Vehicle Efficiency Improvements via Surface-Mount Thermoelectric Generators

The Exhausted Team:

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Lab Section: Thursday 8:00AM
Lab GSI: Roger Isied

A. Abstract

This project introduces a novel approach to recapturing wasted energy in engine exhaust. A thermoelectric generator (TEG) is externally mounted to the surface of the catalytic converter and cooled with airflow; the temperature differential created across the TEG then generates electric potential. Approximately one watt was successfully extracted from a small-scale test platform, demonstrating feasibility and scalability of the energy-saving capabilities of the system.

B. Introduction

Background:

Common methods of vehicle efficiency improvements include experimenting with different fuel types, engine types (Wankel Rotary Engine[I], Turbine Engine[J]), drivetrain types (hybrid, electric, etc[K]), and employing turbochargers. One method of particular interest is the use of a thermoelectric generator (TEG) to recapture wasted heat energy. TEG systems present certain key advantages, like high durability, reliability, and lack of moving parts.[G] Presently, automotive companies have investigated this type of device in a parallel exhaust line heat exchanger utilizing exhaust gas to heat the TEG and the vehicle's radiator to cool it.[M] These systems typically produce around 100 watts of power nominally and up to 400 watts in extreme cases.[G] Although functional, they have yet to be implemented in consumer vehicles in large part due to their high weight, cost, and additional thermal load on the vehicle's radiator.[F]

Theory:

TEGs are solid state devices which take advantage of the Seebeck effect to produce electric potential. Within a TEG, alternating N- and P-type semiconductors use thermal energy to concentrate electrons on its cold-side.[B] These semiconductors are arranged in series, forming a thermocouple battery as shown in Figure 1. The output power of a TEG is highly dependent on three factors: the temperature differential across the device, overall operating temperature, and the system load resistance (Figures 2 and 3).[E] Energy output increases with an increasing temperature differential, but decreases with increasing operating temperature.

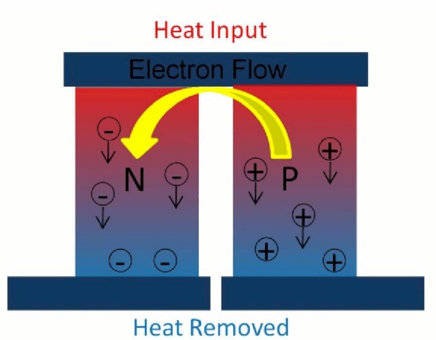


Figure 1: TEG Semiconductor Arrangement

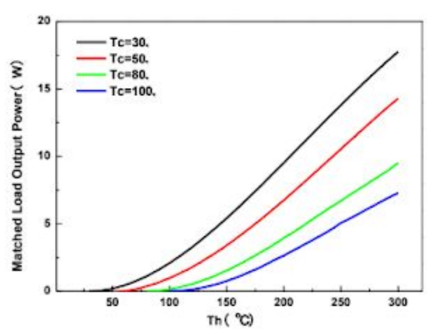


Figure 2: TEG Matched Load Output Power

Our Goals:
To reduce the costs, weight, and complexity of the current TEG systems, the team proposes a externally-cooled, surface-mounted version. Surface mounting removes the need for a heavy additional unit and reduces the operating temperature, thereby allowing for the use of significantly less expensive TEGs (~$56 for temperatures up to 320℃ versus $330 for temperatures up to 800℃).[E] External cooling the system eases the load experienced by the radiator system. Ultimately, our experiments are intended to demonstrate that this simplified system can produce reasonable amounts of power despite its lower cost, weight, and complexity.

***Assumptions*:**
We assume the UC Berkeley's engine dynamometer equipment and data acquisition system accurately measured relevant parameters. These measurements include throttle settings, thermocouple readings, and fluid flow rates. For our energy calculations, we assume complete combustion and gasoline composition of pure octane, C_8H_{18} ,[D] even though the actual gasoline used was 91 octane.[C]

Initial Hypothesis:
Our initial hypothesis was that our TEG module would not produce as much energy as the existing in-series TEG units, but that it would produce a better power-to-cost ratio. According to our TEG's datasheet, we expected an energy conversion efficiency of approximately 2%.

C. Methods:

Rationale:
This study focused on a simplified single-cell version of the system cooled with compressed air. Within time and financial limitations, this simplified device allowed us test its power output curve, confirm its ability to be cooled using airflow, and verify its capability to transfer heat from the exhaust manifold surface. This single-unit prototype can, in theory, be scaled to a larger system by adding more TEG units and covering a larger surface area of the exhaust manifold.

Experiment Design:
Our experimental procedure was divided into subsections including: initial system characterization, hardware design and testing, theoretical modeling, and data processing and analysis. Initial experiments helped develop relationships between throttle percentages, RPMs, energy efficiencies, and exhaust manifold temperatures. That data informed the design of the TEG system, which was then used to measure energy recaptured. The measurements taken from those experiments were then analyzed and compared with a analytical and FEM-based thermal models of the system All experiments were run using 91 octane fuel on the 1986 Pontiac 1.8L Turbocharged 4 cylinder engine in Hesse Hall at UC Berkeley.[C]

System Design:
A Powerwerkz wattmeter was used to measure the output power (dissipated across a load resistor) of the TEG. It was externally powered by a 9V battery to isolate its own power consumption, and provided information on current, voltage, and wattage produced by our device. Two additional thermocouples were added to measure the hot side and cold side temperatures of the TEG. The system's electrical diagram and energy flows are outlined below in Figure 4.

In order to maximize TEG efficiency, the load resistance, R_L, must equal mR_{batt}, where m is a characteristic of the thermoelectric material used and depends on its Seebeck coefficient, electrical resistance, and heat conductance, and R_{batt} is the total electrical resistance of the thermocouple battery, or TEG.[B] Based on TEG specifications and initial test data, the variable resistor is tuned to a R_L value of 3Ω (Figure 3).

