Motorcycle Waste Heat Energy Harvesting

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ABSTRACT

Environmental concerns coupled with the depletion of fuel sources has led to research on ethanol, fuel cells, and even generating electricity from vibrations. Much of the research in these areas is stalling due to expensive or environmentally contaminating processes, however recent breakthroughs in materials and production has created a surge in research on waste heat energy harvesting devices. The thermoelectric generators (TEGs) used in waste heat energy harvesting are governed by the Thermoelectric, or Seebeck, effect, generating electricity from a temperature gradient. Some research to date has featured platforms such as heavy duty diesel trucks, model airplanes, and automobiles, attempting to either eliminate heavy batteries or the alternator. A motorcycle is another platform that possesses some very promising characteristics for waste heat energy harvesting, mainly because the exhaust pipes are exposed to significant amounts of air flow. A 1995 Kawasaki Ninja 250R was used for these trials. The module used in these experiments, the Melcor HT3-12-30, produced an average of 0.4694 W from an average temperature gradient of 48.73 $^\circ C$. The mathematical model created from the Thermoelectric effect equation and the mean Seebeck coefficient displayed by the module produced an average error from the experimental data of 1.75%. Although the module proved insufficient to practically eliminate the alternator on a standard motorcycle, the temperature data gathered as well as the examination of a simple, yet accurate, model represent significant steps in the process of creating a TEG capable of doing so.

Keywords: Thermoelectrics, energy harvesting, motorcycle

1. INTRODUCTION

Due to the surge in environmental concerns and the increase in conservation efforts, energy harvesting research has experienced a rebirth in the last decade. Dramatic breakthroughs in available materials has also created opportunities for new applications of waste heat energy harvesting devices. In 1821 Thomas Seebeck discovered the Thermoelectric, or Seebeck, effect, which states that when the junction of two dissimilar metals is heated there will be a potential difference across them given by $V = S\Delta T$, where V is the voltage, S is the Seebeck coefficient, and ΔT is the temperature difference.[1] Thermocouples are temperature sensors that utilize this effect by having two different metals soldered together. In conjunction with a separate temperature reference, the temperature is then read by scaling the output voltage. Thermoelectric modules take it a step further and connect multiple thermocouples composed of P and N type thermoelements together electrically in series and thermally in parallel, as can be seen in Figure 1. Thermoelectric modules have primarily been utilized in conjunction with the Peltier effect, which is the opposite of the Seebeck effect, as cooling devices because of the low efficiencies of the modules. However, with the availability of doped bismuth telluride for use in thermoelectric modules, the efficiencies have risen to a level capable of creating practical waste heat energy harvesting systems that use the Seebeck effect to generate electric power from a temperature gradient. Therefore, thermoelectric generators (TEGs) are being tested for use in various applications in efforts to reduce moving parts, increase mobility, decrease weight, and increase fuel efficiency.

An important application that has been receiving much attention recently is the use of TEGs as waste heat energy harvesters for internal combustion engines. Haidar and Ghojel[2] tested a TEG constructed on the exhaust pipe of a diesel engine. Using four Hi-Z Technology, Inc. HZ-14 modules and active liquid cooling they achieved 42.3W of electric output from a temperature gradient of 237$^\circ C$. They proposed using 70 of these

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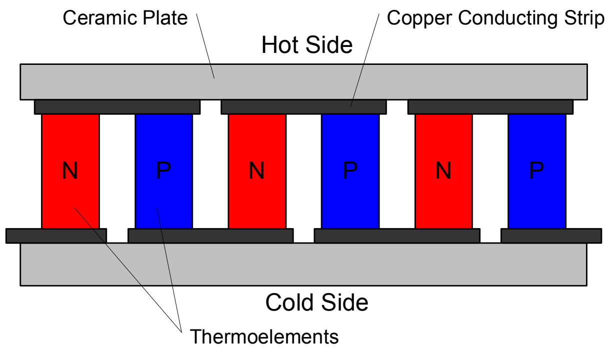

