

Design and Experimental Validation of a Thermoelectric Waste Heat Recovery System for Auxiliary Power Generation in Motorcycles

Ramanjaneyulu Kolla^{1*}, Sakthivel Rajendran¹, Raghu Palani², Rishika A¹, Kalaivani S¹, Manoranjan G R¹

¹Department of Automobile Engineering, Sri Venkateswara College of Engineering, Pennalur, Sriperumbudur – 602 117, Tamilnadu, India

²Department of Mechanical Engineering, Sri Venkateswara College of Engineering, Pennalur, Sriperumbudur – 602 117, Tamilnadu, India

Corresponding author mail id * ramanjaneyulu@svce.ac.in

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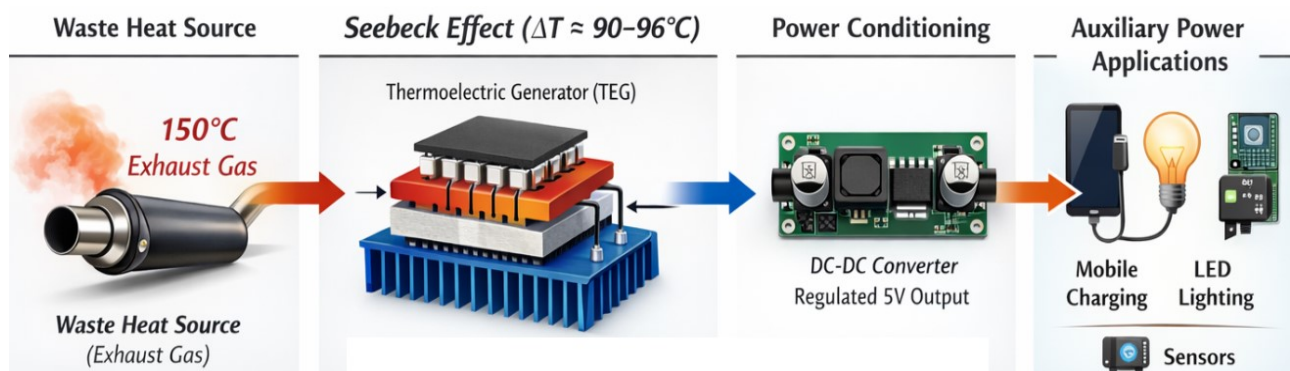
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ABSTRACT

Around two-thirds of the energy of fuel supplied to the spark ignition engine of a motorcycle is wasted in the form of heat via exhaust and cooling systems, while a very little amount of research related to thermoelectric waste heat recovery has been conducted for two wheelers due to space constraints, increased vibration levels and fluctuating exhaust temperatures compared to four wheel passenger vehicles. In this paper, the design and thermal-electric modelling along with the experimentation of the TEG waste heat recovery system for exhaust of Honda Shine motorcycle is presented. Four TEG modules were attached to the exhaust pipe with the finned heat sink on the cold side and their generated output was conditioned via the pulse-width-modulated (PWM) DC–DC boost converter charging lithium-ion power bank with 5 V regulated USB output. The thermal-electric modelling of the system was done in MATLAB Simulink–Simscape. The on-road test showed a temperature difference between hot and cold sides of a module from 9°C to 91°C with corresponding voltage and current being 1.20 V - 2.40 V and 0.430 A - 0.765 A, where connecting four modules in series yielded an output of 10.30 V at maximum temperature differential while the current remained constant as expected from a series circuit. During the steady state of the system, the regulated output voltage of 5 V continued to remain stable that can be used for powering low-power auxiliary loads like USB chargers, sensors and small lights on a motorcycle.

Keywords:

Thermoelectric generator (TEG); Waste heat recovery; Seebeck effect; Motorcycle exhaust energy harvesting; MATLAB Simulink–Simscape; DC–DC boost converter



Graphical abstract

Nomenclature

T_h, T_c	Hot-side and cold-side junction temperature of the TEG module ($^{\circ}\text{C}$)
ΔT	Temperature difference across the TEG module, $T_h - T_c$ ($^{\circ}\text{C}$)
N	Number of thermocouples (p–n pairs) per TEG module
S	Seebeck coefficient of the thermocouple material (V K^{-1})
V_{oc}	Open-circuit (no-load) voltage of the TEG module (V)
V, I	Terminal voltage and current of the TEG module under load (V, A)
R_{int}	Internal electrical resistance of the TEG module (Ω)
R_{load}	External (load) electrical resistance (Ω)
P	Electrical power output of the TEG module (W)
K_c	Thermal conductance of the TEG module (W K^{-1})
Z, ZT	Thermoelectric figure of merit and dimensionless figure of merit
η	Thermal-to-electrical conversion efficiency of the TEG (%)
D	Duty cycle of the DC–DC boost converter
V_{in}, V_{out}	Boost converter input and regulated output voltage (V)
f_{sw}	Switching frequency of the boost converter (Hz)
R^2	Coefficient of determination of a linear regression fit
$RMSE$	Root-mean-square error between a fitted model and measured data
$MAPE$	Mean Absolute Percentage Error

1. INTRODUCTION

Despite their relatively high fuel efficiency and low costs associated with their operation, two wheelers remain the choice mode of transport in most of the developing countries but the IC engine powering the vehicle makes use of only one-third of the total fuel energy input with more than 60% of the total energy going waste in the form of heat through the exhaust gas and cooling process of the engine ([Bhakta and Kundu, 2024](#)); ([Mustafa et al., 2017](#)). From research studies in energy and exergy, it has been found that the exhaust flow is responsible for up to 20-40% of the fuel energy input of any automobile or small IC engine ([Mustafa et al., 2017](#); [Jouhara et al., 2021](#); [Erixno et al., 2022](#)).

