Generating Light from Stoves using a Thermoelectric Generator

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One of the largest obstacles in the acceptance of clean stoves is that they do not give off the light that the traditional fire does. This downside of clean stoves cannot be overlooked if stove programs are to be successful. Many people would rather deal with smoke than complete darkness, and may reject a clean stove for this reason. Developing a means to create light from stoves will solve this dilemma, and could have additional benefits. It is believed that the ability to generate clean, white light will be so highly valued by users that they will be motivated to invest money and effort towards a clean stove.

One of the most promising methods for generating light from stoves is through thermoelectric power generation. A prototype generator has been developed that produces approximately five watts of power, and is projected to cost around $30 in large quantity. An in depth analysis was performed on each component to maximize the system efficiency and reduce cost. The selection process for the thermoelectric module, the heating and cooling fins, and the fan is outlined in detail. Computational and analytical models have been developed to predict the performance of the components individually, and as a system. Initial testing and calculations show that the thermoelectric generator is a feasible and relatively cheap solution to a large problem.

Introduction

In the process of designing a system for generating light from stoves, several options were considered. All the technologies considered are external combustion devices that convert heat into electricity. Devices considered were the Stirling engine, the Rankine cycle engine, a Brayton cycle engine, and a thermoelectric generator. In selecting a technology to successfully address this problem, there are many important considerations. The most critical of these is cost. Most potential users of this technology live at or near a subsistence level, and have very little extra income to invest. The solution must also be quiet. If the generator is loud enough to be distracting, the users will simply be trading one annoyance for another. The generator should also require minimal maintenance, and have an acceptable lifetime. Previous experience has shown that changing the habits of stove users to think of maintenance is difficult. However, it is believed that the ability to generate quality light will motivate the users to take more responsibility. Finally, the generator should not require a battery to store power, since lead acid batteries are prohibited in some regions, and add additional cost.

A thermoelectric generator has many advantages over the various heat engines considered. Thermoelectric modules make no noise when they run, the loudest component of the system would be a small fan used for cooling. Similarly, the only moving part in the system would be the cooling fan, which typically runs for thousands of hours without failure on most personal computers. The thermoelectric generator converts heat directly into electricity, eliminating the need for an electric generator as would be needed by the engines considered. Thermoelectric generators are also very modular. By the selection of the proper module, any increment of power can be produced from half a watt, to a hundred watts. All of the components necessary for the system can be purchased, making cost estimating and prototyping very straightforward. For these reasons, a thermoelectric generator was selected as the most appropriate technology for generating light from stoves.

Design of a Thermoelectric Generator

In designing a thermoelectric generator, there are many complexities that must be considered. Each component must be evaluated on how it will perform with the rest of the system, rather than individually. The components of the system are the thermoelectric module, the heat exchangers, the cooling fan, the power electronics, and the load. This is a very dynamic system that requires a thorough effort in design to maximize performance. The various components of the system are shown in Figure 1.

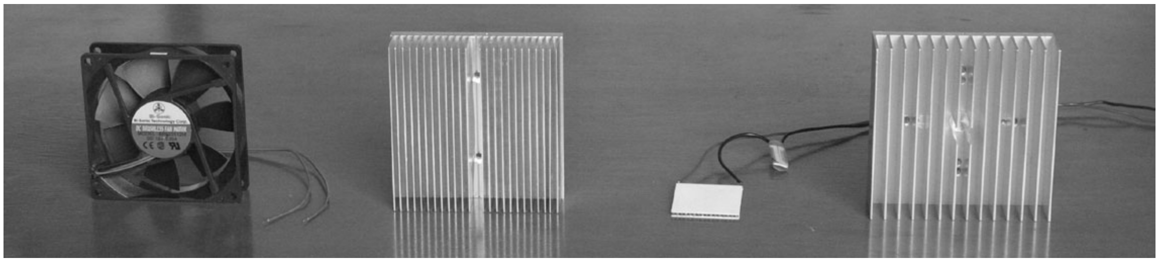

Figure 1: Generator Components – fan, cold sink, module, hot sink.

