Waste Heat Reclamation for Commercial Use

A Senior Project
Presented to
The Faculty of the Liberal Arts and Engineering Studies
California Polytechnic State University, San Luis Obispo

In Partial Fulfillment
of the Requirements for the Degree
Bachelor of Liberal Arts and Engineering Studies

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March 2014

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Introduction

We live in a society that is wasteful in the way we live and the way we conduct business. The purpose of this project is to examine and address one issue in particular to serve as an example how individuals are best suited to address the issue of waste in our everyday lives. How I chose to examine and address the issue of waste was by creating a system of efficiency. In order to create a system of efficiency, three components need to exist (Carbon Trust):

1. Waste and need should be physically close to one another.
2. Waste and need should occur simultaneously.
3. A way to connect the waste and need.

The physical goal of this project is to capture waste heat to raise the temperature of ground water for commercial use, specifically in commercial coffee shops. I chose the venue of commercial coffee shops for several reasons. First, I have extensive experience working in the coffee industry and I have first hand knowledge of how espresso machines work. This aspect illustrates the idea that individuals are best suited to examine ways to make their world more efficient and they should consider themselves experts in their own lives, both at home and in the workplace. Second, although the idea of using waste heat from refrigeration systems to heat water and air for commercial applications already exists (through desuperheating and other various methods), there is currently no technology that focuses on small businesses and caters to the specific problems that are presented with small business. I want to create a system that is low cost, fully passive and has a quick return on investment for the business owner.

Background Research and Related Work

I chose to work specifically with Dutch Bros. Coffee because I have an existing working relationship with several people (franchise owners as well as corporate staff) and Dutch Bros. Coffee has committed to looking outside the box to figure out ways to improve all aspects of business. Dutch Bros. Coffee was started in 1992 in Grants Pass, Oregon. They have established themselves as the premier customer service based drive-thru coffee business on the west coast. Dedicated to providing high customer service without sacrificing quality or speed of service (Dutch Bros Coffee). With this in mind, my project aims to get higher performance out of the espresso machine by raising the temperature of ground water before it enters the machine.

The design of an espresso machine varies from machine to machine but the basics of espresso machine are relatively similar. The broiler system (Figure 1) is a fairly simple system. The broiler itself is usually made of copper and there are heat coils inside the broiler to raise and keep the internal temperature at or around 200°F. The hot water inside the broiler is used to brew the espresso. The steam in the broiler is used to steam milk for various hot drinks. As the machine is being used, water is pumped into the broiler to maintain the optimal water level in the broiler.

As new water is introduced, the temperature in the broiler drops because the water entering the system is approximately 62°F (Approximate ground water temperature for Woodland, California) (Environmental Protection Agency).

