Wood Fired Hot Tub Heat Exchanger

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With guidance from Woodie Flowers
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Introduction

Four years ago my brother, Michael, and I designed and built a wood fired hot tub (Figure 1) (more truthfully, he did the difficult parts of excavating, laying a plywood form, and pouring the cement). The stone and cement tub is in the middle of a 150-acre farm that doesn't have electricity so it is powered by a submerged wood stove made by The Snorkel Stove Company (Figure 2).

Figure 1. The existing wood fired hot tub built by my brother and I.

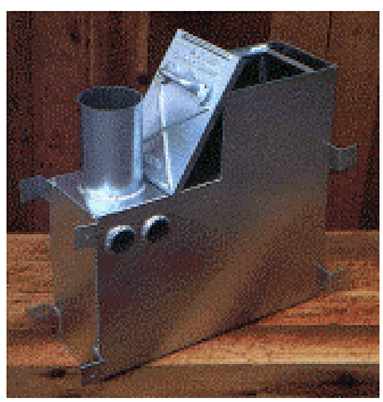

Figure 2. The aluminum wood stove made by The Snorkel Stove Company

The tub operates without jets, filters, or chemicals. Instead, the water is renewed each time it is used by pulling out a drain plug to allow it to drain into a lower pond and then opening a valve to fill it from an upper pond. On a warm day it only takes two hours to heat the tub to 105 F. On a cold day- when an outdoor hot tub is the most fun—it can take six hours to heat up. This paper outlines the development of a heat exchanger I worked on with Professor Woodie Flowers at MIT. The goal of the project was to design and build a heat exchanger to augment the existing stove and reduce heat time.

Safety

This section would more logically go at the end of the report. However, a search for "boiler explosion" on the Internet demonstrated the need for safety and failure analysis. The high temperatures and large thermal masses in close proximity to water make it dangerous. Safety was a driving design criterion.

To avoid steam explosions care was taken not to have closed volumes that could build pressure if heated. The copper tubing is open at one end and even if that end was blocked the maximum pressure could not exceed the pump pressure. The open ends of the tubing are also directed away from the hot tub and down into the water in case the pump failed and water in the tubes boiled.

There is a buoyant force of about 300 pounds on the stove. It is held in place by bolts in the cement, but if it came loose it could rocket out of the water and burn bathers. Braided steel cables, anchored in the cement, loop over the top of the stove in case the other bolts pulled loose. A wood fence also helps to separate bathers from the hot stove (Figure 1). The low voltage needed to operate the pump and blower is safe even around water.

Waste Heat Estimate

Ideally, a complete thermodynamic model of the hot tub system would have been the basis for this project. The model could include such things as conduction losses to the surrounding soil and convection and radiation losses to the environment. However, these variables change drastically with ambient conditions so I decided to evaluate designs based on how much they would improve existing stove performance. A figure of 120,000 Btu/hour was given by The Snorkel Stove Company as the useful heat output of the stove. The term "useful heat" refers to the heat that is transferred to the water. The heat exchanger described in this paper roughly doubles the useful heat output.

Because the entire stove is submerged, all of the heat of combustion is useful heat except for what is lost in hot flu gases. When a large fire is built in the stove, orange flames can be seen at the top of the six-foot stack. This visible color indicates temperatures up to 1400 F.

To get a conservative estimate of the amount of heat lost up the stack, a stack temperature of 800 F was used. This temperature was based on thermocouple readings taken with a moderate fire in the stove. An estimate of the mass flow rate through the stack was based on a balance between the driving pressure due to the buoyant force of the air and the pressure drop due to turbulent flow through the stack and stove. This analysis predicted a heat loss of 160,000 Btu/hour. This shows that capturing some of this waste heat with a heat exchanger could greatly increase useful heat output.

Heat Exchanger Analysis and Design

There are a huge number of different heat exchanger designs. A water tube design was chosen over a fire tube design because it would have been very difficult to duct the exhaust under water. The performance of a water tube heat exchanger is given by the overall convection coefficient, U, which has units of W/m^2K. It is related to the convection coefficient between the internal wall of the tube and the water, h_i, and the convection coefficient between the outside wall of the tube and the air, h_o, by

$$U^{-1} = h_i^{-1} + h_o^{-1}$$

Maximizing U, the area of the heat exchanger, and the driving temperature difference between the two fluids will give a high heat transfer rate.
The following two sections describe the separate modeling of internal water flow and external air flow. The third section, heat exchanger design, shows how these models led to the final design.

