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Article

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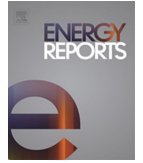
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Waste heat recovery from thermo-electric generators (TEGs)

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Abstract

Thermo-electric generators (TEGs) have been identified as promising solid-state devices to recover exhaust waste in internal combustion engines (ICEs). As the TEGs are able to convert heat directly into electricity, they can be used to down size the alternator of the ICEs. However, the addition of new devices to the engine exhaust system leads to increase the back pressure of the engine and reduces the overall efficiency of the engine. Therefore, this study is conducted to understand the possibility of integrating the TEG to the muffler of the engine, without interrupting the functionality of the muffler to recover the waste heat of the engine exhaust system. Findings of the study shows that the thermo-electric modules (TEMs) can be easily integrated to the muffler and electricity can be conveniently generated using the exhaust energy available in the hot exhaust gas.

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Keywords: Energy recovery; Thermo-electric generators; Exhaust system; Internal combustion engines; Availability

1. Introduction

By 2040, the world energy consumption is expected to increase by 40%. 1/3rd of the world energy consumption belongs to the transportation sector and from that, 85% consumes by the road transportation sector, according to International Energy Outlook [1]. Although there is a huge trend towards renewable energy sources, still the petroleum-based energy sources dominate the road transportation sector, because the renewable energy sources are not reliable and intermittent unlike conventional energy sources as depicted by International Energy Agency, Statistics and Data [2]. Kreith and West [3] showed that, in SI (spark ignition) engines, nearly 70% of the total energy is wasted as heat and in CI (compression ignition) engines, nearly 60% is wasted as heat. Energy efficiency improvement by in-cylinder techniques of the engines have become to its saturation levels. So, introducing a waste heat recovery system (i.e. turbo-compounding devices, bottoming cycles (Rankine cycles based on low temperature organic fluids and inorganic fluids), thermo-electric generators (TEGs), thermo-acoustic generators (TAGs), vapour absorption systems) is promising to enhance the efficiency of the IC engines which will also result in reducing the fuel consumption and GHG (greenhouse gas) emission [4,5].

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Nomenclature

T	Temperature
V	Voltage
α	Seebeck coefficient
ZT	Thermo-electric figure of merit
ρ	Resistivity of the TE material
K	Thermal conductivity of the TE material
$\eta_{conversion}$	Conversion efficiency
P_{max}	Maximum power output of the TEG
OCV	Open circuit voltage
R_{int}	Internal resistance of the TEM

Menchen et al. [6] highlighted that the factors i.e. complexity and amount of energy utilization have to be concerned to choose the best energy recovery system for a particular application. Thermoelectric generators (TEGs) have been identified as a reliable solid-state technology which can directly convert thermal energy into high quality electrical energy. In addition, TEGs have many advantages in comparison to other energy recovery methods, i.e. no moving parts, produce no noise and vibrations, low maintenance and environmentally friendly. The electricity produce by the TEG can be directly used to assist the electrical system of the vehicle and hence, the alternator of the vehicle can be easily downsized. Wijewardane [7] was shown that TEGs can be developed to displace the alternator of the light duty vehicles providing the fuel economy benefits of 3.9–4.7% for passenger cars and 7.4% for passenger busses.

2. Thermo-electric principle

A thermo-electric generator (TEG) consists of a number of thermo-electric modules (TEMs). A TEM consists of a many number of serially connected thermo-electric (TE) elements. Thermo-electric elements are made of p (+) and n (–) semiconductor materials. Power generation by a TEM can be conveniently increased by increasing the number of thermo-electric elements in the TEM. The thermo-electric effect is observed in a circuit of two dissimilar conductors i.e. p–n legs of a thermo-electric module are connected thermally in parallel and electrically in series as shown in Fig. 1(a) [8–10].

