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## Project Number: P13441

# THERMOELECTRIC CHARCOAL COOK STOVE FOR HAITI

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## ABSTRACT

According to the World Health Organization (WHO) more than 2.4 billion people depend on biomass fuels (wood, dung, or agricultural residues) primarily for cooking[1]. In Haiti, lump charcoal is the primary fuel used for cooking, which has led to significant deforestation as well as widespread illness from exposure to biomass smoke. The purpose of this project is to develop two thermoelectric stove prototypes designed to improve upon existing Haitian stove technology with the goals of substantially reducing fuel consumption and dangerous emissions while also providing a means of electricity generation for Haitian citizens. Additionally, two prototype stoves will be sent to Haiti during the summer of 2013 for field-testing. The thermoelectric module (TEM) is a semiconductor device that converts thermal energy into electrical energy due to a temperature gradient across the device. The temperature gradient is maintained across the surface of the TEM through a fan-driven convective heat transfer system, which also provides fresh air for the combustion process. The current design iteration improved upon the maximum power point tracking system, reduced boil time, and reduced CO emissions by 26.6% and 33.0% respectively, and produced an output voltage of 2 volts. Fuel use and particulate matter production increased by 13.3% and 146.7% respectively, however, these values greatly influenced the understanding and recommendations for future projects.

## INTRODUCTION

The practice of cooking with biomass has decimated many ecosystems and requires an enormous amount of human effort to harvest. In addition, there is considerable evidence that exposure to biomass smoke increases the risk of common and serious diseases in both children and adults. Cooking is often performed on a semi-open stove or over a simple three-stone fire. According to the WHO studies, indoor smoke from solid fuels causes an estimated 2 million deaths annually. These methods of cooking are very inefficient and lead to high fuel usage and airborne pollution. Inefficient cooking methods have specifically had a major impact on Haiti. Haiti was once covered with forest, but now suffers from almost 98% deforestation. Much of the deforestation is a result of the need for cooking fuel, with charcoal being the most popular fuel used in Haiti.

To minimize the harmful effects associated with cooking, more efficient cook stoves have been proposed. These new stoves are significantly more fuel-efficient and also reduce indoor air pollution, thereby reducing deaths and illnesses due to biomass cooking. The Rochester Institute of Technology is working with an NGO partner in Haiti, H.O.P.E., originally funded by an EPA Energy Research Grant, to develop an enhanced stove for vendors and institutional users.

The first generation stoves developed by teams P10461 and 11461 were designed to use force draft to improve combustion and heat transfer to the pot. The forced air requires an electric fan, which is to be powered by a thermoelectric module (TEM). The TEM is utilized to convert thermal energy taken from the combustion process into electrical energy. This is possible based on the Seebeck Effect, which occurs when a temperature difference is created between two different metals or semiconductors. Then, a voltage differential is created between the materials and upon the connection of a generator in the loop, current flows. With increased temperature differences, the induced voltage differential increases, resulting in increased power production.

A Maximum Power Point Tracking (MPPT) system is integral to the incorporation of the Thermoelectric Module (TEM) into the stove. It is an electrical system designed to ensure maximum power output from the TEM. In order to output the maximum power, the MPPT adjusts the load to match the TEM's internal impedance. Design and operation of the MPPT can be broken down into three parts. These parts are the timing and half voltage tracking circuit, boost converter, and buck converter.

The development of the next generation stove design builds upon the work done in projects P12441 and P12442. These groups attempted to bring heat to the TEM through the use of a conduction beam, which led to inadequate contact with - and heat transfer to - the TEM. Additionally, no previous group has been able to get the Maximum Power Point Tracking system to be fully functional. These areas are both addressed in the current design.

