COMSOL Multiphysics® Simulation of TEGs for Waste Thermal Energy Harvesting

L. Howard[1], D. Tafone[2], D. Grbovic[1], A. Pollman[1]
1. Naval Postgraduate School, Monterey, CA, USA
2. Ramapo College of New Jersey, Mahwah, New Jersey, USA

Abstract

The U.S. Navy relies on power to operate its systems effectively to complete missions worldwide. Many of these systems generate thermal energy, which is typically lost to the environment and not useful within the system. Capturing the energy that would otherwise be lost and recycling it in the system provides the opportunity to improve the system's efficiency, reduce heat signatures, and decrease some cooling requirements. Thermoelectric Generators (TEGs), which create voltage when exposed to a temperature differential, have the potential to recover the waste heat from naval systems and recycle it back into the system. Modeling and simulation helps establish the feasibility of building a tabletop prototype, thus helping explore whether TEGs have the potential to increase the energy efficiency of military systems. The purpose of this study was to build a model in COMSOL® to simulate a potential prototype system of a TEG array on the muffler of a portable generator. The model will help determine the temperature difference between the TEG sidings, as a measure of the array's efficiency. COMSOL® simulation showed that the average temperature difference between the TEG sidings was 37.52 °C. COMSOL® modeling effort's output will inform design, construction, and testing of a tabletop TEG array energy harvesting prototype for employment on the generator exhaust. Prototype actual performance will be compared to COMSOL® output to check the validity of the model, before using it to design a larger-scale version for actual shipboard deployment and testing.

1.0 Introduction

A fundamental step in systems engineering (SE) is to model a system prior to building a prototype. Modeling can improve understanding of a system and provide useful evaluation and feedback prior to the design and manufacturing of that system. This part of the SE process has become increasingly important in military acquisitions as it may lead to reduced cost and time in the design and construction of the system.

The military is implementing strategies to decrease greenhouse gas emissions, increase fuel efficiency, and rely more on alternative energy sources [1]. Military initiatives, such as the Great Green Fleet and Task Force Energy, have been established to explore ways to reduce the reliance on fossil fuels to promote a more efficient operational fleet. Exploring options to increase efficiency could greatly increase the operational battlespace by improving the range and endurance of military craft, such as ships and aircraft. This energy optimization would both reduce the adversary's ability to exploit the military's energy and fuel usage and also maximize lethal capabilities [2]. Looking at ways to reduce the infrared (IR) signature of military systems may contribute to the operational resiliency. One method to increase efficiency is to recover heat and recycle it back into a system. Thermoelectric generators (TEGs) may have the capability to provide this function to Navy systems.

A TEG is a passive device composed of two semiconductor metals that operate based on the Seebeck effect [3]. One side of the TEG, designated as the hot side, is connected to a heat source. The other side is the cold side, which can be connected to the heat sink to provide heat dissipation. When the TEG is exposed to the heat source and sink, a voltage is created between the two metals. As the temperature difference occurs across the system, the TEG converts this difference into electrical energy. The greater the temperature difference, the more energy the TEG can create.

Since 1961, NASA has utilized radioisotope thermoelectric generators (RTGs) in space to generate electricity for space systems [4]. Furthermore, thermoelectric systems have been applied to vehicles resulting in improvements to fuel efficiency and engine power [5, 6]. Even though thermoelectric devices are currently used for their waste heat recovery capabilities, the full potential and trade space has not yet been fully explored. Currently, many TEG systems can provide 2-5% energy efficiency. As technology improves, TEGs may be capable of creating 15% or greater efficiency [3]. Through modeling, simulation, and prototyping, the feasibility and estimated efficiency of applying TEGs to naval systems can be determined prior to design of large-scale version for actual shipboard deployment and testing.

In this research, COMSOL® utilized the Heat Transfer and AC/DC modules to analyze the potential temperature difference of a TEG array between a muffler and water block. In this trial of military applications, TEGs are applied to the small but vital systems such as portable gasoline generators. The wasted thermal energy released by the muffler can be recycled back into the system. This analysis will inform how to proceed on future prototypes.