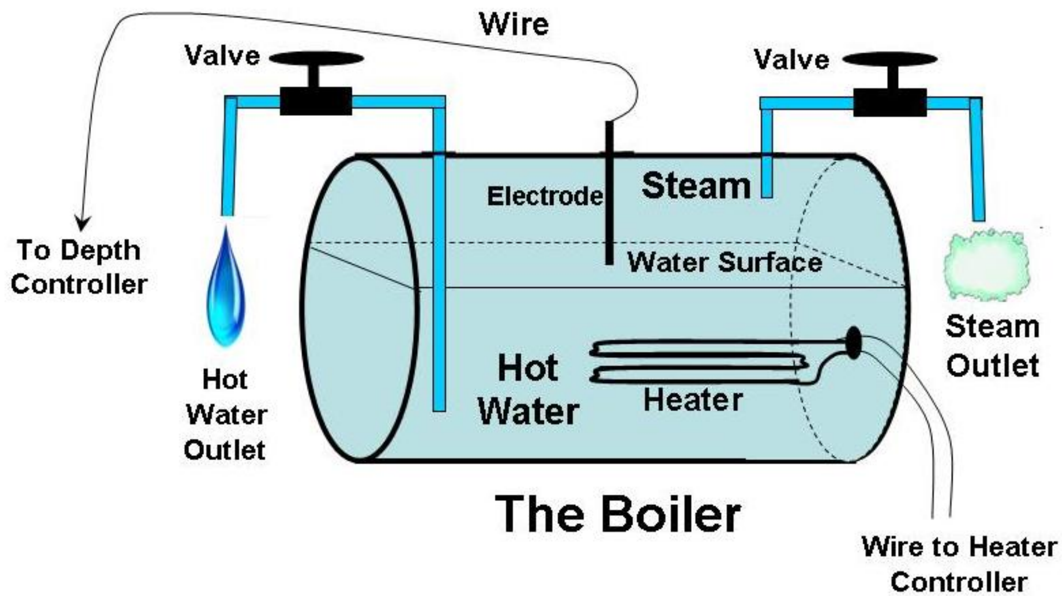

Figure 1: Simple Espresso Machine broiler Diagram
Source: http://ep.yimg.com/ty/cdn/yhst-14463325294384/The-Boiler

Some of the Dutch Bros. Coffee locations are so busy that their espresso machines can't keep up. In the past, some of these locations have installed hot water heaters to run hot water into the espresso machine in an attempt to meet demand. The temperature that was used was 120°F. This temperature was found to be problematic because the water pump inside the espresso machine was not designed to handle water of such a high temperature. Through trial and error, the desired window of 80°F-90°F was obtained. This is the highest temperature that the plastic in the water pump can handle on a regular basis and not give out.

Having established a clear need, an ideal area of waste must be identified. The most obvious area of waste heat is the refrigerator. Large walk-in refrigerators are common for coffee shops because of the need to keep large amounts of milk cold for business use. Before waste heat from refrigeration can be captured, the mechanical refrigeration process must be understood.

Mechanical refrigeration is achieved by circulating a fixed amount of refrigerant in a closed system (SWTC). At the beginning, low pressure liquid expands, absorbing heat, and evaporates, turning into a low-pressure gas at the evaporator outlet. The compressor increases the pressure of the gas as it enters the condenser. In condensing the high-pressure gas, heat is exchanged from the gas to the outside

environment and expelled as waste heat (Figure 2). After leaving the condenser the gas passes through an expansion valve, which lets the gas out at a lower rate than the compressor pushes the gas in. As the gas expands it absorbs heat from the outside. This side of the refrigeration cycle would be inside the refrigerator. The compressor and expansion valve work together to create a pressure difference that makes the refrigeration process possible.

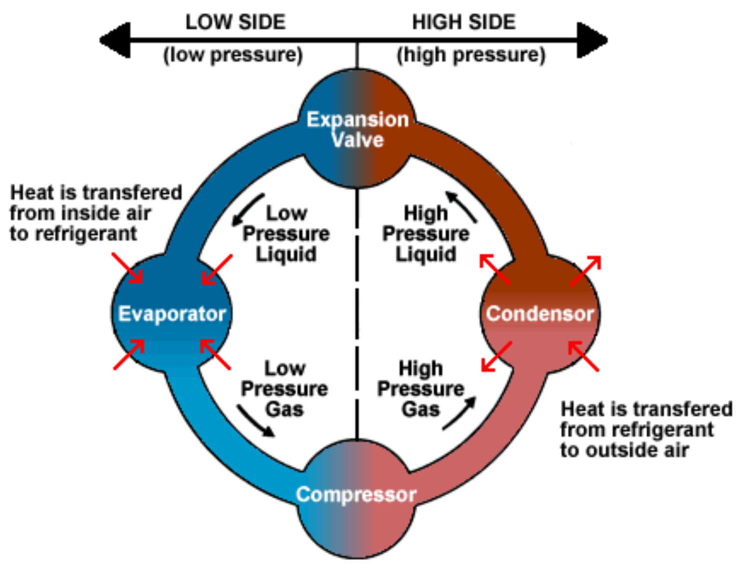

Figure 2: Refrigeration Cycle
Source: http://www.swtc.edu/ag_power/air_conditioning/lecture/basic_cycle.htm

Waste heat that is recovered in the refrigeration process is done typically in two ways. The first is by capturing only the heat needed to desuperheat the gas into a saturated state. Second, is by capturing the heat needed to desuperheat the gas and the heat needed to condense the refrigerant from a saturated vapor into a saturated liquid. These processes are known as desuperheating waste heat and full condensing waste heat. There is more heat available from full condensing waste heat, but the quality of heat available in desuperheating waste heat is much higher. This has to do with the fact that the overall average temperature of the refrigerant in full condensing waste heat is much lower than the average temperature of the refrigerant in the desuperheating of the refrigerant vapor (Fricke).

