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Full Length Article

Potential of energy recuperation in the exhaust gas of state of the art light duty vehicles with thermoelectric elements

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ABSTRACT

About 30% of the fuel energy is lost in combustion engines to the exhaust gas. New development of thermoelectric materials allows to partly recuperating the lost heat. New Half-Heusler materials using only low-priced elements show promising performances for heat conversion in the temperature range of a vehicle exhaust. An investigation of the installation of Half-Heusler-based thermoelectric generators at the manifold and after the exhaust after-treatment system (ATS) of 4 light duty vehicles (2 gasolines and 2 diesels) has been made. Gas temperatures at the manifold and after the ATS were simulated based on measured data. These reach 800 °C and 600 °C respectively during a typical driving cycle. During the WLTC, an average of 100 W of electricity can be generated at the manifold and 30 W after the ATS, without adding specific heat transfer enhancing devices in the exhaust pipe. The geometric dimensions of the TEGs must be adapted in order to match the optimal thermal resistance according to their location in the exhaust and the vehicle type (differing heat flows and temperatures) to recuperate an optimal amount of energy.

1. Introduction

Most of vehicles use internal combustion engines to generate mechanical power. Unfortunately those engines have low efficiency (30–35% maximum) and roughly one third of the fuel energy is lost with the exhaust gas. Different technologies are being developed to recuperate this energy, such as Organic Rankine cycle [1–3]. Thermoelectrics, materials allowing converting heat to electricity and vice versa, could also be used in a vehicle exhaust, and have the advantage of not having moving parts and are somewhat not too heavy. Some vehicle manufacturers are already studying the installation of thermoelectrics after the catalyst [4–6], while other researches show that hybrid vehicles benefit from the installation of such generators [7]. It is however to be noted that adding thermoelectrics increases vehicle weight and cost and that those drawbacks must be taken into account when assessing the overall energy impact [8,9].

Classical thermoelectric materials, Bismuth-Telluride-based ones, present good conversion efficiency at low temperature range (below 400 °C) but are not able to convert heat at exhaust temperatures [10,11]. Newer materials, such as Half-Heusler or Skutterudite, are more suitable for the application. Skutterudite materials are however difficult to use because of their poor thermal stability and antimony evaporation [12]. Lately, Half-Heusler materials show a very good figure of merit in the range of the automotive application temperatures (400–800 °C) [13,14]. Many of those Half-Heusler use rare elements (Hafnium, Zirconium…) whose costs are prohibitive for high number uses in the automotive industry, but recent developments introduce new rare materials free Half-Heusler families [15].

The idea of this study is to use the Half-Heusler materials, presenting promising properties with low-cost elements, to generate electricity at two locations on a vehicle exhaust: at the manifold and downstream the after-treatment system (ATS). Experimental data from four state of the art light duty vehicles was available and a series of simulation models have been made for the energy assessments as well as the heat transfer through the TEGs.

2. Chassis dynamometer measurements

For the assessment of the energy recuperation potential by TEGs data from chassis dynamometer measurements of light duty vehicles have been used. The vehicles were items of several projects and therefore not all important data for the TEGs assessment could be measured directly. Simulations have been setup in order to obtain all important data based on the measurements.

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Abbreviations and symbols

TEG	thermoelectric generator
ATS	after-treatment system
TWC	three way catalyst
EGR	engine gas recirculation
DOC	diesel oxidation catalyst
DPF	diesel particulate filter
LNT	lean NOx trap
WLTC	worldwide harmonized light vehicles test cycle
NEDC	New European driving cycle
λ	material thermal conductivity [W/m·K]
l	wall thickness [m]
S	area of exchange T [m^2]
L	characteristic length [m]
h	convective heat transfer coefficient [W/(m^2 K)]
Re	Reynold number [–]
Pr	Prandtl number [–]
μ	dynamic viscosity [kg/(m s)]
P	power [W]
η	efficiency [–]
ZT	figure of merit [–]
T	temperature [K]

Four state of the art light duty vehicles have been chosen in this study: two gasoline and two diesel vehicles. Each one of the cars conform the Euro 6b standard (Table 1).

