April 2015

FSC Water Heater

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Repository Citation

Cieslewicz, J. F., & Hartzell, Z. R. (2015). *FSC Water Heater*. Retrieved from https://digitalcommons.wpi.edu/mqp-all/3351

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A Major Qualifying Project Report:

Project # JMS 1504

Submitted to the Faculty

of the

WORCESTER POLYTECHNIC INSTITUTE

In partial fulfillment of the requirements for the

Degree of Bachelor of Science

By

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Date: April 30, 2015

Abstract

This project designed and sized a water tank system for use in US Army field kitchens for dish cleaning as contracted to Yankee Scientific. A preliminary computer model was used to predict the tank's stratified layers temperatures and exit temperature based on water consumption rates and reheat flow rates. A physical model of the system was constructed and instrumented to verify the initial estimates of performance. The data acquisition of temperature and flow rates confirmed the computer model estimates of performance. The computer model and experimental testing confirmed the improved performance of the water tank system with interior baffles compared to the existing systems in field use. These test results and modeling system were used to the design of the system and satisfied all specified specifications.

Acknowledgements

We would like to thank Professor John M. Sullivan, Jr. for his constant patience and support guiding us to completion of this project. We would also like to thank our sponsors at Yankee Scientific, especially Mark Macauley and David Brownell for approaching us for this project and giving us this incredible opportunity. Thanks also goes out to Natick Army Research Laboratories.

Executive Summary

This Major Qualifying project developed a water tank system to be included in a stand-alone water heater for use in US Army field kitchens with our sponsor Yankee Scientific. Each field kitchen is equipped with a Food Sanitization Center (FSC) for dish cleaning. A preliminary computer model was used to predict the tank's stratified layers temperatures and exit temperature based on water consumption rates and reheat flow rates. Information from this model was used to create a design that included inlet and outlet ports for the heat exchanger that performed well. We also recommended that a baffle in the center of the tank to improve performance.

A small-scale prototyping phase was conducted. A physical model of the system was constructed and instrumented to verify the initial estimates of performance. The data acquisition of temperature and flow rates confirmed the computer model estimates of performance to be accurate. A second full-scale prototype was built and tested to serve as a design proof-of-concept. These test results and the modeling system were used to provide the fulfillment of the systems design specifications as issued to Yankee Scientific. A single 6-gallon tank designed with an interior baffle and heat exchanger loop ports at 33 percent and 67 percent was able to perform in an acceptable manner to replace the current dual tank design.

The final tank design submitted to Yankee Scientific is shown below as a cutaway to illustrate all critical features. The tank design is shown in Figure 1.

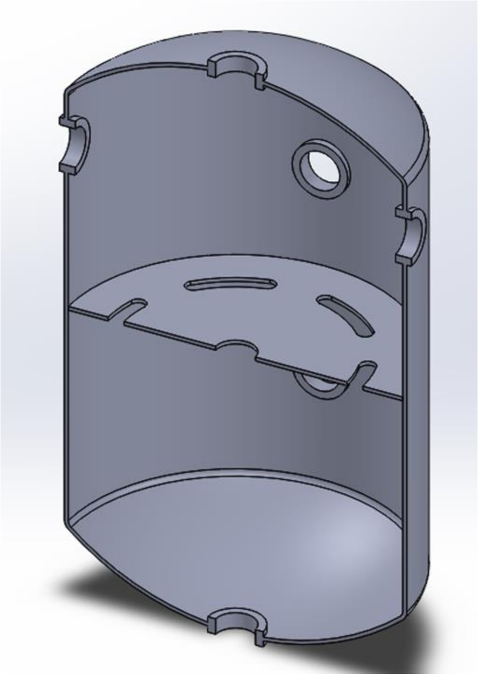

Figure 1: Cutaway of proposed Tank Design.

The holes on the top and bottom are the hot outlet and ground water inlet ports, respectively. The half cutaway holes on the top of the tank support instrumentation and sensors connected to the water heaters control electronics. In the center of the tank the baffle is clearly visible. On the back of the tank on either side of the baffle are the outlet and inlet for the heat exchanger loop. It is recommended that Yankee incorporate this tank design in the next prototype to be delivered to the US Army for evaluation.

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Table of Acronyms

BTU	British Thermal Unit
CK	Containerized Kitchen
DAQ	Data Acquisition
DFM	Direct Firing Module
FEA	Finite Element Analysis
FSC	Food Sanitization Center
GPH	Gallon(s) Per Hour (Flow rate Measurement)
GPM	Gallon(s) Per Minute (Flow rate measurement)
ID	Interior Diameter
MBU	Modern Burner Unit
MFK	Modular Field Kitchen
MKT	Mobile Kitchen Trailer
NTU	Nephelometric Turbidity Units (Cloudiness of water measurement)
OD	Outside Diameter
PSI	Pounds per Square Inch (Pressure measurement)
WHIRL	Water Heating with Integrated Recycling of Liquid

Chapter 1 – Introduction

The goal of this Major Qualifying Project is to design a water tank for a modular water heater. This water heater is a component of a modular field kitchen for the US Army that Yankee Scientific is developing to fulfill a contract with Natick Army Research Labs. The Army has many possible uses for a stand-alone system that can efficiently provide a significant quantity of very hot water. This water heater was originally to be a part of a three 20-gallon basin system Field Sanitation Center (FSC). The formal name of the new system is the Water Heating with Integrated Recycling of Liquid (WHIRL) which included recycling water through the 60-gallon water system.

As the water heater project progressed it became clear that the Army could use this product for a much broader spectrum of applications. While hot water is taken for granted by many of us in our daily lives, military units in the field simply do not have the infrastructure that can supply them with a ready supply of hot water. Many basic activities in our daily lives use hot water, showering, washing our hands and doing our laundry all require a source of hot water. A self-contained water heater could be transported from the kitchen to be used for a hand-washing station, showers, washrooms, or even laundry systems. The water heater could also be adapted to supply a dishwasher with a more commercial spray design, or to feed a tap, which can fill any container as needed. The water heater split away from the strict use of dishwashing to fill stockpots and 3-5 gallon coffee dispensers. From coffee making to cooking or dishwashing, a reliable supply of hot water simplifies many mission critical operations for a field kitchen.

There are four fundamental requirements to operate the water heater. It must be connected to a fuel source and a water source. The burner, pumps and control panel also need a battery or generator to power the systems electronics. Finally, the heater needs a small space to be set up with either good external airflow or an exhaust system. By disconnecting the fuel, water supply and electrical components and reconnecting them at the next station, the water heater can do multiple jobs or be used to replace another that broke down at a more vital operation. This allows the Army a great deal of flexibility on where within the kitchen or field outpost the heater is set up and how it is used.

Chapter 2 - Background

2.1 Existing systems

The US Army commonly uses mobile kitchens to support units deployed in the field or forward operating bases. There are three varieties that have been in use since 2010; The Mobile Kitchen Trailer (MKT), the Containerized Kitchen (CK), and the Modular Field Kitchen (MFK). The MKT is designed to be fully functional within 30 minutes and supports between 250-300 soldiers per meal. The CK can be operational in 45 minutes and supports around 800 soldiers per meal. The MFK is designed to feed around 250 soldiers ("Army Field Feeding and Class I Operations"). However, the modularity of this system allows for different components to be used altering the set-up time and increasing capability. Of these three systems, the MFK is considered the best. The modularity allows for different components of the kitchen to be used, and this is the system that is currently being upgraded. Attached to each kitchen is a FSC used to clean and sanitize the dishes produced by each meal. One FSC supports up to 400 soldiers and can be set up in one hour. The FSC is housed in a large tent and consists of the work tables, the washing stations, and storage racks for the dishes. While this project is working on a FSC upgrade to all field kitchens, most development is focused on the MFK.

Currently the FSC contains three 20-gallon sinks used independently to wash, rinse, and finally sanitize the dishware. These sinks are each heated by a Modern Burner Unit (MBU) heater, which runs on JP8, a kerosene based fossil fuel that the US military uses for a variety of applications. These three tanks operate at different temperatures: 110-120 ^{o}F for the wash, 120-140 °F for the rinse, and greater than 171

^{o}F for the sanitation tank. Yankee's first prototype was designed to produce hot water and replace the three MBUs.

The MBU is a self-contained heating device with an internal fuel tank. It requires 24V DC power source or 110V AC power source. It is currently used in all the components of the MFK including the FSC. It is designed for universal use, however is limited by the heating capacity of the burner as well as the limited amount of fuel that is carried in the burner's internal fuel tank. This system has several drawbacks and the original goal was to replace the three MBUs used in the FSC with a single water heater that would supply each tank with water of the desired temperature. Then the WHIRL system recycles water from the sanitation tank to the rinse tank and then the wash tank.

Figure 2: Modern Burner Unit version 3.

The primary purpose of the water heater, at its most basic level, is to efficiently and quickly supply several gallons of very hot water. The water heater is supposed to be entirely contained within a box of a predetermined standardized size, only requiring external hookups and sources for electricity and fuel as well as a water supply. Yankee has already delivered an initial prototype to the Natick Army Research Laboratories and has received some feedback. This prototype is part of the conceptual WHIRL system. The main components of the water heater are the burner, the heat exchanger, pumps, water tanks and control electronics as well as the piping and outer casing.

The broader project currently in development by Yankee Scientific is a more efficient water heating and recycling system to replace the one currently used by the United States Army in their FSCs. They have proposed to develop the WHIRL system to replace the current system. The WHIRL system would replace the MBUs with a single high efficiency water heater used to supply all three tanks of the FSC. This system should increase the thermal efficiency of the system partly because there would be an integrated system that allows used water to be recycled into the system. Theoretically this system would send wastewater from the first sink; the rinse sink, through a water cleaning module where it is cleaned and returned to the wash tank with minimal debris.

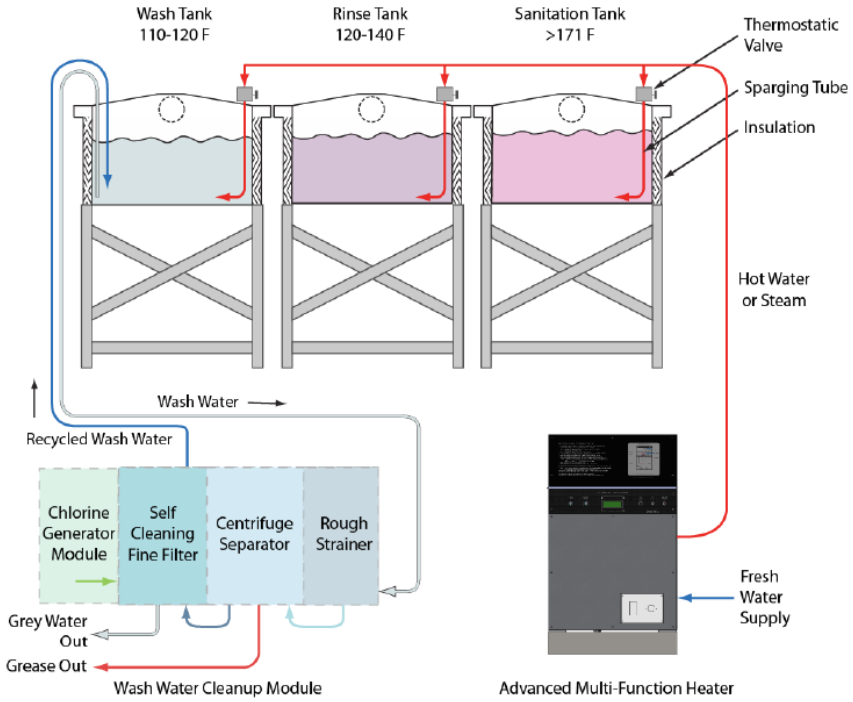


Figure 3: FSC with WHIRL.

With this proposed system the fuel used to operate an FSC could be reduced by up to 50%, while the water used by the system could be reduced by up to 60% (“FSC Water Heater with Integrated Water Recycling”). Since the sinks are filled twice for both hot meals served each day, the theoretical water usage per day is 240 gallons. Theoretically then 144 gallons could be saved each day. A more realistic daily usage to make up for waste and slop would be about 275 gallons per day. The WHIRL system would then save of 165 gallons of water per day. Another added benefit of the WHIRL system is that the cleaning process would not have to be halted halfway through the cycle to drain and refill the sinks because the system is constantly providing clean hot water to the washing sinks. When the sinks are being filled initially water is run through the heater at a relatively high flow rate. This allows the sinks to be filled quickly. Then during the cleaning process the heater has water pumped through it at a slower rate, producing saturated steam. This steam is pumped into the sinks, allowing for make-up water and heat to be put into the sinks to recoup the losses from evaporation. The systems integrated water heater would be able to increase the fluids temperature more efficiently than using separate burners positioned under the sinks. The current heat exchanger as prototyped can provide a flow rate of two gallons per minute while heating raising the water temperature by 65 ^{o}F; however higher firing rates can be achieved.

Another important part of the WHIRL system is the water cleaning and recycling module. This part of the system allows for water to be cleaned and recycled through the system. The cleaning module uses four different steps to allow the water to be reused. First the large debris is removed with a simple strainer. Second, grease and smaller particles are removed using a centrifuge strainer. Next, a reusable, self-cleaning filter removes the remaining debris particles. Finally the water is run through a sanitization generator powered by electro-chlorinator which can provide a verifiable level of sanitization. When cleaning operations are concluded, the chlorinated rinse and sanitation water can be retained and reheated for the next meal. Afterwards, water from the rinse and sanitation sinks can be used as treated grey water, with a target turbidity of < 2 Nephelometric Turbity Units (NTU) and total suspended solids of < 5 mg/L. NTU's are a measurement of how cloudy or hazy a water sample is; the amount of light that is reflected by the sample water can be used to determine the amount of particles suspended in it.

It may be possible to reduce the overall water consumption of the sanitization process by changing the methods and equipment used to wash the dishes. Having a stand-alone water heater allows the Army to experiment with using a more commercialized spray/mist type of dishwasher. These have a pair of rotating heads that strongly spray hot water on the dishes to remove debris and then mist very hot water over the dishes to complete the sanitization part of the process.

This kind of system could potentially save the Army water and energy. A leading manufacturer in the field, Hobart, has a system that uses just .74 gallons of hot water per load of dishes (“AM Select Dishwasher”). To account for rinsing and using a more conservative assumption on the water demands of the dishwasher we can estimate that each load uses ~1.5 gallons of hot water. While each meal could potentially take several loads of dishes, even allowing for 25 loads per meal over 2 meals a day yields a total daily water usage of 75 gallons. This represents a significant reduction in water if this system could be implemented properly.

Another significant factor in the cost and efficiency of any FSC or water heater system is fuel consumption. Currently the energy transfer from the MBU to the water in the sinks by natural convection is less than 50% efficient. Each FSC is equipped with three MBUs to heat the water in the sinks. Some units may still be equipped with the old and dangerous M2 burner; however these burners are being phased out and replaced with the MBU. According to the Army Field Manual written for the MBU, each burner can only consume 0.34 gallons per hour at its highest setting. At the minimum setting it will only consume 0.1 gallons per hour. The fuel tank for each MBU has a capacity of two gallons. Therefore, each meal clean up could be completed without refueling the burners. Since the average time the MBUs are operated per meal is known, along with their fuel consumed by each burner per unit of time; the amount of fuel consumed daily can be calculated. For this calculation the rate of fuel consumed by each burner per hour is represented by FR. The number of burners will be represented by BN. The time that the burners are running each day shall be represented by t, which because each cleanup is 3.5 hours and two meals are cleaned per day is equal to 7 hours.

$$FC = FR\left(\frac{gal.fuel}{hr * units}\right) * BN(units) * t\left(\frac{hr}{day}\right) = 0.34 * 3 * 7$$

$$= 7.14\ gallons\ per\ day\ of\ JP8\ Kerosene$$

With this calculation we can see that each FSC, comprised of three MBUs, consumes over seven gallons of fuel per day, a far from insignificant amount especially when the fact that the military could theoretically have to support dozens of MBUs as well as fueling vehicles and generators with a supply chain hundreds of miles long.

Additionally, each MBU must be refueled twice a day. Since handling fuel is far from safe in field conditions this is not ideal. Ideally any military burner and FSC would consume less fuel per day and not require to be refueled as frequently.