On the contrary, a thermoelectric generator (TEG) functions by the Seebeck effect, where the temperature difference generated between a pair of p-type and n-type semiconductor legs leads to the generation of electric power through the external circuit ([Snyder and Toberer, 2008](#)). Compared to the turbo compound system, the organic Rankine cycle and regenerative braking systems, TEG has no moving parts and is thus noiseless, portable and can work without working fluids, thereby rendering it more appropriate for incorporation within the motorcycle exhaust system ([Twaha et al., 2016](#)). There have been many advancements in the field of thermoelectric materials, such as bismuth-telluride-based materials, within the last two decades, leading to the optimization of figure of merit (ZT) towards increasing efficiencies at a specific hot side temperature ([Snyder and Toberer, 2008](#); [Tie and Tan, 2013](#)).

The technology of automotive exhaust TEGs has been examined in various papers of late. The present review highlights the advancements made in this area, including the first TEG prototypes produced by manufacturers such as BMW, Renault, Honda, Ford, and Nissan, and improvements in the design of components such as heat exchangers and leg geometry ([Bhakta and Kundu, 2024](#)), ([Mohamed, 2019](#)). Research on passenger car applications has investigated the potential of a modularised TEG system being created to achieve a higher heat transfer efficiency ([Li et al., 2017](#)), the

performance of a TEG under transient conditions ([Massaguer et al., 2017](#)) and the opportunity for leg optimization, taking into account the ratio of exhaust leg lengths and segmentations ([Ma et al., 2019](#)), ([Pandey and Hansdah, 2021](#)). The first attempts to generate electricity from the hot exhaust gas energy with the help of thermoelectric generators have been done by the authors who investigated the hybrid-vehicle and light duty applications and concluded that the generation of electricity is possible ([Kim et al., 2011](#); [Saqr, Mansour and Musa, 2008](#)); there were also results regarding the practical aspects of using TEGs in a vehicle ([Crane et al., 2012](#)) and high power TEG modules ([Zhang et al., 2015](#)).

The number of TEG-based applications for motorcycles is rather low; however, there are some publications which state that it is possible to use this principle on a motorcycle. The system for heat recovery of exhaust gas of 50 cc motorcycles by means of TEGs was created by ([Kunt and Gunes, 2022](#)). As a result, they managed to recover 2.05 watts of power and validate GT-SUITE thermal model based on temperature difference of TEGs ([Kunt and Gunes, 2022](#)). Another study where the authors attached TEG modules directly to motorcycle exhaust pipe, recovered electricity for charging of the mobile phone and demonstrated low price of the series connection of TEG modules ([Rizal, Lubis and Amin, 2021](#)). Thus, one can say that there are some limitations in designing the heat recovery system for motorcycle exhaust gases, which differs from that for passenger cars, including limited surface for mounting of TEG modules, great temperature variation of exhaust gas at idle and acceleration phases of motorcycle, vibrations and small amount of recovered electricity.

As the output generated from TEG module is very low in voltage, unregulated and dependent upon change in temperature difference continuously, thus, electrical regulation of TEG is equally essential as thermal management ([Crane et al., 2009](#)). Traditional method of regulating the output of TEG system is through using DC-DC boost converters with Maximum Power Point Tracking (MPPT) ([Twaha et al., 2017](#)). Comparison between MPPT and PWM control of TEG-Converter combination demonstrates that choice of controllers to be used with a particular converter is highly influential on the power supplied to the load regardless of the TEG thermal design ([Twaha et al., 2017](#)), ([Saqr, Mansour and Musa, 2008](#)). Simulation methods that are capable of modelling the interplay between thermal and electrical phenomena in TEG module such as block model of TEG in MATLAB/Simulink are useful in studying the performance of converters and also the thermal dynamics of TEG modules prior to their fabrication ([Tsai and Lin, 2009](#)).

1.1 Research Gap and Objectives

In summary, based on the current literature, we can note that (i) while the research work in the area of thermal electricity harvesting from the TEGs has been done with regard to the passenger cars, the situation is different when it comes to the diesel and stationary engines, and there is a lack of research of motorcycles ([Massaguer et al., 2017](#)), ([Ma et al., 2019](#)), ([Ishaq Khan, Maccioni, and Concli, 2025](#)); (ii) the amount of studies dedicated to the motorcycle-sized TEG system is very limited and covers only the prototype models, and the research is calculated on the basis of general thermal models since there are no studies where thermal and electrical modeling takes place and experiments are conducted on the commercial motorcycle; (iii) Furthermore, there have been no studies dedicated to the process of electricity conditioning including the boosting process, regulation, and battery charging integrated with thermal modelling process ([Tsai and Lin, 2009](#)), ([Twaha et al., 2017](#)).

In this research article, we put forward an integrated TEG waste heat recovery system for the Honda Shine motorcycle to fill in the previously mentioned gap. The system consists of different components such as (1) a combination of thermal and mechanical configurations where TEG modules are fitted onto the exhaust pipe alongside

the cooling fan located on the cold side, (2) a pulse width modulation based DC–DC boost converter to perform voltage regulation and charge the auxiliary power bank, (3) a thermal-electric model simulating the system in MATLAB Simulink–Simscape software, and (4) a practical test of the TEG module on the road using one and four TEG modules connected in series. The paper aims to: measure the temperature difference, voltage, current and energy generation capacity of the designed system at different exhaust temperatures, compare the obtained simulation and experimental findings to evaluate the built model, and assess if the created electricity can be used to power low voltage auxiliary loads such as USB charger, devices and electronics.

