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IMPROVING THERMAL SHIELDS TO PROTECT THERMOELECTRIC GENERATORS (TEGs) IN AUTOMOTIVE ENERGY RECOVERY SYSTEMS

BY

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Abstract. The increasing need for sustainable mobility and enhanced energy efficiency in internal combustion engine (ICE) vehicles has intensified interest in waste heat recovery technologies, particularly thermoelectric generators (TEGs). However, low conversion efficiency and sensitivity to high exhaust gas temperatures from internal combustion engines still limit their practical application.

This study investigates the thermal and electrical behavior of a commercial TEC1-12706 SR module subjected to controlled temperature conditions that simulate exhaust system environments. Using copper and aluminum protective plates to manage heat distribution, experiments were conducted at input temperatures of 250°C and 350°C to assess temperature evolution, thermal gradients, voltage, current, and output power. Copper’s high thermal conductivity facilitated efficient heat transfer on the hot side, while aluminum increased distribution of thermal dissipation on the cold side, though progressive heating reduced ΔT over time. The findings underline the critical role of thermal shielding and cooling strategies in preserving module integrity and maximizing conversion

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efficiency. This research provides experimental insights and design considerations for integrating TEGs into automotive waste heat recovery systems.

Keywords: thermoelectric generator, thermal management, waste energy, automotive, seebeck effect.

1. Introduction

The global transition toward sustainable mobility and the need to reduce greenhouse gas emissions have significantly intensified research dedicated to waste heat recovery in vehicles equipped with internal combustion engines (ICE). Modern engines utilize only approximately 30–40% of the fuel's chemical energy to produce mechanical work, while the remainder is lost as heat through exhaust gases and cooling systems, representing a major but insufficiently exploited energy resource (Bell 2008; Ochieng *et al.* 2022; Rowe 2018). In the current environment of worldwide energy transition and increasing regulatory need to lower vehicular emissions, the recovery of waste heat from ICE exhaust systems becomes a significant research field (Di Battista and Cipollone 2023; Moradi *et al.*, 2024).

In this context, thermoelectric generators (TEGs) have become highly attractive solutions, considering their ability to directly convert temperature differences into electrical energy through the Seebeck effect, without moving components and with increased reliability (Di Battista and Cipollone 2023; Snyder and Toberer 2008). These characteristics make them suitable for automotive applications, including both hybrid and conventional systems, where space constraints and robustness are critical parameters. Furthermore, advancements in thermoelectric materials such as Bi₂Te₃-based alloys, skutterudites, and half-Heusler materials have led to improvements in the thermoelectric figure of merit, ZT, thereby enhancing the applicability of TEGs in the automotive field (Bell 2008; Rowe 2018).

Thermoelectric generators operate based on the Seebeck effect, that occurs when a temperature differential is applied on the sides of a thermoelectric module, generating an electric voltage across it (Ochieng *et al.*, 2022). Multiple pairs of n-type and p-type semiconductor elements are placed electrically in series and thermally in parallel, stacked between protective ceramic plates, to form the thermoelectric device, or module (Achitei *et al.*, 2023).

However, the practical integration of TEGs into vehicle exhaust systems faces considerable challenges. Exhaust gas temperatures can reach 700–900°C in gasoline engines and even exceed 1000°C in high-performance applications, far surpassing the operating limits of most commercial thermoelectric modules, which are designed for maximum temperatures of 150–200°C (Moradi *et al.*, 2024; Snyder and Toberer, 2008). Thus, optimizing heat transfer, controlling thermal gradients, and selecting appropriate materials for interface plates are

essential elements for the efficient and safe operation of TEGs under real-world conditions.

Some studies highlight that system-level optimization, including material selection, heat exchanger geometry, thermal shield architecture, and cooling strategies, has a decisive impact on the overall performance of TEG systems (Snyder and Toberer, 2008).

In this context, the objective of the present study is to conduct a detailed experimental investigation of the thermoelectric behavior of the commercial module TEC1-12706 SR, subjected to controlled thermal conditions that simulate the real environment of an exhaust system. The work examines the evolution of temperatures, the distribution of thermal gradients, and the generated voltage, current, and power, while also analyzing the effectiveness of copper and aluminum as thermal protection materials. The results contribute to advanced design solutions for integrating TEGs into automotive waste heat recovery systems.