2.2 Heat transfer

One of the main measures of how effective any water heater operates is its level of thermal efficiency. That is to say, how much heat energy is transferred to the water relative to energy stored within the fuel burned. While a great deal of the systems efficiency relies on the heat exchanger selected, energy can also be lost through the hot exhaust gas created by burning fuel as well as an incomplete combustion of fuel by the burner. There is a relatively simple method, which determines the net efficiency of the heating system; the amount of heat added into the water is divided by the total amount of energy in the fuel consumed.

The amount of energy added to the water is calculated by measuring the temperature of the water entering the heat exchanger and the water exiting it. As long as the specific heat and the flow rate of the water through the heat exchanger is known, the amount of heat can be easily calculated. An example is shown below where the flow is 5 gallons per minute and the water is raised by a temperature of 26 ^{o}F.

$$Heat\ Added\ per\ minute = c_p\left(\frac{BTU}{lb*degree\ F}\right)*8.34\left(\frac{lb}{gal}\right)*GPM*degree\ F$$

$$.8784\left(\frac{BTU}{lb*degree\ F}\right)*8.34\left(\frac{lb}{gal}\right)*5\ GPM*26\ degrees\ F = 952\left(\frac{BTU}{\min}\right)$$

The amount of energy consumed in the burner over a period of time can be determined by reading how much fuel is consumed and then multiplying it by the known amount of energy in a specific unit of that fuel. The fossil fuel used for the burner in this water heating system is a special kind of kerosene called JP8. It is used in a wide of variety of applications in the US Military. However, the burner is also designed to work on regular kerosene. Since kerosene is easier to obtain, and offers similar performance, it was used in all experiments and testing conducted by this MQP team and Yankee Scientific. The amount of energy in a gallon of kerosene is about 134,000 British Thermal Units (BTU) (Laquatra, Joseph). The amount of energy consumed is expressed in the following equation. An example is shown below where 30 mL (0.00792516 gal) of fuel was consumed in one minute.

$$Energy\ consumed = Volume\ of\ fuel * energy\ Density\ of\ fuel$$

$$Energy\ consumed = \ .00792516\frac{gal}{min} * 134000\ \left(\frac{BTU}{gal}\right) = 1061.97\ BTU/min$$

So to determine the efficiency of the example system, the following equation is used.

$$Efficiency = \frac{Energy\ into\ the\ Water}{Energy\ Consumed} = \frac{952\ (\frac{BTU}{min})}{1061.97(\frac{BTU}{min})} = \ .89645 = 89.645\%$$

A more efficient heating system is desirable for a variety of reasons. They are cheaper to operate, consume less fuel and are more environmentally friendly. According to our project sponsors Yankee Scientific, the US Army's current water heating systems are about 50 percent efficient. The system that they are building to fulfill the contract they have with the Army is between 85 and 90 percent efficient. This represents a vast improvement over the Army's current system.

Army kitchens typically serve two hot meals each day. Clean up after each meal typically takes around 3.5 hours, over which time a significant amount of heat is lost to the environment through evaporation. Water and heat is also is removed from the system by clinging to every plate that is cleaned. The evaporation is determined by finding the amount of water that dissipates in kg/hr.

$$gh(kgh)= \theta(kgm^2h)*A(m^2)*(xs-x)$$

$$\theta=[25+19*(v\ (ms))]kgm^2h$$

The Area of each tank is 0.534 m^2, the velocity of the wind is assumed to be about 12 mph or 5.364 m/s. The ambient temperature is rated to a minimum of 40^o F, around five degrees Centigrade. Therefore we will use that temperature for our calculations. The value 'x' represents a dimensionless ratio to show the mass of water in the same mass of air, commonly known as the humidity ratio. This was found by the ambient temperature of 40^o F. The x_s value is the specific humidity ratio in saturated air at the water temperature. To find the x_s value, the following equation is used.

$$x_s=0.62198\,(pws)/(pa-pws)$$

The variables pws and pa stand for the saturation of water vapor and the atmospheric pressure of warm air respectfully. The constant value converts the pressures to mass for calculation. It is an alternative format of the equation which simply calculates the mass of water (m_w) over the mass of air (m_a) (“Humidity Ratio of Air”).

$$x = \frac{m_w}{m_a}$$

From x_s equation, each tank had a different value for its evaporation rate due to its temperature which directly affects the pressure for each tank. In tank one, the evaporation is 7.123 kg/hr or 1.879 gal/hr. In total the three tanks lose around 4 gal/hr. This large rate of evaporation can determine what burner will need to be used in the project based off the mass flow rates.

While evaporation is one aspect of heat loss, another concern is the open tanks. The Army developed lids to be used in conjunction with the tanks. These lids are the same concept of a pot lid for water on the stove - keep the heat in. The heat lost in W/m2 is calculated below.

$$qrad=\varepsilon*A*\sigma*(Ts^4-Tsur^4)$$

Heat lost in radiation equals the emissivity constant for water multiplied by the surface area, the Stefan-Boltzmann constant, and the temperatures of the surface and the surroundings. Similar to the evaporation, each tank had a different value for the energy lost.

Tank	Heat Lost (W/m^2)
1	133.909
2	163.703
3	267.061

The heat and water losses show the current system is inefficient and wasteful in many regards.

2.3 Packaging

Currently the FSC sinks are a relatively simple package. They consist of a stand, a sink tub, and a MBU. Figure 4 shows the FSC sinks set up with one MBU installed. Clearly, these sinks are not easy to move and are not designed to fit within a uniform appliance footprint for a modular kitchen.


Figure 4: FSC with MBU Heater.

The new water heater design created by Yankee Scientific is designed to be used within a modular kitchen. It is self-contained and designed to be easily moved. Retractable wheels are installed on the bottom. The bottom of the water heater also has a latching mechanism that allows the water heater to lock onto a track system on the floor to prevent it from moving or tipping over. The current prototype is encased in an 80/20 extruded aluminum frame with sheet metal bolted on the outside. The final design however will most likely be constructed of a riveted sheet metal frame and body.


Figure 5: Yankee Scientific Water Heater Prototype.

2.4 Safety

When looking at safety considerations it is obvious that any sort of burner can be potentially dangerous to ignite. Current, the Army requires soldiers to take the MBU outside of the field kitchen building or tent to light. This is because of an unstable flame upon ignition; the last thing the Army wants is to have the flame flare and catch the structure on fire. Once the unit is lit and heated up to maintain a consistent flame it is carried lit back into the tent and inserted into the component in the MFK that it heats. This procedure is dangerous, a dropped burner could result in a fire or severe injuries to the soldiers carrying it. Yankee Scientific has replaced the MBU with a self-contained burner unit in its prototype. It is lit with the push of a button and fires directly into the heat exchanger and is vented with an exhaust system. This allows the burner to be lit in the field kitchen without being removed from the unit. This dramatically decreases the chances of an accident. The burner that Yankee is using will be replaced with the Direct Firing Module (DFM). This universal burner will operate in a nearly identical way and will be implemented in their second prototype of their self-contained water heater. It will also be used throughout the next generation of the MFK. Any burner used will have to either be connected to an exhaust system or be used in a well ventilated area.

There are several other important factors that must be accounted for when designing the water heater system. The tank, along with the rest of the system, must be able to handle a high heat environment because it will be holding water that is potentially at near boiling temperatures. Any failure could release near-boiling water, which could cause burns to soldiers operating the hot water heater. To allow for a safety factor, it is reasonable to require the tank and plumbing to be made of a material that can withstand temperatures of 250 ^{o}F without any structural deformation. It is also critical to keep water flowing through the heat exchanger when the burner is on in order to prevent the build of steam in the heat exchanger. This could cause the system to explode. The burner must also be shut off if the water gets too hot, this is a built in feature of Yankee's prototype. Another crucial component of the tank designed is making it safe as a pressure vessel. The system is under pressure to ensure there are no air bubbles in the system and to allow water pressure at the tap. The anticipated pressure in the system is 75 PSI. To account for a significant safety factor, the system is designed to withstand at least 150 PSI and includes a blow-off valve set at to release before that threshold is exceeded. This design ensures the system always operates at a safe pressure.

For the prototype testing this MQP team conducted, there were other safety concerns. Since our prototypes were not pressurized, they did not have to be designed as pressure vessels. However, the prospect of creating steam and running the risk of an explosion taking place did not appeal to us. We therefore made sure we kept the highest water temperature during all of our testing below 205 °F. Our DAQ system had a visual warning light included to warn us of high temperatures. During all our testing we wore closed toes shoes and safety glasses for personal protection. We took the proper precautions while operating any machinery, and ensured that any burners we lit were in a well-ventilated environment.

Chapter 3 – Methodology

3.1 Preliminary Computer Modeling

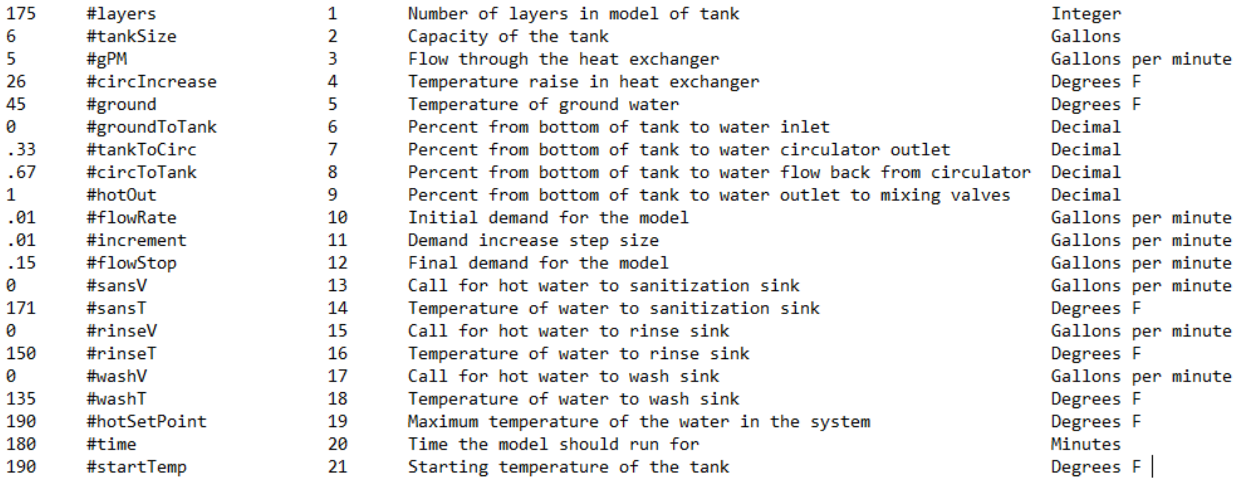
Yankee Scientific has an existing design of the FSC water heater system. There are four main components to the this system. First, there is a buffer tank that the heated water is drawn from and cold ground water is drawn into. The current tank is six gallons, however analysis is being performed in order to optimize the tank capacity. The circulator pumps water from the tank through the heat exchanger and back into the buffer tank. The heat exchanger raises the temperature of the water a fixed amount at a fixed flow rate. Currently, Yankee is considering two different heat exchange and burner units. Both are designed to raise the water temperature 26 °F but at different flow rates. One operates at five gallons per minute (gpm). The second operates at 10 gpm. It is important to design the system so that it is robust while still operating efficiently.

In order to achieve these goals the system must be designed to perform at the highest possible level. One way to do this is to create a mathematical model of the system with an appropriate software package. The model would allow the user to easily enter different values for variables in order evaluate different designs and conditions. Running the model with different parameters allows the engineering team to make informed decisions on things such as the size of the tank and capacity of the heat exchanger in order to meet certain standards.

The concept of our model is to create a set of programs in the mathematic computation program MATLAB that realistically portrays the operation of the modular water heating system. There are several separate but important entities to consider.

First, the amount of water required from the hot water (Buffer) tank to meet a specified demand based on the required flow rates and temperatures. Second, the water flowing through the heat exchanger is considered. Next, the temperature of the layers in the tank is redistributed. Finally, cold ground water is added into the tank to account for hot water drawn from it.

Before any of these functions can be calculated it is essential that the parameters for the model be imported from a text file. The MATLAB is coded in such a way that only the first few characters on each line are read into the program. These are later labelled to become variables in the program.



```
175     #layers                 1       Number of layers in model of tank                      Integer
6       #tankSize               2       Capacity of the tank                                   Gallons
5       #gPM                    3       Flow through the heat exchanger                        Gallons per minute
26      #circIncrease           4       Temperature raise in heat exchanger                    Degrees F
45      #ground                 5       Temperature of ground water                            Degrees F
0       #groundToTank           6       Percent from bottom of tank to water inlet             Decimal
.33     #tankToCirc             7       Percent from bottom of tank to water circulator outlet Decimal
.67     #circToTank             8       Percent from bottom of tank to water flow back from circulator Decimal
1       #hotOut                 9       Percent from bottom of tank to water outlet to mixing valves   Decimal
.01     #flowRate               10      Initial demand for the model                           Gallons per minute
.01     #increment              11      Demand increase step size                              Gallons per minute
.15     #flowStop               12      Final demand for the model                             Gallons per minute
0       #sansV                  13      Call for hot water to sanitization sink                Gallons per minute
171     #sansT                  14      Temperature of water to sanitization sink              Degrees F
0       #rinseV                 15      Call for hot water to rinse sink                       Gallons per minute
150     #rinseT                 16      Temperature of water to rinse sink                     Degrees F
0       #washV                  17      Call for hot water to wash sink                        Gallons per minute
135     #washT                  18      Temperature of water to wash sink                      Degrees F
190     #hotSetPoint            19      Maximum temperature of the water in the system         Degrees F
180     #time                   20      Time the model should run for                          Minutes
190     #startTemp              21      Starting temperature of the tank                       Degrees F
```

Figure 6: Parameter File.

Next, several other factors are calculated. The size of each layer in the tank must be derived. Then the cycle time must be determined. The cycle time is considered to be the time it takes to flow the volume of one layer through the heat exchanger.

In order to calculate the amount of water required by the system several factors must be considered. First, the program must evaluate the temperature and volume of multiple demands. In order to meet these demands, varying levels of hot water and cold water are required. The model uses the volumetric mixing concept to determine the ratio of hot water to cold water. An example of this equation is shown below:

$$T_{Req} = (T_{Hot} * Ratio_{Hot}) + (\,T_{Cold} * Ratio_{Cold})$$

The temperature of the cold water is the ground water temperature. The temperature of the hot water being drawn from the tank is considered to be the temperature of the layer in the tank that it coming from, in most cases the top of the tank. Then the total volume of each is calculated by considering the ratio and the total volume of water demanded. For each separate mixing value these values are calculated. They are then added together in order to ascertain the amount of hot water drawn from the tank. This volume is later used to determine the amount of cold water that flows into the tank.

After the draw of cold water is determined, the heating cycle of the system is modeled. In order to do this, the layer in which the water returns from the heat exchanger has its temperature recalculated. First the temperature of the water flowing from the heat exchanger is determined to be the temperature of the heater supply layer plus the heat increase through the heat exchanger. This number is averaged with the current return layer temperature to determine the temperature of the return layer.

Next, the mixing in the buffer tank is modeled. The temperature of each layer in the tank is recalculated. The temperature of each layer, bar the top and bottom, is recalculated to be equal to the average of itself, the layer above it, and the layer below it. The top layer is averaged with the layer below it while the bottom layer is averaged with the one above it. This series of calculations, especially when the layer size is very small, allows the program to model turbulent mixing in the tank.

After the tank is mixed, cold water is drawn into the tank to make up for that cycle's demand. This water is added to the cold water supply layer, generally the bottom of the tank. The final temperature of this layer is calculated similarly to the temperature of the return layer. The initial temperature of this layer is average with the temperature of the incoming groundwater.

The next step of this project was to output data into an easily viewed analysis. To do this we created graphs of the resulting data. Each graph was the demand of hot water compared against time. The demand started at zero and was incrementally increased until the point that the system could not maintain the demand for the full time. Changing one variable several times produced charts that were easy to read to determine recommendations on the work, and where to move forward.

When the code was completed we started running test cases. We changed some of the variables that we thought could greatly impact the project to benefit for the strongest amount of water output. The categories changed were location of input and output of heat exchanger loop and the tank size, as well as the maximum temperature to be run through system. The prototype had an inlet at 50% of the way up the tank. The inlet had a pipe going inside the tank spraying the water in a downward direction. We looked into simple entry into the tank on one stratified later. The model returned the best results when the water left the buffering tank at 25% up the tank and re-emerged 33% up the tank. This model test allowed for the majority of the tank to remain a buffering area with hot water.