Desuperheating takes place between the compressor and the condenser. Full condensing waste heat takes place between the condenser and the expansion valve. To show that desuperheating waste heat is a better, higher quality heat, consider the following hypothetical refrigerator (Figures 3, 4, and 5).

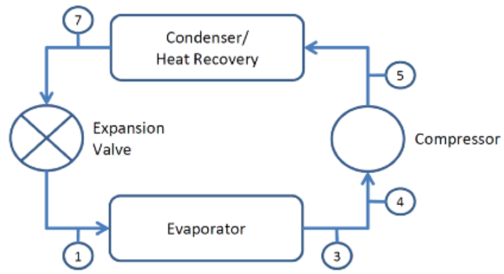

Figure 3: Refrigeration cycle II
Source: http://info.ornl.gov/sites/publications/files/pub31294.pdf

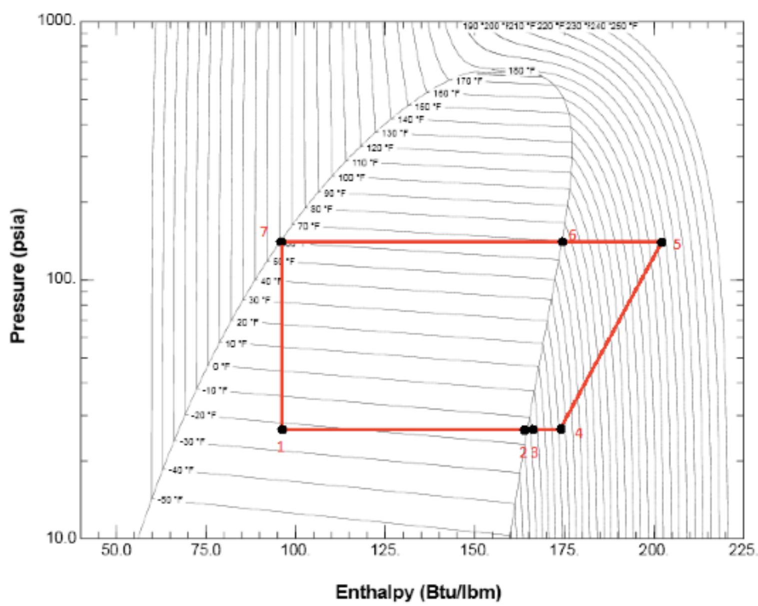

Figure 4: Pressure-Enthalpy Diagram
Source: http://info.ornl.gov/sites/publications/files/pub31294.pdf

State Point	Temperature (°F)	Pressure (psia)	Enthalpy (Btu/lb_m)	Entropy (Btu/lb_m·R)	Quality
1	−23.81	26.0	95.768	0.2643	0.29
2	−15.36	26.0	164.56	0.4206	1.00
3	−9.00	26.0	165.80	0.4234	--
4	30.00	26.0	173.39	0.4396	--
5	187.35	141	202.53	0.4559	--
6	69.17	141	174.27	0.4076	1.00
7	60.51	141	95.768	0.2580	0.00

Figure 5: Thermodynamic States for Hypothetical Refrigerator
Source: http://info.ornl.gov/sites/publications/files/pub31294.pdf

To calculate the total heat available for recovery from full condensing waste heat we will calculate the difference in enthalpy from the superheated discharged gas

leaving the compressor and the saturated liquid refrigerant leaving the condenser (using data from Figure 5):

$$q_{full\ condesing} = h_5 - h_7 = 202.53\frac{Btu}{lbm} - 95.768\frac{Btu}{lbm} = 106.76\frac{Btu}{lbm}$$

