



SAVING ENERGY AND COST DURING PEAK PERIODS

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Abstract

On the hottest days of summer, a typical household consumes 20-30% more electricity than average reflecting an increase in air conditioner usage. To address this need, utility companies must invest in expensive and inefficient “peaker plants” to meet high demand which results in increased prices for consumers during peak periods that can last up to eight hours. Utility companies encourage customers to shift power usage to off-peak hours to reduce strain on the grid. However, customers must balance their desire for comfort with cost. Our goal was to design a heat exchanger that stores “coolness” to assist with cooling loads during peak periods. Using numerical values representative of the Worcester, MA area, the proposed heat exchanger can store a maximum of 18 kWh of thermal energy and produce air at 16.2°C through a home’s existing heating, ventilation and air conditioning system.

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Introduction

As the temperatures increase during the summer months, so do electricity bills. On particularly hot and humid days, a typical household consumes 20-30% more electricity than average, reflecting an increase in air conditioner usage (White, 2015). In fact, 10-20% of generation, transmission, and distribution capacity is used for only 1-2% of the year (Energy Storage Association [ESA], nd). To address this need, utility companies must invest in “peaker plants.” Power companies only turn on these plants for several hours at a time when baseload capacity is surpassed. This additional infrastructure is among the most expensive, least efficient, and most polluting electricity generation (ESA, nd). The costs to operate these plants is passed on to consumers, resulting in higher energy prices throughout the year to subsidize the massive costs of running these plants for only a short amount of time in the summer.

However, some utility companies, such as National Grid in Worcester, MA area, use Dynamic Pricing plans to encourage customers to shift power usage to off-peak hours to reduce strain on the grid. The day before a peak period is set to occur, National Grid sends emails to customers to alert them to the increase in prices. These peak events are typically during summer months, when supply is constrained and which results in a significant price increase (National Grid, n.d.). The emails are sent typically the day before a peak period occurs so customers know to limit their energy usage the next day.

However, customers must balance their desire for comfort with cost. Our goal was to design a heat exchanger that stores “coolness” to assist with cooling loads during peak periods. We used Worcester, MA data to represent and simulate what an average peak day would look like using our proposed system.

In this report, we describe our approach to designing a system capable of storing “coolness” during off-peak times to reduce costs and save energy during peak periods. The proposed design detailed in this report consists of a heat exchanger that uses water as a coolant for air. During nights, when energy is less expensive, a small auxiliary cooler will run to cool the water to 55°F which will then be used to cool air during peak periods. By using this storage, the customer will use less energy from air conditioners during peak periods thus saving them money.

Background

Peak periods result in significantly higher energy costs due to increased air conditioning use. This results in significant strain on the power grid. Utility companies invest in expensive and inefficient “peaker plants” to meet demand, which result in price increases of up to 6.2 times the average rate. To encourage customers to save energy during peak periods, utility companies send a notification the day prior. Our goal is to decrease energy costs and mitigate strain on the power grid during peak periods.

Peak Periods

On the hottest days of summer, a typical household uses 20-30% more electricity than normal mostly due to increased air conditioning (A/C) use (White, 2015). Home electricity consumption peaks in July and August when temperatures, and therefore cooling demand, are at their highest (Energy Information Agency [EIA], 2017). In Worcester, MA, where the calculations for this project were based off, the average high temperature from June through August 2018 ranged from 74-79°F (US Climate Data, n.d.). These high electricity loads put strain on the electrical grid and force utility companies to build additional power plants to satisfy user demand, which in turn increases the cost of electricity (General Electric, 2018).

During the summer months, utility customers use significantly more energy than any other time of the year. This increase in energy use does not typically exceed the baseload capacity. However, during exceedingly hot days, such as during heatwaves, energy use increases and utility companies must begin to operate “peaker plants,” or plants that are used to meet peak demand on the grid (General Electric, 2018). Power companies turn on these plants for several hours at a time when baseload capacity is surpassed. This additional infrastructure typically is among the most expensive, least efficient, and most polluting electricity generation (ESA, nd). The costs to operate these plants is passed on to consumers, resulting in higher energy prices throughout the year to subsidize the massive costs of running these plants for only a short amount of time in the summer.

In the US, anywhere from 75-90% of homes are cooled by some sort of air conditioning system (e.g. central air conditioners, in-window units) (U.S. Department of Energy [DOE], n.d.;

EIA, 2017) A/C is one of the most expensive end-use type of equipment for utilities to serve, primarily because they only operate for a relatively small amount of time during the year. In fact, 10-20% of generation, transmission, and distribution capacity is used for only 1-2% of the year (Energy Storage Association [ESA], nd). This low-asset utilization significantly increases energy costs to users. Energy prices are determined by supply and demand; when the demand for energy is high, the prices rise (White, 2015). High A/C demand typically occurs when overall demand for electricity is high. Summer is also the time when people operate other seasonal equipment such as fans, dehumidifiers, and pool pumps which further compounds the problem (EIA, 2017).

Residential Energy Costs

Energy costs differ by region, utility company, and the pricing plans that are available to consumers. In Worcester, MA, certain areas that are served by the utility company National Grid are eligible for the Dynamic Pricing program which offers different Basic Service rates depending on the time of day, or whether a “Peak Event” is occurring. This pricing system is typically referred to as “time of use” pricing, and encourages customers to shift energy use to times when energy consumption is low. Below is a table showing the pricing from August 2018 (National Grid, 2018).

Table 1: Smart pricing rates for Worcester, MA.

Smart Pricing Rates [\$ kWh] for Residential (R-1, R-2) Customers in Worcester, MA August 2018		
Peak Period (8am-8pm)	Off-Peak Period (8pm-8am)	Peak Event Period
0.10383	0.08488	0.52887

Often during the summer months in Worcester, MA, National Grid sends emails warning people about when peak days will occur. The emails are typically sent the day before a peak period occurs, so customers know to limit their energy usage the next day. The figure below is an

example of an alert that National Grid sends to customers; the email explains how long the peak period will last and how to reduce energy usage.

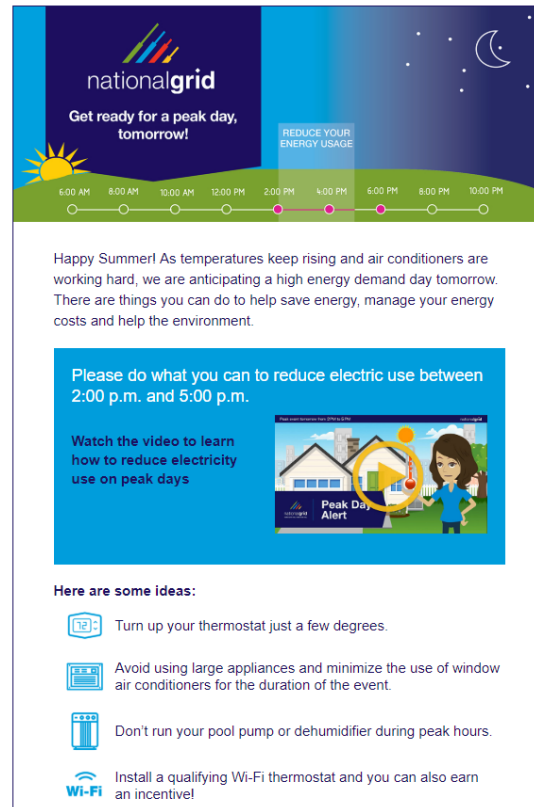


Figure 1: Sample National Grid peak period notification email (National Grid, Email correspondence, August 28, 2018).

National Grid anticipates when a peak period will occur and prepares accordingly. Data gathered during days that are considered peak periods help National Grid decide future peak periods. A modified version of the data National Grid provided of actual energy usage for residential areas during a peak period can be seen below. The data separates the different types of usage into low, medium and high use. The R1 and R2 represent the type of residential area; the technology (tech) level tells which residents have central air conditioning, but it does not tell if residents have window air conditioning units. The window air conditioning units use energy, but it cannot be included in the tech level of the house. As the tech level increases, energy use during peak periods decreases.

Table 2: Modified data from National Grid for actual energy usage for residential areas during a peak period (Joseph Neas, personal communication, September 19, 2018).

Common Evaluation Customer Segments									
Tech Level	Rate	Category	R1			R2			Residential Total
			Low Use	Medium Use	High Use	Low Use	Medium Use	High Use	Usage Segment Total
Level 1 meter+web+mobile apps	CPP	Actual kWh	9,317.03	52,349.24	17,866.74	1,321.14	5,698.12	3,180.07	89,732.34
	PTR-Preferred	Actual kWh	534.77	2,536.26	1,004.05	113.64	448.70	270.73	4,908.15
	PTR-Opt-Out	Actual kWh	60.20	687.87	260.66	4.03	88.44	47.24	1,148.44
Level 2 (level 1+IHD)	CPP	Actual kWh	376.02	3,560.44	1,363.13	34.25	317.38	254.88	5,906.10
	PTR-Preferred	Actual kWh	10.32	302.16	86.04		11.87	48.57	458.96
Level 3 (level 1+PCT+IHD)	CPP	Actual kWh	25.05	217.57	98.27		31.89		372.79
	PTR-Preferred	Actual kWh		11.57	27.79				39.33
Level 4 (levels 1-3 +LCD)	CPP	Actual kWh	106.42	2,118.80	978.31		91.48	115.28	3,410.30
	PTR-Preferred	Actual kWh	1.33	193.29	73.22				267.84

In addition to the data during a peak period, National Grid provided data on the reduced energy usage during a peak period (shown in the table below). The reduced energy usage data shows how when a peak event is announced, residents tend to reduce their energy usage. Residents seem to use less energy during the hours specified for the peak periods which is the main goal for National Grid.

Table 3: Modified data from National Grid for reduced energy usage for residential areas during a peak period (Joseph Neas, personal communication, September 19, 2018).

