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A method to assess the fuel economy of automotive thermoelectric generators

A. Massaguer[a,*], E. Massaguer[b], M. Comamala[a], T. Pujol[a], J.R. González[a], M.D. Cardenas[c], D. Carbonell[c], A.J. Bueno[c]

[a] Department of Mechanical Engineering and Industrial Construction, University of Girona, C. Universitat de Girona, 4, 17003 Girona, Spain
[b] Nabla Thermoelectrics, C. de la Llibertat, 71, 17820 Banyoles, Spain
[c] Energy for Transportation Department, Repsol Technology Centre, Agustin de Betancourt s/n, 28935 Mostoles, Spain

HIGHLIGHTS

- An automotive thermoelectric generator (ATEG) is built and tested experimentally.
- A method for estimating in-vehicle ATEG performance is proposed.
- A 3D FEM model and a vehicle model is used to predict the fuel economy (FE).
- ATEG backpressure, power generation, weight and coolant pumping power are considered.
- The maximum FE point does not coincide with the ATEG maximum power generation.

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ABSTRACT

For the widespread application of thermoelectric generators, it is of vital importance to have convenient simulation tools in order to test the behavioral consequences of a thermoelectric generator in almost real conditions. The simulation by numerical methods of the performance of automotive thermoelectric generators (ATEG) allows for time- and cost-saving assessment of material combinations and variations of crucial design parameters. However, even in the case of promising simulation results, it is complicated to guarantee the ATEG capacity for reducing the vehicle's fuel consumption. This work presents a method to assess the fuel economy of an ATEG design. The procedure, which takes into account the ATEG power generation, backpressure, weight and the coolant pumping power, reveals that the maximum fuel economy value does not occur with the maximum ATEG power generation point. The method applied to the ATEG presented predicts a maximum fuel economy value of 0.18%.

1. Introduction

Thermoelectric (TE) devices are solid-state systems consisting of a number of alternate *p*- and *n*-type semiconductor thermoelements, which are connected electrically in series by metal interconnectors and sandwiched between two electrically insulating and thermally conducting ceramic substrates. TE systems follow the laws of thermodynamics in the same manner as mechanical heat pumps, vapor compressors associated with conventional refrigerators, or other apparatus used to transfer energy [1]. Compared to the traditional power generation systems, thermoelectric generation (TEG) has its special characteristics such as simple structure, high reliability, operate without any noise or vibration and without waste generation [2–5]. Therefore, TEG is very suitable to be used in fields such as waste heat recovery or power generation for supplying electric energy to low or micro-power applications in electronic devices.

On the other hand, there are some obstacles to overcome in order to promote the use of TE technology, such as low thermoelectric conversion efficiency [6–8], low mechanical strength [9–12], need of efficient heat exchangers [13–17], current use of non-environmentally friendly materials [18], relatively high manufacturing cost [19–22], etc.

To deal with this sort of obstacles, the possibility of using numerical methods gains importance. The finite element/volume methods (FEM/FVM) have become essential solution techniques in many areas of engineering and physics. The FEM/FVM versatility lies in their abilities to model arbitrary shaped structures, to work with complex materials, and

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* Corresponding author.
E-mail address: albert.massaguer@udg.edu (A. Massaguer).

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to apply various types of loading and boundary conditions. These methods can be easily adapted to different sets of constitutive equations, which make them particularly attractive for coupled physics simulations like that required in TEG. FEM/FVM programs help to predict the performance of TEG parameters and allow time- and cost-saving assessments of material combinations and variations of crucial design parameters.

Many researchers are focused on improving the physical properties of thermoelectric material and the manufacturing technique of thermoelectric modules. However, the optimization of the thermal system design is equally important for improving the power generation of TEGs.

Recent works have yielded powerful numerical algorithms of one-dimensional models that identify TEG configurations with output power and thermal efficiency maximized for homogeneous, functionally graded and segmented thermoelectric materials. Hsiao et al. [23], Montecucco et al. [24,25], Rodríguez et al. [26], Massaguer et al. [27], Weng et al. [28], Lan et al. [29], and Liang et al. [30] developed computational models to simulate the thermal and electrical behavior of thermoelectric generators. These models solved the system of non-linear equations of thermoelectricity and heat transfer. Riffat and Ma [31] performed the geometry optimization of thermoelectric modules used as generators. Chen et al. [32] and Yu et al. [33,34] explored the influence of various design parameters on the system performance including the effect of having multiple layers of modules and the use of parallel-plate heat exchangers.

Other models [35–38], specifically developed for engine exhaust heat recovery, took into account the spatial-dependent heat flow rate that affected the power generation due to mismatch condition operations of thermoelectric modules. Zhang et al. [39] took also into account both heat and electricity losses at junctions as well as the space-dependent heat flow rate in the thermoelements.