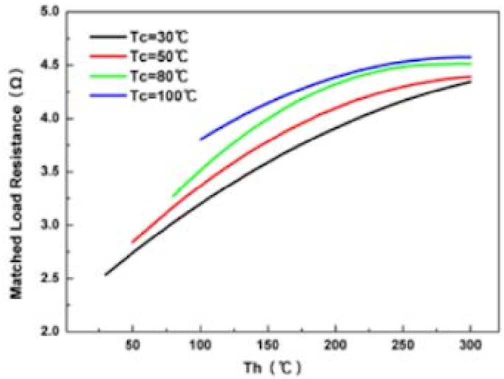


Figure 3: Matched Load Resistor Values

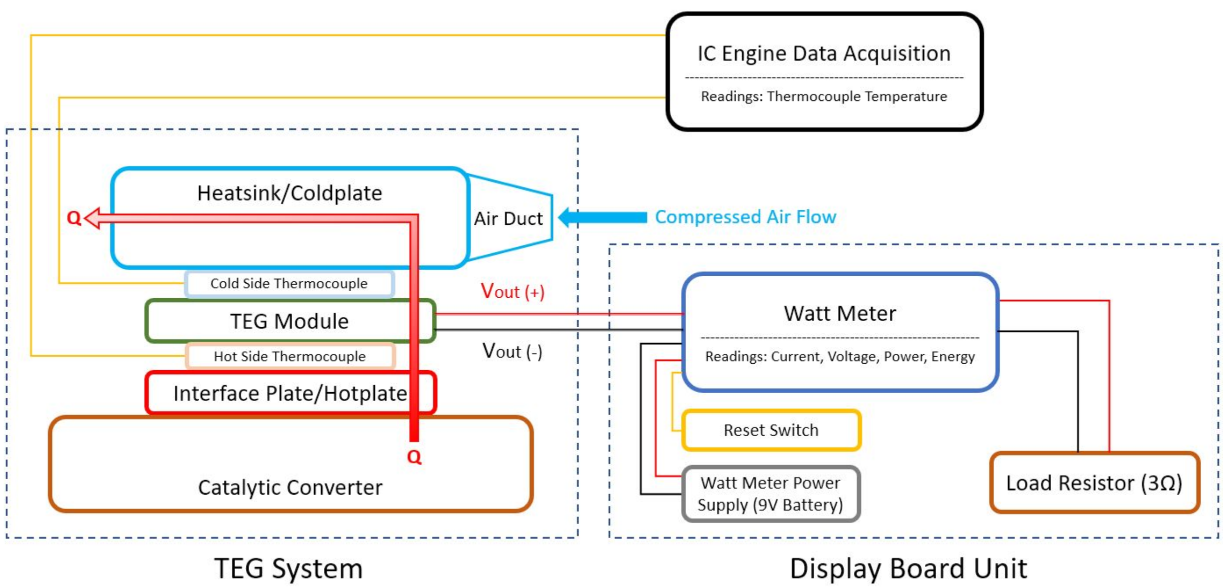


Figure 4: System Diagram of the TEG System, Data Acquisition, and Energy Flow

Hardware Design:

Due to its relatively flat surface, ease of access, and appropriate surface temperatures, the catalytic converter was chosen as our mounting location. A single TEG was clamped between an aluminum hotplate and aluminum heatsink with the aid of shallow pockets machined into the plates that retained the TEG unit and provided a flat surface to maximize conduction (Figure 5). The hotplate interfaced with the catalytic converter and the heatsink was cooled using compressed air to apply forced convection. Aluminum tape and a 3D-printed diffuser ensured uniform flow across the fins. Four bolts clamped the TEG between the hotplate and heatsink and insulating washers reduced heat transfer across those bolts. Two hose clamps affixed the hot plate to the catalytic converter. Overall system weight was 0.48kg and cost was approximately $60. The completed TEG System is shown below in Figure 6.

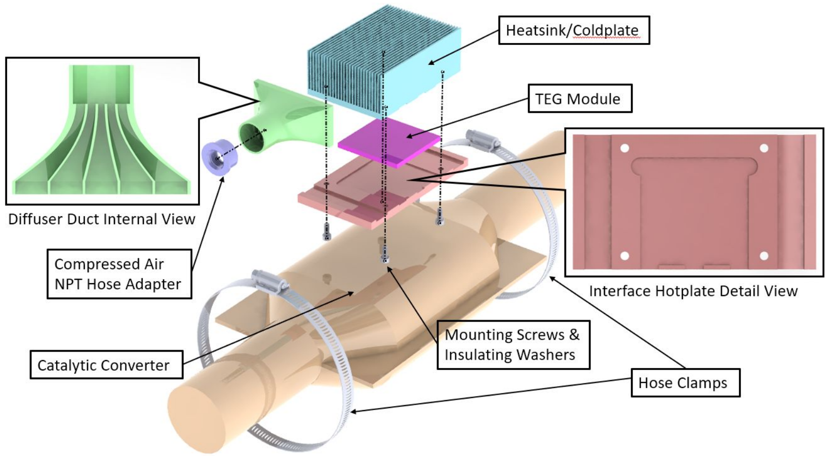


Figure 5: Exploded Assembly View of TEG Mechanical System with Detail Views of the Hotplate and Compressed Air Diffuser Duct

