Experimental and numerical analysis of the influence of the heat exchanger shape on the performance of a TEG module

Hussam Jouhara[1,2*], Alina Żabnieńska-Góra[1,3], Qusay Doraghi[1], Beate Krause[4], Petra Pötschke[4], Cintia Mateo-Mateo[5], Ignacio Ezpeleta[5], Mauro Brignone[6], Emanuele Milani[6]

[1] Heat Pipe and Thermal Management Research Group, College of Engineering, Design and Physical Sciences, Brunel University London, Uxbridge, UB8 3PH, UK
[2] Vytautas Magnus University, Studentu Str. 11, LT-53362, Akademija, Kaunas Distr., Lithuania
[3] Wroclaw University of Science and Technology, Faculty of Environmental Engineering,
Plac Grunwaldzki 13, 50-377 Wrocław, Poland
[4] Department of Functional Nanocomposites and Blends, Leibniz-Institut für Polymerforschung Dresden e.V. (IPF), Hohe Str. 6, 01069 Dresden, Germany
[5] AIMEN Technology Centre, Department of Advanced Materials, Polígono Industrial de Cataboi SUR-PPI-2 (Sector 2) Parcela 3, E36418 O Porriño, Spain
[6] MARELLI EUROPE S.p.A – Italy
*Correspondence: hussam.jouhara@brunel.ac.uk

Abstract

Combustion processes involve a by-product in the form of waste heat. In many cases this energy is unused. Thermoelectric generators (TEGs) enable the capture and reuse of excess heat from existing combustion processes for other purposes. By utilising the Seebeck phenomenon, they allow heat energy to be converted directly into electrical energy. Researchers around the world are working to improve the performance of TEG modules by searching for new, more environmentally friendly thermoelectric materials. The use of a heat exchanger to increase the heat exchange surface area is a second way of improving the performance of the modules by increasing the temperature difference between the hot and cold sides. This enables the efficiency of these modules to be enhanced. In the automotive industry, TEGs ~~are~~ can be used to recover the heat of exhaust gases to supply electricity to several on-board GPS and MEMS sensors.

In this study, which is part of the European InComEss project, the COMSOL Multiphysics software was used to analyse the effect of the heat exchanger shape on the performance of a TEG module. The simulation results were compared with measurements performed in the laboratory.

1. Introduction

Transport accounted for 37% of CO_2 emissions from end-use sectors in 2021 [1]. Rising oil prices and stringent emission norms are driving manufacturers to find new solutions to improve fuel economy, emissions, as well as efficiency of the internal combustion engine. Electric vehicles accounted for more than 14% of global passenger car sales in 2022, an increase of 5% compared to 2021 [2]. This means that the joint target of achieving 30% of electric vehicle sales by 2030 is achievable [3]. Nevertheless, internal combustion engine (ICE) cars will remain the majority in the automotive market.

Currently, automotive combustion engines, according to different literature source, have efficiencies of between 20% and 45%, depending on engine type and operating conditions [4]. The remaining 55%-80% is wasted as heat in both the coolant and the exhaust gas (Figure 1) [5]. Recovering exhaust heat from internal combustion engines leads to reduced fuel consumption, reduced environmental pollution and increased efficiency of the engine itself [6]. By using TEGs, the heat can be converted into electrical energy via the Seebeck effect [7][8], that can be used to re-charge the auxiliaries battery or directly power on-board sensors in cars.

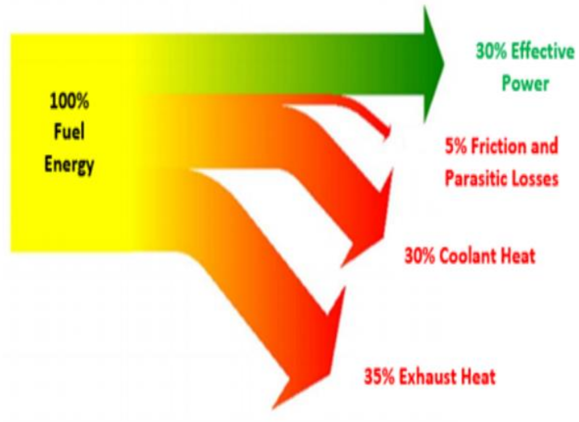


Figure 1. Use of fuel in an internal combustion engine[5].

This paper presents an innovative TEG module based on polymer composites. COMSOL Multiphysics software was used to analyse the effect of heat exchanger shape on the performance of a TEG module. The simulation results were compared with measurements performed in the laboratory.

