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THERMOELECTRIC GENERATOR FOR ENERGY RECOVERY FROM THE EXHAUST GASES OF HEAVY-DUTY VEHICLES

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ABSTRACT

The application of a thermoelectric generator (TEG) to recover energy from the exhaust gases in light and heavy-duty vehicles is addressed using a mathematical model and optimization methods. The TEG is placed downstream of the Diesel particle filter of a commercial vehicle of 3.5 tonnes and a heavy-duty vehicle of 40 tonnes. The exhaust gas is used as heat source and the cooling water as heat sink. Three different heat exchanger fin structures are investigated, namely plain fins, offset strip fins and triangular fins. The analysis is performed for steady state conditions based on typical driving conditions, mass flow rates and temperatures of the exhaust gas and cooling water. The influence of the fin spacing and fin height on the net and electrical power is studied, as well as the height of the thermocouple legs. Then, an optimization study is performed aiming at the maximization of the net power, for fixed size of the TEG. Two different optimization methods are used, namely a gradient-based search method and a direct search method. The analysis carried out shows that, for typical extra-urban driving conditions, the recovery efficiency is low. The best recovery efficiency found is approximately 2%. Although the ratio of the electrical energy generated by the TEG to the thermal energy of the exhaust gases is still very low, 2% of the 2015 European freight transport wasted energy represents 22 million MJ, which is a significant amount.

INTRODUCTION

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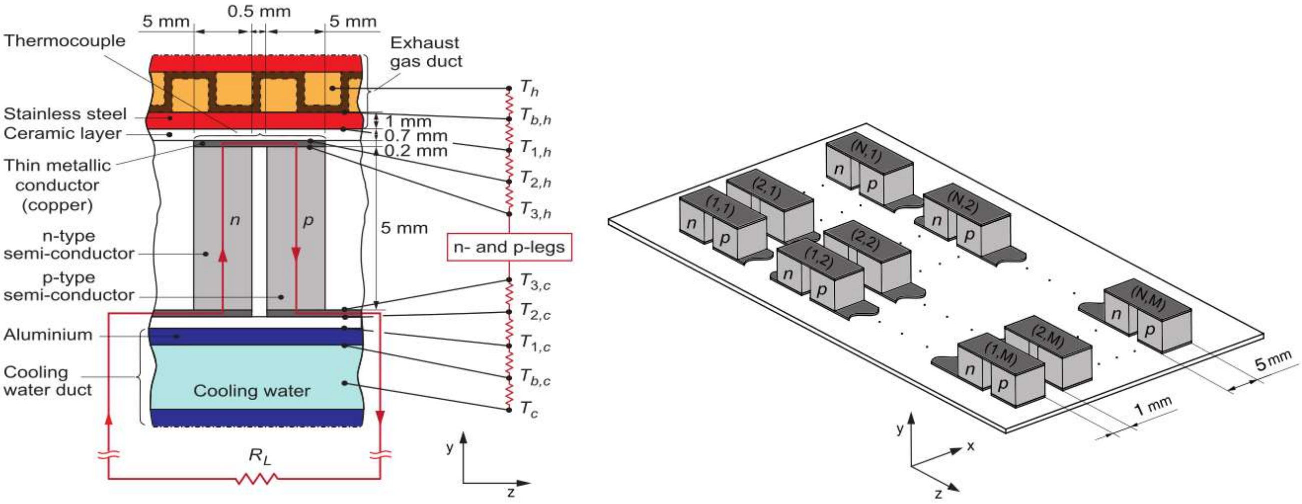
A thermoelectric generator (TEG) is a semiconductor device that converts directly heat into electrical energy through the Seebeck effect. TEGs have been used in a wide variety of applications, e.g., gas pipelines, aerospace industry, remote and off-grid power generation, and automobile applications. The present work is concerned with the application of a TEG for waste heat recovery in the automotive industry, namely in freight transportation. According to Eurostat [2015], the carriage of goods by road transport vehicles in the European Union was about 1.4 trillion tonne-kilometres in 2015. Most of the goods are carried over distances between 300 km and 1,000 km, with average vehicle loads of 13.8 tonnes. Considering 50 L / 100 km energy consumption and 13% overall efficiency, this potentially resulted in an overall tailpipe wasted heat energy amounting to 1,100 million MJ. Hence, there is an enormous potential for energy recovery in these vehicles.