To calculate the total heat available for recovery from desuperheating waste heat we will calculate the difference in enthalpy between the superheated discharged gas leaving the compressor and the enthalpy at of the saturated gas at the condenser:

$$q_{desuperheated} = h_5 - h_6 = 202.53\frac{Btu}{lbm} - 174.27\frac{Btu}{lbm} = 28.26\frac{Btu}{lbm}$$

This shows that there is much more heat potential when using full condensing waste heat. However, the average temperature during the desuperheating stage is approximately 179°F and the average temperature during full condensing is approximately 81°F. This shows that the quality of the waste heat from desuperheating is much higher than that of full condensing waste heat.
In typical commercial uses, the final use of the waste heat will determine whether you use desuperheating waste heat or full condensing waste heat. Generally, commercial use for water must be at least 140°F; desuperheating waste heat is the only option to reach a temperature that high. Additional measures might have to be taken to get the water to a higher temperature if needed. The preheating of HVAC air requires a much lower temperature, around 60°F. In these cases, full condensing heat can be used to meet this demand (Fricke).

A secondary area of waste for possible consideration is the heat expelled from the espresso machine broiler. On the FAEMA Ambassador, (Which is the machine that I am working with) the broiler is not insulated and puts out a tremendous amount of heat that dissipates into the air above the espresso machine. A broiler wrap or a suspended heat transfer unit would be a viable way to capture the waste heat put off by the machine itself.

Original Proposal

The original proposal for my project was to use the waste heat from the refrigerator to raise the temperature of groundwater. This looked like the best option based on previous research. I was also comforted with the knowledge that I was not the first person to do this and that I would not be reinventing the wheel, but rather tweaking it to fit the needs of this project. However, as the project progressed, several issues arose that suggested more and more that capturing the waste heat from refrigeration would not be a good fit for this project. These issues are as follows:

- Distance: The hot side of the refrigerator was on the roof. One aspect of a system of efficiency is that the waste and need must exist in proximity to each other. The refrigerator and espresso machine do exist in the same

building, but a professional plumber would have to be hired to run pipe for the heat transfer unit and that did not fit into the budget of this project.

- In order to capture the heat from the refrigerator, a complete rebuild of the condenser fan assembly would be required, as illustrated in figure 6. A redesign/rebuild of this magnitude was beyond the timeline for this project. In addition to length of time to rebuild the condenser fan assembly, this would have voided the warranty for the refrigerator and that was not in the best interests of the business owner.