Internal Water Flow Analysis

An estimate of the convection coefficient between the copper and the water was based on analysis of turbulent flow in a circular duct as presented by Incropera and Dewitt (2002). The following formula incorporates water density and Prandtl number as a constant. This is not convenient for understanding the derivation of the formula. However, it is helpful for practical application because volumetric flow rate for commercial pumps is usually given in gpm. The internal diameter of the tubing, D_i, is in inches because standard copper tube sizes are in inches (although commercial tubing is specified by OD measurement).

$$h_i = 25 gpm^{4/5} D_i^{-9/5}$$

A high flow rate through a small diameter tube would favor heat transfer, but would also have a high pressure drop. Pressure drop in psi is given by

$$P = 4.037 \times 10^{-5} L D_i^{-4.75} gpm^{1.75}$$

This is based on analysis of turbulent flow through pipes given by White (1994). It applies to water flowing through a pipe of length L inches. Again, the units were chosen for convenience and the viscosity and density of water are incorporated in the constant. Pump power is the product of pressure and volumetric flow rate so a small diameter tube can lead to high power requirements.

External Air Flow Analysis

The choice of how to model convection between the copper tube and the air depends on geometry. A staggered tube arrangement gives high Nusselt numbers with only moderate increases in pressure drop compared to other geometry. Incropera and Dewitt present a model for staggered tube heat exchangers that gives the average heat transfer coefficient for the entire bundle (2002). The model incorporates experimentally determined constants and the following relationship is a rough approximation for this case.

$$h_o \propto V_{\max}^{0.6} D_o^{-0.4}$$

The average convection coefficient, h_o, increases with decreasing tube diameter, D_o. The maximum air velocity, V_{max}, is a function of volumetric flow rate and geometry.
As was the case with internal water flow, a balance must be reached between maximizing the convection coefficient and minimizing pressure drop approximated by

$$P \propto V_{max}^2 N$$

where N is the number of rows of tubes.

Heat Exchanger Design

Geometric constraints and the results from the above models led to the design of a staggered tube heat exchanger with concentric coils. This satisfied geometric constraints because it would fit in a compact cylindrical exhaust stack. Incidentally, coiled tubes also improve heat transfer to the internal fluid through induced secondary vortices (Shah, 1987). Design issues that had to be resolved included the diameter of copper tubing, number of coils, desired flow rates, and method for driving flow.
The diameter of tubing chosen was ½ inch OD. This diameter gave good convection coefficients with low pressure drop. With this size tubing, five optimally spaced coils could fit in the 8 inch diameter stove pipe.
The number of coils was limited by the length of tubing available. A 50 foot length of tubing allowed about 26 coils based on the largest diameter coil of 7.5 inches.
Water flow rate was a trade off between higher heat transfer rate and lower pumping power. A minimum flow rate was determined from the need to keep the water from boiling in the tubes. An iterative Matlab script showed that a flow rate of 5 gpm allowed for a safety factor of 3. The same script showed that counterflow would be about 5% more effective than parallel flow. A twelve volt pump from Pump World matched the system impedance.
Air flow was important not only for heat exchanger performance, but also to support combustion. The heat exchanger will have a pressure drop twenty times higher than the pressure drop with the stove alone. Additionally, natural convection through the stove would be less because the heat exchanger lowered the temperature of the flu gas. A blower was selected to drive air flow. Figure 3 shows the performance curve of a twelve volt Granger blower. The predicted operating point of 150 cfm with the blower was more than the 100 cfm estimated on the original stove.

The blower and pump will be powered by a deep cycle twelve volt battery. Based on power consumption of the blower and pump, one charge should run the system for over twenty hours. An inexpensive solar battery charger will recharge the battery in about a week.

To get an idea of the overall performance of the system, a Matlab script simulation was run. Figure 4 shows a plot of water and air temperatures. Based on expected flow rates and a flu temperature of 800 F, this model predicted an output of 140,000 Btu/hour. The actual output will probably be lower due to fouling.

