Numerical simulation of a thermoelectric generator module for road vehicles

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Abstract

Almost every industry sector in Europe is facing the impose of strict rules regarding energy savings in order to reduce emissions of greenhouse gases. The regulations, encourage industries to constantly look for improvements. Now, the automotive industry is looking for a every possible manner of upgrade allowing to improve cars efficiency. One of the possible solution is to install thermoelectric generators to reuse the waste heat released with fumes. To investigate whether TEGs implementation could be a good manner to improve the efficiency there is a need to mathematically model the device in order to check its performance. The presented thesis focus on elaboration of benchmark procedure for thermoelectric numerical modelling in ANSYS Workbench using Thermal-Electric module. In the introductory part of the thesis one can find the literature survey in the topic of TEGs modeling, the physical fundamentals of thermoelectric along with modelling procedure explained. Then the mathematical model implementation in ANSYS is described. The following part contains the results description and analysis. In the last chapter the final conclusions and future plans are presented

Introduction

Nowadays, the sustainability is the priority not only for researchers but also for business, industry and society. That is why the energy revolution is taking place on our planet. Today, not only the amount of energy produced is a priority but the methods it is obtained with. Broadly understood power sources are expected to affect the environment as little as possible. This is very evident in the automotive industry, where either electric or hybrid solutions are implemented to maximize engine efficiency and reduce emissions. One of the devices that are used to improve the efficiency of internal combustion engines is a thermoelectric generator that uses low-quality waste heat to convert it to useful electricity using the Seebeck phenomenon.

Currently there is a huge pressure on the automotive industry, and a lot of resources are allocated in this sector development. There are three main pathways for car industry to go greener; batteries, fuel cell system and combustion engines efficiency. The first two are still to expensive to be used by the regular people. That is why the automotive industry improves the combustion engines efficiency continuously in order to fulfill severe greenhouse gas emissions limits.

Current car efficiency is around 25 % under typical driving conditions [1] and the remaining is wasted as heat. The abovementioned facts force manufacturers to increase the engine system efficiency via the implementation of different upgrades like turbochargers, exhaust gas recirculation, or thermoelectric generators. Unfortunately, ICEs do not convert chemical energy efficiently to useful mechanical energy, because of the dissipation of energy in exhaust and coolant. That is why, currently the improvements are made in an indirect way, trying to recover the waste heat.[2] Although the internal combustion engine efficiency is limited by the Carnot rule, its efficiency can still be increased through the recuperation of energy carried by exhaust gases. This could help to boost the efficiency of these engines considerably and help the classic powertrain to fulfill severe norms. One of the technologies which are being developed in the area is TEG. This type of waste recovery system allows to convert the remaining heat into electricity reducing the alternator load. Thereby it diminishes fuel consumption which leads to reduced emission of CO2. Thermoelectric generators and heat pipes are a good solution to enhance ICEs performance. They are just simple solid-state devices without any moving parts and additional equipment. Thanks to their light weighted, compact size and simplicity in operation they are an ideal solution to recover waste heat in automotive application.[2]

Currently, the available TEG systems have system efficiency around 5 % which is not enough for the majority of industrial applications, but thanks to the before-mentioned wide range of advantages it can be applied in numerous specific appliances. One of the most promising fields where thermoelectric modules started to get attention is the automotive industry. Big companies like Renault, BMW, Ford, General Motors, and Scania have revealed their interest in exhaust gas recovery systems supported with TEGs. The technology has not been installed in a commercial vehicle yet, but there are researches carried out within the topic.[2] For a car application exhaust based thermoelectric generators (ETEG) are placed at the exhaust pipe. The hot side is heated by the exhaust gases and the other side is cooled by the engine coolant.

The studies in the area of thermoelectricity application in the automotive sector distinguish into two main blocks: experimental analysis and numerical modelling. This thesis focus on the modelling aspect in the area of thermoelectric generator application for road vehicles. Thanks to increasing computer power we can study various processes with minimum financial resources. In the literature, one can find different models of TEGs which differ between each other in dimensionality, numerical schemes, and assumptions. Knowing the current state of the art in thermoelectric generators modelling it is important to know that there is still a lot of research needed in the area of thermoelectric modelling in order to know what parameters are essential for its operation. The focus of the thesis is to model a real thermoelectric module using ANSYS Workbench thermal-electric. One of the key features of the model is to implement non-linear, temperature-dependent physical parameters of p-type and n-type material and contact resistances between legs and couples and examine its influence on the model performance. The aim is to obtain a detailed, well-described numerical model combined with suitable boundary conditions in order to get an appropriate benchmark for modelling thermoelectric generators.