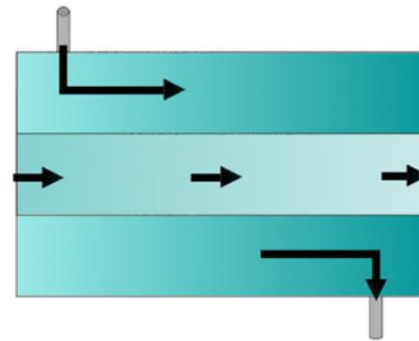
Common Evaluation Customer Segments									
Tech Level	Rate	Category	R1			R2			Residential Total
			Low Use	Medium Use	High Use	Low Use	Medium Use	High Use	Usage Segment Total
Level 1 meter+web+mobile apps	CPP	Reduction kWh	-1,363.19	-6,921.86	-2,371.23	-227.80	-739.90	-174.97	-11,798.94
	PTR-Preferred	Reduction kWh	-90.14	-344.00	-135.75	-5.41	-90.45	-39.30	-705.05
	PTR-Opt-Out	Reduction kWh	10.94	-136.71	5.35	4.67	-0.05	-11.65	-127.86
Level 2 (level 1+IHD)	CPP	Reduction kWh	20.26	22.86	81.96	24.56	45.50	19.20	214.34
	PTR-Preferred	Reduction kWh	0.21	-25.43	19.54		8.05	-25.55	-23.19
Level 3 (level 1+PCT+IHD)	CPP	Reduction kWh	4.80	-37.93	-9.47		10.45		-32.15
	PTR-Preferred	Reduction kWh		-2.11	-0.77				-2.87
Level 4 (levels 1-3 +LCD)	CPP	Reduction kWh	-16.76	86.27	-17.96		4.57	-38.60	17.52
	PTR-Preferred	Reduction kWh	0.20	-1.79	1.92				0.33

Even though customers of National Grid are reducing their energy usage during peak periods, there is still a strain on the power grid. Increasing electricity prices has proven an effective way to encourage customers to limit energy use during peak hours, however, there remains a need to reduce energy usage during peak periods.

Heat Exchangers

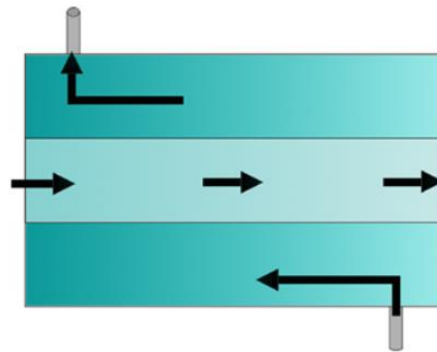
A heat exchanger is a type of equipment that utilizes the second law of thermodynamics which states that two thermodynamic systems, when interacting, will move towards equilibrium (Thomas Publishing Company, n.d.a). Heat exchangers are designed to perform heat transfers such as refrigeration and radiation, and they work by transferring the thermal energy from one substance to another by direct contact or a separator (Thomas Publishing Company, n.d.a). In order to maximize the amount of heat transfer, a heat exchanger needs a design that will allow for maximum surface area of the wall between the two substances (Thomas Publishing Company, n.d.a). Heat exchangers can have any of these three types of flow patterns: parallel-flow, cross-flow, or countercurrent. In addition to having different types of fluid flow, there are many different configurations a heat exchanger can have, but the most common ones are shell and tube heat exchangers and plate heat exchangers.

The different types of flow used in a heat exchanger affect how much heat transfer takes place between the fluids. Parallel-flow involves both fluids traveling in the same direction and entering and exiting the heat exchanger side by side (Thomas Publishing Company, n.d.b). Cross-flow occurs when the two fluids run perpendicular to each other (Thomas Publishing Company, n.d.b). With cross-flow heat exchangers, there are two different types: finned and unfinned tubular. In finned tubular, the fluids will not mix, but in unfinned tubular, the fluids can mix (Heat Exchanger Design, n.d.). Countercurrent (or counter-flow) is when the two fluids flow in opposite directions and one fluid exits where the other one entered (Thomas Publishing Company, n.d.b). Based on how much heat transfer occurs with each type of flow, countercurrent heat exchangers tend to be the most effective (Thomas Publishing Company, n.d.b). The type of heat exchanger being designed will decide which type of fluid flow is best for that specific heat exchanger. The below figures show some of the different flow configurations a heat exchanger can have.



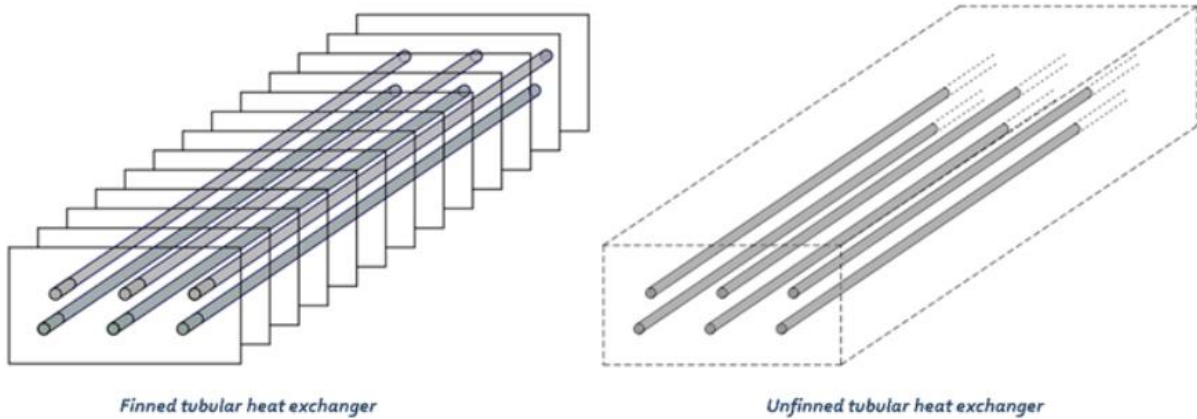
Parallel-flow heat exchanger

Figure 2: Parallel-flow (Heat Exchanger Design, n.d.)



Counter-flow heat exchanger

Figure 3: Countercurrent (counter-flow) (Heat Exchanger Design, n.d.).



Finned tubular heat exchanger

Unfinned tubular heat exchanger

Figure 4: Cross-flow (Heat Exchanger Design, n.d.).

Shell and tube heat exchangers are made up of multiple tubes that allow liquid to flow through them. The tubes are divided into two parts: one part containing the liquid that will be cooled and heated, and the other part contains the liquid that is responsible for the heat exchange as shown in the figure below (Thomas Publishing Company, n.d.b). Designing a shell and tube heat exchanger requires careful consideration of tube thickness and tube diameter; the correct tube thickness and tube diameter will ensure maximum heat exchange (Thomas Publishing Company, n.d.b). The type of fluid flow for a shell and tube heat exchanger can be any of the three types of fluid flow (Thomas Publishing Company, n.d.b).

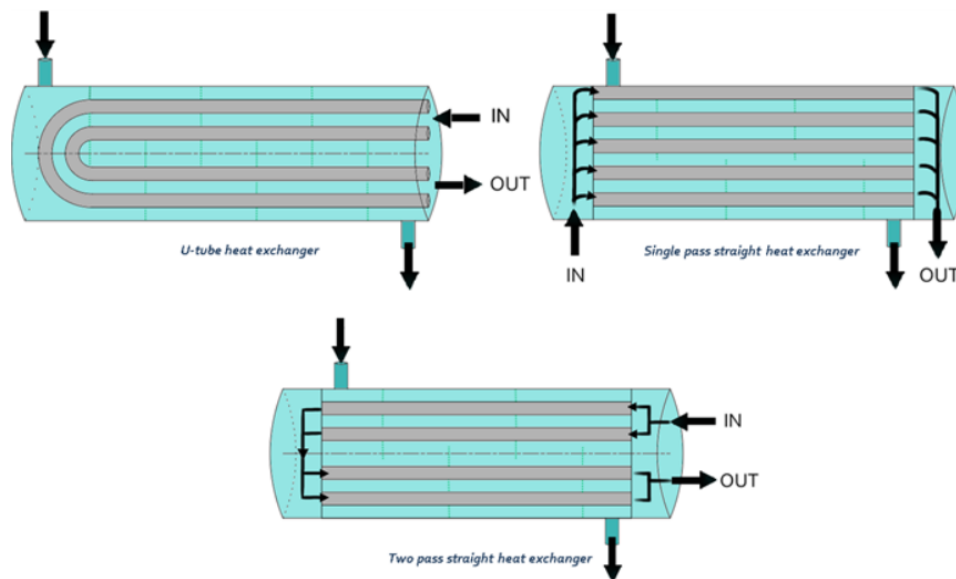


Figure 5: Shell and tube heat exchangers (Heat Exchanger Design, n.d.).

Plate heat exchangers are made up of thin plates that are joined together but have a small space between each plate, as shown in the figure below. The plates are typically stainless steel, and they are often maintained by a rubber gasket (Thomas Publishing Company, n.d.b). Due to the way plate heat exchangers work, they are typically used in refrigeration processes because the fluid channels alternate between hot and cold fluids (Thomas Publishing Company, n.d.b). With a plate heat exchanger, the surface area tends to be large which means the amount of heat exchanged is typically high. Since plate heat exchangers have a larger surface area than shell and tube heat exchangers, plate heat exchangers are typically more effective in terms of heat exchange.



Figure 6: Plate heat exchanger (Araner, 2018).

Alternative Cooling Methods

Air conditioners are not the only method to cool down a house during the hot summer months. Depending on the environment one lives in, an alternative method to cooling can be evaporative coolers. Evaporative coolers are typically used in drier areas such as the southwestern part of the United States (Sylvane, 2018). In the map shown below, it describes the areas where evaporative coolers are the most ideal form of cooling. The drier the environment, the more ideal an evaporative cooler is because an evaporative cooler uses moist pads to help cool air down.