The analyzed module is a commercial one shown in Fig. 1, frequently used in cooling or current generation applications. The main characteristics are:

- dimensions of 40×40 mm;
- thickness of 3.8 mm;
- a nominal voltage of 12V;
- maximum power output of 60W;
- an operating temperature ranges from -30°C to +138°C;
- ceramic surfaces made of Alumina (Al_2O_3).



Fig. 1 – Thermoelectric Generator TEC1-12706 SR.

In addition, the module has an estimated endurance of more than 200,000 hours, representing an excellent option for assessing performance under dynamic heat flow circumstances.

An adjustable and stable thermal input was provided by a regulated hot air pistol, which was used as a heat source to generate the necessary temperature differential for Seebeck stimulation.

Recent literature on global trends in the application of TEGs within automotive systems highlights a continuous improvement in device efficiency, alongside the development of optimized architectures for the effective recovery of waste heat (Bhakta and Kundu, 2024). Furthermore, comparative studies focusing on the geometry and configuration of thermoelectric modules have demonstrated that the latest TEG generations enable more effective integration within exhaust systems, while consistently delivering substantial energy contributions under real operating conditions (Tien *et al.*, 2022).

2. Materials and methods

This chapter presents the comprehensive methodology employed to evaluate the thermoelectric performance of the TEC1-12706 SR module under controlled conditions, replicating the thermal environment typically found near automotive exhaust systems. The methodological framework was carefully designed to ensure reproducibility, measurement accuracy, and practical relevance to real-world applications.

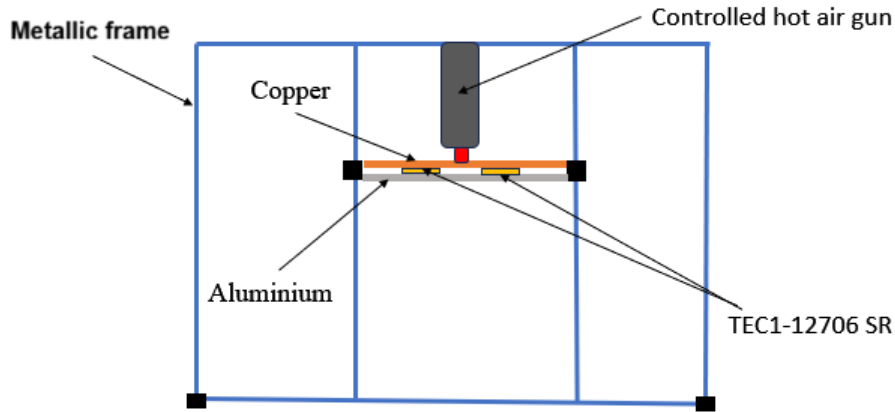


Fig. 2 – Experimental setup.

The experimental setup shown in Fig. 2 comprised the following components:

- The TEC1-12706 SR thermoelectric module, chosen for its widespread use in laboratory research and its well-documented characteristics at moderate temperature ranges.

- Copper and aluminum plates, with copper positioned on the hot side due to its high thermal conductivity, and aluminum on the cold side owing to its effective thermal dissipation capabilities.
- A controlled heating source consisting of an electrical resistance element capable of reaching temperatures up to 350°C.
- Type K temperature sensors connected to a digital data acquisition system with an accuracy of $\pm 1^\circ\text{C}$.
- A digital multimeter and voltage logger used for continuous monitoring of voltage and current intensity.

Two different thermal conditions were tested, corresponding to input surface temperatures (T_p) of 250°C and 350°C, respectively. The TEG module was set up between two plates, copper on the hot side and aluminum on the cold side chosen for their unique thermal conductivities and heat distribution properties in order to protect the module and evaluate the thermal interaction with various interface materials.

Using a TEKTRONIX DTM920 thermometer with dual-channel acquisition for simultaneous monitoring of both surfaces, temperature measurements were constantly recorded, allowing for an accurate determination of the temperature differential, ΔT . The ceramic sides of the TEG were directly equipped with Type-K thermocouples. During the 480-second test, data was gathered every 30 seconds, providing an accurate time-dependent evaluation of the module's behavior.