The organization of the paper is as follows. In Section 2, a thorough description of the system architecture, mechanical and electrical designs, experimental procedures, and MATLAB Simulink-Simscape model is given. Section 3 focuses on the simulated and experimental analysis of a single TEG module and the studies performed on four modules in series. Section 4 concludes the paper and indicates directions for future improvement.

2. MATERIALS AND METHODS

The development process included a design phase, which was supported by literature, mechanical and electrical design of the TEG assembly and the power conditioning circuit, thermal-electrical simulation using MATLAB Simulink/Simscape, and on-road experiments, as illustrated in Fig. 1. The feasibility study examined the available exhaust heat, vibrations, available mounting space and electrical load to be supplied before selecting and assembling mechanical and electrical parts.

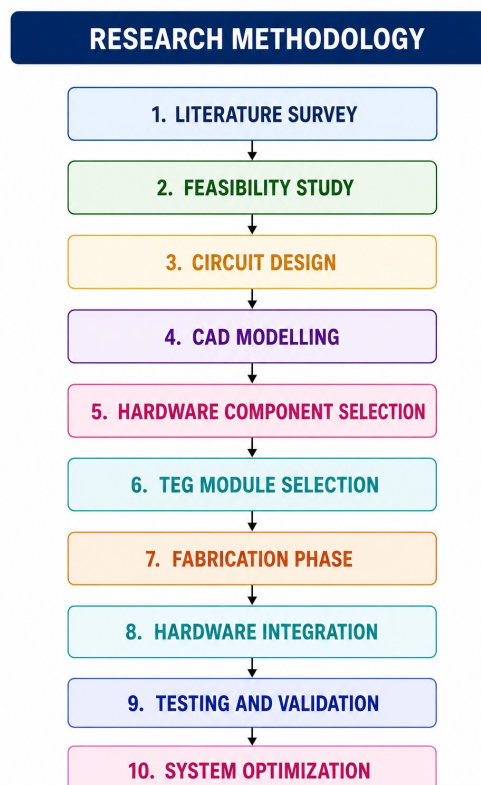


Fig. 1 Overview of the research methodology, from literature review and feasibility assessment through design, modelling and experimental validation

2.1 TEG-Based Power Generation and Regulation Architecture

The diagram of the system is shown in Fig. 2 Each TEG unit has a power source of unstable, low DC voltage, which varies with the temperature difference between its hot and cold faces. In fact, the raw output cannot be used for

charging batteries or powering devices and must first be processed by a DC-DC boost converter that increases and stabilizes the voltage. The output voltage from the converter charges a lithium-ion power bank with a voltage of 3.7 V, while a 7805 linear voltage regulator converts it to a stable 5V output that can apply to USB-powered units, sensors and other low voltage secondary loads.

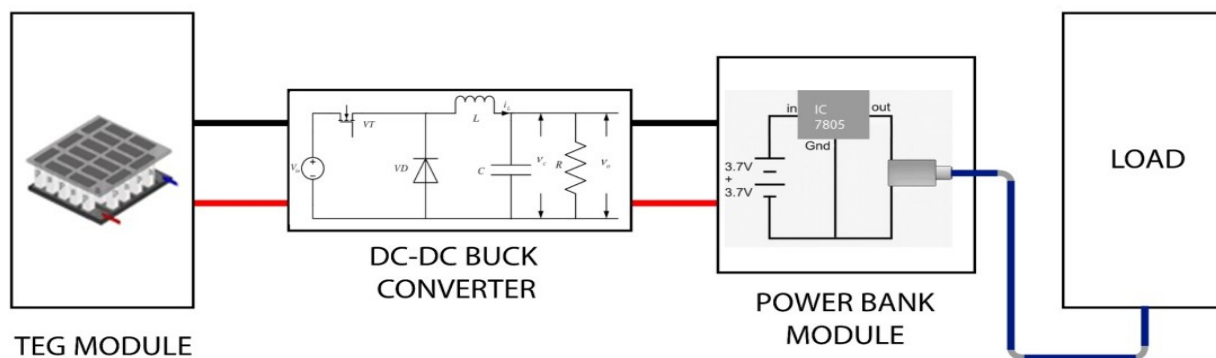


Fig. 2 Block diagram of the TEG-based power generation and regulation system

2.2 Mechanical Integration

The mounting bracket, heat sink and protective case were designed using a CAD model as shown in Fig. 3 to ensure that the TEG modules fit perfectly on the exhaust pipe, providing the highest contact area on the hot side while being structurally sound under vibration. The hot end of each module is located opposite the exhaust pipe. On the hot side, the module collects heat through thermal conduction from the exhaust gases; the cold side has been fitted with a heat sink and a small fan to keep the largest viable temperature difference between the hot and cold sides of the module. While selecting components for the heat sink, fasteners, and case, thermal performance, vibration tolerance and resistance to the motorcycle operating conditions were given special attention.