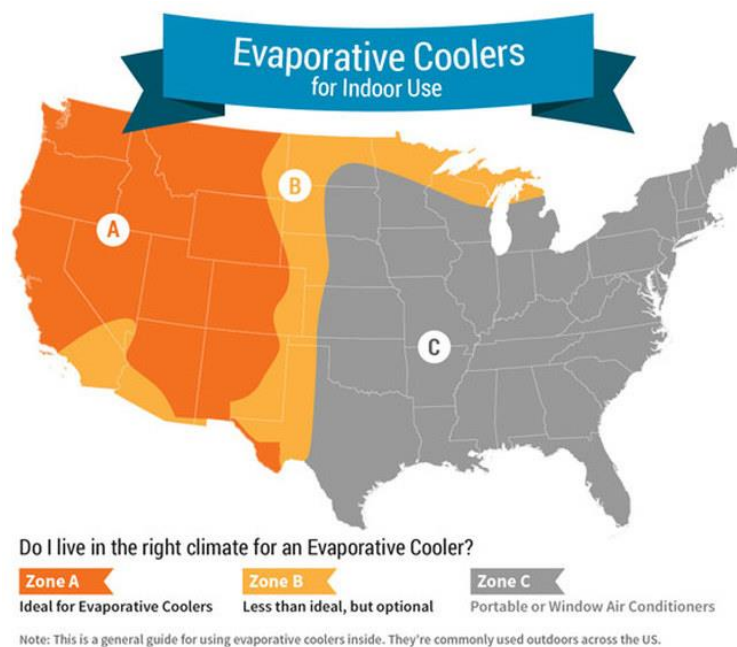


Figure 7: Map of where evaporative coolers are most likely used (Sylvane, 2018).

The first benefit has to do with the introduction of water into a dry climate. Slightly damp air can help reduce side effects of dry air. Itchy or dry eyes, skin, and throat can be alleviated with the help of an evaporative cooler because it provides some moisture back in the air and can help ease these symptoms (Sylvane, 2018). In addition to being environmentally friendly, evaporative coolers are also extremely efficient. They can cool warm air by up to 20 degrees, and since cool air is constantly being recycled through the use of fans, evaporative coolers can make ambient air feel four to six degrees cooler than it actually is. Additionally, evaporative coolers use less energy and typically do not cost as much to purchase; they can cost up to 50% less than a traditional air conditioning system (Sylvane, 2018). An evaporative cooler can typically save a consumer about triple of what they would pay if they used a traditional air conditioner (Sylvane, 2018).

In a humid area, adding water to the environment would not lower the air temperature; instead, it would make the air more humid which provides no cooling benefit. While evaporative coolers are useful in some areas, it might not be the best method of cooling for areas that have a high relative humidity (Sylvane, 2018). Evaporative coolers are the most effective when the relative humidity is at its lowest point which is typically during the afternoon when temperatures are at their peak (Grainger, 2018). Since evaporative coolers work best with low relative humidity, they are not traditionally used in humid areas such as the eastern part of the United States. In humid areas, traditional air conditioners are used because they do the opposite of evaporative cooler; traditional air conditioners take the humidity out of the air (Grainger, 2018). The process of how an evaporative cooler works is shown in the diagram below.

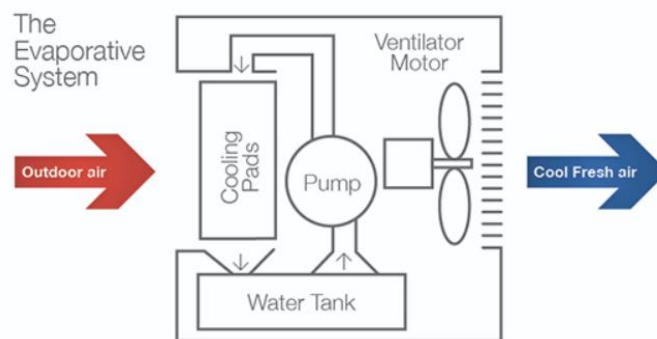


Figure 8: Evaporative cooling process (Scandia, n.d.).

Evaporative coolers are an excellent example of an alternative cooling method that provides an energy efficient option to those living in desert climates. However, evaporative coolers are not beneficial in the entire United States, and there remains a need for those in humid climates, such as in Worcester, MA, to have an alternative to traditional air conditioners, especially when energy use is high.

Methodology

The overall goal of this project is to design an energy efficient heat exchanger as an alternative cooling method to reduce the strain power grids experience during peak events in Worcester, MA. In this section the approach taken to designing a heat exchanger will be discussed in depth. The diagram below outlines the steps taken to achieve our heat exchanger design.

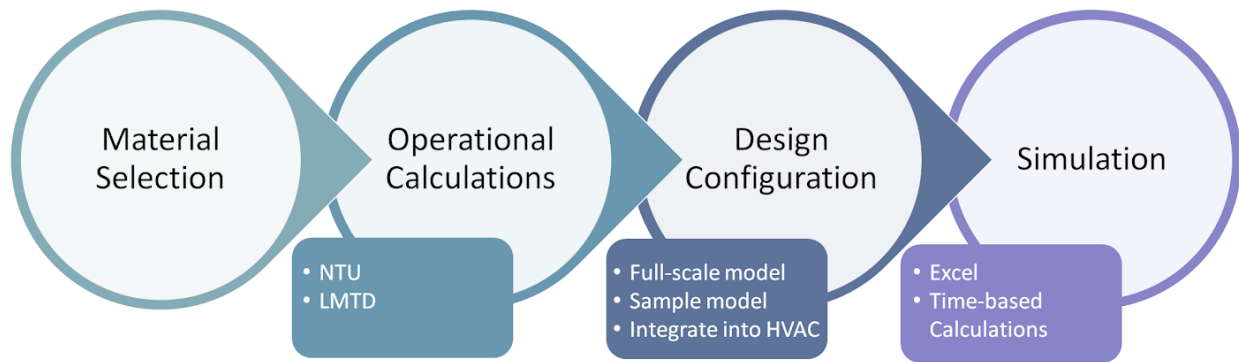


Figure 9: Methodology diagram

Material Selection

In designing our proposed heat exchanger material selection played a crucial role in determining the design parameters and specifications necessary to perform the Logarithmic Mean Temperature Difference (LMTD) and the Effectiveness/Number of Transfer Units (ϵ -NTU method) calculations.

We investigated two fluids for the heat exchanger: air flowing through pipes or water flowing through pipes. Ultimately, the team chose air flowing through the pipes to be directly cooled by water for the heat exchanger system. Although water flowing through pipes would be more effective it would require an additional system to have been built, thus increasing costs, and it was not essential as air flowing through the pipes would provide the necessary heat exchanged for the system. Water was chosen as the coolant in this system because of its abundance and high specific heat capacity, meaning it can store a large amount of thermal energy.

Our goal was to design an efficient and cost-effective heat exchanger using readily available materials. We referenced septic tanks to determine the exact design dimensions necessary for such a large-scale heat exchanger (Friedman, 2019). Ultimately, a concrete 750-gallon septic tank was selected to represent the heat exchanger.

When selecting pipe material, we wanted a metal with high thermal conductivity. We researched two materials for pipes; brass and copper. Copper is used in a variety of products due to its excellent electrical and thermal conductivity, strength, formability, and resistance to corrosion (Metal Supermarkets, 2015). A common application of copper is for the manufacturing of pipes and pipe fittings due to copper being corrosion resistant. Copper is a softer metal and is easier to mold while brass is more difficult to mold and cast (Metal Supermarkets, 2015).

Brass is also used for a variety of products and applications and has high workability and durability. It is an alloy that consists of copper with zinc or other elements added. Depending on the amount of zinc or other elements added, there are a variety of mixtures that can produce a wide range of properties and variation in color. Increased amounts of zinc provide the material with improved strength and ductility (Metal Supermarkets, 2015). If the zinc content of the brass ranges from 32% to 39%, it will have increased hot-working abilities, but the cold-working will be limited. If the brass contains over 39% zinc, it will have a higher strength and lower ductility at room temperature (Metal Supermarkets, 2015). Brass is durable and can withstand high temperatures and is corrosion resistant. Ultimately, we determined that because copper could be soft/malleable when being cut, brass would be preferable in the sample model. However, on a larger production scale, copper would prove to be better for this system.

Operational Calculations

In the process of designing or predicting the performance for a heat exchanger it is essential to relate the total heat transfer rate to the inlet and outlet fluid temperatures, the overall heat transfer coefficient, and the total surface area for heat transfer (Bergman et. al, 2011). The proposed heat exchanger is a shell and tube heat exchanger with one inlet and one outlet for airflow with a bundle of copper tubes. When performing calculations, counterflow heat

exchanger equations were utilized, however the heat exchanger proposed is not counterflow because the water is stationary.

Once the various design assumptions and material properties were found, we compiled all the information, conversion factors, energy costs, and thermal properties into an Excel spreadsheet. Next, we entered in the appropriate equations for the Logarithmic Mean Temperature Difference (LMTD) and Effectiveness/Number of Transfer Units (ϵ -NTU method) calculations. Two such relations may be obtained by applying overall energy balances to the hot and cold fluids.

LMTD Method

The log mean temperature difference (LMTD) can be written for a parallel flow or counterflow arrangement. The LMTD has the form:

$$\Delta T_{LMTD} = \frac{\Delta T_2 - \Delta T_1}{\ln \frac{\Delta T_2}{\Delta T_1}}$$

$$\Delta T_1 = T_{i,water} - T_{i,air}$$

$$\Delta T_2 = T_{f,water} - T_{f,air}$$

Where ΔT_1 and ΔT_2 represent the temperature difference at the end of the heat exchanger. LMTD assumes that the overall heat transfer coefficient is constant along the entire flow length of the heat exchanger (Muzychka, n.d.).

$$Q = UA * \Delta T_{LMTD}$$

To define the effectiveness of a heat exchanger, we had to first determine the maximum possible heat transfer rate, q_{max} , for the exchanger. This heat transfer rate could be achieved in a counterflow heat exchanger of infinite length. In such an exchanger, one of the fluids would experience the maximum possible temperature difference, $T_{h,i}$ and $T_{c,i}$.

