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Experiments and Simulations of an Automotive Exhaust Thermoelectric System

A. Massaguer[1], E. Massaguer[1], M. Comamala[1], A. Cabot[2], J.R. González[1] and A. Deltell[1]

[1]Department of Mechanical Engineering and Industrial Construction
Polytechnic High School, University of Girona
Campus de Montilivi, 17003 Girona (Spain)
Phone number: +0034 972 41 83 77, e-mail: albert.massaguer@udg.edu

[2] Institut de Recerca en Energia de Catalunya
Jardins de les dones de negre, 1 08930 Barcelona (Spain)
Phone/Fax number:+0034 625 615115, e-mail: acabot@irec.cat

Abstract.

Because of the increasing emphasis on environmental protection, applications of thermoelectric technology are being extensively studied.

Before a new car is released to the market, testing is undertaken to ensure it meets the latest emissions regulations. The regulations differ from country to country, but they are always getting more stringent. To meet these tightening regulations, car companies must reduce the fuel consumption of their cars. A waste heat recovery system has the potential to convert some of this waste heat into electricity and consequently reduce the fuel consumption of the car by reducing the load on the car alternator

The present experimental and computational study investigates an exhaust gas waste heat recovery system (WHRS) for vehicles, using thermoelectric modules and a heat exchanger to produce electric power.

Key words

Thermoelectric finite element modeling, thermoelectric generator, LTEH, TEG, simulation

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 interconnects 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 with the traditional power generation systems, thermoelectric generation (TEG) has its special characteristics of simple structure, high reliability, without any noise or vibration, no waste generation [2–5], therefore, it is very suitable to be used in those fields, such as waste heat recovery, for power generation to supply electric energy to low-power or micro-power applications and electronic devices.
On the other hand, there are some obstacles to promote the use of TE technology, such as low thermoelectric conversion efficiency, low mechanical strength, efficient heat exchangers, non-environmentally friendly materials, the relatively high manufacturing cost, etc.

To deal with this sort of obstacles, gain importance the possibility of using numerical methods. The finite element method (FEM) has become an essential solution technique in many areas of engineering and physics. The FEM versatility lies in its ability to model arbitrary shaped structures, work with complex materials, and apply various types of loading and boundary conditions. The method can easily be adapted to different sets of constitutive equations, which makes it particularly attractive for coupled physics simulation like TEG. FEM programs help to predict the performance of TEG parameters and allow time- and cost-saving assessment of material combinations and variations of crucial design parameters.

Recent work has yielded powerful numerical algorithms and one-dimensional models, which identify TEG configurations with maximized power output and efficiency for homogeneous, functionally graded and segmented thermoelectric materials. Hsiao et al. [6], Montecucco et al. [7,8], Rodríguez et al. [9], Massaguer et al. [10] and Liang et al. [11] developed a computational model to simulate the thermal and electrical behavior of thermoelectric generators. The models proposed solve the nonlinear system equations of the thermoelectric transport equation and heat transfer. Riffat and Ma [12] performed the geometry optimization of the thermoelectric modules used as generator. Chen et al. [13] and Yu et al. [14,15] explored the influence of various parameters on the performances including the effect of multiple layers of modules and parallel-plate heat exchanger respectively.

The purpose of the present study is to realize this. The study compares the outputs of a thermoelectric energy harvester system installed in an exhaust system of a gasoline engine with a finite element model of the same device. The analysis model considers the temperature dependency of all the important thermoelectric material properties.

2. Experimental setup

The waste heat recovery system (WHRS) presented in **¡Error! No se encuentra el origen de la referencia.** is designed for exhaust pipes of automobiles. The purpose of these kind of systems is to turn the wasted energy into a useful one. In this case, into a source of electrical power, in order to feed many electrical parts of the vehicle, leading to fuel and greenhouse emissions savings.

The working mode is based on the conversion of heat into electricity. Thermoelectric materials generate a voltage while in a temperature gradient on their junctions. In such case, electrons flow from hot to cold side by Seebeck effect.

The size of the device is 160x500x60mm (WxLxH) with a total weight of 6,97kg. It is composed by 12 thermoelectric modules (TEM) connected electrically in series but thermally in parallel. These modules are arranged on the both surfaces of a copper heat exchanger, through which the exhaust gas is passed, and two aluminum water cooled plates.