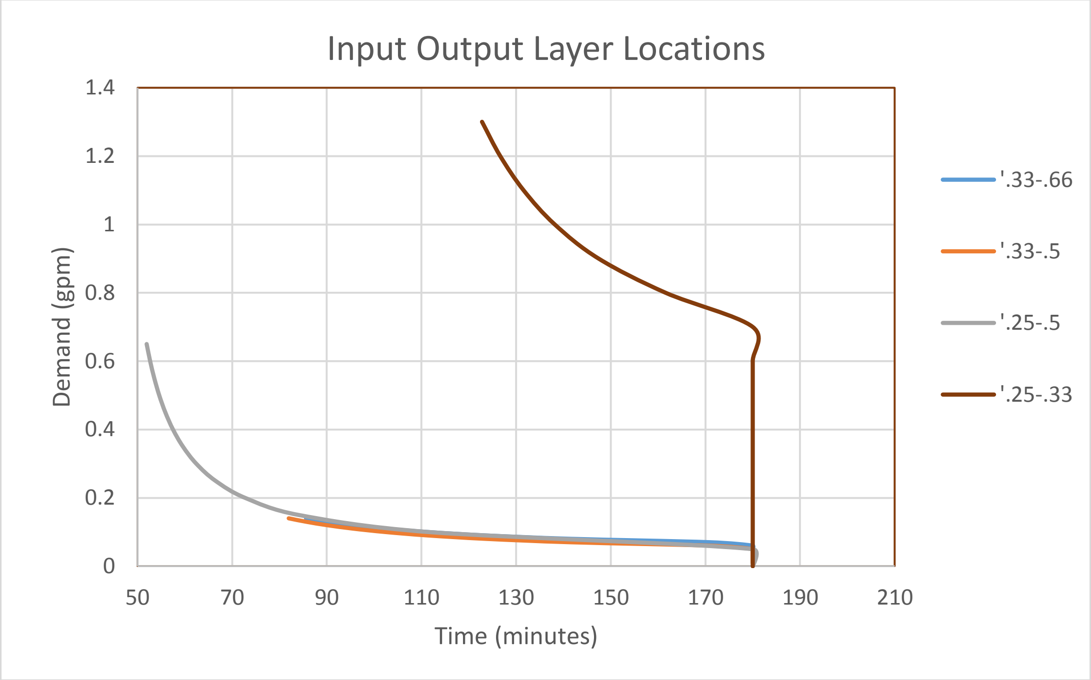


Figure 7: Graph changing input and output locations of heating cycle.

While this is not an optimization program, the results showed significant improvement from the current locations of the input and output. We started with these recommendations for our next round of testing.

3.2 Preliminary Testing

This part of the project focuses on confirming the data from the computer model. The goal is no longer to fill three 20-gallon tanks of water. The WHIRL water heater has been repurposed to supply hot water needed in the kitchen for stock pots or 3-5 gallon hot beverage dispensers.

Figure 8: 4.75 gallon Coffee Dispenser similar to US Army device.

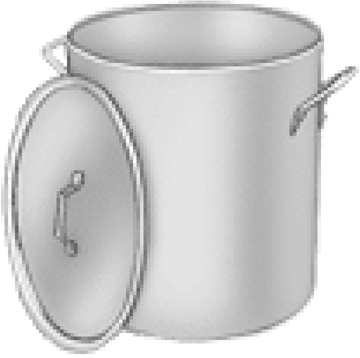


Figure 9: Stock pots from 5-15 gallons can be filled with hot water to expedite cooking process.

In order to evaluate the validity of the theoretical data provided by the mathematical model we needed to collect empirical data from an experiment. Empirical data is important because it is hard data that pertains to how things are really working within the system, not just how they theoretically would in an idealized system. The concept of the prototype is to create a basic model of the water heating system. This includes a tank, pump, heat exchanger, and a method for measuring temperatures in various locations of the system.

The materials required for the experiment are a 5 gallon bucket, layers of foam insulation, plastic boards for baffles, metal rod to mount thermocouples, stock pot at room temperature, fish tank pumps, Tygon tubing, spiral copper tubing for heat exchanger, turkey fryer burner, and propane tank for fuel. Additionally, a National Instruments Data Acquisition box and computer are required to collect temperature values.

The general experiment procedure:

1. System assembled for Experimentation
    a. 1 inch layers of Styrofoam circles with plastic boards interspersed as baffles
    b. Top, bottom, and Heat loop input and output layers have hoses to pass through Styrofoam to tank area.
    c. Styrofoam used to shrink volume within the 5 gallon tank as well as insulate the tank
    d. Fish tank pumps and spiral copper tubing used for input and output of heat loop
    e. Thermocouples located at cold input, input and output of heat loop, output of tank, temperature of hot water tank, and ambient temperature
2. Fill the bucket with cold water at a consistent rate using a siphon from the room temperature stock pot, time the collection of 1 quart of water to calculate the flow rate in gallons per minute of the cold water input.
3. Using the bucket filled with cold water start the fish tank pump to circulate water through the heat exchanger (copper coil on turkey fryer burner)
4. Ignite the burner to increase the temperature of the cold water in the bucket. Heat the tank to 105 ^{o}F.
5. Record data heating the tank from 105-110 ^{o}F up to 165 ^{o}F.
6. Input cold water to displace hot water off the top, measure amount of exiting tank until temperature of output drops to 165 ^{o}F.
7. Stop the cold water input and continue the heating loop until the system returns to 180 ^{o}F.
8. Repeat Procedure for consistency and change parameters as necessary.

The tank of the system is made from a common 5-gallon bucket from Home Depot. In order to reduce the volume of the tank and provide some semblance of insulation, the inside of the bucket is filled with foam 'donuts’ in Figure 10.

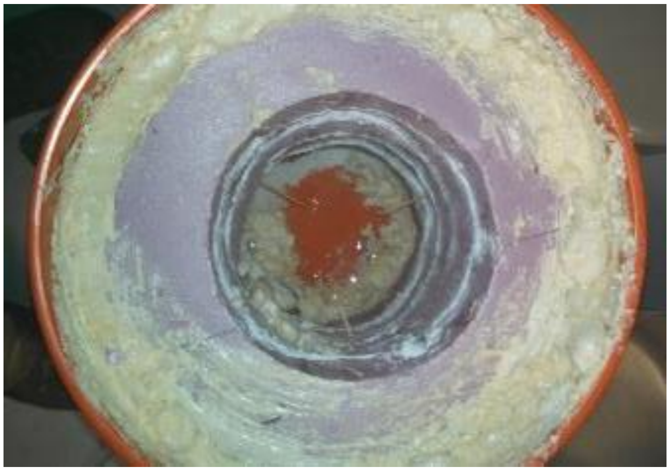


Figure 10: Polystyrene foam insulation donuts reducing volume and providing insulation to the experimental tank.

These donuts reduce the diameter of the tank, allowing for reduced capacity and limit heat transfer outside of the system. The pump this prototype uses was originally designed to be operate in fish tanks, but works well for our system. The heat exchanger is a coil of copper tubing that will be placed over a propane burner. In order to draw water out of the system, there will be water injected into the bottom of the tank, forcing the top layer off.

The heat exchanger is a 10 foot length of 3/8 inch outside diameter (OD) copper tubing twisted into a coil of about 4.5 inches in diameter. Since the plastic tubing for the rest of the system is 1/2 inch interior diameter (ID), it was required to fit 3/8 inch ID plastic to the coil and a set of adapters connect to each end. The heat applied to the coil is provided by a propane burner, shown in Figure 11. The burner is rated to provide up to 45000 BTUs/hour of heat, however when it was run for these experiments it was turned down to a low setting. The burner was originally designed as a turkey deep fryer unit with base and stand. It allowed the heat exchanger to rest above the burner.

Figure 11: Copper coil on a propane burner serves as the heat exchanger.

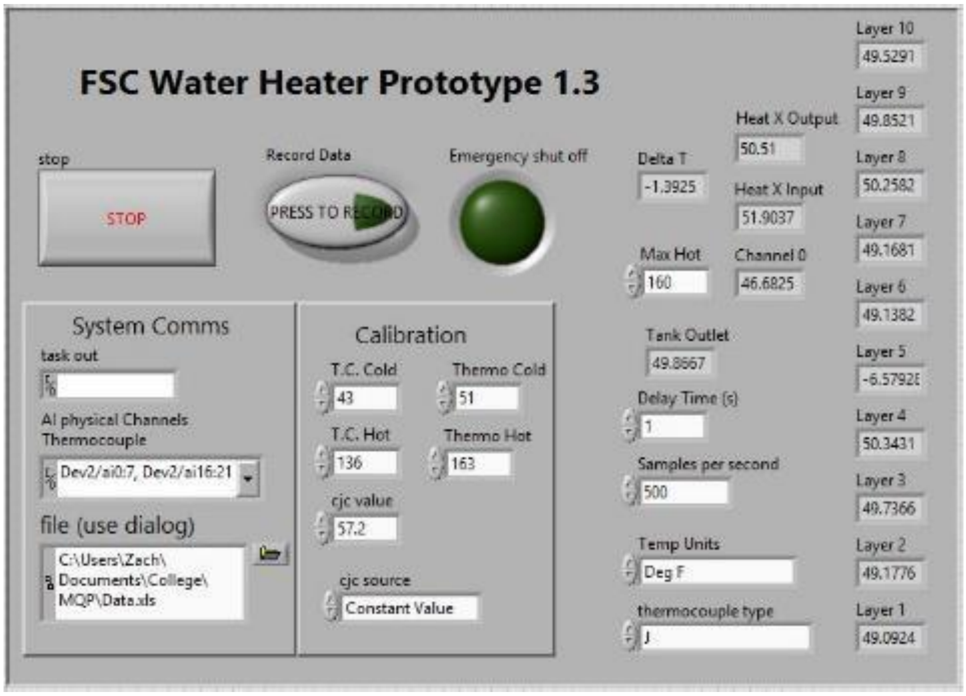
The capacity of our tank and heat exchanger is reduced because our pump cannot provide the full 5 gpm of the real prototype. Our pump, a Hydor Seltz 1200, is specified to be able to pump at maximum 320 gallons per hour. The maximum head height is 77 inches and the pump absorbs 23 watts of power. When tested, the pump was able to pump between 1 and 1.25 gpm through the coil and a few yards of 1/2 inch ID plastic tubing. Originally, the heat exchanger coil was going to be 1/4 inch OD copper and the pump was set to be a similar unit with just 185 gallons per hour (gph) capacity. However, we found that both these options were insufficient for our purposes. Therefore, we ran a trial test and determined that a 3/8 OD coil and the 320 gph pump would be an ideal pairing for our model.

Figure 12: Hydor Seltz pump circulating water from the tank through heat exchanger.

Since our pump, shown in Figure 12, had a relatively large difference in pumping capacity compared to the real system, it was necessary to reduce the capacity of the tank in prototype setup. Inserting foam insulation donuts layers, the tank size can be reduced. Additionally, the donuts allow the tank to be insulated from the outside environment, reducing heat loss and increasing the accuracy of the models testing. The donuts were cut on the outside with a knife, however it became clear that the rough cut edge would not be acceptable for the interior surface of the tank. After some careful thought, we decided to use a hot wire cutter to make the inside holes of the donut. The diameter of the tank is approximately 6 inches. There are 6 layers of 2-inch nominal thickness foam. This allows for a bit of slop because the final height of the outlet hole is 11 inches. This results in a theoretical tank volume of 311 cubic inches, or 1.35 gallons. This creates a more realistic ratio between tank size and pump flow rate. Originally, the gaps between the donuts and between the bottom of the bucket and the bottom donut was going to be sealed by simply applying pressure from weights placed on the cover of the bucket. However, after initial testing, it became apparent that this method would not provide the necessary seals. Therefore, we used caulk to glue the donuts together and to seal the edges of the gap. This method effectively creates a double seal that, theoretically, keeps the tank from leaking. However, after curing the caulk and further testing it was evident that the tank still leaked significantly. Expanding foam insulating sealant was applied to eliminate any gaps and this effectively keep leaks to a minimum. Tubing to allow for the hot water outlet, ground water injection, and various levels for the intake and return lines from the pump and heat exchanger is inserted through holes drilled into the tank, then caulked and spray foamed to provide a seal. Tubing that in not being used in that test case is sealed with an end cap.

There are a total of 14 thermocouples in the system to monitor the temperatures over the period of the experiment. These are connected to a National Instruments data acquisition (DAQ) box connected to a computer running LabVIEW software. The system collects 500 data points for each thermocouple once every second, averages it over the course of the second and outputs it to a spreadsheet file.   This data can later be plotted to show trends of each experimental set. The full design is pictured in Figure 13.

Figure 13: Tank with thermocouples, water pump, and on top of coolers is the cold water reservoir.



FSC Water Heater Prototype 1.3

System Comms
task out
AI physical Channels Thermocouple
Dev2/ai0:7, Dev2/ai16:21
file (use dialog)
C:\Users\Zach\Documents\College\MQP\Data.xls

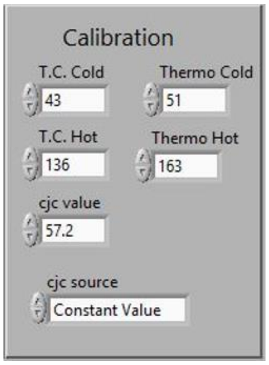
Calibration
T.C. Cold
43
Thermo Cold
51
T.C. Hot
136
Thermo Hot
163
cjc value
57.2
cjc source
Constant Value

Delta T
-1.3925
Heat X Output
50.51
Heat X Input
51.9037
Max Hot
160
Channel 0
46.6825
Tank Outlet
49.8667
Delay Time (s)
1
Samples per second
500
Temp Units
Deg F
thermocouple type
J

Layer 10
49.5291
Layer 9
49.8521
Layer 8
50.2582
Layer 7
49.1681
Layer 6
49.1382
Layer 5
-6.5792
Layer 4
50.3431
Layer 3
49.7366
Layer 2
49.1776
Layer 1
49.0924

Figure 14: Front panel of the LabVIEW program.

The setup of the system, while simple, can be time consuming. First, the systems tubing must be connected and the siphon started, slowly filling the tank. Once the system is full, the siphon hose should be kinked in order to only allow a small amount of water to flow into the system. This will account for any leakage in the system, and to ensure the tank is always full, there should be a light trickle of water to flow out the top through the exit hole. The pump is plugged in allowing water to begin flowing through the heat exchanger. It is important to ensure that there are no air bubbles in the system, if there are the pump will not function at capacity which could lead to creation of steam in the heat exchanger. This is a potentially dangerous situation, if the pump is not flowing while the propane heater is on, superheated steam can be created in a short time. Once the system is full and circulating the top can be placed on the tank, with the center rod with the thermocouples attached. All the thermocouple BNC connectors must now be connected to the DAQ box.



Calibration

T.C. Cold: 43
Thermo Cold: 51
T.C. Hot: 136
Thermo Hot: 163
cjc value: 57.2
cjc source: Constant Value

Figure 15: Calibration Values from front panel.

Before testing can be executed, the system must be calibrated. Calibration takes the cold junction constant which is the temperature at the DAQ box and adjusts the thermocouple readings accordingly. However it does not provide accurate calibration because it is at room temperature. The four temperature values are recorded, thermocouple and thermometer cold water create an ordered pair, as well as the thermocouple and thermometer readings from a hot water sample. The two ordered pairs are graphed with thermocouple values on the x-axis, and thermometer values are on the y-axis. The values from Figure 15 are used to calculate the trend-line in Figure 16 to find the slope and y-intercept. With the relatively simple equation $y = mx + b$, y is the calibrated thermocouple value, x is the raw thermocouple value, m is the slope from calibration (1.2043) and b is the y-intercept from calibration (-0.7849).