Figure 1. Basic configuration of a thermoelectric module

modules to create a TEG powerful enough to replace the alternator, theoretically increasing gas mileage by two to five percent. Kushch et al.[3] took the next step in Hi-Z Technology, Inc's own project by building the second generation of a TEG mounted on the exhaust of a heavy duty class eight diesel truck engine, specifically the Cummins 335hp engine. Using 72 HZ-14 modules and active liquid cooling it was tested in the lab to produce over 900W at an engine load of 300hp, giving them enough power to consider starting road-tests of the TEG. Thacher et al.[4] built a TEG on the exhaust of a 1999 GMC Sierra pickup truck with 16 HZ-20 modules. The TEG consistently produced 177W at a speed of 112.6km/h on a zero grade. They ran multiple tests while varying the characteristics of the cooling system and concluded that reducing the cold side temperature was more effective in increasing the power of the TEG than increasing the hot side temperature. This, however, does depend on the temperature range the specific module was designed for.

On a smaller scale, Fleming et al.[5] created and tested the VHHFM-2HE, a small, high power density module based off of a Hi-Z Technology, Inc. module on the OS Max 0.61 in^3 off-the-shelf model aircraft engine. They examined the possibility of replacing the batteries in a microair-vehicle to reduce weight and increase run-time. In the end they achieved a power density of 0.21W/g. They also concluded that reducing the weight of the TEG by using high-temperature thermally conductive adhesive instead of mechanical fasteners as well as using miniature heat exchangers on both the hot and cold sides of the modules made a big difference in the resulting power density. On this small of a scale, obtaining a large enough power density for most applications has proven difficult for the basic modules composed of bismuth telluride. In addition, most manufacturers focus on raising the figure of merit (ZT) of the material beyond 1 instead of decreasing the size of their modules. The ZT of a material is determined by the Seebeck coefficient, the thermal conductivity, the electrical conductivity, and the mean operating temperature. High-Z thermoelectric thin-films show great promise in boosting the power density of TEGs, however, due to their small height, creating a large temperature gradient across the films remains difficult.[6] Therefore, until modules with ZTs higher than 1 become commercially available, the usable temperature gradient in some new applications should be explored and optimized by concentrating on the entire TEG system.

One such application is on a motorcycle. With an automobile, the exhaust pipes are underneath the car where airflow is restricted to increase the aerodynamic down force. On a motorcycle, however, the exhaust pipes are typically on the side of the frame completely open to airflow. The focus of this paper is to determine the feasibility of mounting a TEG on the exhaust of a motorcycle and replacing the alternator with currently commercially available thermoelectric modules.

2. EXPERIMENTAL SETUP

On a motorcycle, the exhaust leaves the engine block through the headers, which in turn take it to the rest of the exhaust pipe and the muffler. According to an analysis performed by Park et al.,[7] the temperature of the exhaust is highest in the headers, decreasing as it travels further away from the engine block. A motorcycle's exhaust system does not include a catalytic converter, therefore, decreasing the temperature of the exhaust too much is not of any concern. Also, another aspect of a motorcycle's exhaust system that should be noted is that the temperature of the surface of the muffler decreases dramatically from that of the outside of the exhaust pipe leading up to it. A 1995 Kawasaki Ninja 250R was used in this experiment. It has a two cylinder, 248cc internal

Figure 2. The Kawasaki Ninja 250R

combustion engine and the alternator produces 14V at 17A. Initial tests with an infrared thermometer after various rides around town and on the highway showed that the headers reached at least 280°C. In addition to this temperature being too high for most commercially available high temperature thermoelectric modules, where the typical maximum operating temperature is around 220°C, the headers are highly curved and the airflow is blocked by the wheel. Therefore the ideal place for a TEG would occur farther along the exhaust, right before the muffler. In this location, not only was the outside temperature of the pipe within the operating limits of the modules, but it was more exposed to air flow allowing a lower cold side temperature. The modules that were used for this experiment were the Melcor HT3-12-30's. They are 1.18in wide by 1.34in long and 0.126in tall, consisting of 127 Bismuth Telluride thermocouples soldered together with 271°C SnSb solder and enclosed in Alumina ceramic plates. They have a maximum operating temperature of 200°C. These modules were used