2.0 Use of COMSOL Multiphysics®

2.1 Governing Equations

To determine the temperature difference across each TEG in the array, it is necessary to use both the heat transfer and AC/DC modules to account for heat transfer in fluids, laminar flow, electric current interfaces. The primary governing physics applied to the model is the following:

Heat Transfer Module:

Heat Transfer in Fluids:

$$\rho C_p u \cdot \nabla T + \nabla \cdot q = Q + Q_p + Q_{vd} \tag{1}$$

Heat Transfer in Solids:

$$\rho C_p u \cdot \nabla T + \nabla \cdot q = Q + Q_{ted} \tag{2}$$

Conduction heat flux:

$$q = -k\nabla T \tag{3}$$

Convective heat flux:

$$q_o = h \cdot (T_{ext} - T) \tag{4}$$

Laminar Flow:

$$\rho(u \cdot \nabla)u = \nabla \cdot [-p + \mu\left(\nabla u + (\nabla u)^T\right) - \frac{2}{3}\mu(\nabla \cdot u)I] + F \tag{5}$$

Continuity equation:

$$\nabla \cdot (\rho u) = 0 \tag{6}$$

AC/DC Module:

Electric Currents:

$$\nabla \cdot J = Q_j \tag{7}$$

$$J = \sigma E + J_e \tag{8}$$

$$E = -\nabla V \tag{9}$$

Notations:
C_p = heat capacity
ρ = fluid density
u = velocity of flow
T = temperature
Q = heat source
Q_p = work due to change in pressure
Q_{vd} = work due to viscous dissipation
Q_{ted} = work due to thermoelastic damping
P = fluid pressure
μ = fluid dynamic viscosity
σ = conductivity
E = electric field
V = electric potential
J = current density
J_e = external current density
Q_J = current source

2.2 COMSOL Modules

The model designed in COMSOL® uses the Heat Transfer module and AC/DC module.

Specifically, the Heat Transfer module involved the Heat Transfer in Fluids interface and the Laminar Flow interface. The Laminar Flow interface simulated the movement of fluid, such as air being pushed through the muffler and water flowing through the water block. The Heat Transfer in Fluids interface identified the components of the system, both solids and fluids, as conductors of thermal energy and showed how heat will spread through them. Also, the Heat Transfer in Fluids interface assigned temperatures to various components, such as air entering the nozzle of the muffler.

Laminar Flow and Heat Transfer were joined together using multiphysics nonisothermal flow, which simulated the varying temperatures throughout the flow of water and air within the system.

The physics of the AC/DC module in conjunction with Heat Transfer were applied to the TEGs. Heat Transfer in Solids and Electric Currents interfaces were joined in multiphysics to create the thermoelectric effect and electromagnetic heating of the TEGs based on the known material and geometry.

The Heat Transfer module helped determine the temperature difference between the TEG sidings. Specifically, as a result of selecting Conjugate Heat Transfer, the two physics of Laminar Flow and Heat Transfer in Fluids were used throughout all simulations.

2.3 Component Material and Geometry

The model consists of three main components: the muffler as the heat source, TEG array, and water block as the heat sink. Two aluminum sidings, a platform and a plate, surround the TEG array, acting as a conductive material. Each components' dimensions are provided in Table 1.

Table 1. Model Component Dimensions.

Component	X (m)	Y (m)	Z (m)
Muffler	0.39	0.195	0.23
TEG	0.056	0.056	0.0045
Water Block	0.23	0.23	0.014
Aluminum Base Sheet	0.23	0.23	0.003
Aluminum Top Sheet	0.23	0.23	0.005

A commercial off-the-shelf (COTS) gasoline powered generator provided the design and material composition of the muffler used in COMSOL®. The muffler's material composition is carbon steel [7]. The interior of the muffler is assumed to be hollow and modeled this way to simulate air flowing through it. The walls of the muffler are assumed to be 0.5 cm thick based on the measurements of the nozzle wall thickness.

A side view and top views of the Muffler geometry are displayed in Figure 1.

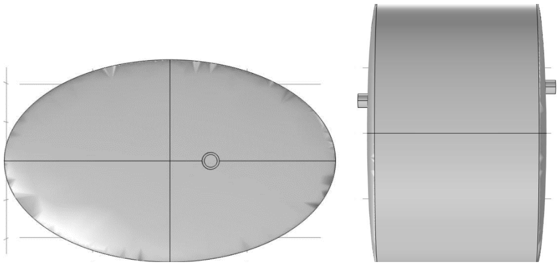

a) b)

Figure 1. Muffler Geometry: a) Top View, b) Side View.

