




Thermoelectric Generators as a Heat Recovery System for Exhaust Gases of Vehicles Driving at Low Speeds

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HIGHLIGHTS

- Thermoelectric generators (TEGs) were directly recovering the waste heat from the exhaust and converting it into power.
- The TEGs generate power when there is a temperature difference between the hot and cold sides of the exhaust pipe.
- EGs waste heat recovery system (WHRS) produced 4.6 W that was used for the cooling process within the vehicle.
- TEGs waste heat recovery system achieved a real thermal efficiency of 15.9%, closer to ideal thermal efficiency.
- Implementing TEGs WHRS provides a higher potential to be a successful low-weight heat recovery system that could be installed on the vehicles

ABSTRACT

To save the environment and utilize the waste heat associated with exhaust gases of internal combustion engines, it is crucial to design an efficient system that can recover this heat loss and convert it into useful energy. This study is devoted to developing, through an experimental approach, a practical technical solution to minimize the waste heat of the exhaust gases and convert it into a source of power for further applications in the vehicle. Six thermoelectric generators (TEG1-1263-4.3) were attached to the exhaust pipe in an arrangement of three connected in parallel and three connected in series. The thermoelectric generators were in a square shape of size 30 mm x 30 mm, and operated at a maximum temperature of 320°C. The experiments were conducted for a vehicle speed limit between (10 km/h - 60 km/h). It has been found that at a vehicle speed of 55 km/h, the exhaust pipe surface temperature reached approximately 116°C. For six models of TEGs, the output voltage was 4.13 volts. And the system efficiency was found to vary between 3.6% -15.9%, depending on the surface temperature of the exhaust pipe, i.e., the surface temperature that is in contact with the hot side of the thermoelectric generators. Such outputs refer to the efficiency of TEGs to be used as a heat recovery system. Furthermore, the produced power can be used for feeding other applications within the vehicle, such as using a small fridge for a cooling process.

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1. Introduction

Due to the increase in energy prices, it becomes more economically profitable to recover and reuse the waste heat in many industrial applications. For example, in the automobile sector, only 30 to 40% of the fuel energy in the engine is converted to useful energy. The rest is lost to the environment in the form of waste heat (20% - 40%), coolant and lubrication (10%-35%), friction and pumping (2%-10%), and brake power (20% - 40%) [1-3]. Thus, converting this waste heat into a useful energy source for further applications is significantly urgent.

Waste heat recovery (WHR) is the use of thermal energy that would be wasted to perform a useful function. In many situations, WHR eliminates or decreases the extra fuel energy required to achieve the system's functionality. There are two concepts where the heat can be recovered by either absorbing the heat and converting it into a source of heat or directly converting it into power. These techniques can increase the engine's efficiency and reduce fuel consumption [4]. Generally speaking, WHR will help increase the engine's efficiency, reduce fuel consumption, and decrease global warming. Higher-quality heat sources enable more waste heat to be turned to power. The "quality" of a specific heat source is strongly affected by its temperature. The higher the temperature is, the greater proportion of the heat to be transferred to productive work [5].

A number of research studies focused on investigating the waste heat recovery system associated with the exhaust gases of vehicles. Gu et al. [6] used R600a as a working fluid and hot water as a heat source for an Organic Rankine Cycle. The

maximum achieved efficiency of the tested system was 5.2% and the efficiency was found insensitive to the temperature of the heat source but sensitive to evaporating pressure. Bundela and Vivek [7] researched using heat exchangers with thermos oil as a working fluid. The heat exchanger uses the thermal oil to evaporate the organic fluid, which will, in turn, drive a turbine yielding a high amount of power. Domingues et al. [8] analyzed the Rankine cycle for recovering the vehicle exhaust waste heat using water, R123, and R245f as working fluids. They found the effectiveness of the organic fluids (R123 & R245f) was more than water. Later, Magar and Bhosale [9] used different nanofluids like boron nitrate water-based (BN/H₂O) nanofluids with hot air and cold air streams. The achieved maximum effectiveness was 0.28 by using BN/H₂O, whereas the effectiveness of the conventional working fluid (water) was 0.16. Afterward, While et al. [10] used the Phase Change Material (PCM) to store heat and generate steam. It has been found at an engine load of 11 kg. It takes 90 minutes to charge the PCM. During the charging procedure, the PCM saved 5.5% energy from the exhaust. PCM takes 20 minutes and uses just 1.6 percent of the energy in the water to generate steam, with the remaining 3.6 percent lost to the environment.