ε -NTU Method

The effectiveness/number of transfer units (NTU) method was developed to simplify a number of heat exchanger design problems. The heat exchanger effectiveness is defined as the ratio of the actual heat transfer rate to the maximum possible heat transfer rate if there was infinite surface area (Muzychka, n.d.). The heat exchanger effectiveness depends upon whether the hot fluid or cold fluid has the minimum heat capacity rate. That is the fluid which has the smaller capacity coefficient $C = \dot{m} * C_p$ (Muzychka, n.d.). If the cold fluid has the minimum heat capacity rate then the effectiveness is defined as:

$$\varepsilon = \frac{C_{max} (T_{h,i} - T_{h,o})}{C_{min} (T_{h,i} - T_{c,in})}$$

Otherwise, if hot fluid has the minimum heat capacity rate, then the effectiveness is defined as:

$$\varepsilon = \frac{C_{max} (T_{c,o} - T_{c,i})}{C_{min} (T_{h,i} - T_{c,in})}$$

Then the equation for the heat transfer rate is:

$$Q = \varepsilon C_{min} (T_{h,i} - T_{c,i})$$

When relating the heat exchanger effectiveness to another parameter referred to as the number of transfer units (NTU), the value of NTU is defined as:

$$NTU = \frac{UA}{C_{min}}$$

Develop Design Configuration

Once the overall design parameter were assigned, the team then proceeded to produce two SolidWorks models. The first model, was a full scale model design of a shell and tube heat exchanger intended for residential use. The second model produced in SolidWorks was designed as a visual representation model of the heat exchanger.

Full Scale Design

The first model was designed based off the dimensions and material of a septic tank. Septic tanks range in terms of volume, and the team decided to use a 750-gallon septic tanks for the design and calculations. The dimensions of the septic tank are: 120 inches long, 67 inches wide, and 57 inches tall. These dimensions were used to create a SolidWorks design. Based off the SolidWorks design, calculations were performed to determine the specifications needed for the heat exchanger. The full scale design uses 50% water and 50% pipes for the volume. The space between the tank and the pipes is 6 inches.

Sample Model

The second model's dimensions were chosen to be approximately the size of a shoebox, as we needed to be able to transport the model for presentation. Constructing a full-scale model would be too large to transport and would not be economically feasible given the allotted budget. Instead, a sample model was constructed to serve as a visual representation of the full-scale proposed heat exchanger design. The sample model tank was made from acrylic and brass pipes.

In order to build the model, we utilized the following equipment: SolidWorks to design an assembly of the tank and the Versalaser VLS-4.60 laser cutter by Universal Laser Systems to cut the acrylic sheet into the tank pieces. Below is an image of the laser cutter used to make the headers.



Figure 10: Versalaser VLS-4.60 laser cutter

After cutting the acrylics sheet, a horizontal band saw was used to cut pipes to size. Once all the pieces of acrylic and pipes were cut, we proceeded to assemble the sample model using acrylic cement. Next the headers' holes were reamed as necessary to ensure a tight pressure fit with the ¼-inch diameter brass pipes. The headers were placed ½-inches from each end of the tank.

Simulation

In order to determine how effective our proposed heat exchanger system is, conducting a thorough simulation was established to determine what the optimal operating parameters are. The design assumptions, conversion factors, energy costs, and thermal properties were compiled into a Microsoft Excel spreadsheet.

The energy that was transferred from the air in the pipes to the water, was calculated at 10-minute intervals up to 400 minutes, and these Q-values were used to determine the temperature change of the water in the tank. The temperature change of the water was calculated at 60 second intervals, up to 400 minutes. The water temperature at the end of each 10 minute interval was then used to find the Q-value for the next 10 minutes.

Results

The “coolness” storage system presented in this report can store 18 kWh at 55°F. This thermal energy would be stored at night during off-peak hours when the cost of electricity is the least expensive. It would then be delivered to the customer during the peak period. The cost to charge this system is \$1.81, and the cost to operate the system during a peak period (using a 500W A/C motor fan) would be \$2.15. Compared to a traditional central air conditioning unit, which would cost \$17.18 to use during the same time period, the average customer would see a savings of 77%.

Design

The full-scale design of the “coolness” storage system would be a shell and tube heat exchanger with 255 pipes. The design is based off the dimensions of a 750-gallon concrete septic tank. This system would be able to be integrated into a residential HVAC system.

Heat Exchanger Analysis

Based on the dimensions and material of the full-scale model, we were able to perform calculations that simulated how the heat exchanger would perform during a peak period. The tank contains 50% water and 50% pipes. The table below shows the assumptions used to perform the required calculations.

Table 4: Assumptions for temperature and volume of septic tank.

Category	Value (Imperial units)	Value (SI units)
Septic Tank Volume	750 gal	2.84m ³
Space Between Tank and Pipes	6 in	0.1524 m
Length of Tank	120 in	3.048 m
Width of Tank	67 in	1.7018 m
Height of Tank	57 in	1.4478 m
Initial Temp of Water	75°F	23.9°C
Final Temp of Water	55°F	12.8°C
Initial Temp of Air	50°F	10°C
Final Temp of Air	54°F	12.2°C

The tables below show the properties for the type of pipe (copper), air, and water. These properties were used to calculate how the heat exchanger would perform under certain conditions.

Table 5: Copper pipe properties.

Category	Value (Imperial units)	Value (SI units)
Diameter	2 in	0.0508 m
k		401 W/m*K
Thickness	0 in	0 m
$r_{in}=r_{out}$	1 in	0.0254 m

Table 6: Water properties

Category	Value
μ_{water}	8.9×10^{-4} Pa
$C_{p,water}$	4.817 kJ/kg*K
k_{water}	598.03 milliW/m*K
ρ_{water}	997 kg/m ³

Table 7: Air properties

Category	Value
μ_{air}	0.00001722 Pa
$C_{p,air}$	1.006 kJ/kg*K
k_{air}	25.14 milliW/m*K
ρ_{air}	1.204 kg/m ³
Velocity	1.5 m/s

Table 8: Energy costs.

Time of day	Cost	Units
Peak Event	0.6137	\$/kWh
Daytime	0.1211	\$/kWh
Evening	0.0991	\$/kWh

Operational Calculations

The team used the LMTD method to determine how the heat exchanger will function under the previously stated conditions. The following calculations are the preliminary steps used to get the specifications for the heat exchanger. The calculations listed below are for air in pipes.

Prandtl Number (air):

$$Pr = \frac{\mu_{air} * c_{p,air}}{k_{air}}$$

$$Pr = \frac{0.00001722Pa * 1006 \frac{J}{kg * K}}{0.02514 \frac{W}{m * K}}$$

$$Pr = 0.689$$

Reynolds Number (air):

$$Re = \frac{\rho_{air} * Vel_{air} * 2 * r_{in}}{\mu_{air}}$$

$$Re_D = \frac{(1.204 \frac{kg}{m^3}) (1.5 \frac{m}{s}) * (2 * 0.0254m)}{0.00001722Pa}$$

$$Re_D = 5327.8$$

Nusselt Number (air):

$$Nu_D = 0.023 * Re_D^{\frac{4}{5}} * Pr^{0.3}$$

$$Nu_D = 0.023 * 5327.8^{\frac{4}{5}} * 0.689^{0.3}$$

$$Nu_D = 19.7$$

Heat transfer coefficient (air):

$$h = \frac{Nu_D * k_{air}}{D}$$

$$h = \frac{19.7 * 25.14 \frac{milliW}{m * K}}{0.0508m}$$

$$h = 9.75 \frac{W}{m^2 K}$$

Resistance (air):

$$R = \frac{1}{2 * \pi * r * h * L}$$

$$R = \frac{1}{2 * \pi * 0.0254m * 9.75 \frac{W}{m^2 * K} * 700.37m}$$

$$R = 0.000917 \frac{m^2 * K}{W}$$

Based on the calculations above, certain specifications can be obtained. The table below shows specifications for the heat exchanger, such as the number of pipes, how much it costs to run, and how much the “coolness” system costs compared to a typical A/C unit. The calculations for how to find these values are below the table.

Table 9: Specifications for full-scale model

Category	Value	Unit
Thermal storage	18	kWh
LMTD	4.14	K
Power	504.5	kW
Cost to charge	1.81	\$
Cost to run “coolness” system during peak period	2.15	\$
Cost to run A/C during peak period	17.18	\$
Total length of pipe	700.37	m
Length of one pipe	2.7	m
Number of pipes	255	pipes
Surface area	111.77	m ²
Overall heat transfer coefficient	1089.7	W/ m ² *K

Overall heat transfer coefficient:

$$R_{total} = R_{air}$$

$$R_{total} = 0.000917 \frac{m^2 * K}{W}$$

$$U = \frac{1}{R_{total}}$$

$$U = \frac{1}{0.000917 \frac{m^2 * K}{W}}$$

$$U = 1089.7 \frac{W}{m^2 * K}$$

Power:

$$\dot{Q} = LMTD * A * U$$

$$\dot{Q} = \frac{4.14K * 111.77m^2 * 1089.7 \frac{W}{m^2 * K}}{1000}$$

$$\dot{Q} = 504.5kW$$

Energy stored:

$$Energy\ stored = \frac{(\%_{tank\ with\ water} * Volume_{tank} * c_{p,water} * \Delta T_{water} * \rho_{water})}{3600s}$$

$$Energy\ stored = \frac{(0.5 * 2.84m^3 * 4.187 \frac{kJ}{kg * K} * (23.9^{\circ}C - 12.8^{\circ}C) * 997 \frac{kg}{m^3})}{3600s}$$

$$Energy\ stored = 18\ kWh$$

Cost to charge:

$$Cost\ to\ charge = Energy\ stored * Energy\ cost\ at\ night$$

$$Cost\ to\ charge = 18\ kWh * 0.0991 \frac{\$}{kWh}$$

$$Cost\ to\ charge = \$1.81$$

Cost to run system during peak period:

$$Cost\ to\ run_1 = Power\ of\ AC\ fan * hours\ to\ run * cost\ of\ peak\ period\ energy$$

$$Cost\ to\ run_1 = 500W * 7hr * 0.6137 \frac{\$}{kWh}$$

$$Cost\ to\ run_1 = \$2.15$$

Cost to run A/C during peak period:

*Cost to run₂ = Power of Central AC unit * hours to run * cost of peak period energy*

$$Cost\ to\ run_2 = 4kW * 7hr * 0.6137$$

$$Cost\ to\ run_2 = \$17.18$$

Compared to a typical A/C unit (with a power of 4kW), the “coolness” system is more efficient. The “coolness” system is 77% less expensive than a typical A/C unit.