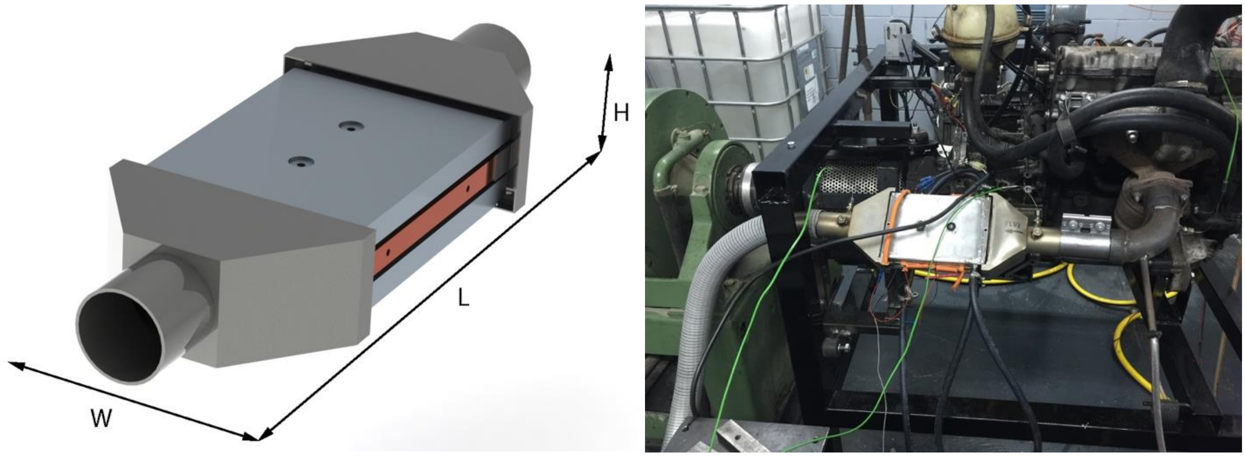

Fig. 1. Waste heat recovery system prototype.

3. Boundary conditions

The study set different boundary conditions to simulate the research model. **¡Error! No se encuentra el origen de la referencia.** shows the boundary conditions of each element in the simulation. The system design of these thermal management solutions was supported by using commercially available multiphysics software, ANSYS 17.1.

Boundary conditions were taken in one single engine regime and was collected under steady state conditions.

Table I. – Engine regime

Regime	1
Exhaust gases inlet temperature (ºC)	407,95
Exhaust gases outlet temperature (ºC)	264,88
Exhaust gases mass flow (g/s)	5,95
Coolant inlet temperature (ºC)	38,41
Coolant outlet temperature (ºC)	39,56
Coolant mass flow (l/s)	0,12
TEG Hot side temperature (ºC)	104,58
TEG Cold side temperature (ºC)	41,22
TEG Power generated (W)	5,52

4. Governing equations

The general heat flow and continuity equations of electric charge for the thermoelectric analysis can be expressed as Eq. (1) and (2).

$$\rho C \frac{\partial T}{\partial t} + \nabla \boldsymbol{q} = \dot{q} \qquad (1)$$

$$\nabla \left(\boldsymbol{J} + \frac{\partial \boldsymbol{D}}{\partial t} \right) = 0 \qquad (2)$$

Eq. (1) and (2) are coupled by the set of thermoelectric constitutive equations and the constitutive equation for a dielectric medium. Considering this and the absence of time-varying magnetic fields, the coupled equations of thermoelectricity can be expressed as Eq. (3) and (4).

$$\rho C \frac{\partial T}{\partial t} + \nabla([T\alpha]\boldsymbol{J}) - \nabla([\lambda]\nabla T) = \dot{q} \qquad (3)$$

$$\nabla\left([\varepsilon]\nabla\frac{\partial\varphi}{\partial t}\right)+\nabla([\sigma][\alpha]\nabla T)+\nabla([\sigma]\nabla\varphi)=0 \qquad (4)$$

Where ρ, C, T, $\boldsymbol{J}$, φ, λ, σ, α and ε are the density, specific heat capacity, absolute temperature, electric current density vector, electric scalar potential, heat generation rate per unit volume, thermal conductivity, electric conductivity, Seebeck coefficient and dielectric permittivity, respectively. Square brackets mean matrixes.