Compared to other waste heat recovery technologies, thermoelectric generators (TEGs) in a waste heat recovery system has many desirable features such as small size, no moving parts, no chemical reactions, and requiring little maintenance. However, the drawback of TEGs is their low efficiency compared to a Rankine cycle waste heat recovery system [11]. However, TEGs are still a promising economic approach as there is no cost associated with using waste heat as an input source for TEGs. Singh et al. [12] used a co-generation system consisting of a combination of thermoelectric cells and heat pipes to recover the thermal energy of exhaust gases. In their study, eight thermoelectric cells were used and produced 6.03W when charging the battery, which could enhance the overall fuel consumption efficiency in a vehicle. A similar approach has been implemented by [13], where an increase in the effectiveness of the heat exchanger increased from 67.9% to 72.4% with an increase in air face velocity. Merkisiz et al. [14] used an experimental approach to determine the influence of applying a TEG in the exhaust system on the engine's overall efficiency under varied operating conditions. The tests were conducted in an actual vehicle driving cycle of 12.6 km for a 1.3-L 66-kW diesel engine. The TEG was located upstream of the muffler at the end of the exhaust system. It has been found that the maximum energy conversion efficiency of the TEG (thermal into electrical) was 1.7%. The application of the TEG also decreased the engine power due to increased flow resistance, whose value was greater than the generated power. Yaakob et al. [15] conducted experiments in stagnation conditions in the laboratory using a 1500 cc petrol engine DOHC (4G91). Four TECs (SP1848-27145) were connected to the top of the exhaust muffler. The experiments were run in two cooling methods using airflow from a standing fan and the flowing cold water. The maximum voltage of 2.42V was produced when the temperature difference reached 83°C. Khan et al. [16] achieved thermal efficacy for TEGs of about 4-5%. Despite such low efficiency, the zero cost for the heat source, and the benefits of TEGs, it has become a promising alternative green technology. However, the thermoelectric materials and their installation position are vital in improving the efficiency of the waste heat recovery system. Another experiment has been performed to determine the output power of TEGs with a variable vehicle speed of 48.3, 80.6, and 112.7 km/h. It has been concluded that the output power increased as the speed of the vehicle increased due to the increase in inlet and outlet temperatures of the exhaust gases. At 80 km/h, the power output with 72 mm * 4 mm TEG was 75 W [17]. Kumar et al. [18] found that an output voltage of 200 mV can be generated using a single Bi₂Te₃ thermoelectric module for a temperature difference of 40°C, which can be used in charging the battery, headlight, etc. It was possible to generate 1.4 kW of electricity from a heat recovery system in the exhaust of a vehicle if the power produced by the engine is 150 kW. Belgaonkar et al. [19] concluded that despite the low efficiency (only 3-5%), TEGs still play a very vital role and add a new dimension to the air conditioning system. Researchers are still working on enhancing the properties of TEGs materials to improve their thermal efficiency. Such efforts may increase the potential of using TEGs in the future in a wide range of applications.

Despite such research efforts that have been done to recover the waste heat of the exhaust gases of vehicles, this area still needs continuous research studies, especially in investigating the heat recovery systems using TEGs at different positions along the exhaust pipe and for different driving profiles. Since Oman is facing an economic challenge in terms of increasing fuel consumption for power production as well as for the transportation sector, accordingly, this study was established to come up with a valid and practical technical solution to minimize the waste heat of the exhaust gases of low size engines 2000 cc petrol vehicles and convert into a source of power for further application in the vehicles.

2. The Statistical Information in Oman

From the statistical information on vehicles in Oman between August 2020 and August 2021, an increasing about 0.26-1.14% has been recorded in registered vehicles in Oman, as listed in Table 1. This is reflected in the vehicle's exhaust energy losses of 3.208 GW. According to the National Statistics Center in Oman [20], 1.5-3 liter capacity engines are the most often used automobiles in Oman, around 54% (828,501 cars) of all cars in the country. The next category is automobiles, with engines ranging from 3-4.5 liters (22.7%). The total heat loss from 1.5-3 liter and 3-4.5-liter engines are around 105 GW and 68.9 GW, respectively, a very large quantity.

Table 1: The amount of heat loss from exhaust vehicles in Oman

Engine capacity	Δ cars number = August 2021 - August 2020	Percentage of increasing or decreasing	Percentage* exhaust heat loss energy	Total Δ of exhaust heat loss energy
less than 1500	-3764	-3.165%	-3.165%*7.72 GW	-0.244 GW
1500-3000	2162	0.262%	0.262%*105 GW	0.275 GW
3001-4500	1491	0.426%	0.426%*68.9 GW	0.318 GW
more than 4500	2269	1.14%	1.14%*250.8 GW	2.859 GW
			Total	3.208 GW

3. Research Methodology

The utilized methodology consists of three main stages. In stage I, the required technical and statistical data related to the exhaust system of internal combustion engines were collected and analyzed to be a tool for stage II, which is devoted to generating and evaluating the design concepts of the waste heat recovery system. Using the data collected in stage I, it was possible to identify the design constraints and then convert them to engineering specifications of the waste heat recovery system. After that, in stage III, the modified waste heat recovery system was manufactured and subjected to experimental investigations.

3.1 Design Constraints

Constraints might limit the engineer’s flexibility while working in the project's design stage. The following are the main constraints implemented in this study.

- 1) Environmental: Be environmentally friendly by reducing the heat loss from the exhaust.
- 2) Legality: Use appropriate standards and codes through designing.
- 3) Health and safety: Understand any safety aspects, safety standards, and legislation covering the product.
- 4) Sustainability: The system has to be reliable and durable. In addition, the parts of the system should have the same lifespan.
- 5) Physical: The size and weight of the device must not affect the car's performance.

3.2 Design Parameters

Table 2 shows the geometrical and thermal parameters of the exhaust system. These parameters were selected to be the design parameters while calculating the generated concepts. Figure 1 shows the temperature values when a vehicle is at a part and full load. The average temperatures are taken as thermal design parameters.