To simulate the electric load for output power conditions a 3.3 Ω resistive load was incorporated into the circuit. Two high-precision digital multimeters were used to record voltage and current, and the Ohm's Law ($P = U \times I$) was used to determine electrical power. To evaluate the viability of implementing TEGs for waste heat recovery in automotive applications, the main goal was to examine the effects of various temperature inputs and interface configurations on voltage (U), current (I), and output power (P). By incorporating these experimental findings, this work advances our knowledge of TEG behavior under heat stress and provides design recommendations for the safe and effective installation of thermoelectric systems in exhaust conditions found in automobiles.

The goal of the setup for the experiment was to evaluate the TEC1-12706 SR module electrical and thermal behavior under regulated heat exposure. The heat source was a temperature-adjustable hot air pistol that provided hot airflow across the upper surface of the module at constant temperatures of 250°C and 350°C.

3. Results and discussion

The primary objective of testing TEC1-12706 SR thermoelectric module under controlled temperature conditions was to assess its behavior in relation to

variations in the temperature gradient and to determine the module's actual capability to generate electrical power in scenarios analogous to automotive applications.

The temperature differential (ΔT) grew quickly during the first 30 to 60 seconds at an input temperature of 250°C before stabilizing. The temperature gradient was more noticeable at 350°C, which led to increased electrical conversion, with power levels above 0.8 W. The crucial function of copper as quick heat conductor on the hot side was confirmed by measured values, which showed a peak voltage of around 2.6 V and current levels reaching about 0.25 A at the higher temperature. The aluminum plate helped maintain the ΔT required for continuous module operation by dispersing heat on the cool side. Heat transmission toward the cold plate caused the temperature gradient to peak during the tests and then gradually declined. The experimental methodology is validated by the electrical circuit's uniformity and the measurements' reproducibility.

The results of this experiment can be found in the following tables, and to see exactly what these thermoelectric generators produce on the stand we have attached some relevant graphs showing exactly how much electric power is as a function of temperature variation and how much the voltage of the electric current is obtained.

In the following tables and figures, T_p is the temperature measured by the gun, T_s represents the surface temperature, T_1 and T_2 are the temperatures at the upper and lower thermal coupling points, respectively, ΔT denotes the temperature difference, D indicates the distance between the gun and the device, U is the voltage, [V], I is the current intensity, [A], R stands for the electrical resistance, [Ω], and P represents the electrical power, [W].

The first experiment was performed at a set hot air gun temperature of 250°C. Table 1 summarizes the values considered in this study.

Table 1
Values recorded at 250 Celsius degrees

Time	T_p	T_1	T_2	ΔT	T_s	U	D	I	P	R
30	0	20.2	20.2	0	20.2	0	4	0.000	0.000	3.3
60	250	69.2	24.5	44.7	40.6	0.4	4	0.121	0.048	3.3
90	250	77.1	29.6	47.5	40.6	0.42	4	0.127	0.053	3.3
120	250	80.6	34.6	46	42.6	0.41	4	0.124	0.051	3.3
150	250	82.6	38.8	43.8	43.3	0.39	4	0.118	0.046	3.3
180	250	83.7	42.3	41.4	39.5	0.38	4	0.115	0.044	3.3
210	250	85.2	45.6	39.6	43.2	0.36	4	0.109	0.039	3.3
240	250	86.5	48.4	38.1	40.2	0.35	4	0.106	0.037	3.3
270	250	87	50.6	36.4	41.6	0.34	4	0.103	0.035	3.3
300	250	87.7	53	34.7	37.8	0.32	4	0.097	0.031	3.3

330	250	88.2	55.1	33.1	38.8	0.31	4	0.094	0.029	3.3
360	250	88.7	56.7	32	39.8	0.3	4	0.091	0.027	3.3
390	250	89.2	58.5	30.7	38.9	0.29	4	0.088	0.025	3.3
420	250	89.4	59.4	30	36.6	0.29	4	0.088	0.025	3.3
450	250	90	60.6	29.4	39.5	0.28	4	0.085	0.024	3.3
480	250	90.2	61.6	28.6	39.8	0.28	4	0.085	0.024	3.3