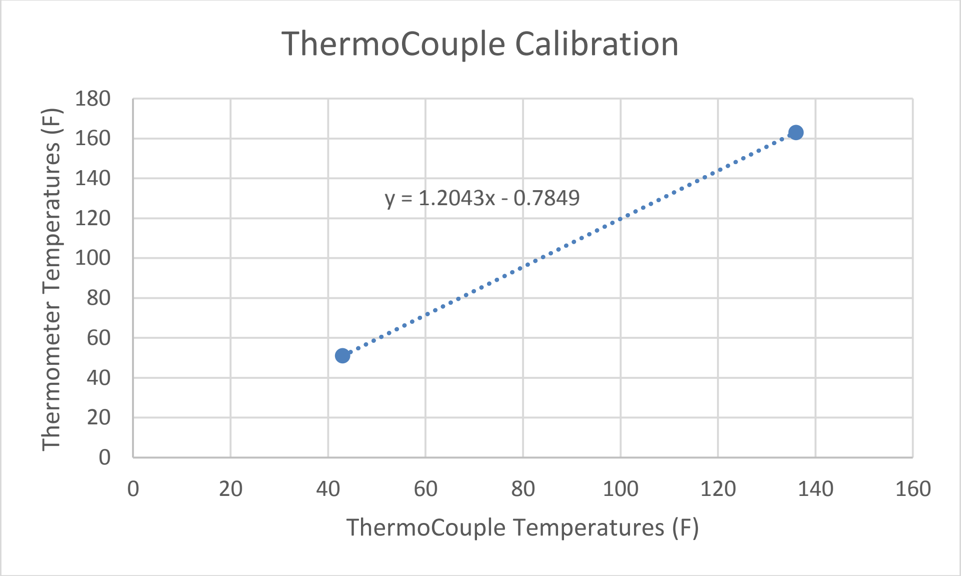
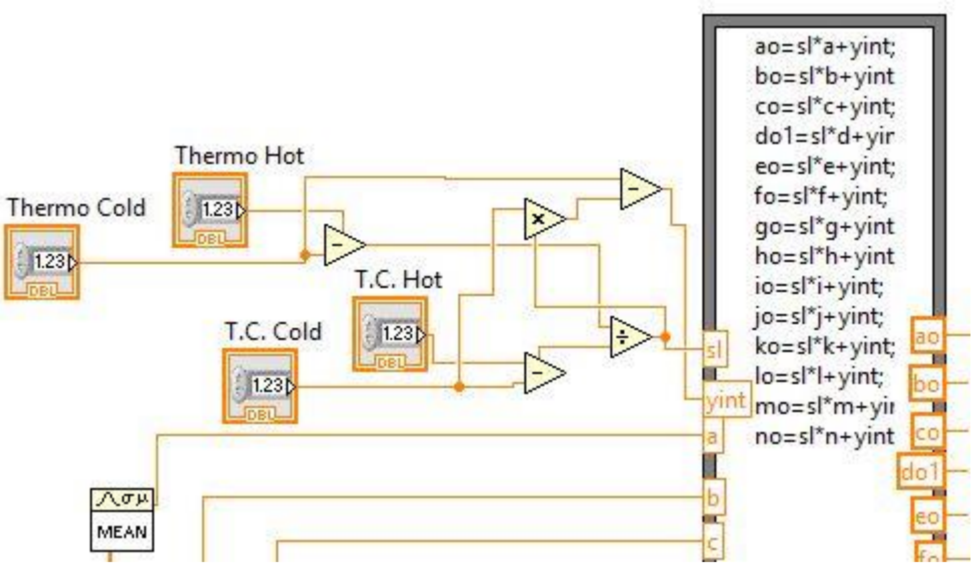


Figure 16: Slope of line and y-intercept calculated using a graph.

Figure 17 shows the program automatically calibrating itself, using the data values from Figure 15, the slope and y-intercept are calculated automatically. The system is saved to run automatically calibrated based off four inputted values. To calibrate it has to be adjusted so that channel 0 of the thermocouples (marked by variables “a” and “ao” in Figure 17) is unaffected by the calibration. Input “a” and output “ao” are removed as well as the slope-intercept equation for these variables. The wire then bypasses the formula node (gray box in Figure 17) to allow the thermocouple to give an accurate reading. Hot and cold water samples with the zero channel thermocouple and a thermometer are inputted into the LabView front panel.



```
ao=sl*a+yint;
bo=sl*b+yint
co=sl*c+yint;
do1=sl*d+yir
eo=sl*e+yint;
fo=sl*f+yint;
go=sl*g+yint
ho=sl*h+yint
io=sl*i+yint;
jo=sl*j+yint;
ko=sl*k+yint;
lo=sl*l+yint;
mo=sl*m+yir
no=sl*n+yint
```

Figure 17: Automated calibration of the thermocouples to real temperature.

Once the calibration values are inputted, the program must be rewired back to match Figure 17 and restarted. The program now automatically calibrates all thermocouples simultaneously. The burner can now be turned on to begin heating the system. There is a visual indicator that the water exiting the heat exchanger is above a certain set temperature. This gives the operators time to turn off the burner before there is steam and pressure are created.

There are several tests that we ran for each arrangement of the system. Before any test can be run, the tank should be allowed to heat to around 110 ^{o}F. Once the desired temperature is reached, data is recorded for roughly seven minutes while the system continues to be heated. After the initial trial period, the heat can be turned off and the system should be allowed to cool to the starting temperature. The test can then be run again to get a second set of data for the arrangement. Two sets of data ensure that any errors in one set of data do not ruin the entire experiment. The next test is started after the tank is heated to a higher temperature, say around 145-150 ^{o}F. Then the data recording is restarted again to record data on how the tank heats while at a higher temperature. After around five minutes, the recording is stopped and the system should be cooled back to 145-150 ^{o}F. Then the burner can be restarted and data recording should begin. On this test the cold water input hose should be unkinked to allow the maximum amount of cold water to flow into the bottom of the tank, forcing hot water to be drawn off the tank. This test is used to see how the system can handle a draw of hot water for a period of time. The test should continue until the temperature of the water leaving the tank drops significantly, around 20 °F.

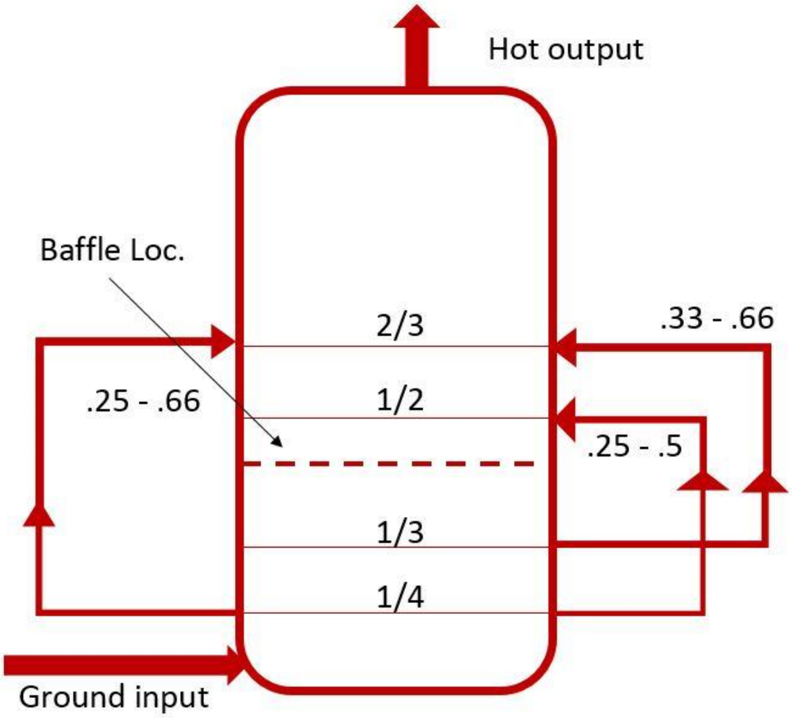


Figure 18: Diagram of Tank with I/O of Heat Exchangers Tested.

The locations of the input and output for the heat exchangers is shown in Figure 18. The baffle was located in between the input and output of the heat exchanger for every test.

These three graphs show the differences in the flow between tests. It shows how the input and output locations matter to the system in Figure 18. Figure 19 shows that the baffle does not impact the heating of the system. Figure 21 shows how the change in temperature is depicted across the tank. The jumps in Figure 21 correspond to the decrease in water temperature mixing in the bottom layer taking control of the layer.

Based off these tests, we would recommend that the heat exchanger draw and return be located at 33% and 66% of the total vertical height of the tank with a baffle located between these points. The next step is to make and test a full scale prototype using the actual heat exchanger and burner that the prototype water heater uses.

The experiment was conducted six times. Three tests without a baffle, and three tests with one baffle between the input and output of the heat exchanger. This location was determined to hold the hotter water higher in the tank. Figure 19 is a compilation of six tests with and without baffles to show how quickly the system heats up at a medium temperature, around 110 ^{o}F. Low temperature is considered around 40 ^{o}F while high temperature is around 150 ^{o}F for this experimental system. Figure 19 was used as a baseline test, the ground water flow through the tank was a trickle of cold water to compensate for leaks in the system. This resulted in a constant trickle out of the system. It is important to notice that the system heats up in similar fashion whether it has a baffle in the system or not.

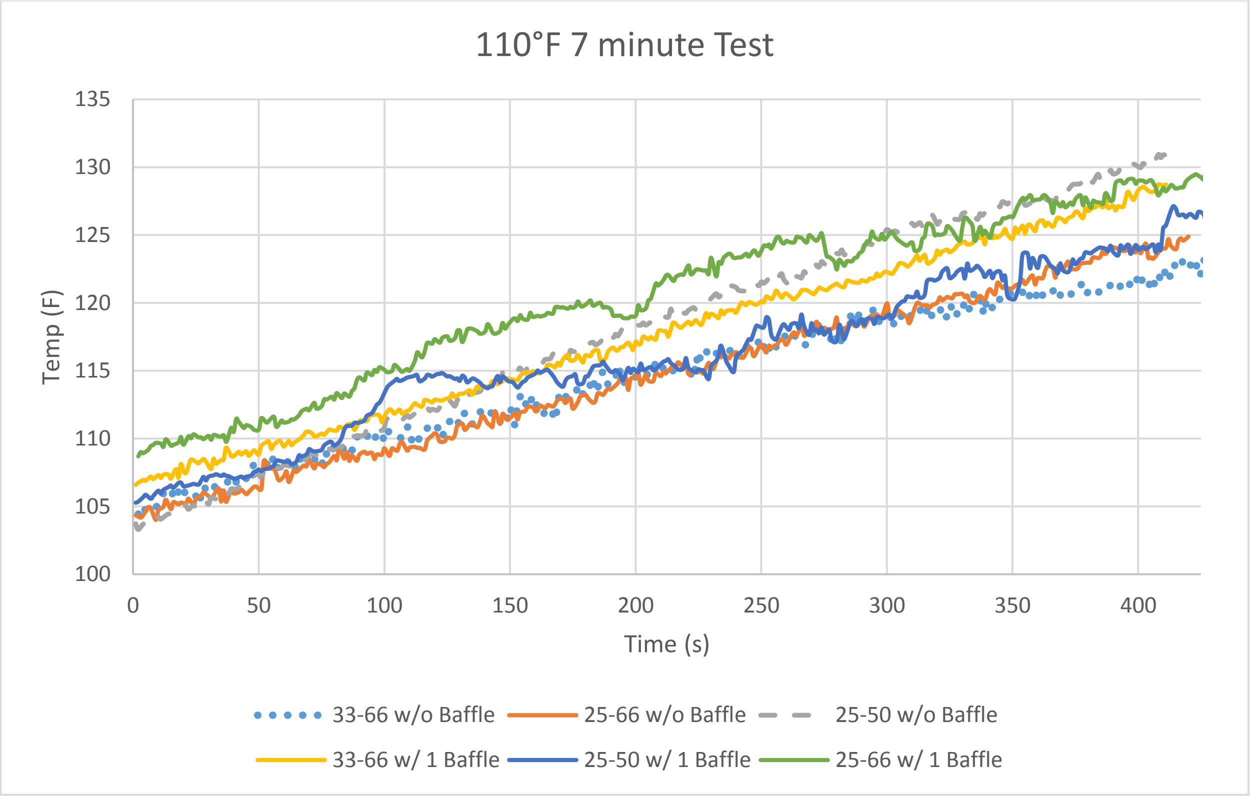


Figure 19: Data collected when system reaches around 110 °F.

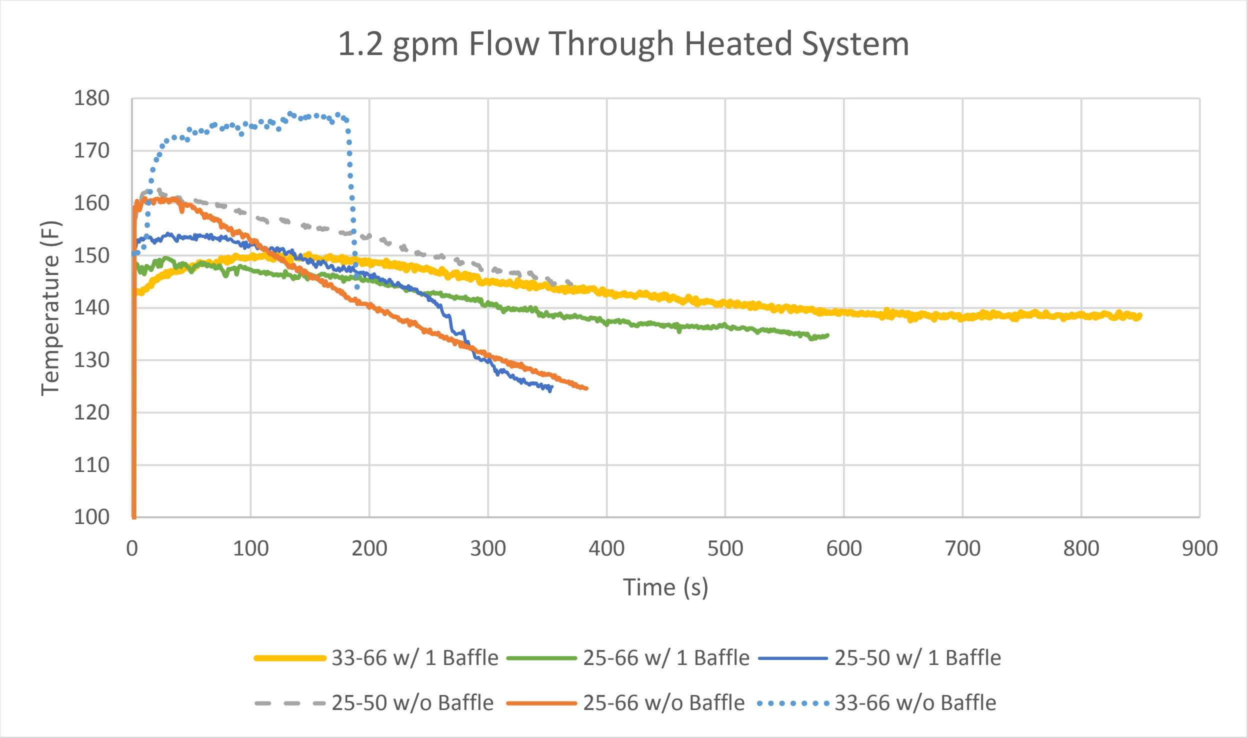


Figure 20: System around 150 with 1.2 gpm flow through the system.

Figure 20 shows six tests where the starting temperature is around 150 °F. The test was run to show how long the system would last at a given temperature with cold water inputted through the bottom at its maximum flow rate. The numerical values for each label of the legend correspond to the percentages of the tank from the bottom of where the I/O of the heat exchanger. This graph shows that the baffle system works better than not having a baffle based off the general slope of each graph as it starts to decrease.