Table 2: Geometrical and thermal parameters of exhaust system [22]

Geometric parameters	Thermal parameters
Length = 600 mm	Inlet temperature = 355°C
Diameters = 100 mm	Outlet temperature =295°C
Thickness = 1.5 mm	

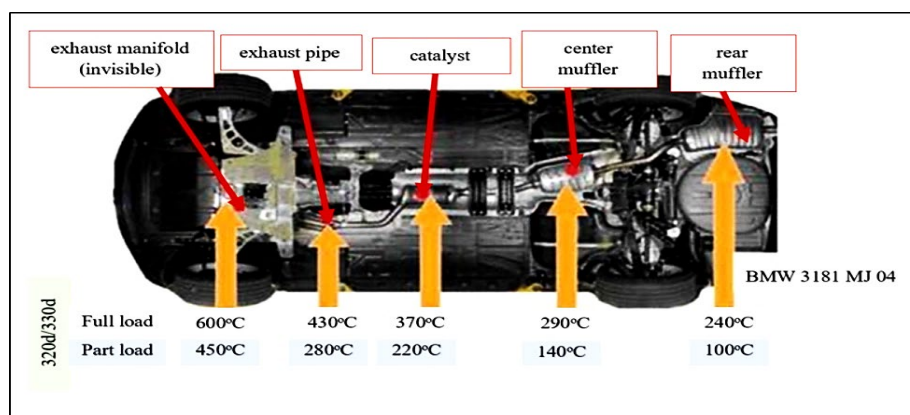


Figure 1: Exhaust gases temperature at different locations when a vehicle is at part and full load [21]

3.3 Generated Concepts

Five concepts (as shown in Figure 2) were generated according to all information, properties, and limits defined previously. For example, concept 1 is about converting the waste heat from the exhaust gases into power that shall be used later for further vehicle applications. Simply, when the exhaust gases exit the internal combustion engine and flow through the exhaust pipe at a high temperature, TEGs will absorb the waste heat and generate electric power due to the existing temperature difference between the two semiconductor plates.

Concept 2 is about converting the waste heat from the exhaust gases into power using the combination of TEGs and phase change material. When the exhaust gases exit the internal combustion engine, they exchange heat with the phase change material that covers the top side of the exhaust pipe while the other sides are well insulated. Thermoelectric generators will absorb the heat from phase change material and convert it into power to be saved in a battery for further utilization.

In concept 3, the waste heat from the exhaust gases will be converted into useful power using piezoelectric generators and a nano-fluid. The exhaust gases start to exchange the heat with the nanofluid till reaching the boiling process. Some steam will be generated that will move up and cause the plastic ball containing piezoelectric generators to vibrate. The vibration will cause piezoelectric material to generate a current stored in power storage. The idea of concept 4 is to use a heat pipe, fluid like water or nanofluids, and TEGs to convert the waste heat into power. Using a material like naphthalene as the heat pipe heat exchanger with a working temperature range of 250°C to 450°C to minimize the exhaust gas temperature and avoid overheating on TEGs. In concept 5, the waste heat will produce warm water using a heat pipe heat exchanger.

To evaluate and rank the concepts based on the overall idea of the concept, the feasibility, the availability of the materials, and the required manufacturing process, firstly, the Go/No go screening method was used, from which it has been found it is difficult to go ahead with concept 3 and 5. This is, in fact, due to the complexity of the concepts and the difficulty in manufacturing them. After that, the absolute scoring method was used for the remaining concepts. Finally, concept 1 was selected because it got the highest rating.