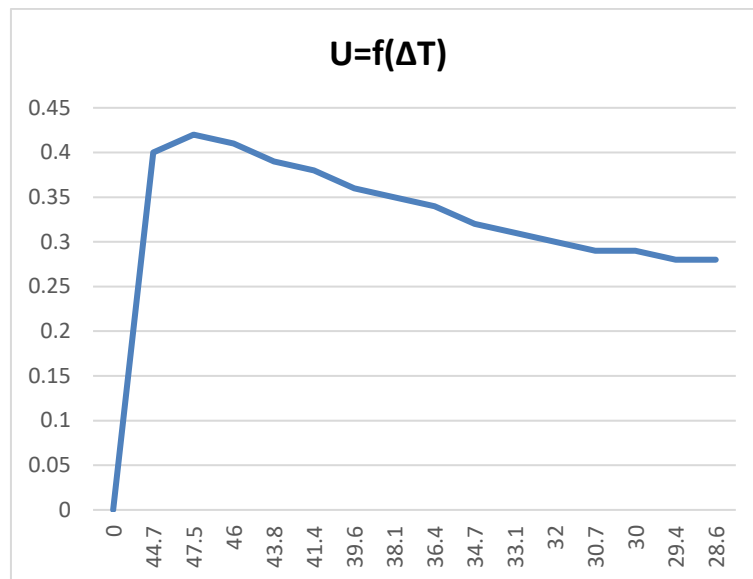
Fig. 3 – Electrical voltage versus ΔT .

Figure 3 illustrates the relationship between the electrical voltage (U) generated by the thermoelectric module and the temperature difference (ΔT) across its surfaces. Initially, as ΔT increases, voltage rises sharply, indicating efficient thermoelectric conversion at higher temperature gradients. The voltage reaches a maximum value at approximately 44.7°C, after which it gradually decreases despite further increases in temperature difference. This behavior suggests the presence of optimal operating conditions for the module, beyond which factors such as increased thermal losses or saturation effects reduce its conversion efficiency.

The diagram highlights that the thermoelectric module does not continuously increase its output voltage with increasing ΔT ; instead, it demonstrates an optimum point followed by a decline. This information is valuable for designing systems that aim to maximize electrical output under variable thermal gradients, particularly in automotive applications where conditions may fluctuate significantly.

Figure 4 illustrates the variation of electrical power (P) generated by the thermoelectric module as a function of the temperature difference (ΔT) across its surfaces. As can be observed, the electrical power increases nearly linearly with the rise in ΔT , indicating that raising the temperature gradient directly enhances the module's ability to convert thermal energy into electrical energy within the tested range.

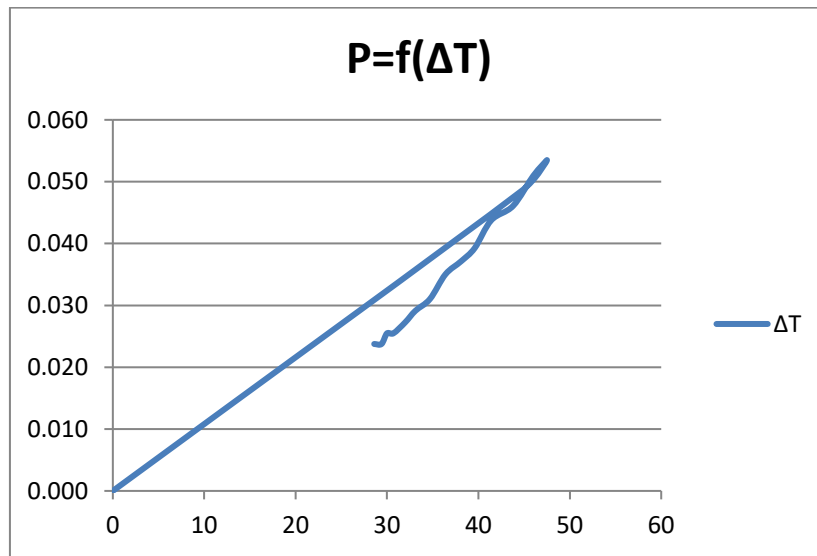


Fig. 4 – Electrical Power versus ΔT diagram.