Module Selection

There are several considerations in selecting the appropriate module. The most important are the material and module construction. There are many materials capable of producing power from a temperature difference. These materials vary in cost, efficiency, and operation temperature. Module construction also affects these three categories, as well as the maximum power of a module, and the voltage/current characteristics of the system. In selecting a module it is important to evaluate each one as it will perform in the entire system. In many cases, especially when using air for cooling, the power output listed by the manufacturer is very difficult to achieve.

Initially, it was believed that a low cost, low efficiency material may be the best solution for this application since the heat source is abundant and could be considered free. However, this is not necessarily the case. In general, thermoelectric materials have very low efficiencies, typically less than 10%. A very cheap material may have an efficiency of around 1%. This means to generate 5 watts of power, 500 watts must be moved through the system. This would require a very large heat exchanger, including a powerful cooling fan. These components have additional monetary and power costs, negating any advantage of using a low cost material. Bismuth telluride (Bi_2Te_3) is the material with the highest efficiency in the range of temperatures that could be seen in a stove [1]. Bismuth telluride is also the most common material used in Peltier coolers, making it relatively cheap. High temperature bismuth telluride modules achieve around 4% efficiency at max power. For these reasons, a Be_2Te_3 module was selected for this application.

There are also many decisions to be made in module construction. The module construction consists of the number and geometry of the thermo-elements, as well as the method for connecting the elements. Figure 2 shows the construction of a thermoelement. Modules are typically composed of around a hundred elements. Modules can be constructed as Peltier coolers or as high temperature generators. Both of these use the same materials and can be used to produce power, but they differ in how the thermoelements are soldered to the conducting strip. The solder on a Peltier cooler is typically BiSn, which melts at approximately 138 °C [1]. Most high temperature generator modules can withstand intermittent temperatures up to 400 °C. This increased performance comes at a cost though, typically twice as much as a low temperature Peltier module, but is compensated by a dramatic increase in power. The reason for this is explained below.

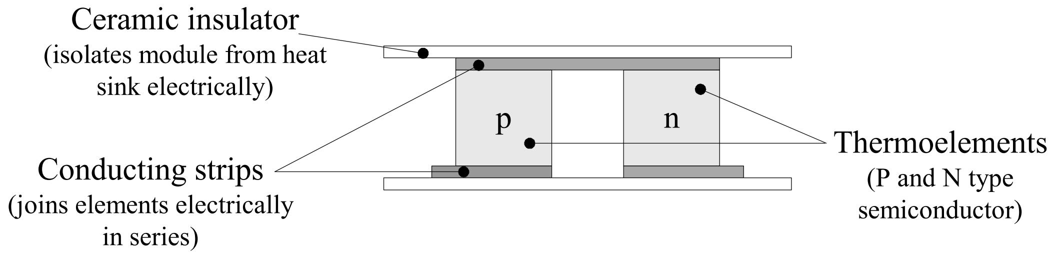

Figure 2: Construction of a thermoelement.

Element geometry is important to consider when selecting a module, however, most designers will have to pick from what is being produced unless the volume is high enough to warrant custom module design. The geometry of the thermoelements affects the power of the module, the efficiency, and the voltage achieved [1,2,3]. The effects of element geometry and the number of elements can be seen in the following equation [2].

$$P = \frac{\alpha^2 \quad N\,A}{2\,\rho\,(L + \rho/\rho_c)(1 + 2(\lambda/\lambda_c)(L_c/L))^2}(T_H - T_C)^2 \qquad \text{(equation 1)}$$

Where:

P	is the module power	α^2	is the Seebeck coefficient
N	is the number of elements	A	is the area of elements
T_H	is the module hot side temperature	T_C	is the module cold side temperature
L	is the element length	L_c	is the thickness of the insulating ceramic
ρ	is the electrical resistivity	ρ_c	is the contact electrical resistivity
λ	is the thermal resistivity of the module	λ_c	is the contact thermal resistivity

The previous equation is very useful in estimating the power output of a module. Unfortunately, getting all this information from a manufacturer can be difficult. Typical values for some of these constants can be found in the references. For the ideal module, neglecting contact resistances, the following equation can be applied [4].

$$P = \frac{\alpha}{\rho}\frac{\Delta T^2}{2}\frac{N\,A}{L} \qquad \text{(equation 2)}$$

One important observation that can be made from this equation is that power is proportional to the temperature difference squared. This is extremely useful when given a power output at a certain temperature difference from a manufacturer. The power at other temperatures can be estimated by:

$$P = \frac{P_{ref}}{\Delta T_{ref}^{\ 2}}\Delta T^2 \qquad \text{(equation 3)}$$

Another interesting observation from equation 1 is that the power increases as the thermoelement leg length decreases. This means in some cases a higher power module requires less material than a lower power module. Because of this, modules of very different power outputs may cost the same if they have the same footprint. This is true for the 2.7 W module and 5.9 W module made by the Thermonamic Electronics Co.