An aluminum base sheet was added to the muffler to provide a flat surface for the TEG array. The TEG array with the TEG's "hot side" was assembled on the aluminum base sheet with an aluminum sheet on top of it.

An aluminum water block was constructed and placed on the top aluminum sheet for heat dissipation. Two nozzles were made to simulate a water cooling system connected to the water block to provide constant cooling to the TEGs. The thinner aluminum walls of the water block's interior forced the water from the cooling system to spread evenly throughout the block. The water block design is displayed in Figure 2.

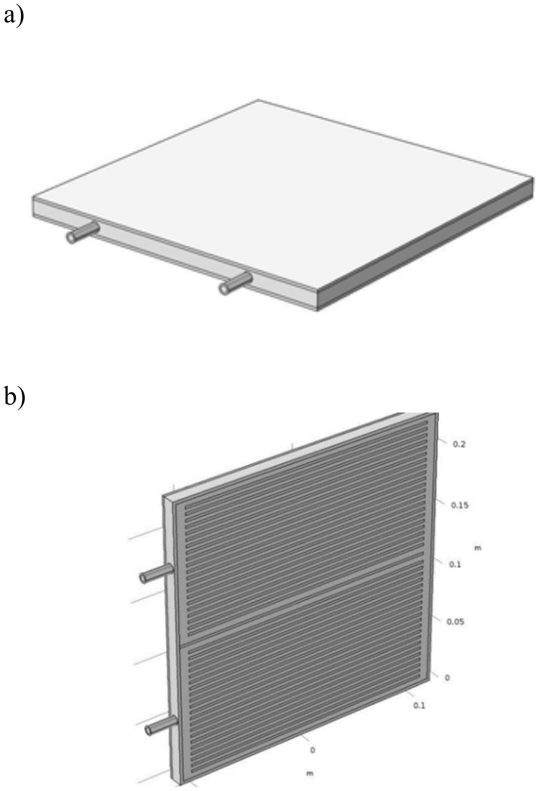


Figure 2. a) Water block exterior design, b) Water block interior design.

Each TEG in the TEG array was modeled based on a COTS TEG [8]. The TEG was disassembled as shown in Figure 3 in order to gather the structural details to design a more accurate internal representation.

Figure 3. TEG Exterior and Interior.

To simulate the real TEG, the model was designed with 22 rows of bismuth telluride pellets with 11 pairs in each. Each pellet was 1.5mm x 1.5 mm x 1.5 mm. Aluminum plates were constructed on the top and bottom of the pellets. Figure 4 shows one row of this internal design.

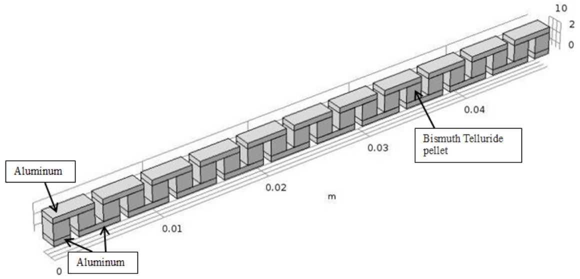


Figure 4. Complex Internal TEG Design.

The COTS TEG was designed with silicone based adhesive. This was simulated by adding hollow boxes of 3.5 mm by 2.5 mm of silicone internally throughout the TEG to serve as insulation.

A simplified TEG was constructed in COMSOL to compare computation time and thermal conduction. This TEG had the same external dimensions and same volume of materials. The materials were inserted into two 23 mm by 23 mm blocks centered in the TEG. Figure 5 displays a comparison of the designs.