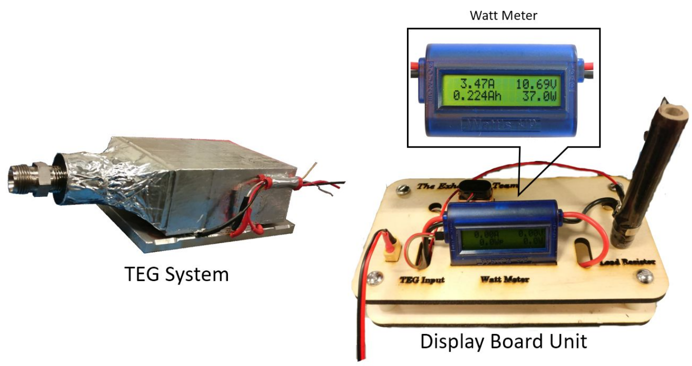


Figure 6: Manufactured and Assembled TEG System and the Display Board Unit

D. Results:

Initial Engine Characterization:

We began by collecting temperature data of the exhaust system using the FLIR Ax5 thermal camera.[L] This data was used identify the ideal mounting location for the TEG system and guide TEG part selection based on operating temperature. Figures 7 and 8 show thermal images of the engine at rest and at 2200 RPM at 60% throttle, respectively. To ensure accuracy, the temperature measurements of the FLIR camera were confirmed with IR gun.

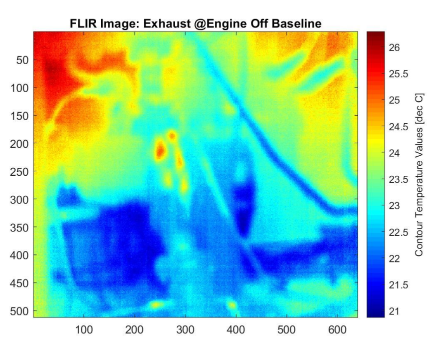


Figure 7: FLIR Image of the Engine Exhaust at Rest

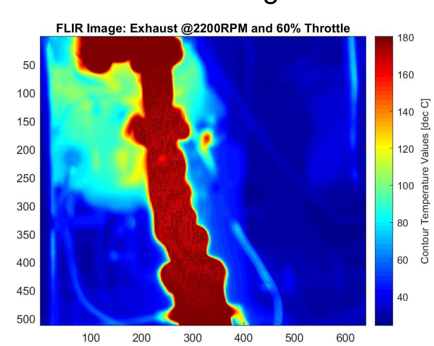


Figure 8: FLIR Image of Engine Exhaust at Load

From initial engine characterization data measured by the IC Engine sensor suite, four performance characteristics of interest were calculated: the energy input rate through the fuel, the energy loss rate through the exhaust, the percentage of total energy input lost through the exhaust, and energy loss rate across the catalytic converter. The following equations were used to calculate these values:

Energy Input Rate: $\dot{E}_{in} = \eta_{gas} f_{gas}$

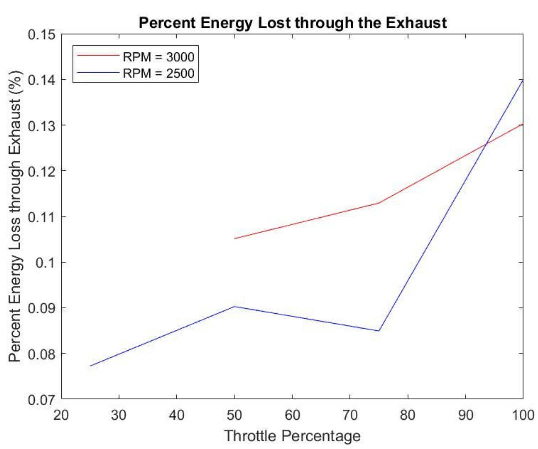
Energy Output Rate: $\dot{E}_{out} = \rho_{air}\, c_{air}\, \dot{V}\,(T_{\infty} - T_{CatIn})$

Percent Energy Wasted through Exhaust: $Percent_{exhaust} = \frac{\dot{E}_{out}}{\dot{E}_{in}}$

Energy Loss Rate across Catalytic Converter: $\dot{E}_{Cat} = \rho_{air}\, c_{air} \dot{V}\,(T_{CatIn} - T_{CatOut})$

For these calculations, η_{gas} was assumed to be the energy density of pure octane and the values associated with air (ρ_{air}, c_{air}) were taken at the temperature at the beginning of the catalytic converter. The values for flow rate (f_{gas}, $\dot{V}$) and temperature (T_{∞}, T_{CatIn}, T_{CatOut})were measured using the lab equipment and an average of the temperature within steady-state region was used in the calculations.

These measurements and calculations were performed for steady-state engine values at 2500 RPM with 25%, 50%, 75%, and 100% throttle and 3000 RPM with 50%, 75%, 100% throttle.These plots can be seen in Figure 9 below. As expected, the relative percentage of energy loss increased as throttle and RPM increased which indicates that, as increased loads and speeds are demanded of the engine, it becomes less efficient. The values for the energy loss rate across the catalytic converter did not display as clear of a trend, but did demonstrate that a significant amount of energy was lost across the catalytic converter.



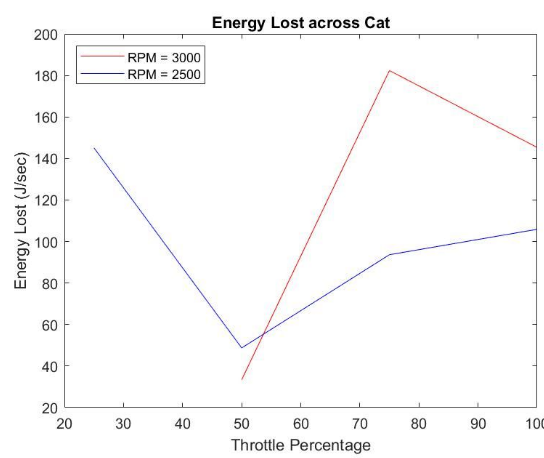


Figure 9: Initial Engine Characterization Results

TEG System Performance:

Next, the TEG system was mounted to the catalytic converter, the engine was run at various parameters, and the watt meter was used to measure power output of the TEG. Figure 10 shows the resulting characteristic plots of our system performance.