Although the earliest studies on the use of TEGs for waste heat recovery in the automotive industry date back from the sixties, the research on this topic has received a new boost in recent years. While many studies address only one thermocouple or the heat exchanger, a few works addressed the performance of the overall TEG. Several optimization studies have also been reported. However, little research has been done on the application of TEGs in Diesel vehicles for freight transport, which is the subject of the present work.

THERMOELECTRIC GENERATOR CONFIGURATION

The TEG is constituted by 6 layers of thermoelectric modules. Each layer is bounded by a heat exchanger, through which flows the exhaust gas, and a duct through which flows the cooling water, as shown in Fig. 1(a). The thermoelectric modules are composed by thermocouples, which are located and connected as shown in Fig. 1(b). It is assumed that both fluids have the same flow direction, the inlet temperatures and velocity distributions are uniform, and the temperature is uniform along the *z*-direction.



(a) TEG design.

(b) Thermoelectric module design.

Figure 1. Sub-assembly of the TEG and thermoelectric module arrangement at a layer.

MATHEMATICAL MODEL

The mathematical model is described in Vale *et al.* [2017]. The thermal analysis assumes one-dimensional steady state heat transfer along the *y*-direction. The heat losses due to radiation and the thermal contact resistances are neglected, and the gaps between the legs of the thermocouples are considered perfectly insulated. The heat exchanger gas and the duct of cooling water are discretized along the flow direction, considering a number of control volumes (CVs) equal to the number of thermocouples in that direction. A system of 10 non-linear equations is solved for each thermocouple. These equations describe the energy balances at every node of the thermal resistance network in Fig. 1(a). The solution of these equations yields the temperatures of the hot (T_h) and cold (T_c) fluids downstream of the CV under consideration and the eight interface temperatures shown in the resistance network in Fig. 1(a). The CVs are treated sequentially along the *x*-direction, setting the temperature of the fluids leaving a CV equal to the inlet temperature of the fluids entering the neighbouring CV. The intensity of current in every thermocouple is evaluated from the temperature difference across its junctions. The electrical power of the TEG is calculated by adding the electrical power of every thermocouple, which is readily computed from its electrical resistance and the current intensity. The net power of the TEG is then determined by the difference between the electrical and the pumping powers.

RESULTS AND DISCUSSION

The mathematical model was used to investigate the performance of a TEG placed downstream of the Diesel particle filter (DPF) of a commercial vehicle of 3.5 tonnes and a heavy-duty vehicle of 40 tonnes. The analysis was performed for steady state conditions based on typical driving conditions, mass flow rates and temperatures of the exhaust gas and cooling water. Assuming constant speed of 90 and 120 km/h for the light and heavy-duty vehicles, respectively, and typical values of the vehicle's frontal area, engine displacement, power, and torque, the ADVISOR Advanced Vehicle Simulator [2017] software was employed to determine the mass flow rate and the temperature of the exhaust gases, as well as the temperature of the cooling water. These data are listed in Table 1. The cooling water mass flow rate was fixed at 2.1 kg/s. The thermoelectric materials were selected according to the data given in Table 1 (see Vale *et al.* [2017] for details).

