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Modeling and Simulation Approach to Inform TEG Waste Heat Harvesting Prototype for Fossil Fuel Exhaust

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Abstract **–** Many military systems produce thermal energy as a by-product. Generally, this so-called waste heat is lost to the surroundings. Capturing the waste heat and putting it to beneficial use could increase the efficiency of military systems, while having the added benefit of reducing thermal signatures. This paper outlines the application of modeling and simulation to estimate the usable electric power produced by a thermoelectric generator (TEG) array on the exhaust muffler of a small fossil fuel generator. The simulation results informed design, construction, and testing of an initial prototype. Key prototype test variables were temperature difference, load resistance, and electric current. The results of the experiment were compared to and used to update the initial model. This small-scale effort provides initial insight into the efficacy of applying thermoelectric generators to military systems. Future work will explore larger arrays, as well as detailed investigation of the tradespace to identify promising equipment or applications, and inform capability and acquisitions requirements.

Keywords**:** thermoelectric generator, waste heat, modeling, simulation

1. Introduction

The purpose of this research is to model a waste heat energy recovery system using thermoelectric generators (TEGs) on the muffler of a portable generator, and then use modeling and simulation to predict how a prototype TEG system will perform under certain conditions. Comparing measurements from an experimental prototype system to the model allows for validation of the model while also providing new information to improve the model for future use. Having a validated performance model could be used to support feasibility and trade-off analysis during the design of future military systems that might employ waste energy recovery.

2. Background

The military relies on energy at sea to conduct operations such as fueling aircraft, launching missiles, and providing logistical resources to sailors. Implementing energy efficiency and optimization methods will reduce refueling at sea operations as well as increase the overall longevity of military platforms. This operational energy is critical to mission success, but runs the risk of increasing susceptibility to an enemy that is capable of exploiting energy usage [1]. The Department of Defense is researching different methods to reduce reliance on fossil fuels to increase the efficiency of military forces [2]. Thermoelectric generators may help to provide the military this capability as these devices can capture wasted heat and recycle it back into military systems.

2.1. Thermoelectric Generators

A thermoelectric generator is comprised of two different semiconductor metals, p-type and n-type [3]. A TEG operates by the Peltier and the Seebeck effects. In the Peltier effect, heat is absorbed at the junction of the two metals when an electrical current flows through the device [4]. The Seebeck effect describes the phenomenon of subjecting a TEG to a temperature difference, causing the dissimilar semi-conductor metals to induce a voltage, thus creating usable energy.

A heat source and heat sink can provide the resources to create the required temperature difference. A TEG has a designated hot side and cold side. The hot side is subjected to a heat source, such as a gas turbine found in a ship, and the cold side of the TEG connects to a heat sink, such as sea water. With a greater temperature differential, the TEG module can generate more energy. The material composition of the TEGs affects the temperature difference. Semiconductor materials that have higher-rated temperatures have the potential to produce more voltage [5]. The TEG's voltage, current, and internal resistance changes as the temperature difference changes.

Multiple TEGs can be applied at one time to produce power, and the number required depends on the application. For example, in an automotive study, 72 TEG modules were applied to a heat pipe as a means to replace the radiator. This resulted in producing 28W at idle and 75W at 80 km/hr [6]. Thermoelectric generator modules in an array can be arranged in parallel, in series, or in combination to produce the most efficient amount of power for their application. In an ideal environment, each TEG is exposed to the same temperature differential, resulting in each TEG creating the same output voltage [5]. However, most situations are not ideal, and particular system geometries can cause each module to experience different temperatures, and therefore different voltages and internal resistances, across the array [5].

2.2. Role of Modeling and Simulation

Model-based systems engineering (MBSE) is an informative tool that can be used to study a system prior to applying it to real-world use. In MBSE, engineers utilize models "to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later lifecycle phases" [7]. Models can represent theory and concepts that have the potential to be applied to real-world applications [8]. The application of modeling provides insights into how a system will function.