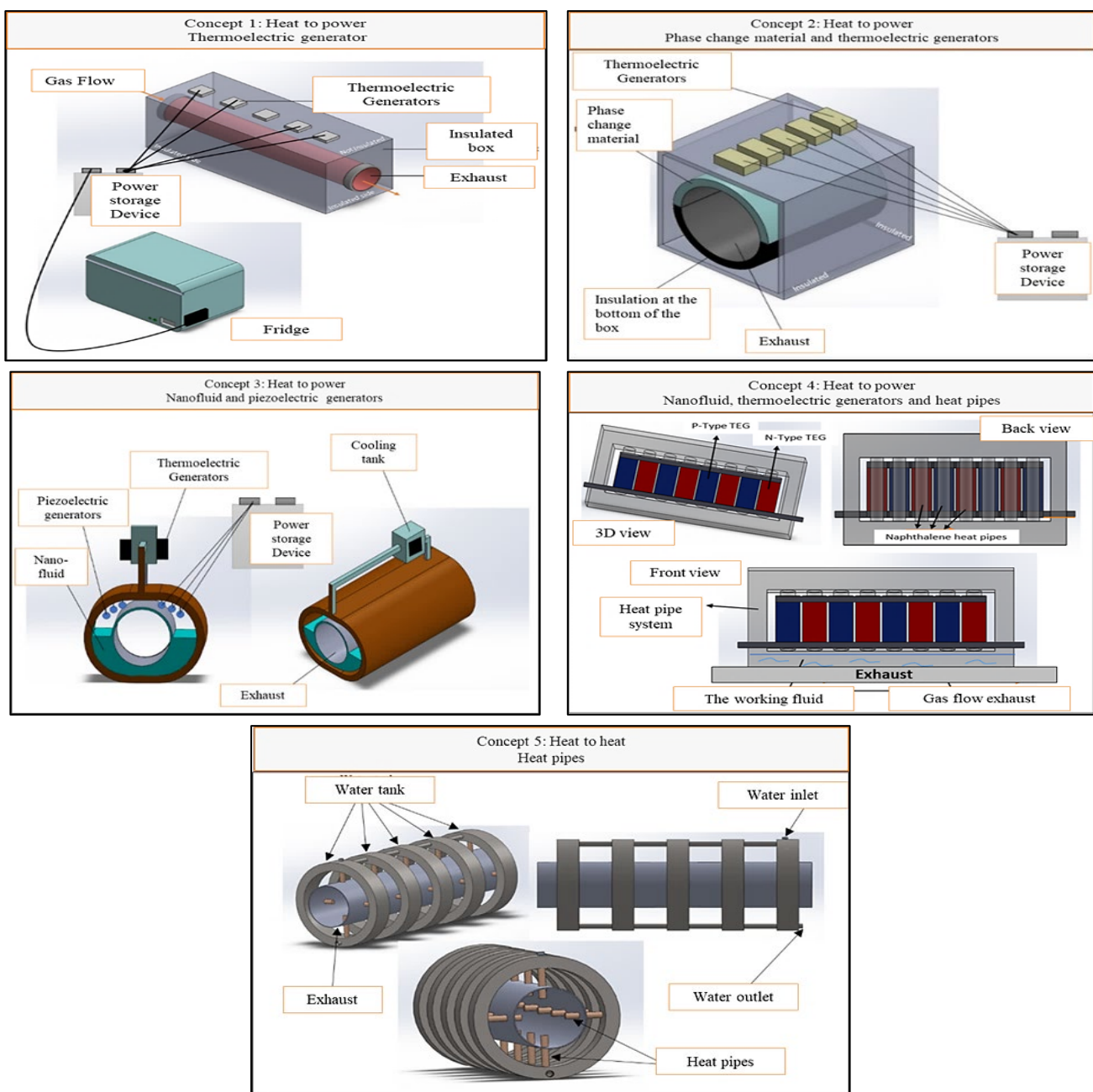


Figure 2: Generated design concepts

4. Experimental Set-Up and Procedure

Figure 3 shows the manufactured waste heat recovery system based on concept 1. It consists of an exhaust pipe which the hot gasses will pass through. The exhaust pipe was covered by an outer cover (aluminum box) size 70 mm x 70 mm x 1.5 mm. The purpose of the outer cover was to hold the TEGs on top of it. An insulation material was used to cover the exhaust pipe from all sides except the top side, where six TEGs (Module: TEG1-1263-4.3) were attached to it in an arrangement of three connected in parallel and the other three connected in series. The purpose of using the insulation was to avoid heat transfer with the environment and guide the heat to be passed only in one direction. The TEGs were in a square shape of size 30 mm x 30 mm, and they can operate at a maximum temperature of 320°C. Furthermore, the maximum output voltage that a TEG model can provide is 4.6 volts. The TEGs were fixed on the top of the outer cover by using high-quality thermal glue. The TEGs were then connected to the Maximum Power Point Tracking (MPPT) connector. The purpose of the MPPT device was to collect the voltage from TEGs and store it in a battery. Then, the MPPT will convert the voltage from the battery to the cooling system.

An ammeter and voltmeter were used to monitor the output of TEGs. Four temperature sensors (uxcell K Type) were used to measure the exhaust gas temperature at the inlet port, middle, and outlet port of the exhaust pipe, as well as the surface temperature of the aluminum cover box. The sensors were selected to measure the temperature from 0°C to 500°C. To avoid any damage to the Arduino or laptop, the length of the sensor was selected to be 3 meters, which will keep them at a safe distance from the high temperature. All sensors were fixed in their places and connected to Arduino board UNO (open-source microcontroller board), which, in turn, connected to the laptop where the data were stored for later calculations. The Arduino was linked to the laptop through a USB cable, and the sensors were linked to the Arduino by three wires attached to the voltage, digital, and ground pins.

