Thermal Heat Exchange Chamber Project User Manual

Submitted by

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Abstract

This report details the fundamental functions and features of The Heat Exchanging Camber hardware and software, created for clients. The user manual outlines how the features and function were developed through the design process and combined and implemented to create the final product. This report also explains the installation, operations, and maintenance of The Heat Exchanging Camber, and the future steps to improve the product design. This document will provide the user with all the work completed through the duration of the project, and how all of the moving parts fit together. In the final section of the report, further recommendations and suggestions for future updates and additions are included to provide the reader with examples of improvement.

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1 Introduction

In North America heating is a crucial need for living as a result of the cold climate in the winter. Temperatures reach below -30ºC and heating systems are required in homes to provide a safe living environment. The purpose of this project is to design a sustainable and cost-efficient prototype that can operate underground with all anticipated conditions (pressure, ventilation, air condensation etc.). The product must be portable and convenient for users to install and make automated adjustments towards the change of inside room temperature. Higher efficiency is highly favored.

The requirements the client specified are that the parameter of the THEC system cannot exceed 12ft x 7ft x 7ft. The space must be used efficiently. The HEC box must be closed, strong enough to be buried under ground, hold all necessary components and must be well-insulated. Additionally, configuration of shape, size, coil configuration and material of inner pipes for optimal air flow and heat transfer capacity must be considered. The electronic system including fan must be activated by the thermostat and a pump must be included to eliminate condensation. The air quality must be controlled with filters, linings, and shutters. To maintain a temperature of 20ºC in the winter, THEC must be well-insulated, system must have a lifespan of 35-40 years, low installation fee, and finally the system must be environmentally friendly therefore, must not emit any greenhouse gases.

2 Need Identification and Problem Statement

2.1 Client Meeting Summary

An initial client meeting was held on January 28th, 2022, with our client, Chinedu J. Enendu, to discuss their patented low-tech zero emission HVAC system. During the meeting, Chinedu described system functionalities, benefits, impediments, and potential areas of improvement while Team Pandora obtained information to determine client needs for the requested prototype. Our client described that the current problem is to raise the indoor temperature to about 20°C during the winter, where he suggested deploying other sustainable innovation in the project, such as a solar water heater.

2.2 Customer Needs and Needs Hierarchy

Table 1. Client Needs and Importance

#	Client statement	Interpreted need	Importance
1	The parameter of the box does not exceed 12ft x 7ft x 7ft	Spaces must be used efficiently	5
2	Box/enclosure for THEC which is strong enough to be buried, hold all the necessary components, and well insulated	The quality of the box needs to be achieved to maintain the basic operation	5
3	Configuration of shape, size, coil configuration and material of inner pipes for optimal air flow and heat transfer capacity	The components deployment must be considered to achieve the best performance	4
4	Electronic system including fan (blower) activated by a thermostat as well as a pump to eliminate condensation	The system must be automated	5
5	Air quality control with filters, linings, shutters etc.	Air quality must meet the standard regarding user's health	5
6	Installment of innovation to achieve 20°C during the winter	The higher magnitude of the function is desirable	3
7	THEC will be most efficient when installed in a well-insulated building envelope and can be installed as a retrofit.	The portability and the convenience of the product is necessary.	2
8	Life span of system should be 35-40 years.	Durable and easy maintenance.	2
9	Low cost for installation and operation.	Cost efficient for consumer.	5
10	Environmental sustainability	Does not emit any greenhouse gases.	5

* The importance of needs has been interpreted and ranked, using a scale from one to five. One is deemed least important and five as most important.

2.3 Problem Statement

Design a sustainable and cost-efficient prototype that can operate underground with all anticipated conditions (pressure, ventilation, air condensation etc.). The product must be portable and convenient for users to install and make automated adjustments towards the change of inside room temperature. Higher efficiency is highly favored.

2.4 Benchmarking: Traditional Heating Systems vs THEC

Since there was no previous attempt of similar product as our client required therefore, we are comparing to traditional heat system using gas. We take the system and the control device as one and compare it with our future prototype. Differences between these two options were expected although both products have the same purpose.

Table 2. Benchmarking: Traditional Heating Systems vs THEC

	Traditional system	THEC
Item weight	Heavy	Light
Portability	No	Yes
Cost	-	100$
Assembly required	No	Yes
Manipulation of temperature	Effective	Limited
Air quality	Independent	Dependent
Automation	Yes	Yes

3 Design Criteria and Target Specification

A design criterion was identified based on the interpreted client's needs as shown in *Table 3*. These criteria are then further translated into design metrics and classified as functional, non-functional or as a constraint in the design metric table (*Table 4*).

Table 3. Design Criteria

#	Interpreted Client Need	Design Criteria
1	**[Non-Functional]** Spaces must be used efficiently	Components arranged to obtain client specifications without compromising the product's output and efficiency.

2	**[Functional]** The condition of the box is essential to maintain basic operations	Use qualified material that can withstand the pressure underground
3	**[Functional]** The heat control system must be automated	Devices have a heat sensor and control system
4	**[Functional]** Device must meet the standard air quality output	Devices have fans and air ventilation system
5	**[Functional]** The higher system efficiency is desirable	Use additional energy source to achieve 20°C during the winter
6	**[Non-Functional]** The portability and the convenience of the product is necessary	Easy to assemble and transport
7	**[Non-Functional]** Durable and easy maintenance	Qualified material and simplistic system
8	**[Constraints]** Low cost for installation and operation	Cost efficient for consumer
9	**[Constraints]** Does not emit any greenhouse gasses	No greenhouse gas emission
10	**[Non-Functional]** Ease of use	Detailed user manual
11	**[Constraints]** Material and manufacturing cost	Maximum of $100 CAD
12	**[Constraints]** Reduce size from conventional HVAC systems	The box does not exceed measurements $(l \times w \times d)$ 4ft x 2.5ft x 2.5ft
13	**[Constraints]** The ability to achieve temperature higher than 15°C during the winter	Temperature output during the winter is greater or equal to 15℃

Table 4. Design Metric

#	**Design Metric**	**Unit**	**Importance (1-5)**
Functional Requirements			

2	Use qualified material that can withstand the pressure underground	Pascal (Pa)	5
3	Devices have a heat sensor and control system	Yes/No	4
4	Devices have fans and air ventilation system	micrograms per cubic meter (µg/m^3)	4
5	Use additional energy source to achieve 20°C during the winter	Yes/No	3
9	No greenhouse gas emission	Yes/No	4
Non-Functional Requirements			
1	Components arranged to obtain client specifications without compromising the product's output and efficiency	Yes/No	2
6	Easy to assemble and transport	Yes/No	3
7	Qualified material and simplistic system	Yes/No	5
8	Cost efficient for consumer	$	3
10	Detailed user manual	Yes/No	3
Constraints			
8	Cost efficient for consumer	$	
9	No greenhouse gas emission	Yes/No	
11	Material and manufacturing cost	$	
12	The box does not exceed measurements ($l \times w \times d$) 4ft x 2.5ft x 2.5ft	Feet (ft)	
13	Temperature output during the winter is greater or equal to 15℃	℃	
Possible Constraints			
14	Time budget	Days	

Note: The importance of needs has been interpreted and ranked, using a scale from one to five where one is deemed least important and five as most important.

3.1 Benchmarking: Existing HVAC Systems

Since there is currently no attempt of a similar product to our client's, we are comparing our client's Heat Exchange Chamber (THEC) to sustainable HVAC systems that are currently available to users. Although the products serve the same purpose, there are many variations for the designs analyzed.

Table 5. Sustainable HVAC System Benchmarking

HVAC System / Specifications	Geothermal Heat Pump	Baseboard Hydronic radiant heat system	DeVap (Green Air Conditioning)	Passive Solar Heater
Item Weight	2-10 tons	19 lbs	3-10 tons	7.2-9.5 lbs
Portability	No	Yes	Yes	Yes
Dimensions	1,200-1,800 ft (for pipe)	59x6x9”	Dependent on building size	Dependent on building size
Energy Intake System	Draws energy from earth via pipes.	Use an internal reservoir of heated liquid to produce mostly radiant heat.	Move air via liquid desiccant heat exchanger (dehumidifies air), air flows through evaporative cooler	Collects heat via sunlight and stores in a thermal mass.
Limiting factor	Location and terrain may prevent installation. Requires a large plot of land to install pipes.	Suggested use with dehumidifier	Currently only developed for commercial market	Output dependent on window location
Infrastructure required	Yes	No	No	Yes

Equipment Cost	$18,000-45,000	$269 / 200sq ft	$6,000-20,000	>$4,000
Operational Cost / month	$20-40	$20 / sq ft	$45-95	N/A – Passive system
Temperature manipulation (°C)	10-25	10-30	10-25	10-25
No greenhouse gas emission	No	No	No	No
Safety / Dependability (1-5 scale: 5 as the highest level)	5	3 (Mold or water damage may result from condensation)	4	4

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Table 6. Design Matrix

HVAC System / Specifications	Importance (weight)	Geothermal Heat Pump	Hydronic radiant heat system	DeVap (Green Air Conditioning)	Passive Solar Heater
Item Weight	3	1	3	1	3
Portability	3	1	3	3	3
Dimensions	5	1	3	1	3
Energy Intake System	1	3	3	3	3
Limiting factor	5	1	2	3	1
Infrastructure Required	5	1	3	3	1
Equipment Cost	3	1	3	1	2
Operational Cost	5	2	2	1	3

Temperature manipulation	3	3	3	3	3
No greenhouse gas emission	4	3	3	3	3
Safety/dependability	5	3	1	2	2
Total		73	106	89	98

Note: The design specifications are ranked on a scale of 1-3 (3=green, 2=yellow, 1=red). 3 being the "best" and 1 being the "worst". The ranking of each specification will depend on user needs. After determining the best specifications, multiply the importance of weight by its value (1-3}.

Based on our design matrix, we found that the hydronic radiant heat system met majority of our design specifications and we would like to incorporate some of the design features into our prototype.

3.2 Target Specification

The prototype target specifications are defined after both the design criteria and metrics are defined. *Table 7* details the justified, marginal, ideal and target values of the final prototype to be presented on design day. It also includes justifications of why these target specifications are important, and how each of these metrics can be verified in the future.