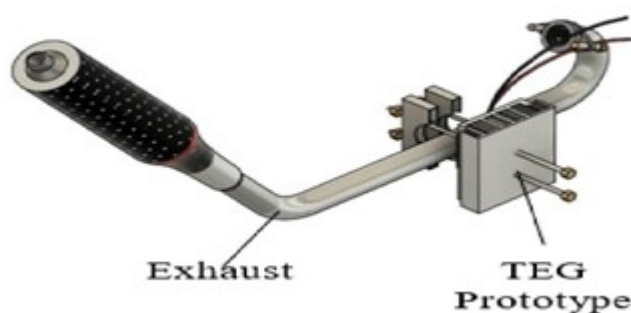


Fig. 3 CAD model of a TEG module mounted directly on the exhaust pipe

2.3 Experimental Setup

The entire setup as shown in Fig. 4, was attached to a Honda Shine motorcycle exhaust to simulate actual riding conditions. K-type thermocouples were used to collect the hot-side (T_h) and cold-side (T_c) temperature of the TEG modules and a DC voltage/current sensor gathered the electrical output at the converter's input. The regulated 5 V output was connected to a USB port at the handlebar, which allowed charging almost all devices with the help of the power generated during riding. Two configurations of the modules were applied namely a single TEG module and four TEG modules connected in series electrically but in parallel in terms of temperature distribution, i.e., each of them was able to take independently the heat from the exhaust gas and generate electrical energy.



Fig. 4 Experimental TEG waste heat recovery setup mounted on the Honda Shine exhaust pipe, with the DC–DC converter and USB charging point

2.4 Governing Equations and Theoretical Framework

In Section 2.5, the development of the design and simulation model utilizes the typical lumped-parameter model of a thermoelectric module. A thermal module contains N thermocouples having a Seebeck coefficient S leading to an open-circuit voltage at a temperature differential $\Delta T = T_h - T_c$ given as follows:

$$V_{oc} = N \cdot S \cdot \Delta T \quad (1)$$

When an external load is applied, the voltage drops below the V_{oc} due to the internal resistance of the module R_{int} that can be expressed as follows:

$$V = V_{oc} - I R_{int} = N \cdot S \cdot \Delta T - I R_{int} \quad (2)$$

In addition, the application of Ohm's law to the Thévenin-equivalent circuit yields the following relation for the current flowing through an external resistor R_{load} :

$$I = N \cdot S \cdot \Delta T / (R_{int} + R_{load}) \quad (3)$$

The power used by the load in electrical energy transfer is given by formula $P = I^2 R_{load}$, which combined with equation (3) results in

$$P = (N \cdot S \cdot \Delta T)^2 \cdot R_{load} / (R_{int} + R_{load})^2 \quad (4)$$

Equation (4) reaches its maximum value when $R_{load} = R_{int}$ (maximum-power-transfer condition), meaning that the maximum output performance of the module can be defined as $P_{max} = (N \cdot S \cdot \Delta T)^2 / (4 R_{int})$. Considering the fixed value of R_{load} in the actual system, which matches the boost-converter input, this means that the operation of the module does not necessarily occur at optimum values, meaning that this is one of the reasons that the application of

MPPT control to this technology is promising. The analysis presented in Equation (4) demonstrates that the output electric power generated by the thermoelectric module increases with the increase in the value of the temperature difference, which was confirmed in the Section 3.5 by experimental results. The efficiency of thermal-to-electric conversion provided by the thermoelectric module can be derived from the total heat balance equation of the module that incorporates the Seebeck, Peltier and Joule heating terms.

$$\eta = (\Delta T / T_h) * [\sqrt{(1 + Z\bar{T})} - 1] / [\sqrt{(1 + Z\bar{T})} + T_c / T_h] \quad (5)$$

where $\bar{T} = (T_h + T_c)/2$ is the average module temperature and $Z = S^2 / (R_{int} K_c)$ is the figure of merit of the material, $Z\bar{T}$ is the corresponding dimensionless figure of merit evaluated at $\bar{T}$; K_c is the module thermal conductance. Equation (5) indicates explicitly why cold side cooling is as important as hot side heating, that is, the efficiency depends on $\Delta T / T_h$ and T_c / T_h , thus, for a constant T_h , lowering T_c using the heat sink and fan in Section 2.2 makes η higher and increases the generated power according to Equation (4).

On the electrical conditioning side, the DC–DC boost converter illustrated in Fig. 2 brings the variable TEG voltage to the regulated bus voltage.

$$D = 1 - (V_{in} / V_{out}) \quad (6)$$

The efficiency of the converter can be expressed with the equation $\eta_{conv} = P_{out} / P_{in}$, where the losses in switching, conduction, and core of the MOSFET, diode, and inductor contribute into the difference between P_{in} and P_{out} . In this case V_{in} is not constant as in the expression above but represents a variable, ΔT -dependent TEG output from (2). This causes D to change at any moment and thus requires real-time adjustments of the PWM controller to keep V_{out} at the level of 5 V. The need for such relation is also apparent in the equations (1) to (6) which provide a theoretical basis for the Simulink-Simscape solution discussed in the following section of the paper 3.5 against the measured data in Tables 1 and 2.

2.5 MATLAB Simulink–Simscape Thermal–Electrical Model

The equations signals (1) through (6) were implemented in a system-level model making use of MATLAB Simulink–Simscape to link the thermal and electrical domains of the TWHRS by means of the block-based thermoelectric module method applied in the literature for the circuit-level TEG modelling (Tsai and Lin, 2009).