## PROCESS

*Stove Design*

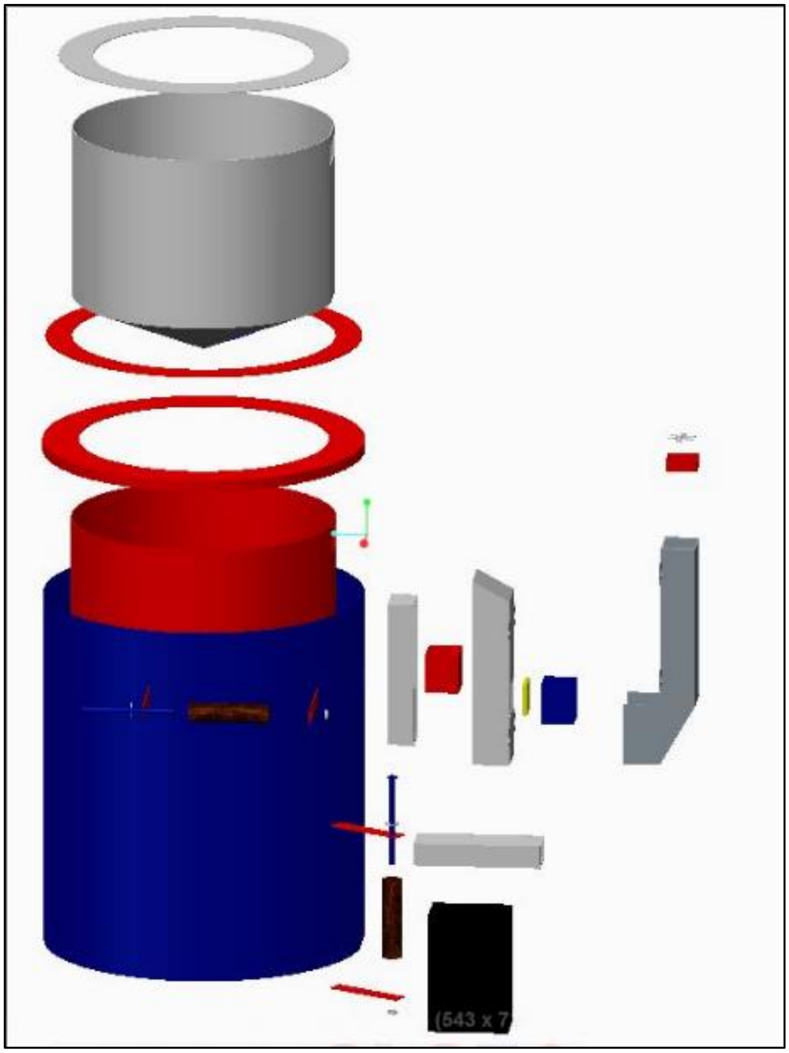
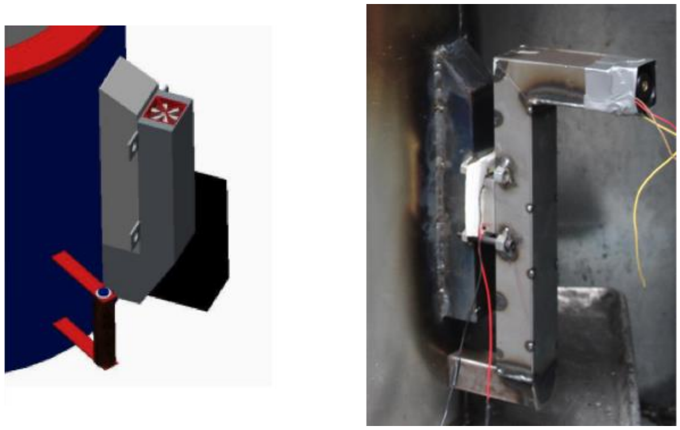


**Figure 1: Conceptual stove design, exploded view**

The conceptual stove body, shown in Fig. 1, was loosely based on the design of the Hecho Mirak - a slightly more efficient stove used in Haiti - which incorporated a rounded bottom into the combustion chamber that collected the charcoal pieces into the center of the stove and improved combustion efficiency. This bowl shape was later changed into a cone in order to simplify manufacturing. A skirt was also incorporated into the stove body to reduce heat losses, and a cap was placed on top of the skirt to allow for different sized pots to be used with the fixed skirt design.