Table 7. Engineering Design Specifications

Metric	Unit	Marginal Value	Ideal value	Target Value	Justification	Verification Method
Functional Requirements						
Use qualified material to meet the requirement	Pa	>3	4.5	4.5	Can hold the pressure from the ground	Measurement
Devices have a heat sensor and control system	Yes/No	Yes	Yes	Yes	To achieve the automation and safety for the user	Test
Devices have fans and air ventilation system	$\mu g/m^3$	<12	9-12	9	Provide quality air for health concerns	Measurement

Use additional energy source to achieve 20°C during the winter	Yes/No	Yes	Yes	Yes	To achieve higher temperature	Test
No greenhouse gas emission	Yes/No	Yes	Yes	Yes	Reduce green-house gas emission	Test
Non-Functional Requirements						
Components arranged to obtain client specifications without compromising the product's output and efficiency	ft	<25	18-25	18	Minimize the space needed of the device	Measurement
The box is easy to collect all the components and close, add wheels under the box	Yes/No	Yes	Yes	Yes	To achieve the portability and convenience	Test
Qualified material and simplistic system	Yes/No	Yes	Yes	Yes	Easy to use	Test
Cost efficient for consumer	$	<100	80-100	80	Make the device less expensive	Measurement
Detailed user manual	Yes/No	Yes	Yes	Yes	Help user installing the device	Survey
Constraints						
Cost efficient for consumer	$	<100	80-100	80	Make the device less expensive	Measurement
No greenhouse gas emission	Yes/No	Yes	Yes	Yes	Reduce green-house gas emission	Test
Material and manufacturing cost	$	<100	80-100	80	Make the device less expensive	Measurement
The box does not exceed measurements ($\boldsymbol{l \times w \times d}$) 4ft x 2.5ft x 2.5ft	ft	<25	18-25	18	Minimize the space needed of the device	Measurement
Temperature output during the	℃	>15	15-23	20	Increase system efficiency	Measurement

winter is greater or equal to 15℃						

After meeting with our client Chinedu, we analyzed and interpreted their needs to formulate an effective problem statement that encompasses the goal of their patented low-tech zero emission HVAC system. A benchmarking analysis was conducted to examine where present solutions do not address all the needs of our client and in which ways our device could improve upon those shortcomings. Moving forward, various conceptual designs will be formulated, and each will be analyzed and ranked depending on their suitability and their fulfillment of customer needs.

3.3 Concept Generation

3.3.1 Sub-System 1: Air Intake (Inlet) and Output (Fan)

3.3.1.1 Air gathering system

For the tubes, the box should have 3 distinct tubes without valve for gathering heat from the ground, made of heat conducting materials. A main output tube is needed as well to deliver the processed air into the house, the tube must be made of heat conducting material, it may branch according to the user’s need. Furthermore, a fan is necessary for the output tube, the filter should be filtering the air after they pass through the air inlet. There are two types of air vents such as, supply vent and return vent.

- **Supply Vent (air inlet)**: takes air from outside and blows air into indoor spaces
  - Smaller than return vent
  - Has louvers (behind grill) to direct air flow
- **Return Vent**: pull air out of indoor spaces to deliver to heating/cooling system
  - Larger in size
  - Does not have louvers

3.3.1.2 Fan

For the air inlet fan, it is recommended to implement centrifugal fans because they are suitable for generating high-volume air. Two types of fans are used in HVAC systems, Axial and Centrifugal.

1. Axial fans have enclosed fan blades in a tube allowing for consistent airflow. This is useful for consistent cooling and uniform air volume output.
2. Centrifugal fans also can increase the volume of air and deliver high-pressure, high-volume air output.
    a) In this case, the product should be energy efficient so, applying a backward curved centrifugal fan is recommended because it consumes less power and generates less noise.
    b) A forward curved design indicates that the tip of the blade is forward curved, and this results in high pressure air output.
    c) When the blades are inclined then this implies that it has an airfoil design where these fans can generate high speed air output without creating a swirl. They also produce low noise and most optimal for HVAC that require active ventilation.

3.3.2 Sub-system 2: Piping Network and Sump Pump

3.3.2.1 Piping Network

Configuration

There are various methods to configure a piping network for a geothermal heat pump system, however given the client's needs we will review each configuration and discuss the benefits and setbacks.

There are three piping layouts that will be considered for a horizontal configuration as they are the most cost-efficient configuration for residential installations and most suitable for residential installation. There are other configurations such as pond, lake and well configurations, however they will not be considered for this prototype because they require a large body of water which is not suitable for urban residential neighborhoods. There are also vertical configurations, but the pipes need to be buried a 100 to 400 feet underground which is not realistic for a residential system.

Horizontal Pipe Layouts:

- Straight pipes buried at same depth: Require a large amount of space.

- Straight pipes buried at different depths: Require a large amount of space and is exposed to a range to soil vertical temperature profiles.
- Looped pipes (aka the Slinky method) buried at same depth: Conserves space, is increasingly cost-efficient and is exposed to a range to soil vertical temperature profiles.

Material

The most used materials for geothermal heat pump systems are high-density polyethylene (HDPE) and crosslinked polyethylene (PEX). These materials are highly recommended due to their flexible yet durable material characteristics and lifespan of approximately 50 years. HDPE is currently the preferred material because it is exceptionally reliable, has high chemical resistance, high pressure rating, no mechanical fittings and has the best thermal conductivity in comparison to other piping materials. Another consideration is that it is available for different pressure ratings and is easily obtainable. PEX is a good alternative to HDPE since PEX has a higher thermal conductivity and shares similar desired properties with HDPE but the material costs twice the amount than its counterpart. So, the main consideration when selecting the material is the value of the system efficiency vs cost.

3.3.2.2 Sump Pump

For this initial design, it requires a sump pump therefore, sump pumps are interchangeable making it more efficient by saving time and lowering cost. The sump pump can be installed outside so that it can relocate water during storms or floods. There are four types of sump pumps, pedestal sump pump, submersible sump pump, battery backup sump pump, and combination sump pump.

- **Pedestal Sump Pump**
  - Common choice for homes
  - Cheapest option
  - Ideal for smaller sump pits

- Can run the risk of overheating because the motor can be cooled down since its mounted high on the rod, keeping it dry

- **Submersible Sump Pump**
  - Cost-effective choice because they have better performance and longer life span
  - Fully submerged in water
  - Motor is covered and enclosed in waterproof casing so, there is less chance of water damage
- **Battery Backup Sump Pump**
  - Useful for when power goes out
  - Powered by electric outlet
  - Can continuously pump water out for 12 hours
  - Cannot be used as main pump since it can only handle small rain events
- **Combination Sump Pump**
  - Combination of primary pump and battery back up
  - Protected under normal circumstance and when there's a blackout

The check valve of the pump can be installed horizontally or vertically, however, it is more optimal if it's installed horizontally when pumping out solid or semi-solids. The sump pump check valve tends to be designed as a flapper style where one valve is installed in the discharge pipe. By gravity the flapper closes when the pump is shut off.

3.3.3 Sub-system 3: Temperature Sensor

Temperature Sensor

A temperature sensor is a device that is used to measure temperature. For this project, we're specifically interested in using a thermocouple or resistance temperature detector (RTD):

- **Thermocouple**: Composed of two wires of different metals joined together at their ends. If the junctions are exposed to different temperatures, a voltage is produced which tells you the temperature. Thermocouples are cost effective however they are prone to error and inaccurate temperature readings

- **RTD:** Uses electrical resistance to measure temperature. They are very accurate in comparison to other temperature sensors however they are also the most accurate.

3.3.4 Additional heat source

Solar Panel

A solar panel can be installed above the ground, which will be connected to a thermal mass inside the box. The installation of the thermal mass makes the product able to further increase the maximum temperature. The limiting factor is that the output is dependent on the location and size of the solar panel.

Hydronic Baseboard Heater

Hydronic baseboard heaters are another viable option as they release no green-house gases and use an internal reservoir of heated liquid to produce radiant heat. The only issue is that one system does not provide sufficient energy to heat a building, so it may be beneficial to explore system modifications to increase efficiency.

3.3.5 Sub-system 4: Heat Exchange Chamber and Thermal Energy Storage

3.3.5.1 Heat Exchange Chamber

Heat exchangers function by transferring heat from one area to another. There are many different types and sizes of heat exchange chambers. Some of these include, shell and tube, double pipe plate heat exchangers and more. Shell and tube exchangers are constructed of single tube or series of parallel tubes closed with a sealed cylindrical pressure vessel. Double pipes employ the simplest heat exchanger design and configuration which consists of two or more concentric, cylindrical pipes. Finally, plate heat exchangers are constructed of several thin pates stacked on top of each other. The shape that we will be using in our design will be a rectangular heat exchange chamber. The ideal material choices are clay and concrete. These materials are the most sufficient. The two most common materials used for heat exchangers are aluminum and copper. They are both cost-efficient and are highly effective. Other materials include bronze, titanium, carbon steel and more.

Table 8. Benefit and Drawbacks for different materials of the heat exchange chamber

Material	Benefits	Drawbacks
Clay	• Does not absorb or retain much heat • Can be easily shaped • Increase of strength • Reduction of plasticity • Durable • Reduces dust and allergens in air • Absorbs odor	• Potential cracking
Concrete	• Warm and cools slowly • Stays warm/ cool for long period of time • Delays and releases heat transfer through walls • Reduces heat loss from buildings • Highly durable and resilient • Low maintenance • Energy efficient • Cost effective • Can be recycled	• Heavy Weight
Copper	• Thermal conductivity • Excellent conductor of heat • Ease of inner grooving	• Venerable to corrosion • Lower lifespan • Due to corrosion, it loses efficiency
Aluminum	• Weight • Performance • Corrosion resistance • Cleanability	• Doesn't transfer heat very well • Rust • Breaks down easily

Furthermore, the thickness of the chamber affects heat transfer. The minimum thickness of a heat exchange chamber is 3mm. The rate of heat transfer is inversely proportional to thickness.

3.3.5.2 Thermal Energy Storage

This heating device requires thermal storage. Thermal energy storage is achieved with a wide variety of different technological devices. These technologies allow excess thermal energy to be stored and used months later at scales ranging from building, district, town, or region. It also allows heat to be transferred and stored. A thermal storage is like a battery for a building's air conditioning/heating system. This method is built into new technologies that complement energy solutions such as solar and hydro. Different types of materials include metals, concrete, rocks, sand, and bricks. These can be utilized by both higher and lower temperature energy storage because they will not boil or freeze.