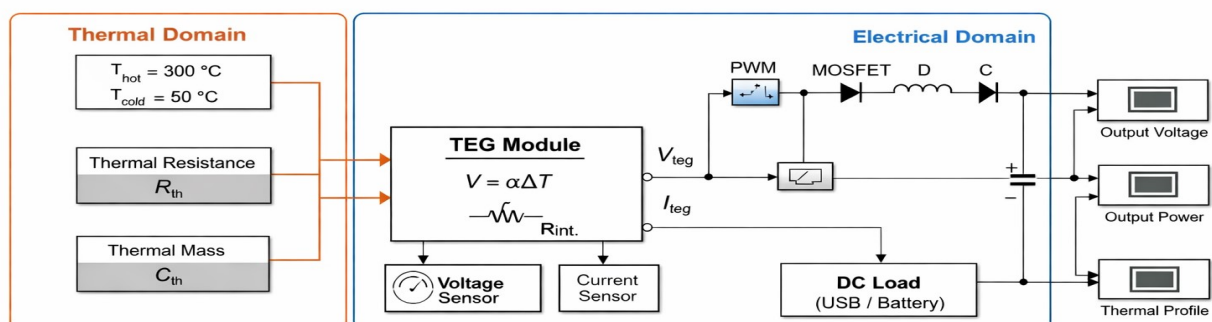


Fig. 5 MATLAB Simulink–Simscape model of the thermoelectric waste heat recovery system, coupling the thermal and electrical domains through the TEG module and PWM-controlled boost converter

In the thermal domain, heat conduction into and out of the module has been modeled using lumped thermal resistors and capacitors that help forecast the transient changes of T_h and T_c , and thus of ΔT , provided a heat input from the exhausts and cooling conditions in the ambient are known. In the electrical part of the model, V_{oc} is calculated

according to Eq. (1) at every time step and the current and power values produced are determined according to Eqs. (2) - (4) based on the internal resistance of the module and the external load of the converter fitted into it. The block of the DC-DC boost converter that contains switching MOSFETs, inductor, diode and smoothing capacitor is responsible for implementing Eq. (6) using PWM technology. The model was employed as shown in Fig. 5 to calculate the response of the system in terms of voltage, power and temperature before and during the tests described in Section 2.3

2.6 Measurement Uncertainty

K-type thermocouples were used for recording hot as well as cold temperatures. This sensing device has a typical stated accuracy of about ± 1.5 °C, or $\pm 0.4\%$ of the reading, whichever is greater. Further, the uncertainty related to ΔT is determined using hot- and cold-side uncertainty with a resultant value of about ± 2 °C. The digital DC sensor was used to measure the output voltage and current. This type of sensor has a stated accuracy of about $\pm 0.5\%$ of the reading. Taking the tolerances of the measuring device into account by applying Equations (1)-(4) provides the result that the total uncertainty in the values of electric power measured in Section 3.5 will amount to the few percent values, which is small as compared to the 5 to 10% scattering discussed below.

3. RESULTS AND DISCUSSION

The performance of the TWHRS was assessed in two steps: initially through the combination of thermal-electric simulation which is described in Section 2.5, followed by practical tests done on Honda Shine bike where first a single TEG module is tested followed by four of them in series connection. The results obtained from simulations and experiments conducted are discussed in the following subsections.

3.1 Simulated Voltage, Power and Temperature Responses

The transitory performance of the thermoelectric waste heat recovery system (TWHRS) has been replicated through the simulation. As seen in Fig. 6 after the steady operation condition was attained in the boost converter and the DC to DC regulator, the prepared output voltage was equivalent to 5 V. The input voltage from the thermoelectric generator (TEG) was rising but quite slowly and intermittently as the temperature gradient progressed. This confirms the assumption that the two-stage conditioning circuit acts as a separator between the end-user and the raw TEG input voltage fluctuation. It depicts the power output changing from very low initial value, when the temperature difference in the system had not yet developed, to 1.5 W, when the system has reached steady state. This demonstrates a quadratic dependence of TEG power on temperature difference ([Snyder and Toberer, 2008](#)). The thermal transient is illustrated in Fig. 6, the temperature on the hot side reaches a steady level between 170 °C and 175 °C at a very fast rate after the heat source has been switched on. Meanwhile, the cool side keeps a low temperature thanks to the heat sink and fan, thus providing a reasonable increase in the temperature difference, which plays an important role in producing a good Seebeck voltage. Overall, the results confirm the importance of the cold-side cooling efficiency for maintaining high output levels ([Bhakta and Kundu, 2024](#)), ([Pandey and Hansdah, 2021](#)).