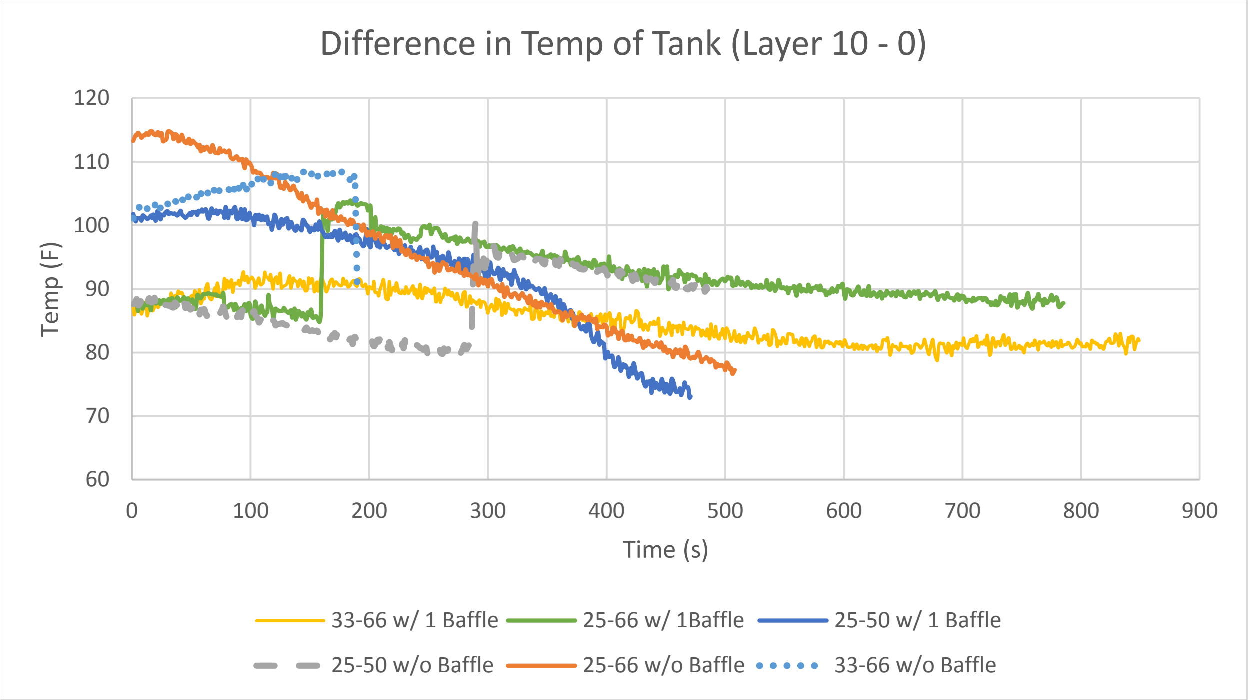


Figure 21: The range of temperature in the tank from top to bottom.

Figure 21 shows the difference in temperature throughout the entire tank with and without the baffles. Again, from this data, it shows that a baffle system works better than a non-baffle system. The vertical jumps on the graph is when the base layer mixes enough with the cold water coming in now at a faster rate to drop the temperature.

3.3 Final Prototype Design for Testing

The main design objective for this MQP was to create a conceptual tank design for the next round of prototyping being conducted by Yankee Scientific. Based on the computer modeling and small scale testing we conducted, a design for the tank was produced. The tank designed is cylindrical in shape with a domed top and bottom in order to mitigate high stress concentrations in the material when the tank is subjected to high pressures. This makes the tank less likely to fail and therefore safer. The tank blank is 1393.71 cubic inches in volume, or just over 6 gallons. The footprint of the tank fits within a 19x12x12 inch box. 0.125 stainless steel is used for the tank walls. The tank is made of stainless steel because it resists corrosion, is safe food applications, and is strong enough to withstand the pressure. Included in the tank design are the inlet and outlet ports, as well as ports for the heat exchanger and necessary sensors.

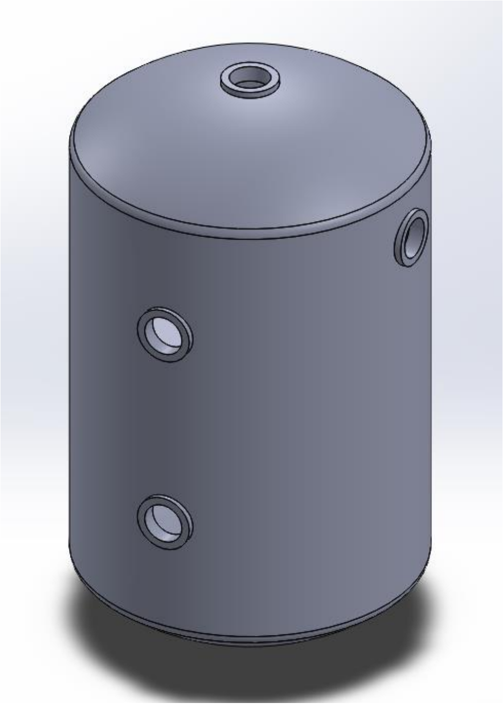


Figure 22: Tank Design.

Each port is designed to be 1.5 inches in diameter. While most connections may only be 3/4 inch in diameter, the larger ports can be sized down with an adaptor but also offer the flexibility to use larger piping and connections. Similarly, for the sensor ports, larger or more robust sensors could be inserted into the tank. Additionally, there 1.5 inch ports allow the end user to conceivably clean the inside of the tank if it ever becomes clogged or dirty. Included in our tank design is a baffle to reduce mixing within the tank.

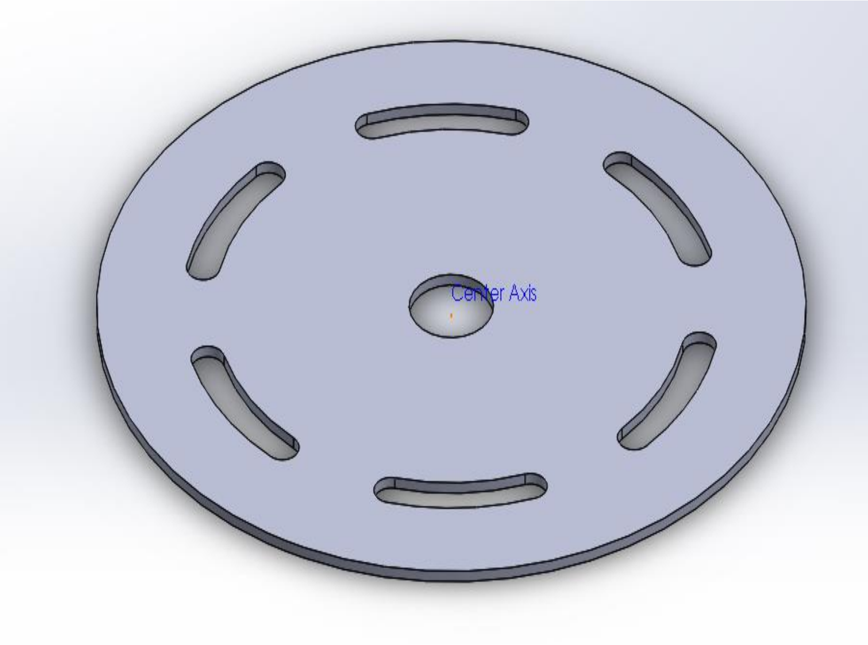


Figure 23: Baffle Design.

The baffle is designed using 0.125 sheet metal with slots and a center hole. It covers about 90% of the cross sectional area of the tank when it is installed horizontally. This means, theoretically, that there should only be 10% of the mixing across it when compared to having no baffle in the tank. A cutaway of the tank design with baffle is shown below.

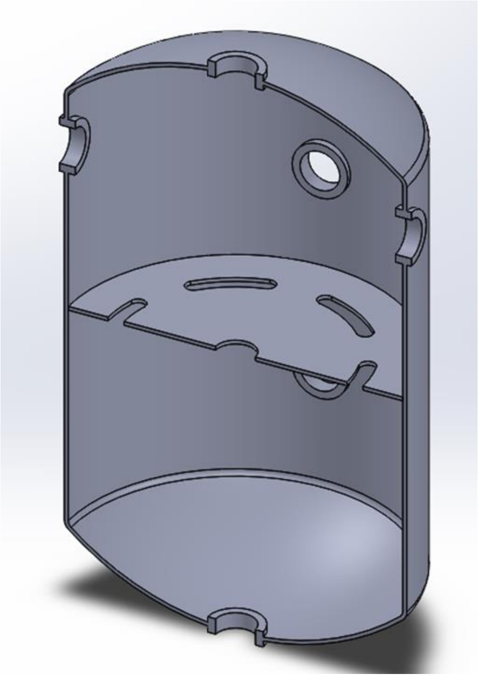


Figure 24: Cutaway View of Assembled Tank.

A primary concern of the tanks design is its ability to withstand pressure. Therefore a Finite Element Analysis (FEA) simulation was conducted using the built in DS SolidWorks 2014 simulator. The bottom ring of the cold water inlet port is considered to be fixed and all interior surfaces are subjected to a 150 PSI pressure. The Von Mises Stress analysis and Factor of Safety analysis results are shown below.

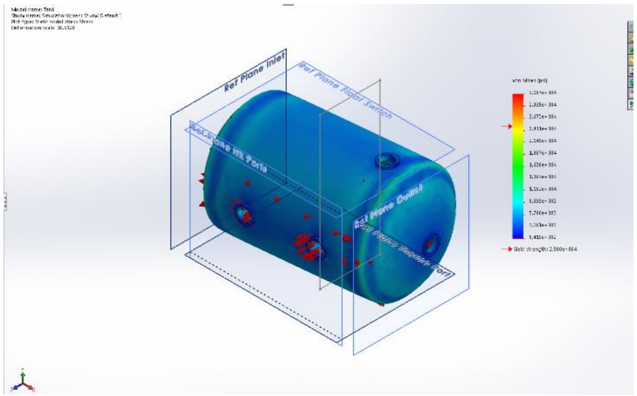
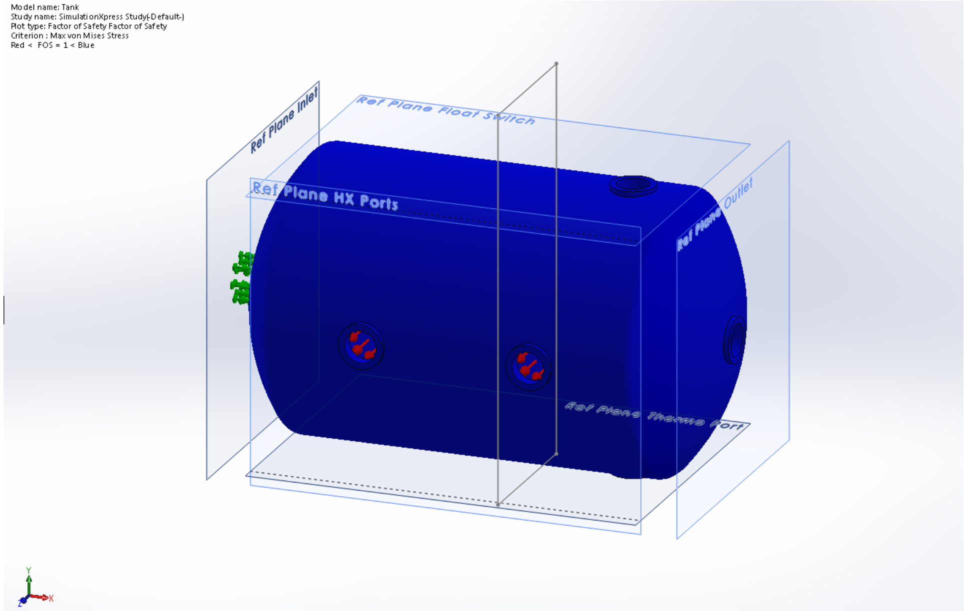


Figure 25: FEA Von Mises Stress analysis.



Model name: Tank
Study name: SimulationXpress Study(-Default-)
Plot type: Factor of Safety Factor of Safety
Criterion : Max von Mises Stress
Red < FOS = 1 < Blue

Figure 26: FEA Factor of Safety analysis.

The simulation demonstrated that the tank can safely hold the required pressure. The only remaining safety concern regarding the tank stems from the manufacturing methods. It is vital that the welds on the tank are of the highest quality so that the tank does not fail.

Chapter 4 – Prototype Development

4.1 Concept of Design

The materials required for the experiment are a five gallon aluminum stock pot, clear acrylic plate for baffle and lid, metal rod to mount thermocouples, second metal rod to hold baffles in place, rotameter to measure the cold tap, heat resistant tubing, circulating pump, copper piping for dip tubes, heat exchanger, Carlin burner and kerosene fuel, venting ducts for the exhaust from kerosene burner, data acquisition box and computer to collect thermocouple values

The general experiment procedure:

1. System assembled for Experimentation
    a. Cut Acrylic sheet for baffle to have half inch of clearance from the interior of the tank. Holes drilled for dip tubes and baffle
    b. Copper piping taped together for dip tubes
    c. Thermocouples located at cold input, input and output of heat loop, output of tank, temperature of hot water tank, and ambient temperature
    d. Assemble Carlin Burner with heat exchanger and vents
2. Fill the bucket with cold water at a consistent rate using cold tap, measure flow rate from roller meter in line with the cold tap.
3. Start the circulation pump to pull water from the tank and push it through the heat exchanger.
4. Record data as the burner is ignited to increase the temperature of the cold water in the bucket. Heat the tank to 140 ^{o}F.
5. Input cold water at 1 gallon per minute to displace hot water off the top, increase to 1.5 gallons per minute as temperatures drops to 105 ^{o}F.
6. Stop the cold tap until the tank returns to 140 ^{o}F exiting tank
7. Start draw of 1 gallon per minute for three minutes. Stop the cold water input and continue the heating loop until the system reaches 180 ^{o}F.
8. Repeat Procedure for consistency and change parameters as necessary.

The system schematic is shown below in Figure 27. The black arrow show the dip tubes following into the bottom.

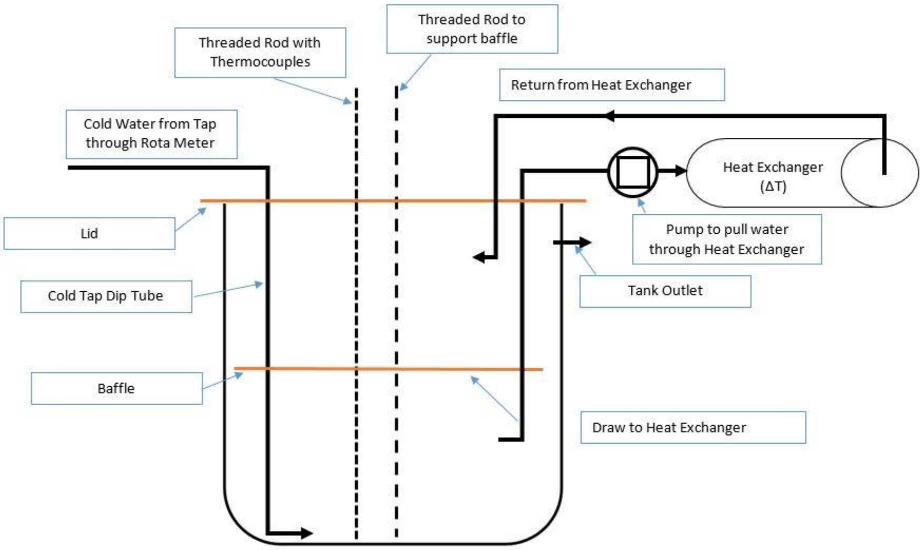
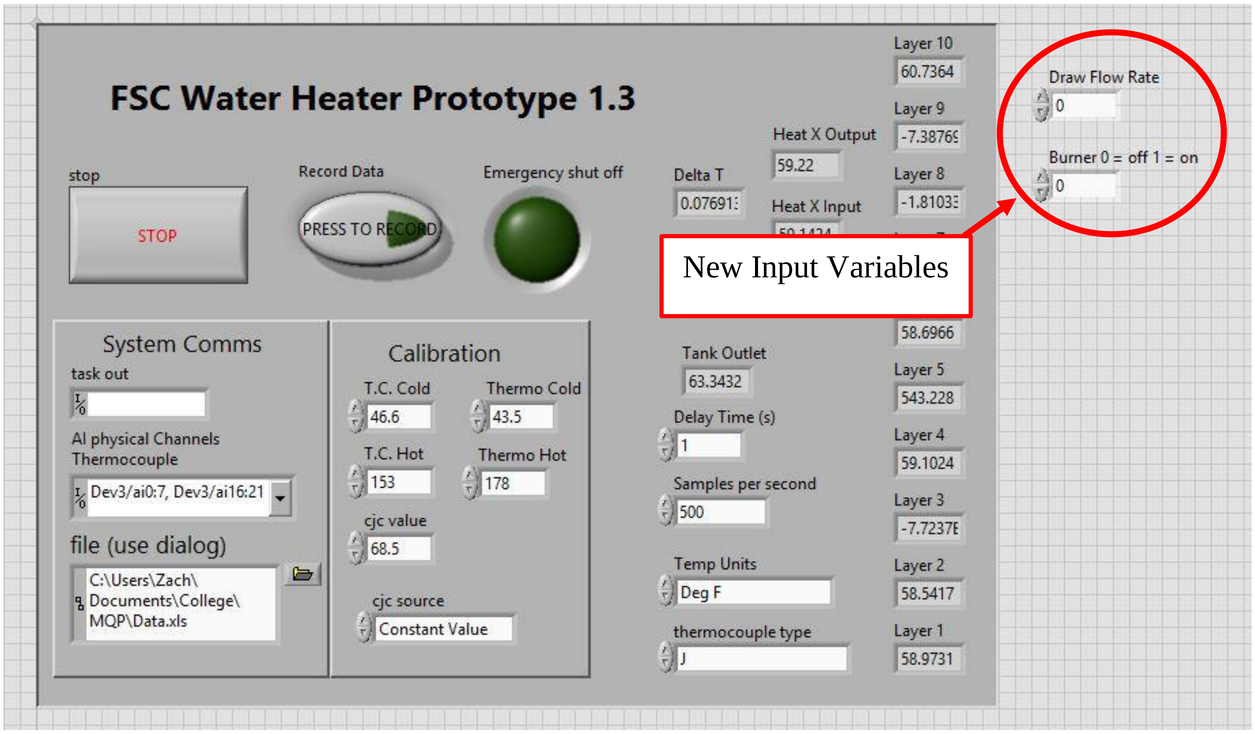


Figure 27: Final Testing Design.