Table 9. Benefit and Drawbacks to different type of materials for thermal energy storage

Materials	Benefits	Drawbacks
Brick	• Good for storing energy • Can be converted into energy	• Difficult to mold into desirable shapes
Clay	• Good for storing energy • Low cost • Unique structure • Abundant • Environmentally benign	• Lower stress threshold than other material.
Sand	• Store up to 26,000 megawatt hours of thermal energy • Eco friendly	• Limited to a Rankine cycle for energy transfer

3.4 Conceptual Design

Table 10. Listing various solutions for the different components of the sub-systems

Sub-System	Components	Team Member Generated Solutions
1	Air Inlet	• Supply Vent • Return Vent
	Fan	• Axial • Centrifugal
2	Piping Network Configuration	• Straight pipes buried at same depth • Straight pipes buried at different depths • Looped pipes (aka the Slinky method) buried at same depth
	Pipe Material	• high-density polyethylene

		• crosslinked polyethylene
	Sump Pump	• Pedestal sump pump • Submersible sump pump • Battery backup sump pump • Combination sump pump
3	Control System	• P-Controller • PI-Controller • PID-Controller
	Temperature sensor	• Thermocouple • RTD
	Additional Heat Source (optional)	• Solar panel with a heater • Hydronic baseboard heater connected into the box
	Heat Exchange Chamber	• Clay • Concrete • Sopper Aluminum

3.5 Refined Design Concepts

From each sub-system, there are correlating components that were incorporated in the three design concepts. For instance, Design Concept 1 focused on which type of component was the cheapest while Design Concept 2 was fixated on the most efficient component and lastly Design Concept 3 determined the most optimal components needed for our prototype.

Table 11. Comparing different components for each design concept and determining the most suitable component for each design based on certain criteria

Sub-System	**Components**	**Design Concept**		
		1	**2**	**3**
1	Air Inlet	Supply	Return	Return
	Fan	Axial	Centrifugal	Centrifugal
2	Piping Network Configuration	Straight pipes buried at different depths	Looped pipes buried at the same depth	Looped pipes buried at the same depth

	Pipe Material	high-density polyethylene	crosslinked polyethylene	high-density polyethylene
	Sump Pump	Pedestal Sump Pump	Combination Sump Pump	Submersible Sump Pump
3	Control System	PI-Controller	PI-Controller	PI-Controller
	Pressure Sensor	Capacitance	MMS	MMS
	Temperature Sensor	Thermocouple	RTD	RTD
	Additional Heat Source (optional)	N/A	Solar panel with a heater	N/A
4	Heat Exchange Chamber	Clay/Concrete	Clay/Concrete	Clay/Concrete
	Thermal Energy Storage	Sand	Brick	Sand

Figure 1. Design Concept 1

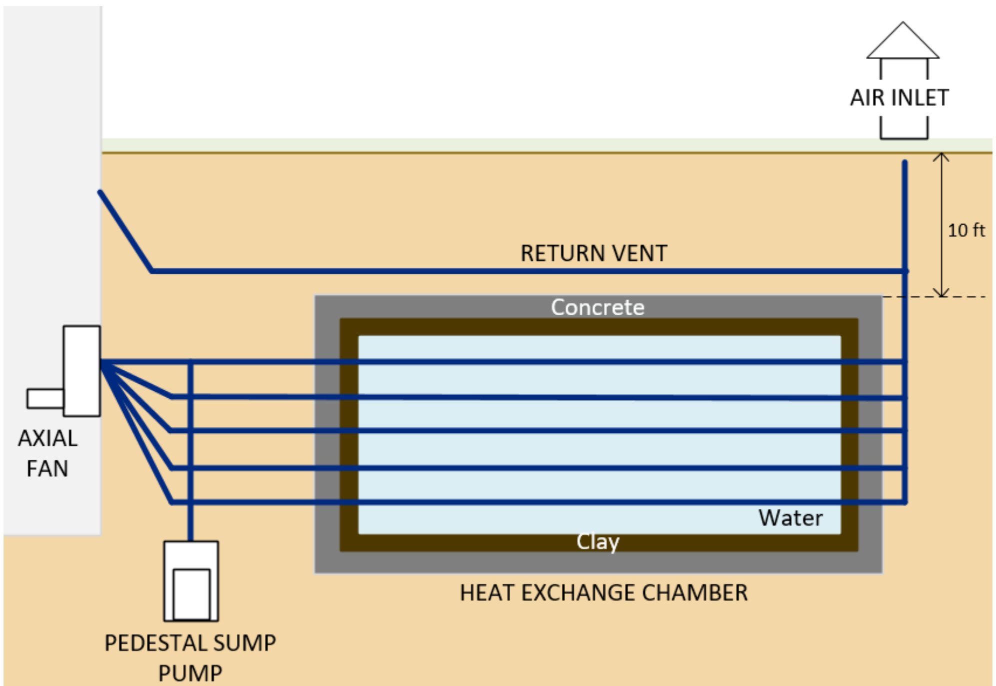


Figure 2. Design Concept 2

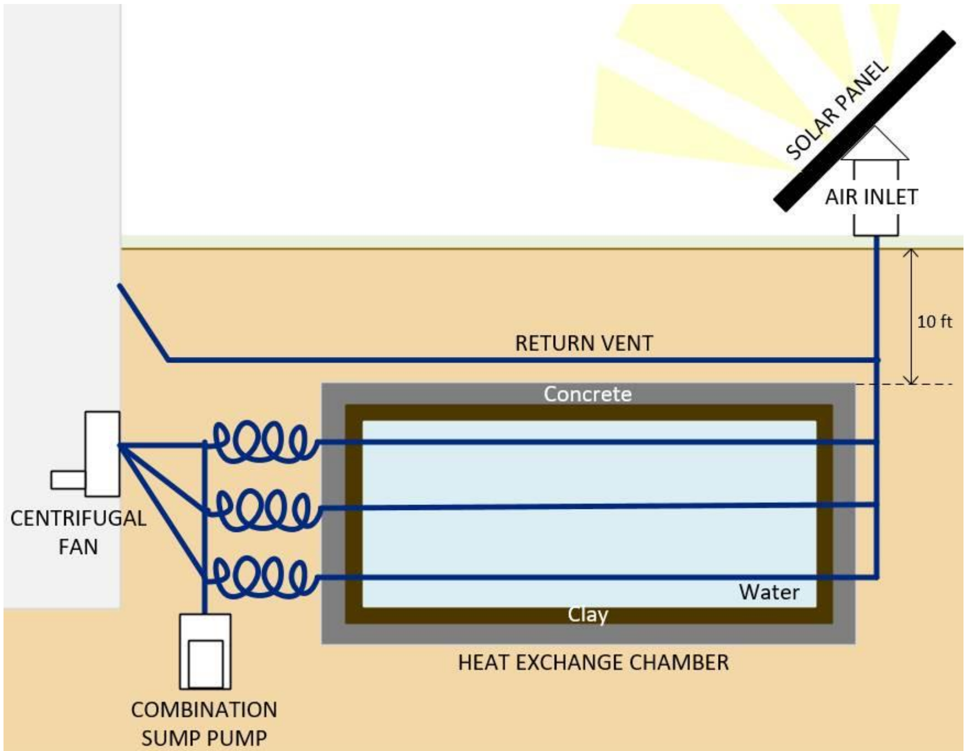


Figure 3. Design Concept 3

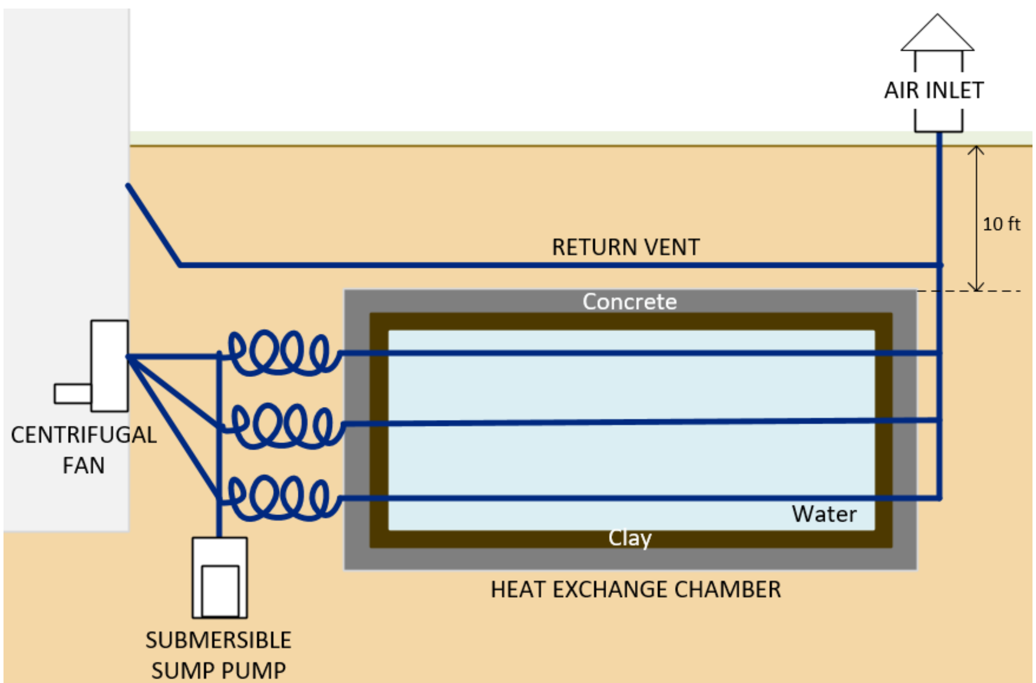


Table 12. Benchmarking for the Three Design Concepts

DC / Specifications	Design Concept 1	Design Concept 2	Design Concept 3
Item Weight	23 lbs	30 lbs	24 lbs
Portability	Yes	Yes	Yes
Dimensions	28.125 square feet	28.125 square feet	28.125 square feet
Energy Intake System	Draws energy from earth via pipes.	Draws energy from earth via pipes and draws extra solar energy.	Draws energy from earth via pipes.
Limiting factor	The temperature is limited due to insufficient energies	budget is insufficient for this solution	The temperature is limited due to insufficient energies
Infrastructure required	Yes	Yes	Yes
Equipment Cost	$50	$150	$85
Operational Cost / month	$20-40	$20 / sq ft	$45-95
Temperature manipulation (°C)	15-20	15-30	15-22
No greenhouse gas emission	No	No	No
Safety / Dependability (1-5 scale: 5 as the highest level)	3	4	5

Table 13. Design Matrix for the Three Design Concepts

HVAC System / Specifications	Importance (weight)	Design Concept 1	Design Concept 2	Design Concept 3
Item Weight	3	3	1	2
Portability	3	3	3	3
Dimensions	5	3	3	3
Energy Intake System	1	2	3	2
Limiting factor	5	1	2	2
Infrastructure Required	5	3	3	3
Equipment Cost	3	3	1	2

Operational Cost	5	2	2	2
Temperature manipulation	3	1	2	1
No greenhouse gas emission	4	3	3	3
Safety/dependability	5	1	2	3
Total		94	96	103

Note: The design specifications are ranked on a scale of 1-3 (3=green, 2=yellow, 1=red). 3 being the "best" and 1 being the "worst". The ranking of each specification will depend on user needs. After determining the best specifications, multiply the importance of weight by its value (1-3}.