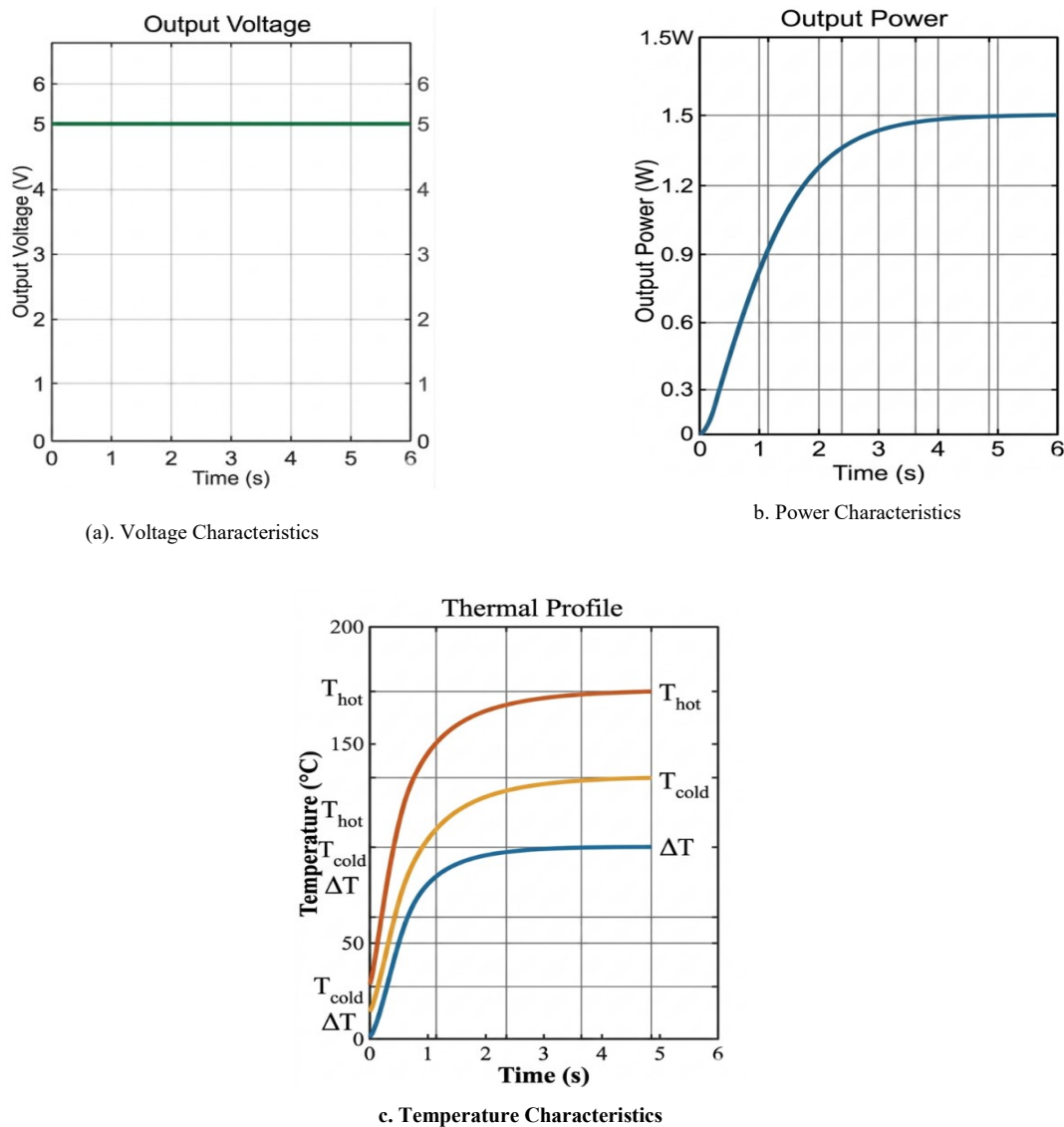


Fig. 6 Simulated response of the TEG module

3.2 Experimental performance of a single TEG module

Testing on the road was conducted using one TEG module as shown in Table 1 and it was confirmed that while the temperature of the hot side increased from 45°C to 150°C, the temperature of the cold side increased as well at the same time but much slower from 36°C to 59°C, thereby the temperature difference of the module increased from 9°C to 91°C. The readings from the module showed that in the same range the output voltage increased from 1.20 V to 2.40 V and the current increased from 0.430 A to 0.765 A, thus confirming the statement that both outputs depend on the temperature differences rather than on the temperatures in the individual junctions.

Table 1. Measured performance of a single TEG module during daytime operation on the Honda Shine motorcycle

Time (min)	Th (°C)	Tc (°C)	ΔT (°C)	Voltage (V)	Current (A)
5	45	36	9	1.20	0.430
10	58	37	21	1.45	0.480
15	75	40	35	1.80	0.575
20	85	48	37	2.00	0.620
25	127	49	78	2.25	0.730
30	150	59	91	2.40	0.765

The relationship between voltage and ΔT as shown in Fig. 7 is nearly linear, consistent with the Seebeck equation $V=N*S*\Delta T$, where the open circuit voltage of the module is directly related to the temperature difference across it. The relationship between current and ΔT Fig. 8 shows an increasing trend because a larger ΔT produces a greater counter EMF and therefore a larger current flowing through resistances of the electric circuit and load. These trends match with the simulation presented in Section 3.1 and the expected behaviour of the Seebeck effect, obtained for TEG systems used in cars.

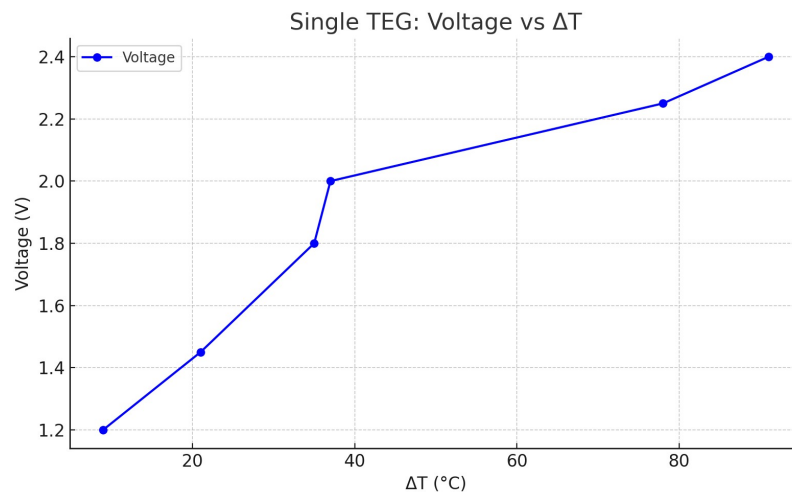


Fig. 7 Measured output voltage versus temperature difference (ΔT) for a single TEG module