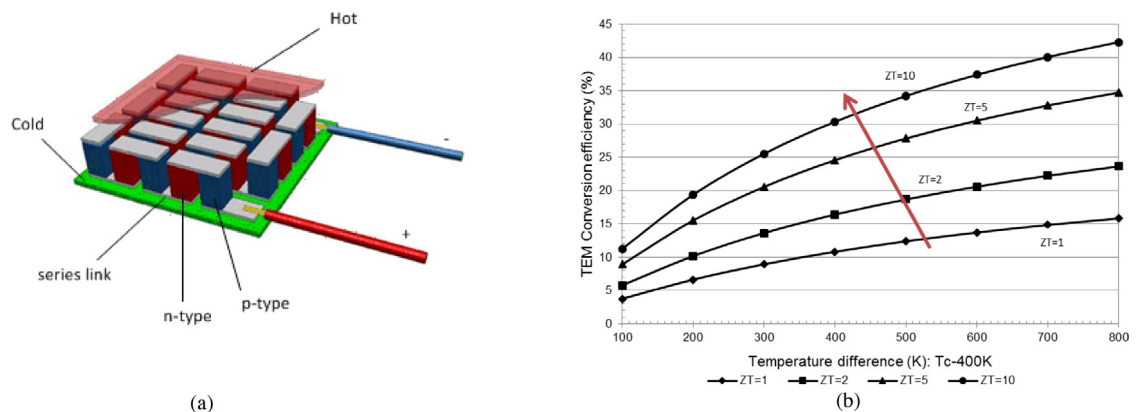


Fig. 1. (a) A Thermo-electric module (TEM), TEG [11]; (b) Variation of conversion efficiency with ΔT and ZT [7].

‘The Seebeck Effect’ is a phenomenon in which a temperature difference between two dissimilar electrical conductors or semiconductors produces voltage difference between the two substances, according to Eq. (1) [12]. Heat to electricity conversion efficiency of a TE module is a function of temperature difference across the hot side

and the cold side and the properties of the thermo-electric material i.e. electrical resistivity, thermal conductivity and the Seebeck coefficient.

$$\Delta V = \alpha \cdot \Delta T \quad (1)$$

TEGs are not yet popular among the scientific community as the heat to electricity conversion efficiencies are not yet satisfactory. Commercially available TEMs are made of Bismuth Telluride (Bi_2Te_3) material, whose conversion efficiency ($\eta_{conversion}$) is less than 5% with a thermo-electric figure of merit (ZT – Eq. (2)) less than 0.5. As a result, overall heat to electricity conversion efficiency of a TEG is limited and is less than 5% due to the performance constraints of the available materials [13].

$$ZT = \frac{\alpha^2}{\rho K} T \quad (2)$$

Conversion efficiency (Eq. (3)) of thermo-electric materials is a function ZT as shown in Fig. 1(a). Therefore, efforts are in place to improve the ZT of the TE materials. Theoretical works carried out by Dresselhauls et al. [14] and Yang [15] envisage that the ZT of 20 at all temperatures are achievable using low-dimensional materials. Further, the possibility of 20% maximum conversion efficiency has been predicted for such TE materials.

$$\eta_{max} = \left(\frac{\sqrt{1 + ZT_{avg}} - 1}{\sqrt{1 + ZT_{avg}} + \left(\frac{T_c}{T_h}\right)} \right) \frac{(T_h - T_c)}{T_h} \quad (3)$$

3. Modelling of a thermo-electric generator

3.1. Selecting the location to mount the TEG

TEGs are mainly designed to recover the waste heat from the exhaust gas of the internal combustion engines (ICEs). Exhaust system of an ICE consists of several components i.e. CAT (catalytic converter), muffler, DPF (diesel particulate filter), SCR (selective catalytic reduction) system, EGR (exhaust gas recirculation) system and resonator, to control the tail pipe emission and the noise. Exhaust gas produced by the engine needs to be removed during the exhaust stroke through the exhaust system. To accomplish this, the engine needs to utilize the energy of the burnt gas. As the exhaust gas flows through the above after treatment devices and noise attenuators, a significant pressure drop creates across the exhaust system. This additional pressure-drop (or the back pressure drop) increases with the speed and the load of the ICE and leads to increase the exhaust gas pumping power and, reduces the engine performance eventually.

An engine dynamometer test was carried out by Davis [16] on a modified Ford 351-4V Cleveland V8 engine, to investigate the influence of back pressure development on a road car engine performance. It was shown that the 10.4 kPa back pressure increment reduced the peak torque by 4% and the peak power by 5% while a 17.3 kPa back pressure increment decreased the peak load and peak power by 7%. Masoudi [17], Wagh et al. [18] and Wendland et al. [19] showed that the muffler and resonator contribute to the major fraction of the overall pressure drop about 50%–60% of the total exhaust pressure drop after the turbine. It is reported that the back pressure developed by a modern automobile muffler is about 16 kPa, whereas a DPF contributes around 30%–40% of the total exhaust back pressure drop.

According to the above facts, it is noticeable that addition of any other component (i.e. heat exchanger or a waste heat recovery device) to the exhaust system will further increase the engine back pressure and will adversely affect to the engine performance. Exhaust gas temperature at the secondary muffler (rear muffler) of a naturally aspirated SI engine is around 430 °C whereas, exhaust gas temperature at the secondary muffler (rear muffler) of a naturally aspirated CI engine is around 240 °C [7]. Therefore, integrating the TEMs to the muffler and develop the muffler as a TEG will avoid the additional back pressure increments and will ensure that the addition of TEG-muffler waste heat recovery device to the exhaust system will not reduce the performance of the engine and heat recovery from the exhaust gas is still highly possible. Therefore, this study conducts by integrating the TEMs to the rear muffler and develop the rear-muffler as a TEG.