Based on our design matrix, we found that the third design concept met majority of our design specifications and we would like to use this to develop our prototype.

In the solution generating process, we have learned to generate ideas in both vertical and lateral directions, and solved problems with different approaches and techniques. The brainstorming was successful, and in the first stages no ideas were left out. Upon further refinement, more solutions were eliminated. Together, our team generated three solutions and narrowed it down to one upon further analysis and benchmarking. According to the information we gathered from the client interview, the matrix created based on the demands and the requirements of clients, including the function of our product from the user's perspective.

Following the conceptual design process involving the definition of subsystems and potential solutions for these subsystems three unique global solutions that fulfilled all the defined criteria were developed and explained. Solution analysis led to identifying that the only difference between the solutions came down to cost and what was more tailored to the request of the client.

4 Project Schedule and Costs

The prototype design can be split into 2 parts: system concept and prototype assembly. In concept system design we constructed a system responding to the change of room temperature that heat sensor collected. The prototype assembly design has shown the details of the construction of the physical model of our project.

4.1 Prototype Design

The prototype is composed of plastic containers and flexible plastic tubes. The plastic box for the HEC was selected due to budgetary constraints and the flexible plastic tubes have been chosen so that the looped pipes can be made (we were advised that 3D printers cannot print circles and whenever there is an attempt, the shape is slightly deformed), and because it is like HDPE in terms of thermal properties that we have selected for our real-life design. Since the air inlet pipe and the return pipe needs to be connected to the six pipes that goes into the HEC, we are using a small plastic container to act as a mixing chamber and as well as a connectivity medium.

Since the HEC is filled with water, we used silicone caulking to seal any gaps we may have made while cutting the holes in the plastic box for the flexible tubes. To cut holes in all the plastic boxes, we heated a sharp knife over a gas stove and cut the holes after measuring and marking where to cut. It would have been preferable to use the drill press and laser cutters in the Makerlab, however the structure of the plastic boxes did not allow us to safely use the desired equipment (the plastic boxes were not completely flat and the faces were already assembled).

We also selected a large plastic container to put our HEC and piping network in so that we can simulate the ground temperature. We were able to do this by cutting a hole in the container lid to put a blow-dryer so that we can heat the system to ground temperature and we cut holes for the air inlet, return pipe and the air outlet where the DC fan is placed. Again, these holes were made by heating a knife over a gas stove and then cutting the holes except this time, the air pockets were sealed with a glue gun to prevent undesired heat transfer and air loss in the system.

The last part of the prototype design is our circuit where we selected various components including a DHT11 Temperature Sensor and a 12V DC fan, which are both apart of the control system and the physical build.

4.2 Project Expenses

Table 14 contains the materials of that will be used in the prototype. This includes all the components necessary to build our final product. These materials were compiled using the conceptual designs we found in the last deliverable. The cost of each product was listed, with this a sum then was taken for all the materials. This was to ensure we were not surpassing the set budget, however since the project scope changed (we were initially told that we were allowed to simulate our circuit which later changed so that we had to build our circuit), so unfortunately, we exceeded our budget.

Table 14. Bill of Materials

Materials	Description	Unit	Quantity	Cost	Extended cost	Link (inserted as Hyperlink)
Zip Ties	Sip ties are used to hold the flexible plastic tubes in place so that they are looped as per the piping network design	100	1	$5.68	$0	Bought at Home Depot (in store, no URL link)
Transistor 2N3904	Used to amplify and switch power in the circuit	1	1	$0.15	$0	https://edu-makerlab.odoo.com/shop/product/transistor-83?search=transistor#attr=231
Jump Wires	Male to Male and Male to Female jump wires are used to connect components in the circuit	1	15	$15	$0	https://edu-makerlab.odoo.com/shop/product/jumper-wires-44#attr=45
Temperature Sensor DHT11	Used to measure final output temperature – connected to the circuit	1	1	$12.35	$0	https://www.amazon.ca/Robojax-Temperature-Relative-Humidity-Sensor/dp/B09M

						7R99L4/ref=sr_1_5?crid=WLA62LCYH6WY&keywords=dht11&qid=1647306048&s=industrial&sprefix=dht11%2Cindustrial%2C73&sr=1-5
Breadboard 16.7x5.7 cm	The breadboard is used to prototype the circuit	1	1	$5.00	$0	https://edu-makerlab.odoo.com/shop/product/breadboard-53#attr=59
Arduino UNO	The Arduino is used as the circuit platform	1	1	$9.00	$0	https://edu-makerlab.odoo.com/shop/product/arduino-5?search=arduino#attr=5
Protoboard 5x7cm	The protoboard is used in the final design (with soldered components) and will replace the breadboard	1	1	$0.50	$0	https://edu-makerlab.odoo.com/shop/product/protoboard-51?search=board#attr=5
USB A to B	The USB A to B is used to connect the Arduino to a computer	1	1	$7.00	$0	https://edu-makerlab.odoo.com/shop/product/usb-cable-68?search=USB#attr=80
Hook-up wire	Hook-up wire is used to replace the jump wires in the final prototype. The hook-up wire will be soldered to components and the protoboard.	1	2	$3.20	$0	https://makerstore.ca/shop/ols/products/5ft-hook-up-wire-22awg-red
Potentiometer	Circuit component	1	1	$0.95	$0	https://edu-makerlab.odoo.com/shop/product/potentiometer-30?search=potent#attr=
220-ohm resistor	Circuit component	1	1	$0.01	$0	https://edu-makerlab.odoo.com/shop/product/resistor-6?search=resistor#attr=11
5V relay	A switch used to open and close the circuit	1	1	$8.59	$0	https://www.amazon.ca/gp/product/B073HX1DK2/ref=ppx_yo_dt_b_asin_title_o00_s00?ie=UTF8&psc=1

12V DC fan	URBEST 90mm x 25mm DC 12V 2Pin Cooling Fan for Computer Case CPU Cooler The 12V DC fan is used to pull air from the system at the air outlet.	1	1	$13.99	$0	https://www.amazon.ca/URBEST-90mm-Cooling-Computer-Cooler/dp/B01CHXUSGS/ref=asc_df_B01CHXUSGS/?tag=googleshopc0c-20&linkCode=df0&hvadid=292968375828&hvpos=&hvnetw=g&hvrand=13646520862966074192&hvpone=&hvptwo=&hvqmt=&hvdev=c&hvdvcmdl=&hvlocint=&hvlocphy=9000673&hvtargid=pla-493119463403&psc=1
LCD Screen		1	1	$10.56	$0	https://edu-makerlab.odoo.com/shop/product/lcd-screen-92?category=11#attr=171,224
Small plastic container		1	1	$2.00	$0	$1.75
34-quart plastic container		1	1	$21.99	$0	Bought at Lowes (in store, no URL link)
Polythylene Tubing 0.17 inside diameter. 25ft.		1	2	$15.84	$0	Bought at Home Depot (in store, no URL link)
5/8 inch/10ft vinyl tube		1	1	$7.99	$0	Bought at Lowes (in store, no URL link)
Glue sticks	Pack of 20 glue sticks. Used as adhesive medium for prototype.	20	1	$2.25	$0	Bought at Dollarama (in store, no URL link)

1 ½" coupling	Used as outlet pipe	1	1	$2.49	$0	Bought at Lowes (in store, no URL link)
Medium plastic containers	Used as output air chambers	1	2	$0	$0	Found in house (no purchase required)
Small plastic container	Used as a mixing chamber for the	1	1	$0	$0	Found in house (no purchase required)
Felt pads	Used to supper HEC inside larger container. Also used to raise entire system so that the outlet will not offset the entire system and make it crooked.	1	20	$0	$0	Found in house (no purchase required)
9V Battery	Since the 12V DC fan requires an external power source, a 9V battery is used and attached to the circuit	1	1	$0	$0	Found in house (no purchase required)
9V Battery Connector	This is used to attach the 9V battery to the circuit	1	5	$7.99	$0	https://www.amazon.ca/gp/product/B07D6RNJVR/ref=ppx_yo_dt_b_asin_title_o02_s00?ie=UTF8&psc=1
Digital LCD Thermometer	These five thermometers were placed throughout the prototype to measure the heat transfer throughout the systesms	1	5	$17.99	$0	https://www.amazon.ca/gp/product/B07X57LZ2R/ref=ppx_yo_dt_b_asin_title_o07_s00?ie=UTF8&psc=1
Total product cost (without taxes or shipping)				$170.52		
Total product cost (with taxes and shipping)				$192.69		

Table 15. Incudes a list of software and hardware equipment needed to design each prototype. A description of each material is given.

