

Thermoelectric Module Construction for Low Temperature Gradient Power Generation

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Abstract

Energy related carbon dioxide emissions are the largest contributors to greenhouse gasses [1]. Thermoelectric power generation that exploits natural temperature differences between the air and earth can be a zero-emission replacement to small stand-alone power sources. Maximizing the temperature drop across the module is crucial to achieving optimal output power. An equation relating output power to thermoelectric module parameters is derived. In addition, several configurations are investigated experimentally. Output power shows a significant dependence on module surface area. In the setups tested, one side of the thermoelectric module was thermally coupled to the earth, while the other side was left exposed to air. This paper evaluates three 110-hour experiments. The surface area of the exposed side was varied by a factor of about 15 without changing the area covered by thermoelectric elements. The output power shows a direct dependence on exposed surface area and changes by about a factor of 25.

Nomenclature

S	surface area of module
A	cross sectional area covered by elements
K_A	thermal conductivity of air
K_e	thermal conductivity of elements
ρ	resistivity of elements
q	heat transfer through module
q'	heat transfer from module to air
U	heat transfer coefficient
T_A	air temperature
T_C	cold side temperature
T_H	hot side temperature
L	element length
α	Seebeck coefficient
R_{tot}	total thermal resistance of module
N	number of elements

Introduction

In 1827 Jean-Baptiste Joseph Fourier observed a phenomenon that today we call the greenhouse effect. Carbon dioxide emissions are the main source of United State's greenhouse gases, 82 percent of which are energy related emissions, followed by methane at 9 percent. The United State's energy related carbon dioxide emissions were up 0.9 percent in 2003 from 2002 levels. Carbon dioxide is responsible for over half of the enhancement of the greenhouse effect. The concentration of carbon dioxide in the atmosphere has been measured in Mauna Loa, Hawaii since 1958 and rose by about 17 percent in 42 years measured in parts per million by volume [2].

Without the greenhouse effect, the temperature of the earth would be about 16°C cooler and life as we know it

would not be able to exist [3]. The greenhouse gases in the atmosphere (e.g. carbon dioxide) absorb and reradiate infrared radiation trying to escape from the earth's surface. This in turn heats the earth. Since the beginning of the 20th century, the mean temperature of the earth's surface has increased about 0.6°C [4]. This is the greatest rise in temperature over the last 400 to 600 years. A rise in the sea level, droughts, heat waves, and more extreme weather events are just a few consequences of surplus greenhouse gasses.

Thermoelectric generators (TEGs) generate no emissions while producing electrical power. TEG systems have been shown to reduce greenhouse gas emissions significantly as an alternator replacement in automobiles [5]. They have no moving parts and produce energy solely from a temperature difference across the module. TEGs require no maintenance and their lifetimes are on the order 200,000 hours (which is approximately 23 years of continuous use) [6]. Besides being an ideal candidate for an environmentally friendly energy source, TEGs have many current day applications. Anything that creates waste heat (e.g. engines, computers, electronics, etc.) can benefit from TEGs.

Small natural temperature gradients can also be used to generate electrical power. Some research has been done on exploiting the temperature difference between the air and earth to generate electrical power [7, 8]. Temperature differences of about -0.35° to 0.7°C were measured. Exploiting the temperature difference between air and solid structures has also been researched [9]. The air-solid structure setup achieved an average output power density on the order of 5mW/m².

This paper examines theoretically and experimentally the optimum design of thermoelectric power generators for waste heat recovery applications using natural temperature differences between the air and earth. The TEG used was a commercially available Marlow DT12-2.5.

As expected the output power increased with TEG surface area. With a matched load, the maximum total power achieved over the 110 hours was 63.3 mWh and the average power per hour was 0.575 mW.

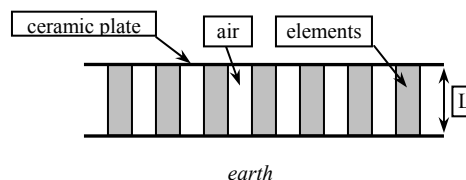


Figure 1: Composite wall approximation and module construction.