The combustion chamber was designed to have a snug fit with the inner wall, which acts as a radiative barrier and helps to increase thermal efficiency. The cone section of the combustion chamber was double layered to improve longevity. The flanges on top of the inner wall and the combustion chamber were staggered to accommodate pots ranging in size from 30 cm to 40 cm in diameter. The outer wall is separated from the inner wall on the sides and bottom to allow room for insulation. In order to incorporate the skirt into the outer wall, the outer wall was extended an extra 6 inches past where the base of the pot sits.

After deciding that conduction was not an effective method of heat transfer, a series of Pugh charts were used to evaluate a set of possible solutions. Eventually, it was decided that a chimney system would be used to funnel hot exhaust air from the stove to the TEM. When the pot is placed on top of the combustion chamber, it effectively seals the top of the chamber, and forces the air out through the chimney. Convective heat transfer occurs in the chimney as the hot air passes over a heat sink in contact with the TEM. The air then re-enters the stove in the skirt section because experimentation showed that exhausting this air immediately after the TEM caused significant reductions in thermal efficiency.



**a) (b)**

**Figure 2: Conceptual chimney design (a) and finalized chimney design (b)**

The cold air inlet was designed with a ninety-degree bend at the top of the chimney that moves the fan farther away from the hot air exit. The hot duct is made of sheet steel and welded to the stove body, and the cold duct is made from a combination of sheet steel and one inch square metal tubing. The cold duct can be removed from the stove and connects to the hot duct via four Allen screws threaded through nuts on the outside of the chimneys. The conceptual and final duct designs are shown in Fig. 2.

*Pressure Section*

In order to optimize the fuel efficiency and reduce harmful emissions from the stove, it was necessary to determine the airflow rate that provides the most complete combustion. A flow rate too high or too low for optimal combustion efficiency results in decreased TEM performance and increased emissions. Empirical research done on charcoal stoves in Mongolia found that the lowest rates of carbon monoxide production occur when excess air supplied to the stove does not exceed 300%. Through the application of stoichiometric combustion equations, it was determined that the optimal rate of air addition to the stove is 8.75 cubic feet per minute (CFM).

Air must be supplied to the stove at both the proper flow rate and appropriate pressure. The pressure drop through the stove is calculated using Bernoulli's Equation--shown below--by assuming that the flow is fully developed at all points of interest, the effect of elevation on pressure variation is negligible, and all pressures are gage pressures.

$$\left(\frac{P_1}{\rho_1}+\alpha_1\frac{\overline{V}_1^2}{2}+gz_1\right)-\left(\frac{P_2}{\rho_2}+\alpha_2\frac{\overline{V}_2^2}{2}+gz_2\right)=h_{\ell t} \qquad (1)$$

The overall pressure drop in the system was determined to be 47.2 Pa, and the calculated pressures at points of interest are shown below in Fig. 3 and Table 1.