Fundamental concept

Thermoelectric generators are a group of devices that are able to directly convert thermal energy into electrical energy. TEGs are consisted of n-type and p-type semiconductor elements, which are connected thermally in parallel electrically in series through copper interconnectors which simultaneously play the role of hot and cold sides of TEG, connecting thermocouples thermally in parallel what can be seen in figure 1.[4]

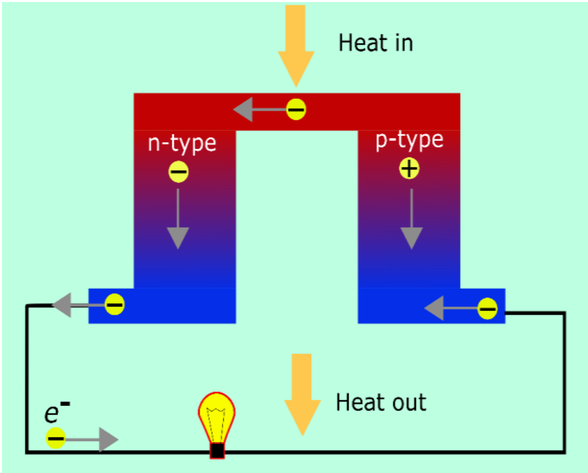

Figure 1. Thermoelectric generator operation

Due to the temperature difference between heat and cold side the voltage difference is generated, which forces electrons to flow. In an n-type semiconductor, the electrons flow from hot to the cold side and in p-type semiconductor, the holes move from hot to cold side as presented in the figure above. In the thesis, the basic physical relations essential to TEG operation and its construction is explained in details.

Mathematical model

The described model concerns a single thermoelement which is the part of the module HZ-14 [5]. Within the element, the charge transfer and heat flow are considered. The simulation is steady state (time-independent) and studied in 3D. The physical properties of thermocouples are assumed to be temperature-dependant [6]. The model includes also a contact resistances between the legs and copper connectors. In order to perform thermoelectric analysis, the coupled equations of continuity of electric charge and heat flow are used as a governing equation:

$$\nabla([\Pi]\cdot[J]) - \nabla([k]\nabla T) = \dot{q}, \qquad (1)$$

$$\nabla\cdot([\sigma]\nabla\phi) + \nabla\cdot([\sigma][\alpha]\nabla T) = 0. \qquad (2)$$

where:

T - temperature [K],

J - electric current density vector [V/m^2],

q - heat flux vector [W/m^2],

ϕ - electric potential [V],

[Π] - Peltier coefficient matrix [V],

$[\alpha]$ - Seebeck coefficient matrix [V/K],

$[\sigma]$ - electric conductivity matrix [S/m],

$[k]$ - thermal conductivity matrix [W/m K].

The boundary conditions for charge transfer are represented by the following equations:

$$\phi(y = y_{\max})\Big|_{C} = 0 \qquad (3)$$

$$J(y=0)\Big|_{D} A_{D} = I \qquad (4)$$

$$\frac{\partial\phi}{\partial\vec{n}}\Big|_{F} = 0 \qquad (5)$$

And for the heat balance accordingly:

$$T(x = x_{\max})\Big|_{\mathrm{A}} = T_{\mathrm{hot}} \quad (6)$$

$$T(x = 0)\Big|_{\mathrm{B}} = T_{\mathrm{cold}} \quad (7)$$

$$\frac{\partial T}{\partial \vec{n}}\Big|_{\mathrm{E}} = 0 \quad (8)$$

The outer surfaces of the calculation domain where boundary conditions were set, are marked with A, B, C, D, E, F are presented on the figures 2 and 3 below:

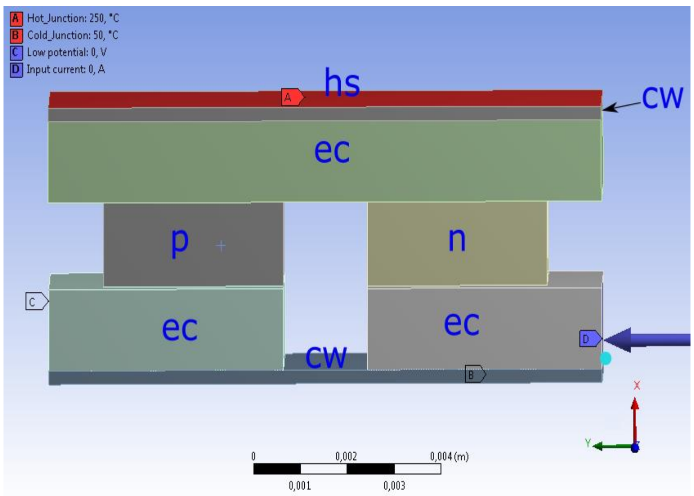

Figure 2. Boundary condition thermoelectric generator domain.