The vehicles have been tested over two typical driving cycles: the NEDC (New European Driving Cycle) and the WLTC (Worldwide harmonized Light vehicles Test Cycle). The simulations however have been run mainly on the WLTC, the new standard cycle for vehicle testing. Figs. 6 and 7 include the time velocity profile of the WLTC cycle. The vehicles have been taken from everyday use and thus only small modifications were possible. The data acquired by the chassis dynamometer relevant for this study are vehicle velocity, power at the wheels, engine rotational speed, fuel mass flow, exhaust gas mass flow, and exhaust gas temperature at the tailpipe exit.

3. Simulation

Three models were built for this study:

- An engine model to compute gas temperatures at the manifold using the measured fuel flow, engine rotational speed and the power at wheels (Section 3.1)
- An exhaust pipe model to compute the temperature downstream the ATS using the measured exhaust mass flow and the temperature at the tailpipe exit (Section 3.2)
- A thermoelectric generator model using the TEG material properties (see Section 4.4)

3.1. Modelling of gas temperatures at the manifold

The energy balance of the engine has been modelled in order to obtain the gas temperature at the manifold according to Fig. 1. Measurement data from the chassis dynamometer has been used as the input. The experiments were conducted in the chassis dynamometer, Schenk 500/GS60/V200. The power at the wheels was recorded by the system. The engine rotational speed was measured by Ono Sokki CT-651. The fuel consumption was estimated based on exhaust emissions (CO2, CO), which were measured by Horiba Mexa 9400H. The exhaust flow rate was measured by the Horiba CVS-9300, and the exhaust gas temperature by K-type thermocouples.

The proportion of heat going to the exhaust is computed from the engine speed and mean effective pressure, according to [16].

3.2. Modelling of gas temperatures after ATS

Temperature after the ATS was simulated with a pipe model. As inputs the measured tailpipe exit temperature and the exhaust mass flow have been used. The inverse heat transfer process had to be solved modelling the convection from the exhaust gas to the pipe walls, conduction through the pipe walls, natural an forced convection to the ambient air as well as radiation exchange with the ambient.

The following equations are used [17]:

- Conduction

$$Q_{cond} = \frac{\lambda * S}{l}\Delta T \tag{1}$$

- Convection

$$Q_{conv} = h * S * (T_{wall} - T_{fluid}) \tag{2}$$

$$h = \frac{\lambda * Nu}{L} \tag{3}$$

$$\mathrm{Nu} = 0.027 \cdot Re^{4/5} \cdot Pr^{1/3}\left(\frac{\mu}{\mu_s}\right)^{0.14} \tag{4}$$

- Radiation

$$Q_{rad} = \sigma * \varepsilon * S * (T_{wall}^4 - T_{ambient}^4) \tag{5}$$

where

λ – Material thermal conductivity
l – Wall thickness
S – Area of exchange
L – Characteristic length
h – Convective heat exchange coefficient
Re – Reynolds number (evaluated at fluid temperature)
Pr – Prandtl number (evaluated at fluid temperature)
μ – Dynamic viscosity (evaluated at fluid temperature)
μ_s – Dynamic viscosity (evaluated at wall temperature)

4. Thermoelectric materials

4.1. Fundamentals

A thermoelectric generator (TEG) consists of pairs of n- and p-thermoelectric legs, which are connected in series electrically and in parallel thermally in order to convert heat into electricity. The efficiency of such an element can be computed from the hot and cold side temperatures (T_h and T_c respectively) and the material dependent figure of merit (ZT). Electrical power generated is given by the amount of heat

Table 1
Light duty vehicles used for the present study.

Fuel	Gasoline	Gasoline	Diesel	Diesel
Injection	Indirect	Direct	Direct	Direct
Displacement (cm**3)	1368	1997	1496	1995
1st enrolment	02.2014	03.2014	10.2014	09.2014
Mass (kg)	1360	1810	1250	1810
Emission code	Euro 6b	Euro 6b	Euro 6b	Euro 6b
Exhaust systems	TWC	TWC	EGR, DOC, DPF, LNT	EGR, DOC, DPF, LNT