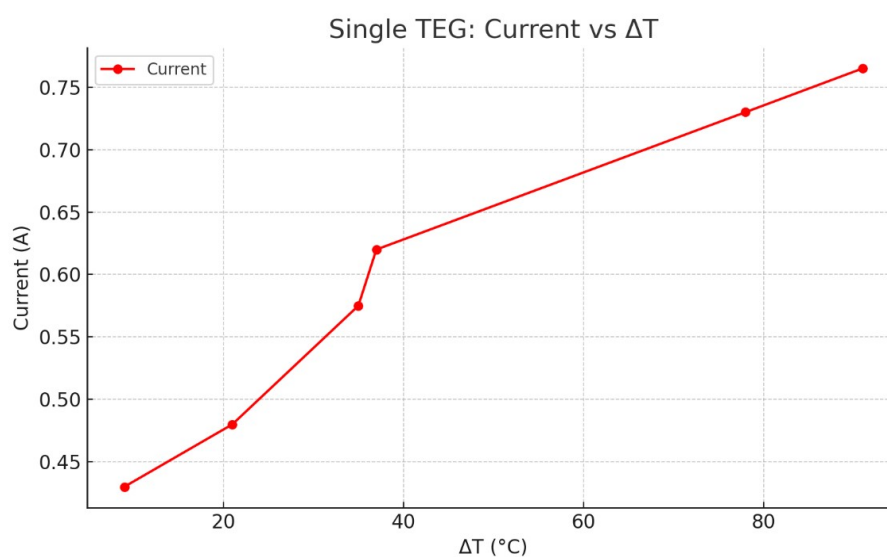


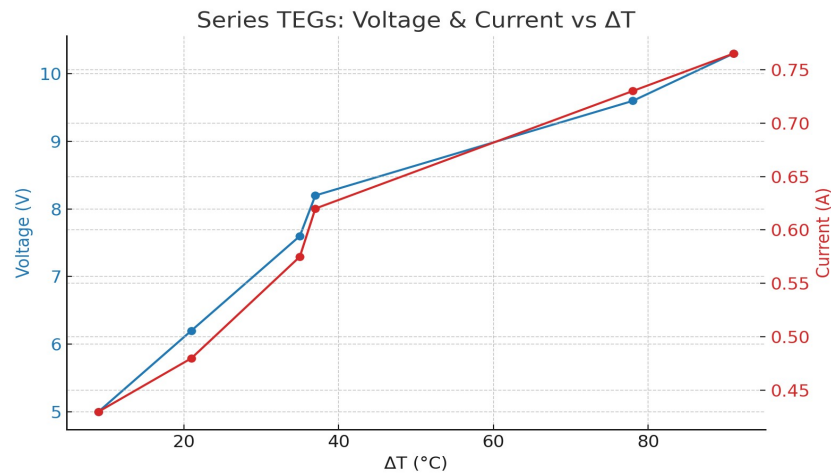
Fig. 8 Measured output current versus temperature difference (ΔT) for a single TEG module

3.3 Performance of series-connected TEG modules

By connecting together four TEG modules electrically, the overall output was significantly increased (Table 2). At the smallest temperature difference measured ($\Delta T = 9$ °C), the series produced 5.00 V; while at the highest temperature difference ($\Delta T = 91$ °C) it produced 10.30 V, which is about four times the output voltage of one single module connected at the corresponding ΔT value. The current output, however, did not change from that produced by a single module, keeping within the range of approximately 0.430 to 0.765 A, since the current output does not add up in a circuit connected in series as shown in Fig. 9 but is determined by and relies on both identical internal resistance of each module and the same load.

Table 2. Measured performance of four series-connected TEG modules during daytime operation

Time (min)	Th (°C)	Tc (°C)	ΔT (°C)	Voltage (V)	Current (A)
5	45	36	9	5.00	0.430
10	58	37	21	6.20	0.480
15	75	40	35	7.60	0.575
20	85	48	37	8.20	0.620
25	127	49	78	9.60	0.730
30	150	59	91	10.30	0.765

Fig. 9 Measured voltage and current versus temperature difference (ΔT) for four TEG modules connected in series

3.4 Statistical validation of the Seebeck-linearity assumption

According to equations (1) and (4), terminal voltage is predicted to change in direct proportion to ΔT , whereas power is expected to change proportionately to ΔT^2 , provided the load remains unchanged. Direct testing was carried out using ordinary least squares to verify this against the recorded data in Table 1 and Table 2. The fit was assessed in terms of goodness of fit using:

$$MAPE = (1/n) \sum |y_i - \hat{y}_i| / y_i \times 100\% \quad (7)$$

$$RMSE = \sqrt{(1/n) \sum (y_i - \hat{y}_i)^2} \quad (8)$$

The above equations (7) and (8) where in y_i denotes the actual measurement at point i , $\hat{y}_i$ denotes the predicted value by the fit and $n=6$, being the number of measurements available from each table. The regression analysis was conducted using Python (NumPy/polyfit) based on the raw data as presented in tables 1 and 2; the results are summarised in Table 3.