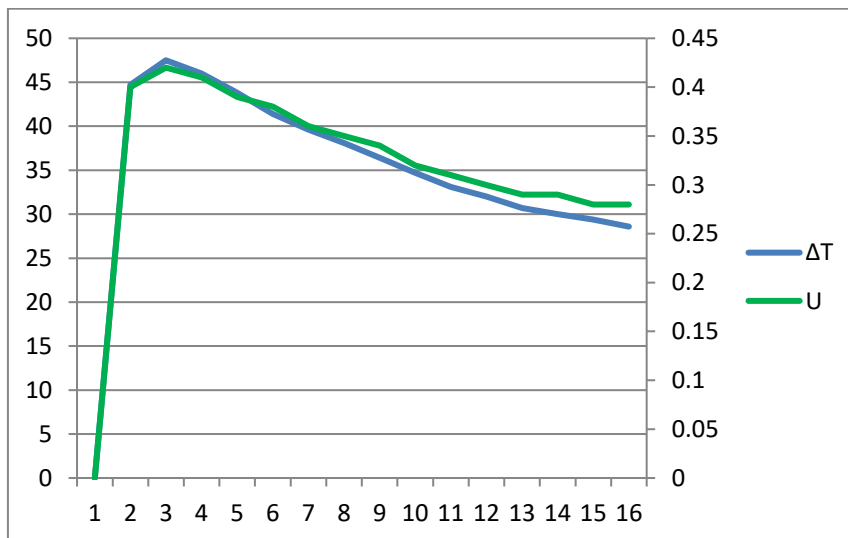


Fig. 5 – Voltage U [V], and ΔT -Temperature difference.

Graph 5 illustrates the direct correlation between the electric voltage (U) generated by the TEG and the temperature difference (ΔT) between its hot and cold sides. Both U and ΔT increase sharply at the beginning of the measurement cycle, reaching their maximum values almost simultaneously. After this peak, both parameters experience a gradual decline, which indicates a loss in driving thermal gradients and subsequently a decrease in voltage output.

This behavior confirms that the output voltage is highly sensitive to the temperature gradient: the highest electrical voltage is produced when the system registers the biggest temperature difference. As thermal equilibrium is approached through heat transfer and loss mechanisms, ΔT decreases and thus the generated voltage drops accordingly. The matching patterns shown in the graph reinforce the principle that optimizing the temperature difference across a TEG is essential for maximizing voltage generation in practical applications such as automotive energy recovery.

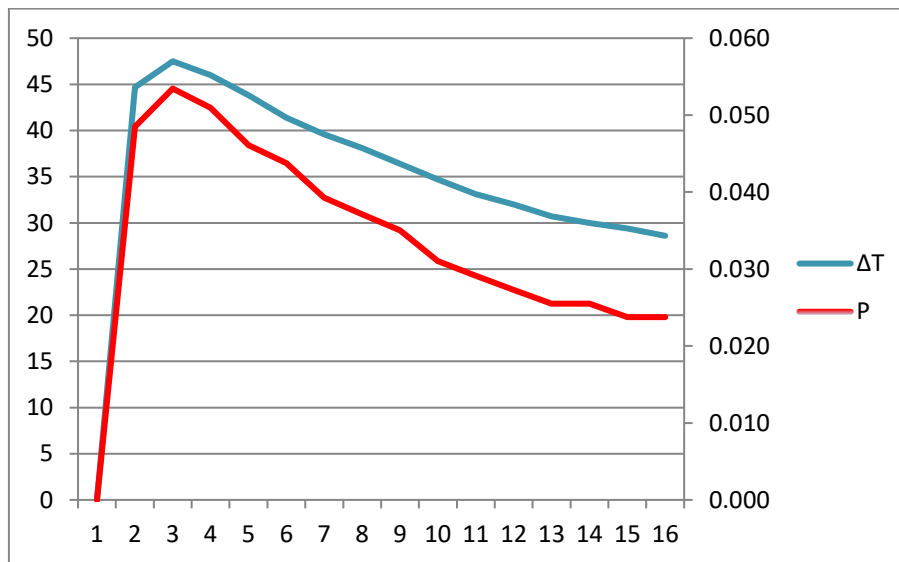


Fig. 6 – Electrical power P , [W], and temperature difference, ΔT .