Table 15. List of Equipment

Item name	Description	Type	Prototype #	Source
Arduino ide	To build prototypes	Software	1,2,3	Arduino
Onshape	Used to design prototype	Software	1,2,3	Onshape
Glue gun	Used to glue components together	Hardware	3	Found in house (no purchase required)
Knife	Used to cut holes in the plastic containers.	Hardware	3	Found in house (no purchase required)
Gas Stove/Lighter	A gas stove (and sometimes lighter) was used to heat the knife so that holes can easily be made in the plastic containers.	Hardware	3	Found in house (no purchase required)
Caulking Gun	The caulking gun was used to seal the HEC around the tubes so that water will not leak out.	Hardware	3	Found in house (no purchase required)
Blow dryer	The blow dryer is used to heat the large 32-quart container to simulate ground temperature.	Hardware	3	Found in house (no purchase required)

4.3 Project Risks and Contingency Plans

Since every project has risks and issues, we proactively discussed and listed potential risks that may negatively impact our project during the design process. These risks can be physical, economical, and environmental. We also included our mitigation strategies and contingency plans should we encounter these issues.

Table 16. Description of Project Risks and Contingency Plans

Project Risks	Mitigation and Contingency Plans
Electric shock from touching the wrong electrical components or not grounding the system.	The group will be careful when working with software and working with products that are powered with electricity.
Exceeding budget	To tackle this limitation, our group has ensured that our budget is within $100 for example swapping out materials for low-cost alternatives.
More expensive in long run	Our expenses may exceed the $100 budget as we re-iterate the design of our prototype. If

	this occurs, we will be budget conscious and ensure that we are selecting the least expensive part.
Delay in Receiving Parts	To avoid this issue our team will ensure to check the delivery times of each product. Additionally, we will use amazon prime when purchasing from amazon to receive quick deliveries.
Box contains sharp corners, unsafe for users.	Sanding the corners of the box will prevent this risk.
Design does not achieve heat requirements	The solution to this is our control system, including the temperature sensor which will detect the temperature and ensure it releases the required temperature.
Errors in Arduino code that may result in further failure of control system performance	Debugging and experimenting before the assembly of the prototype. If the circuit does not work, attach fan directly to a power supply. If the temperature sensor does not work, use digital thermometers with probes.

5 Prototype I

5.1 Customer Feedback

After receiving customer feedback, it was evident that our initial design needed a lot more improvisions. The customer indicated that the design of the heat exchange chamber should promote heat transfer whereas our initial design was solely an insulated box filled with air. Therefore, the design was re-iterated to foster heat transfer so, that air will reach steady state at ground temperature. The heat exchanger will be filled with water as it is good for heat conduction and inside there will be several straight __ pipes connecting to the air inlet to the loop pipes to promote further heat transfer. In addition, the customer also stated that our design should focus on efficiency since it is low-tech. Therefore, it was decided that a compressor would be added into our re-iterated design after the looped pipes and above the sump pump. The purpose of the compressor is to increase pressure and consequently, increase temperature as well as increasing efficiency.

5.2 Prototype 1: Description and Test Plan

The purpose of prototype 1 is to determine if our HEC and piping network can obtain an outlet temperature of 20ºC and to ensure that the HEC does not fail when forces are exerted on it (0 deflection). In this prototype, we are testing and analysing the material properties of the HEC, piping network and compressor. The results will determine if we are using the correct dimensions and materials to achieve our desired design specifications and if a design re-iteration is required. Once our proof of concept is complete, we will obtain additional feedback so that the system may be further improved in future prototypes. The building and testing process took a duration of 2 days from March 5-6.

Table 17. Prototype 1 Test Plan

Test ID	Test Objective (Why)	Description of Prototype used and of Basic Test Method (What)	Description of Results to be Recorded and how these results will be used (How)	Estimated Test duration and planned start date (When)
1	To ensure that the HEC does not fail under the pressure of the ground	The outer layer of the HEC is a thick layer of concrete. A beam stress test will be used to determine the amount of pressure that can be applied to HEC's layer of concrete without failure.	Based on the result we will adjust the material being used for our piping network. This material needs to withhold the pressure from the ground.	2 days March 5-6
2	The concrete shell can support the weight of the contents inside the HEC.	Calculations were done to determine whether or not the concrete base of the HEC will fail under the weight of the HEC and contents inside of it.	Based on the result we will adjust the material being used for inside the HEC. This material supported the weight of the contents inside the HEC.	2 days March 5-6
3	To achieve a temperature	The heat transfer from the HEC to the piping network will be used to determine if the system's final outlet	Depending on the results from the calculations this will determine if our prototype meets the	2 days March 5-6

	of 20°C during the winter.	temperature can reach 20°C without the compressor.	client's requirements. If not, we will adjust our ideas in the future prototypes.	

5.3 Analysis of Critical Components

Prior to the analysis on the HEC and the piping network, a detailed sketch was completed for each component to ensure that all dimensions required for the analysis are determined and the physical build is feasible.

Figure 4. Detailed Sketch of HEC

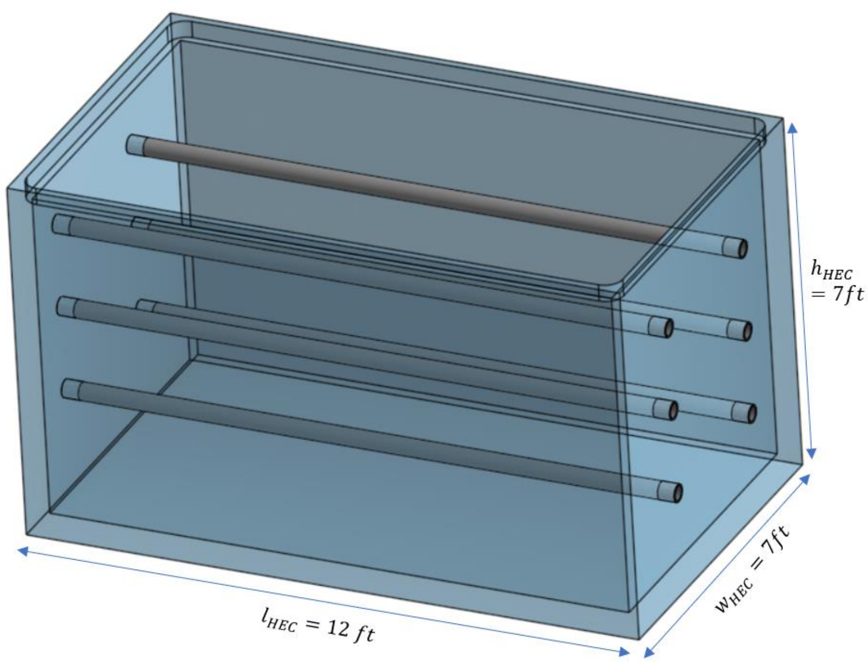
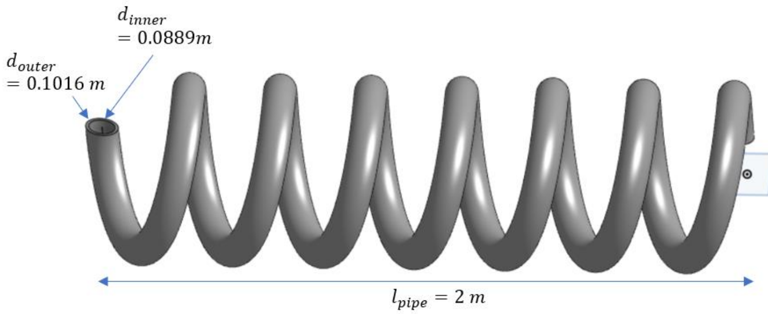


Figure 5. Detailed Sketch of Looped Pipe



5.3.1 Test ID 1: Uniform Distributed Load Deflection - Top of HEC

<u>Assumptions:</u>

- Neglect lateral earth pressure on the HEC
- Weight of soil is equally distributed on the HEC
- Maximum deflection occurs in the centre of the HEC lid
- Concrete has a thickness of 0.1m

Table 18. Test ID 1 Variables for Uniform Distributed Load Deflection - Top of HEC

Description	Variable	Value
Length of Concrete	l_C	$12ft\ =\ 3.6576\ m$
Width of Concrete	w_C	$7ft\ =\ 2.1336\ m$
Depth of Concrete	d_C	$10ft\ =\ 3.048\ m$
Thickness of Concrete	t_C	$0.1\ m$
Density of soil	ρ_{soil}	$1500\ kg/m^2$
Gravity	g	$9.81\ m/s^2$
Modulus of Elasticity	E_C	$30\ GPa = 3.0\ x\ 10^{10}$

<u>Volume of soil on HEC:</u>

$$V_{soil} = l_{HEC}w_{HEC}d_{HEC} = 11.9\ m^3$$

<u>Total distributed weight of soil:</u>

$$w_{soil} = \frac{g\rho_{soil}V_{soil}}{l_{HEC}} = \frac{(9.81\ m/s^2)(1500\ kg/m^2)(11.9\ m^3)}{3.6576\ m} = 47875.25\ N$$

<u>Moment of Inertia:</u>

$$I = \frac{w_C t_C^3}{12} = \frac{(2.1336)(0.1)^3}{12} = 1.78 \times 10^{-4}\ m^4$$

<u>Maximum deflection for top of HEC:</u>

$$\delta_{t,max} = \frac{5w_{soil}l_C^4}{384E_C I} = \frac{5(47875.25)(3.6576)^4}{384(3.0\ x\ 10^{10})(.78 \times 10^{-4})} = 0.02089\ m$$

5.3.2 Test ID 2: Uniform Distributed Load Deflection - Bottom of HEC

<u>Assumptions:</u>

- Neglect lateral earth pressure on the HEC
- Neglect the weight of the pipes in the HEC (they are supported by the HEC walls, not the concrete base)
- Weight of water in HEC is equally distributed on the concrete base
- Maximum deflection occurs in the centre of the concrete base
- Concrete has a thickness of 0.1m

Table 19. Test ID 2 Variables for Uniform Distributed Load Deflection - Bottom of HEC

Description	Variable	Value

Length of Concrete	l_C	$12ft = 3.6576\, m$
Width of Concrete	w_C	$7ft = 2.1336\, m$
Height of Concrete	h_C	$7ft = 2.1336\, m$
Thickness of Concrete	t_C	$0.1\, m$
Density of water	ρ_{H_2O}	$997\, kg/m^2$
Gravity	g	$9.81\, m/s^2$
Modulus of Elasticity	E_C	$30\, GPa = 3.0\, x\, 10^{10}$

