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Evaluating thermoelectric modules in diesel exhaust systems: potential under urban and extra-urban driving conditions

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ABSTRACT

In light-duty internal combustion engines, approximately only the third part of the fuel energy consumed is converted to effective mechanical work. Since waste energy through the exhaust system represents also around a third part of this energy input, it strikes as a remarkable source for energy recovery to reduce fuel consumption and pollutant emissions in automotive engines. Test-bench engine experiments were performed to have accurate data of exhaust gas in the most used part of the engine map in passenger diesel vehicles. To assess the potential of exhaust gases for thermoelectric modules, a simple but robust methodology has been developed. Heat transferred was calculated through fundamental equations applied to a concentric tube heat exchanger. Exergy analysis is presented in conjunction with a study of electrical power that could be produced by commercially available Bi_2Te_3 thermoelectric modules. These results are obtained using the exhaust system and engine coolant as they can be found in a current car, so they can be used as starting point in design of devices for harvesting exhaust waste energy, improving automotive engines sustainability. Thermoelectric generators recovery limits were made visible without focusing in a specific design.

1. Introduction

Around a third part of the energy input of a light-duty diesel engine is wasted through the exhaust system (Hossain and Bari, 2014). Rising awareness of environmental issues together with fuel economy have encouraged research upon heat recovery in engines. Main technologies to recover energy from exhaust gas are: six stroke engines, turbocharging, electric turbo-compound generators, thermoelectric generators (TEGs) and Rankine cycles (mainly with organic fluids) (Hatami et al., 2014; Gabriel-Buenaventura and Azzopardi, 2015).

Six stroke engines (Hayasaki et al., 1999; Conklin and Szybist, 2010) take advantage of heat from exhaust gases yet inside the cylinder. Turbocharging (Bontempo et al., 2015; Ravaglioli et al., 2015) systems are already implemented in most diesel vehicles. Electric turbo-compound systems (Gabriel-Buenaventura and Azzopardi, 2015; Arsie et al., 2015) (also known as TERS, Thermal Energy Recovery Systems) consist on generator units that slow the turbocharger's turbine and recover energy otherwise wasted by the compressor when the pressure produced exceeds the requirements. TEGs (Saidur et al., 2012; Zang et al., 2008) and Rankine cycles (Sprouse and Depcik, 2013; Yu et al., 2016; Dolz et al., 2012a) can be employed to convert heat from exhaust systems into electrical or mechanical energy, respectively.

This work is focused on the application of TEG technology in light duty diesel vehicles, which work with lower equivalence ratio compared to petrol engines and, in consequence, produce lower exhaust temperature. As known, TEGs convert thermal energy from a temperature gradient between hot and cold ends of a semiconductor into electrical energy (Saidur et al., 2012). Main advantages of TEGs are the following: lack of moving parts, silent operation and reliability. The main challenge of energy recovery using TEGs is their low thermal efficiency in present-day modules (Karvonen et al., 2016) with merit factors no more than 2–3. Hence, temperature at the hot side of the module should be high to harvest a significant amount of energy.

The simplest way of heat extraction from exhaust gases is using the exhaust pipe as thermoelectric hot side source and air cooling, as in Sandu et al. (2012). The high thermal resistance of exhaust gas causes pipe temperature to be lower than desired and insufficient external heat dissipation leads to cold side heating (as a result of

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Nomenclature

c_p	Specific heat at constant pressure, J/kgK
T	Temperature, K
U	Global heat transfer coefficient, W/mK
x	1-D coordinate, m
L	Total heat exchanger length, m
$\dot{m}$	Mass flow rate, kg/s
h	Convection heat transfer coefficient, W/m^{2}K
K	Thermal conductivity, W/mK
D	Diameter, m
$\dot{Q}$	Transferred heat, W
$\dot{E}$	Exergy power, W
$\dot{P}$	TEG power output, W
ΔT	Temperature difference among hot and cold streams, K

Subscripts

al	Aluminium sleeve
c	Coolant
g	Exhaust gas
cold	Cold source
ext	Exterior
hot	Hot source
in	Interior
inlet	Inlet
p	Pipe

conduction heat transfer through the module). Consequently, the gradient of temperature needed for the TEG to produce an electrical output is hard to achieve. Heat exchangers are necessary to enhance heat transfer from the exhaust pipe and broaden the temperature difference between both sides of the thermoelectric module.