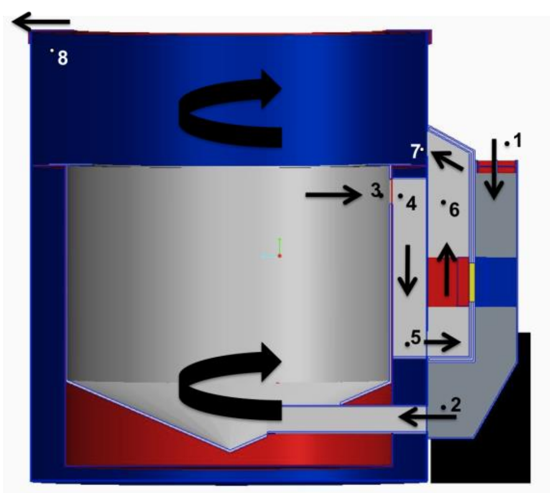
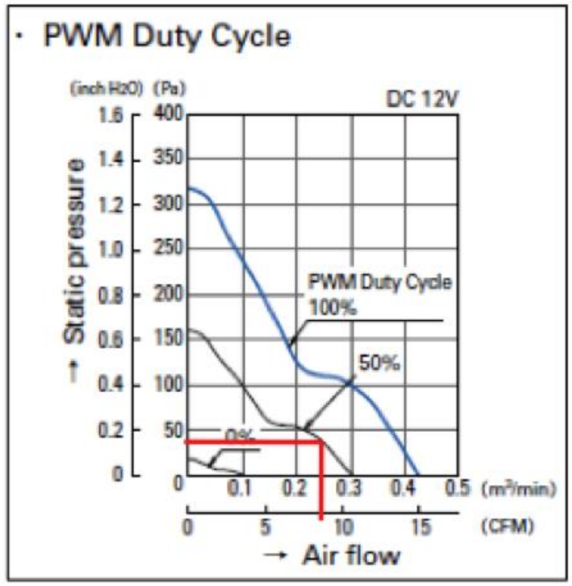



**Figure 3: Conceptual stove cross-section with air flow path and points of interest**

**Table 1: Calculated pressure drop at key points of the stove cross-section**

| State Point | Temp. (K) | Gage Pressure (Pa) |
|---|---|---|
| 1 | 300 | 0 |
| 2 | 385 | 2.3 |
| 3 | 775 | 1.7 |
| 4 | 775 | 14.6 |
| 5 | 775 | 20.4 |
| 6 | 690 | 25.6 |
| 7 | 690 | 26.3 |
| 8 | 475 | 47.2 |

Fan selection was governed by three key values: flow rate, pressure drop, and fan power consumption. The selected fan is manufactured by Sanyo Denki and has a rated power consumption of 2.76W while supplying air at a rate of 14.8 CFM or a pressure of 318 Pa. Additionally, the fan has the ability to function through the use of a pulse-width modulation (PWM) control, which means that the fan is able to accept an input signal that is changing between the on and off positions so rapidly that the fan appears to run continuously, albeit at a lower output. The fan was selected to be operated at a flow rate of approximately 9 CFM at a pressure of approximately 45 Pa (50% duty cycle). The operation curve is shown in Fig. 4, at right.




*Heat sink Selection*

Heat sink selection was based upon the temperature of exhaust gases during empirical testing of a prototype stove that incorporated a primitive chimney concept which mimicked the final design. After the water came to a boil, the exhaust gases were measured at 500 C. Following the assumption that the average ambient temperature in Haiti is 25 C, fin resistance was calculated based on the design heat transfer rate of 200 W. The resistance was calculated with the equation below.

$$Q = \frac{\Delta T}{R} \tag{2}$$

The Birmingham Aluminum 8052HS heat sink provides the nearest resistance to the calculated ideal at 0.6 C/W for an airflow of 4 m/s. To verify that the heat sink would perform adequately, an internal flow analysis was used. It was assumed that the heat sinks would fully fill the chimney, channeling all flow between the fins. Manufacturer-provided schematics were used to determine the hydraulic diameter, Reynolds' number, and Nusselt number. It was assumed that the area around the heat sink in the chimney would be insulated.

Fin efficiency was determined to be 0.3 C/W, far better than the design specifications. However, this heat sink was selected on the assumption that previously unaccounted for losses would likely occur and would reduce the amount of heat transferred through the heat sink.