<u>Volume of water in HEC:</u>

$$V_{H_2O} = (l_C - 2t_c)(w_C - 2t_c)(h_C - 2t_c)$$

$$V_{H_2O} = (3.6576 - 2(0.1))(2.1336 - 2(0.1))(2.1336 - 2(0.1))$$

$$V_{H_2O} = 12.927\, m^3$$

<u>Total distributed weight of soil:</u>

$$w_{H_2O} = \frac{g\rho_{H_2O}V_{H_2O}}{l_C - 2t_C} = \frac{(9.81)(997)(12.927)}{3.6576 - 2(0.1)} = 36566.82\, N$$

<u>Moment of Inertia:</u>

$$I = \frac{(w_C - 2t_c)t_C^3}{12} = \frac{(2.1336 - 0.2)(0.1)^3}{12} = 1.61 \times 10^{-4}\, m^4$$

<u>Maximum deflection of concrete base:</u>

$$\delta_{b,max} = \frac{5w_{H_2O}(l_C - 2t_c)^4}{384E_C I} = \frac{5(36566.82)(3.6576 - 0.2)^4}{384(3.0 \times 10^{10})(1.61 \times 10^{-4})} = 0.0176\, m$$

5.3.3 Test ID 3: System Heat Transfer and Output Temperature

5.3.3.1 Heat Transfer in the HEC

<u>*Assumptions:*</u>

- The temperature of water is $20°C$
- HEC inlet temperature is $10°C$
- Mass air flow is constant throughout entire system; mass air flow is $0.1 \frac{kg}{s}$
- Temperature varies along 1 coordinate only (along x-axis)
- Temperature at every point does not change with respect to time

Table 20. Test ID 3 Variables for Heat Transfer in HEC

Description	Variable	Value
Temperature of HEC pipe = temperature of water	$T_{HEC.s}$	$20°C$
Inlet temperature of HEC	$T_{HEC.i}$	$10°C$
Outlet temperature of HEC	$T_{HEC,o}$	$17°C$
Pipe diameter	d_{pipe}	$4\ inch = 0.1016\ m$
Pipe length	l_{pipe}	$12ft = 3.6576\ m$
Heat transfer to air in HEC pipe	$\dot{q}_{HEC}$	N/A
Heat transfer coefficient of air	$\overline{h}$	$100\ \frac{W}{m^2K}$
Heat capacity of air	C_p	$1.006\ J/kgK$
Mass air flow	$\dot{m}$	$0.1 \frac{kg}{s}$

<u>Area of pipe:</u>

$$A = \pi \cdot d_{pipe} \cdot l_{pipe} = \pi(0.1016)(3.6576) = 1.167\ m^2$$

<u>Temperature Calculations:</u>

$$\Delta T_i = T_{HEC.s} - T_{HEC.i} = 20 - 10 = 10°C$$

$$\Delta T_0 = T_{HEC,s} - T_{HEC.o} = 20 - 17 = 3°C$$

$$\Delta T_{lm} = \frac{\Delta T_0 - \Delta T_i}{\ln\left(\frac{\Delta T_0}{\Delta T_i}\right)} = \frac{3 - 10}{\ln\left(\frac{3}{10}\right)} = 5.81°C$$

<u>Heat Transfer and Mass Air Flow Calculations:</u>

$$\dot{q}_{HEC} = \bar{h}A\Delta T_{lm} = (100)(1.167\ )(5.81) = 678.5W$$

$$\dot{q}_{HEC} = \dot{m}C_{p,}(\Delta T_i - \Delta T_0)$$

$$\dot{m} = \frac{q}{(C_p(\Delta T_i - \Delta T_0)} = \frac{678.5}{1006(7)} = 0.01\frac{kg}{s}$$

The assumptions from the values tables gives an output temperature of $17°C$ for the HEC, so we can conclude that the specifications in this prototype are acceptable as the mass flow rate and the temperatures are within a realistic range.

5.3.3.2 Heat Transfer in Piping Network

<u>Assumptions:</u>

- Pipe surface temp = ground temp = $24°C$
- Inlet temperature of the piping network = HEC outlet temperature
- Mass air flow is constant throughout entire system; mass air flow is $0.1\frac{kg}{s}$
- Temperature varies along 1 coordinate only (along x-axis)
- Temperature at every point does not change with respect to time
- Assume pipe is straight (it is supposed to be looped, so the length of the pipe has been adjusted, but for the sake of the calculation we are assuming that the pipe is straight)

Table 21. Test ID 3 Variables for Heat Transfer in the Piping Network

Description	Variable	Value
Surface Temperature of piping network	$T_{PN.s}$	$24°C$

Inlet temperature of Piping Network	$T_{PN.i} = T_{HEC,o}$	$17°C$
Outlet temperature of Pipe Network	$T_{PN,o}$	$23°C$
Pipe diameter	d_{pipe}	$4\ inch = 0.1016\ m$
Length from pipe inlet to outlet	$l_{i,o}$	$6.56ft = 2m$
Heat transfer to air in HEC pipe	$\dot{q}_{HEC}$	N/A
Heat transfer coefficient of air	$\bar{h}$	$100\ \frac{W}{m^2K}$
Heat capacity of air	C_p	$1.006\ J/kgK$
Mass air flow	$\dot{m}$	$0.096\ \frac{kg}{s}$
Number of loops	n	7
Length of each loop	l_{loop}	$0.5\ m$

<u>Area of piping network:</u>

$$A = \pi \cdot d_{pipe} \cdot l_{pipe} \cdot n \cdot l_{loop} = \pi(0.1016)(2)(7)(0.5) = 2.23\ m^2$$

<u>Temperature calculations:</u>

$$\Delta T_i = T_{PN.s} - T_{PN.i} = 24 - 17 = 7°C$$

$$\Delta T_0 = T_{PN,s} - T_{PN.o} = 24 - 23 = 1°C$$

$$\Delta T_{lm} = \frac{\Delta T_0 - \Delta T_i}{ln\left(\frac{\Delta T_0}{\Delta T_i}\right)} = \frac{1-7}{\ln\left(\frac{1}{7}\right)} = 3.08°C$$

<u>Heat transfer and mass air flow calculations:</u>

$$\dot{q}_{PN} = \bar{h}A\Delta T_{lm} = (100)(2.23\ )(3.08) = 688W$$

$$\dot{q}_{PN} = \dot{m}C_{p,}(\Delta T_i - \Delta T_0)$$

$$\dot{m} = \frac{\dot{q}_{PN}}{(C_p(\Delta T_i - \Delta T_0)} = \frac{688}{1006(7)} = 0.01\frac{kg}{s}$$

To achieve a final outlet temperature of $23°C$ (which is higher than the minimum requested temperature from our client), our prototype will use the pipe specifications indicated in the table above. We can consider this prototype a success since the temperature and mass air flow values are within a realistic range.

5.4 Prototype #1 Feedback

Upon receiving feedback from various potential clients and individuals who would be interested in a heating system, changes were made accordingly to our prototype. The feedback received included the following: focusing more on the technological part of the system and as well as making the piping network as the main aspect. The potential client stated that the system is physical based and needs technological features to meet the requirements of heating a room to 20º C during the winter. For example, adding a heat sensor will control the heat levels of the system and it will ensure that the system will stay at that specific temperature. Another example the costumer provided is adding a pressure sensor to control the pressure underground. Additionally, the costumer suggested that we include a fan into the system to deliver high volume air output through the pipes, to the heat exchange chamber.

Our team's initial plan was to focus on the physical aspects of the system in prototype 1 and later focusing on the control system and sensors in our second prototype. We also were planning to include a centrifugal fan to blow air into the pipes. The primary focus of prototype 2 was the programming and technological components of the system. This feedback from the potential client helped us stabilize our test plan for prototype 2 and ensured us that we were on the right track.

5.5 Prototype 2 Test Plan: Control System

Table 22. Prototype 2 Test Plan

Test ID	Test Objective (Why)	Description of Prototype used and of Basic Test Method (What)	Description of Results to be Recorded and how	Estimated Test duration and planned

			these results will be used (How)	**start date (When)**
1	The fan needs to be automated	It is important to make sure that the fan is automated with the correct instruction	It will be tested through the waveform diagram on Quartus II simulation	2 days March 12-13
2	Devices have a heat sensor and control system	The controlling system for heat sensor will be built with C language and later integrated into the Arduino.	It will be tested through the input-output simulation on VS Code software.	2 days March 12-13
3	Devices have a pressure sensor and control system	The controlling system for pressure sensor will be coded with C language and the output signal will be indicated on Arduino.	It will be tested through the input-output simulation on VS Code software	2 days March 12-13

The first prototype was created using the feedback received, in which it was later tested and completed. The team also labelled key components needed in our system in our proposed design. The test plan was carefully documented and additionally the feedback taken from the prototype assisted in the testing plan to build prototype 2. As a result, these recommendations were incorporated in prototype 2 test plan.

6 Prototype II

A control system is essential for making the whole project automatically react to the change of temperature, we designed a prototype of the conceptual design proposed. This prototype including mostly software function. In addition, it can receive the data input from the sensor. After multiple re-iterations, our design of the prototype was built through the given instruction where it was broken down and used to improve our initial design. After building the prototype, the feedback is taken in consideration again to further refine the plan for the third prototype.

6.1 Customer Feedback from Prototype 1

Team Pandora met with the client on March 11, 2022, to present prototype 1 and the results of our critical analysis. Prototype 1 is composed of our piping network and HEC. For this prototype, we determined that:

Deflection Test:

- That the lid of the HEC will not fail when exposed to vertical ground pressures.
- The base of the HEC will not fail under the weight of the HEC and the contents inside of it.

Heat Transfer Analysis:

- The HEC can maintain a stable air temperature before the air enters the piping network.
- The piping network can increase the air temperature from the HEC to achieve temperatures over 20°C.

The client was receptive of our design and gave a general comment that was not specific to prototype 1; they noticed that we added a compressor to our design and asked if it could be removed. We are in agreeance and will remove the compressor from future designs. The compressor was added in our second iteration of design because we wanted to use it as a backup in case our low-tech system was not able to reach desired temperatures, however after completing our heat transfer analysis, we determined that the compressor was not necessary and should be removed. After considering our response, the client stated that our design is interesting, and they look forward to our future work.

6.2 Prototype 2: Description and Test Plan

The purpose of prototype 2 is to determine if our control system for HEC will enable the automation of temperature control. In this prototype, we are testing and analysing the function of the control program. The results will determine if we the program meet the expected performance. Once our proof of concept is complete, we will obtain additional feedback so that the system may be further improved in future prototypes. The building and testing process took a duration of 2 days from March 11-12.