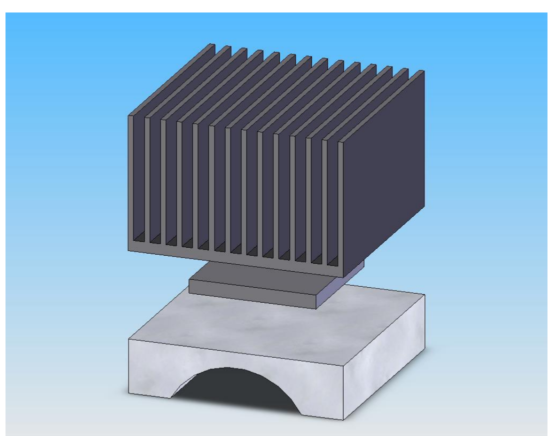

Figure 3. The HT3-12-30 module between the heat sink and the bracket

Figure 4. The TEG mounted on the exhaust pipe of the Ninja 250R

because they were readily available and the focus of this initial experiment was to find possible temperature gradients and evaluate the accuracy of a basic model. A mounting bracket was machined out of aluminum to fit around one side of the exhaust pipe. A simple aluminum cold-side heat sink was attached directly to the mounting bracket with screws. A basic exploded view of the assembly can be seen in Figure 3. With the module securely sandwiched between the mounting bracket and the heat sink with Arctic Silver thermal grease on both sides and standard heat sink grease between the mounting bracket and the exhaust pipe, the entire TEG was secured to the exhaust pipe with a hose clamp, visible in Figure 4. K-type thermocouples were used to read the hot and cold side temperatures of the module and placed inside grooves made on the surfaces of the heat sink and the bracket. In order to prevent a closed electric circuit from developing between them, the grooves were lined and the thermocouples were secured with high temperature Kapton tape. A Pace Scientific, Inc. XR5-SE-M-50mV data logger secured underneath the seat of the motorcycle collected the data. It has eight analog inputs at 12 bit resolution and the capability of reading all types of thermocouples with an internal cold-junction temperature compensation source. A simple RadioShack switch served as an external trigger that came out from underneath the seat so that the rider of the motorcycle could easily turn the data logger off and on repeatedly during the ride. A resistance placed in the circuit allowed a measurement of the current as well as the calculation

Figure 5. The Pace Scientific, Inc. XR5-SE-M-50mV data logger mounted underneath the seat

of the power output of the module. A thermoelectric module works best when the load resistance of the circuit matches the internal resistance of the module. Although given with the manufacturer's specifications, a resistor sweep test confirmed that the maximum power output would occur at that value, 5Ω. The results of this test are shown in Figure 6.