*Maximum Power Point Tracking*

In order to provide enough power to each electrical subsystem, maximum power point tracking of the thermoelectric module's output is required. Fundamentally, it must be understood that there is a linear relationship between temperature difference across the TEM and TEM power output. Therefore, any changes in the temperature difference will yield a proportional change in power output. The half voltage tracking circuit is where the output voltage from the TEM is compared to that of the desired output. For this particular TEM, half of the open circuit voltage guarantees an output with maximum power. The key components to track the half voltage at a given time are power FETs (as switches) and Capacitors (storage of the voltage). The power FET's are switched on and off, allowing two equal valued capacitors to sample half of the TEM's open circuit voltage. This value, as well as the TEM output is then fed to a comparator. The comparator output is used to control the Boost converter section of the MPPT.

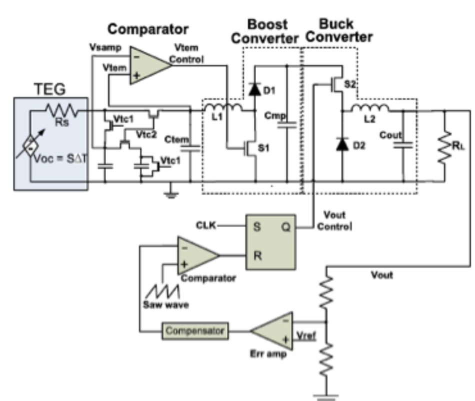



Figure 5: Layout of the MPPT circuit[4]

The next step in constructing the MPPT is designing a boost converter that can step up the output voltage above minimum value needed to charge a 6.5V sealed lead acid battery. This portion of the system is controlled by the duty cycle (D) generated from the comparator of the timing circuit. As the TEM's output voltage increases it causes the boost converter to pull more current, which causes the comparator to switch more frequently. This creates a greater load on the device thereby regulating its output. Output voltage of the boost converter will then be dependent on the voltage across the TEM and D. Equation 3, shown below, relates the input voltage to the output voltage with respect to the duty cycle D. This relation helps design the boost for a certain output values. In addition, Equation 4 allows the design of an inductor that will maintain a Continuous Current Mode (CCM) in the boost converter. It also ensures the converter is capable of handling the desired current.

$$V_O = \frac{V_S}{1 - D} \quad (3)$$

$$L_{\min} = \frac{D(1 - D)^2 R}{f} \quad (4)$$

Lastly, the ramped up voltage is passed through a buck converter. The purpose of the buck converter is to step down the varying output range of the boost and provide a constant voltage that is necessary to operate all other additional circuits. For simplicity a pre-built buck converter was implemented for this project. The chosen buck converter required a large enough input voltage to handle the range provided by the boost converter as well as a programmable output voltage small enough to safely charge the 6.5V sealed lead acid battery. The prototype MPPT is shown in Fig. 6.

