Marina Giannakopoulou

Student, Athens College

mgiannakopoulou583@athenscollege.edu.gr

Supervisor

Victoria Giakoumopoulou

PhD Physicist, Athens College

vgiakoumopoulou@athenscollege.edu.gr

Summary

Most energy in gasoline cars is lost as heat. Heat loss, however, can be recovered via the Seebeck effect, which allows temperature difference ΔT to create electric potential difference ΔV and transform a thermocouple (tc) into an electric generator able to power small-scale car electronics. Using Peltier modules and regression analysis, it was confirmed that (i), in an open circuit, $\Delta V_{oc} \propto \Delta T$, and (ii), in a closed circuit with $\Delta V_{oc}, \Delta T = const$, maximum power P_{load}^{max} occurs when $R_{tc} = R_{load}$. Overall, although their efficiency is low, thermocouples can only reduce energy waste and improve fuel efficiency, for their operation relies solely on heat loss.

Keywords*: Gasoline cars, energy waste, Seebeck effect, 12th Sustainable Development Goal*

Introduction

Because it is an expanding gas at $> 1500°C$ that provides mechanical energy to gasoline cars, heat loss accounts for $\sim 60\%$ of the energy consumed and can reach $> 80\%$ during traffic congestion in Athens (Çengel et al., 2019, p. 483; European Environment Agency, 2025).

Being in line with Target 12.5 of the SDGs on reducing waste production, the present research examines heat-loss harnessing via the Seebeck effect.

Theoretical Framework

The Seebeck effect is a thermoelectric phenomenon, where temperature difference ΔT across a thermocouple yields electric potential difference ΔV_{oc}:

$$\boldsymbol{S = \frac{\Delta V_{oc}}{\Delta T}} \qquad [S \text{ Seebeck coefficient}] \qquad \textbf{\textit{(1)}}$$

A thermocouple consists of two thermoelements, preferably semiconductors, wired electrically in series. Their common end is exposed to high temperatures, while the other ends are maintained at a lower temperature (Figure 1; Goldsmid, 2010, p. 3).

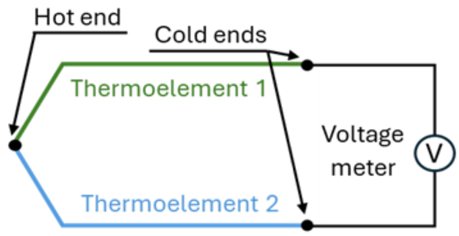

Figure 1: Thermocouple-Voltmeter Open Circuit

In both n-type and p-type semiconductors, doping allows great charge mobility in the conduction or valence band when those are heated (Figure 2). However, because high-energy carriers tend to move towards the thermocouple's cold end to increase total entropy, charge imbalance emerges, and an electric potential difference is induced (Goldsmid, 2010, pp. 25-26).

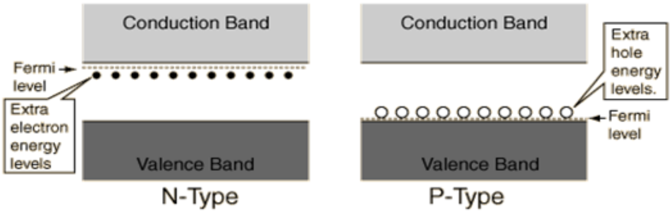

Figure 2: Band Structure in N-Type and P-Type Semiconductors (Nave, n.d.)

In a closed circuit, electrical power given to a resistive load by a thermocouple (*tc*) treated as an ideal source connected in series with a resistor $R = R_{tc}$ and, thus, providing $\Delta V_{total} = \Delta V_{oc}$ (open circuit), is given by (2), which is maximized when $\frac{dP_{load}}{dR_{load}} = 0$. At P_{load}^{max}, $R_{load} = R_{tc}$ (3).

$$\boldsymbol{P_{load}} = (\boldsymbol{\Delta V_{oc}})^2 \cdot \frac{\boldsymbol{R_{load}}}{(\boldsymbol{R_{load}}+\boldsymbol{R_{tc}})^2} \text{, assuming } \boldsymbol{\Delta V_{oc}}, \boldsymbol{\Delta T}, \boldsymbol{R_{tc}} \text{ remain constant} \quad \textit{(2)}$$

$$\frac{\boldsymbol{dP_{load}}}{\boldsymbol{dR_{load}}} = \mathbf{0} \Leftrightarrow (\boldsymbol{\Delta V_{oc}})^2 \cdot \frac{\boldsymbol{R_{tc}}-\boldsymbol{R_{load}}}{(\boldsymbol{R_{load}}+\boldsymbol{R_{tc}})^3} = \mathbf{0} \Leftrightarrow \boldsymbol{R_{load}} = \boldsymbol{R_{tc}} \text{ since } \boldsymbol{\Delta V_{oc}} \neq \mathbf{0} \quad \textit{(3)}$$