The system of thermoelectric finite element equations is obtained by applying the Galerkin FEM procedure to the previous coupled equations.

5. Results

Experiment was conducted under one operating condition, the measured data at that engine regime is summarized in **¡Error! No se encuentra el origen de la referencia.**. Simulations were performed at identical temperatures and exhaust gases mass flow, as in the experiment. To improve the computational calculations, only a half of the entire WHRS is modeled.

The temperature distribution of the longitudinal section of the entire system is shown in Fig. 2. As expected, exhaust gases temperature decreases while flowing through the WHRS. Energy is transferred from the exhaust fumes to the water coolers.

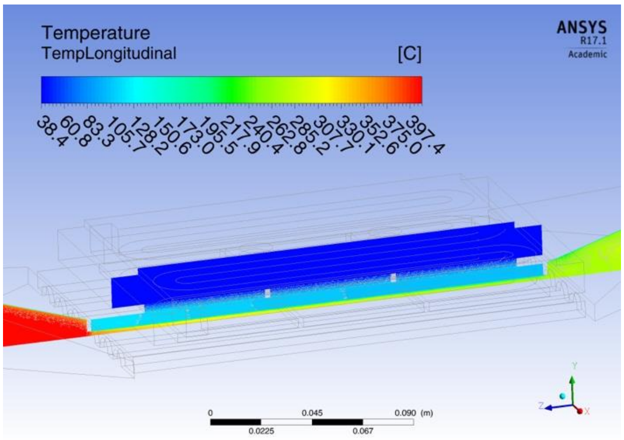

Fig. 2. Longitudinal temperature distribution of WHRS.

The temperature evolution of exhaust fumes is presented in Fig. 3, where the inlet temperature at 407,95ºC decreases to 258ºC at the end of the WHRS.

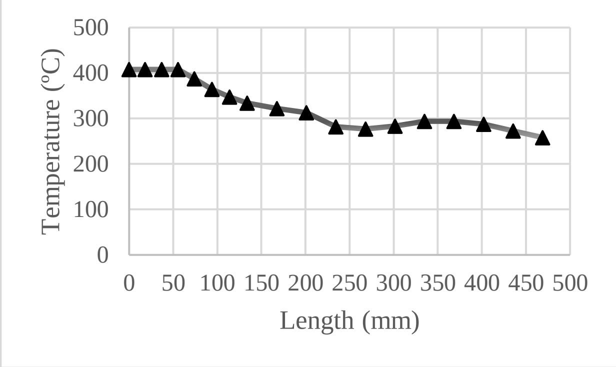

Fig. 3. Longitudinal temperature evolution of exhaust gases.

An important parameter that affects directly to the final performance of the WHRS is the temperature gradient of TEMs. The higher the gradient between hot and cold sides, the higher the amount of electric generation. Fig. 4. shows the temperature evolution from the water cooler to the exhaust gases through TEM 1.

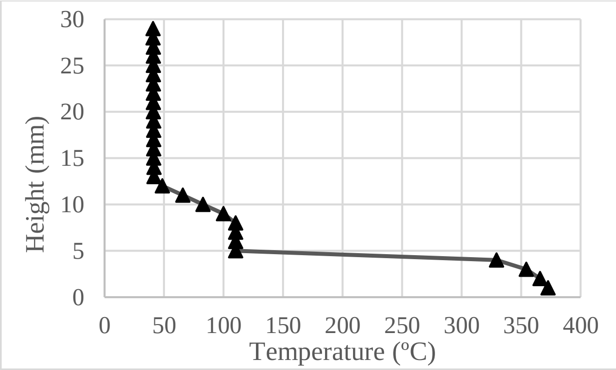

Fig. 4. Cross sectional temperature evolution through TEM 1.

Temperature starts at 40,87ºC, which is the temperature at the cold side of TEM1, and increases linearly up to 110,19ºC, at the hot side of TEM1. Then, the temperature gradient between hot and cold side is 69,32ºC.

Temperatures of both cold and hot sides are shown in Fig. 4 and Fig. 5.