The graph 6 illustrates the direct correlation between the electrical power (P) generated by the system and the temperature difference (ΔT) between its two surfaces. Both parameters increase sharply at the beginning of the measurement cycle, reaching their maximum values almost simultaneously. After this peak, both experienced a gradual decline, indicating a loss in thermal gradients and a subsequent decrease in power output.

This behavior confirms that the output power is highly sensitive to the temperature gradient: the highest electrical power is produced when the system registers the greatest temperature difference. As thermal equilibrium is

approached through heat transfer and loss mechanisms, ΔT decreases, and thus the generated power drops accordingly. The matching patterns in the graph reinforce the principle that optimizing the temperature difference across such systems is essential for maximizing power generation in practical applications, including energy recovery solutions.

The second experiment was performed on the same experimental setup, using the same circuit, but the temperature of the hot air gun was set to 350 degrees. These tests were done on different days to get the most realistic results, at room temperature in the laboratory. The data are presented in Table 2.

Table 2
Values recorded at 350 Celsius degrees

Time	T _p	T ₁	T ₂	ΔT	T _s	U	D	I	P	R
30	0	34.1	36.6	0	21.9	0.02	4	0.006	0.000	3.3
60	350	95.1	38.2	56.9	47.1	0.45	4	0.136	0.061	3.3
90	350	134.7	47.2	87.5	64	0.69	4	0.209	0.144	3.3
120	350	142.2	55.1	87.1	59.9	0.68	4	0.206	0.140	3.3
150	350	145.3	61.1	84.2	65.1	0.66	4	0.200	0.132	3.3
180	350	147.1	68.3	78.8	63.9	0.63	4	0.191	0.120	3.3
210	350	149	74	75	63.8	0.6	4	0.182	0.109	3.3
240	350	150.4	77.7	72.7	73.2	0.58	4	0.176	0.102	3.3
270	350	151.7	83	68.7	73.5	0.56	4	0.170	0.095	3.3
300	350	152.4	86.2	66.2	102.5	0.54	4	0.164	0.088	3.3
330	350	152.6	88.7	63.9	108.1	0.52	4	0.158	0.082	3.3
360	350	153.2	91.9	61.3	117.9	0.5	4	0.152	0.076	3.3
390	350	154.2	94.1	60.1	124.9	0.49	4	0.148	0.073	3.3
420	350	154.9	96.3	58.6	117.5	0.48	4	0.145	0.070	3.3
450	350	155.2	97.9	57.3	128.3	0.46	4	0.139	0.064	3.3
480	350	155.3	99.5	55.8	133.2	0.45	4	0.136	0.061	3.3

Graph 7 illustrates the direct correlation between the electrical power (P) produced and the temperature difference (ΔT) across the two surfaces of the system. Both P and ΔT sharply increase at the start of the measurement period, and they reach their maximum value nearly simultaneously. Following this peak, both parameters decline gradually, which leads to a reduction in the driving thermal gradient and, therefore, a decrease in electrical power output.

This behavior shows that the electrical power output is highly sensitive to the temperature difference: the maximum power is achieved when the temperature difference is at its highest. As the thermal system approaches

equilibrium, losing heat and equalizing temperatures, ΔT decreases, and so does the generated power. The matching trends in the graph confirm that keeping a high temperature difference is essential for maximizing electrical power generation in such applications.