The thermocouple's efficiency is given by $\boldsymbol{\eta} = \frac{\boldsymbol{P_{load}}}{\boldsymbol{P_{thermal}}} = \frac{\boldsymbol{P_{load}}}{\frac{\boldsymbol{Q_{in}}}{\boldsymbol{\Delta t}}} = \frac{\boldsymbol{P_{load}}}{\frac{\boldsymbol{mc\Delta T}}{\boldsymbol{\Delta t}}}$ *(4)*

Research questions:

i) What is the relationship between ΔT and ΔV_{oc} across a thermocouple in an open circuit?
ii) How can power be maximized in a closed circuit?

Hypotheses:

i) In an open circuit, $\Delta V_{oc} \propto \Delta T$ with $\frac{\Delta V_{oc}}{\Delta T} = S = const.$
ii) In a closed circuit with $\Delta V_{oc}, \Delta T = const$, P_{load}^{max} is obtained when $R_{tc} = R_{load}$.

Materials-Methods

A TEC1-12706 Peltier module was used as a thermoelectric generator. To trigger ΔT, two beakers, filled with cold water and water heated at $65°C$ using a heating plate, were thermally connected to a Peltier module by copper sheets (Figure 3). Hot water was cooled by dilution to vary ΔT by $\sim 5°C$, and ΔV across the Peltier was measured using a multimeter set to $20V/DC$. The experiment was repeated using sensors to capture $\sim$1,000 data pairs to be processed by a Python-based AI-powered data analysis tool (Julius AI). Artificial intelligence performed linear regression to plot the $\Delta V - \Delta T$ graph, determine the Seebeck coefficient, and calculate the voltage at $\Delta T = 100°C$, a realistic ΔT between the exhaust pipe and the surrounding air.

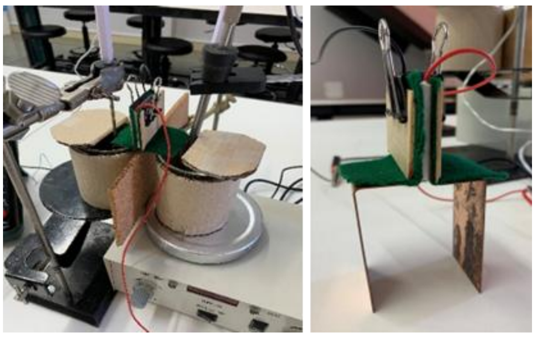

Figure 3: The Two Beakers (left) and the Peltier Module Setup (right)

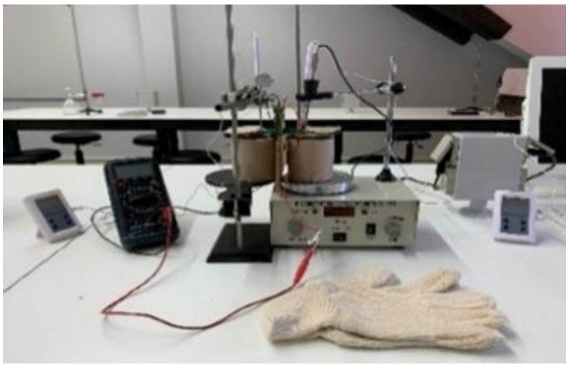

Figure 4: Experimental Setup

To enhance heat distribution and ΔT maintenance, beakers were replaced by one tank containing cold water and another tank heated by four candles. Four Peltier modules, connected in series to increase ΔV, were placed between the tanks, while a varying resistor and sensors measuring voltage and current were added to the circuit (Figure 5, left/center). While $\Delta V = 2.5\ V$ and $\Delta T = 50\ K$, the switch was closed, and current I, voltage V were measured instantaneously for every $R = 0{,}5\Omega$. From the sensors' measurements, the highest I value and the corresponding V value were manually extracted (Figure 5, right). AI-assisted non-linear regression using least squares analysis was employed to plot the $P - R$ graph, where $P = VI$.