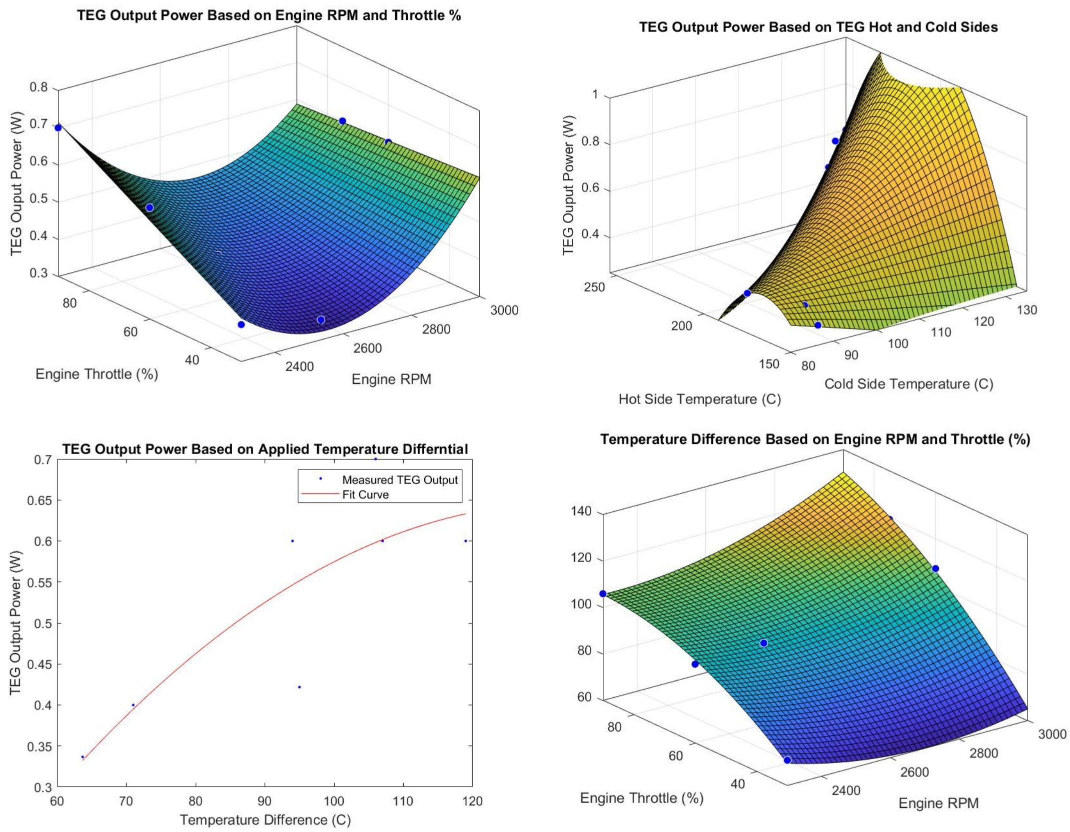


Figure 10: Graphs of the Temperature Difference and the TEG Power Output at Different Parameters

The resultant curve-fit equation and their associated confidence intervals are presented below in the following tables:

Table 1: TEG Output Power as a Function of Engine RPM and Throttle Percent

$Power\ (r = RPM,\ t = Throttle\ \%) = 1.5 * 10^{-6}\ r^2 - 0.0074\ r\ +\ -7.8 * 10^{-6}\ rt\ +\ 0.023t\ +\ 9.3$					
Value	$1.5 * 10^{-6}$	-0.0074	$-7.8 * 10^{-6}$	0.023	9.3
95% Bound Low	$2.3 * 10^{-7}$	-0.014	$-2.3 * 10^{-5}$	-0.015	1.5
95% Bound High	$2.8 * 10^{-6}$	-0.0011	$8.0 * 10^{-6}$	0.061	$17.$

Table 2: TEG Output Power as a Function of Coldplate and Hotplate Temperatures

$Power\ (c = T_{Cold},\ h\ =\ T_{Hot}) =\ -3.0 * 10^{-4}\ h^2\ +\ 0.059\ h\ +\ 4.8 * 10^{-4}\ hc\ -\ 0.079\ c\ -\ 1.4$					
Value	$-3.0 * 10^{-4}$	0.059	$4.8 * 10^{-4}$	-0.079	-1.4
95% Bound Low	$-1.2 * 10^{-3}$	-0.090	$-1.4 * 10^{3}$	-0.41	-5.3
95% Bound High	$6.5 * 10^{4}$	-0.21	$2.4 * 10^{-3}$	0.25	2.5

Table 3: TEG Output Power as a Function of Temperature Differential

$Power\ (dt = Temperature\ Difference)\ =\ -6.5 * 10^{-5}\ dt^2\ +\ 0.017\ dt\ -\ 0.51$			
Value	$-6.5 * 10^{-5}$	0.017	-0.51
95% Bound Low	$-3.8 * 10^{-4}$	-0.040	-3.0
95% Bound High	$2.5 * 10^{-4}$	0.075	2.0

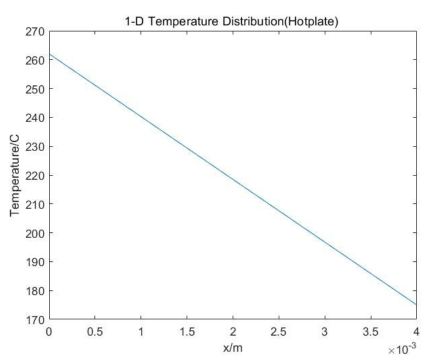
Table 4: Temperature Difference as a Function of Engine RPM and Throttle Percent