2. Materials used in small-scale TEG prototypes

The materials used for TEGs should have high electrical conductivity, a high Seebeck coefficient and, at the same time, low thermal conductivity. TEG modules currently available on the market and in use are based on bismuth telluride(Bi_2Te_3), lead telluride (PbTe) and others, with bismuth telluride being the most widely used material [9]. Because of their environmental impact, researchers are looking for materials that are more environmentally friendly, accessible and cheaper to produce and process. New lead-free thermoelectric materials are being investigated as part of the EU project InComEss [10][11] with one of the anticipated uses being converting wasted heat into electric energy. The properties of the materials used in the simulation have been addressed in accordance to the materials developed in the project. Due to the requirements of the automotive use case (e.g. long term stability, operation temperature), poly(ether ether ketone) (PEEK) was selected as the polymer matrix. The recipes of electrically conductive nanocomposites used for the TEG prototype were developed at IPF and the materials used in the TEG prototype were prepared at AIMEN (p-type legs) and IPF (n-type legs) by melt-mixing in compounders. The conductive nanofiller, namely singlewalled carbon nanotubes (SWCNTs), was incorporated into the molten polymer via a hopper and dispersed while the material was conveyed along the screws. For achieving n-type conduction behaviour an additive was applied (in this case the ionic liquid trihexyltetradecylphosphonium chloride THTDPCl) which was premixed with the SWCNTs. Details of the material preparation are described in [12][13]. Table 1 shows the main properties of the materials used to build the TEG prototype for automotive application.

Table 1. Thermoelectric parameters of the materials used in the prototype, as determined at IPF.

Composite	**Electrical volume conductivity [S/m]**	**Seebeck coefficient [μV/K]**	**Power factor [μW/(m·K^2)]**	**Thermal conductivity [W/m·K]**
P-type (PEEK+2.5 wt% SWCNT, AIMEN)	12.2	40.9 ± 2.6	1.9E-02	0.30 (40°C) … 0.37 (190°C)
N-type (PEEK/ 0.75wt% SWCNT + 3 wt% THTDPCl; IPF)	3.4	-37.1 ± 0.2	6.0E-03	-

3. Model

A number of TEG module models were prepared and verified during the prototype development. The impact of the shape of the single legs as well as the different types of connections between the p- and n-legs was analysed [11][14]. This paper presents a model of the prototype being tested at the test bench in MARELLI laboratory. COMSOL Multiphysics was used for this purpose as it enables the analysis of all phenomena occurring in the TEG at the same time. The model preparation was carried out in a multi-stage process: definition of the phenomena taking place, creation of the geometry of the TEG module, specification of the properties of the individual materials, definition of the boundary conditions, creation of the mesh, simulation, postprocessing and analysis of the results. The TEG module under analysis consisted of 30 p-type and n-type pairs connected by silver at their ends and had a module thickness of 2.5 mm.

The simulation results presented in Table 2 confirm that the generators developed in the project cannot be compared to modules currently available on the market. Commercial modules generate significantly higher voltages than the small-scale prototype. This is due to the number of pairs used in a single TEG module. To compare the modules, it would be necessary to use the same geometry for both cases. This approach will be examined in the future.

Table 2. Measurement results of the commercial TEG module and simulation results of the InComEss TEG prototype

	T_{hot}=165°C T_{cold}=95°C (ΔT=70°C)	T_{hot}=195°C T_{cold}=112°C (ΔT=83°C)	T_{hot}=235°C T_{cold}=133°C (ΔT=102°C)
Commercial TEG measurement results	1.62 V	2.03 V	2.22 V
InComEss TEG module simulation results	162.67 mV	192.88 mV	237.04 mV

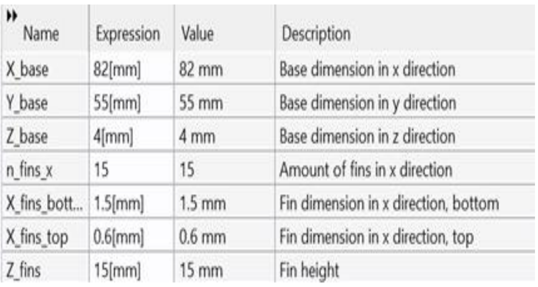
In the real-life application, the module will be combined with a heat exchanger on the cold side to increase the heat exchange surface area. For this reason, simulations with heat exchangers were carried out. Two different heat exchanger geometries were selected and analysed (Figure 2):

(1) Fins with constant width (10 fins with width 1.5 mm);

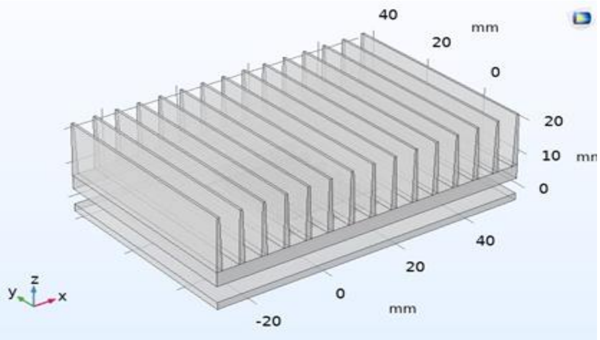
(2) Fins tapered towards the top (15 fins with width from 1.5 mm to 0.6 mm).