This research expanded on MBSE by the addition of simulation. This methodology, known as modeling and simulation (M&S)-based systems engineering, incorporates executing the model to understand how the system operates in a dynamic environment [9]. This provides the engineer and stakeholder numerical analysis as a means to evaluate the system [9]. By studying the system in a simulated operational environment, the engineer is able to identify issues earlier in the developmental process leading to reduced risk, reduced cost, and enhanced system performance [9]. Having an understanding of how a system will operate prior to building a prototype helps to inform design, ultimately aiding in defining operational and performance requirements [10].

Once the prototype is tested, its performance data can be compared to validate the model. New information gained from the prototype can be integrated into the model, helping to improve conceptual understanding and design of the system. This loop of modeling and refining the prototype helps to mitigate unexpected behaviors in a system and refine requirements. Applying the insight gained in testing the prototype to a future model will provide validity for when the model is scaled for future production of the system.

3. Methodology

The overall methodology followed in this research was to construct thermal and electrical models of a prototype TEG array system, measure performance of individual TEGs to be used in constructing an experimental prototype, and then use measured and estimated parameters to predict the performance of the prototype. Measurements of the actual TEG prototype's performance were then compared to the initial modeling predictions to validate and adjust modeling parameters.

3.1. Thermal Modeling

This research expands on previous research that utilized COMSOL Multiphysics software to model a future prototype TEG system [11]. The system consisted of an array of eight simulated TEGs between a muffler operating at steady state and a water block. The physical geometry of the experimental prototype's actual TEG modules, muffler, and the water cooling system utilized in this research were input into COMSOL to determine the estimated temperature difference between the TEG sidings. Results are displayed in Table 1. The simulation data indicated the TEGs are capable of recycling a portion of the muffler's wasted thermal energy back into the system. The predicted temperature differences will be applied to additional electronic circuit modeling to determine the optimum series or parallel arrangement of the array, thus predicting the voltage and power output capabilities.

Table 1: Simulation temperature results of TEG array [11].

TEG	Hot Side Temp (°C)	Cold Side Temp (°C)	Temp Difference (°C)
1	91.00	39.51	51.48
2	72.74	36.18	36.56
3	72.87	35.83	37.04
4	79.61	36.93	42.68
5	61.52	33.09	28.43
6	66.30	33.45	32.84
7	74.65	36.32	38.37
8	66.29	33.53	32.76

3.2. TEG Performance Characterization

An experimental setup was designed to characterize the TEG module to determine its performance parameters, as shown in Figure 1. To collect data, a hot plate was used as the heat source. A water cooler pumping water into a water block simulated a heat sink. The TEG was placed between two aluminum spacer plates with cutouts to allow for insertion of thermocouples, used to measure the temperature difference across the module. The water block sat on the top aluminum spacer plate, and the entire system rested on a hot plate. A clamp held the system together.

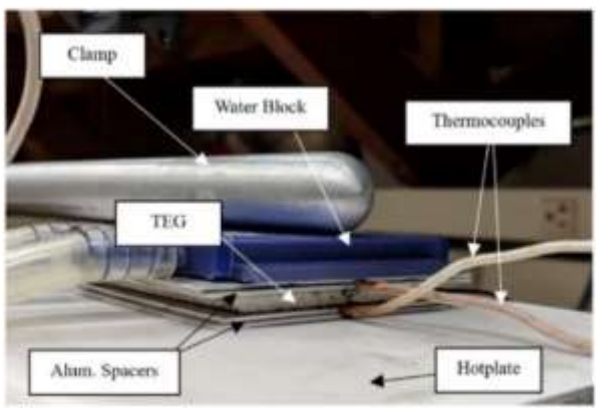

Fig. 1: Experimental apparatus of characterization [12].