$Temperature\ Difference\ (r = RPM,\ t = Throttle\ \%) =\ -9.1 * 10^{-3}\ t^2 + 7.0 * 10^{-4} rt\ + 5.6 * 10^{-5} r^2 + 0.088t\ - 0.33\ r\ +\ 478$						
Value	$-9.1 * 10^{-3}$	$7.0 * 10^{-4}$	$5.6 * 10^{-5}$	0.088	-0.33	478
95% Bound Low	-0.061	$-5.2 * 10^{-3}$	$-4.2 * 10^{-4}$	$-16.$	-2.7	-2500
95% Bound High	0.043	$6.6 * 10^{-3}$	$5.3 * 10^{-4}$	$16.$	2.0	3400

These curves were chosen to be the lowest-order equation which sufficiently fit the data. As expected, increased throttle led to higher hotplate temperatures, increased temperature differential across the TEG, and higher power output. The larger confidence intervals is due to the low number of datapoints that were able to be collected because of long steady-state settling times and extreme vibrations which reduced hardware robustness.

Analytical and Finite Element Thermal Models:

Analytical models were developed using data from a representative TEG system experiment to describe the behavior of the system. A 1-dimensional heat transfer model was developed to describe the energy flow through the fins of the heat sink under steady state assumptions. Compressed air velocity was measured to be about $4.5\ \frac{m}{sec}$ average using a hot-wire anemometer, and the Reynolds Number was calculated to be ~800, correlating with laminar flow. Using convection correlations, the average convection coefficient was calculated to be $71.3\ \frac{W}{m^2K}$.[H] Figure 11A shows the linear temperature distribution across the hotplate. Figure 11B shows the resulting temperature distribution. This distribution correlates to a net heat flux of $85.2\ W$ and the resultant conversion efficiency of the device when compared with experimental data is found to be ~1%.



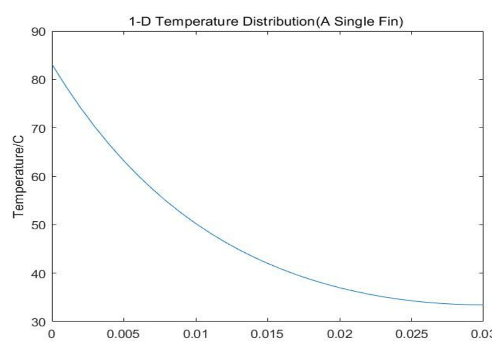


Figure 11A: 1-D Hotplate Temperature Distribution **Figure 11B:** 1-D Heatsink Fin Temperature Distribution

Using the calculated convection coefficient and heat flux from the analytical model as boundary conditions, a steady state Finite-Element Model was developed to characterize the temperature gradients of the system (Figure 12).

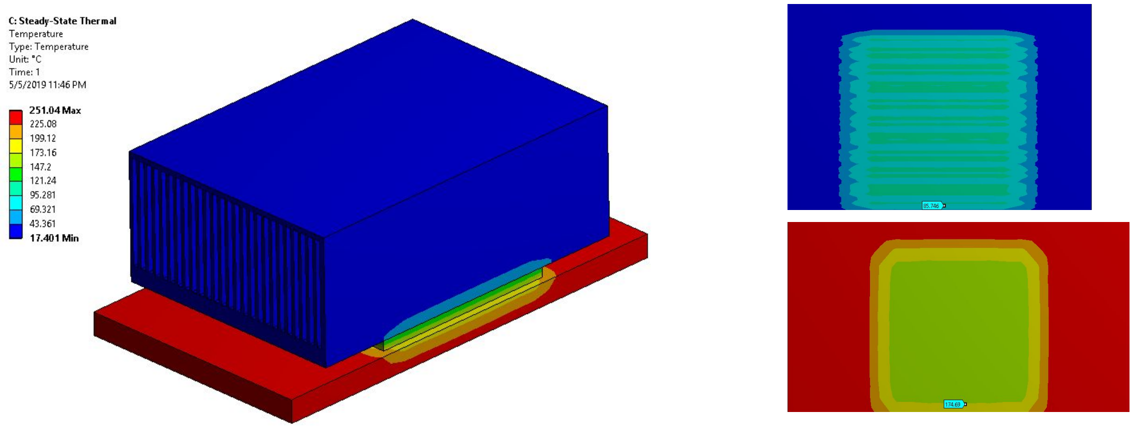


Figure 12: Finite Element Heat Transfer Model of the TEG System with Detail View of Heatsink and Hotplate Temperature Distributions

The estimated temperature distributions of both the hotplate and the heatsink are shown in Figure 12's detail views. The temperatures (probed at approximate actual thermocouple locations) read 174.69°C (hot-side) and 85.75°C (cold side). This matches our experimental results of 175°C and 83°C. Thus, the finite element model correlates well with the actual system, and can be extrapolated to simulate other theoretical exhaust temperatures in the future.

E. Discussion:

The project functioned generally as expected, but the team did run into a variety of difficulties. Namely, we were unaccustomed to working with extreme temperatures, long-term transient properties, intense vibration, and we were limited by the IC Engine workstation. Unfortunately, due to these setbacks, we were forced to spend significant amounts of time fixing our experimental setup instead of collecting data. Ultimately, we were able to successfully produce energy from the TEG, although it was less than expected.

High Temperature:

Thermal shielding was required to prevent the exterior of the 3D-printed PLA diffuser from melting. Insulating washers and carefully-placed hose-clamps had to be utilized to reduce the effects of thermal shorts between the hotplate and heatsink which bypassed the TEG. Additionally, the heat transfer between the hot-side interface and the catalytic converter proved to be incredibly important. Unfortunately, the catalytic converter had embossed letters on it which significantly reduced the contact area between the two surfaces, thus also reducing our heat transfer to the hot-plate.

Long-Term Transient Characteristics:

Due to the complexity of the system, steady-state properties were difficult to achieve. The temperature of various engine components took a significant amount of time (approximately 10-15 minutes) to stabilize, making data acquisition a time-consuming process and reducing the number of points that we were able to obtain. This could have introduced errors if our data was taken before steady-state was reached.