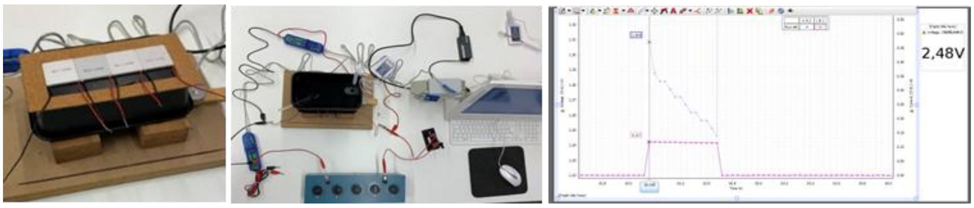

Figure 5: Experimental Setup and I, V Measurements

Heating water in a beaker using a candle, as in the previous experiment, and measuring ΔT after $5\ min$, thermal power given to the Peltier module was approximated using formula (4).

Results

Linear regression showed with 99% accuracy that $\Delta T \propto \Delta V$ with a proportionality constant $S = 5.6\ mV/K$ (Figure 6, left). Regression analysis also showed that $P_{load}^{max} = 0.165\ W$ was achieved at $R_{load} = R_{Pel.} = 5.31\ \Omega$ (Figure 6, right). In addition, it found $\Delta V_{oc} = 1.88\ V$ and $\Delta V(100K) = 0.56V$. The efficiency of the thermocouples was $\eta = 3\%$.

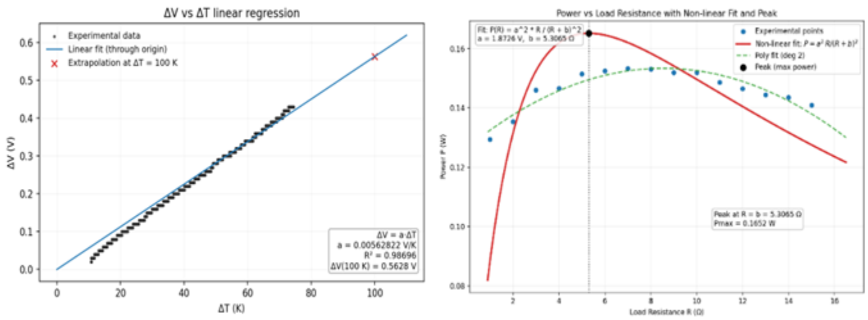

Figure 6: $\Delta V - \Delta T$ and $P - R$ Plots
Note. Author-collected data; AI-assisted (Julius AI) regression and plot.

Discussion

Although insulation was sufficient to show $\Delta T \propto \Delta V$, significant heat loss ($\Delta T_{exp\,(beakers)} \gg \Delta T_{real\,(Pel.)}$) caused $S_{exp} = 5.6\, mV/K \ll S_{th} = 21.2\, mV/K$.

Furthermore, $R_{load} = R_{Pel.(exp)} = 5.31\,\Omega > R_{Pel.(th)} = 4 \cdot 0.85\,\Omega = 3.4\,\Omega$ is due to $R_{int(wires/sensors)}$ and Joule heating, which decreased $\Delta T_{Pel.}$. Consequently, ΔV_{oc} decreased, making $\Delta V_{tot} = \Delta V_{oc} - IR_{tot}$ and $P_{load}^{max} = \frac{\Delta V_{tot}{}^2}{R_{tot}}$ smaller. To explain that decrease, the algorithm increased R_{tc} in (2) and decreased ΔV_{oc}. That is why $\Delta V_{oc\,(exp)} = 2.5\,V > \Delta V_{oc\,(graph)} = 1.88\,V$.

The above is evident thanks to non-linear regression, which—although numerically less precise than the polynomial fit—reflects the underlying theory and has physical meaning, unlike the latter fit.

Finally, though low, $\eta = 3\% \sim \eta_{TEC1-12706}^{max} = 5\%$. Besides, because the supplied energy is exhaust heat, low efficiency η yields no waste, so fuel efficiency always improves. At the same time, P_{load}^{max}, provided by four modules, suffices to power dashboard LEDs and temperature or voltage sensors, and it can be increased using more serially arranged thermocouples.

Conclusions

The utilization of the Seebeck effect not only reduces energy waste in gasoline cars; it also decreases the amount of heat that causes urban warming. The efficiency of thermocouples is yet to be improved. However, because they operate without direct energy cost, large-scale implementation, especially in cities like Athens, will enhance environmental sustainability.

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