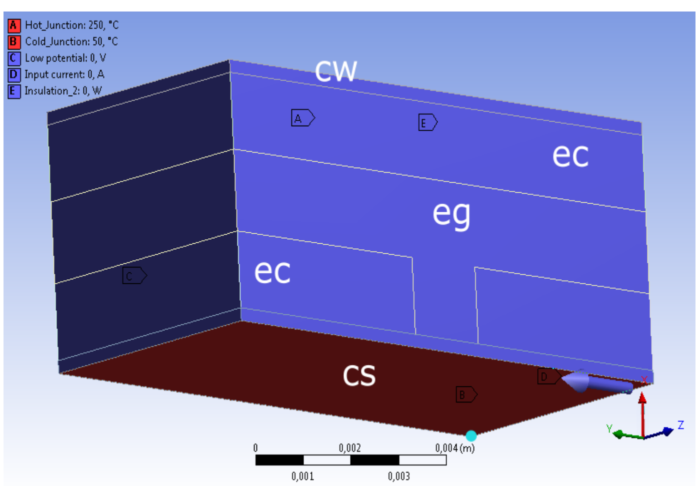

Figure 3. Boundary conditions full domain.

The meaning of the abbreviations are: **cw** - ceramic wafer, hs - hot source, **cs** - cold source, **ec** -electrical connector, **p** - p-type leg, **n** - n-type leg, **eg** - eggcrate material. Aiming at good graphics visibility the origin of the reference frame was marked with ●.

Numerical tools

In order to solve the equations presented in previous section, the numerical code is needed. One of the most promising device to solve numerical problems for engineering is ANSYS Workbench. Within this software one can find a various number of in-built modules which are useful at every stage of solving engineering problems. In the described case for the geometry preparation the Design Modeler was used in order to build a thermocouple, define calculation domain and material properties. Then with ANSYS mesh module the discretization of numerical domain was performed. The discretized calculation domain is presented on the figure 4.

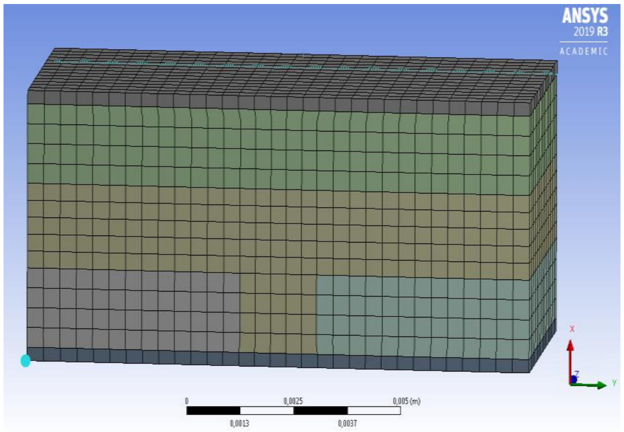

Figure 4. Mesh.

Finally, the ANSYS thermal-electric module was used to set boundary condition, solve the equations and collect results. The equations were transformed according to Galerkin FEM techniques and the system of equations was solved with ANSYS Mechanical iterative solver. Once the calculations were ready, Matlab and Microsoft Excel was used to analyse and plot the interesting results.

Results

The model development was performed in three stages. In the beginning, two basic models were

prepared. Based on conclusions from two first versions of the model the final 3rd version was developed. All the versions are 3-dimensional models, having the same geometry and boundary conditions. In the first one, the physical properties were averaged to obtain constant non-temperature-dependent values and compared with the experimental data provided by Hi-Z Technology - the HZ-14 thermoelectric module manufacturer.[5] Since the results were not tolerable, the second model included nonlinear temperature-dependent material properties, which also has not given adequate results. Then after the literature survey, the full model was elaborated. Apart from nonlinear material properties, the final model has implemented contact resistances [7] which led to the satisfactory performance of the analysis. The performance of these models were presented using voltage, power and efficiency curves and compared to experimental data provided by Hi-Z technology[5]. The chosen comparison are presented on figure 5 and 6.