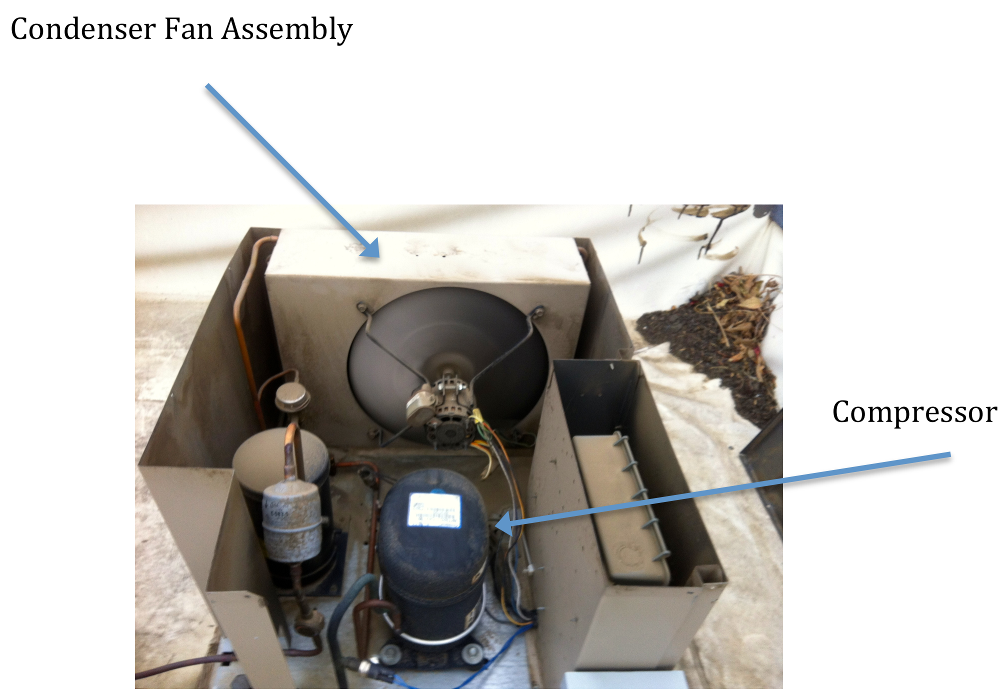

Figure 6: Photo of Condenser Unit on the Roof
Source: Andrew Webber

- In addition to the issue of the rebuild of the condenser fan unit, the actual temperature of the hot line of the refrigerator was approximately 115°F. I did not believe this temperature was high enough to achieve the 80°F-90°F window that I was shooting for. The temperature of the upper cavity of the espresso machine was 156°F which provided much more energy to work with.

- The last issue of concern for working with the refrigerator was the impact of the outside temperature on the final results. Extreme heat could raise the temperature of the water above acceptable limits and extreme cold could cause the unit to freeze, crippling the business.

For these reasons I decided to move ahead without using the waste heat from the refrigerator. The only viable option left was to use the waste heat from the espresso machine itself. This process is described in the following section.

Secondary Proposal

After I decided to move away from working with the refrigerator to working with the espresso machine, the next decision was whether to do a broiler wrap (essentially creating a heat transfer unit that comes into direct contact with the broiler), or create a suspended heat transfer unit (HTU) that captures waste heat as it leaves the top of the machine. When looking at these two options mathematically, it is clear that the broiler wrap makes the machine work harder because it essentially just increases the volume of the broiler, so the heating element has to use more energy to heat more water. Whereas the suspended HTU does not come into contact with the broiler and it only uses the heat that is put off by the broiler. These ideas are mathematically represented below:

Suspended HTU $Q_{energy} = V_{Broiler} \times Specific\ Heat_{H_2O} \times \Delta temp$

Broiler Wrap $Q_{energy} = (V_{Broiler} + V_{HTU}) \times Specific\ Heat_{H_2O} \times \Delta temp$

Given that a suspended HTU was the only clear option, material choice and specific design for the HTU were the next questions to be answered. I chose refrigerant copper tubing for the material of the HTU itself. The heat transfer coefficient for copper is 2.3 $BTU/ft^2\ hr \times F$ when dealing with air to water (Engineering Toolbox). This was much higher than any other tubing in the price range. Copper tubing is also viewed as standard and safe when dealing with drinking water in commercial applications.

I chose to use a pipe bender over copper fittings at the angles to reduce the risk of leaks and also to keep the cost low. By using a pipe bender (Figure 7) I was constrained on the type of bends I could make and I decided to go with a spiral design (Figure 8) because it allowed me to fit in the most amount pipe over other designs.

