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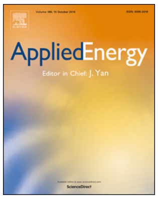

A thermoelectric generator in exhaust systems of spark-ignition and compression-ignition engines. A comparison with an electric turbo-generator

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HIGHLIGHTS

- Study of a thermoelectric generator in two different types of engines.
- Effects of bypassing part of the flow from the thermoelectric generator were studied.
- The thermoelectric generator was compared to a turbine-based energy recovery system.
- Implementation of a thermoelectric generator in automotive engines was evaluated.

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ABSTRACT

Approximately a third of the fuel energy in internal combustion engines is wasted through the exhaust gas. Thermoelectric generators have been employed in automotive engines to recover energy from the exhaust system. The purpose of this work is to broaden the knowledge of thermoelectric generators and help designers to evaluate of their implementation in light-duty vehicles. Several works have tested a thermoelectric generator in spark-ignition engines and others in compression-ignition engines. This work provides results from the same thermoelectric generator prototype in a spark-ignition and in a compression-ignition engine to study the actual difference in thermoelectric energy recovery potential of both sorts of engine. Thermoelectric generators are also compared with a promising turbine-based waste energy recovery technology (electric turbo-generators). Full-load curves are swept to study the performance of the thermoelectric generator under limit conditions. The effect of by-passing the thermoelectric generator to limit the pressure drops produced at full-load conditions is also analysed. A validated three-dimensional Computational Fluid Dynamics model of a thermoelectric generator built and tested supports the study.

1. Introduction

Due to the growing concern for environmental problems, research on fuel economy improvements in internal combustion engines (ICEs) has drawn the attention of automobile manufacturers and researchers as a solution to face increasingly demanding standards for vehicle fuel consumption and emissions. Together with the enhancement of engine performance using in-cylinder techniques, the concept of energy recovery has emerged as an area of interest, especially for the exhaust system, where approximately a third of the energy from the fuel is wasted as heat [1]. There is a wide spectrum of Waste Energy Recovery (WER) techniques varying in complexity, potential to recover energy and interaction with the exhaust gas.

Some technologies use the exhaust gas only as heat source, such as Organic Rankine Cycles (ORC) (as heat intake to develop a turbine-based power cycle with other fluid) [2] and thermoelectric modules (to create a temperature gradient and produce electric energy) [3], but enhancement of heat transfer and heat exchange surface area needed to make heat exchangers for both technologies, causing some back-pressure to the engine.

Although the fuel economy benefits from ORC are considerable, their complexity makes them not suitable for small-scale applications

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Nomenclature

$BSFC$	brake specific fuel consumption (g/s)
$\Delta\dot{m}_{f,0}$	increase in total fuel mass-flow to provide electric energy with an alternator (g/s)
$\Delta\dot{m}_{f,TEG}$	increase in total fuel mass-flow to provide electric energy with the thermoelectric generator (g/s)
Δp	pressure drop (Pa)
η_{eng}	engine efficiency
η_{alt}	alternator efficiency
LHV	lower heating value (J/kg)
$\dot{m}_{f,0}$	total fuel mass-flow rate of the engine using an alternator to provide electrical energy (baseline conditions) (g/s)
$\dot{m}_g$	exhaust mass-flow rate (kg/s, g/s)
M	engine torque (N m)
n	engine speed (min^{-1})
p	pressure (Pa)
P	electric power output (W)
P_L	engine pumping losses (W)
P_{net}	net power output (W)
ρ	density ($\mathrm{kg/m^3}$)
$T_{g,in}$	inlet gas temperature (°C)
$\dot{V}$	volumetric flow ($\mathrm{m^3/s}$)

Acronyms

BSFC	Brake Specific Fuel Consumption
CFD	Computational Fluid Dynamics
CI	Compression-Ignition
eTG	Electric Turbo-Generator
ICE	Internal Combustion Engine
ORC	Organic Rankine Cycle
SI	Spark-Ignition
TEG	Thermoelectric Generator
WER	Waste Energy Recovery

such as passenger cars [4]. On the other hand, thermoelectric generators [5] (TEGs, devices that generate electric power employing several thermoelectric modules) have low complexity [6] but commercially available materials still have very low efficiency [7].