Thus, there are several parameters involved in the mathematical model of a TEG. Many of them are difficult to determine, which often implies the acceptance of assumptions, leading to a lack of accuracy in the results. Generally, these models intend to propose thorough performance predictions as well as design recommendations. However, they show limited capabilities, or at least a low flexibility, for the implementation of additional effects such as geometry variations or non-uniform temperatures on the output power of the TEG system.

Otherwise, even though the simulation tools are capital in ATEG design aspects, it is also important to evaluate the ATEG performance in terms of vehicle's fuel economy. There are many studies in this field that present a wide variety of advances in ATEG design, but only very few [40–44] of them address the problem from the fuel economy point of view.

The purpose of the current work is to present a method to assess the performance of an ATEG design. The procedure is divided into two main parts. The first one consists in predicting the ATEG performance by using a FEM/FVM-based methodology. The present study validates the theoretical FEM/FVM-based model comparing its output values with those obtained experimentally by an ATEG installed in the exhaust system of a gasoline engine. The goal is to determine the feasibility of the numerical model on predicting its performance. The second part proposes a method to, based on the results obtained in the FEM/FVM analyses, forecast the expected fuel economy when using the ATEG.

2. Experimental setup

2.1. System architecture

The ATEG presented in Fig. 1 and used in this paper was previously designed and tested in [44]. However, in this study, it will be used to model the behavior of a random ATEG for validation purposes of the methodology proposed.

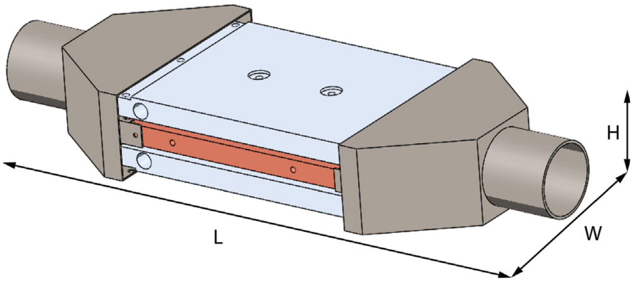

Fig. 1. Waste heat recovery system prototype. Dimensions are 160 × 444 × 64 mm (W × L × H).

The goal of ATEGs is to convert exhaust gases energy into a useful one. In this case, wasted energy is turned into a source of electrical power, in order to feed many electrical parts of the vehicle, finally leading to savings in both fuel consumption and greenhouse gas emissions.

The working mode is based on the conversion of heat into electricity by using commercial thermoelectric modules (TEMs). TEMs used are TELBP1-12656-0.45 from Thermonamic Electronics Corp. Ltd. These consists of an array of *n*- and *p*-type semiconductor pellets connected electrically in series and thermally in parallel between ceramic substrates.

The objective of this ATEG is to get a high temperature gradient on both sides of the TEMs by using the energy contained in the exhaust fumes of a combustion engine. The gases flow internally through the device and transfer a portion of its heat through the TEMs to the cold plates. Then, the cooling circuit, that uses water as a coolant, takes the heat and dissipates it using a forced convection heat-exchanger. The more heat flows through the thermoelectric modules, the higher the power generated.

The size of the device is 160 × 444 × 64 mm (W × L × H) with a total weight of 7 kg. It is composed of 12 TEMs connected electrically in series but thermally in parallel. These modules are arranged on both surfaces of a copper heat exchanger (#2 in Fig. 2), through which the exhaust gas flows, and two aluminum cold plates (#3 in Fig. 2). ATEG is joined to the exhaust system using inlet and outlet parts (#1 in Fig. 2) made of steel. Fig. 2 shows the schematic diagram of the experimental ATEG.

The cooling system is composed of one pump and a forced-air heat exchanger. The pump drives the water through the cold plates (#3 in Fig. 2) that are connected in parallel. The aluminum cold plates are heat exchangers with S-shaped flow paths within which the cooling fluid moves. Heat received from the ATEG is finally dissipated to the ambient air using a forced-air heat exchanger. In the present design, the room temperature in which the engine is installed is 20 °C. The cooling fluid used is water with a volumetric flow rate equal to 0.12 L/s measured at the exit of the volumetric pump.

2.2. Series array configuration

All TEMs are interconnected forming an electrical array of twelve modules arranged in series. Fig. 3 illustrates the series connection. Each TEM is represented by a voltage source $V_{1,...,12}$ and an internal resistance $R_{1,...,12}$.

Although there are several ways to interconnect TEMs, the way selected evaluates the model in a series configuration. Under ideal operating conditions, this configuration will make each TEM experience an equal temperature difference and consequently all TEMs will generate the same output voltage. In this case, the load resistance at the maximum power point would be $12R_1$ and the voltage $12V_1/2$ with R_1 the internal resistance of a TEM.

However, considering that TEMs are not connected thermally in parallel, this ideal operating condition is no longer valid in the present system. In a practical case, each TEM will experience a reduction of