Table 23. Prototype 2 Test Plan

Test ID	Test Objective (Why)	Description of Prototype used and of Basic Test Method (What)	Description of Results to be Recorded and how these results will be used (How)	Estimated Test duration and

				planned start date (When)
1	To ensure that the program react properly under different temperature input	One of the most important features of our project is the control to the fan when the temperature changes, it must be ensured that the output is correct under different circumstances.	It will be run on VS code for testing, based on the test result we will improve the function for the final prototype.	2 days March 11-12
2	To ensure that the entire program loops automatically.	To make sure that the temperature can adjust automatically even without the manual input, a loop must be added to the program.	The function will be converted into a logic circuit and will be tested through a digital waveform diagram.	2 days March 11-12

6.3 Analysis of Critical Components

6.3.1 Control System

Below is the completed code of temperature control program within a time loop. The program will be designed to open the file where the temperature sensor stores its data and read it for input, but for testing purpose, here in the screenshot below the program introduce two input option where we type in a number for temperature and another for desired temperature setting. The program will react based on these 2 inputs and give output as the command of the fan. And the loop makes this function run automatically once every 4 second, to check if the room temperature has exceeded or below the desired temperature.

Figure 6. Source Code for Fan Controller (Part 1)

```
import time
import board
from adafruit_emc2101 import EMC2101

i2c = board.I2C()  # uses board.SCL and board.SDA
emc = EMC2101(i2c)
settemp=input("set the desired temperature")
temperature=input("received temperature from sensor")
con1=settemp+0.5
con2=settemp+1
con3=settemp+1.5
con4=settemp+2
Fan=true
    while True:
        if temperature>con4
        print("fan is off")
        mc.manual_fan_speed = 0
        time.sleep(1.5)
        print("Fan speed", emc.fan_speed)
        time.sleep(1)

        if temperature>con3
        print("Setting fan speed to 25%")
        emc.manual_fan_speed = 25
        time.sleep(2)
        print("Fan speed", emc.fan_speed)
        time.sleep(1)

        if temperature>con2
        print("Setting fan speed to 50%")
        emc.manual_fan_speed = 50
        time.sleep(1.5)
        print("Fan speed", emc.fan_speed)
        time.sleep(1)

```

Figure 7. Source Code for Fan Controller (Part 2)

```
if temperature>con1
print("Setting fan speed to 75%")
emc.manual_fan_speed = 75
time.sleep(1.5)
print("Fan speed", emc.fan_speed)
time.sleep(1)

if temperature<settemp
print("Setting fan speed to 100%")
emc.manual_fan_speed = 100
time.sleep(1.5)
print("Fan speed", emc.fan_speed)
time.sleep(1)

print("External temperature:", emc.external_temperature, "C")
print("Internal temperature:", emc.internal_temperature, "C")

print("")
time.sleep(0.5)
```

6.3.2 Control System Testing

1. To test if the pressure control function works, we created a simplified version of our actual program, and we run the program in VS code and the output results are as expected.

Figure 8. Source Code for Testing Purposes Only

```
temp=input("temperature recevied")
set=input("set the temperature to")
fan=True
if temp>set:
    print(fan is turned off)
    fan=False
if temp<set:
    print(fan is turned on)
```

Figure 9. Test Result when temperature is above desired temperature

```
Windows PowerShell
Copyright (C) Microsoft Corporation. All rights reserved.

Try the new cross-platform PowerShell https://aka.ms/pscore6

PS C:\Users\kaiyi\Desktop\lab>  & 'C:\Users\kaiyi\AppData\Local\Programs\Python\Python39\python.exe' 'c:\Users\kaiyi\
.vscode\extensions\ms-python.python-2022.2.1924087327\pythonFiles\lib\python\debugpy\launcher' '58933' '--' 'c:\Users
\kaiyi\Desktop\lab\Untitled-1.py'
set the temperature to 20
temperature received 21
the inside temperature is 21
the fan is off
PS C:\Users\kaiyi\Desktop\lab>
```

Figure 10. Test Result when temperature is below desired temperature

```
PS C:\Users\kaiyi\Desktop\lab>  c:; cd 'c:\Users\kaiyi\Desktop\lab'; & 'C:\Users\kaiyi\AppData\Local\Programs\Python\
Python39\python.exe' 'c:\Users\kaiyi\.vscode\extensions\ms-python.python-2022.2.1924087327\pythonFiles\lib\python\deb
ugpy\launcher' '53526' '--' 'c:\Users\kaiyi\Desktop\lab\Untitled-1.py'
set the temperature to 15
temperature received 14
the inside temperature is 14
the fan is on
PS C:\Users\kaiyi\Desktop\lab>
```

2. To test the automation of the program, based on its input output characteristic, we drew a logic circuit to present the system, and the expected output result is validated through the waveform diagram.

Figure 11. Equivalent Logic Circuit of the Fan Control System

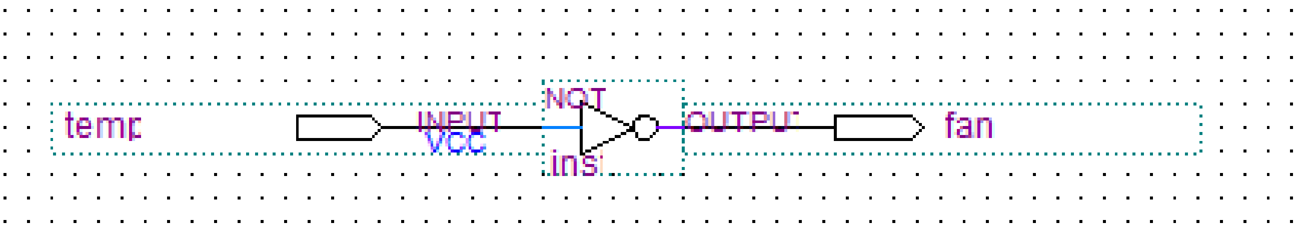
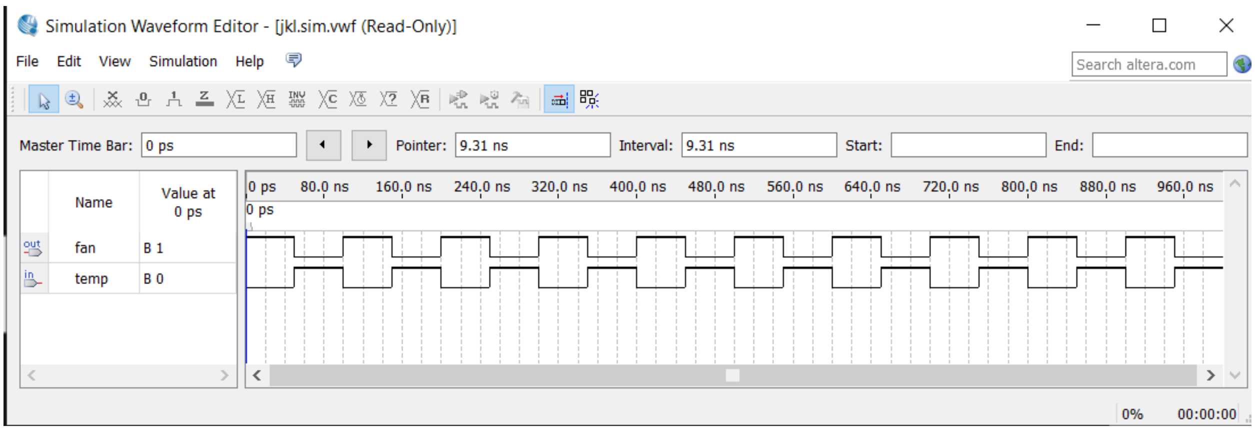


Figure 12. Waveform Testing Result of the Logic Circuit



6.4 Prototype 2 Feedback

Our design for prototype 2 is a combination of physical and simulated components; our piping network and HEC control system (Arduino, temperature sensors and pressure sensors). We received feedback from our program manager, who noted that our final prototype must be completely functional with no simulated parts. They stated that a functional system is impressive and appealing, so our plan for prototype 3 is to complete and test our physical build so that it is ready for Design Day.

6.5 Prototype 3 Test Plan: Control System

Table 24. Prototype 3 Test Plan

Test ID	Test Objective (Why)	Description of Prototype used and of Basic Test Method (What)	Description of Results to be Recorded and how these results will be used (How)	Estimated Test duration and planned

				start date (When)
1	Final Temperature Testing	Test entire physical system to determine the final temperature output of the prototype. This will be done by putting the air inlet pipe outside (by opening a window) and taking the outlet temperature measurement inside a building.	The temperatures throughout the system will be measured using a thermometer while the final temperature outlet that feeds into the control system will be measured with a temperature sensor connected to an Arduino (our control system). The results will be used to determine how effective our final design is and if we have met client needs.	March 17-20
2	Final Control System Testing	Test the control system with an Arduino connected to the temperature sensor and fan from the physical prototype. To see if the control system reacts appropriately to a fluctuation in temperature, a hair dryer on different settings (hot/cold) will be used to blow air into the system while we monitor fan settings and the temperature output of the system.	The temperature output should remain the same as the desired temperature input despite any fluctuations in temperature. An increase/decrease in temperature will determine if we built and programmed our control system correctly.	March 24-27

The second prototype was created using the feedback received from prototype one, in which it was later tested and completed. The team also labelled key components needed in our proposed design. The test plan was carefully documented and additionally the feedback taken from the prototype assisted in the testing plan to build prototype 3. As a result, these recommendations were incorporated in prototype 3 test plan.

7 Prototype III

This report details the final testing stages of the design of a thermal heat exchange chamber (THEC) where the physical prototype will be tested as a fully functional integrated system. In prototype I and II, simulations for each sub-system of the THEC was successfully tested. In this prototype, the real (physical) prototype will be tested in two stages. The first stage is the control system where we will test whether the Arduino and circuit will function as expected in conjunction with the code. The second stage will determine if the prototype can increase the temperature output to an acceptable range, as requested by the client. The prototype testing will take place from March 19, 2022, to March 26, 2022, which will allow time for minor adjustments to the design if required.

7.1 System Overview

Control system schematic

The temperature sensor sends temperature value as input to the system which will trigger the fan based on the values to a certain level.