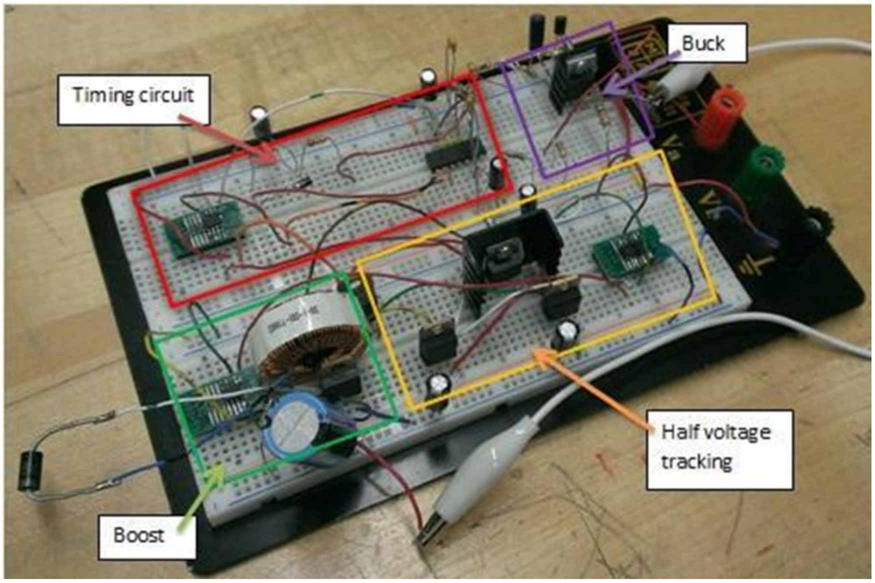



**Figure 6: Physical Layout of MPPT**

The remaining electrical subsystems utilize power output by the MPPT circuitry, and use it to charge a sealed lead acid battery, power a DC fan and provide power to a 5 V external USB charger. Various low voltage cut off circuits are used to prevent the battery from depleting fully in between cooking cycles. A 555 timer controlled restart circuit is implemented to allow the user to power the DC fan from battery power just long enough to start a fire within the stove. In order to further conserve battery power, the DC fan is controlled using a PWM signal that is adjustable between 45%-65% duty cycle. This reduces power used by the fan by 35%-45%.

## RESULTS AND DISCUSSION

Most of the electrical subsystems designed were successful in testing. All voltage cutoff circuits worked as intended, and correctly cut off power to various subsystems to prevent the battery from being over depleted. The USB charger and PWM fan control also operate exactly as expected. Figure 7 shows the adjustable control signal running the fan at 60% duty cycle. A startup circuit was implemented to allow the fan to run for 15 min off of battery power. This allows for the fan to be started multiple times even without fire to generate more power.

The only system that caused major issues while testing was the maximum power point tracking system (MPPT). The first issue that arose when testing was generating two timing signals that would switch the power FETs at the correct time. The signals were overlapping and causing two unmatched FETs to be turned on at the same time, which prevented the capacitors from charging. It was determined that a slight dead time between the falling edge of one signal and the rising edge of the second signal would fix the problem. This dead time was achieved using a 555 timer in astable mode. The astable 555 timer sends a signal to the power FETs as well as through an RC delay and into another 555 timer set to monostable mode. By triggering the second signal off the first signal the overlap is eliminated.

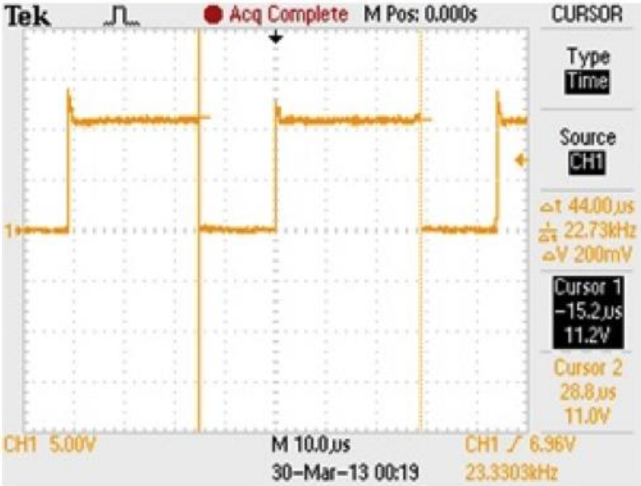



**Figure 7: Physical Layout of MPPT**

The next issue was that the power FETs weren't switching over the voltage range required for proper operation. This had a two part solution: first a new power FET was chosen with a smaller gate to source voltage, allowing it to switch at lower voltage levels, and second, by feeding the control signals through a premade gate driver IC before connecting to the gate of the FETs. After these changes, the timing section of the MPPT was able to correctly track the TEM's output voltage and generate a half voltage value.

The most difficult problem with the MPPT circuit was designing the boost converter. Due to the varying input voltage coming from the TEM, as well as the varying switching frequency from the timing circuits comparator, it was impossible to calculate an ideal inductor value. The best solution was to use trial and error, testing a wide range of inductor values, and measure the output voltage over a range of input voltages. As the input voltage and switching frequency changed, so did the boost's output voltage. The goal was to ensure the boost converter constantly outputs a voltage greater than the minimum requirement over the given input range. Eventually a proper inductor value was found, but it overheated in a matter of seconds. The solution to this issue was to order an equivalent inductor with a much greater current rating.