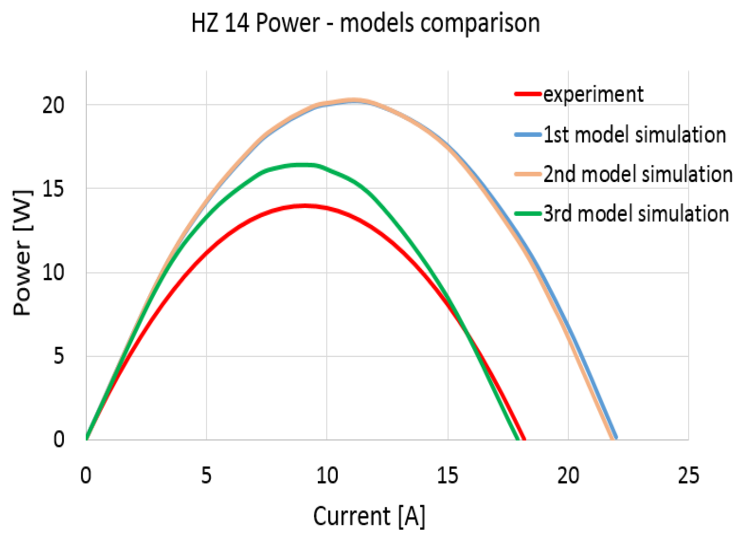

Figure 5. Power curves comparison for different models and experiment

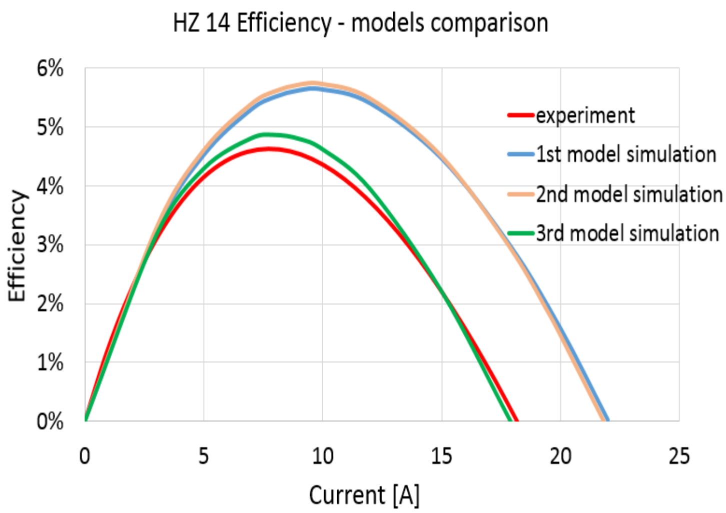

Figure 6. Efficiency curves comparison for different models and experiment

Although the above presented curves generated by the model seems to be very accurate, the model output for voltage, power and efficiency was also tested versus temperature difference between hot and cold junction and compared with experimental data. On the figure 7 the module power versus temperature difference is presented. It can be observed that although the model results overestimate the performance of HZ-14 module, the shape of the curves replies the thermoelectric generator behaviour. On the other side in figure 8 the same comparison is presented but for model when the contact resistances are included. There it can be seen that for higher temperature difference the power curves tightly correspond to experimental curves but for lower temperature differences the shapes are incorrect. Therefore, there is a need for further investigation of contact resistance value, which should be tested against various operating temperatures.

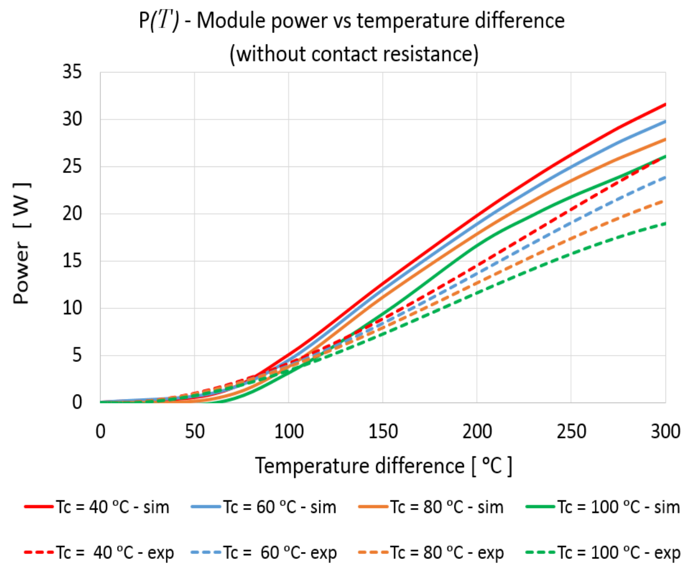

Figure 7. Module power versus temperature difference(without contact resistances included)