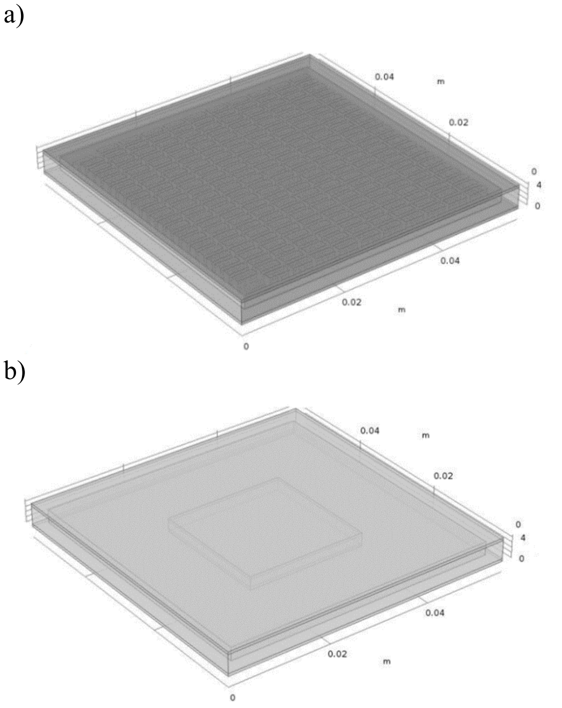


Figure 5. Comparison of TEG Design: a) Complex Design, b) Simplified Design.

2.4 TEG Model Comparison

To compare models, the Heat Transfer module simulated placing the TEG in a block of air at ambient temperature, then heating one side of the TEG at 20°C intervals from 100-180°C. Measuring the temperature of the opposite side showed how heat transferred though the TEG. Results are displayed Table 2 below, verifying that there was no difference in thermal conduction between TEGs constructed of the same material but with complex or simplified designs. However, computation time was 9 times faster for the simplified design at 3 seconds per simulation compared to the complex design at 27 seconds. Based on this performance, the simplified TEG design was utilized in the overall system design.

Table 2. TEG Comparison.

Temperature Input (°C)	Complex TEG Temperature (°C)	Simplified TEG Temperature (°C)
100	373.04	373.04
120	393.00	393.01
140	412.97	412.97
160	432.93	432.92
180	452.88	452.88

2.5 TEG Array Design

In the model, eight simplified TEGs were closely spaced on the aluminum plate directly on top of the muffler as displayed in Figure 6. Having a small gap between the TEGs in the array has been found to provide the maximum amount of thermal energy produced by the muffler to be absorbed by the TEGs [9].

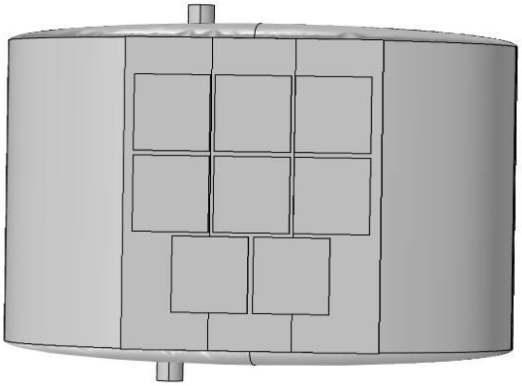


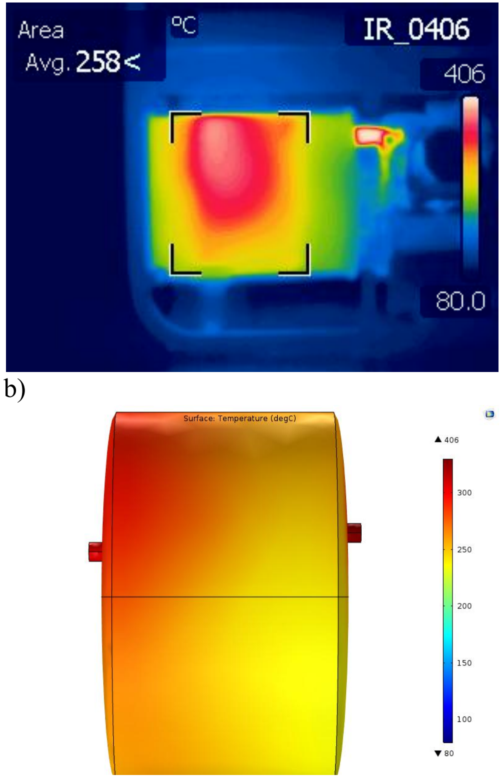
Figure 6. Designed TEG Array on aluminum base plate of muffler.

2.6 Boundary Conditions

Boundary conditions were applied to the muffler and the water block. A forward looking infrared (FLIR) camera helped determine the inflow temperature and average surface temperature of the muffler by capturing images after the generator operated for 10 minutes at steady state. Analyzing the FLIR images determined that the inflow temperature entering the nozzle of the muffler was approximately 406°C. This condition was inputted into the Heat Transfer of Fluids interface.

