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Thermal analysis of a thermoelectric generator for light-duty diesel engines

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HIGHLIGHTS

- Challenges in energy recovery from light-duty diesel engines with thermoelectric generators are clearly identified.
- A thorough new approach to validate CFD thermoelectric generator models was developed.
- Insight of internal thermal performance of thermoelectric generators is given.
- Considerations for implementation of prototypes in exhaust systems are provided.

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ABSTRACT

Efficiency of internal combustion engines can be improved indirectly using a waste heat recovery system. Thermoelectric generators (TEGs) are employed to convert thermal energy from exhaust gases to electrical energy. Research in this area has been focused on gasoline and heavy-duty engines. The novel purpose of this work is to study the potential of TEGs in light-duty diesel engines, where available energy in the exhaust systems is lower and, therefore, energy recovery is more difficult to achieve. Furthermore, the engine was tested in the most used area of the engine map for passenger cars, far from the full-load curve. This work also provides a new useful insight of the flow inside TEGs and the influence of catalytic converters (commonly immediately upstream of TEGs) to fill the gaps in implementation and development of thermoelectric generator prototypes. A TEG was designed following a different approach focused not only on maximizing electrical power output but also on minimizing influence on the engine (not always considered). Main challenges for the design of devices in this scenario are identified and effects of size and internal topology are studied using Computational Fluid Dynamics (CFD). The CFD model that estimates electrical production was validated thoroughly following a novel and thorough module-by-module approach. Results show that it is possible to recover a modest amount of energy in the high load, high engine speed region of the common driving conditions in the engine map.

1. Introduction

Around a third of the energy input of a light-duty diesel engine is wasted on exhaust gases [1]. Consequently, research on exhaust heat recovery in engines has been encouraged to improve fuel economy and to lower pollutant emissions.

A thermoelectric module (TEM) is a device that, under the Seebeck effect, produces electrical energy from a temperature gradient. The advantages of thermoelectric generators (TEGs, composed of several TEMs) are the lack of moving parts, their silent operation and being maintenance-free. The main challenge of energy recovery using TEGs is the low thermal efficiency in present-day modules. Temperature gradient across the module should be high to harvest a considerable amount of energy. In energy harvesting applied to automotive exhaust systems, the exhaust gases are the heat source (hot side) and engine coolant is normally the heat sink (cold side).

Usually, the low heat transfer coefficient of the gas flow makes necessary heat exchangers to enhance the heat transfer from the exhaust pipe and broaden the temperature gradient between both sides of the thermoelectric module [2].

Energy harvested depends strongly on the type and the power of the engine tested. Typically, research has been focused on gasoline engines,

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Nomenclature

a	distance from the core of the heat exchanger (m)
b	distance to the symmetry axis of the heat exchanger (m)
c_p	specific heat at constant pressure (J/kg K)
C	contrast
D_h	hydraulic diameter (m)
f	friction factor
F	external body forces (N)
g	gravitational acceleration (m/s^2)
J	diffusion term (kg/m^2 s)
k	variable in the design of experiments
K	thermal conductivity (W/m K)
$l_{s,z}$	level of the variable
L	length (m)
n_{fins}	number of fins
n_{exp}	number of experiments
n_s	number of parameters
p	pressure (Pa)
P	electrical power output (W)
P_L	engine pumping losses (W)
P_{net}	net power output (W)
$\dot{Q}$	transferred heat (W)
r	trade-off ratio
R	reaction rate (mol/m^{3}s)
s	parameter in the design of experiments
S	source term
SS	sum of squares
T	temperature (°C, K)
$T_{g,out}$	temperature of gas at the outlet (°C)
T_{max}	maximum temperature (K)
T_{norm}	normalized temperature
T_{surf}	surface temperature (°C)
u_i	vector component of velocity (m/s)
u_j	vector component of velocity (m/s)
v	velocity (m/s)
$\dot{V}$	volumetric flow (m^3/s)
x_i	Cartesian coordinate (m)
x_j	Cartesian coordinate (m)
$y+$	dimensionless wall distance
Y_m	mass fraction of species
z	experiment number index