Another useful equation describing thermoelectric performance relates the output voltage to the operating temperature [2].

$$V_m = \frac{\alpha\, N\,(T_H - T_C)}{1 + 2\,(\lambda/\lambda_c)(L_c/L)} \qquad \text{(equation 4)}$$

For the ideal module, the denominator of equation 4 can be omitted. From this equation, it can be seen that voltage is proportional to the number of elements since they are combined electrically in series. Voltage is also proportional to the temperature difference. This is important since many electrical loads may require higher voltages than the module provides, therefore a module operating at a higher temperature difference will require less of a boost. This is another reason why high temperature modules are preferred over cheaper Peltier modules.

Finally, the effect of temperature on module efficiency can be described by:

$$\phi \ \propto \ \frac{T_H - T_C}{T_H} \qquad \text{(equation 5)}$$

Heat Exchangers

In order to maintain a large temperature difference across the module, heat exchangers are required on each side. Since the fluid on both sides of the module in this case will be air, large finned heat exchangers are necessary. Proper use and selection of these heat exchangers is critical to a successful design. In order to predict the performance of the generator, the characteristics of the heat exchanger must be well understood.

On the hot side of the module, the heat exchanger is less critical. Most high temperature modules can operate with hot side temperatures up to 250 °C. Temperatures inside a stove can be up to 600 °C. This allows the designer to use this high temperature difference as leverage. Even if the hot side heat exchanger is inefficient, the large temperature differential can compensate for this. The hot side heat exchanger has larger gaps within the fins for better performance using natural convection. It is also a solid extruded piece so there are no bonded joints that could melt.

The cold side heat exchanger must be much more efficient. The air used to cool the cold side of the module can only be as cold as the ambient air. Because of the quadratic dependence of temperature on power, the cold side should be kept as cold as possible. There is a trade off though, since power must be put into the cooling fan to keep the module cold. For this reason, an in depth analysis of the cold side heat exchanger has been undertaken.

Thermoelectric generators are traditionally analyzed using a thermal resistance model. All components in the system are given a resistance in °C/W. This value tells the temperature drop through any component of the system for each watt passed through. For the heat exchanger, the resistance is used to calculate the cold side temperature of the module given the ambient temperature. Most heat exchangers require forced air to be effective. Because of this, manufacturers may list a thermal resistance at a given flow rate. Some may have plots of thermal resistance at various flow rates. Figure 3 shows the thermal circuit used in analyzing a generator. In this work, the hot side heat exchanger has been omitted.

Figure 3: Thermal resistance circuit.

The thermal resistances at the interfaces between the module and heat sinks are also important to keep to a minimum. This requires very flat surfaces (within .001”), high temperature thermal grease, and uniform clamping pressure (up to 200 psi). Belleville spring washers are also included in the assembly to compensate for thermal expansion. The thermal resistance seen in this work was around .1 °C/W.

The heat sinks chosen for this work are the HX6-202 and HX6-202 sold by Melcor. These are bonded fin heat sinks, so they can only be used on the cold side. Melcor gives the thermal resistance for these sinks as .2 °C/W and .18 °C/W at 45 CFM, respectively. Unfortunately, no additional data is available for the heat sinks at different flow rates. A computational fluid dynamics (CFD) model was created to model these heat sinks as well as other possible geometries. From the CFD model, curves of thermal resistance vs. flow rate were generated for various configurations. In the model, the flow is parallel to the fins as it flows through a duct from the fan. This configuration was chosen so that the cooling air could be ducted into the stove to improve combustion. The fins were modeled with the duct tight against the fins (2mm gap above), and with a larger gap above the fins (10mm gap). The results from the HX6-202 analysis are shown in Figure 4.