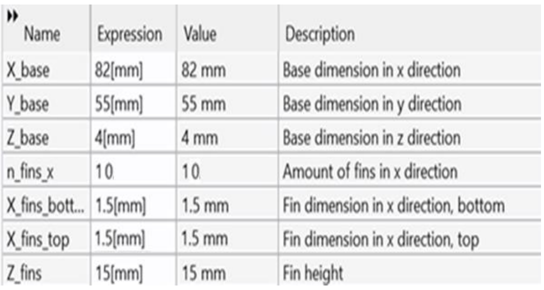
In the analysis, the temperature difference from measurements for commercial TEG modules was used as the boundary condition. Results showed that the slightly better configuration is a heat exchanger with fins tapered towards the top (2). This heat exchanger was used in laboratory tests.

A)

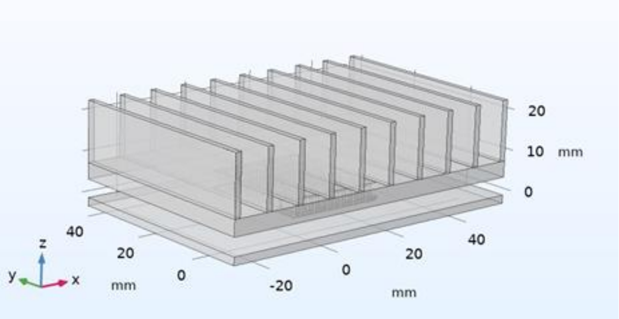


Name	Expression	Value	Description
X_base	82[mm]	82 mm	Base dimension in x direction
Y_base	55[mm]	55 mm	Base dimension in y direction
Z_base	4[mm]	4 mm	Base dimension in z direction
n_fins_x	15	15	Amount of fins in x direction
X_fins_bott...	1.5[mm]	1.5 mm	Fin dimension in x direction, bottom
X_fins_top	0.6[mm]	0.6 mm	Fin dimension in x direction, top
Z_fins	15[mm]	15 mm	Fin height





Name	Expression	Value	Description
X_base	82[mm]	82 mm	Base dimension in x direction
Y_base	55[mm]	55 mm	Base dimension in y direction
Z_base	4[mm]	4 mm	Base dimension in z direction
n_fins_x	10	10	Amount of fins in x direction
X_fins_bott...	1.5[mm]	1.5 mm	Fin dimension in x direction, bottom
X_fins_top	1.5[mm]	1.5 mm	Fin dimension in x direction, top
Z_fins	15[mm]	15 mm	Fin height



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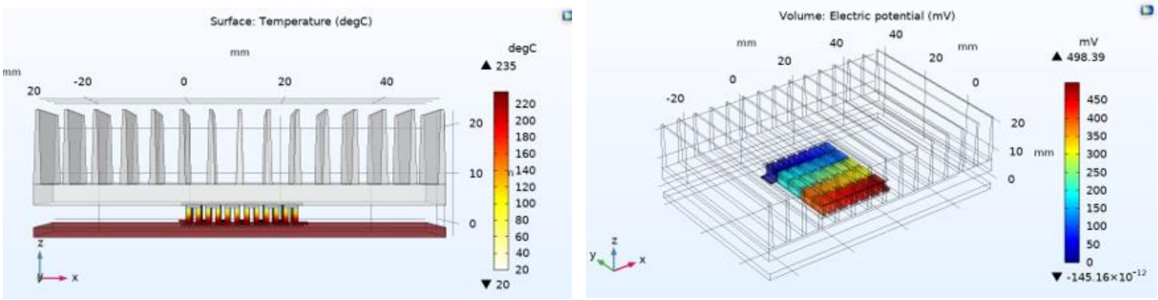