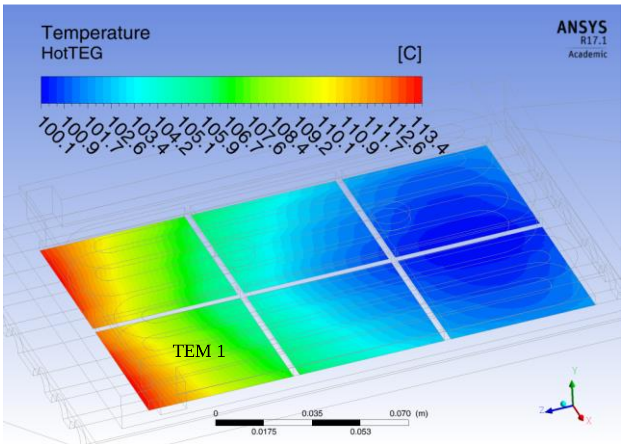

Fig. 4. Thermoelectric hot side temperature distribution.

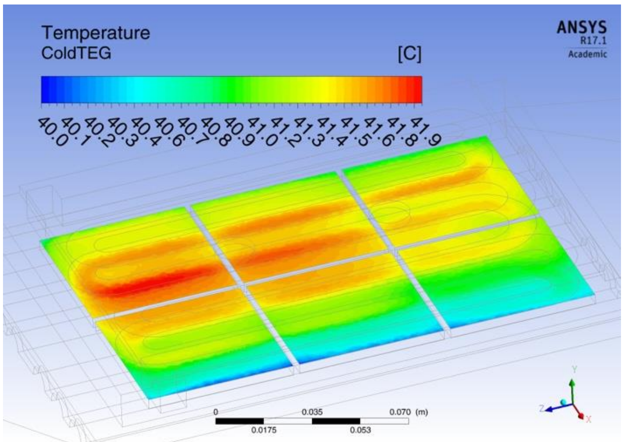

Fig. 5. Thermoelectric cold side temperature distribution.

Then, with this specific temperature gradient, each TEM is capable to generate an open circuit voltage. In case of TEM1, voltage generated is 1,10V, see Fig. 7. When the optimal load resistance is applied to the TEM, voltage is cut in half and the current generated is 0,862A.

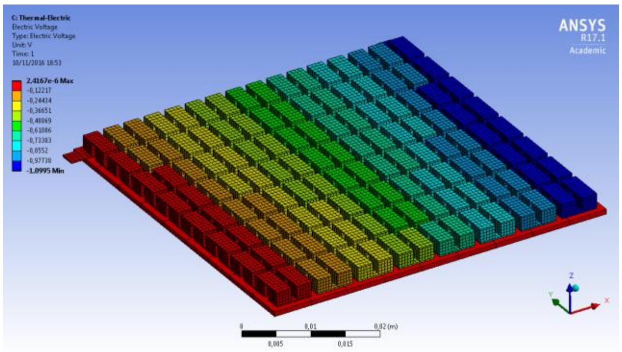

Fig. 7. Waste heat recovery system prototype.

Finally, considering the temperature distributions of hot and cold sides of TEMs, the total voltage generated is 6.93V and the total current is 0,812A. Then, the total power generated is 5,63W.

The comparison between experimental and computational study is summarized in Table 2.

Table 2. – Experimental and computational study

Regime	1 exp.	1 comp.	error (%)
Exhaust gases inlet temperature (ºC)	407,95	407,95	-
Exhaust gases outlet temperature (ºC)	264,88	258	2,60
Exhaust gases mass flow (g/s)	5,95	5,95	-
Coolant inlet temperature (ºC)	38,41	38,41	-
Coolant outlet temperature (ºC)	39,56	39,41	0,38
Coolant mass flow (l/s)	0,12	0,12	-
TEG Hot side temperature (ºC)	104,58	104,4	0,17
TEG Cold side temperature (ºC)	41,22	41,26	0,10
TEG Power generated (W)	5,52	5,63	1,99

Results show the consistency of this simulation tool, revealing a minimum agreement of 97,4%.

5. Conclusion

Considering the agreement between the experimental results and the thermoelectric simulation, the present methodology is clearly capable to predict the performance of a TEG system. It is important to note that both electrical and thermal resistances have an important influence on the TEM performance, and need to be well defined.

In future studies, the method of simulation with ANSYS software will be improved by adding few more engine regimes to assess the agreement of the results at higher engine temperatures. In addition, will be interesting to investigate the influence of the temperature gradients over TEMs on the final power generation when they are electrically connected.

This kind of studies help to improve the overall exhaust heat utilization and enhance the power generation.

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