Excessive Vibration:
The engine experienced high frequency vibrations which made it difficult to develop a robust testbed. During our first tests, we had difficulties mounting the air diffuser. Initially, we attached it using aluminum tape. When this proved insufficient, we added epoxy to create a stronger bond. This too failed after four tests. Next, metal mounting brackets were added for increased stability. This combination of tape, epoxy, and brackets worked, but then the screws connecting the hotplate and the heatsink vibrated loose despite the use of Loctite adhesive. Whenever a component vibrated loose, the group was unable to work on the engine until the system cooled sufficiently, causing serious delays in our data gathering.

IC Engine Workstation:
Due to the existing system architecture, the only wind speed available for use in cooling the heatsink was $4.5\ \frac{m}{sec}$ ($\sim 10\ mph$). This is below typical driving speeds, so it is expected that our TEG would be more efficient on a real vehicle if wind could be routed properly.

F. Conclusion:
Although small, the power we were able to generate with our TEG module was significant, especially when compared to our relatively small cost ($60) and low weight (0.48kg). Our experiment proved that our design, with improvements, could be applied to a vehicle to recapture energy. Commercial viability would require significant improvements to robustness of the mounting system. Design difficulties surrounding vibration resilience and airflow redirection to the heatsink for cooling would require more research and experimentation with the vehicle's fairing that could not be performed on the IC engine alone. For external cooling, air would likely have to be redirected through the use of ducts and flues, which would produce different flow rates at different speeds.

Within the scope of this class, our experiment was a success in that we learned important aspects of mechanical design and data processing, gained a working knowledge of TEG systems, and, through the IC engine, gained experience with a complex system and data acquisition platform. Despite mechanical and temporal difficulties which limited our ability to collect data, we managed to compile enough experimental results to support our hypothesis and prove the feasibility of our proposal. Future work would target these difficulties to produce a much more robust system with the potential to improve vehicle efficiency and create a more environmentally friendly vehicle.

G. Author Contributions:

Ben Chang **Signature:** **Date: 5/10/2019**

- Coordinated project management, TEG research & procurement, data acquisition research, initial engine data processing, created finite element thermal models
- Designed air diffuser duct, display board assembly, electrical system, TEG system design reviews
- Machined hotplate and heatsink, assembled TEG system, created wire harnessing of electrical system
- **Report Contributions:** extensive contributions to abstract/introduction/methods/results, revised ABET goals, created system diagram, assembly/detail view renders, citation review, document theme, overall report editing/formatting

Derek Pan **Signature:** **Date: 5/10/2019**

- TEG research
- Machined hotplate and heatsink, 3D printed diffuser, assembled module, debugged mechanical issues, made 3D assembly of CADed parts.
- **Report Contributions:** extensive contributions with abstract, background, discussion, and conclusion, overall system diagram, references, overall report editing/formatting

Ryan Cosner **Signature:** **Date: 5/10/2019**

- **I**nitial measurements and CAD model of system, part acquisition and manufacturing (display board + 3D-printed diffuser), epoxy fix for diffuser
- Initial characterization and TEG system performance: model development, data processing, figure creation, and analysis
- Created pitch presentation slide deck, first version of 4/6 sections for the poster presentation
- **Report Contributions:** wrote first version of abstract, introduction, methods, results, discussion, and 2nd half of ABET; edited entire document extensively, overall report editing/formatting

Allen Romero **Signature:** **Date: 5/10/2019**

- Designed hotplate and coldplate for TEG system
- Researched, procured, and assembled thermocouple
- **Report Contributions:** contributed to ABET goals and hardware design section

Boru Chen **Signature:** Boru Chen **Date: 5/10/2019**

- Developed analytical model of the system
- **Report Contributions:** Analytical model in results section

H. References

[A] Stabler, Francis. *Automotive Thermoelectric Generator (TEG) Controls.* US Department of Energy. www.energy.gov/sites/prod/files/2014/03/f10/stabler.pdf.

[B] Vieira da Rosa, A. (2013) *Fundamentals of Renewable Energy Processes 3rd edition.* Waltham, MA: Elsevier

[C] *1986 Pontiac 1.8L Turbocharged Internal Combustion Engine Datasheet*, provided by Hesse Lab Staff.

[D] National Center for Biotechnology Information. PubChem Database. Octane, CID=356, https://pubchem.ncbi.nlm.nih.gov/compound/356 (accessed on May 9, 2019)

[E] Specification of Thermoelectric Module TEG1-24111-6.0. https://thermoelectric-generator.com/wp-content/uploads/2016/08/TEG1-24111-6.0-Spec-sheet-.pdf

[F] Yang et al., 2018. *Optimization of Thermoelectric Generator (TEG) Integrated with Three-Way Catalytic Converter (TWC) for Harvesting Engine's Exhaust Waste Heat*

[G] Quan et al., 2018. (2018) *Performance Investigation of an Exhaust Thermoelectric Generator for Military SUV Application*

[H] Bergman, Theodore L. *Fundamentals of Heat and Mass Transfer 7th edition. Table 8.1*

[I] Felix, Wankel, and Hoeppner Ernst. *"Rotary internal combustion engine." U.S. Patent No. 2,988,065. 13 Jun. 1961.*

[J] Santos, Jaime Rios. *"Turbine engine for automotive vehicles." U.S. Patent No. 4,043,126. 23 Aug. 1977.*

[K] Tung, Simon C., and Michael L. McMillan. "Automotive tribology overview of current advances and challenges for the future." *Tribology International* 37.7 (2004): 517-536.