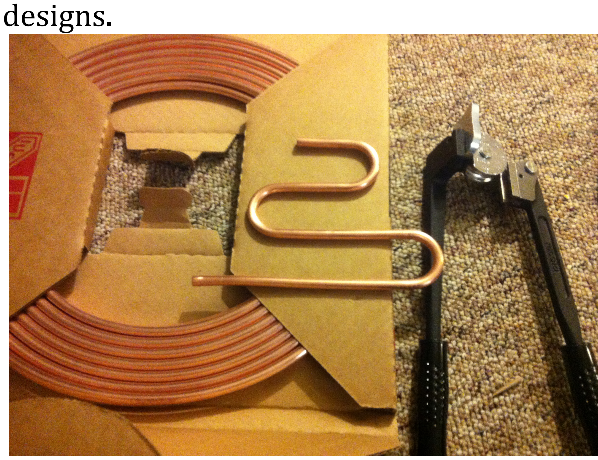

Figure 7: Pipe bender & Refrigerant Copper
Source: Andrew Webber

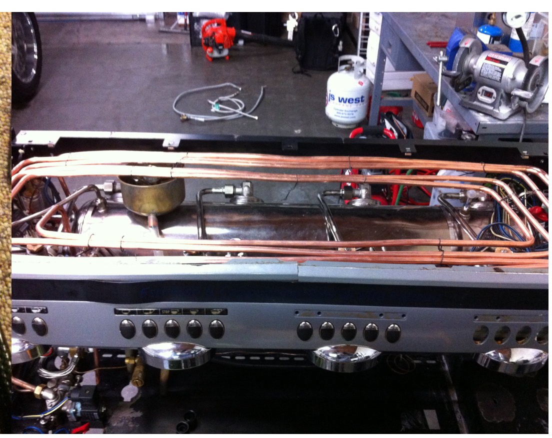

Figure 8: Spiral design
Source: Andrew Webber

Ground water enters into the HTU, passes through the HTU while being heated by the ambient temperature inside the top of the espresso machine and then travels to a split valve. This valve directed the heated water to both the machine and to a needle valve (Figure 9) that was used to measure the temperature of the water after it was heated by the HTU as well as bleed off any air left inside the HTU during installation.

Figure 9: Needle Valve for Temperature Measurements
Source: Andrew Webber

Societal Impact

The idea of a system of efficiency is more than just linking a waste with a need. It is an idea that encourages people to examine how they lived and how they do business. There is a notion in society that states that large change comes from either the government or large corporations. A system of efficiency relies on everyday people who are experts in their own lives, and who are in the best position to determine how to make them better. The main reason I chose to make the HTU and put it in a coffee shop was because I have expertise and I should know better than others on how to make the business better.

The concept of taking ownership of our own lives is not an entirely new one. iFixit is a company in San Luis Obispo that promotes the idea that everyone can fix their own broken electronic devices instead of throwing them away and buying new ones (iFixit). This idea could have major impacts on the environment as well as in the quality of people's lives. Another project that fully encompasses the idea of individuals as experts is the Open Prosthetics Project; this project utilizes the knowledge of prosthetics users to produce useful innovations in the field of prosthetics. These innovations are shared freely with the end goal of producing industry leading prosthetic designs that are affordable to all (open Prosthetics). The idea of taking ownership in one's world is contagious and has the potential to snowball and change many industries. While working on this project and discussing it with others, I have heard many people say that they would love to get involved

with this idea. It is empowering to take ownership of your surroundings and make change not only for you, but also for the greater good.

Deliverables

The physical and data related deliverables for this project are simple and straightforward. I will deliver the following items:

- I will design and build a heat transfer unit to successfully capture waste and use that energy to raise the temperature of groundwater in a commercial setting.
- I will install said HTU in a coffee shop in Woodland California.
- I will collect temperature data with the goal of achieving a window of 80°F-90°F during normal working conditions.
- I will obtain power data to compare the power usage with and without the HTU installed.

Analysis

After successful installation of the HTU into the Dutch Bros. Coffee shop in woodland California, temperature levels were taking during three different modes of operation. First, the temperature was measured twenty minutes after the espresso machine was brought up to full temperature from a cold state directly after installation. I measured at this time to get an idea of how long it would take to heat the HTU from a cold state. Second, I measured the temperature of the water after forty minutes of sitting without making any coffee to simulate the upper limits of the HTU. High temperatures (such as 120°F) can be tolerated as long it is not constant and water of that temperature is moved through the water pump infrequently. Lastly, I ran the machine at full capacity (which is higher than busy working conditions) to see what temperatures could be achieved while replacing the water in the HTU as fast as possible. These temperatures can be seen in Figure 10.