Theoretical Description

Applying a constant heat flux to one side of the thermoelectric element, an equation for output power can be derived. This equation depends on thermoelectric element geometry and material parameters. To calculate the thermal

resistance across the module, a composite wall approximation was used, as seen in Figure 1 [10]. The total thermal resistance of the module is

$$R_{tot} = \frac{L}{K_{\epsilon}A + K_A(S - A)}. \quad (1)$$

The thermal transfer across the module due to conduction is

$$q_{cond} = \frac{T_H - T_C}{R_{tot}} = \frac{[K_{\epsilon}A + K_A(S - A)](T_H - T_C)}{L}. \quad (2)$$

The total heat transfer including current effects across the module is given as

$$q = q_{cond} + q_{Peltier} + q_{resistive} + q_{Thomson}. \quad (3)$$

Thomson heat flux is due to the Seebeck coefficient having a small dependence on temperature and is given as

$$q_{Thomson} = \pm \int_{T_C}^{T_H} T \frac{d\alpha}{dT} IdT. \quad (4)$$

This effect can be neglected because temperature gradients on the order of only several degrees Kelvin are experienced by the TEGs [11]. The Seebeck coefficient will not change enough to affect the analysis. The resistive heat transfer through the module is given as

$$q_{resistive} = \frac{1}{2} I^2 r. \quad (5)$$

This effect can also be neglected because the modules experience very small currents. The effective heat transfer that is considered is

$$q = q_{cond} + q_{Peltier} = \frac{[K_{\epsilon}A + K_A(S - A)](T_H - T_C)}{L} + \alpha T_C I. \quad (6)$$

At steady state, the heat flux through a solid is the same as the heat flux emitted by the solid, as seen in Figure 2. The thermal transfer (q') is assumed to be entirely convective. Using the relations

$$\frac{V}{R_{el}} = I, \quad \alpha \Delta T = V, \quad \frac{\alpha(T_H - T_C)}{R_{el}} = I, \quad \frac{\rho L}{A} N^2 = R_{el}, \quad (7)$$

and equating q and q' we obtain

$$US(T_C - T_A) = \frac{[K_{\epsilon}A + K_A(S - A)](T_H - T_C)}{L} + \frac{A\alpha^2 T_C (T_H - T_C)}{LN^2 \rho}. \quad (8)$$

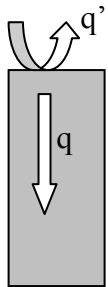


Figure 2: Heat flux in and out of solid

The output power with matched load is given as

$$P = \frac{V_{oc}^2}{4R_{el}} = \frac{\alpha^2 (T_H - T_C)^2 A}{4\rho LN^2}. \quad (9)$$

Combining equations 8 and 9, yields

$$L_{opt} = \frac{N^2 \rho (K_{\epsilon}A + K_A(S - A)) + A\alpha^2 T_H}{USN^2 \rho}. \quad (10)$$

This is the final equation relating thermoelectric module parameters. This optimal length is related to the heat transfer coefficient and the electrical resistivity of the module. From heat conduction considerations, it can be concluded that the longer the element the greater the temperature drop across the element. From electrical considerations, the shorter the element the lower the electrical resistance. An optimal length is described by Equation 10 that takes both factors into account.

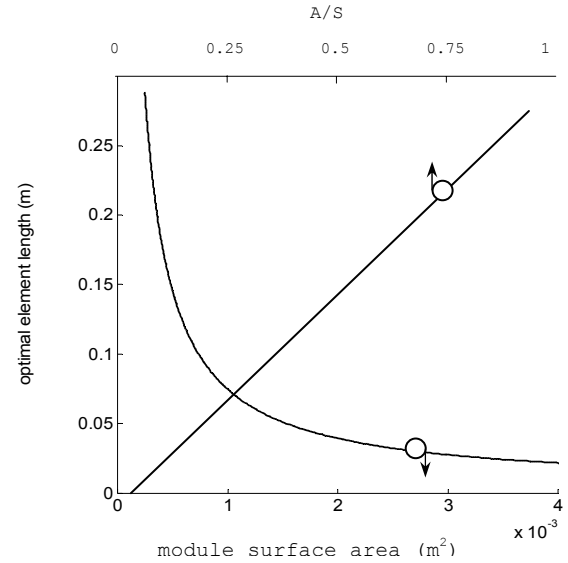


Figure 3: Optimal element length vs. module surface area and fractional area (A/S).