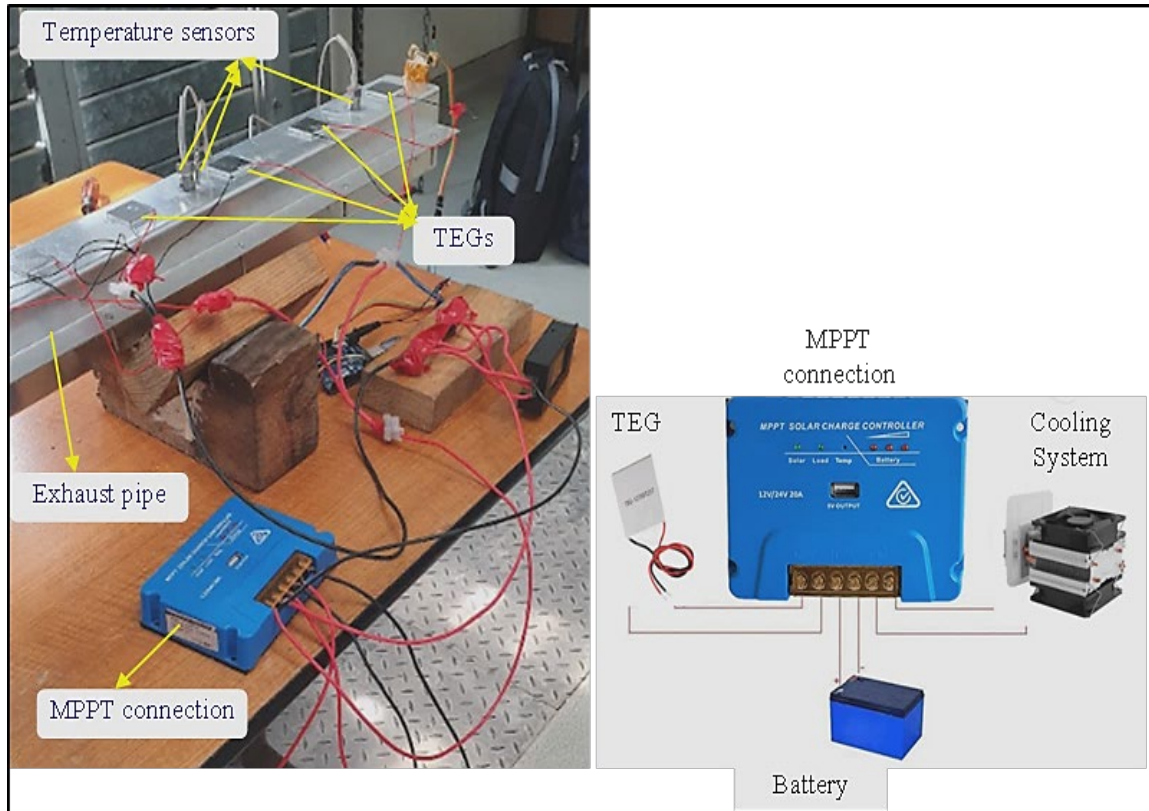


Figure 3: The experiment apparatus

5. Results Analysis and Discussion

After ensuring that everything was ready and taking safety precautions, the experiments were started. As the majority of the roads in Oman have a speed limit between 50-100 km/h, and considering the high traffic jam of the driving profile in Oman, it has been decided to conduct the experiments with a vehicle speed limit between (10 km/h - 60 km/h) for a four cylinders engine of size 2000 cc petrol engine. For each test, the exhaust gas temperature at different locations, the output voltage of TEGs, and the surface temperature of the aluminum cover box (which implicitly refers to the surface temperature of the exhaust pipe) were measured. Figure 4 shows the relationship between the vehicle speed and the temperature of hot gases at the inlet port of the exhaust pipe. The exhaust gas temperature, here, implicitly refers to the amount of thermal energy of exhaust gases where part of it will be lost through exchanging heat with the environment. It can be seen that the exhaust gas temperature increased with increasing the vehicle speed in a manner that almost has a linear trend.

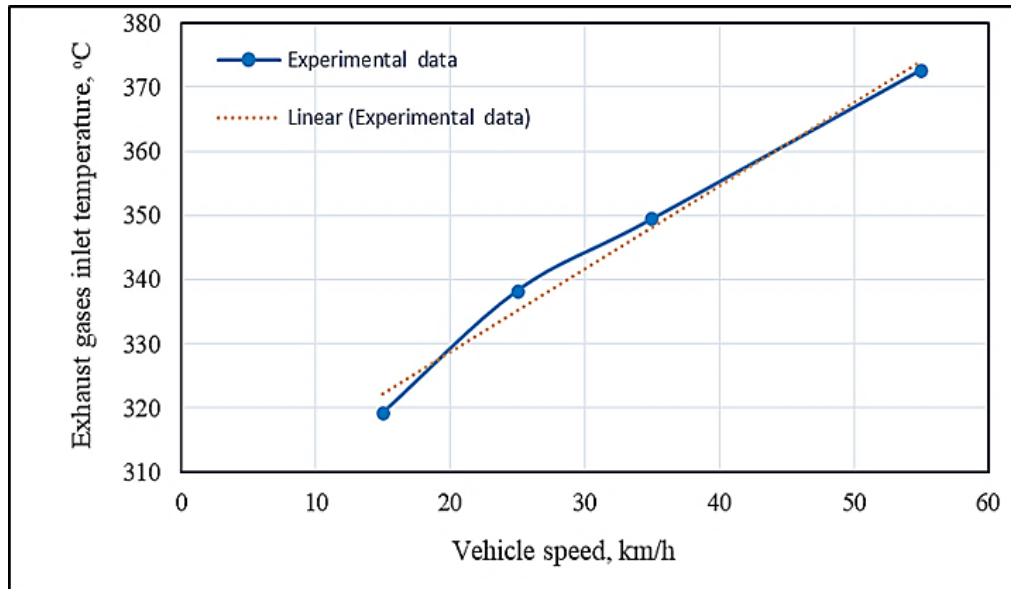


Figure 4: Exhaust gases inlet temperature as a function of vehicle speed

To have aware of the amount of waste heat through the exhaust pipe, the surface temperature of the exhaust pipe shall be measured and used to calculate the heat losses to the environment. To accomplish the calculations, it has been assumed that the ambient air temperature surrounding the exhaust pipe is 30°C, and the heat loss by radiation has been ignored, i.e., convection heat transfer is the dominant heat transfer mode here. Based on the fundamental of heat transfer, heat transfer to the environment through the exhaust system was calculated using Equations (1-3) [23]:

$$Q = \frac{T_{s, exhaust} - T_{\infty}}{R_1 + R_2} \tag{1}$$

Where the T_s (in °C) is the surface temperature of the exhaust pipe. T_{∞} (in °C) is the ambient temperature. R_1 (in °C/W) is the conduction thermal resistance of the air enclosed in the top cavity between the exhaust pipe and the aluminum cover box, as expressed in equation 2. Since the cavity size is too small, it has been assumed that the air in the cavity is stagnant, and the mode of heat transfer will be pure conduction.