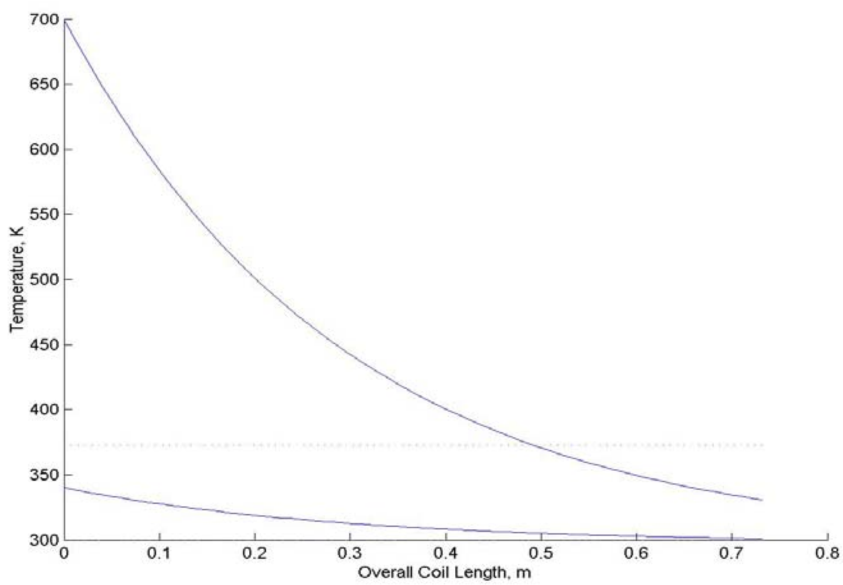

Figure 4. Matlab generated plot showing temperature changes for water and air based on iterative model. The top curve shows exhaust gas temperature and the bottom curve shows average water temperature.

Experiment

During spring break, I went to the farm to gather data on the tub during operation and to test a small heat exchanger. Airflow data was difficult to gather because velocities were below the range of my homemade anemometer. However, good temperature data was gathered using a thermocouple.

The small coil heat exchanger had eighteen feet of 3/8 inch copper tubing. Figure 5 shows Michael and me testing it. Measurements showed that it extracted 10,000 Btu/hour. That was 30% lower than the model predicted. However, given all the uncertainties about flow rates and flu temperatures, that error is acceptable. Also, the flow rate was too low and the water boiled in the tubes making it difficult to gage maximum heat transfer.

Figure 5 Michael and I testing the output of the scaled down experimental heat exchanger.

Fabrication

Building the heat exchanger proved challenging. The copper coils were formed on different sized mandrels with the help of Gerry Wentworth at the MIT LMP. We used a lathe to rotate the mandrels while guiding the copper tubing by hand. The tubing was filled with water and capped prior to winding to prevent kinking.
The staggered tube geometry required that the coils be spaced correctly. A stainless steel plate was cut using a water jet. The 300 holes in the plate lined up with the copper coils that were threaded in place. The following figure shows the plate with two coils in place midway through construction. Getting everything to line up took some work.

Figure 6 Heat exchanger midway through fabrication. The copper coils thread into the holes that were water jetted into the stainless steel plate.

A ¼ inch stainless steel plate was welded onto the perforated plate to form a base (thanks to Steve Haberek at the MIT Pappalardo Lab). All connections were made using flare fittings. The upper ends of the tubes were routed down through the center of the coils and out the base to maintain a compact cylindrical package.
The finished coil assembly is shown on the stove in Figure 7. In operation, a double walled stove pipe slides down around the outside of the coils.

Figure 7. The finished heat exchanger and blower assembly on the stove.

The aluminum blower shroud and duct assembly is visible to the right of the coils. It also functions as a hinged lid for the stove. The air from the blower is forced across the top of the stove, preheating the air before it enters the firebox. The curved hood protects the blower from weather.

Additional Considerations

A few other modifications were made to the hot tub to decrease heat time. These ideas focus on reducing heat loss and increasing fire intensity.

Heat is lost as water evaporates into the air. A foam cover that floats on the surface of the water can significantly reduce evaporation. This improvement was already in place, and the foam cover Michael constructed a few years ago can be seen in the corner of Figure 1.

A large amount of heat is also lost through conduction in the cement and surrounding soil. Unfortunately, this is hard to reduce because insulating around the tub would be very difficult.

Ed Seldin at MIT had several suggestions for increasing fire intensity. These included a fire grate and increased stack height. The fire grate would improve airflow around the fire and is currently being fabricated out of rebar. Increasing the stack height would improve convection flow through the stove but was not practical due to lack of support for the stack.

Testing and Actual Performance

So far, the system has not been tested with a fire in the stove. A test of the plumbing system was encouraging because water flowed vigorously through all five coils. Blower performance was a little disappointing, maybe because of high resistance to flow in the duct. This could be remedied with another blower in parallel. The system will not be tested with a fire until we anchor the steel cables described in the Safety section above. I'll update this section with a measured value for heat output as soon as we fire it up.

References

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