Two main areas of research have been stressed for achieving higher power outputs for thermoelectric systems. The first is the improvement of the efficiencies of thermoelectric materials. The second is to improve how thermoelectric modules are integrated in thermal systems (thermal management).

Early studies on thermoelectric generators for automotive engines were focused on maximizing the electrical output despite the backpressure that may be originated.

LaGrandeur et al. [8] modelled an electrical output of 600 W from a six cylinder gasoline engine (maximum power 190 kW) using a hot-side heat exchanger that should provide the target temperature ranges while presenting no more than a 10 kPa incremental increase in exhaust backpressure across all operating conditions. The model by Hussain et al. [9] predicted the potential to generate 300–400 W under the EPA highway drive cycle conditions for a 2.5L gas-electric hybrid vehicle with a maximum pressure drop of 25 kPa.

Later designs have been shorter in electrical output but awareness in backpressure effects has been increased. Ikoma et al. [10] obtained 35.6 W from a 3L gasoline engine. Haidar et al. [11] harvested 42.3 W from a diesel stationary engine. Friedrich et al. [12] 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. Mori et al. [13], harvested 200 W from an exhaust system with a pressure drop of approximately 6 w, and Kim et al. [14] recovered 120 W from a 4 L diesel engine. Wang et al. [15] harvested a total of 133 W using four thermoelectric generators in a 3.9 L engine from an off-road vehicle.

Energy extracted strongly depends on the type and the power of the engine tested. Durand et al. [16] modelled theoretical equations of thermoelectric materials and heat transfer correlations to study the differences in thermoelectric production of diesel and gasoline engines, pointing that gasoline engines could have more energy recovery potential. Typically, research has been focused on gasoline engines, since it is stated that higher exhaust temperatures (compared to diesel engines) can be found [17] and a higher percentage of the energy of the fuel turns into waste heat instead to mechanical energy to move the car compared to diesel engines.

Apart from scattered results of several thermoelectric generators in a diesel or a gasoline engine, there is a need to know the actual difference in thermoelectric production that could be achieved with diesel and gasoline engines passenger vehicles with the same thermoelectric generator at urban and extra-urban velocities and the factors that influence this difference.

Other sort of WER techniques require direct contact with the exhaust gas, such as mechanical and electrical turbogenerator (currently also known as turbocompounding), commonly yielding more energy but with higher influence on the engine. In turbocompounding, usually an additional turbine is placed downstream of the turbocharger to recover energy from the exhaust gas. In mechanical turbocompounding [18], the turbine is linked mechanically to the engine, whereas in electrical turbocompounding [19], the turbine is linked to an electric generator and the output is electrical energy (turbo-generators). For high-pressure turbocompounding, the turbocharger turbine is employed to recover energy [20]. In this case, the turbine must produce more power than the required by the compressor.

Turbocompounding started in aircraft piston engines, due to the favourable requirement of long hours of operation at high load and low ambient pressure allowing high expansion ratios [21]. It was also applied to large maritime ships that operate at high loads for great periods of time [21]. Later, turbocompounding has been applied to heavy-duty road vehicle engines [22]. While being successfully applied on heavy-duty engines, it has been implied that would be harder to improve fuel economy with turbocompounding in small vehicles, especially at urban conditions [23].

Thermoelectrics and turbocompounding technologies cause parasitic power losses. In turbocompounding, power output rises with the pressure ratio (directly related to the pressure drop caused in the engine) of the turbine [24].

On the other hand, TEGs need heat exchangers to enhance heat transfer to the thermoelectric modules [25], but have low influence in the engine due to the relatively low pressure drop caused by the heat exchanger (since pressure drop is only a side-effect from the heat transfer enhancement).

The aim of this work is to analyse thermoelectric power production in different contexts. First, quantifying the difference in power output that could be achieved driving diesel and gasoline passenger vehicles. This was accomplished using exhaust gas data from both types of engines in the same prototype of TEG. Secondly, comparing thermoelectrics with another WER technology, electric turbo-generators (eTGs). While the purpose of this paper is not to study in depth eTGs, this comparison helps to understand limitations and strengths of TEGs compared to more developed energy recovering techniques, such as turbine-based technologies.

Two engines (diesel and gasoline) from two passenger cars were studied. Engine conditions from driving cycles representing urban and extra-urban conditions were selected and tested to evaluate the exhaust gas from both engines.