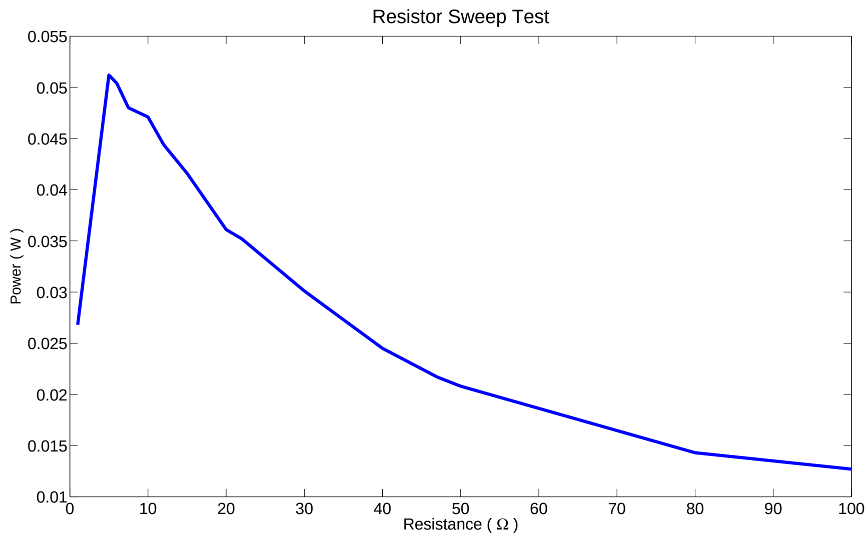

Figure 6. The results of the resistor sweep test in the lab

3. RESULTS

3.1 Experimental Results

Five trials, outlined in Table 1, were run at various driving conditions. These conditions cover all general motorcycle usage. In order for the motorcycle to heat up to normal operating temperatures, the rider activated

Trial Descriptions		
Trial 1	25mph	Around Campus Driving
Trial 2	35mph	City Main Street Driving
Trial 3	45mph	Country Road Driving
Trial 4	55mph	Highway Driving
Trial 5	65mph	Freeway Driving

Table 1. Trials Performed

the data logger in the middle of the ride. An example of some of the raw data that was obtained during the fifth trial can be seen in Figure 7. The temperatures obtained from the K-type thermocouples have a significant amount of noise, so in order to obtain a more accurate representation of the temperatures, the data was run through a smoothing algorithm in Matlab. More specifically, a robust loess algorithm with a span of 2.5%. This uses linear least squares fitting and a second-degree polynomial that is resistent to outliers. An example of the results of the smoothing algorithm with the fifth trial can be seen in Figure 8. The Seebeck coefficient as well as the output power for the five trials were found using the smoothed temperature data as well as the matched load resistance of 5Ω. The Seebeck coefficient being defined as $S = V/\Delta T$, and the output power being defined as $P = V^2/R$. As Figure 9 illustrates, the mean temperature gradient as well as the mean power output increased along with the speed of the motorcycle during the trials. Overall, the trials resulted in an average temperature gradient of $48.73°C$, an average Seebeck coefficient of 0.02601V/C, and an average power output of 0.4694W. These were obtained by averaging the means of the trials.

Using the average power output of the module it would require 570 modules to match the 14V, 17A output of the motorcycle's alternator. This corresponds to around 5m of exhaust pipe with a TEG wrapped completely around it. This number resulted because it would require 10 modules in series and 57 in parallel to match the voltage and current outputs of the alternator, respectively.