4.2 Data Acquisition Method

For this testing we were able to use the LabVIEW program from the previous testing. However during this testing, we realized that we would need to record the changing variables throughout the test. The rotameter allows for different measurable flow rates through the system. The burner can be shut off and turned back on easily to replicate how it will be used in the final water heater. Instead of sitting with a clipboard in hand to write down the changes at given times, we ensured that the variable changes were captured real-time by adding input variables to the array. In Figure 28 these new variables are highlighted. With every iteration of the loop that collects the data, we now know without doubt if the burner is on or off and what the draw is on the system.


FSC Water Heater Prototype 1.3

stop: STOP
Record Data: PRESS TO RECORD
Emergency shut off
Delta T: 0.07691
Heat X Output: 59.22
Heat X Input
Layer 10: 60.7364
Layer 9: -7.3876
Layer 8: -1.8103
58.6966
Layer 5: 543.228
Layer 4: 59.1024
Layer 3: -7.7237
Layer 2: 58.5417
Layer 1: 58.9731
Draw Flow Rate: 0
Burner 0 = off 1 = on: 0

New Input Variables

System Comms
task out:
AI physical Channels Thermocouple: Dev3/ai0:7, Dev3/ai16:21
file (use dialog): C:\Users\Zach\Documents\College\MQP\Data.xls

Calibration
T.C. Cold: 46.6
Thermo Cold: 43.5
T.C. Hot: 153
Thermo Hot: 178
cjc value: 68.5
cjc source: Constant Value

Tank Outlet: 63.3432
Delay Time (s): 1
Samples per second: 500
Temp Units: Deg F
thermocouple type: J

Figure 28: Final Testing LabVIEW Front Panel.

4.3 Scheduled Tests

After looking at the data collected from the preliminary testing, we had an understanding of the system at different points. But to replicate the actual use of the tank we had to collect data on how the system responded to changes. How fast does the water temperature drop when the burner is turned off? What flow rate can this system maintain at a given temperature? What is the maximum flow rate for this system without overflow off the top?

Additionally, to understand the flow within the tank we will take advantage of the clear acrylic lid and baffle and observe ink flowing through the system. Inserting a couple ink drops through the cold tap dip tube will allow us to see its path through the tank.

Chapter 5 – Results and Discussion

5.1 Physical design

The second experimental prototype built for this project was made to more rigorously test the effectiveness of the baffle in the tank and. It consisted of a nearly full scale tank (~5 gallons) as well as the burner and heat exchanger used in the original prototype. The testing is mostly the same as the previous experiment, however there is a difference in the scale and intensity of the testing. This second prototype is much more refined than the first one. The only major inconsistency this second prototype has with the real prototype Yankee made was the pump we used for the system. It was rated at 4 gpm, however when the change in temperature over the heat exchanger was measured and compared to the amount heat energy input water (thermal efficiency is known within a range), we were able to determine that it was operating at between 2.75 and 3 gpm. While this is not the ideal flow rate, there is something to be said for using the resources available to you.

The water tank constructed for this experiment was built with an aluminum stock pot with a capacity of 5 gallons. This capacity is very close to the final capacity of the tank. One key difference in this design when compared to the first is that it utilizes 'dip tubes' that come into the tank from the top to serve as all the plumbing into and out of the tank save for the hot water outlet drilled through the side at the top, seen in Figure 29.

Figure 29: Completed Tank Assembly.

All the plumbing within the tank was with 1/2 inch copper piping. Bulkhead fittings were used on the clear acrylic cover that allow the pipe outlets to be fixed at a given height within the tank. Flexible and sturdy rubber tubing is connected to the piping to plumb the rest of the system. The original thermocouple rod from the first experiment was recycled for this experiment, although since the stockpot is shorter and more rotund than the 5 gallon Home Depot bucket, only 8 of the thermocouples are submerged when the system is running. This was determined to still offer a sufficient number of different layers to read temperature distribution within the tank. The thermocouple rod it offset from the center of the tank by a few inches because it not used to structurally support the baffle and retain the lid. There is another identically threaded rod located in the center of the tank that is used to hang the baffle and is attached to the lid while touching the bottom of the tank.

Figure 30: Baffle Assembly.

The baffle and the lid are cut from a sheet of clear acrylic plastic. The lid was deliberately cut to be oversized so that it will cover the entire tank even with a lot of slop in the system. The baffle was cut in such a way that it had a 1/4 inch gap between the edge of the tank and edge of the baffle. Flow of water within the tank across the baffle is limited to this area and the hole where the thermocouple rod passes through. Holes for the center rod, interior plumbing and thermocouple rod were drilled into each as required, shown in Figure 30.

Again in this experiment hot water drawn from the system was forced off the top by injecting cold water into the bottom of the tank. The water was supplied by a garden hose connected to a rotameter to measure flow rate, it is shown in Figure 31.

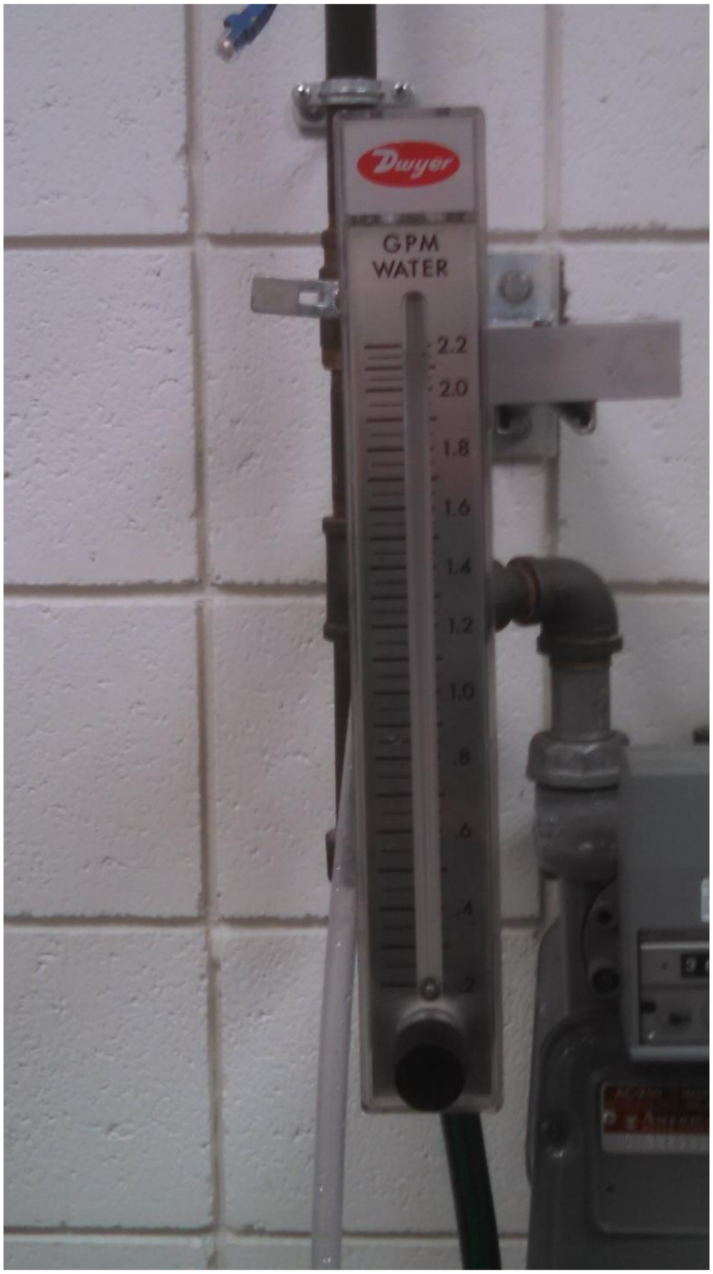


Figure 31: Rotameter in line with cold water tap.

The rotameter had a 2.5 gpm capacity which was sufficient to facilitate our testing but small enough to provide accurate measurements. The rotameter was plumbed into the system with Tygon tubing. A complex valve system was included to allow water to flow directly through the pump loop from the tap. This was added after an initial trial because it was found to be nearly impossible to purge the pump loop of air unless tap water was sent through it before the pump was started.

The heat exchanger was mounted horizontally on a workbench with the Carlin burner firing into it. The opposite end of the heat exchanger was connected to an exhaust duct. Fitting on the heat exchanger were copper that allowed a surface to attach thermocouples and connect to the rubber tubing of the rest of the system.

Once the system was assembled we tried to start the pump. But there was air in the system. It was difficult to determine where in the system the air was located. With the heat exchanger mounted horizontally, there are multiple points in the coil that air could be trapped. Through rearranging the “not-so-quick” quick release couplings we were able to push water through the system from the tap water backwards through the heat exchanger. This forced all the air-bubbles out of the system.

This worked, but with multiple days of testing ahead, we developed a system of three ball valves to redirect the water backwards through the heat exchanger to purge the system of all air. Figure 32 shows a schematic of the normal flow of the system with ball valves in place. The Figure 33 shows the ball valves in backflow position moving the water through the heat exchanger.

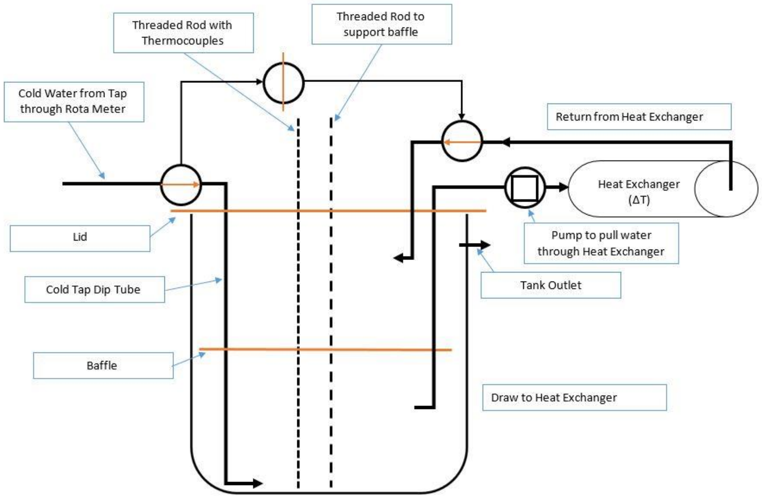


Figure 32: Normal Flow with Ball Valves.

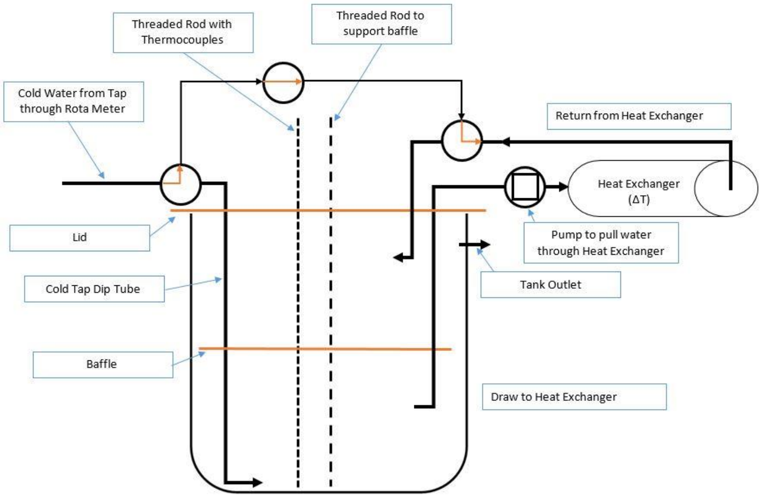


Figure 33: Backflow of system using Ball Valves.

The final system was not pretty as illustrated in Figure 34, but it successfully purged the system of all air bubbles. The quick connect couplings were able to direct the water flow correctly.

Figure 34: Completed system with Ball Valves.

We used the threaded rod with thermocouples from the preliminary testing, however with a tank with new dimensions, only eight of the thermocouples were submerged in the water. Also on different tests, the hot water output thermocouple proved to be difficult to mount, which produced skewed results. However, the eighth thermocouple on the rod was very close to the tank outlet and its temperature is used at times to compare results.

5.2 Objectives

The first testing that we completed was a baseline view on how the system performed while turning on and off the burner and changing the flow rate. We started with no flow rate, and heated the water to ~140 ^{o}F. At this point the burner was left on, and a flow rate was added at 1.0 gpm. After four minutes at this flow rate, it is increased to 1.5 gpm for three minutes. The burner is turned off, and the flow rate is dropped back to 0.0 gpm to allow the tank to mix. The burner is turned back on to bring the temperature back to ~140 ^{o}F. At this time the flow rate is increased to 1.0 gpm for three minutes. The flow rate is dropped to 0.0 gpm, and the temperature of the heat exchanger return is brought up to 180 ^{o}F. At this time the test is complete and cooled. This was conducted first with a baffle, and then replicated without a baffle.

To prepare the data it is shown time-averaged across each constant state. Every line under “DRAW (gpm)” or “BURNER” on Figures 37-42 represents a stop and start point for the averaging. Also thermocouples 1-4 are averaged as well as thermocouples 5-8. This shows an even representation below and above the baffle. This method was consistently applied to all test results to give consistency and ease of view regardless if the test used a baffle or not.

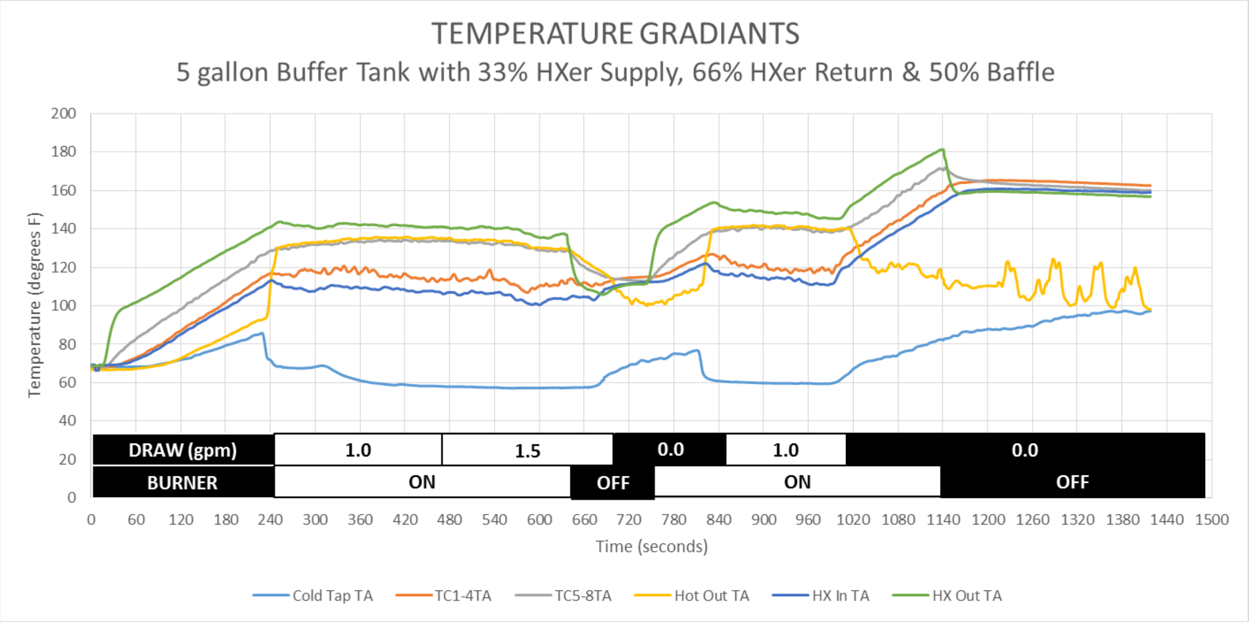


Figure 35: Test with Baffle.