Data was collected over a temperature a range of 180°C to 250°C at 10°C intervals. The temperature range was selected based on the heat profiles near the portable generator's muffler. The TEG was placed in a simple circuit and three different load resistors were used – 1 Ω, 2.5 Ω, and 3 Ω. Three sets of data were collected using a multimeter for each resistor. In each data set, the following data was collected five times at each temperature increment: voltage across the resistance load (v_{load}), measured voltage in an open circuit (v_{oc}), short circuit voltage (i_{sc}), current across resistance load (i_{load}), and temperature difference (T_{diff}).

The data collected was averaged for each parameter and empirical mathematical models developed using linear regression. These models reflected the aggregate open circuit voltage as well as the internal equivalent resistance (R_{eq}) of the TEG module. Equation 1 represents the temperature-dependent open circuit voltage equation and Equation 2 is the temperature-dependent internal TEG resistance determined through the Thévenin Theorem.

$$v_{oc} = 0.0187T_{diff} - 0.0051 \quad (1)$$

$$R_{eq} = 0.0078T_{diff} + 2.1829 \quad (2)$$

3.3. TEG Array Performance Prediction

The array of eight TEGs needs to be connected to produce a combined voltage. The temperature differences displayed in Table 1 were applied to several models in a circuit simulation software, OrCAD PSpice, to analyze current, voltage, and power output. Two models were developed in PSpice to simulate the TEG arrays: eight modules in series and eight modules in parallel. The temperature differences from Table 1 were applied to Equation 1 and Equation 2 to simulate each TEG's expected voltage and internal resistance, as shown in Table 2. These calculations predict how the temperature of the air moving through the muffler and the temperature of water circulating through the water block affects each TEG module's voltage and equivalent resistance. Figure 2 shows the PSpice graphical model of the all series arrangement of eight TEG modules. Each TEG is represented by the predicted voltage and internal resistance displayed in Table 2.

Table 2: Predicted voltage and internal resistance across each TEG module.

TEG	v_{oc} (V)	R_{eq} (Ω)
1	0.958	2.584
2	0.679	2.468
3	0.688	2.472
4	0.793	2.516
5	0.527	2.405
6	0.609	2.439
7	0.712	2.482
8	0.696	2.438

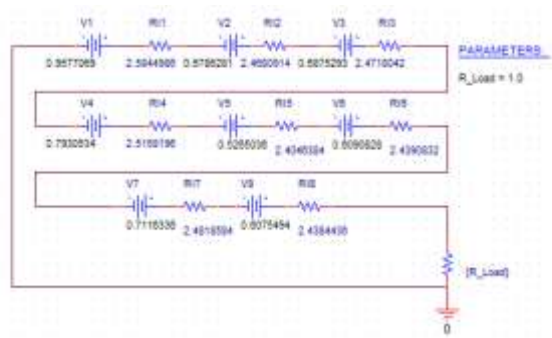

Fig. 2: Thermoelectric generator module in series.

A simulation was run to determine the open circuit voltage for each circuit. For the series arrangement and the parallel arrangement, the v_{oc} was determined to be 5.57 V and 0.46 V, respectively. For each arrangement, the resistance load was changed in PSpice from 1 to 55 Ω at 1.0 Ω increments to determine when peak power occurs for each model. Table 3 displays peak power for each arrangement to include the resistance load as it occurred and the resulting v_{load} and i_{load}.

Table 3: PSpice simulation results for peak power.

	TEG Arrangement	
Parameter	Series	Parallel
Resistance Load (Ω)	20.00	1.00
v_{load} (V)	2.79	0.35
i_{load} (A)	0.14	0.35
Peak Power (W)	0.39	0.12

For prototype testing, the arrangement producing the most voltage, all series, was utilized as it shows the potential to harvest more energy. The prototype's open circuit voltage, voltage across the resistance load, and the current across the resistance load were compared to the PSpice model outputs.