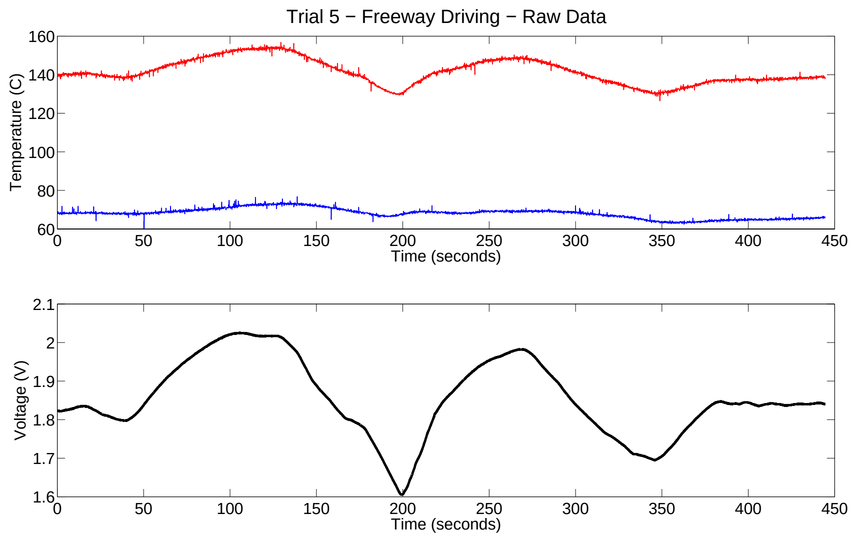

Figure 7. An example of data received from the Pace Scientific Data Logger

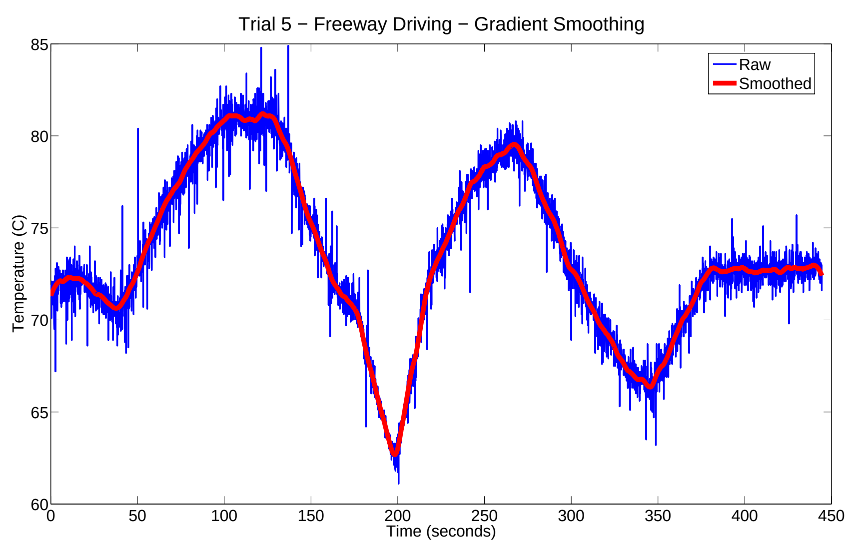

Figure 8. An example of the smoothing of the data obtained from the thermocouples

3.2 Mathematical Model

Using a simple model one can determine whether it would be possible to accurately predict the output of a thermoelectric module. First, the Seebeck coefficient of the module was calculated using the mean Seebeck coefficient from all the trials. The little variation in the Seebeck Coefficient between the trials as illustrated in Figure 9 validates this assumption. Then, varying the temperature gradient between 0-90°, the voltage, current, and power were calculated given the same 5Ω load. The result can be seen in Figure 10. Using the model and the mean temperature gradient of $48.73°C$, theoretical outputs of 1.268V, 0.2535A, and 0.3213W resulted. These values differ slightly from the averages from the trials, which were 1.516V, 0.3033A, and 0.4694W. Further analyzing the data, Figure 11 shows the voltage and resulting power outputs from the module against the projected outputs according to the model for Trial 5. The mean errors of the model for each of the trials can

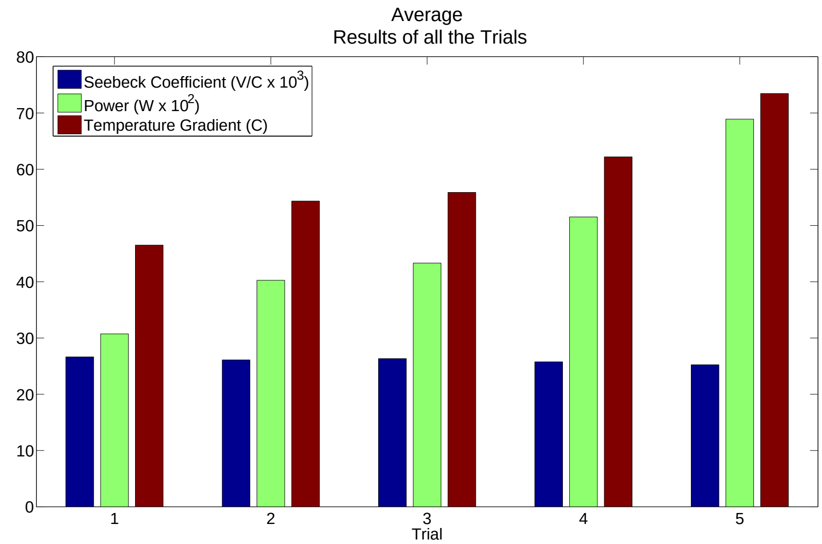

Figure 9. The mean Temperature Gradient, Seebeck Coefficient, and Power for each of the trials