Percent savings:

$$\% \text{ saved} = \frac{Cost\ to\ run_2 - Cost\ to\ run_1 - Cost\ to\ charge}{Cost\ to\ run_2} * 100$$

$$\% \text{ saved} = \frac{\$17.18 - \$2.15 - \$1.81}{\$17.18} * 100$$

$$\% \text{ saved} = 77\%$$

Models (Full Scale and Sample Model)

Two models were designed for this project. One is a full-scale model with dimensions based on those of a septic tank. This would theoretically be used in a commercial application of this concept. The second was a sample model, designed to visually represent the full-scale design that could feasibly be built within the budget that was allotted.

Sample Model

The dimensions of the final sample model are shown in the tables below.

Table 10: Sample model dimensions

Piece	Length (inches)	Width (inches)	Thickness (inches)
Acrylic Wall 1	8	5.75	0.25
Acrylic Wall 2	8	5.75	0.25
Acrylic Wall 3	11.5	5.75	0.25
Acrylic Wall 4	11.5	5.75	0.25
Acrylic Top	12	8	0.25
Acrylic Base	12	8	0.25

Table 11: Sample model header dimensions

Acrylic Header (2x)	Value
Length (inches)	7.5
Width (inches)	5.75
Thickness (inches)	0.25
Number of holes per header/Number of pipes	36
Spacing Between Holes center to center (inches)	0.81
Diameter of Brass Pipes	0.25
Length of Brass Pipes (Inches)	9

Table 12: Assembled sample model box overall dimensions

Length (Inches)	12
Width (Inches)	8
Height (Inches)	6

The SolidWorks assembly and parts are shown below. A picture of the actual model is also shown below. Additional pictures of the sides and base are shown in Appendix A.

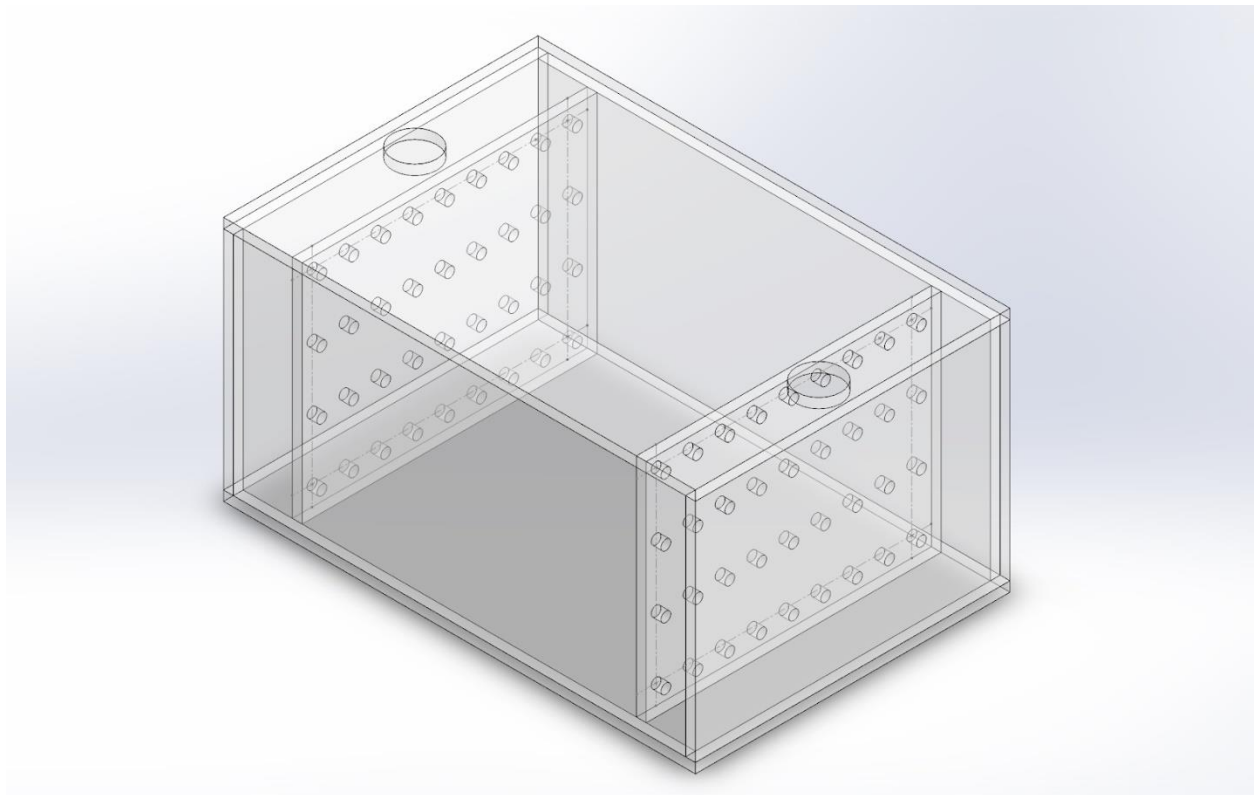
*Figure 11: Sample model-isometric view*



Figure 12: Sample model header



Figure 13: Sample model top

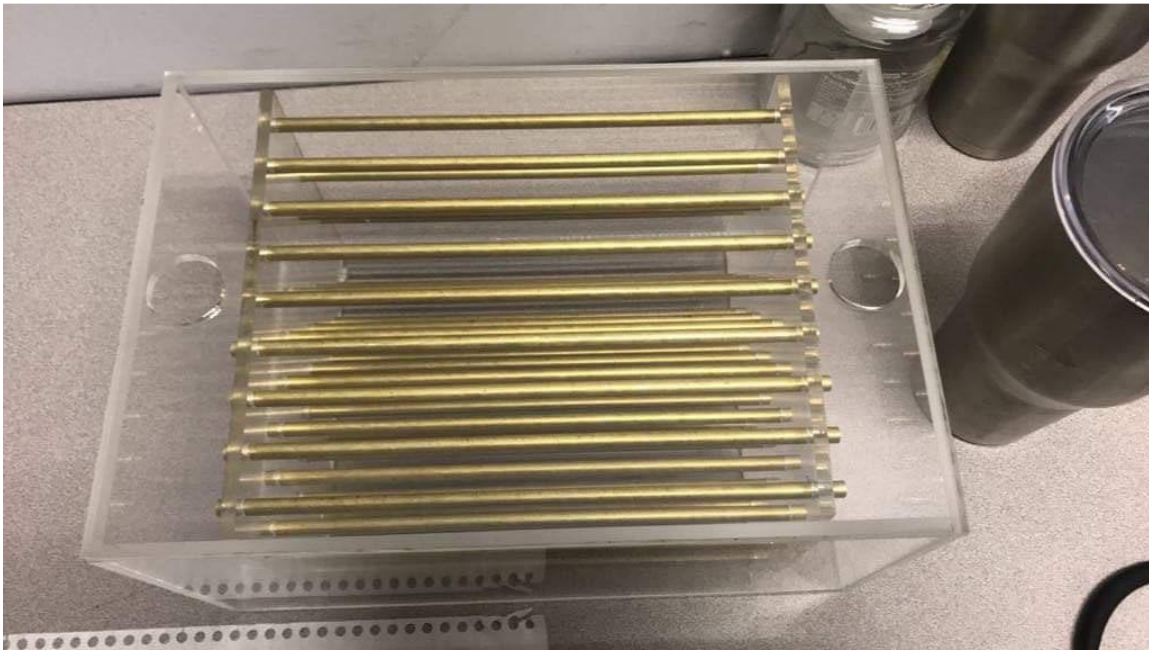


Figure 14: Sample model

Full-Scale Model

The full-scale model provided realistic parameters and insight to help simulate a peak period in Worcester, MA. With this model, we were able to simulate outcomes grounded in a realistic design. The dimensions of the full-scale model are shown in the tables below.

Table 13: Full-scale model overall dimensions

Length (Inches)	120
Width (Inches)	67
Height (Inches)	57

The SolidWorks assembly and parts are shown below.

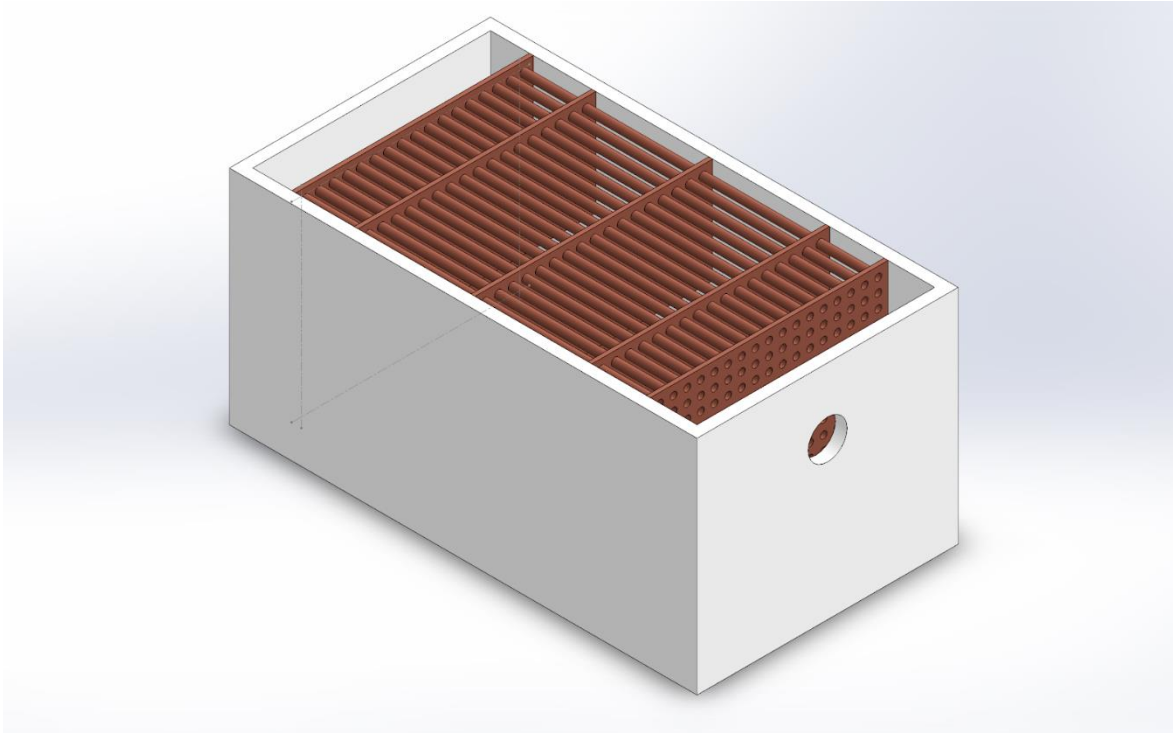


Figure 15: Full-scale model.