Studies in literature tend to focus on validating and testing specific TEG designs but fail to give a potential analysis of the heat source in the most used part of the engine map for light-duty diesel engines, which is the purpose of this paper. For example, the target of some thermoelectric generator studies (Weng and Huang, 2013; Meng et al., 2016) is optimization of a certain design and tend to present a single exhaust gas condition that can be different from common urban and extra-urban driving. Cold side temperature is also an important variable in TEG electrical production and some authors presented studies conducted with coolant water temperatures hardly achievable in vehicles (Meng et al., 2016; Ikoma et al., 1998).

Furthermore, a great number of studies have been applied on spark ignition (Thacher et al., 2007; LaGrandeur et al., 2006) or on heavy-duty or power plant diesel (Bass et al., 1994; Niu et al., 2014) engines, where available thermal energy from the exhaust gases is higher and results cannot be extrapolated to light-duty diesel engines.

Generic energy and exergy analyses on exhausts systems have been carried out in the past (Rakopoulos and Giakoumis, 2006; Liu et al., 2013). Although useful to assess energy lost through exhaust gas, they are less precise to narrow the amount of energy that could be recovered with a particular technology. Consequently, it is hard to find information about heat recovery that could be currently achieved by thermoelectric generators when driving diesel light duty passenger cars.

Thermoelectric modules make use of heat from the exhaust gas, but, when implemented, thermoelectric generation systems modify this heat transfer, due to new thermal resistances added. It is also of great importance to consider the gas temperature reduction across heat exchangers. Therefore, energy and exergy results in exhaust systems to be applied on thermoelectric generators should include, to a certain extent, the technology to be employed for energy recovery, as it has been previously done with other energy recovery approaches, such as Rankine cycles (Domingues et al., 2013; Zhu et al., 2013; Dolz et al., 2012b).

The aim of this work is to propose a methodology to analyse potential of exhaust systems for TEG heat recovery and its application to usual urban and extra-urban conditions. This is accomplished by modelling a TEG device using a concentric-tube heat exchanger configuration. Test-bench engine experiments were performed to have accurate data of exhaust gas in the desired part of the engine map.

The exhaust system analysis used in this study covers two main issues found in literature that hinder the understanding of TEGs potential in diesel passenger vehicles: the dependency of the heat exchanger configuration (since the target is to evaluate the energy source, not a specific design) and the non-representative engine conditions.

Information about available energy in exhaust systems of light-duty diesel engines is provided. Exergy analysis (*i.e.* second law analysis) of heat transferred through pipe and electrical power output of commercial TEG modules are presented.

2. Materials and methods

2.1. Engine

Tests were carried out in a Nissan YD22 four stroke, turbocharged, four-cylinder diesel engine. The engine bore and stroke are, respectively, 86 mm and 130 mm and the compression ratio is 16.7:1. The exhaust system is equipped with a diesel oxidation catalyst (DOC) and a muffler. Piezo resistive pressure sensors and K-type thermocouples were used for measuring pressure and temperature of the gas along the exhaust system. The exhaust mass flow rate was calculated from the addition of the fuel and the air mass flow rates. The only error in this estimation is the engine blow-by, which represents a small fraction of the exhaust gas (around 0.5–1% related to the mass of the engine air intake (Ebner and Jaschek, 1998)).

2.2. Test schedule

The velocity profile imposed by the New European Driving Cycle (NEDC) used for light-duty vehicle certification, was translated into engine operating conditions (torque and engine speed), as shown in Fig. 1 (black dots), employing longitudinal dynamics equations (Cárdenas et al., 2016; Cárdenas, 2016). Then, a matrix of nine steady-state modes (see Fig. 1, colored dots) covering the most used quarter of the engine map in both urban and extra-urban conditions was selected for testing. Although NEDC data was used to translate engine conditions, this test matrix covers the most used quarter of the engine map in light-duty vehicles in both urban and extra-urban conditions (for any known driving cycle) (Steven, 2013).

This matrix was also defined according to two additional