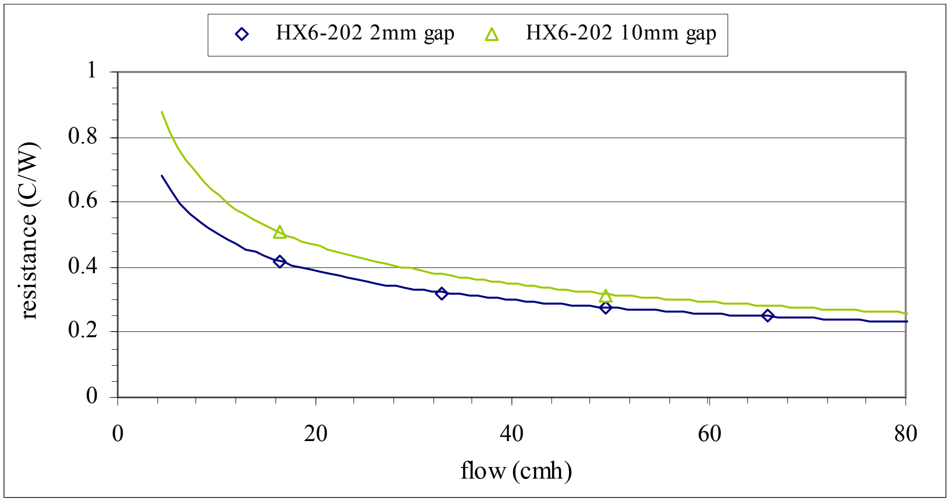

Figure 4: Thermal resistance of heat sink vs. flow rate.

Figure 4 shows the effect of flow rate on thermal resistance. In this figure the non-linear nature of thermal resistance is illustrated. It is important to know where on this curve the system is operating. If the system is operating on the flat part of the curve at high velocities, it may be possible to achieve almost the same amount of cooling with less power into the fan. If the system is operating on the steep part of the curve at low flows, significant improvements may be made by a slight increase in fan power. In most cases, a heat sink is well matched to the system if it operates near the knee of the curve.

Fan Selection

The selection of the appropriate fan is as important as the heat sink and module. The purpose of the fan is to increase the power output of the system. If the fan is inefficient, or poorly matched to the system, it may consume more power than it generates. In order to choose the best fan, it is once again necessary to evaluate each one as it would perform with the rest of the system.

As a starting point, it is important to look at the no load flow rate and the power consumption of a fan. This gives an indication of the fan efficiency, but is not the flow rate that will be seen in a real application. Typically, a fan that generates over 30 CFM/watt is fairly efficient. It has also been found that the larger the fan, the more efficient it is. Larger fans typically generate higher flows at lower powers than their smaller counterparts. For example, the 60 mm fan by Panaflo creates 14 CFM at 1.3 W, while the 92 mm fan produces 42 CFM at 1.3 W. The smaller fan does generate a higher pressure, but it is not enough to compensate for the difference in flow rates. Of all the fans evaluated, the Vantec 120 mm “Stealth” fan is the most efficient, and very quiet. Unfortunately, the fan is larger than the heat sink, which is 102 mm, so a duct is required to direct the air. Of the 92 mm fans, the Panaflo low power fan is one of the most efficient.

In order to know how the fan will perform as a part of the system, the static pressure vs. flow rate must be known at all points. These curves can then be compared to the heat sink characteristics to find the operating point of the system. Figure 5 shows the manufactures fan data, along with the data for the heat sink generated by the CFD model. For the Panaflo fan, data was given for 12 V, 10 V, and 7 V operation. Note that the point of intersection is the operating point.