The average surface temperature of the muffler was 258°C. Through reverse engineering, the inlet flow rate in the Lamar Flow interface was adjusted until the muffler matched 258°C, resulting in an inlet flow rate of 0.0117 m^3/s. The FLIR image and the COMSOL image of the muffler's average surface temperature is displayed in Figure 7.

a)



b)

Figure 7. Comparison of Muffler Average Surface Temperature: a) FLIR Image, b) COMSOL Simulation.

The inflow in the Heat Transfer of Fluids interface was set to simulate a cooling system chiller with a water temperature of 19°C and pressure 60 Psi. This simulated the pressure and temperature of the water leaving the cooling system and entering the water block. The cooling system's inlet flow rate into the water block for the Laminar Flow interface was 0.00014 m^3/s [10].

3.0 Simulation Results

All of the systems' components with their individual physics already applied were compiled together to form the entire system. The system was meshed and the model was run with the resulting simulation displayed in Figure 8.

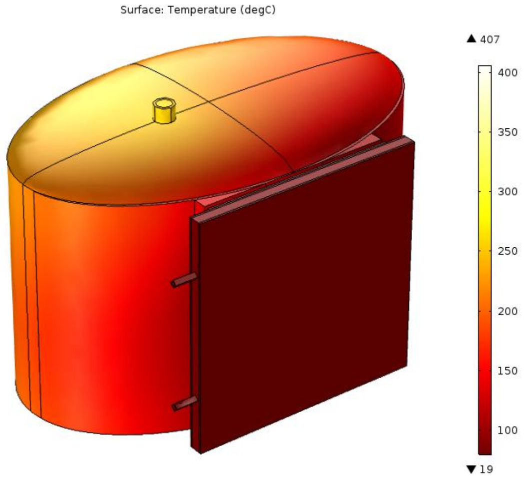


Figure 8. Final System Surface Temperature Distribution.

The hot and cold temperature of each TEG was measured as displayed in Table 3.

Table 3. Simulation Temperature Results of TEG Array (5mm Aluminum Plate).

TEG	Hot Side Temp (°C)	Cold Side Temp (°C)	Temp Difference (°C)
1	89.26	37.47	51.79
2	70.68	34.26	36.42
3	71.01	34.27	36.74
4	77.27	34.94	42.33
5	58.50	31.06	27.44
6	62.3	31.35	30.95
7	67.82	33.58	34.24
8	60.24	30.99	29.25
Average Temp Difference			36.15

Another simulation was performed in which the aluminum plate width between the TEG array and the water block was reduced from 5mm to 3mm to determine if the temperature difference across the TEGs would change. Table shows the results of this simulation.

Table 4. Simulation Temperature Results of TEG Array (3 mm Aluminum Plate).

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
Average Temp Difference			37.52

By decreasing the width of the plate, the average temperature difference increased from 36.15°C to 37.52°C.

4.0 Future Work

Future work includes comparing the COMSOL model output to a tabletop prototype in order to validate the COMSOL model. Additional modeling could be done, such as applying the temperature differences across each TEG determined by COMSOL to PSPICE to predict the voltage and amperage produced by each TEG and TEG array. This work will influence the design and allow for a TEG array to be built to a specific requirement. Future modeling of the TEG design includes determining the most efficient parallel and series combinations of the TEG array to support the specified requirement. This initial tabletop prototype will provide insight in the applicability of a TEG array as a proof-of-concept system in military applications.

Further research includes investigating the ability of a COTS TEG to reduce the IR signature. If proved practical, this could be beneficial to military systems. Reducing the heat signature of engines in military systems such as aircrafts and tanks, would increase platform survivability.

5.0 Conclusion

COMSOL helped study the temperature difference between the sidings of each TEG by simulating an array of eight TEGs on the muffler of a portable generator. Through simulation, COMSOL verified the physical characteristics of the TEG, water block, and muffler to their physical counterparts. Two simulations were run in which COMSOL determined the hot and cold side temperature for each TEG. In the first simulation, the average temperature difference with a 5.0 mm aluminum plate between the water block and array was 36.15 °C. This increased to 37.52°C in the second simulation with a 3.0 mm plate. These findings will be utilized in further modeling, design, and construction of a TEG array prototype.

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Acknowledgements

This research was funded and scoped by the Office of Naval Research’s Naval Enterprise Partnership Teaming with Universities for National Excellence (NEPTUNE).