3.2. Modelling the TEG mounted on the muffler

A standard passenger car muffler made of steel was used to mount the TEMs to modify the muffler as the TEG, as shown in Fig. 2(a) and (b). Modelling work has been performed in the ‘ANSYS Fluent’ software platform.

As shown in the figures, six (06) TEMs (8 cm × 8 cm × 5 mm) are mounted on the muffler body (03 in the top and 03 in the bottom). Hot exhaust gas is passing through the muffler and heat-up the muffler body. An aluminium (Al) base plate is fixed to the hot muffler body and then the TEMs are mounted on the Al base. The Al coolant fluid body is then mounted on the other side of the TEMs to provide a heat sink. A separate user defined function (UDF) was developed and defined in the ANSYS Fluent program to predict the electrical power output by the TEMs. The UDF was developed to represent the commercially available 20 W - Bi₂Te₃ TEMs as they were already purchased from Hi-Z Technology Inc. [20] to fabricate the test rig.

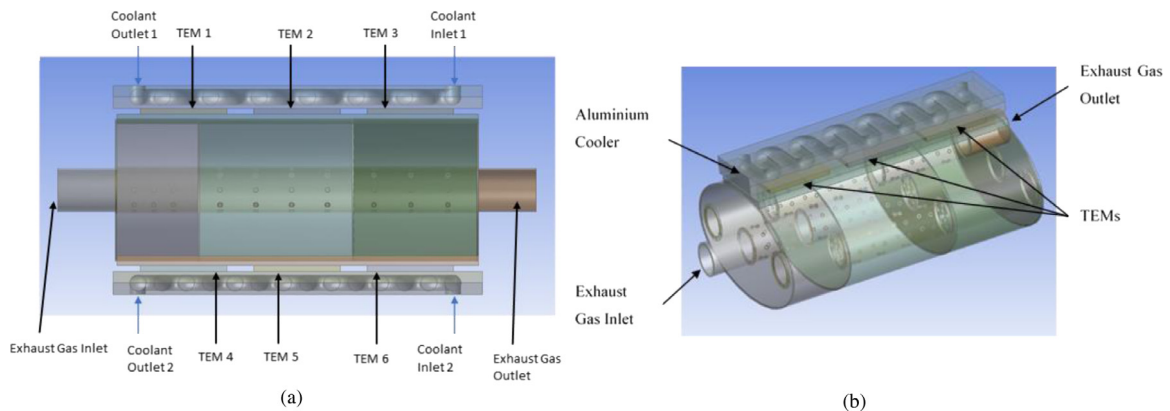


Fig. 2. (a) Cross section of the muffler modified as the TEG; (b) Isometric view of the muffler modified as the TEG.

Maximum power (P_{max}) generation by a TEM can be calculated by Eq. (4) and it was defined as an UDF during the simulation.

$$P_{max} = \frac{(OCV)}{4R_{int}} \quad (4)$$

Simulations were performed with reference to the following base case parameters shown in Table 1 and afterwards, exhaust gas inlet temperature was varied from 600 K–750 K, exhaust gas inlet mass flowrate was varied from 0.05 kg/s–0.20 kg/s, coolant inlet temperature was varied from 280 K–295 K and finally coolant inlet mass flowrate was varied from 0.05 kg/s–0.20 kg/s.

Table 1. Base case parameters of the simulations.

Parameter	$T_{ex.gas}$ (K)	$m_{ex.gas}$ (kg/s)	$m_{coolant}$ (kg/s)	$T_{coolant}$ (K)
Base case	700	0.10	0.16	280

The HZ-20 TEMs are designed to generate 20 W maximum, when the hot and cold side temperature difference is maintained at 250 K. So, expected maximum power of the TEG would be around 140 W considering the intermittent total power generation. Simulations were performed to obtain the total power produced by the TEG, the pressure drop across the TEG and the temperature profiles of the different locations of the TEG and are present in the results and discussion section below.

4. Results and discussion

The availability of the exhaust gas increases from 30 kW to 47 kW as the temperature increases from 600 K to 750 K. As shown in Fig. 3(a), the TEG power output also increases when increasing the temperature of the exhaust flow. The pressure drop across the muffler was also calculated and it was found as 28 kPa.