3.4. Prototype Construction and Measurements

The initial prototype system is composed of an aluminum base plate that conforms to the muffler, eight TEG modules connected in series using electrical cap connectors, and an aluminum water block. This entire system sits on top of a muffler of a portable generator and is held together with two hose clamps. The aluminum base plate acts as a flat surface to hold the TEG array. The hot side of the TEGs in the array touches the aluminum base plate, which sits directly on the muffler acting as the heat source. The cold side of the TEGs touch the water block, acting as the heat sink. The water block is connected to a circulating refrigeration unit to provide cooling to the TEG system. The aluminum base plate and the side of the water block touching the surface of the TEGs each have grooves that allow for space to add thermocouples, which measure the temperature difference across each TEG. Figure 3 shows this TEG prototype system mounted to the muffler of the generator.

Fig. 3. Thermoelectric generator waste heat harvesting prototype mounted to muffler of generator.

Five sets of data were collected. For each data set, the generator ran for 10 minutes to reach steady state operations prior to collecting data. In each data set, the hot and cold side temperatures of each TEG were collected using a thermocouple meter. A multimeter was used to measure the v_{oc} of the TEG array circuit as well as the v_{load} and i_{load}. To measure the v_{load} and i_{load}, the circuit was connected to several resistors – 1 Ω, 10 Ω, 20 Ω, 33 Ω, 47 Ω, and 55 Ω. By using multiple resistors, the peak power of the system was determined.

4. Results and Comparison to Model

Excel was used to determine the average for each data parameter collected. Table 4 represents the average hot and side temperature for each TEG as well as the T_{diff} across each module.

Table 4: Average experimental temperature results of the TEG array. Experimental error analysis was applied to the average temperature difference for TEG in the array.

TEG	Hot Side Temp (°C)	Cold Side Temp (°C)	Temp Difference (°C)
1	74.42	17.56	56.86 ± 1.45
2	81.52	20.20	61.32 ± 0.40
3	89.08	22.64	66.44 ± 2.23
4	88.42	22.06	66.36 ± 3.36
5	70.34	19.10	51.24 ± 2.25
6	76.20	18.26	57.94 ± 3.03
7	84.58	20.20	64.38 ± 2.03
8	83.38	20.86	62.52 ± 2.04

The experimental average open circuit voltage for the prototype was determined to be 10.11 volts. The average v_{load}, i_{load}, and power for each resistance load is shown in Table 5.

Table 5: Average experimental voltage, current, and power across the resistance load. Note: Experimental error analysis was applied to the average v_{load} , i_{load}, and power per resistance load.

Resistance Load (Ω)	v_{load} (V)	i_{load} (A)	Power (Watts)
1.0	0.471 ± 0.043	0.481 ± 0.028	0.226 ± 0.033
10.0	3.002 ± 0.187	0.304 ± 0.021	0.913 ± 0.120
20.0	4.658 ± 0.248	0.233 ± 0.010	1.084 ± 0.102
33.0	5.874 ± 0.235	0.180 ± 0.009	1.058 ± 0.090
47.0	6.640 ± 0.352	0.141 ± 0.007	0.936 ± 0.094
55.0	6.842 ± 0.367	0.135 ± 0.006	0.926 ± 0.087

Table 4 and Table 5 display the experimental error for each parameter that was measured. As the key measurement tools, the multimeter and thermocouples may have contributed to the source of error. Results may have been more precise if more than five sets of data were collected and if each set of data was collected simultaneously. The data sets were not collected within the same day to allow for proper startup and shutdown of the generator. While this allowed for each set to be collected after the generator reached steady state, this means variations in the outside temperature may have influenced the temperature difference across each TEG. The performance of the TEGs may degrade after each use as well. These dynamic factors may have affected the overall accuracy of the experimental results.

The average experimental temperature differences collected from the prototype was applied back to the PSpice model. This was used to update the model to more accurately reflect the real world system as well as help to improve design when arranging modules in a series, parallel, or combination on the muffler, depending on the purpose of the TEG array. Applying the updated temperature differences to the all series PSpice model resulted in a closer representation of the prototype results. Figure 4 displays power plotted against resistance for the initial PSpice model results, the average experimental power data with its experimental error, and the updated PSpice model data with the average experimental temperature difference applied.