Table 1
Input data for the TEG mathematical model

Vehicle (tonnes)	Speed (km/h)	Exhaust gas mass flow rate (g s^{-1})	Exhaust gas temperature at DPF (K)	Coolant fluid temperature (K)
3.5	120	80.12	568.93	368.15
40	90	201.48	710.86	368.15

Two different fin structures in the exhaust gas duct were investigated: plain fins and offset strip fins. A parametric study was carried out to investigate the influence of the fin spacing and fin height on the net and electrical power. In the case of plain fins, a smaller fin height leads to higher electrical power. Subsequently, for a fixed height, there is an optimum fin spacing that maximizes the net power. Regarding the offset strip fins, it was found that the heat transfer increases with the reduction of the length of the fins, but the pumping power increases too. In both plain and offset strip fins, a compromise is needed to simultaneously achieve high electrical and net power. The analysis of the size of the TEG shows that doubling the length in order to achieve maximum electrical power is more effective than doubling the width. On the other hand, doubling the width is more effective when the net power is considered. It was further observed that the height of the thermocouple legs plays a significant role in the thermoelectric behaviour of the thermocouples, and there is an optimum height dependent on the configuration that maximizes the electrical power.

Following the preliminary parametric study, two different optimization methods were used, namely a gradient-based search method (FMINCON from Optimization Toolbox in MATLAB), and (Global and Local Optimization using Direct Search − GLODS, Custódio and Madeira [2014]). Triangular fins were used in this optimization study in addition to the two configurations mentioned above. The following variables were taken as design variables: fins spacing, height, thickness, and length (the length is a variable only in the case of offset strip fins); height of the water duct; thickness of the copper, ceramic, aluminium, and steel layers (see Fig. 1a); height and side length of the legs of the thermocouples; spacing between *n* and *p* legs; distance between thermocouples in *x* and *z* directions. Minimum and maximum allowed values were prescribed for every design variable. The total length and width of the TEG were fixed, as well as the maximum height. The optimization criterion is the maximization of the net power of the TEG.

The gradient-based search method is more sensitive to the initial guess and more likely to convergence to a local minimum. It requires fewer iterations and objective function evaluations than GLODS, for the same initial guess. However, the two optimization methods lead to similar results, but not identical ones, provided that the initial guess is close to the optimum. The analysis of the gradients of the objective function reveals the variables that have the greatest influence on the net power. The dimensions of the heat exchangers and the height of the cooling water duct play always an important role due to their influence on the convective heat transfer coefficients and on the heat transfer area. The height of the legs of the thermocouples has a major influence, while the length of the side and the other design variables are not so important. The Lagrange multipliers in the gradient-based search method yield information about the effect of each restriction on the optimum results. The restrictions on the minimum height of the cooling water duct, the thickness of the fins, and thickness of the copper, ceramic, aluminum, and steel layers are the most important ones. In the heavy-duty vehicle, the minimum fin spacing for plain fins is also an important restriction.

Table 2 summarizes the net output power for the best configurations found in the parametric study, in which only the dimensions of the fins were varied, and only a relatively small set of values were considered for those dimensions. It is clear that the net powers obtained are well below those computed using the optimization methods, particularly in the case of the heavy-duty vehicle. The comparison between the different fins configuration should be cautious because the structure of the TEG is different in the three cases, i.e., the number of layers of thermoelectric modules and the size of the exhaust gas duct is different, as an outcome of the optimization procedure.

Table 2
Net output power [W] of the TEG for the parametric study and optimization method

Vehicle (tonnes)	Plain fins		Offset strip fins		Triangular fins
	Parametric study	Optimization	Parametric study	Optimization	Optimization
3.5	78	96	73	102	102
40	357	800	320	786	695

CONCLUDING REMARKS

The analysis carried out shows that, for typical extra-urban driving conditions, the recovery efficiency is low. The maximum net power is about 800 W for the heavy-duty vehicle and the corresponding recovery efficiency found is about 2%. This could be used to generate the vehicle's electrical network demand, which is state-of-the-art in that value area. Although the ratio of the electrical energy generated by the TEG to the thermal energy of the exhaust gases is still very low, 2% of the 2015 European freight transport wasted energy represents 22 million MJ, which is a significant amount.

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