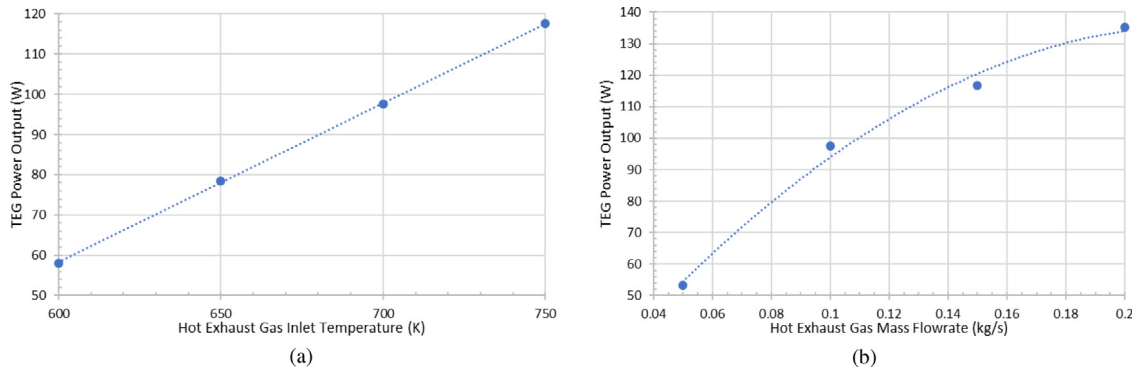


Fig. 3. (a) Exhaust gas temperature vs. TEG power output; (b) Exhaust mass flowrate vs. TEG power output.

The availability of the exhaust flow was estimated for different exhaust gas flow rates and found to be varied from 20 kW to 82 kW as the exhaust mass flow rate varies from 0.05 kg/s to 0.20 kg/s. The simulation results show that the power generation by the TEG increases as the exhaust mass flow rate increases. The pressure drop across the muffler was found to be varied from 7 kPa to 112 kPa as the exhaust mass flow rate varies from 0.05 kg/s to 0.20 kg/s.

Availability and the pressure drop across the TEG were found to be constants and are, 41 kW and 28 kPa respectively for constant exhaust mass flow rates and temperatures. As shown in Fig. 4(a), the simulation results show that the TEG power output reduces as the coolant temperature increases.

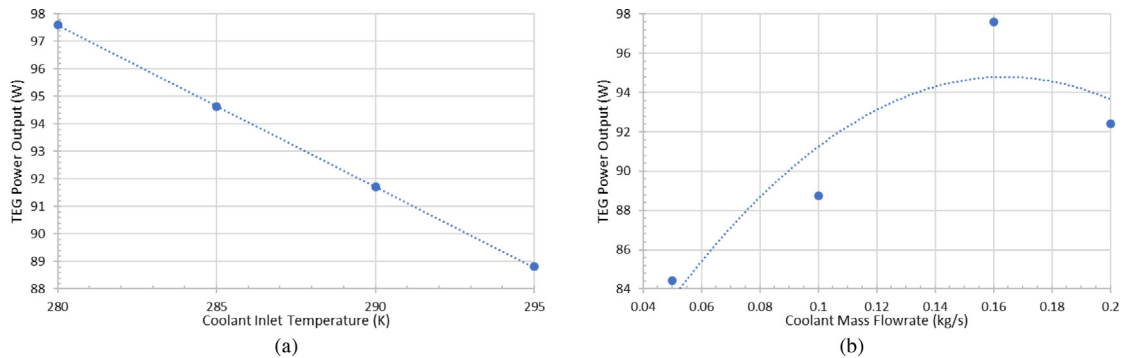


Fig. 4. (a) Coolant temperature vs. TEG power output; (b) Coolant mass flowrate vs. TEG power output.

Fig. 4(b) shows that the TEG power output does not increase as increasing the coolant mass flowrate. There is an optimum coolant mass flowrate and when the mass flowrate is higher than the optimum, the TEG power output reduces. However, the availability and the pressure drop across the muffler remains constant as the exhaust mass flowrate and temperature do not vary.

5. Conclusion

As shown in the above results, the power generation by the TEG coupled to the exhaust muffler increases when increasing the exhaust gas temperature and the exhaust mass flow rate. TEG power generation reduces when increasing the coolant temperature. However, the TEG power output can be maximized when selecting the optimum coolant mass flow rate.

Back pressure or the pressure drop created in the muffler increases when increasing the exhaust mass flow rate. It is well known that the brake specific fuel consumption (BSFC) increases and the overall efficiency of an IC engine reduces, while increasing the back pressure of the exhaust after treatment system. So, addition of a new device to waste heat recovery will lead to increase the back pressure of an engine and leads to reduce the overall engine

performance. When the TEG integrates to the exhaust muffler, waste heat can be recovered without sacrificing an additional back pressure in the engine exhaust system.

As identified in the literature review, exhaust heat recovery can be significantly enhanced by fabricating the TEMs from higher figure of merit (ZT) thermo-electric materials. Use of efficient TE materials to fabricate the TEG and integrate it with the muffler, will be resulting in designing efficient TEGs without adding extra back pressure in the engine. As a future work, the proposed TEG integrated with a muffler is expected to fabricate and test to validate the above simulation results.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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