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Parametric study of a thermoelectric generator system for exhaust gas energy recovery in diesel road freight transportation

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ABSTRACT

A parametric study and optimization approaches of a thermoelectric generator (TEG) for the recovery of energy from the exhaust gas in Diesel vehicles used in freight transport is reported. The TEG is installed in the tailpipe of a commercial vehicle (3.5 tonnes) and a heavy-duty vehicle (40 tonnes). The exhaust gas is used as the heat source and the cooling water as the heat sink. Two different heat exchanger configurations are considered: plain fins and offset strip fins. The influence of the height, length and spacing of the fins on the electrical and net power is analysed for the fixed width and length of the TEG. The influence of the length and width of the TEG and of the height of the thermocouple legs is also investigated. According to the criteria used in this study, plain fins are the best choice, yielding a maximum electrical power of 188 W for the commercial vehicle and 886 W for the heavy-duty vehicle. The best recovery efficiency is about 2%, with an average thermoelectric material efficiency of approximately 4.4%, for the light-duty vehicle. Accordingly, there is significant room for further improvement and optimisation based on the thermoelectric modules and the system design.

1. Introduction

In recent years, the thermoelectric generator has emerged as a promising form of technology for waste heat recovery in the automotive industry, due to the improvement of the thermoelectric materials [1]. According to Eurostat [2], over 50% of freight transportation in Europe is performed by road. This is typically executed by vehicles with Diesel engines and represented a total of about 1.7 trillion tonne-kilometres in 2014. Most of the goods are carried over distances between 300 km and 1000 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 1330 million MJ. The use of a TEG could help with the reduction of the waste heat. From the literature review, it is concluded that most studies focused on gasoline engines due to their higher exhaust gas temperatures (e.g. see Table 1). However, the mass flow rate and the available energy in the exhaust gas are greater for Diesel heavy-duty vehicles. In addition, the space constraints for installation of a TEG in the tailpipe are lower for the former vehicles. Moreover, the driving durations are longer and the velocities are steadier for heavy-duty vehicles than for passenger cars.

The present study focus on Diesel vehicles for freight transport, particularly the heat exchanger numerical simulation has been tackled. The energy transfer from the engine exhaust of two vehicles is investigated: a commercial 3.5 tonne and a heavy-duty 40 tonne vehicle, both simulated in ADVISOR [3] in constant speed and world harmonized transient cycle (WHTC) [4]. The influence of two different heat exchanger structures, with either plain fins or offset strip fins, on the electrical and net power output, is assessed. The influence of the height, spacing and length of the fins, as well as the effect of the width and the length of the heat exchanger, and the height of the thermocouple legs, are investigated. The recovery efficiency from the TEG configurations studied is also determined and compared with existing results.

2. State of the art

Our goal is to maximize electrical output power by improving the heat exchanger and build a model for integration with a road vehicle simulator such as ADVISOR or AVL-CRUISE™. Apart from the heat exchanger, the simulation and prediction of the behaviour

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Nomenclature

A	area (m^2)
c_p	specific heat (J kg^{-1} K^{-1})
CV	control volume (–)
D_h	hydraulic diameter (m)
f	Darcy friction factor (–)
h	convective heat transfer coefficient (W m^{-2} K^{-1})
I	electric current (I)
k	thermal conductivity (W m^{-1} K^{-1})
K	thermal conductance (W K^{-1})
l	fin length (m)
L	length/height (m)
N	number of thermocouples in x-coord. direction (–)
M	number of thermocouples in z-coord. direction (–)
$\dot{m}$	mass flow rate (kg s^{-1})
p	pressure (N m^{-2})
P	power output (W)
q	total heat transfer rate (W)
$\dot{Q}$	heat power (W)
R_i	load resistance (Ω)
s	fin spacing (m)
T	temperature (K)
u	mean flow velocity (m s^{-1})
$\dot{V}$	volumetric flow rate (m^3 s^{-1})
ZT	figure of merit (–)

Greeks symbols

α	difference between Seebeck coefficients (V K^{-1})
η	efficiency (%)
ρ	electrical resistivity (Ω m)
φ	correction factor (–)

Subscripts/superscripts

c	cold
d	exergy destruction
el	electrical
ex	exhaust gas
f	fins
fu	fuel
h	hot
L	load
loss	heat loss
n	n-type semiconductor material
net	net
p	p-type semiconductor material
pump	pumping

of the thermoelectric modules for different boundary conditions and different locations in the exhaust is essential for the development of the TEG.