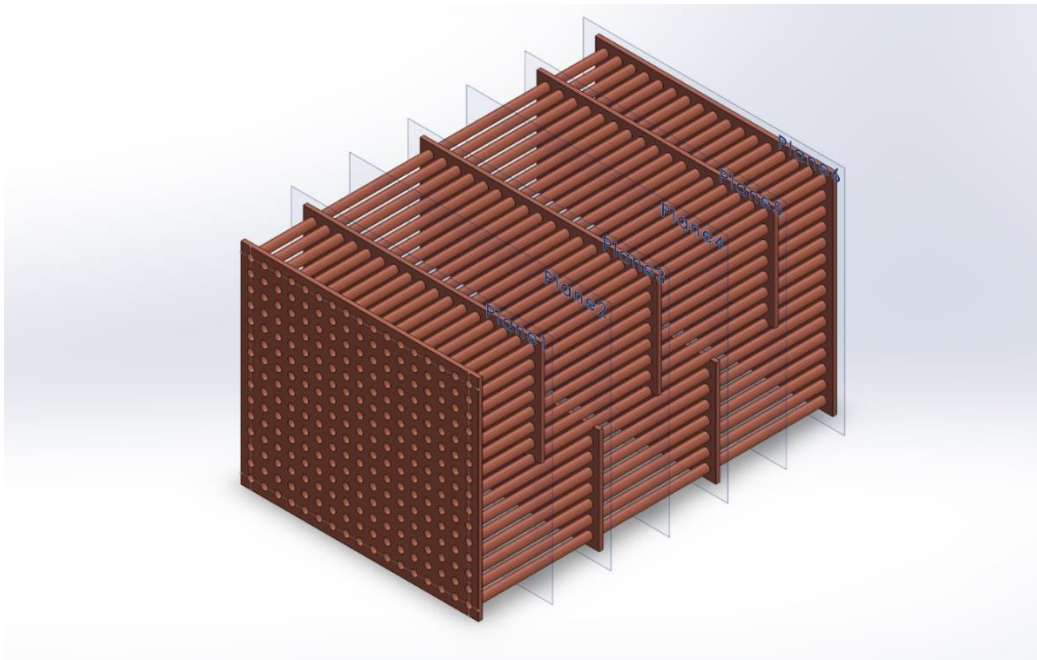


Figure 16: Pipes and headers in full-scale model

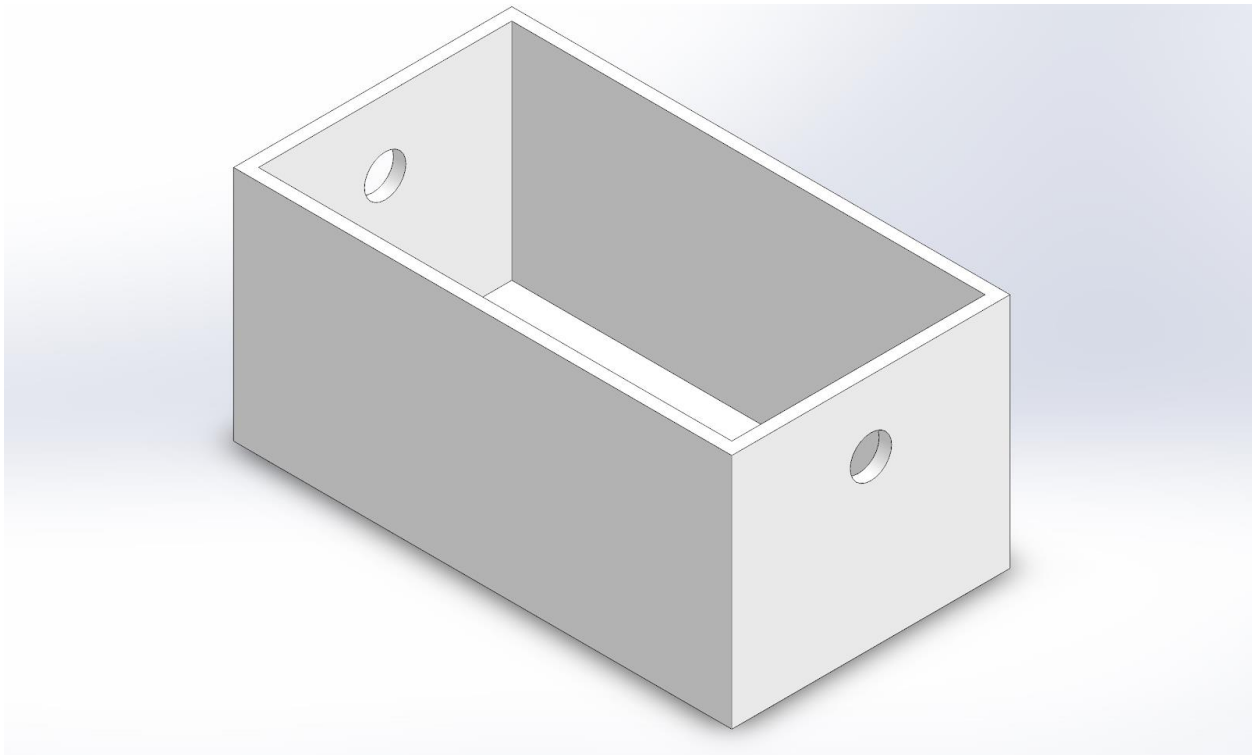


Figure 17: Concrete tank for full-scale model

Auxiliary Cooler

An auxiliary cooler will be used to provide the necessary cooling load to lower the water temperature to the desired starting temperature. An auxiliary cooler is another type of heat exchanger that uses a refrigerant to cool the water. The auxiliary cooler would function during off-peak hours to provide the cooling charge to the water. To cool the water from 75°F to 55°F, it would require a cooling load of 18 kWh and cost \$1.81 to operate. The figure below shows how the auxiliary cooler would be connected to the system.

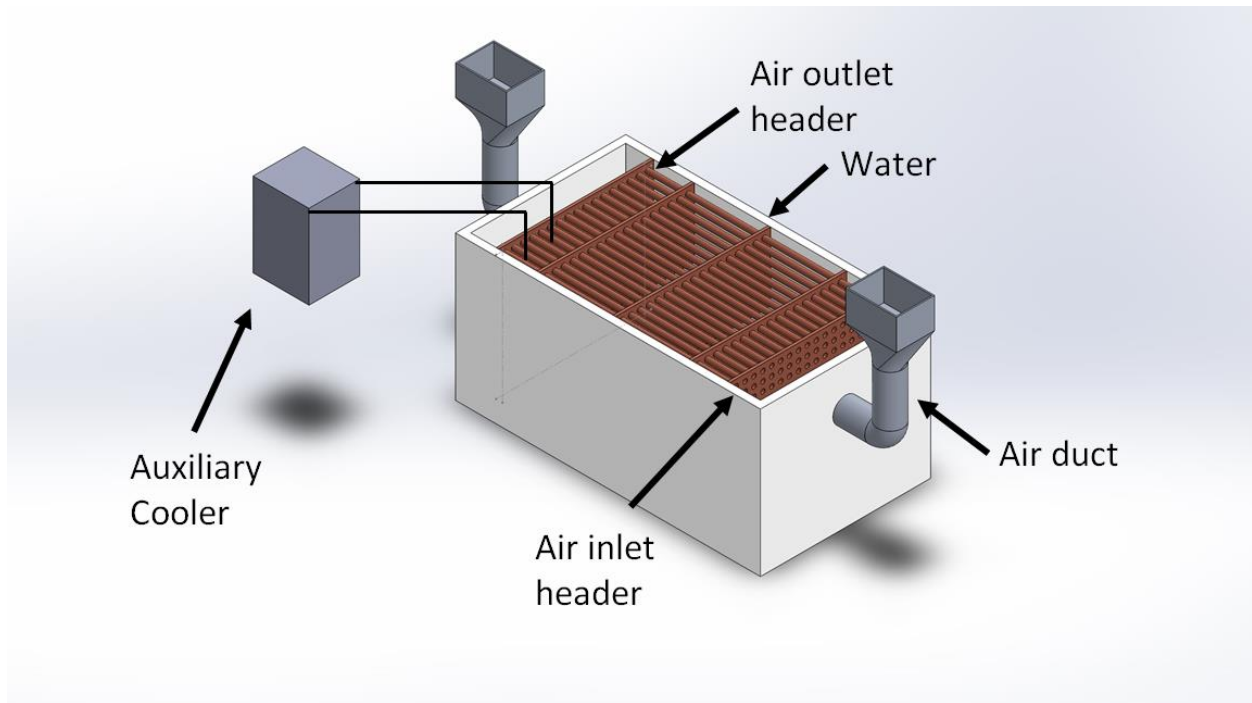


Figure 18: Labeled full-scale model with auxiliary cooler

Integration in Residence

In order for this system to connect to the customer's home, the system needs to connect to the ductwork of the pre-existing HVAC system. The best way to connect the "coolness" storage to the HVAC system is to use dampers.

A damper is used in the HVAC system of a house to control and direct airflow. Dampers are installed inside of a duct in order to control the amount of heating or air conditioning allowed into a room. The damper is connected to a zoning system that splits the house into different zones. The zoning system ensures that air is directed to the space that needs it the most, and the damper helps control the direction of airflow based on the temperature (Lennox International Inc., n.d.). Dampers used for heating and air conditioning can be motorized or manual.

For this project, the best type of damper to use is the control damper. The control damper works by opening and closing based on what the temperature control system commands (High Performance HVAC, n.d.). The control damper can work with zoning systems and direct the

airflow to different zones based on its needs in relation to other zones. Additionally, the control damper can work alongside an occupancy sensor; the occupancy sensor will alert the damper to open or close depending on if the zone is occupied or not (High Performance HVAC, n.d.). The diagram below shows how the “coolness” storage system will be integrated into the residential HVAC system.