After finding the boost converters output range and acceptable buck converter was purchased. With the final component in place a constant output voltage was found given various input voltages and output loads. This constant output value was exactly what was expected. Unfortunately when testing with the actual stove it seems that the TEM is not reaching the minimum voltage level required to turn on necessary IC's and switch the power FETs on and off.

For the mechanical side of the project, in accordance with the customer needs and specification, fuel use, emissions production, time to boil, and ability to provide the necessary heat to the TEM were the main focuses. The fuel use was analyzed over the whole cooking session and was also split into pre-boil and simmer periods. While we did not decrease the amount of fuel used during a cooking session, the results helped make recommendations for any future groups that may be assigned to a similar project. Fuel consumption was increased from 0.670 kg used in the rebar stove to 0.759 kg used in the updated stove. This represents a 10.7% increase in fuel use.

For carbon monoxide emissions, the concentration of carbon monoxide was measured using a sensor. For the rebar stove test, carbon monoxide measurements were taken every minute, while measurements were only taken every five minutes during the updated stove test. Additionally, data was extrapolated for the updated stove test in place of missing data as a result of power failure in the test setup. Integrating the carbon monoxide measurements over time and then multiplying by a constant provided by the project that created the test setup provided the total carbon monoxide emissions of the testing session. For the rebar test, carbon monoxide production totaled 279.969 g with 89.770 g and 190.199 g of CO being produced in the pre-boil and simmer phases respectively. The updated stove provided an improved overall total of 187.610 representing a 33% decrease in carbon monoxide production. During the pre-boil portion of the test, the updated stove did show a 2.6% increase in emission, however, the 49.8% decrease in CO emission during the simmer portion of the test more than made up for that decrease.

Time to boil was another important metric used to determine the success of the stove. For the rebar stove, boil time was benchmarked at 25:45. The updated stove was able to achieve a boil time of 18:54 minutes. This represents a 26.6% decrease in boil time.

For emissions control, particulate matter is equally important as carbon monoxide. Following the method established by the team responsible for building the test setup, the particulate matter was measured using small paper filters through which a fraction of the exhaust air passes. The change in mass of these filters before and after the cooking tests will determine the total particulate matter produced by the stove. The updated stove produced 850.575 mg per session, while the rebar stove produced only 344.828 mg per session. This represents a 146.7% increase in particulate matter production over traditional methods. These results seem to contradict qualitative observations made during testing that saw much of the particulate trapped within the chimneys or the combustion chamber of the stove.

Finally, the ability to provide adequate heat to the TEM was measured. During testing, an ideal 200 degree temperature difference was achieved resulting in an output voltage around 2 V. This indicates that there is a problem with the TEM that it cannot output an ideal 4 Volts even with the necessary heat transfer. Never the less, the updated stove can induce power from the TEM and assuming the MPPT could provide the necessary load, the TEM would function as expected. In this area, the stove was a success.

**Table 2: Calculated pressure drop at key points of the stove cross-section**

| | Rebar Stove | New Stove | % Improvement |
|---|---|---|---|
| Simmer Time (min) | 45 | 45 | n/a |
| Time to Boil (min) | 25:45 | 18:54 | 26.6% |
| Fuel Burn (kg) | 0.670 | 0.759 | -13.3% |
| Cold Start | 0.299 | 0.353 | -18.1% |
| Simmer | 0.371 | 0.406 | -9.4% |
| CO (g) | 279.969 | 187.610 | 33.0% |
| Cold Start | 89.770 | 92.090 | -2.6% |
| Simmer | 190.199 | 95.520 | 49.8% |
| PM (mg) | 344.8275862 | 850.575 | -146.7% |
| Max recorded voltage (V) | n/a | 2.018 | n/a |