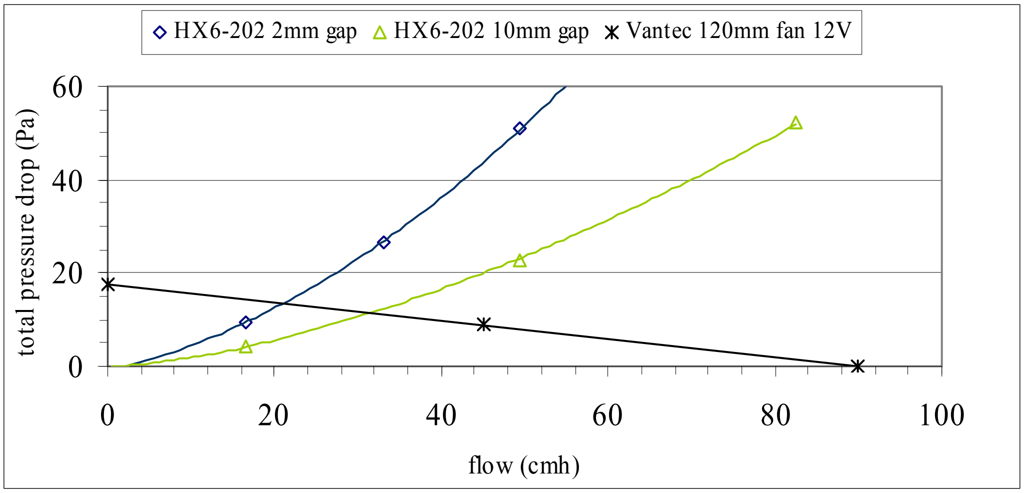

Figure 5: Matching source(fan) to load (heat sink).

Once the flow rate is known, the heat sink thermal resistance can be determined from Figure 4. Finally, the system can be analyzed as a whole, and component selections can be made.

System Integration

In order to determine the system performance, only a few parameters are required for a good approximation. These are a reference power and reference temperature difference for the module as used in equation 3. In addition, the thermal resistance of the module is required. This may be calculated if a heat flux is given with the reference temperature differential. For the heat sink, the thermal resistance and power consumed by the fan is required. In addition to the heat sink resistance, a contact resistance should be included.

First, the heat flow (Q) though the module must be determined. Given a fixed hot side temperature (T_hi), the following equation can be used based on the thermal model in Figure 2.

$$Q = \frac{T_H - T_{amb}}{R_{\text{mod}} + R_{\text{int}} + R_{\sin k\_cold}} \qquad \text{(equation 6)}$$

The temperature on the cold side of the module (T_ci) can be calculated from:

$$T_C = T_H - Q\,R_{\mathrm{mod}} \qquad \text{(equation 7)}$$

Finally, the power can be calculated from:

$$P = \frac{P_{ref}}{\Delta T_{ref}^{\;2}}(T_H - T_C)^2 - P_{fan} \qquad \text{(equation 8)}$$

From this analysis, the total system power can be determined for various module, heat sink, and fan combinations. These equations are only approximations, and are most accurate when the actual temperatures are close to the reference temperatures.

For this work, a power output of at least 3.8 W is desired to power a high intensity light emitting diode (LED). The module selected is the Thermonamic TEP1-1264-1.5. This module has a maximum continuous temperature of 250 °C. As a reference, it generates 5.9W at Th = 230 °C and Tc = 50 °C. The thermal resistance is 1.28 °C/W. From the tests conducted for the HX6-202 module, and the Vantec Stealth fan, the heat sink resistance is .4 °C/W. At a hot side temperature of 250 °C and ambient temperature of 20 °C, the net power output is predicted to be 4 W.

Experimental Results

In order to validate the CFD models and determine the optimum configuration, a series of experiments were performed. In these experiments, the HX6-202 and HX8-202 heat sinks were used. Each heat sink was tested in several configurations. Both heat sinks were tested with a 2mm gap and a 10mm gap above the fins, as well as with the fan impinging on the fins (flow perpendicular to the fins). The Vantec 120 mm fan and the Panaflo 92 mm fan were used on both. During these experiments, flow rate could not be measured, but stagnation pressure behind the fins was. At each point, the temperature of the hot side and cold side heat exchangers was measured. The actual temperature at the module was determined by measuring the power dissipated in a 3 ohm resistor, and comparing to a reference value as in equation 3.

A comparison of the predicted heat sink properties to the experimental values is presented in Table1.

Table1: Experimental results vs. model predictions.

HX6-202	P drop model (Pa)	P drop experiment (Pa)	Thermal resistance model (C/W)	Thermal resistance experiment (C/W)
2mm gap	9	8.7	0.38	0.5
10mm gap	6	6.5	0.38	0.5

Considering the many simplifications in the CFD model, the results are reasonably close to the experimental values. Some of the largest sources of air could be the resistance where the fins are bonded to the base plate, which was not included in the model, and variability in the fan output. From these results, further improvements will be made to the model to improve its accuracy.