Greek

Δ	variation
ε	surface material roughness (m)
μ	dynamic viscosity (Pa·s)
ρ	density (kg/m^3)
θ	diffuser's angle (deg)

Subscripts

exp	experiment
g	exhaust gas
i	Cartesian coordinate
j	Cartesian coordinate
k	variable
out	outlet
m	species
s	parameter
T	thermal

Acronyms

CFD	Computational Fluid Dynamics
DOC	diesel oxidation catalyst
TEG	thermoelectric generator
TEM	thermoelectric module
RANS	Reynolds-averaged Navier-stokes

since higher exhaust temperatures (compared to diesel engines) can be found [3]. Early studies were focused on maximizing the electrical output despite the backpressure that may be originated. LaGrandeur et al. [4] estimated a power output of 600 W from a 190 kW gasoline engine. Simulations from Hussain et al. [5] show a 300 W power output from a 2.5 L engine. Nevertheless, the backpressure (around 10 kPa) was too high to be implemented in passenger vehicles. Later designs have been shorter in electrical output, but awareness in backpressure effects has been increased. Mori et al. [6], harvested 200 W from an exhaust system with a pressure drop of approximately 6 kPa.

The engine common operating water temperature, usually around 80–90 °C [7], is too high for an optimum working point and diminishing the cold side temperature could be an option to enhance the electrical production.

Since external air temperature is lower than engine coolant temperature, is not unreasonable to think of an on—board cooling down (e.g. through finned duct) to approximately 40–50 °C before reaching the TEG. More recent studies are conducted employing coolant temperatures within this range. Crane et al. [8] achieved a power output of 600 W on a gasoline engine with water temperature around 55 °C, but no pressure drop is reported. Friedrich et al. [9] reported a 200 W electrical production with a backpressure of 2.5 kPa using coolant at 50 °C in a BMW 535i with a 3 L gasoline engine. Massaguer et al. [10] obtained a power output 111 W in steady conditions from a 1.4 L gasoline engine but with a maximum pressure drop of 8 kPa.

Some studies used water temperatures in the range of 20–30 °C, but it is difficult to think of and on-board system to reduce so much engine water temperature without incurring in more energy expense. Ikoma et al. [11] obtained 35.6 W from a 3 L gasoline engine. Haidar et al. [12] harvested 42.3 W from a diesel stationary engine and Kim et al. [13] recovered 120 W from a 4 L diesel engine.

Lower diesel exhaust temperatures compared to gasoline exhaust systems have caused energy recovery to be mainly aimed at high-displacement, diesel engines, such as the ones found in trucks or even in power generation.

Bass et al. [14] achieved an energy recovery of 1 kW from a 14 L stationary diesel engine, Frobenius et al. [15] obtained 416 W from a heavy-duty truck and Zhang et al. [16] developed a 1 kW thermoelectric system for heavy-duty engines similar to fighting-vehicle engines. Wang et al. [17] harvested a total of 133 W using four thermoelectric generators in a 3.9 L engine from an off-road vehicle.

Usually, the TEG design is only approached from the perspective of maximization of harvested energy, not always considering the increase in engine pumping work or using representative operating conditions.

The purpose of this study is to evaluate the potential of a TEG not for commonly studied engines but for engines with low exhaust energy at representative engine operation points: light-duty diesel engines under in-city and on-road conditions. As a result, a different approach focused also on minimizing influence on the engine and not only on maximizing electrical power output was followed to design the TEG device for tests.

The models for thermoelectric generators are usually validated monitoring thermal variables such as the heat transfer coefficient [18] or cold and cold side temperatures [19] and not for every. In this work, a novel approach based on a thorough module-by-module validation of the open circuit voltages was employed.