ρ	$1.02 \cdot 10^{-5} \Omega m$
K_{ϵ}	1.44 W/(mK)
α	$2.06 \cdot 10^{-4} \text{ V/K}$
N	254
K_A	0.02 W/(mK)
T_H	300° K
U	$5 \text{ W/(m}^2\text{K)}$
A	$0.249 \cdot 10^{-3} \text{ m}^2$

Table 1: Values used for figure 3.

Experimental Method

The TEG was thermally coupled to a square copper plate which measured 38 x 38 x 0.32 cm, leaving one side of the TEG exposed. The temperature of the copper plate did not fluctuate quickly due to its large thermal mass; it was also used as a thermal spreader. To minimize thermal contact resistance, a heat sink compound was used in both the copper and ceramic plate TEG contacts. This copper plate was buried

in soil in order to set the copper plate temperature to the ground temperature. The open circuit voltage and temperature drop across the module was measured every 10 minutes for 110 hours per setup.

Three different setups were evaluated. The first setup left the exposed side of the TEG open to air. The second setup used a 33 cm² ceramic plate mounted to the exposed side of the TEG. The third setup used a 131 cm² ceramic plate also mounted to the exposed side of the TEG. The ceramic plates were used to simulate an increased surface area of the module. The plates used were aluminum nitride. The experiment was performed outdoors in a field away from all objects that could cast a shadow on the module. The TEG used was a Marlow DT12-2.5. Physical characteristics of the module are outlined in Table 3. The mounting mechanism used is seen in Figure 4.

Weather Conditions	
Clear	C
Overcas	O
Cloudy	CL
Misty	M

Table 2: Weather conditions.

Results and Analysis

In setup 1, the total power generated over the 110 hours was 2.511 mWh. The average power generated per hour was 0.023 mW. The maximum temperature drop across the module was ±4°C. To calculate output, total, and average power with matched load Equation 11 was used.

$$P = \frac{V_{oc}^2}{4R}, \quad P_{tot.} = \int_0^T PdT, \quad P_{ave.} = \frac{1}{T} \int_0^T PdT. \quad (11)$$

V_{oc} is the open-circuit voltage in volts and R is the electrical resistance of the TEG in ohms. T is 110 hours.

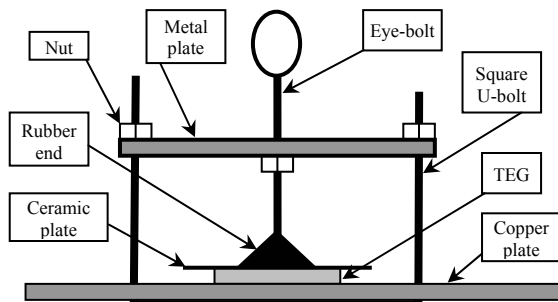


Figure 4: TEG mounting mechanism (not to scale).

TEG	# of active elements	Surface Area (cm ²)	Thickness (mm)	Resistance (Ω)
DT12-2.5	254	9	4.04	4.9

Table 3: TEG physical characteristics.



Figure 5: Picture of TEG mounting mechanism.