Through these experiments, and further modeling based on the results, some interesting phenomena can be illustrated. First of these is the effect of the gap height on the thermal resistance of the heat sink. As the gap is increased, the total flow rate increases due to the reduced fluid resistance, however, the thermal resistance stays nearly constant. In both cases there is nearly the same amount of flow passing though the fins. If the air is to be used for space heating or to aid combustion, the large gap would be preferred to keep the flow rate high. Also seen was the fact that the impinging configuration outperforms the parallel flow configuration. This is believed to be due to the fact that most of the cooling in the parallel configuration occurs at the front of the fin where the thermal boundary layer is small. As the flow nears the end of the fin the air has been heated significantly so that little cooling occurs. In the impinging configuration, cool air is contacting the tips of all the fins. The fact that there is a stagnation zone at in the middle of the fin does not seem to be significant. Also, the pressure drop through the air box used to redirect the flow in the parallel configuration is about 1/3 of the total pressure drop. This results in a lower flow rate.

These experiments also illustrated how improvements in system performance can be achieved by running the fan at reduced power, especially at low hot side temperatures. Figure 6 is of the net power out of the module with different fan voltages. This data is for the Panaflo 92 mm fan in the impinging configuration, with the HX8-202 heat sink.

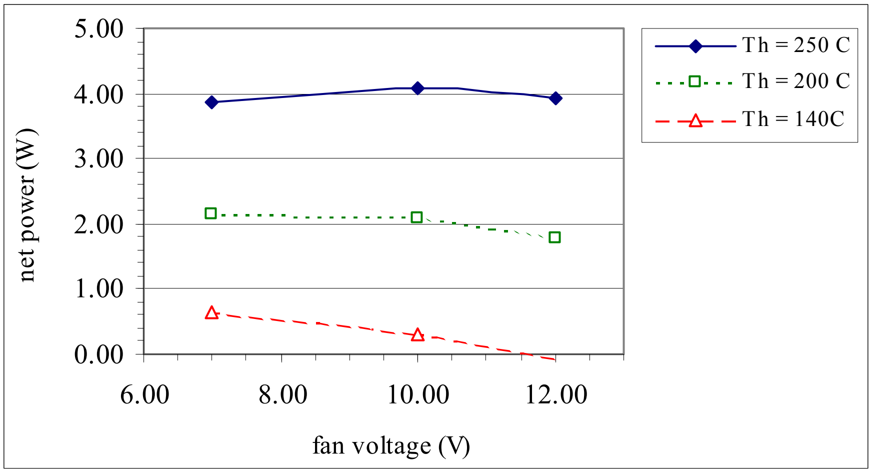

Figure 6: Effect of fan voltage on net power at various hot side temperatures.

Figure 7: Bench testing the generator

Power Management

In order to power the LED and the fan from the module, a power electronics circuit will be required. Due to the nature of the thermoelectric module, the voltage and current both vary as the module temperature difference changes. For maximum power, the load resistance must match the module internal resistance, which also changes slightly with temperature. Unfortunately, the voltage and current at maximum power are typically different than the voltage required by the light or the fan. In order to keep the module operating at maximum power, the voltage from the module must be boosted to power the fan, and may need to be increased or decreased to power the light. This circuit will need to sense the conditions of the module, and make the appropriate changes to the power distribution. An example load curve is shown below for a module made by the Tellurex Corporation.