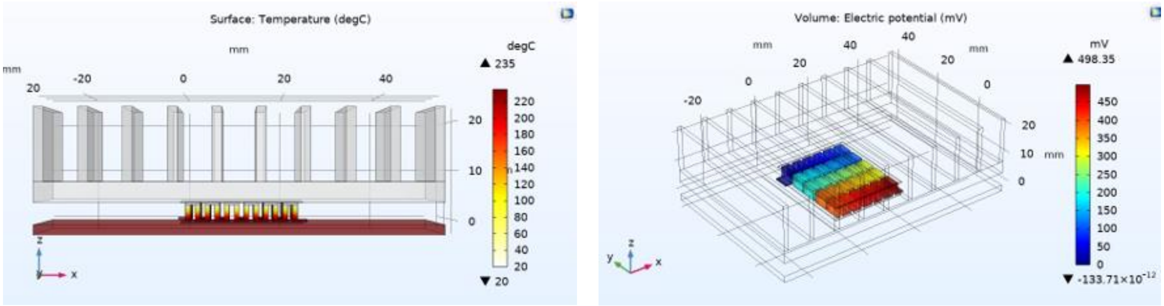

Figure 2. A) Dimensions of the heat exchangers used in the analysis. B) Example simulation results for both heat exchangers with the InComEss TEG prototype.

4. Test bench measurements

A testing device was designed and manufactured in order to characterize the thermoelectric module (TEG) performance in the laboratory. The device consists of a planar stainless-steel sheet (same material as the vehicle rear muffler), a finned aluminium heat exchanger and a thermoelectric module sandwiched between them. Thermally conductive foils are inserted between TEM and metal parts to optimize thermal interfaces. The whole device is kept together by four screws; two thermocouples (TCs) are embedded both in the metal sheet and in the heat exchanger in order to measure the temperatures on the hot and cold sides of the TEG (Figure 3).

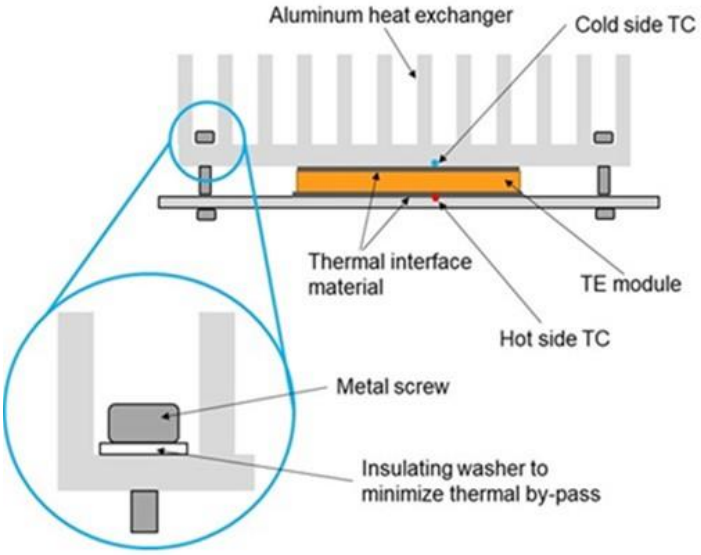

Figure 3. Scheme of device for TEGs characterization.

For laboratory testing the stainless-steel sheet is put in touch with a hot-plate simulating the heat coming from vehicle exhaust system, while an air flow is blown on the heat exchanger simulating the air flow coming from vehicle motion. The TEG prototype developed in InComEss is connected with a variable load device equipped with Maximum Power Point Tracking (MPPT) function that permits to extract the maximum power from the TEG. Both thermocouples are connected with a TCs reader in order to monitor TEG hot and cold sides temperature. The results of the measurements are shown in Table 3.

Table 3. Comparison of measurement results with simulation results carried out in COMSOL for the InComEss TEG prototype combined with heat exchanger.

	T_{hot}=165°C T_{cold}=53°C (ΔT=112°C)	T_{hot}=195°C T_{cold}=62°C (ΔT=133°C)	T_{hot}=235°C T_{cold}=75°C (ΔT=160°C)
Measurement	130 mV	154 mV	185 mV
Simulation	260.27 mV	309.08 mV	371.82 mV

1. Conclusions

The paper briefly describes the possibility of using a polymer-based TEG module in heat recovery from car exhaust system. The developed model of the TEG module together with the selected heat exchanger was simulated in COMSOL and the results were then compared with the measurements on the fabricated prototype combined with the real heat exchanger in the laboratory. The shape of the heat exchanger slightly affects the electrical potential differences. The higher values of the electrical potential difference for the TEG module model compared to the measured results are a consequence of the boundary conditions adopted in the model (steady state conditions), the assumed constant values of the material-describing parameters depending on temperature (Seebeck coefficient, electrical and thermal conductivity). Furthermore, the model assumes ideal conditions: the precise joining of materials with no heat exchange with the environment within the p and n leg. In addition, differences may be due to the production process of the prototype itself (manual assembly of all components). The feasibility of using the polymer based TEG module under study in automotive applications is established, but further work is required both on the model and on improving the manufacturing process.

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