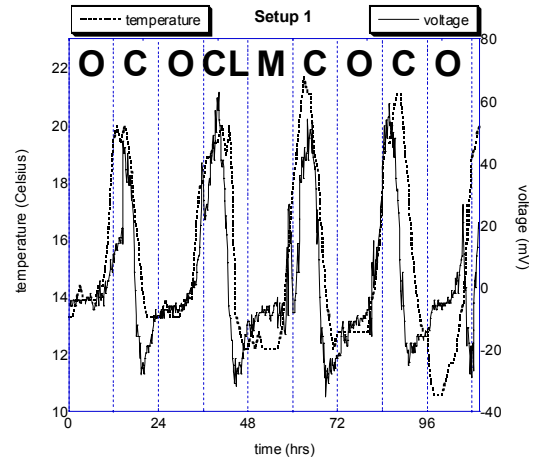


Figure 6: Open circuit voltage and outdoor temperature for setup 1.

All of the time axes start at midnight. In setup 2, the total power generated over the 110 hours was 7.81mWh. The average power generated per hour was 0.071 mW. This is an increase of about 3.1 times that of setup 1. The ceramic plate mounted on the TEG was 33 cm² and increased the surface area of the TEG by a factor of 3.6.

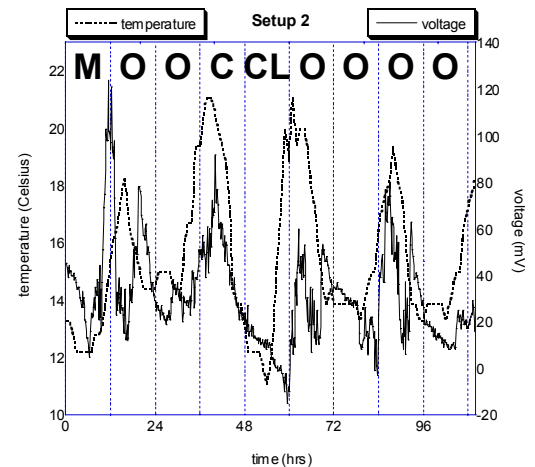


Figure 7: Open circuit voltage and outdoor temperature for setup 2.

In setup 3, the total power generated over the 110 hours was 63.3 mWh. The average power generated per hour was 0.575 mW. This is an increase of about 25.2 times that of setup 1. The ceramic plate mounted on the TEG was 131 cm² and increased the surface area of the TEG by a factor of 14.5.

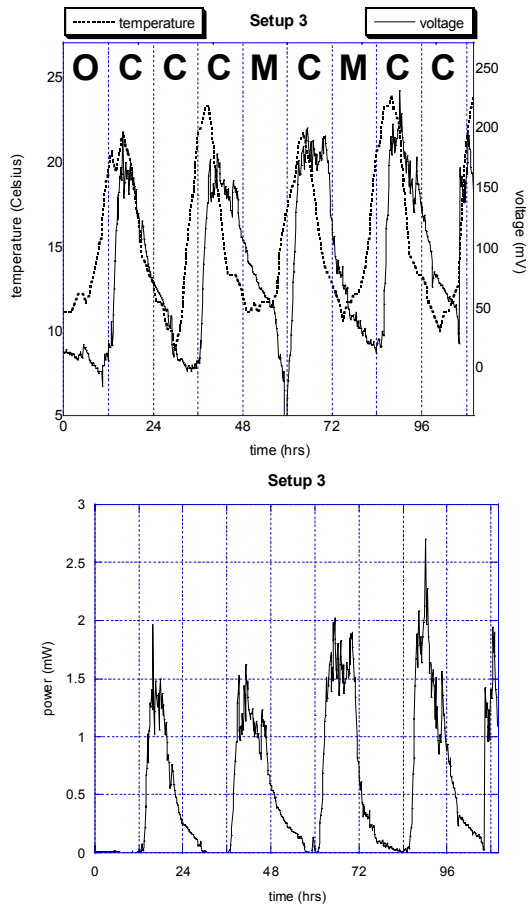


Figure 8: Top: Open circuit voltage and outdoor temperature. Bottom: Output power with matched load for setup 3.