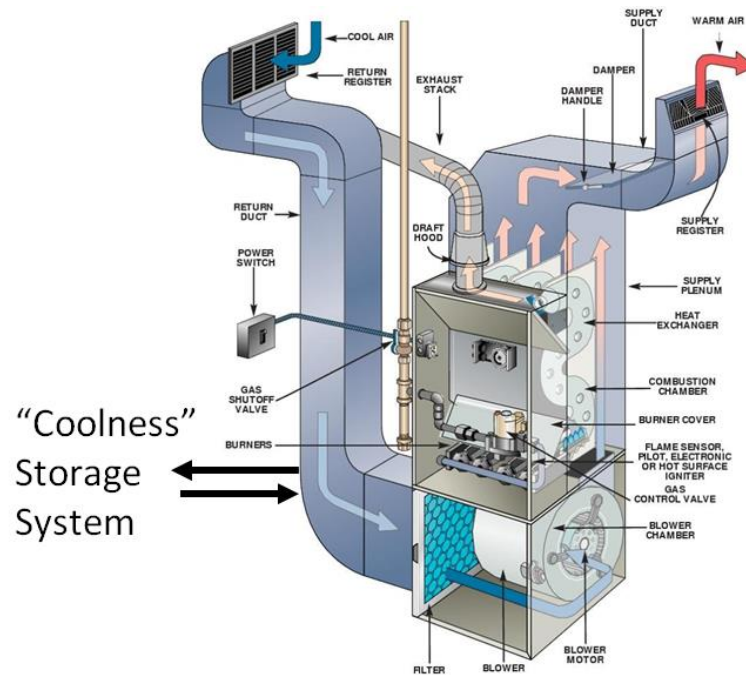


Figure 19: Residential HVAC integration diagram

The system should only be used during a peak period. In order to ensure that the system is running during this time frame, the below figure details when the “coolness” storage system should operate.

Conditions	R1	R2	R3	R4	R5	R6	R7	R8
Is a peak event occurring?	N	N	N	N	Y	Y	Y	Y
Is air temperature at least 3°F greater than water temperature?	N	Y	Y	N	Y	Y	N	N
Is a person present in residence?	N	N	Y	Y	Y	N	Y	N
Actions								
Turn on Storage System	Off	Off	Off	Off	On	Off	Off	Off

Figure 20: Decision table to decide when to run “coolness” storage system

Time-Based Calculations

The graphs below show the resultant temperature of water over time and the temperature change of air in the pipes of the full-scale model. These calculations assume the presence of a pump in the tank to prevent stratification of the water for even heat transfer.

Temperature Change over Length Calculations of Air in Pipes

Below are tables containing the values necessary to calculate the temperature change over length of the air flowing through the pipes.

Table 14: Properties of air at 20°C

Properties of Air at 20°C	Value
Dynamic Viscosity (μ)	1.72×10^{-5} Pa
Specific Heat (C_p)	1.006 kJ/kgK
Thermal Conductivity (k)	25.14 mW/mK
Density (ρ)	1.204 kg/m ³
Velocity (Vel)	1.5 m/s
Mass Flowrate (\dot{m})	0.004 kg/s
C_{min}	0.012 kJ/K*S = kW/K
\dot{q}	126.913 kW

Table 15: Heat transfer values of full-scale model

Prandtl Number	6.89×10^{-1}
Reynold's Number	5.33×10^3

Nusselt Number	19.7
h_{inner}	9.8 W/m ² K
f	0.027

Table 16: Initial properties of fluids

Initial Temperature of Water (K)	285.9 K
Initial Temperature of Air (K)	296.9 K
Percent of Water (%)	0.5

Below are the calculations to find the change in temperature over length of the air in pipes.

$$T_{m,o} = T_s - (T_s - T_{m,i}) \exp\left(-\frac{\pi DL}{\dot{m} C_p} \bar{h}\right)$$

$$T_{m,o} = 285.9 K - (285.9 K - 296.9 K) \exp\left(-\frac{\pi(0.0508)(0.3)}{\left(0.004 \frac{kg}{s}\right)\left(1.006 \frac{kJ}{kgK}\right)} 9.8 W/m^2\right)$$

$$T_{m,o} = 296.9 K$$

This equation was reiterated for every foot for a total of 9ft (2.74m). All calculations are done in metric units but converted to English units. The final resultant outlet temperature of air at 9ft was 289.8 K.

$$\dot{q} = \dot{m}C_p (T_{m,o} - T_{m,i}) * \text{Number of pipes}$$

$$\dot{q} = \left(0.004 \frac{kg}{s}\right)\left(1.006 \frac{kJ}{kgK}\right)(296.9K - 289.8K)*(255)$$

$$\dot{q} = 6.639 kW$$

The equation above was reiterated for every 10 minutes for up to 400 minutes. The graph below shows the change in temperature over length of the air in the pipes during the first pass through the system. As the air moves through the pipes, it extracts coolness, resulting in a temperature drop in the air.

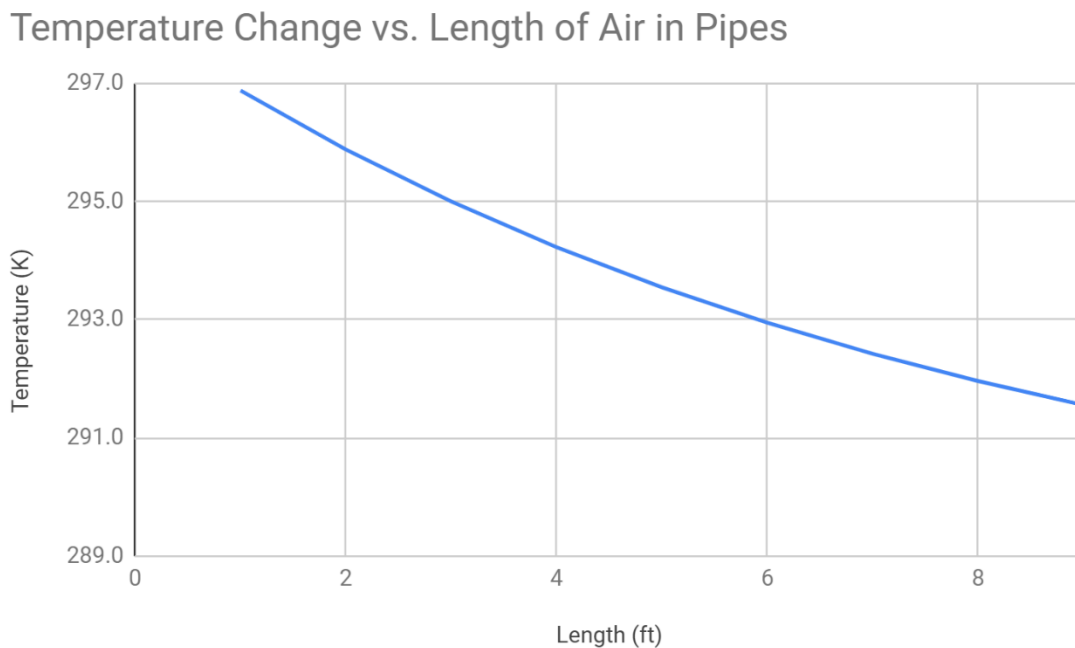


Figure 21: Temperature change vs. length of air in pipes

Change in Temperature for Water Over Calculations

Below are the calculations to find the change in temperature over time of the water in the tank.

$$\text{Thermal Energy} = \dot{q} * \Delta\text{Time}$$

$$6.639 \frac{\text{kJ}}{\text{s}} * 60 \text{ sec} = 398.34 \text{ kJ}$$

$$T_{o,\text{water}} = \frac{\dot{q} * \Delta t}{\text{Vol} * C_p * \rho} + T_{i,\text{water}}$$

$$T_{o,water} = \frac{398.34 \text{ kJ}}{1.89 \text{ m}^3 * 4.2 \frac{\text{kJ}}{\text{K}} * 997 \text{ kg/m}^3} + 285.93 \text{ K}$$

$$T_{o,water} = 286.00 \text{ K}$$

This equation was iterated every minute for 400 min (6 hours and 40 min) until the water reached about the same temperature as air, as shown in the graph below.

Temperature vs. Time of Water in Tank

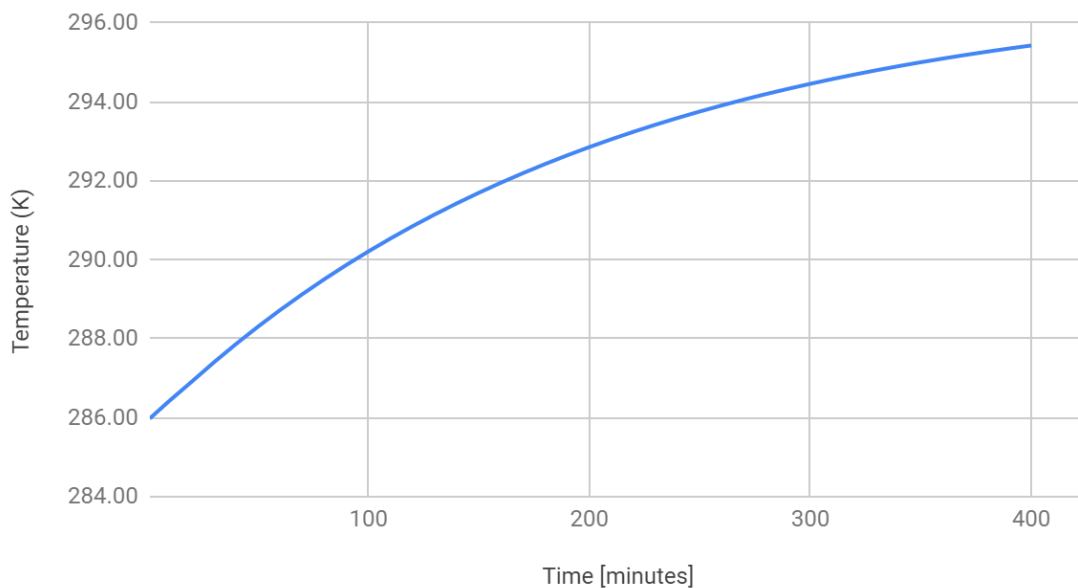


Figure 22: Temperature vs. time of water in tank

The graphs showing the heat exchange for the air and water mirror each other. As the air moves through the pipes, it extracts coolness from the water, resulting in a drop in temperature. Conversely, as the coolness is extracted from the water, it will warm up, eventually moving towards equilibrium with the outside air temperature.