[L] FLIR. (2016). *User's Manual: FLIR Ax5 Series*

[M] "A Review of Car Waste Heat Recovery Systems Utilising Thermoelectric Generators and Heat Pipes." *Applied Thermal Engineering,* Pergamon, 10 Nov. 2015,www.sciencedirect.com/science/article/pii/S135943111501128X.[

Appendix A: MATLAB Data Processing Code

Contents


```
RPM = [2300, 2300, 2300, 3000, 3000, 2560, 2500]';
Throttle = [30, 60, 90, 60, 75, 32.9, 60]';
Power = [0.4, 0.6, 0.7, 0.6, 0.6, 0.3366, 0.4218]';
Cold = [86, 110, 122, 120, 135, 86.3, 80];
Hot = [157, 204, 228, 227, 254, 150, 175];

figure
f = fit([RPM, Throttle], Power, 'poly21');
plot(f, [RPM, Throttle], Power);
xlabel("Engine RPM")
ylabel("Engine Throttle (%)")
zlabel("TEG Ouput Power (W)")
title("TEG Output Power Based on Engine RPM and Throttle %")


figure
f2 = fit([Cold', Hot'], Power, 'poly12');
plot(f2, [Cold', Hot'], Power);
xlabel("Cold Side Temperature (C)")
ylabel("Hot Side Temperature (C)")
zlabel("TEG Ouput Power (W)")
title("TEG Output Power Based on TEG Hot and Cold Sides")
zlim([0.25, 1])

figure
f3 = fit([Hot'-Cold'], Power, 'poly2')
plot(f3,[Hot'-Cold'], Power)
xlabel("Temperature Difference (C)")
ylabel("TEG Output Power (W)")
title("TEG Output Power Based on Applied Temperature Differntial")
legend("Measured TEG Output", "Fit Curve")


figure
f4 = fit([RPM, Throttle], [Hot'-Cold'], 'poly22')
plot(f4, [RPM, Throttle], [Hot'-Cold'])
xlabel("Engine RPM")
ylabel("Engine Throttle (%)")
title("Temperature Difference Based on Engine RPM and Throttle (%)")
```

Read Table of General Engine State Data

```
OUR USABLE TEG DATA RANGES FROM: 30% to 90% throttle
                                 2300 to 3000 RPM
```

```
airConsumption2500_0  = 2.6; %L/sec
fuelConsumption2500_0 = 0.0157; %kg/min
airConsumption2500_25 = 7.1;
fuelConsumption2500_25= 0.0378;
```

```
airConsumption2500_50 = 14.9;
fuelConsumption2500_50= 0.0838;
airConsumption2500_75 = 22.0;
fuelConsumption2500_75= 0.1406;
airConsumption2500_100= 35.4;
fuelConsumption2500_100=0.1517;
airConsumption3000_50 = 17.2;
fuelConsumption3000_50= 0.0853;
airConsumption3000_75 = 35.0;
fuelConsumption3000_75= 0.1805;
airConsumption3000_100= 42.5;
fuelConsumption3000_100=0.2020;


load('energyData.mat');
fuelEnergy = 45*10^6; %J/kg
heatCapacity = 1.12*10^3; %J/kg/K
density = 0.54; %kg/m3
Tinf = 20;
```

```
% Column 16 is Hot Thermocouple
% Column 17 is Cold Thermocouple
energyIn(1:4,1) =2500;
energyIn(5:7,1) =3000;
energyIn(1:7,2) = [25;50;75;100;50;75;100];
energyOut=energyIn;
percentEnergyLossInExhaust = energyIn;
energyLossCat = energyIn;

% RPM 2500, Throttle 25%
energyIn(1,3) = fuelConsumption2500_25*fuelEnergy/60; %J/sec
energyOut(1,3) = density*heatCapacity*airConsumption2500_25*10^-3*(mean(rpm2500_thr25(5:en
d, 16)) - Tinf);
percentEnergyLossInExhaust(1,3) = energyOut(1,3)/energyIn(1,3);
energyLossCat(1,3) = density*heatCapacity*airConsumption2500_25*10^-3*(mean(rpm2500_thr25(
5:end, 17)) - mean(rpm2500_thr25(5:end, 16)));

% RPM 2500, Throttle 50%
energyIn(2,3) = fuelConsumption2500_50*fuelEnergy/60; %J/sec
energyOut(2,3) = density*heatCapacity*airConsumption2500_50*10^-3*(mean(rpm2500_thr50(5:en
d, 16)) - Tinf);
percentEnergyLossInExhaust(2,3) = energyOut(2,3)/energyIn(2,3);
energyLossCat(2,3) = density*heatCapacity*airConsumption2500_50*10^-3*(mean(rpm2500_thr50(
5:end, 17)) - mean(rpm2500_thr50(5:end, 16)));


% RPM 2500, Throttle 75%
energyIn(3,3) = fuelConsumption2500_75*fuelEnergy/60; %J/sec
energyOut(3,3) = density*heatCapacity*airConsumption2500_75*10^-3*(mean(rpm2500_thr75(5:en
d, 16)) - Tinf);
percentEnergyLossInExhaust(3,3) = energyOut(3,3)/energyIn(3,3);
energyLossCat(3,3) = density*heatCapacity*airConsumption2500_75*10^-3*(mean(rpm2500_thr75(
5:end, 17)) - mean(rpm2500_thr75(5:end, 16)));

% RPM 2500, Throttle 100%
energyIn(4,3) = fuelConsumption2500_100*fuelEnergy/60; %J/sec
energyOut(4,3) = density*heatCapacity*airConsumption2500_100*10^-3*(mean(rpm2500_thr100(5:
end, 16)) - Tinf);
percentEnergyLossInExhaust(4,3) = energyOut(4,3)/energyIn(4,3);
```

```
energyLossCat(4,3) = density*heatCapacity*airConsumption2500_100*10^-3*(mean(rpm2500_thr10
0(5:end, 17)) - mean(rpm2500_thr100(5:end, 16)));

% RPM 3000, Throttle 50%
energyIn(5,3) = fuelConsumption3000_50*fuelEnergy/60; %J/sec
energyOut(5,3) = density*heatCapacity*airConsumption3000_50*10^-3*(mean(rpm3000_thr50(5:en
d, 16)) - Tinf);
percentEnergyLossInExhaust(5,3) = energyOut(5,3)/energyIn(5,3);
energyLossCat(5,3) = density*heatCapacity*airConsumption3000_50*10^-3*(mean(rpm3000_thr50(
5:end, 17)) - mean(rpm3000_thr50(5:end, 16)));

% RPM 3000, Throttle 75%
energyIn(6,3) = fuelConsumption3000_75*fuelEnergy/60; %J/sec
energyOut(6,3) = density*heatCapacity*airConsumption3000_75*10^-3*(mean(rpm3000_thr75(5:en
d, 16)) - Tinf);
percentEnergyLossInExhaust(6,3) = energyOut(6,3)/energyIn(6,3);
energyLossCat(6,3) = density*heatCapacity*airConsumption3000_75*10^-3*(mean(rpm3000_thr75(
5:end, 17)) - mean(rpm3000_thr75(5:end, 16)));
```

```
% RPM 3000, Throttle 100%
energyIn(7,3) = fuelConsumption3000_100*fuelEnergy/60; %J/sec
energyOut(7,3) = density*heatCapacity*airConsumption3000_100*10^-3*(mean(rpm3000_thr100(5:
end, 16)) - Tinf);
percentEnergyLossInExhaust(7,3) = energyOut(7,3)/energyIn(7,3);
energyLossCat(7,3) = density*heatCapacity*airConsumption3000_100*10^-3*(mean(rpm3000_thr10
0(5:end, 17)) - mean(rpm3000_thr100(5:end, 16)));

close all
figure
plot(energyIn(5:7,2), energyIn(5:7,3), 'r')
hold on
plot(energyIn(1:4,2), energyIn(1:4,3), 'b')
title('Energy Input from Gasoline')
xlabel('Throttle Percentage')
ylabel('Energy Input (J/sec)')
legend('RPM = 3000', 'RPM = 2500', 'Location', 'NorthWest')

figure
plot(energyOut(5:7,2), energyOut(5:7,3), 'r')
hold on
plot(energyOut(1:4,2), energyOut(1:4,3), 'b')
title('Energy Out Through Exhaust (After Turbo)')
xlabel('Throttle Percentage')
ylabel('Energy Lost (J/sec)')
legend('RPM = 3000', 'RPM = 2500', 'Location', 'NorthWest')

figure
plot(percentEnergyLossInExhaust(5:7,2), percentEnergyLossInExhaust(5:7,3), 'r')
hold on
plot(percentEnergyLossInExhaust(1:4,2), percentEnergyLossInExhaust(1:4,3), 'b')
title('Percent Energy Lost through the Exhaust')
xlabel('Throttle Percentage')
ylabel('Percent Energy Loss through Exhaust (%)')
legend('RPM = 3000', 'RPM = 2500', 'Location', 'NorthWest')
```

```
figure
energyLossCat = abs(energyLossCat);
plot(energyLossCat(5:7,2), energyLossCat(5:7,3), 'r')
hold on
plot(energyLossCat(1:4,2),energyLossCat(1:4,3), 'b')
title('Energy Lost across Cat')
xlabel('Throttle Percentage')
ylabel('Energy Lost (J/sec)')
legend('RPM = 3000', 'RPM = 2500', 'Location', 'NorthWest')
```