## CONCLUSIONS AND RECOMMENDATIONS

Though this year's design was not successful in meeting all of the customer's needs and specifications, it certainly took the project in a new direction, and significant insights were gained with regard to improving the design for next year. The design showed great promise in overcoming the issues faced by previous groups, which struggled to provide a consistent and uniform temperature gradient across the thermoelectric module. By incorporating convective heat transfer as the primary means of providing thermal energy to the TEM, a consistent temperature gradient of 200 C was achieved for prolonged periods of time. Despite having the requisite design temperature difference, the TEM was unable to produce an output voltage large enough to power the MPPT circuit.

A key issue with the convective heat transfer system was that throttling the fan to control the boil or simmer phase of the test resulted in very different convective heat transfer coefficients. This caused significant design issues, as the TEM was vulnerable to being damaged if the system was designed for a steady-state convective system, and if the system was designed so that the TEM would survive the pre-boil phase then it wouldn't generate the requisite voltage during the simmering portion of the cooking process. In this iteration of the project, the stove was designed to operate at the pre-boil temperatures, and was therefore not adjustable down to a simmer. The results show that the stove and the thermoelectric system meet the required temperature difference of 200 C across the TEM, however the voltage output does not meet expectations.

In order to remedy the TEM issues, a couple of practical solutions exist. The simplest solution to implement would be to select a new TEM with a more appropriate operating range and design operating point, that would allow the TEM to operate continuously during both the pre-boil and post-boil stages of the cooking process. The current TEM is severely limited because in order to get the appropriate temperature difference of 200 C across the module, the hot side of the module must be kept at nearly 350 C, the maximum operating temperature for the module. Operating the TEM at lower temperature ranges is impossible given the available cooling system, which relies upon ambient air to cool the cold side of the TEM. A second solution is to install a bypass system into the stove, which allows the hot exhaust from the combustion chamber to bypass the thermoelectric portion of the system in the pre-boil stage, and that could be switched to the thermoelectric portion of the system in the post-boil, steady state stage.

Major improvements still need to be made within the electrical systems. The fact that the maximum power point tracking system was unable to operate at the low voltage being output by the thermoelectric module prohibits the remaining subsystems from working as intended. It is recommended that future teams trying to improve upon these results focus their time and energy into the MPPT design. It might be worthwhile to look into a digital approach to maximum power point tracking, using a microcontroller. This would involve slightly more initial effort to design the necessary tracking algorithms and learn how to code them, but could save time during the debugging stages. Regardless of the approach used, this project cannot be successful without a fully operational MPPT system. Given that the remaining subsystems have already been successfully built and tested, all future efforts should mainly focus on MPPT operation and not the remaining subsystems.

Over the course of the design process, it was decided to focus primarily on the thermoelectric component of the system, because it had proven to be the most problematic system throughout the previous iterations of the project. As a result, little attention was paid to the impact of design decisions on reducing emissions and fuel usage.

Furthermore, additional effort was put into troubleshooting the thermoelectric system, so emission and fuel usage data was not collected for a controlled-cook test. In order to improve upon the current design in future project iterations, it is strongly recommended that the project scope should be trimmed back to focus exclusively on either the environmental aspect of the stove design, or on the thermoelectric component of the design. Once the first of these two goals is attained, a second project can focus on altering the design so as to meet the second set of goals. It is the recommendation of this group that primary focus be given to the design of a fully functional thermoelectric cookstove, and that subsequent projects focus on improving the fuel efficiency and emissions of the working thermoelectric stove.

## REFERENCES

[1] WHO, ed. The World Health Report 2002: Reducing Risks, Promoting Healthy Life. Geneva, World Health Organization, 2002.

[2] Kim, Shiho, Sungkyu Cho, Namjae Kim, and Jungyong Park. "A Maximum Power Point Tracking Circuit of Thermoelectric Generators without Digital Controllers." 7 (2010): 1539-545. Print.

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