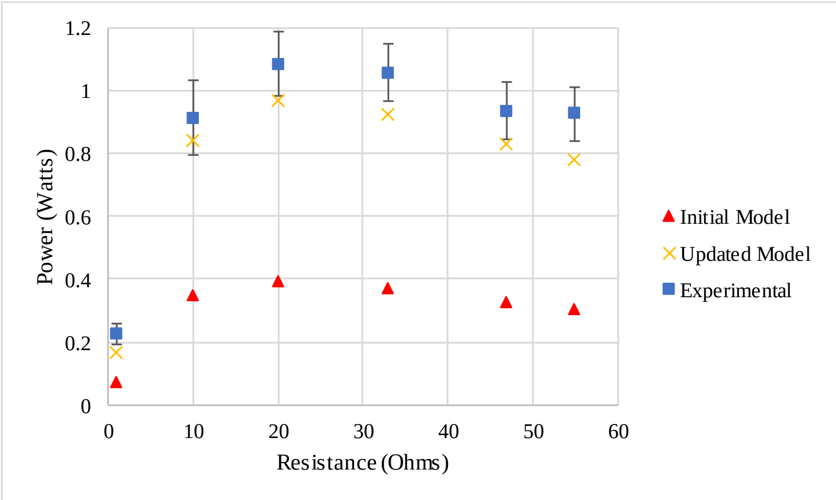

Fig. 4: PSpice power versus average prototype collected experimental data.

5. Conclusions

Overall, the hot side temperature was higher and the cold side was colder in the prototype when compared to the model. The v_{oc}, v_{load} , and power of the circuit were higher when compared to the model output. This corresponds to the TEGs in the prototype being exposed to a greater temperature difference. Both the model and the prototype showed an increasing voltage with increasing resistance. Also, the prototype exhibited peak power at approximately 20 ohms, as did the model.

In the model that predicted the hot and cold side temperatures of each TEG, the muffler was assumed to be hollow and software was applied to vary the temperature and movement of the water through the water block as well as the air moving through the muffler. The muffler and water block used in prototype testing have internal geometry that is more complex than in the model. This affects the movement and temperature of the air in the muffler and water in the water block. The temperature of the water and air in the actual system may have different variations than that simulated by computer software. With these assumptions and parameters applied to the model, it did not accurately portray every aspect of the system in a real world environment. However, it did capture the trend of the system.

This paper presented a modeling and simulation approach by depicting the modeling of a TEG system prior to building and testing a prototype system. Modeling a TEG system on a muffler of a generator increased the understanding of how a TEG system operates. This knowledge was used to build an actual system for testing. A prototype system of eight TEGs on top of a muffler of a generator was built based off the insights provided by the model. The system was tested and its experimental data was compared to that of the model. Even though the model did not accurately capture the prototype's experimental data, it did capture the trend of how the system operates in the real world. This research reinforces the idea that modeling and simulation can represent concepts that occur in the real world.

6. Future Work

Future work includes applying the results of the prototype to additional modeling to create a higher fidelity model. Applying the results from this research will help to model and build a system for a defined requirement. For example, additional models can be created to simulate shipboard systems to further predict the practicality in applying TEGs to recover waste heat. Military systems that could benefit from the application of TEGs need to be identified. This also includes conducting an analysis of alternatives for which heat sources/sinks would provide most benefit for the TEG to produce energy. From there, the architecture needs to be explored to determine which systems benefit from the greatest efficiency while exploring other factors such as cost, weight, reliability, and maintainability.

Off-ship military systems may benefit from the application of TEGs. For example, systems such as a tactical vehicles or aircraft also lose waste heat to the environment. Models and prototypes need to be explored to determine the application of TEGs in different environments to help increase the military's energy efficiency. Finally, it's important to consider the tradespace of applying TEGs to reduce the infrared signature in military systems. Reducing heat signatures in military systems that emit waste thermal energy could reduce the adversaries' ability to detect and target those systems, thus increasing the survivability of military platforms.

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