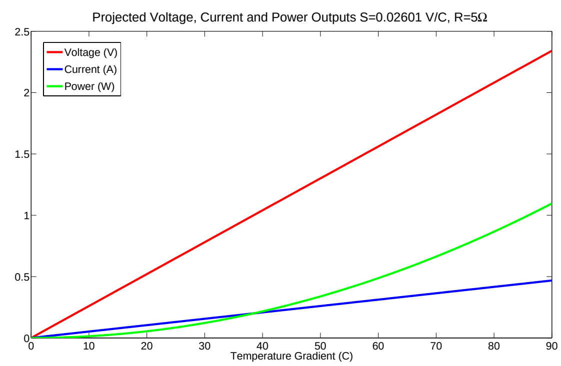

Figure 10. The mathematical model for the HT3-12-30 module with a 5Ω load

been seen in Table 2 along with the averages of these values. There does not appear to be any correlation between the raw data and the individual mean errors. What can be seen, however, is that the model is relatively accurate, with a maximum mean error of 6.2%. Taking the absolute value of all of the errors and then averaging produces an average voltage error of 1.75% and an average power error of 3.18%, which are more representative of the accuracy of the model than the averages shown on the table.

Model Errors (percentages)		
Trial	Voltage	Power
1	−2.37	−4.67
2	−0.35	−0.69
3	−1.99	−2.36
4	0.99	1.99
5	3.05	6.20
Average	−0.13	0.09

Table 2. The mean errors of the model for all the trials

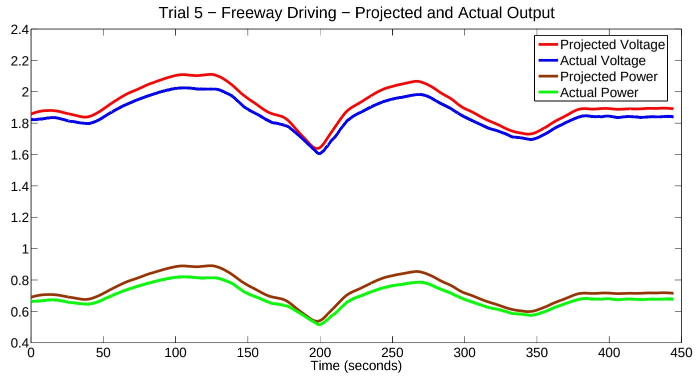

Figure 11. The projected as well as the actual voltage and power outputs of the module for Trial 5

4. CONCLUSIONS

Although the specific module used in this study lacks the output required to feasibly replace the alternator of the motorcycle, many promising results emerged from this experiment. First, the temperatures obtained from the thermocouples on either side of the module show that even with a basic cold-side heat sink and no hot-side heat sink, large enough temperature gradients can be obtained to produce a fair amount of electrical power. Also, a decent number of commercially available thermoelectric modules exist that operate within this temperature range. Second, Table 2 shows that a simple model can be used to predict the output of a module with relative accuracy. Although information on the Seebeck coefficient of a module proved difficult to obtain without calculating it from experimental data, the relative consistency of the value throughout the various trials gives the impression that it can be easily calculated in a lab with just a hot plate and some sort of heat sink.

Further work on this application is necessary before it can be said whether TEGs would be advantageous or not on motorcycles with the current technology. The TEG used in these experiments is far from optimized. The module that was used is not the most advanced module commercially available. As mentioned in Fleming's article,[5] there are better options than standard mechanical fasteners, especially one as massive as a hose clamp. Smaller modules would create a better overall energy harvester even if the power density remained the same because they could be molded closer around the outside of the pipe and increase the efficiency of the heat transfer. Lastly, the heat sink was not optimized for this application and there was no hot-side heat sink present. All of these issues should be addressed before a definitive conclusion is made concerning the feasibility of using doped Bismuth Telluride thermoelectric modules to replace the alternator on a motorcycle.

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