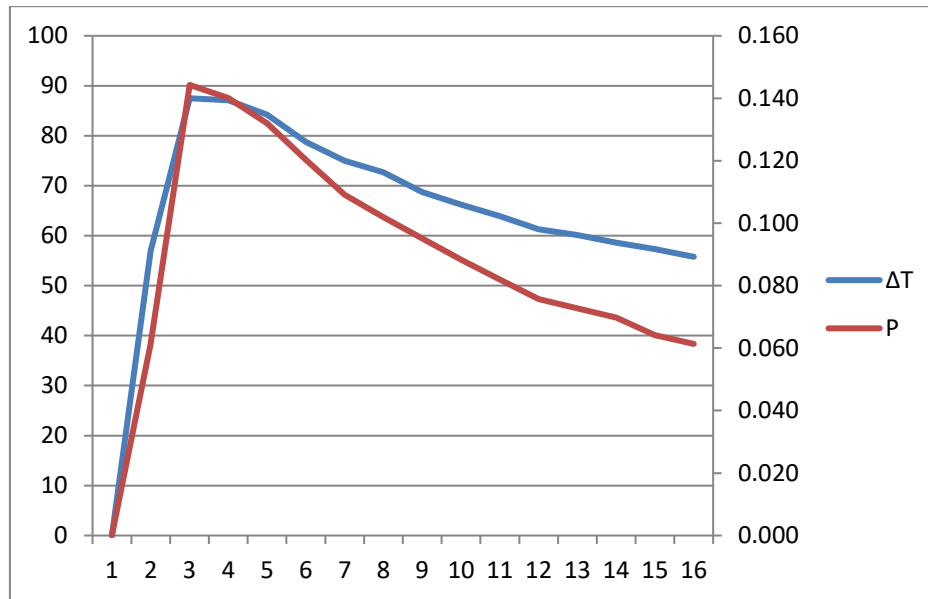


Fig. 7 – Electrical power P , [W], and temperature difference, ΔT .

Graph 8 illustrates the direct correlation between the electric voltage (U) generated by the system and the temperature difference (ΔT) between its two surfaces. Both the voltage and the temperature difference rise sharply at the beginning of the measurement cycle, reaching their maximum values almost simultaneously. After this peak, both parameters gradually decrease, which indicates a reduction in the thermal gradient and a subsequent drop in voltage output.

The behavior shown confirms that the voltage output is highly sensitive to the temperature gradient: the highest voltage output is for the maximum temperature difference. As heat transfer and loss mechanisms lead the system toward thermal equilibrium, ΔT decreases and, therefore, the voltage drops as well. The near-identical evolution of the two curves underscores the principle that maximizing the temperature difference is key to optimizing voltage generation in such thermoelectric applications.

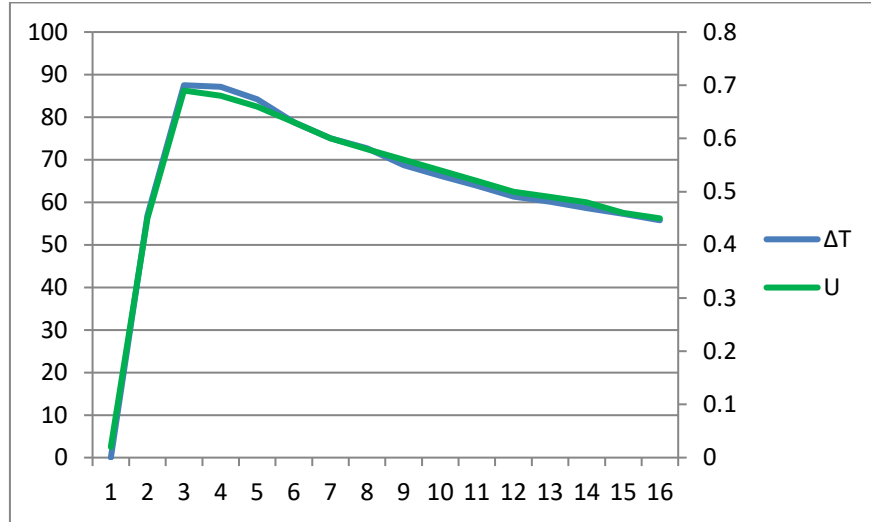


Fig. 8 – Voltage, U [V], and temperature difference, ΔT .

Following the second experimental measurements, where the inlet hot air gun temperature was increased to 350 degrees Celsius, a substantial elevation in Temperature 1 (the upper measurement point) was observed. This resulted in a significantly larger temperature differential (ΔT) across the thermoelectric module. Consequently, the enhanced thermal gradient facilitated markedly higher output values for both electrical power and temperature difference, underscoring the system's improved conversion efficiency under these operating conditions. These findings indicate that adjusting the inlet temperature positively influences the thermal driving force and the resulting performance characteristics, providing promising prospects for further optimization of thermoelectric power generation in practical applications.

4. Conclusions

The generated electrical power and voltage are directly influenced by the temperature difference (ΔT) maintained across the module surfaces, according to experimental tests carried out at input temperatures of 250°C and 350°C with the TEG module shielded by copper on the hot side and aluminum on the cold side.