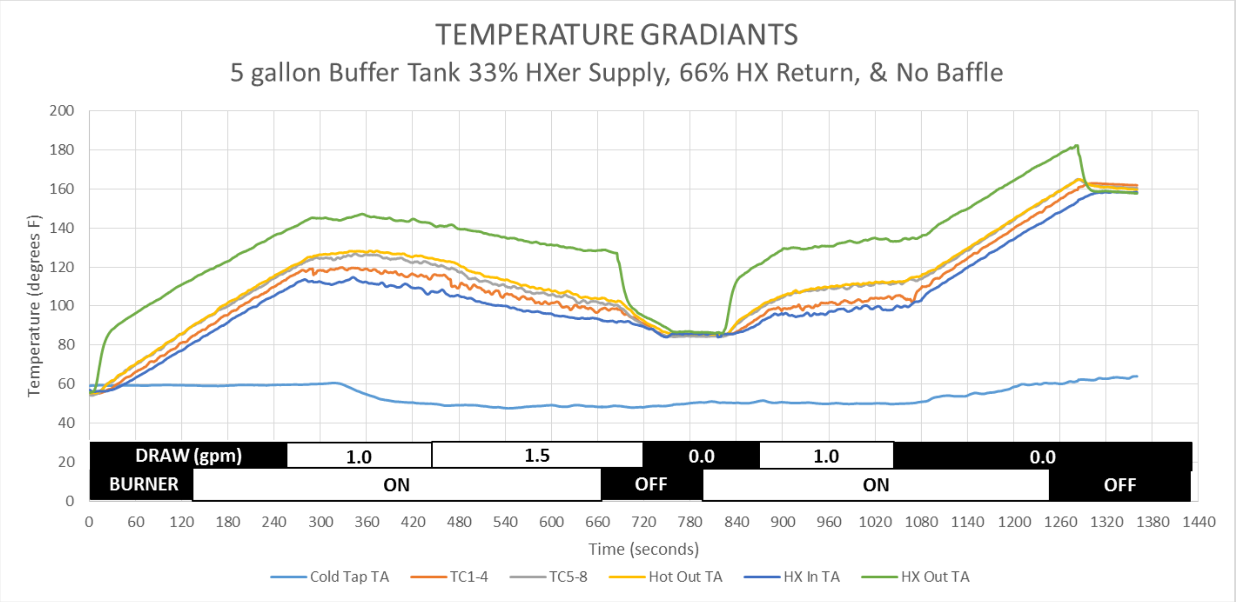


Figure 36: Test without Baffle.

To compare these graphs we took the TC5-8 data and divided it up through each state. It divides the test into linear segments than can be analyzed to see the slope of the lines from an overlaid linear trend line populated by Microsoft Excel. During the initial heating there is minimal difference between the slopes. Looking at Figure 36, the difference in slope is minimal. When there is no flow rate through the system it acts as if there is no baffle. This is also seen based off the difference in temperature between the layers inside the tank. In Figures 35 and 36.

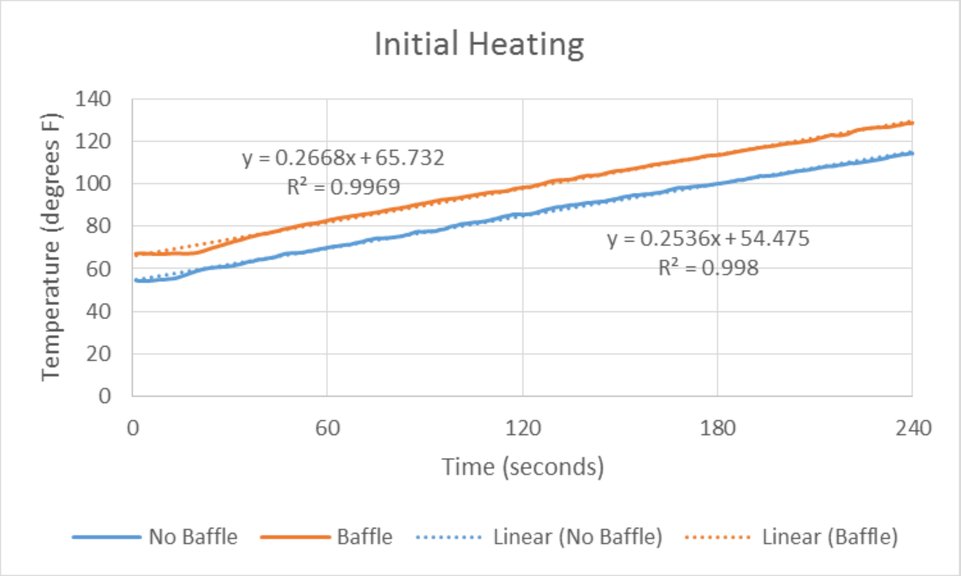


Figure 37: Initial Heating from Cold.

At this point the baffle helps sustain the flow rate showing the temperature slightly increasing while the system without a baffle begins decreasing at this point.

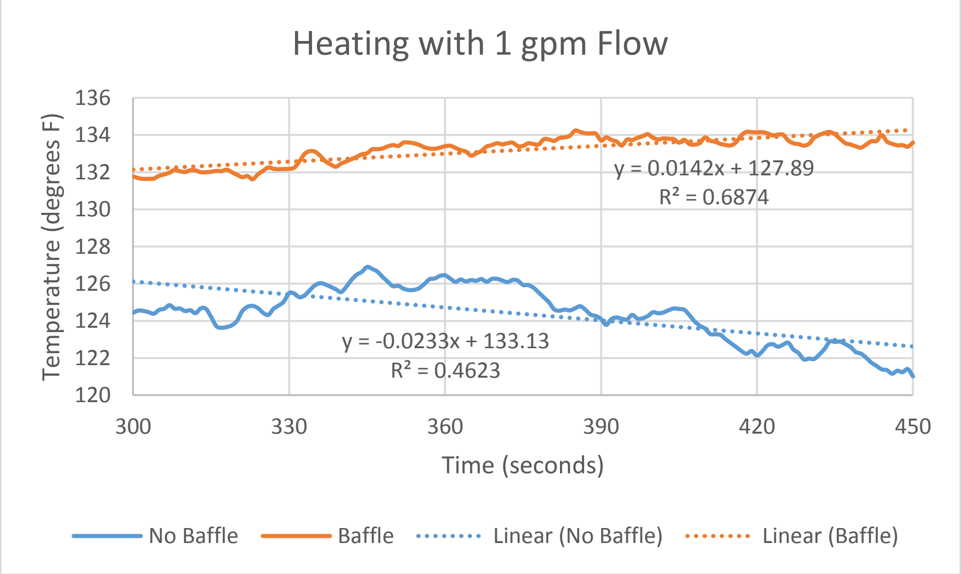


Figure 38: One gallon per minute Flow Rate.

Increasing the flow rate to 1.5 gpm shows that while the baffle decreases in temperature, no baffle decreases at a steeper rate.

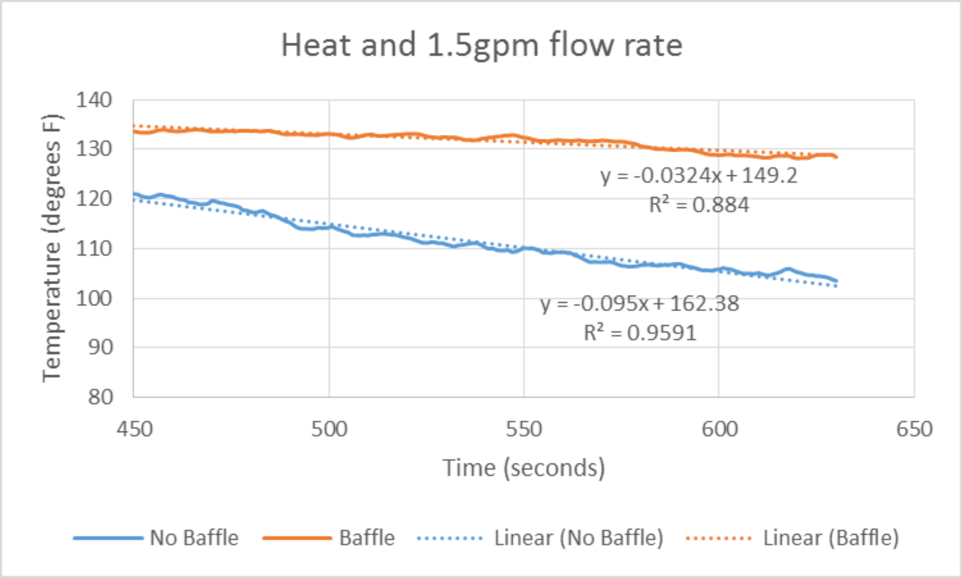


Figure 39: 1.5 gpm flow with Burner On.

When there is no heat in the system it acts similar to no flow, where the baffle does not affect the change of temperature. The times are adjusted for each section because the times did not line up later in the test. But the variables are equal.

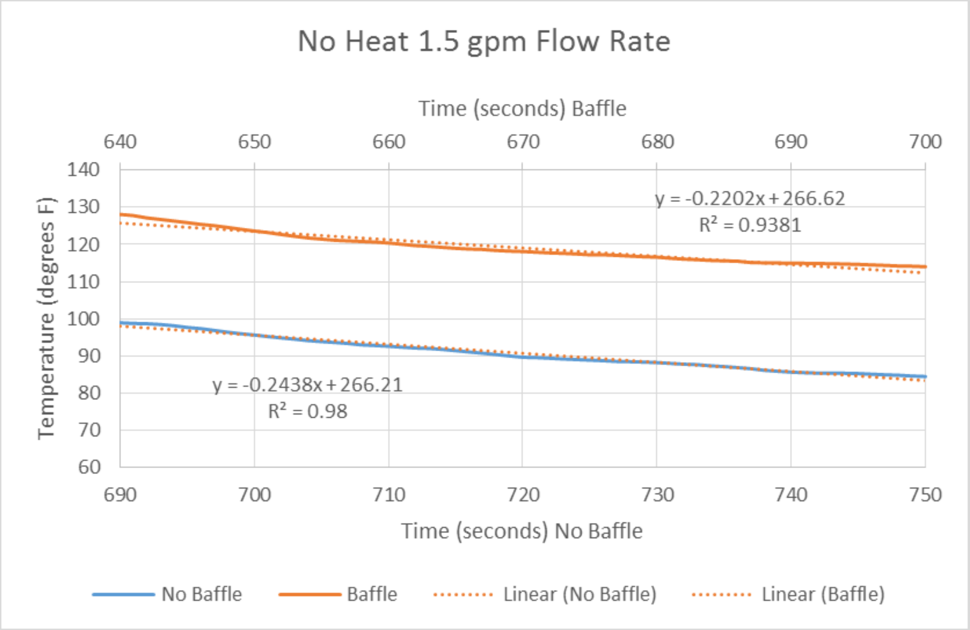


Figure 40: 1.5 gpm Flow Rate with No Heat.

The rest of the sections show little or no difference in the slope between the states.

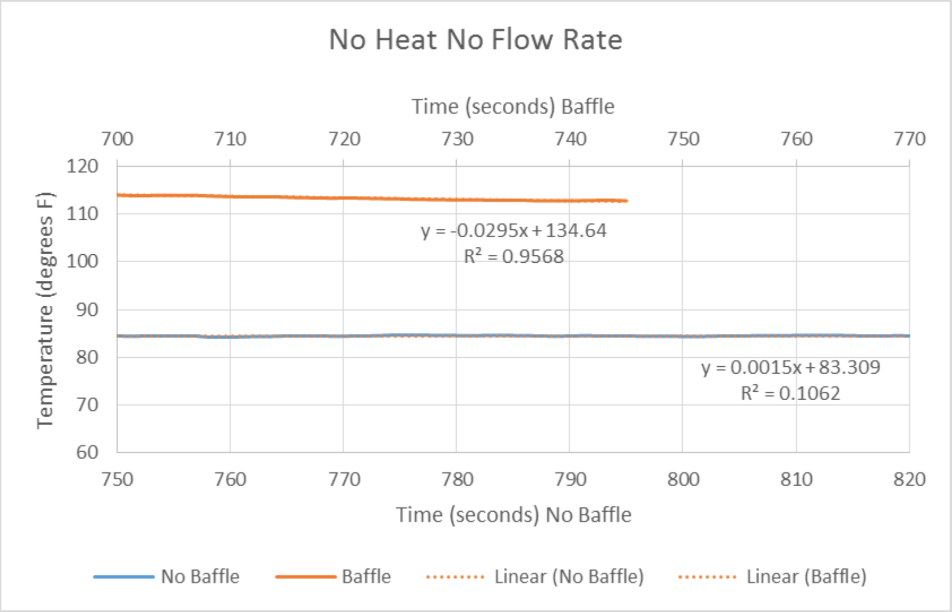


Figure 41: Mixing of Tank.

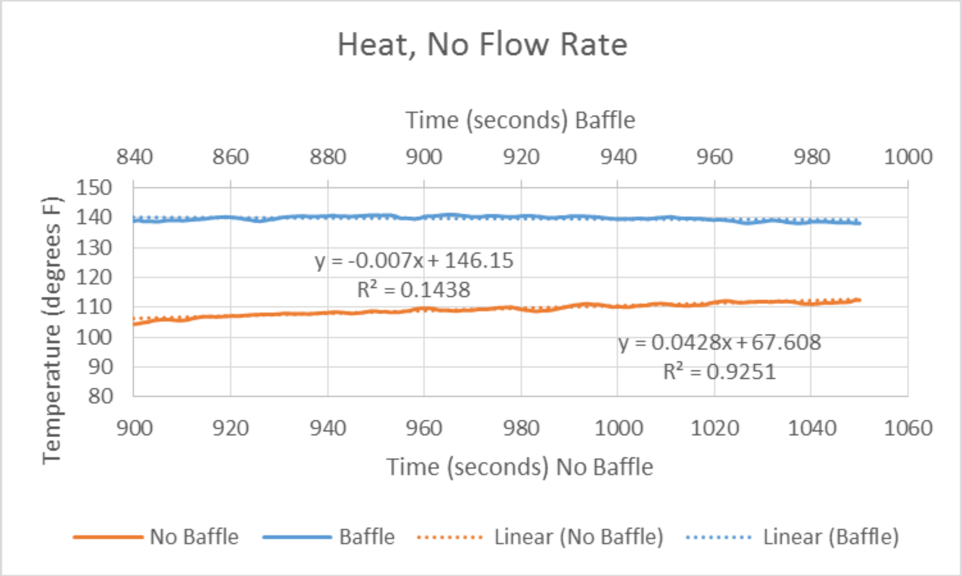


Figure 42: Heating with No Flow Rate.

Chapter 6 – Conclusions

The testing of the proof-of-concept prototype demonstrated that our tank design will work well in the next prototype that is delivered by Yankee Scientific to the US Army. The tank design this MQP team has proposed will function in the desired manner.

Both the prototypes that we tested demonstrated that a baffle designed into the tank allows the tank and water heater system to provide a significant amount of hot water for longer than a single tank without a baffle. The mixing of the cold water entering the bottom of the tank with hot water on the top is significantly reduced by the inclusion of the baffle in the tank. This kind of design does not, however, hinder the ability of the system to heat the tank quickly or prevent it from mixing together to provide a uniform temperature where the draw is removed from the system but the heating loop is kept on. The baffled, single tank design also greatly simplifies the overall design of the water heater system while acting in much the same way as the older two-tank unit when water is being drawn from the tank.

This one-tank design will be used in the next prototype delivered for evaluation by the Natick Army Labs. Yankee's self-contained water heater will give the Army an efficient and effective option to provide hot water to be used in their Food Sanitization Centers attached to field kitchen units. The water heater can also be used throughout the kitchen for cooking and drink preparation. It could also be adapted for a variety of applications for military units deployed in the field.

Chapter 7 – Recommendations

Since the full scale prototype was shown to operate at or above the required levels it is recommended that the second prototype delivered to US Army by Yankee Scientific should include a single tank design with baffle. The tank and baffle design will allow Yankee to deliver a simplified water heater design while still ensuring it performs as required. The tank for the next prototype should be custom built since it will be produced on a very limited scale. While custom build items are generally more expensive than stock items, it is important that Yankee receives the tank they need in a timely manner and built as it is designed. The very limited number that will be purchased allows the company to afford to use a custom tank.