Yu and Zhao [5] developed a numerical model for a TEG and compared the performance of a parallel flow and a counter flow heat exchanger. They concluded that both of these tend to result in the same electrical output power, since the average temperature difference between the hot and the cold fluids is essentially equal for the two types of heat exchangers. Their results also show that the variation in temperature of the hot and cold fluids in the flow direction is approximately linear. Lu et al. [6] investigated two types of heat transfer enhancement structures, namely rectangular offset strip fins and metal foams, for the exhaust gas heat exchanger of a gasoline light-duty vehicle. They found that the electrical power from the metal foams was significantly higher (approx. 130–294 W) than that from the offset strip fins. However, the metal foams produced a higher pressure drop, and even though the total output power can significantly increase, the net power output is lower. The solution suggested by these authors, to apply in the near future, was to develop a TEG that combines simultaneously thermoelectric generation and catalytic conversion.

Bai et al. [7] used a computational fluid dynamics (CFD) code to investigate the heat transfer and pressure drop for six different internal structures of the heat exchanger in a light-duty 1.2 L gasoline engine vehicle. They showed that the serial plate structure presents the highest heat transfer, but also the highest pressure drop. They concluded that there is a compromise between high heat transfer and low drop in pressure. The maximum electrical and net powers were not determined. Su et al. [8] compared three internal heat exchanger structures for automotive exhaust-based TEGs: fishbone-shaped, accordion-shaped and scatter-shaped. It was proved that the accordion-shape design presents a better uniform temperature distribution. Again, the maximum electrical and net powers were not presented. Likewise, Liu et al. [9] focused on the temperature distribution in the heat exchanger mounted on the exhaust of a 2.0 L naturally aspirated gasoline engine. They compared two internal heat exchanger geometries, fishbone-shaped and chaos-shaped, and concluded that the chaos-shaped structure leads to better results (maximum electrical power approx. 183 W).

Apart from the heat exchanger, the simulation and prediction of the behaviour of the thermoelectric modules for different boundary conditions is essential for the development of the TEG. Hence, Niu et al. [10] developed two 3D numerical models to study the behaviour of the thermocouples under different prescribed boundary conditions. They concluded that these can strongly influence the results. They also investigated in detail the influence of the shape of the thermocouples on their performance and found that the temperature gradient could be enhanced if a proper cross section area is used. The shape of the thermocouples was also investigated by Rezania et al. [11]. The maximum power generation and maximum cost performance of a thermocouple are achieved when the ratio of the area of the cross section of the n-leg to that of the p-leg of the thermocouple is lower than unity. Abdelkefi et al. [12] developed an analytical electro-thermal model for thermoelectric modules and used experimental data from a previous study for validation purposes. The effect of different hot side temperatures, temperature differences, load resistances and clamping forces on the electrical output power from a single thermocouple was analysed.

Häfele et al. [13] developed a numerical model for a TEG and analysed its behaviour using bismuth telluride (Bi_2Te_3) and lead telluride (*PbTe*) thermoelectric modules. A TEG prototype with 24 Bi_2Te_3 HZ-20 thermoelectric modules was integrated into a test vehicle and about 200 W electrical power was measured. Yu et al. [14] also developed a numerical model for a TEG and analysed its behaviour using 16 commercial Bi_2Te_3 HZ-20 thermoelectric modules. It was found that the vehicle speed is a significant factor affecting the TEG performance for waste heat recovery. Gou et al. [15] developed a theoretical dynamic model for a TEG with a finned heat exchanger. The temporal variation of the temperatures on the hot and cold semiconductor surfaces, maximum output power and system efficiency was analysed by means of step changes of the heat reservoir temperatures and mass flow rates. Tatarinov et al. [16] carried out a similar work, but considered four different car driving patterns, two from Europe and two from the