$$R_1 = \frac{L}{K_{air} A_s} \tag{2}$$

Here, K_{air} (in W/m.°C) is the thermal conductivity of the air, L (in m) is the thickness of the air cavity between the outer surface of the exhaust pipe and the aluminum cover box and A_s (in m²) is the surface area where the heat is transferred. R_2 is the convection thermal resistance between the aluminum cover box and the ambient, as expressed in equation 3. Where h (in W/m².°C) is the convection heat transfer coefficient of the air that is calculated using the fundamental concept of free convection, the case of the upper surface of the hot plate (see Equation 4).

$$R_2 = \frac{1}{h A_s} \tag{3}$$

$$h = \frac{Nu K}{D} \tag{4}$$

Where Nu is the Nusselt number. However, it was difficult to measure the exhaust pipe temperature. Also, the important temperature here is the surface temperature of the aluminum cove box where TEGs were installed. However, it was possible to measure this temperature; consequently, the waste heat was calculated using Equitation 5. Figure 5 shows a proportional relationship between the waste heat from the exhaust and the vehicle speed. Therefore, increasing the vehicle speed was associated with increasing the waste heat through the exhaust pipe.

$$Q = \frac{T_{s, cover box} - T_{\infty}}{R_2} \tag{5}$$

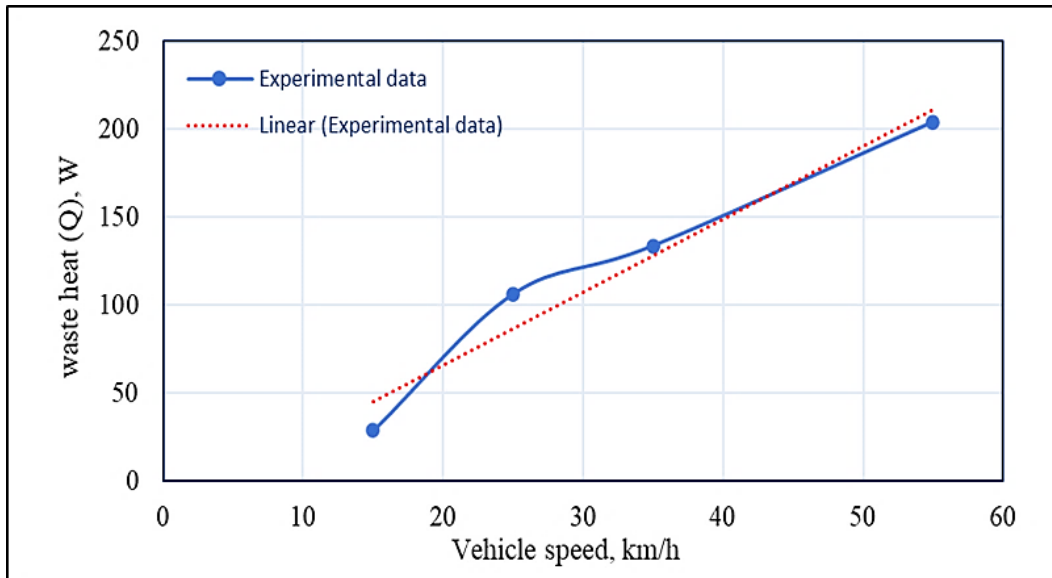


Figure 5: Waste heat through the exhaust pipe as a function of vehicle speed

After that, the relationship between vehicle speed and the surface temperature of the exhaust pipe represented by the aluminum cover box is illustrated in Figure 6, from which it can be seen that with a speed of 55 km/h, the surface temperature reached approximately 116°C. Such high values of surface temperature were used to generate power using TEGs.