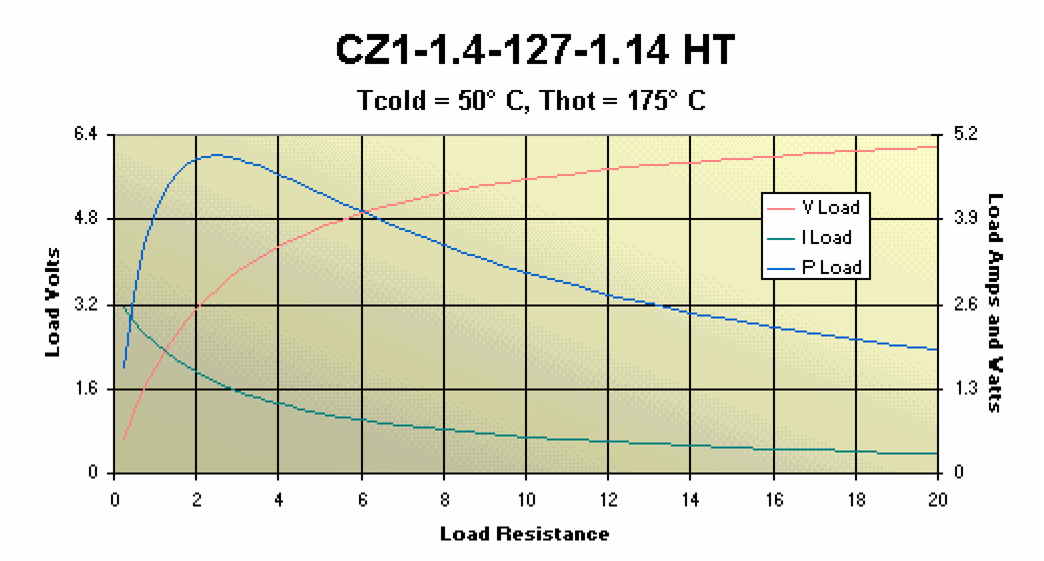

Figure 7: V-I characteristics of a module with a 125 degree temperature differential.

Cost Analysis

Table 2: Projected costs

Component	Single unit cost	High volume cost (10,000+)	Natural convection (10,000+)
Module	$100	$10	$10
Hot Sink	$10	$3	$3
Cold Sink	$16	$8	$12
Fan	$7	$3	$0
Hardware	$2	$0.50	$0.50
Electronics	?	$4	$1
LED	$7	$4	$4
Total	$142	$32.50	$27.50

Further reductions in cost may be accomplished in several ways. First, if the cold heat sink could be made locally, its cost may be reduced. Also, if the cold heat sink is large enough, it may be possible to operate without a fan. This would make the heat sink more expensive, but would eliminate the cost of the fan and greatly simplify the electronics required. If the hot side can be placed near the combustion chamber where the temperature is high enough, it may be as simple as a steel block to distribute the heat, further reducing costs.

In order to get enough cooling using natural convection only, a duct has been proposed that would use the heat from the chimney to increase the draft at the heat sink. After the air passes through the heat sink it would travel upward along the chimney. As it is heated further, its added buoyancy will increase the draft and improve the performance of the cold sink. The proposed design is shown in Figure 8.

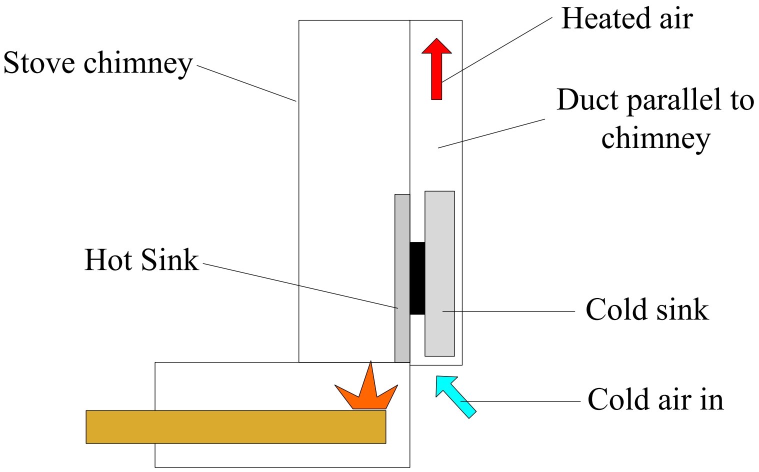

Figure 8: Setup for natural convection operation.

Conclusions and Future Work

Through this work a thermoelectric generator has been designed and tested that produces enough power for a small fan and a high intensity LED. An in depth analysis has been performed in selecting each component of the system to maximize power. A high temperature Be_2Te_3 module made by Thermonamic has been selected as the most cost effective module for this application. System costs in large quantity are estimated to be around $30. Through CFD modeling and bench testing, the most efficient heat sink/fan configuration has also been identified. The best performance was achieved when the fan was in the impinging configuration. Also, it was seen that at lower operating temperatures the greatest power is achieved with a reduced fan voltage.

Further work will focus on improving the heat sink effectiveness through the use of the CFD model. Alternative fin configurations such as a staggered geometry will be modeled and tested. Work will also focus on the design of the power electronics circuit.

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