Figure 13. Flow chart of the control program

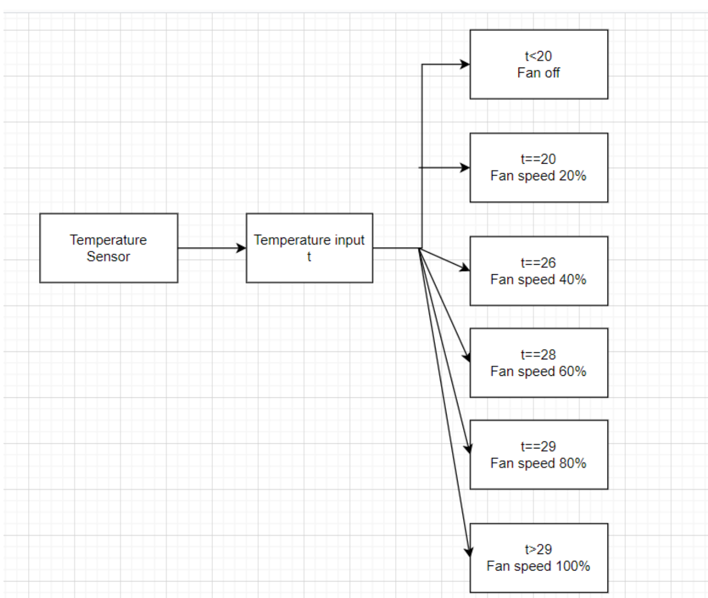


Photo of entire system

Figure 14. The heat exchange chamber

Figure 15. Output port

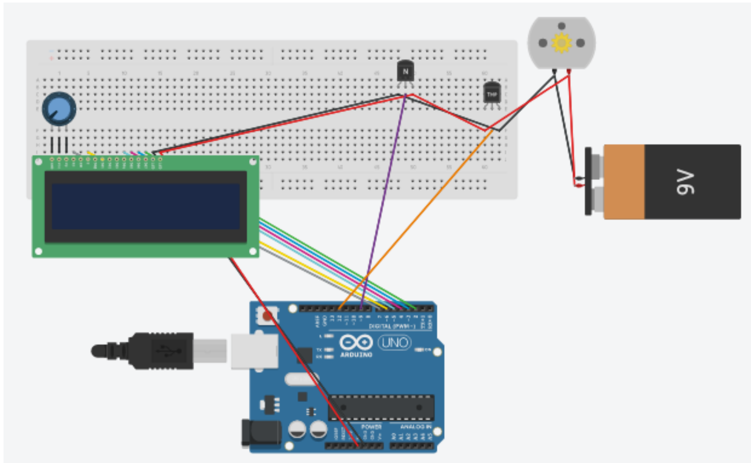
Figure 16. Transparent view of inside the chamber

Figures above display the system. It includes the heat exchange chamber in the middle of the box, piping network, a fan to suck the air in the system and blow it into the grey pipe which is where we get our output. Overall, the system functioned well as long as the temperature sensor was higher than the temperature outside therefore, concluding that the project was a success. Temperature outputs for the thermometers were all effective meaning that the final output given was nearly the temperature desired.

7.2 Control System Test

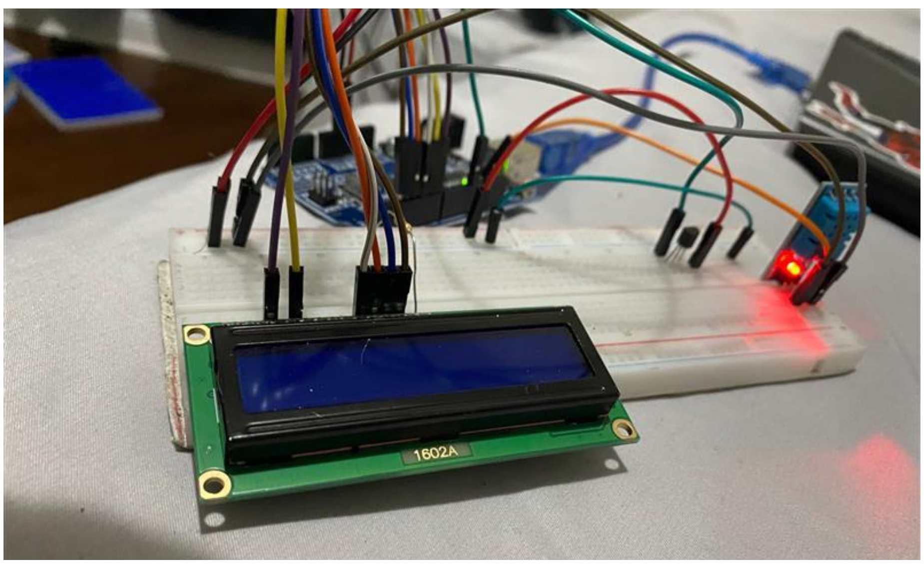
The simulation on Tinkercad was successful, the following physical implementation was built according to the simulation.

Figure 17. Simulation on TinkerCad



As seen in the image the temperature sensor is not functioning. This may have been caused by the LCD connection, since this is only a prototype, we used a battery to power the fan.

Figure 18. Control system implementation



7.3 Temperature Test

The physical build was tested by controlling the temperature input by putting the air inlet pipe and its thermometer outside and using the hairdryer to heat the underground components to simulate the ground temperature during the winter. The air flow is efficient and there is no blockage at any passage; the physical test was successful, and the final system output temperature was 20.7°C.

Figure 19. Return vent testing result

Figure 20. Air inlet testing result

Figure 21. Heat exchange chamber testing result

Figure 22. Ground Tube Testing Result

Figure 23. Output port testing result

7.4 Prototype III Customer Feedback

After speaking with the potential clients, they offered feedback for our design. The client suggested that we attach the circuit to the fan rather than connecting only the battery to the fan. They stated that this will give a more accurate and effective output for the temperatures of each component of the physical build including the temperature of the ground, air inlet, heat exchange chamber and etcetera. Using an Arduino and Temperature sensor will help control the temperature of these components where the code compiled will turn the fan on and off depending on the output temperature. This is to ensure the desired temperature is reached. The potential client did not give any feedback on the physical design. They made it clear that we must get the circuit to function and attach it to the system.

7.5 Sources of Error

The system occasionally is not able to reach the desired temperature of 21ºC and this is mainly due to sources of error involved. These errors also affected the displayed temperature of the ground and heat exchange chamber. Sources of error are shown below,

- Choice in materials (different thermal properties)
- Different dimensions
- Perhaps some areas were not sealed properly so there may be heat loss/air flow in areas that should be a closed system
- Calculations assumed that each analysed part was a closed system, and we did not complete the calculations as though it was one integrated system
- Water spilled from the heat exchange chamber in the box of the entire system

8 Conclusion and Recommendations

In conclusion, by creating and following a thorough rapid iterative prototype plan, both software and physical prototypes were created. The project was a success because the temperature output given was higher than the temperature outside. The conceived final prototype as outlined in this document, is a high-fidelity comprehensive prototype of an application that fulfills the needs of our client. The implementation of feedback received from the first and second prototype resulted in the development of the second and final prototype which exceeds the targeted metrics in ease of navigation and user experience.

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10 Annex: Arduino Code

```
//Robu.in

#include "TMP.h"

#include<LiquidCrystal.h>

LiquidCrystal lcd(7, 6, 5, 4, 3, 2);

#define DHTPIN 12     // what pin we're connected to

#define DHTTYPE DHT11   // DHT 11

#define pwm 9

byte degree[8] =

              {

                0b00011,

                0b00011,

                0b00000,

                0b00000,

                0b00000,

                0b00000,

                0b00000,

                0b00000

              };
```

```
// Initialize DHT sensor for normal 16mhz Arduino

DHT dht(THPPIN, THPTYPE);



void setup() {

  lcd.begin(16, 2);

 lcd.createChar(1, degree);

 lcd.clear();

 lcd.print("   Fan Speed  ");

 lcd.setCursor(0,1);

 lcd.print("  Controlling ");

 delay(2000);

 analogWrite(pwm, 255);

 lcd.clear();

 lcd.print("Robu ");

 delay(2000);

  Serial.begin(9600);

  dht.begin();

}
```

```
void loop() {

  // Wait a few seconds between measurements.

  delay(2000);

  // Reading temperature or humidity takes about 250 
milliseconds!

  // Sensor readings may also be up to 2 seconds 'old' (its a 
very slow sensor)

  float h = THC.readHumidity();

  // Read temperature as Celsius

  float t = THC.readTemperature();

  // Read temperature as Fahrenheit

  float f = THC.readTemperature(true);

  // Check if any reads failed and exit early (to try again).

  if (isnan(h) || isnan(t) || isnan(f)) {

    Serial.println("Failed to read from DHT sensor!");

    return;

  }



  // Compute heat index

  // Must send in t in Fahrenheit!
```

```
float hi = THC.computeHeatIndex(f, h);


Serial.print("Humidity: ");

Serial.print(h);

Serial.print(" %\t");

Serial.print("temperature: ");

Serial.print(t);

Serial.print(" *C ");

Serial.print(f);

Serial.print(" *F\t");

Serial.print("Heat index: ");

Serial.print(hi);

Serial.println(" *F");


  lcd.setCursor(0,0);

lcd.print("temp: ");

lcd.print(t);   // Printing terature on LCD

lcd.print(" C");

lcd.setCursor(0,1);
```

```
if(t <20 )

 {

   analogWrite(9,0);

   lcd.print("Fan Speed: 0%            ");

   delay(100);

 }



 else if(t==26)

 {

   analogWrite(pwm, 51);

   lcd.print("Fan Speed: 20%   ");

   delay(100);

 }



  else if(t==20)

 {

   analogWrite(pwm, 102);

   lcd.print("Fan Speed: 40%   ");

   delay(100);
```

```
}


 else if(t==28)
{
  analogWrite(pwm, 153);
  lcd.print("Fan Speed: 60%   ");
  delay(100);
}


else if(t==29)
{
  analogWrite(pwm, 204);


  lcd.print("Fan Speed: 80%    ");
  delay(100);
}
 else if(t>29)
{
  analogWrite(pwm, 255);
```

```
      lcd.print("Fan Speed: 100%    ");
      delay(100);
    }
  delay(3000);
}
```