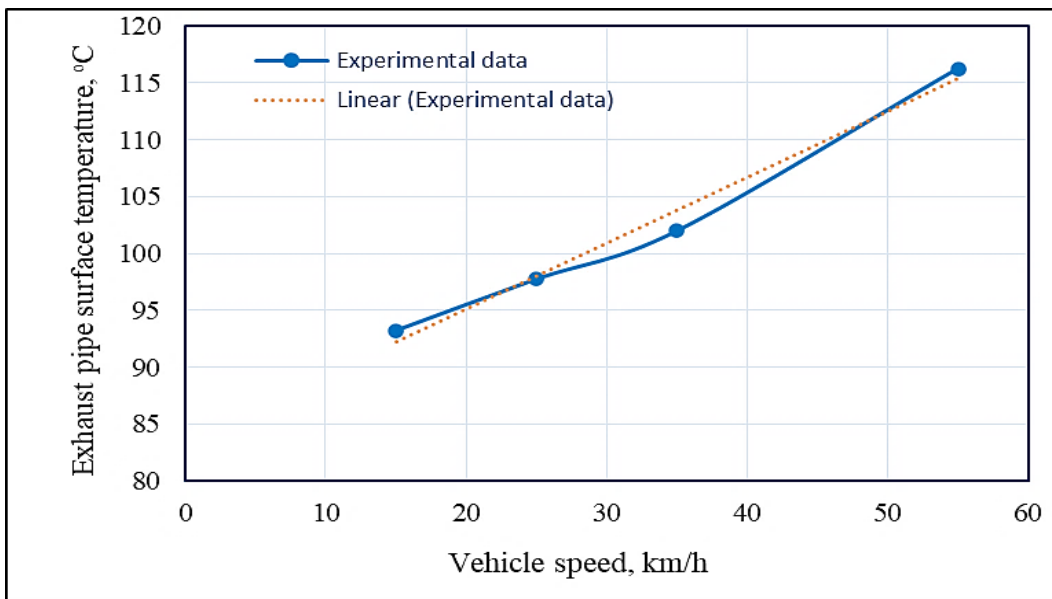


Figure 6: Exhaust pipe surface temperature as a function of vehicle speed

The output voltage achieved by TEGs is presented in Figure 7, from which it can be observed that the maximum voltage for six models of TEGs was 4.13 volts. To fully understand TEGs performance, the theoretical values of the output voltage were obtained using Equation (6), which provides the theoretical background for calculating the output voltage in terms of T_s [24].

$$V = 0.0215 (T_{s,cover\ box}) - 0.575 \tag{6}$$

It is obvious there was little difference between the theoretical and experimental data. However, the experimental values of the output voltage were less than the theoretical values, and the variation was between 40-46%. The plausible reason for such variation can be attributed to the assumption of the ambient temperature of 30°C. The basic operating principle of the TEG is based on the Seebeck effect, which states that an electrical potential is generated by applying different temperatures on both sides in which one side is heated (as a heat source). In contrast, the other side is kept at a lower temperature (ambient temperature as the heat sink), and electric current is induced because of the thermoelectric effect [25].

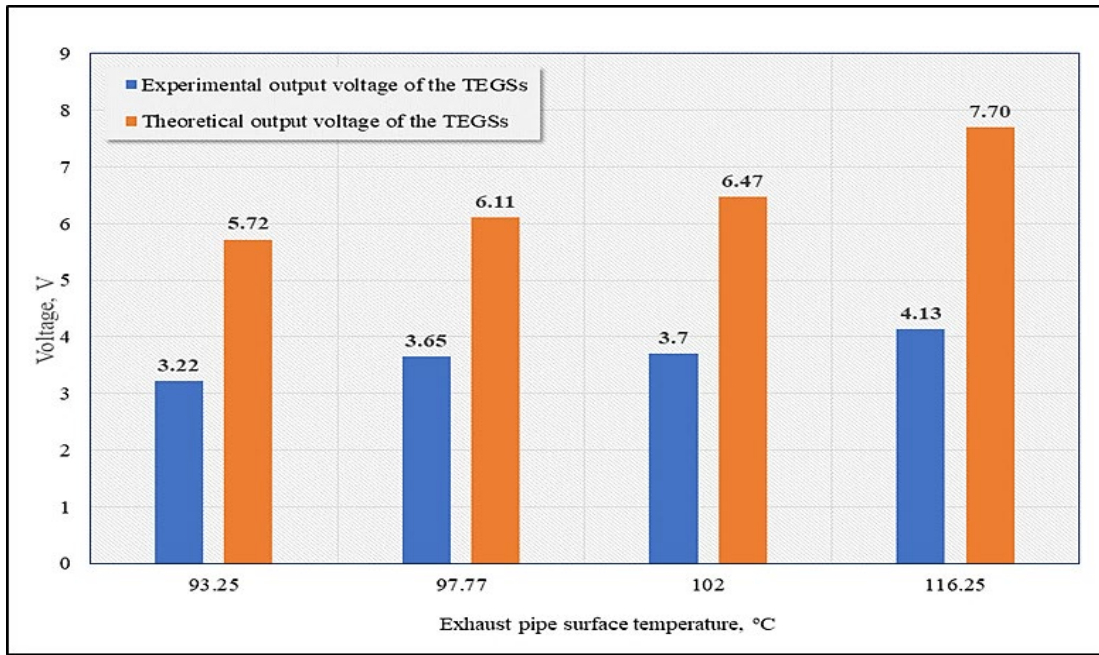


Figure 7: The theoretical and experimental output voltage of TEGs

Due to the variation between the theoretical and experimental values, the system thermal efficiency was determined and compared with the ideal thermal efficiency, as shown in Figure 8.