If the Army decides to enter serial production of the water heater designed by Yankee, there are some design refinements to be made to the system. The whole water heater has to be tweaked in order make it easier to produce on a larger scale. It would be advisable to search for an existing tank that can be adapted for application in this water heater. If a suitable tank can found and modified to include a baffle it could potentially be much cheaper than a custom made tank. This would allow Yankee to produce the water heaters at a lower cost, which in turns means a higher profit margin and a less expensive product for the US Army.

Add reference here Then appendix.

Appendix A – MATLAB Code

PARAMETER FILE:

```
% Reading Input Information File
[fname,pname] = uigetfile('*.txt','Please select the Input Parameter file');

if (fname ~= 0)
  filename = sprintf('%s%s',pname,fname);
else
  disp('No file selected...Program will quit');
  return;
end

fid1 = fopen(filename,'r'); %# open csv file for reading

info = ones(1,22);
i = 1;

while ~feof(fid1)
  line = fgets(fid1); %# read line by line

      [token, remain] = strtok(line);
      info(i) = str2double(token);
      i = i + 1;

 end

%disp(info)
fclose(fid1);

[tankTemp,callHcycle] = Range(info);

%tankTemp

%callHcycle
```

PUMP22:

```
% Layers sets the number of layers.  ground sets ground water temp. Tank to
% circ sets the layer at which water leaves the tank to the heat exchanger.
% circ to tank assigns the layer at which the heated water is returned to
% the tank.  ground to tank sets the layer at which cold water is drawn
% into the tank.  the hot set point is the maximum temperature the water
```

```
% can be heated to.  the circ increase is the temp change of the water from
% the heat exchanger.  SansT and SansV represent the temperature and volume
% of the make up water required by the sanitization sink.  Rinse and wash
% follow suit.
function [tankTemp,callHcycle,stopwatch] = pump22(passed)
layers = passed(1);
ground = passed(2);
tankToCirc = max(1,int32(layers*passed(3)+.5));
circToTank = min(layers,int32(layers*passed(4)+.5));
groundToTank = max(1,int32(layers*passed(5)+.5));
hotOut = min(layers,int32(layers*passed(6)+.5));
hotSetPoint = passed(7);
circIncrease = passed(8);
sansV = passed(9);
sansT = passed(10);
rinseV = passed(11);
rinseT = passed(12);
washV = passed(13);
washT = passed(14);
gPM = passed(15);
cycleTime = passed(16);
tankSize = passed(17);
time = passed(18);
flowRate = passed(19);

if (sansV + rinseV + washV) == 0
    sansV = flowRate / 3;
    washV = flowRate / 3;
    rinseV = flowRate / 3;
else
    flowRate = 0;
end

layerSize = tankSize/layers;
cycleTime = layerSize / gPM;
flowPerCycle = (cycleTime*gPM);



% Creates a matrix vector of ground temperature water with the assigned # of
% layers


tankTemp = hotSetPoint * ones(layers,1);

%stopwatch is 1 iteration of the system, which is a closed loop of 5
%gallons per minute heated through circIncrease
stopwatch = 0;

% The while loop below carries out the mixing process of the layers of
```

```
% water in the main tank (using simple averages) and continues the process
% as hot water is pumped in from the circ. When the stopwatch goes to a
% certain point or the tank reaches a specific average temperature, the
% loop terminates.  No layer within the tank shall exceed the hot set point

while stopwatch < time


    %Ratio Hot Rinse
    RHrins = (rinseT - ground) / (tankTemp(hotOut) - ground);
    %Ratio Cold Rinse
    RCrins = 1 - RHrins;

    %Call Hot Rinse
    callHrins = rinseV * RHrins;
    %Call Cold Rinse
    callCrins = rinseV * RCrins;

    RHsans = (sansT - ground) / (tankTemp(hotOut) - ground);
    RCsans = 1 - RHsans;

    callHsans = sansV * RHsans;
    callCsans = sansV * RCsans;


    RHwash = (washT - ground) / (tankTemp(hotOut) - ground);
    RCwash = 1 - RHwash;

    callHwash = washV * RHwash;
    callCwash = washV * RCwash;

    %total call of Hot water through hotOut
    callH = callHrins + callHsans + callHwash;
    %total call of Cold water through ground
    callC = callCrins + callCsans + callCwash;

    callHcycle = callH * cycleTime;
    callCcycle = callC * cycleTime;


    % The layer which is being pumped with hot water

    if flowPerCycle > layerSize;

        m = int32(circToTank + (flowPerCycle / layerSize)/2);
        k = max(1, (circToTank - m));

        %pure displacement of water, no mixing occurs.
        tankTemp(k:m) = min(hotSetPoint,(tankTemp(tankToCirc) + circIncrease));
```

```
        %averages groundToTank with ground water
    else
        tankTemp(circToTank) = min(hotSetPoint, ((flowPerCycle * (tankTemp(tankToCirc)
+ circIncrease) + ((layerSize - flowPerCycle)*tankTemp(circToTank)))/layerSize));
    end

    %averages layers in tank
    for i = 1:layers

        if (1 < i && i < layers)
            tankTemp(i) = (tankTemp(i) + tankTemp(i-1) + tankTemp(i+1)) / 3;
        else
            if i == 1
                tankTemp(1) = (tankTemp(1) + tankTemp(2)) / 2;
            else
                tankTemp(layers) = (tankTemp(layers) + tankTemp(layers-1))/2;
            end
        end






    end

    %mixing or displacement with groundToTank layer, depending on the
    %amount called through callHcycle

    if callHcycle > layerSize;

        n = int32(groundToTank + (callHcycle / layerSize)/2);
        l = int32(max(1, (groundToTank - n)));

        %pure displacement of water, no mixing occurs.
        tankTemp(l:n) = (ground);

        %averages groundToTank with ground water
    else
        tankTemp(groundToTank) = ((callHcycle*ground) +
(tankTemp(groundToTank)*(layerSize - callHcycle))) / layerSize;
    end


    % Limits the maximum temperature of any layer to the hot set point
    for k = 1:layers
        tankTemp(k) = min(tankTemp(k),(hotSetPoint));
    end

    %adds cycle time to stopwatch
    stopwatch = stopwatch + cycleTime;
```

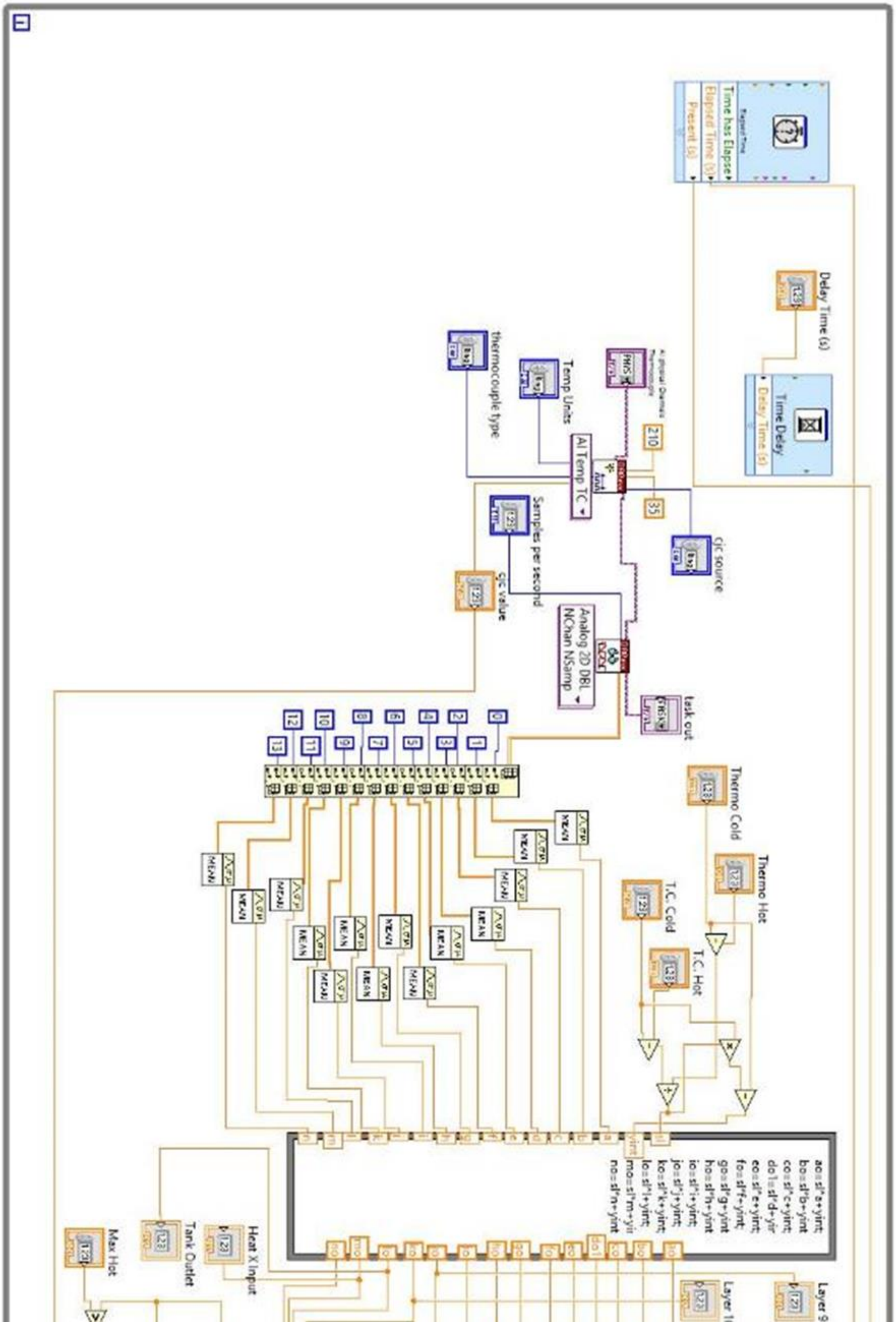
```
    % displays temperature of the layers in the tank, hot water demand and
    %disp(tankTemp)
    %disp(callHcycle)
    %disp(stopwatch)


    %shuts off system if tank temp drops too much
    if tankTemp(hotOut) < sansT
        return
    end

end
```

RANGE:

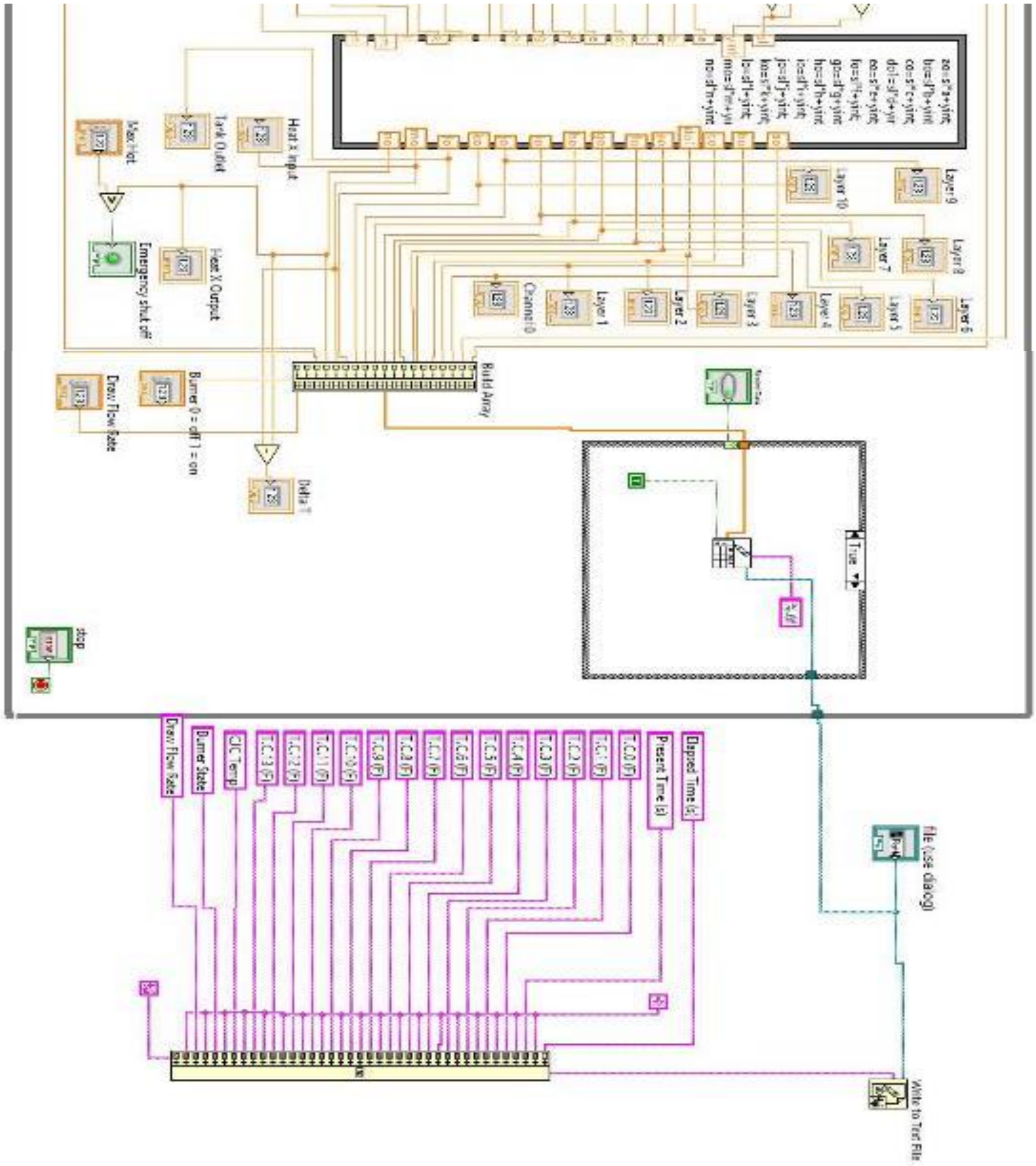
```
%This document calls pump22 and creates horizontal histograms based off the
information,
%changing the demand throughout the document.

%callH needs to be brought into range and edited for every iteration
%Use 'histogram' to display results. change Orientation to Horizontal
%Time is set to 180 minutes (3 hours) for all events
%hotSetPoint always going to be 190 deg F

function [tankTemp,callHcycle] = Range(infoset)
flowRate = infoset(19);
increment = infoset(20);
iterations = infoset(21);

demand = ones(1,iterations);

sw = ones(1,iterations);

for i = 1:iterations
    [tankTemp,callHcycle,stopwatch] = pump22(infoset);
    demand(i) = infoset(19);
    infoset(19) = infoset(19) + increment;


    %info(1,19) = demand(i);


    %if tankTemp(infoset(6)) < infoset(10)
        %break
     sw(i) = stopwatch;
    %end
end
```

```
    plot(sw,demand);
    %histogram((i,2,demand)
```

Appendix B – LabVIEW Program



```
ao=sl*a+yint;
bo=sl*b+yint;
co=sl*c+yint;
do1=sl*d+yir
eo=sl*e+yint;
fo=sl*f+yint;
go=sl*g+yint
ho=sl*h+yint
io=sl*i+yint;
jo=sl*j+yint;
ko=sl*k+yint;
lo=sl*l+yint;
mo=sl*m+yi
no=sl*n+yint
```



ao=s*a+yint
bo=sl*b+yint
co=s*c+yint
do1=sl*d+yi
eo=s*e+yint
fo=s*f+yint
go=sl*g+yint
ho=sl*h+yint
io=sl*i+yint
jo=sl*j+yint
ko=s*k+yint
lo=sl*l+yint
mo=sl*m+yi
no=sl*n+yint
Max Hot
Tank Outlet
Heat x input
Heat X Output
Emergency shut off
Channel 0
Layer 1
Layer 2
Layer 3
Layer 4
Layer 5
Layer 6
Layer 7
Layer 8
Layer 9
Layer 10
Build Array
Draw Flow Rate
Burner 0 = off 1 = on
Delta T
stop
True
Draw Flow Rate
Burner State
CJC Temp
T.C.13 (F)
T.C.12 (F)
T.C.11 (F)
T.C.10 (F)
T.C.9 (F)
T.C.8 (F)
T.C.7 (F)
T.C.6 (F)
T.C.5 (F)
T.C.4 (F)
T.C.3 (F)
T.C.2 (F)
T.C.1 (F)
T.C.0 (F)
Present Time (s)
Elapsed Time (s)
file (use dialog)
Write to Text File

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