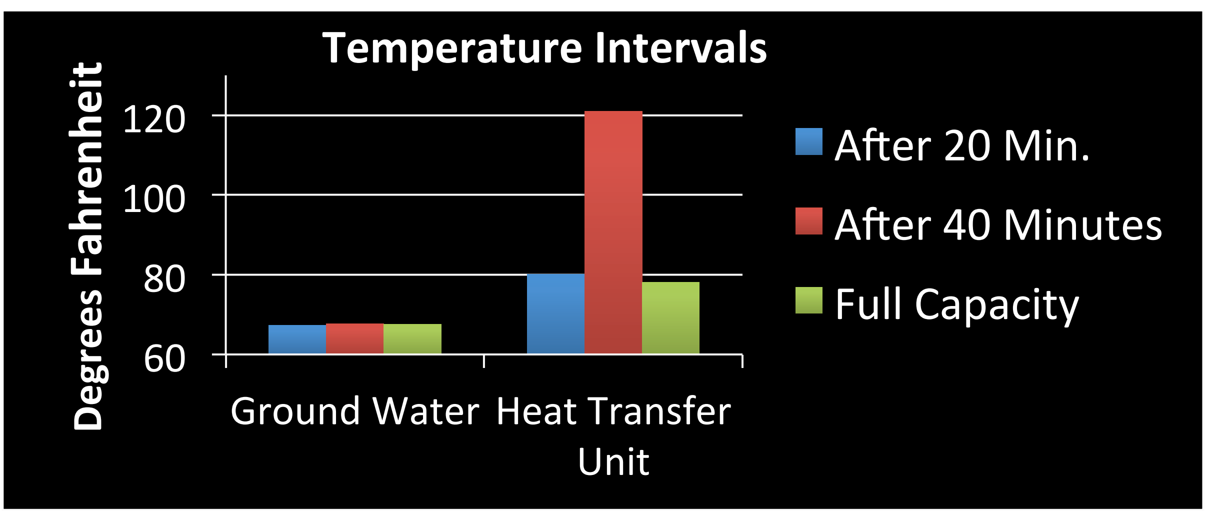

Figure 10: Temperature Intervals
Source: Andrew Webber

In order to get the machine to run at full capacity, I pulled sixty shots of espresso, and fully replaced the water in the HTU two times. The temperature of 79.1°F was achieved during full capacity. Given that normal business full capacity replaces the water in the HTU at a slower rate I believe that the window of 80°F-90°F will be achieved during normal business use.

Before I could get a chance to measure the power usage of the machine, with and without the HTU installed, an unrelated computer failure occurred on the machine and the machine had to be replaced. This is the reason why I do not have more temperature data and no power readings.

Miscellaneous Specs for the HTU:

- Approximate volume = 29.3oz or 0.23gal
- HTU has enough water to make 15 double shots of espresso
- 124sec or 2min 4sec for total HTU water turnover at full capacity

Conclusion

I am extremely pleased with how this project turned out. The temperature data was very promising and I look forward to working more on this concept. The computer malfunction was an unfortunate turn of events and given the limited timeline of the project I was unable to reinstall the HTU in the machine that replaced it. I believe that the success of this project is an example of how individuals can make a difference in their world and hopefully on a larger scale as well.

Future Work

Moving forward I am excited to build a new HTU that is easier to install/uninstall and collecting more data on temperature and power usage. I also plan on collecting data from baristas who use these machines everyday to find out if the machine seems to work better or worse with the HTU and if the coffee output is more consistent in texture and taste. With the data collected from the next HTU, I plan to pursue at patent and then decide where to go from there.

Source Links

Pressure-Enthalpy Diagram:
http://info.ornl.gov/sites/publications/files/pub31294.pdf

Refrigeration cycle:
http://www.swtc.edu/ag_power/air_conditioning/lecture/basic_cycle.htm

Refrigeration cycle II:
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Thermodynamic States for Hypothetical Refrigerator:
http://info.ornl.gov/sites/publications/files/pub31294.pdf

References

Carbon Trust. “How to Implement Heat Recovery in Refrigeration.” Web. Oct 15, 2013.

Dutch Bros. Coffee. “About Us.” Web. Oct 15, 2013.

Engineering Toolbox. “Overall Heat Transfer Coefficients.” Web. Feb 22, 2014.

Environmental Protection Agency. “Average Temperature of Shallow Ground Water.” Jan 10, 2013. Web. Mar 2, 2014.

Fricke, Brian. “Waste Heat Recapture from Supermarket Refrigeration Systems.” Oct 4, 2011. Web. Nov 2, 2013.

iFixit. “Background.” Web. Mar 9, 2014.

Open Prosthetics. “The Project.” Web. Mar 9, 2014.

SWTC. “Basic Refrigeration Cycle.” 2006. Web. Nov 10, 2013.

The Coffee Brewers. “How an Espresso Machine Works: What’s Inside.” Web. Mar 3 2014.