The non-unity ratio of fractional area to fractional power is attributed to cloud cover and other weather factors.

$$\text{Fractional power} = \frac{\text{power generated}}{\text{power generated by setup 1}} \quad (14)$$

$$\text{Fractional area} = \frac{\text{surface area of ceramic plate}}{\text{surface area of TEG}}$$

As expected, a very strong dependence on cloud cover was observed. The weather during setup 2 was mostly cloudy and overcast. Due to these weather conditions the voltage plot does not mimic the temperature plot. Setups 1 and 3 saw mostly clear weather and no two consecutive overcast periods. These temperature and voltage graphs exhibit similar trends.

The earth side was often the hot side. This was detected by the polarity of the open circuit voltage. Positive voltage indicated the earth side as the hot side while negative voltage indicated the air side as the hot side. This shows that the sun heats up the ground via radiation and convection. The heat dissipates through the device via conduction and is reradiated into the atmosphere. The larger ceramic plate has more surface area to dissipate heat via convection and radiation into the atmosphere.

The weather data was logged at the Watsonville airport, about 16 miles from the test site [12].

Conclusion

A fundamental equation relating several TEG variables was evaluated and supported. The variable experimented with was the TEG module surface area. To simulate increased surface area, aluminum nitride ceramic plates were thermally coupled to the TEG. As the surface area of the TEG was increased, the power generated increased. All other variables were held constant. The maximum output power was achieved using the largest ceramic plate, which measured 131 cm². This setup generated a total power over 110 hours of 63.3 mWh and an average power per hour of .575 mW. This is a fractional area increase by a factor of 15 and a fractional power increase by a factor of 25. The non-unity ratio of fractional area to fractional power is attributed to weather factors. This was generated using only one Marlow DT12-2.5. This research was performed in Santa Cruz, CA in the summer of 2004.

Setup	P _{TOT.} (mWh)	P _{AVE.} (mW)	Fractional Area	Fractional Power
1	2.5	.0228	1	1
2	7.8	.071	3.6	3.1
3	63.3	.575	14.5	25.2

Table 4: Results.

References

1. U.S. Carbon Dioxide Emissions from Energy Sources, 2003 Flash Estimate. EIA U.S. DOE; 2004.
2. C.D. Keeling and T.P. Whorf, "Atmospheric carbon dioxide record from Mauna Loa," *Carbon Dioxide Research Group*. Scripps Institution of Oceanography. University of California, La Jolla, California.
3. Environmental Protection Agency, "Climate Change, the Greenhouse Effect," NOAA/NASA/EPA Climate Change Partnership. www.epa.gov. September. 2004.
4. Union of Concerned Scientists, "Climate Science of Global Warming: Has the Climate Changed Already?" www.ucsusa.org. September. 2004.
5. J. I. Ghojel, "Environmental Impact Analysis of Thermoelectric Generation in Automotive Waste-Heat Recovery Application," *23rd International Conference on Thermoelectrics*, Adelaide, Australia. July. 2004.
6. G. Gromov, "Thermoelectric Cooling Modules," *Business Briefing: Global Photonics Applications and Technology*.
7. E. E. Lawrence, G. J. Snyder, "A Study of Heat Sink Performance in Air and Soil for Use in a Thermoelectric Energy Harvesting Device," *21st International Conference on Thermoelectrics*. Long Beach, CA, August. 2002.
8. J. Stevens, "Optimal Design of Small Delta-T Thermoelectric Generation Systems," *Energy Conversion and Management* Vol. 42 (2001) pp.709-720.
9. Y. Meydbray, R. Singh, T. Nguyen, J. Christofferson, A. Shakouri, "Feasibility Study of Thermoelectric Power Generation for Stand Alone Outdoor Applications," *23rd International Conference on Thermoelectrics*, Adelaide, Australia. July. 2004.
10. F. Incropera, D. DeWitt, *Introduction to Heat Transfer*, John Wiley and sons; 1985.
11. A. F. Ioffe, *Semiconductor Thermoelements and Thermoelectric Cooling*, Infosearch Ltd; 1957.
12. Weather Underground, www.wunderground.com. September; 2004.