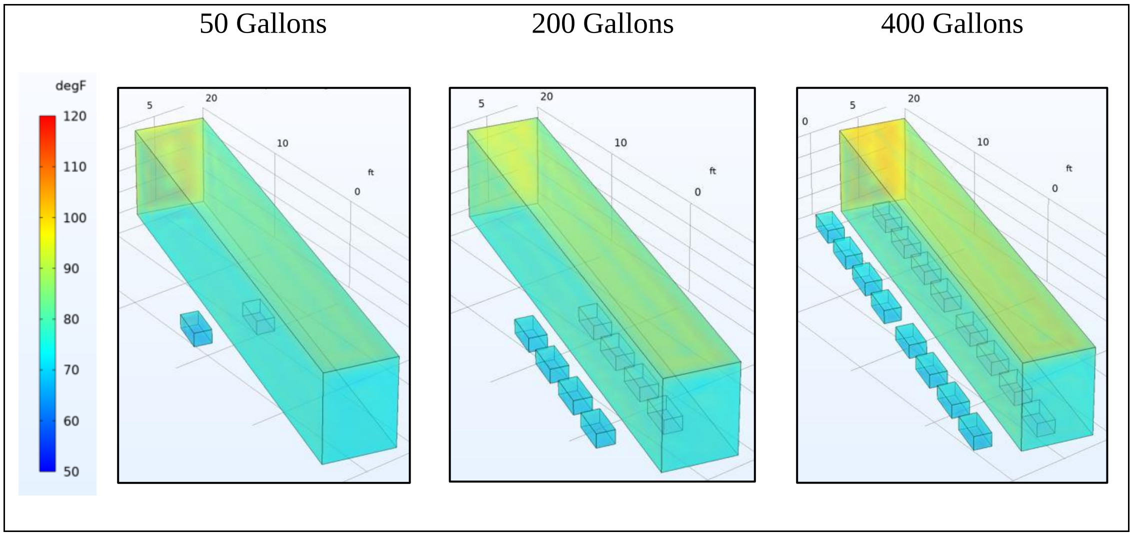


Figure 46: Simulation with different amount of water

Figure 47: Submersible pump (50W) and water reservoir.[45, 46]

5.3 Result and Analysis

In order to select the optimum condition for transferring the water between outside to inside reservoirs, the following conditions are desired:

1. Water: higher the better
2. Temperature difference: negative and larger

3. Pump energy: lower the better

The main input variable that affects the output variables and the output variables are listed in Table 7.

Table 7: Main input variable and dependent output variables

No.	Water Gallons	Temperature Difference	Energy Consumption (Wh)
1	50	2.5	5
2	50	- 2.6	5
3	50	1.2	5
4	200	- 1.1	20
5	200	-2.1	20
6	200	2.5	20
7	400	-5.7	40
8	400	2.8	40
9	400	- 3.4	40

By analyzing the data from the table above, it is found that at row 7, the temperature difference is negative and largest and the amount of water is highest but the energy consumption is also higher which is not preferable. And at row 5, the temperature difference is still negative (-2.1 degrees) and the energy consumption is half. So, if saving 20Wh energy is the main factor, then we can choose row 5 which is 200 gallons of water transfer with 20Wh energy consumption. Otherwise, row 7 is most efficient.

Finally, we can conclude that designing an integrative system design combining all the passive cooling systems can determine the optimum condition to save the energy cost and can keep the environment livable to plants which is hypotheisi 4. So we accept hypothesis 4.

6. CONCLUSION AND DISCUSSION

A smart passive temperature control system for indoor vertical farmingis developed in a way that it operates with optimum conditions of equipment use, time of water transfer, etc. As a result, it saves energy and cools down the growing solution or water temperature, and makes it livable for plants. The theoretical calculation is done and found the cooling load required to make the air temperature favorable for plants and then found out that the air conditioning units can be minimized by using more vents and exhaust fans which will also save energy. A CFD model is developed to determine indoor air and water temperature at any given time of the year and the model is validated with experimental data. The empirical study is carried out with 8 different experiments with different weather conditions and also different lighting conditions. The experimental data are analyzed and found out how different weather and lighting condition affects the water temperature. Finally, with all the data obtained from the experiments, a design of experiments is developed to determine the optimum time and condition for passive temperature control of water as well as saving energy and cost.