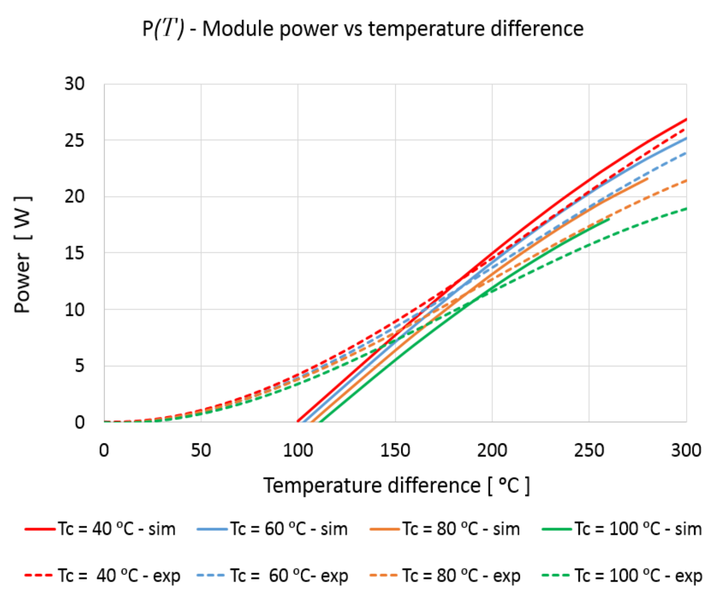

Figure 8. Module power versus temperature difference (with contact resistances included)

Conclusions

The goal of the thesis was to proposed a benchmark approach for 3-D modelling of thermoelectric generator using Thermal-Electric module in ANSYS workbench. The starting point for model development was a simple model with constant parameters in order to check if the simplest solution has an acceptable level of error. However in order to accurately predict thermoelectric module performance there was a need to capture more physical phenomena like non-linear temperature-dependent behaviour of material properties and contact resistances. This helped to significantly improve the model to the level of acceptable utility.

From the results it can be observed that incorporation of temperature-dependant material properties does not significantly improves the result of the simulation, but it complicates the model implementation and prolongs the numerical calculation. The fact is that, contact resistances play a significant role in model performance. In this research only electrical contact resistances between legs and connectors were included, but it could be beneficial to include also thermal resistances between other components.

Going even deeper, the contact resistances should be also implemented as the temperature dependent functions what could be a key factor for accurate model development.. All in all, the results are satisfactory but there are still a few doubts regarding applied methodology. From the perspective of implementation of TEGs in hybrid vehicles, the conversion efficiency level of is still very low and the economic profitability doubtful. As it was presented in parametric study the maximum available efficiency is around 5 % what is still low. As it was shown in the result analysis, all the limits lie in material properties. Now, the research should focus on minimization of the negative effects of contact region between thermocouple components.

Moreover, the outcome of the thesis confirms that Thermal-Electric module in ANSYS Workbench is an efficient, convenient and user-friendly environment to perform analysis dedicated for thermoelectric generator. The in-build submodules provide the easiness of implementing physics, boundary conditions, material properties and etc. Thanks to that, the numerical models elaboration is much faster and efficient than it would be with the help of scripting languages like C++, Python or even MATLAB. Moreover, the Multiphysics packages allows the user to incorporate the models like this presented in the thesis into more complicated model-assembly in coupling simulations of few different devices.

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References

[1] S. Kim, S. Park, S. Kim, and S. H. Rhi. A thermoelectric generator using engine coolant for light-duty internal combustion engine-powered vehicles. J. Electron. Mater, 40:812–816, 2011.

[2] B. Orr, A. Akbarzadeh, M. Mochizuki, and R. Singh. A review of car waste heat recovery systems utilising thermoelectric generators and heat pipes. Applied Thermal Engineering, 101:490–495, May 2016.

[3] D. Champier. Thermoelectric generators: A review of applications. Energy Conversion and Management, 140:167–181, 2017.

[4] A. Massaguer, E. Massaguer, M. Comamala, T. Pujol, J. Gonz´ alez, M. Cardenas, D. Carbonell, and A. Bueno. A method to assess the fuel economy of automotive thermoelectric generators. Applied Energy, 222:42–58, 2018.

[5] I. Hi-Z Technology. Hz-14 datasheet. http://www.hi-z.com//wpcontent/uploads/ 2016/09/Hi-Z-DataSheet-HZ-14-1.pdf - Internet access on: 18-07-2020.

[6] T. Zhang. New thinking on modeling of thermoelectric devices. Applied Energy, 168:65–74, Feb.2016.

[7] O. Hogblom and R. Andersson. Analysis of thermoelectric generator performance by use of simulations and experiments. Journal of Electronic Materials, 43:2247–2254, 2014.