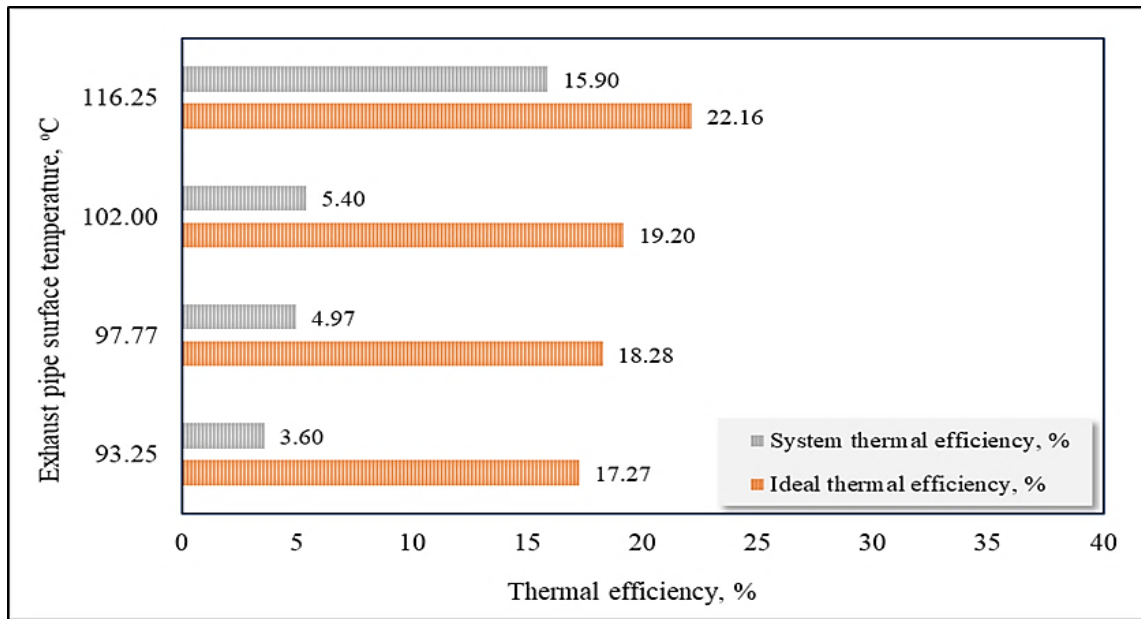


Figure 8: System and ideal thermal efficiency as a function of exhaust pipe surface temperature

Therefore, the system thermal efficiency is defined based on the first law of thermodynamics as the ratio between the energy output (power output of TEGs) to the energy input (waste heat of the exhaust pipe) as depicted in Equation (7). While the ideal thermal efficiency (also called Carnot efficiency) is an expression for the thermal efficiency of a system undergoing a reversible power cycle while operating between thermal reservoirs at temperatures T_H (hot reservoir) and T_C (cold reservoir) as expressed in Equation (8) [26].

$$\eta_{sys} = \frac{\text{Output power of TEGs (in W)}}{\text{Input energy in terms of the waste heat (in W)}} = \frac{\dot{W}_{TEGS}}{\dot{Q}_{waste\ heat}} \tag{7}$$

$$\eta_{ideal} = 1 - \frac{T_C}{T_H} = 1 - \frac{T_{\infty}}{T_{s,cover\ box}} \tag{8}$$

The range of the ideal thermal efficiency varied between 17% and 22% and has a linear relationship with the exhaust pipe surface temperature representing the heat source. The system's thermal efficiency was found to be lower than the ideal thermal efficiency. The maximum thermal efficacy achieved by the system was 15.9% which is less than the ideal thermal efficiency by 28%.

As with all heat engines, their efficiency is limited by the Carnot efficiency, so the higher the temperature difference, the more efficient they will be. This is an expected and accepted result, as there is always an entropy loss associated with the system's thermal performance. Entropy can be interpreted as the entropy generated by internal irreversibilities associated with heat transfer within the environment during the cycle, as expressed in Equation (9) [26].

$$S_2 - S_1 = \int_1^2 \left(\frac{dQ}{T_b} \right)_{int,rev} \quad (9)$$

5. Conclusion

Unfortunately, converting the chemical energy of the fuel into mechanical energy in internal combustion engines is not a highly efficient process. A majority of this energy is wasted as heat in the exhaust system. Despite there still ongoing industrial research activities to improve the efficiency of the engine directly, efforts are also devoted to improving the engine efficiency indirectly through implementing waste heat recovery systems. There are different technologies for recovering thermal energy. However, in this study, the focus was on using TEGs due to their desirable features represented by small size, chemically inert, and almost free of maintenance. In contrast, the limitations of using TEGs are low-temperature limits and relatively low efficiency compared to Rankine cycle and heat pipe technologies. In this study, a waste heat recovery system was designed and manufactured using six TEGs of Module: TEG1-1263-4.3, which have a square shape of size 30 mm x 30 mm, and operate at a maximum temperature of 320°C. They were attached at the top of the 2000 cc petrol vehicle exhaust pipe, arranged to be three in parallel and three in series. The waste heat recovery system was experimentally investigated under a speed limit of 10-60 km/h. 4.13 Volts were produced at a vehicle velocity of 55 km/h and exhaust surface temperature of 116°C. Such an output is enough to feed other applications within the vehicle with the required power, such as using a small fridge for cooling, which might be a comfortable option, especially considering the hot climate conditions in Oman. In addition, the system thermal efficiency reached a maximum value of 15.9%, which is 28% less than the ideal thermal efficiency (22.16%). This indicates the efficiency of using TEGs as a heat recovery system.

Nomenclature

Q	waste heat	[W]
R ₁	conduction thermal resistance	[°C/W]
R ₂	convection thermal resistance	[°C/W]
S ₁	entropy at initial state	[kJ/K]
S ₂	entropy at final state	[kJ/K]
T	temperature	[°C]
T _∞	ambient temperature	[°C]
W _{TEGs}	generated power by the TEG	[W]

Greek symbols

η _{sys}	system thermal efficiency	[%]
η _{ideal}	ideal thermal efficiency	[%]

Subscripts

b	boundary
C	cold reservoir
H	hot reservoir
s	surface of the exhaust gas pipe

Abbreviations

BN/H ₂ O	boron nitrate water-based nanofluid
MPPT	Maximum PowerPoint Tracking
Nu	Nusselt number
PCM	Phase Change Material
R123	hydrochlorofluorocarbon refrigerant
R245f	hydrofluorocarbon refrigerant
TEGs	Thermoelectric Generators
WHR	waste heat recovery

Author contribution

All authors contributed equally to this work.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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