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On the Recovery of Wasted Heat Using a Commercial Thermoelectric Device

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Waste heat recovery from car's exhaust gases provides an opportunity to significantly improve the overall car engine efficiency. One approach for recovering energy from the exhaust gases is to generate electrical power through thermoelectric conversion. A thermoelectric device, using a commercially available thermoelectric generator module was made, in order to measure the gained power and efficiency at different places of the exhaust pipe of a small size car (Toyota Starlet, 1300cc), for various engine loads. With the use of a modeling approach, we evaluated the thermal contact resistances and their influence on the final device efficiency.

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1. Introduction

The emerging global need for energy production, conservation, and management has intensified interest in more effective means of power generation. Enhancements to the existing energy supply must come from a variety of renewable sources including solar, wind, biomass, and others. Another potential source of power is electricity from heat sources through the use of thermoelectric (TE) materials. The heat can come from the combustion of fossil fuels, from sunlight, or as a byproduct of various processes (e.g. combustion, chemical reactions, nuclear decay). Therefore, thermoelectric materials can play a role in both primary power generation and energy conservation (i.e. waste-heat harvesting).

Thermoelectric (TE) generators make use of the Seebeck effect in semiconductors for the direct conversion of heat into electrical energy, which is of particular interest for waste heat recovery [1]. A thermoelectric generator (TEG) usually consists of several pairs of alternating p- and n-type semiconductor blocks, which are arranged thermally in parallel and connected electrically in a series circuit. Heating one side of the arrangement while the opposite side is cooled induces the heat flow, which is partly converted into electrical power.

Thermoelectric materials hold promise in devices such as power generators, heat pumps, coolers, and thermal sensors wherein they can convert thermal energy to electrical energy without any moving parts; they are reliable, lightweight, robust, and environmentally friendly [1–3]. The key issue in research for TE is to develop materials with a significantly increased so-called figure of merit, $\mathrm{ZT} = \sigma S^2 T/\kappa$, where σ is the electrical conductivity, S is the Seebeck coefficient, and κ is the thermal conductivity.

TE device performance relies directly on the temperature gradient (DT) and an intrinsic material parameter, the thermoelectric figure of merit (ZT). For power generation, the thermoelectric efficiency is defined by combining the Carnot efficiency ($\Delta T/T_{\mathrm{HOT}}$) and ZT as [4]:

$$\eta = \frac{\Delta T}{T_{\mathrm{HOT}}} \frac{\sqrt{1+\mathrm{ZT_{AVG}}}-1}{\sqrt{1+\mathrm{ZT_{AVG}}}+\frac{T_{\mathrm{COLD}}}{T_{\mathrm{HOT}}}}\,, \tag{1}$$

where T_{HOT} and T_{COLD} are the temperature of the hot and cold ends in a thermoelectric module and ΔT their difference. The term $(1+\mathrm{ZT_{AVG}})^{1/2}$ varies with the average temperature T_{AVG}. Equation (1) indicates that increasing efficiency requires both high ZT values and a large temperature gradient across the thermoelectric materials.

The first generation of bulk thermoelectric materials was developed over four decades ago with ZT of ≈ 0.8–1.0, and devices made of them can operate at ≈ 5–6% conversion efficiency. Out of a wide variety of research approaches to increase ZT, one has emerged recently which has led to nearly doubling of the ZT at high temperatures and has now given rise to the second generation of bulk thermoelectric materials with ZT ranging from 1.3 to 1.7. This approach is the optimization of existing materials using nanoscale inclusions and compositional inhomogeneities, which can dramatically suppress the lattice thermal conductivity. The new materials are expected to produce power generation devices with conversion efficiencies of 11–15%. Continued progress is expected to raise the ZT by a factor of 2, and depending on ΔT, the predicted efficiency increases to over 20%, a highly exciting prospect which will surely have a large impact in the energy production [5].

In previous works we have studied the efficiency of this device [6], its long-term stability in various thermal cycles [7], and the assembling pressure [8]. A theoretical model has been developed [9], which allows the calculation of gained power and efficiency of a thermoelectric generator device under different electric charges and temperature gradients. With the use of this model we evaluated the thermal contact resistances and their influence on the final device efficiency. Earlier works focus on investigating the temperature distribution along the exhaust pipe of a small sized car for various engine loads [10]. In this work we overview the recovery of wasted heat from a small car (Toyota Starlet 1300cc) using commercially available (1st generation) TE materials. Harnessing the wasted heat from car's exhaust gases provides an opportunity to significantly improve the overall car engine efficiency.