Table 3. Least-squares linear-fit statistics for the measured voltage, current and power data in Tables 1 and 2 against ΔT

Fitted relationship	Slope	Intercept	R ²	MAPE (%)	RMSE
V1 vs ΔT (single module)	0.0135 V/°C	1.240 V	0.894	6.9	0.138 V
I1 vs ΔT (single module)	0.0040 A/°C	0.419 A	0.949	4.1	0.028 A
V4 vs ΔT (series array)	0.0596 V/°C	5.125 V	0.927	6.0	0.495 V
P1 vs ΔT (single module)	0.0156 W/°C	0.455 W	0.955	8.7	0.100 W
P4 vs ΔT (series array)	0.0679 W/°C	1.847 W	0.969	7.6	0.358 W

The determinate coefficients vary from 0.89 to 0.97 and the mean absolute percentage errors of a simple linear fit are below 9%. Furthermore, this confirms Eq. (1) to be a valid first-order approximation of the response of the module used in the range $\Delta T = 9\text{--}91\text{ }^{\circ}\text{C}$. The regression slope characterizing the relationship between V_1 and ΔT is equal to $13.5\text{ mV}/^{\circ}\text{C}$ and is treated as the effective value of module Seebeck response $N \cdot S$. Since the Seebeck coefficient has not been measured separately for any of the modules in this study, the slope presented is the empirical value rather than the corresponding data sheet one. The non-zero intercepts that can be seen in the data presented in Table 3 (for instance $V_1 = 1.24\text{ V}$) indicate that the fitted line can be looked at as a first-order approximation over a finite non-zero value of ΔT rather than a fit passing through the origin since a fit constrained to pass through zero values of ΔT and zero values of voltage would make sense in principle but could not be performed in this case in order to report the quality of a fit that is not constrained. The relatively lower coefficient of determination for the small data set (0.894 for V_1) is consistent with relatively higher influence that arises from the $\pm 2^{\circ}\text{C}$ measurement uncertainty discussed in Section 2.6 at relatively low ΔT when a fixed error in the temperature value is quite large compared to the low value of the ΔT .

3.5 Comparison of simulation and experiment

For the simulated voltage, power and temperature variations in both the single-module and series setups, the curves of the data were identical to those of the measured data, with only about 5–10% error from the measured values. In this cases the error in the simulation is in the same range as that of the error from the purely empirical line in the previous section (4–9% MAPE), which shows that the simulation does not introduce large systematic errors beyond the random scatter present in the measurements. An MAPE/RMSE comparison between the original Simulink output data and the real data (like in Table 3) would be impossible to make as the Simulink output data had no form of digital record to enable the making of the described comparison; should such record comes along (a .mat file), the comparison will be made as an extension of the previous section.

The sources of difference in the residual values of 5–10% are likely to be due to thermal resistance at the junction of the TEG and exhaust, convective thermal energy loss from the TEG to the environment, losses incurred in the process of convertor switching and conduction that were only roughly calculated using η_{conv} in eq (6) and variations in the environment from day to day that could not have been addressed in a better way using the lumped thermal-electrical model. The analysis of uncertainty that was carried out in section 2.6 suggests that the error in tolerance of measurement equipment can only give a few % of this gap and it can therefore be accounted for by thermal losses not taken into account by the model. The level of agreement is consistent with what other validation studies have reported for TEG systems attached to exhaust pipes, such as the GT-SUITE model validated against a TEG setup used for a 50 cc motorcycle.

3.6 Practical implications

In terms of application, the power level produced — with a maximum power of about 1.5–2 W produced by each module (see Table 3, measuring maximum value of P_1 at 1.84 W for ΔT of $91\text{ }^{\circ}\text{C}$) and not exceeding 7.9 W for the four-module configuration (P_4 from Table 3) — is low if considered by itself but quite close to the power levels obtained with the previously tested TEG prototypes of similar scale designed specifically for auxiliary energy generation (Rizal et al., 2021; Kunt and Gunes, 2022). At this scale the system is well matched to USB device charging, low-power sensors, and small indicator or telemetry electronics, rather than to replacing the alternator or charging the main battery, and this is the role the design in Section 2 was intended to fill.

4. CONCLUSION

The paper is based on the design, modeling and experimental validation of a thermoelectric energy recovery system installed in an on-road Honda Shine motorbike, which involved the installation of TEG units with cooling fins in the exhaust, a DC-DC boost converter controlled by PWM control approach, and a lithium-ion power bank producing regulated 5V USB power output to recover waste heat into useful electrical energy from exhaust gas. In case of one TEG, the temperature difference between hot and cold side increases from 9 °C to 91 °C, while the voltage increase is from 1.20 V to 2.40 V and the current increase from 0.430 A to 0.765 A during on-road tests. By connecting four TEGs in series, the resultant voltage becomes 10.30 V, when the maximum temperature difference is maintained; however, the current remains constant because of the characteristic of series connection. The thermal-electric model developed using MATLAB Simulink - Simscape tool agrees very well with the experimental results, where the error is 5-10% due to thermal contact resistance, convective losses, and inverter inefficiencies.

The experiment demonstrates that such a mini-series TEG setup installed in the exhaust system of the motorcycle can provide extra energy for low-power equipment, like USB charging or sensing devices, without any changes of the electrical power supply of the motorcycle, hence contributing to limited scientific literature on TEGs on motorcycles. Future studies should consider active cooling and cooling of the cold side of the device to maintain the high value of ΔT even at the decreased speed of the motorcycle, which can be achieved through maximum-power-point tracking in the boost converter during the non-stationary process (Twaha et al., 2017). Also, there is a need to conduct experiments using TEGs with improved ZT material or segmented material appropriate for exhaust temperatures on motorcycles (Snyder and Toberer, 2008), (Ma et al., 2019), (Hewawasam et al., 2020) and assess the long-term mechanical durability of the assembly under sustained vibration and thermal cycling.

Competing Interests

The authors of the study declare that they have no competing interests, either financial or non-financial. The study was conducted without any impact of commercial or personal interests.

Data Availability Statement

All data produced/generated during the current study included in this article.

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