Future Works:

- Implementation of vents and exhaust fans and calculating exact energy saving with passive temperature control of inside air of the shipping container
- Adding lights, vents, exhaust fans in the CFD model and running the simulation and validation.
- As the simulation only uses the most recent weather data, so it will not work on any unpredictable weather condition like a snowstorm. So, a large amount of

historical weather data needs to be considered to make a better prediction of weather and hence more accurate results from the simulation.

- More experiments and a full factorial design of the experiment need to be done to have a more accurate optimum condition for passive temperature control.
- Geothermal energy will be utilized by transferring the water through underground which will cool down the water in summer and warm up the water in winter, and hence will save energy by passive temperature control.
- Optimum location of the water reservoir placement will be determined to get best possible output for passive temperature control

APPENDIX SECTION

Appendix A: Temperature data from the experiment (sample)

Table A-1: Temperature data with no light and no water flow (4.11.21-4.14.21).

Time	No	Inside Water Temperature°F	Inside Air Temp °F	Outside Air Temp°F
11-04-2021 13:18:46	1	68.54	70.16	81
11-04-2021 13:33:46	2	67.46	70.7	
11-04-2021 13:48:46	3	67.28	70.34	
11-04-2021 14:03:46	4	67.28	70.7	84
11-04-2021 14:18:46	5	67.28	71.24	
11-04-2021 14:33:46	6	67.28	71.96	
11-04-2021 14:48:46	7	67.46	72.68	
11-04-2021 15:03:46	8	67.64	73.22	85
11-04-2021 15:18:46	9	67.64	73.94	
11-04-2021 15:33:46	10	67.64	74.48	
11-04-2021 15:48:46	11	67.82	75.2	
11-04-2021 16:03:46	12	67.82	75.92	87
11-04-2021 16:18:46	13	68	76.46	
11-04-2021 16:33:46	14	68.18	77.18	

Table A-2: Temperature data with no light and no water flow (4.24.21-4.27.21).

Time	No.	Outside Water Temp°F	Inside Air Temp°F	Inside Water Temp°F	Outside Air Temp°F
24-04-2021 13:45:33	1	67.46	75.2	66.2	
24-04-2021 14:00:33	2	67.64	73.76	66.38	82
24-04-2021 14:15:33	3	67.64	72.5	66.38	
24-04-2021 14:30:33	4	67.82	72.14	66.38	
24-04-2021 14:45:33	5	68	72.14	66.56	
24-04-2021 15:00:33	6	68.18	72.32	66.56	83
24-04-2021 15:15:33	7	68.36	72.5	66.56	
24-04-2021 15:30:33	8	68.36	72.86	66.56	
24-04-2021 15:45:33	9	68.54	73.22	66.56	

Table A-3: Temperature data with 2 light and no water flow (5.11.21-5.14.21).

Time	No.	Outside Water Temp°F	Inside Air Temp°F	Inside Water Temp°F	Outside Air Temp°F
11-05-2021 15:45:37	1	74.3	79.34	77.36	
11-05-2021 16:00:37	2	73.58	79.16	77.54	67
11-05-2021 16:15:37	3	73.04	79.34	77.72	
11-05-2021 16:30:37	4	72.32	79.34	77.9	
11-05-2021 16:45:37	5	71.78	79.52	77.9	
11-05-2021 17:00:37	6	71.42	79.7	78.08	65
11-05-2021 17:15:37	7	70.16	79.52	78.26	
11-05-2021 17:30:37	8	69.8	79.52	78.44	
11-05-2021 17:45:37	9	69.98	79.52	78.44	
11-05-2021 18:00:37	10	69.8	79.52	78.62	65

Complete temperature data from the experiment:

- shorturl.at/juvyG
- https://docs.google.com/spreadsheets/d/1sdR5-ihvTWO8poTmDpCXrNVuCdGu6ZFvVl3x2ZJ0ADE/edit?usp=sharing

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