2. Experimental

As TEG, in this work, a commercial (Melcor HT9-3-25) 2.5×2.5 cm^2 Bi_2Te_3 based module with $N = 31$ thermocouples was used. This device was designed to operate under cycling conditions and relatively high temperature ($\approx 225\,°C$) applications, which makes it suitable for power generation applications.

The experimental prototype was mounted at a position after the catalyst and just before the front muffler, and examined under real road conditions (Fig. 1). The application of a TE device before the catalyst is considered to be undesirable, since it may influence the proper operation of the catalyst and the oxygen sensor.

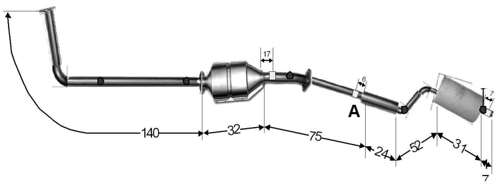

Fig. 1. Schematic drawing of the exhaust pipe for Toyota Starlet 1300cc car. The point marked with "A" is the position where TEG was mounted.

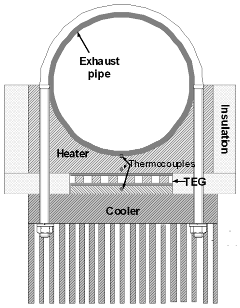

Fig. 2. Cross-section of the experimental prototype.

The development of a measuring prototype at the exhaust pipe has been reported elsewhere [10]. A semi--cylindrical aluminum piece was used as heater and was attached directly to the exhaust pipe and to the top of the TEG module. A 60×68 mm^2 aluminum heat sink with 156 fins of 20 mm was used as cooler by the ambient air. All pieces were bonded together at a pressure on TEG surfaces of 4 MPa (Fig. 2). In order to reduce the thermal contact resistance, all surfaces were lapped and a thin layer of graphite thermal grease (Melcor GRF-159) was used. Measurements were made at the exhaust pipe of a Toyota Starlet 1300cc car.

Three K-type thermocouples were mounted for monitoring the temperature, one in a hole near the exhaust pipe (Tex), the second near the bottom surface (T1) of the heater and the third in a thin aluminum plate on the bottom of the TEG module (T2).

In order to have a measurement of a possible TEG material degradation, as it was exposed to elevated temperatures, a "Z-meter" device type DX4065 of RMT Ltd was used.

3. Results and discussion

A thermoelectric generator (TEG) usually consists of several pairs of alternating p- and n-type semiconductor blocks (generator legs), which are arranged thermally parallel and connected electrically in a series circuit. The heat flow, which is partly converted into electrical power, is induced by heating one side of the arrangement while the opposite side is cooled.

The possible use of a device consisting of numerous TEG modules in the wasted heat recovery of an internal combustion (IC) engine can considerably help the world effort for energy savings. The use of a thermoelectric generator device will offload the alternator and thus will reduce its size. Generally, the wasted heat from IC engines is a great percentage of the fuel's energy. In gasoline fuelled IC engines, about 75% of the total energy of the fuel is rejected in the environment [11]. The recovery of a 6% of the exhaust's energy could lead to 10% saving of fuel [12]. The use of a TEG device will thus offload the alternator and may reduce its size.

Among the sources of rejected energy that exist in a petrol engine, an application of a thermoelectric device can be implemented at the exhaust pipe. The basic reason for this is the high temperatures that prevail there and the big rate of thermal power that goes through [7]. The exhaust gases exiting the engine contain up to 40% of the energy from the fuel burned by the engine. Typical operating exhaust gas temperatures at the exit of the catalytic converter are 400 to 600 °C, with exceptions above (up to 1000 °C) and below this range. The average flow rate for a mid-sized car is about 1.13 m^3/min [11]. The application of a thermoelectric device before the catalyst is considered to be undesirable, because it influences the proper operation of the catalyst and the oxygen sensor.