The findings unequivocally show that TEG's electrical and thermal performance is greatly impacted by shielding material selection. A quick rise in temperature on the hot side was made possible by copper's excellent thermal conductivity, which also effectively conducted heat and shielded the module during the experiments. As the test went on, however, the ΔT decreased because aluminum, employed on the cold side, absorbed heat rather quickly, raising the temperature on the cold face over time.

These results demonstrate that maintaining high efficiency requires efficient heat dissipation management on one side of the module. To help maintain a steady temperature gradient and optimize thermoelectric conversion while in operation, future research should concentrate on creating passive or active cooling solutions for the TEG's cold side.

REFERENCES

- Achitei G., Dontu A.I., Chiriac B., Popescu A., *State-of-the-Art and Future Trends of Thermoelectric Generation Systems in Automotive Industry*, 1-8 (2023).
- Di Battista D., Cipollone R., *Waste Energy Recovery and Valorization in Internal Combustion Engines for Transportation*, *Energies* 16(8):3503 (2023), doi:10.3390/en16083503.
- Bell L.E., *Cooling, Heating, Generating Power, and Recovering Waste Heat with Thermoelectric Systems*, *Science* 321(5895):1457-1461 (2008), doi:10.1126/science.1158899.
- Bhakta S., Kundu K., *A Review of Thermoelectric Generators in Automobile Waste Heat Recovery Systems for Improving Energy Utilization*, *Energies* 17(5):1016 (2024), doi:10.3390/en17051016.
- Moradi J., Andwari A.M., Könnö J., Gharehghani A., Pesyridis A., *Waste Heat Recovery Technologies in Modern Internal Combustion Engines*, *Future Energy* 3(3):49-54 (2024), doi:10.55670/fppl.fuen.3.3.5.
- Ochieng A.O., Megahed T.F., Ookawara S., Hassan H., *Comprehensive Review in Waste Heat Recovery in Different Thermal Energy-Consuming Processes Using Thermoelectric Generators for Electrical Power Generation*, *Process Safety and Environmental Protection* 162:134–542022, doi:10.1016/j.psep.2022.03.070.
- Rowe D.M. (Ed.), *Thermoelectrics and Its Energy Harvesting, 2-Volume Set*, CRC Press., 2018.
- Snyder G.J., Toberer E.S., *Complex Thermoelectric Materials*, *Nature Materials* 7(2), 2008.
- Tien T.N., Vu Q.K., Duy V.N., *Novel Designs of Thermoelectric Generator for Automotive Waste Heat Recovery: A Review*, *AIMS Energy* 10(4):922–942, 2022, doi:10.3934/energy.2022042.

ÎMBUNĂȚIREA SCUTURILOR TERMICE PENTRU PROTEJAREA GENERATOARELOR TERMoeLECTRICE (TEG) ÎN SISTEMELE DE RECUPERARE A ENERGIEI DIN AUTOMOBILE

(Rezumat)

Una dintre cele mai importante strategii pentru creșterea eficienței energetice în sistemele contemporane ale vehiculelor este recuperarea căldurii reziduale. Bazate pe efectul Seebeck, generatoarele termoelectrice (TEG) sunt foarte atractive pentru aplicațiile auto, deoarece permit transformarea directă a unui gradient de temperatură în

energie electrică, fără a fi nevoie de piese în mișcare. Cu toate acestea, eficiența scăzută a conversiei și sensibilitatea la temperaturile ridicate ale gazelor de eșapament provenite de la motoarele cu ardere internă (ICE) limitează încă aplicarea lor practică.

În această publicație este prezentată o analiză experimentală detaliată a performanței modulului termoelectric TEC1-12706 SR (12V, 60W). folosind un pistol cu aer cald ca sursă de căldură, bancul de testare a fost realizat pentru a reproduce condițiile termice reale din apropierea unui sistem de evacuare. Au fost utilizate multimetre digitale pentru a măsura tensiunea și curentul TEG în timp real. Cu o putere maximă de ieșire de 0,8 W, rezultatele testelor arată că cuprul este cel mai bun material pentru ecranarea părții calde, datorită conductivității sale termice și eficienței de conversie a energiei mai bune. Propagarea căldurii către interfața inferioară a făcut ca gradientul de temperatură (ΔT) să scadă treptat după ce a crescut rapid în primele 30-40 de secunde.