ABET Goals Reflection:

An ability to apply knowledge of mathematics, science, and engineering

The project required fundamental understanding of the internal combustion engine system, heat transfer, material science, and thermoelectric generator operation principles. The project was essentially an exercise in applying coursework in thermodynamics, heat transfer, and mechanical behavior of materials. Our understanding of the underlying theory allowed us to design, analyze, and classify our system with mathematical models, energy efficiency calculations, etc. Lastly, the design and manufacturing of our experimental hardware required application of engineering and manufacturing techniques, including design methodologies, machining, soldering, 3D-printing, and more.

An ability to design and conduct experiments, as well as to analyze and interpret data

The project served as a well rounded exercise in experiment design. Various supplementary sensors like the FLIR camera, hot wire anemometer, and IR gun assisted in initial system classification. Special considerations were taken to design around and take advantage of the existing IC Engine experimentation platform, including its existing suite of sensors and input control parameters. Additional sensor requirements in the form of a watt meter and additional thermocouples were carefully chosen and utilized to provide useful experiment data for later analysis. Extensive post-processing of data and integration with our mathematical models were key in producing meaningful results and figures.

An ability to identify, formulate, and solve engineering problems

The project itself presented numerous unexpected problems involving high temperature and extreme vibrations. These required us to think quickly and produce engineering solutions like developing new mounting mechanisms and increasing system robustness.

An ability to communicate effectively

Communication was essential to allow for the sharing and revision of ideas, improvement of work, and delegation of tasks outside of regular lab time. Additionally, both verbal and written technical communication skills were honed through the pitch competition, project showcase, and proposals, and reports.

An ability to function on multi-disciplinary teams

The project required a variety of different skills and each team member brought a diverse set of experiences that was crucial to completing the project. Members focused on the their areas of expertise to best utilize their skills.

A recognition of the need for, and an ability to engage in, lifelong learning

This project presented new and interesting engineering problems that the team had not little experience in. Particularly problems involving vibration and high temperatures. These problems required quick learning demonstrated that learning is a constant and lifelong process.

An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice

The team combined a wide variety of engineering tools and skills: traditional heat transfer analysis, modern FEM tools, curve-fitting analytical tools, 3D design software, traditional manufacturing tools, and design methodology; all of which were crucial to project success.