However, temperatures much higher than the desired operating range of the heat pipe could cause structural failure of the thermoelectric elements. The exposure of thermoelectric materials to such environments, causes generally, an increase in electrical resistivity, as well as a decrease in material ZT [13]. Furthermore, the continuous thermal cycling charge and the harsh environment under the vehicle, could lead to reduced efficiency and lifetime of the TEG [7].

Figure 3 shows the measured temperatures in the prototype, for 10 min cruising at speeds of 90 and 110 km/h. As can be seen, in such driving conditions, the hot side temperature (T1) does not exceed the TEG maximum operating temperature (225 °C), at the 110 km/h vehicle speed. Thermal inertia of the aluminum heater mass eliminates the quick temperature changes of the exhaust pipe, ensuring a smoother TEG operation. Natural funless air cooling seems to be fairly efficient, as the TEG

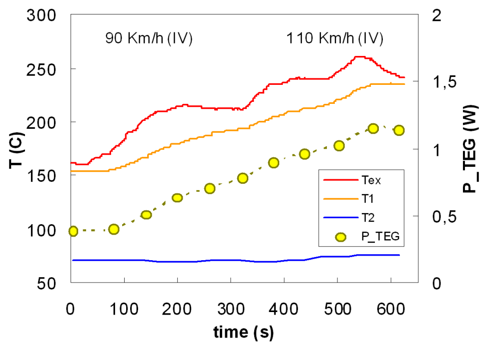

Fig. 3. Temperatures and TEG's gained power, for a 10 min cruising at speeds of 90 and 110 km/h.

cold side temperature (T2) does not exceed the 80 °C, at ambient temperature of 20 °C.

The calculated TEG efficiency varies from 2.5% to 3.2%, according to our theoretical model. The gained power could be about 20% higher if the prototype had about 40% smaller thermal resistances. It can be seen that at cruising driving situations (with a vehicle speed around 110 km/h) a power of 1.2 W is easily obtained. Assuming a total covering of this part of the exhaust pipe (from the catalyst to the front muffler) with a device with a single row of TEGs, a total power of 30 W could be achieved. This power is enough to offload the car's alternator by 7%, as the nominal alternator power at this car is 420 W at 2000 rpm.

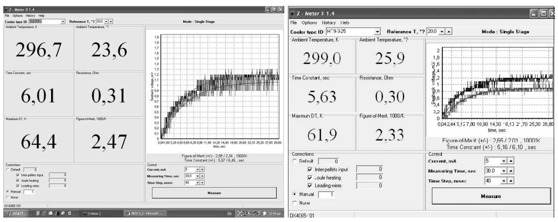

Fig. 4. Screen shots of the Z-meter before (left) and after (right) the experiment.

Measurements with "Z-meter" are shown in Fig. 4, before assembling and after the experiment. With "Z-meter" the TEG electrical resistance and Z value are measured. The measurements showed a reduction of 5.5% at Z, with no significant change at TEG's resistance, however, some brittleness at TEG soldering after the experiment was observed. This implies the TEG susceptibility at temperatures above the maximum operating temperature.

From the results it seems that, even though TEG efficiency is low, a significant amount of power could be gained with the use of a properly designed device consisting of numerous TEGs. Harnessing wasted heat will be far more efficient when TEG devices, based on 2nd generation, higher ZT thermoelectric materials will be commercially available.

4. Conclusions

In this work there has been investigated the implementation of a thermoelectric device for use in the recovery of wasted heat, in a small car. A commercially available TEG device was used in a position after the catalyst of the exhaust pipe. Using a theoretical model, the device's thermal resistances and the TEG efficiency of the TEG were evaluated. From the results, it seems that a significant amount of power could be gained with the use of a properly designed device consisting of numerous TEGs. The natural cooling of the device seems to be efficient, as the use of an electric fun should reduce the overall efficiency of the thermoelectric device. Using a single commercial TEG, power of 1 W was easily obtained, for cruising driving situations with a vehicle speed around 110 km/h. Assuming a total coverage of the exhaust pipe from the catalyst to the front muffler with a single row of TEGs, a total power of 30 W could be achieved, which is enough to offload the car's alternator by 7.1%.

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