Conclusions and Recommendations

The goal of this project was to design a system capable of storing “coolness” during off-peak times to reduce costs and save energy during peak periods. Currently “peaker” plants are being used to meet demand during peak periods. These plants are inefficient and costly for utility companies, which result in increased costs for customers. The proposed design detailed in this report consists of a heat exchanger, using water as a coolant for air. During nights, when energy is less expensive, a small air conditioner will run to cool the water to 55°F which will then be used to cool air during peak periods. By using this storage, the customer will use less energy from air conditioners during peak periods thus saving them money.

In order for this heat exchanger to perform in an energy efficient manner, we needed to determine a reasonable temperature that air can be cooled to during peak periods. By calculating how temperature changes throughout the length of the heat exchanger, we determined how long the system can run while still producing cooler air. After approximately seven hours, the temperature of the water in the tank will be roughly the same as the temperature of the incoming air thus requiring the system to be shut off. During the time frame the system is running, air can be cooled to as low as 63.1°F with a velocity of 1.5 m/s. At night when the system is charging, the customer would pay about \$1.81 (\$0.0991 per kWh). Utilizing a typical 500W A/C motor fan to send air through the system, the cost would be approximately \$2.15 for seven hours of use during a peak period. This proves to be significantly lower than regular air conditioners used during peak periods.

The full-scale model is used to represent a large-scale production of the heat exchanger proposed in this report. This model provided realistic parameters to simulate and test our design. The full-scale model provided insight and helped to correctly simulate a peak period in Worcester, MA. With this model, we were able to simulate outcomes grounded in a realistic design. The sample model was made to serve as a portable visual representation of the full-scale model.

For future improvements to this project, we recommend exploring more in-depth ways to store “coolness” not only on a residential scale but also on a larger scale for commercial applications. Material analysis can be performed to optimize heat transfer capacity. Additionally, utilizing smart equipment such as sensors and smart thermostats can improve how often the

system needs to run and if it is necessary to run during a peak period. Note that if the mass flow rate of the air through the system is lowered, it would allow for a greater heat transfer to occur, thus providing cooler air but a shorter operating window. Implementing a smart thermostat system may help to optimize the performance of this system.

The design presented in this report addresses the need for an alternative cooling method to reduce strain on the power grid during peak periods. Our proposed heat exchanger system will save energy and costs for both the consumer and the utility company, thus helping to reduce reliance on inefficient and polluting “peaker” plants. Further research and testing may result in a more efficient system that can serve the needs of customers and utility companies while providing much needed relief on hot summer days.

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Appendix A

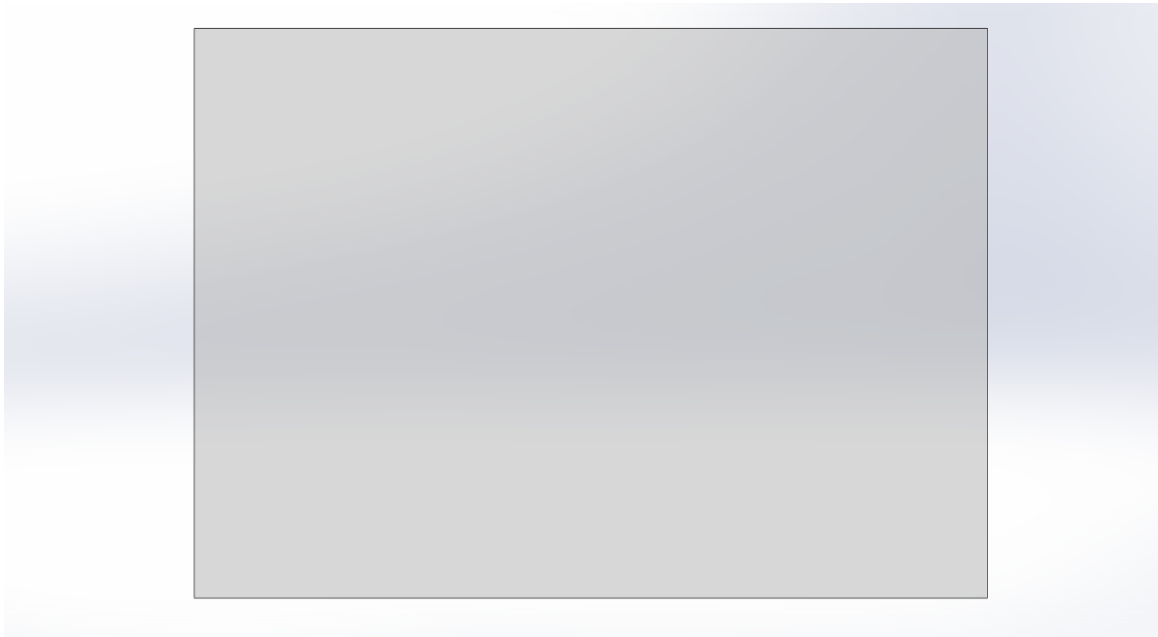


Figure 23: Model-acrylic wall 1, 2

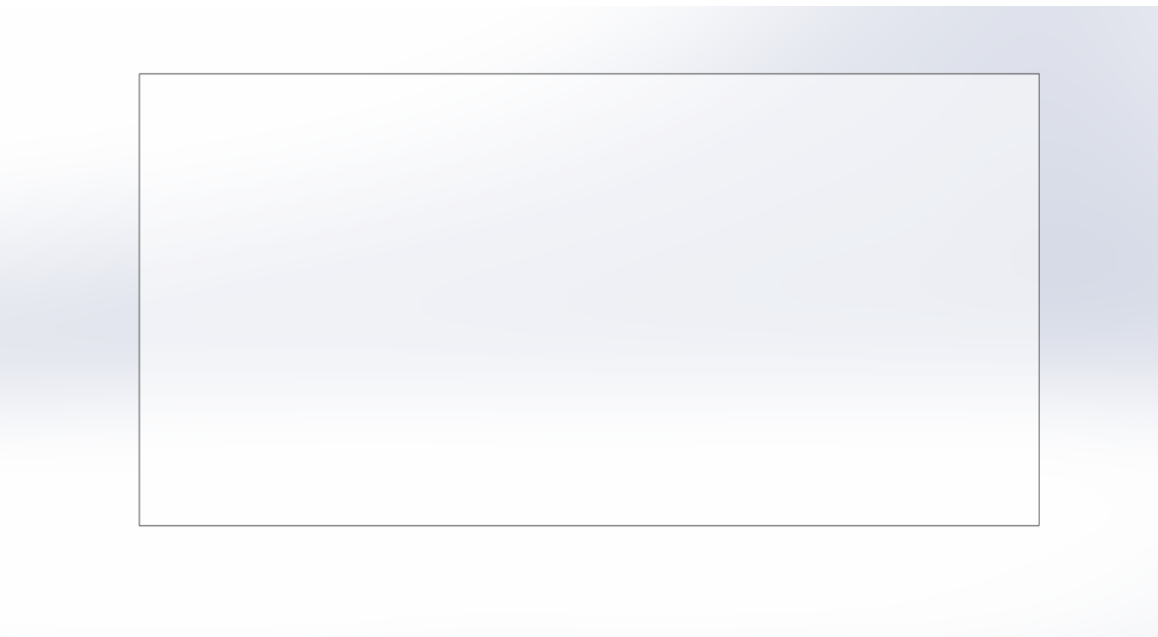


Figure 24: Acrylic wall - 3,4

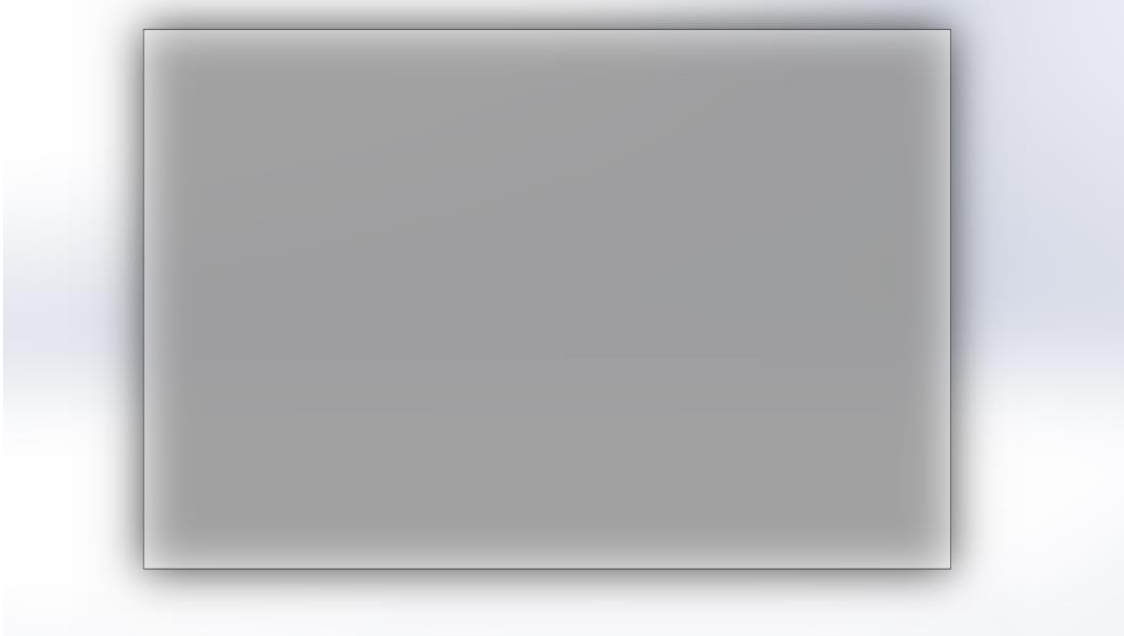


Figure 25: Acrylic base