RESEARCH AND SIMULATION WORK OF TEG IN COGENERATION TASK OF THE EXHAUST SYSTEM

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Abstract

One of the main directions of development of power transmission systems in vehicles involves improvement of energy efficiency of combustion engines, especially reduction of the loss related to waste heat in cooling and exhaust systems. The traditional role of the exhaust system is to remove exhaust gases from a combustion engine and muffle the noise created during the engine's operation. Relevant distribution of temperatures along the entire length of the exhaust system is a very important element in such a complex structure. The examples could be the particulate solids filter or the converter which have to reach a relevant temperature to operate properly while the temperature's growth is simultaneously restricted due to the limitations associated with the materials used.

The research was conducted while using the ECOTEC 1.8 litre engine from Opel, the X18XE model. The engine was installed in a tested, in the mechatronic lab at the Faculty of Automotive and Construction Machinery Engineering (SIMR) of Warsaw University of Technology.

The paper reviews the energy efficiency of TEG depending on deferent parameters of gas stream an weather conditions. This is original value of this paper. The results of the experiment are presented in the last section of the article.

Keywords: *cogeneration of energy, exhaust system, thermoelectric generator*

1. Introduction

The 21st century, in addition to great leaps in science and technology, brought four major, initial crises, as well as a growing population, the depletion of available natural resources, environmental degradation and an unstable world economy. These factors are the reason why continued attempts have been made to provide new solutions for the new century. Of particular importance is finding solutions regarding energy needs of the world. According to the American authorities [1] oil, coal and natural gas constitute 84% of primary sources of consumed energy in 2011 [2].

According to the data presented in [3], the global need for power is currently about 16TW. It should also be noted that the power radiated towards Earth from the Sun is 10^4 times larger, assuming that half of that part of solar energy reaches the Earth's surface. Consequently, converting even a small percentage of the energy into electricity may significantly contribute to solving the energy challenges posed before mankind.

Regarding Poland, the climate change package of the EU imposes on Poland the duty to purchase 100% of CO_2 emission allowances, starting in 2020. This will result in a significant rise in the price of energy both for the industrial sector and for households. This is the reason for the growing interest in distributed generation and the prosumer system in energy generation. It has been shown that, as early as 2016, it is possible to reach the price of 1000 Euro for a photovoltaic cell which, after suitable changes in energy laws, could be profitable after as few as 1000 hours of energy production. This is linked to the necessity of developing intelligent energy networks, which means that it will become cost effective to implement energy-saving solutions in households as well [2].

The European Commission energy policy is intended to reduce the dependency of the EU states on imported oil and to develop its own, local energy carriers in the form of biofuels [4]. In addition, renewable technologies as well as energy policy put emphasis on systems that allow for the recycling and cogeneration of energy. Investments are being made into the development of heat pumps, Stirling engines, gas turbines in the automobile industry, as well as energy recycling systems for the energy wasted in the process of combustion of air-fuel mixture in conventional combustion engines [5]. This leads to a heightened interest in research and analysis of the prospects of increasing power density and energy efficiency of the kinematic, thermoelectric and thermoacoustic processes of energy recycling, as well as increasing the density of the accumulated energy in vehicles. One of the major directions of development of propulsion systems in vehicles is the increase of energy efficiency of combustion engines, and in particular the possibility of reducing losses due to dispersion via waste heat in cooling and exhaust systems. One of such methods is the recycling of thermal energy thanks to a thermoelectric generator (TEG).

The traditional purpose of an exhaust system is to drain exhaust products from a combustion engine as well as to lower the noise resulting from operation. In a modern vehicle, the exhaust system has been considerably expanded, introducing environment-protecting systems, such as the well-known for years catalytic converters, exhaust gas recirculation (EGR), solid particle filter, as well as measurement and executive elements necessary for the operation of those systems. In such a complex structure, an important element is the proper distribution of temperature along the exhaust system. For example, for a solid particle filter or a catalytic converter that require a certain working temperature while simultaneously limiting its excessive rising due to the limitations of materials used. Another significant limitation is the impossibility of interference with exhaust gas flow and, consequently, hindered access to the exhaust gas heat inside the gas stream and, indirectly, on the surface of the exhaust system.

With such a task to solve, utilizing exhaust gas heat is made further more difficult due to the systems used to convert heat into electricity, in this case thermoelectric generators (TEG), commonly known as Peltier elements, being designed for a set difference in temperature, which in turn depends on the period of operation as well as the environmental conditions.

Traffic conditions have a similar impact. Driving in an urban environment implies frequent stops, a relatively low driving speed, and results in quicker heating and less efficient cooling, while driving outside of urban areas allows for better cooling with a longer heating time. All these dependencies require the optimized placement of heat collection in an exhaust system. For that reason, an analysis has been made of the distribution of, and changes in, temperature. The results of temperature analyses have been presented in [6]. It is commonly known that, due to the heat balance of a combustion engine, it is impossible to fully convert the heat resulting from combustion into mechanical work [7]. Such a conversion occurs only for 25–40% of heat provided for the engine. The remaining 60-75% of the heat escapes with exhaust gases or is drained by a cooling agent. It is expected that the recycling of 6% of the lost energy could result in a 10% drop in fuel consumption [8].

We have developed a heat balance [7,9] to illustrate the way in which the heat supplied to the engine has been used:

$$Q_d = Q_e + Q_{ch} + Q_w + Q_{ns} + Q_{ot} \quad \left[\frac{kJ}{s}\right], \tag{1}$$

where:

Q_d – the total amount of heat supplied to the engine during one second,

Q_e – useful heat, i.e. the amount of heat which has been converted during one second into effective work,

Q_w – exhaust loss, i.e. the amount of heat which is removed together with exhaust fumes during one second,

Q_{ch} – cooling loss, i.e. the amount of heat which is removed with the cooling agent during one second,

Q_{ns} – combustion loss, i.e. the amount of heat lost during one second as a result of incomplete combustion,

Q_{ot} – heat loss to the environment, i.e. the amount of heat emitted to the environment during one second, without involvement of cooling agents.

The biggest problems have been encountered while trying to determine the last two components of the heat balance – heat loss during combustion process and heat loss to the environment. Heat loss means the heat lost as a result of incomplete combustion of fuel. Heat loss to the environment, in turn, constitutes the remaining part of the heat balance and includes the heat loss which is impossible to be captured, such as the heat which is emitted or given off to the environment as a result of conduction, the heat generated by friction in the engine's mechanisms etc. To simplify the process, the components Q_{ns} and Q_{ot} are often determined jointly, after the remaining components of the heat balance have been calculated.

The value of the exhaust-related and cooling loss depends on the operational conditions as well as on the structure of an engine. Cooling loss decreases as the rotational speed of an engine increases since the time during which the hot gases are in contact with the cylinder walls is shorter (for small power and constant rotational speed), thus the cooling loss decreases while the exhaust-related loss increases.

2. The purpose of the research.

The purpose of the research conducted was to compare the results of TEG operation as an energy converter and the analysis of the efficiency of TEG use as related to energy cogeneration in a laboratory, for varying environmental conditions.

3. Description of the research station.

For the purpose of the research, TEG was used with designation „430140-502 HT4, 12" Laird PG13. It is a cell manufactured by the Laird Technologies company [10]. The description and dimensions of the cell have been presented in Fig. 1.

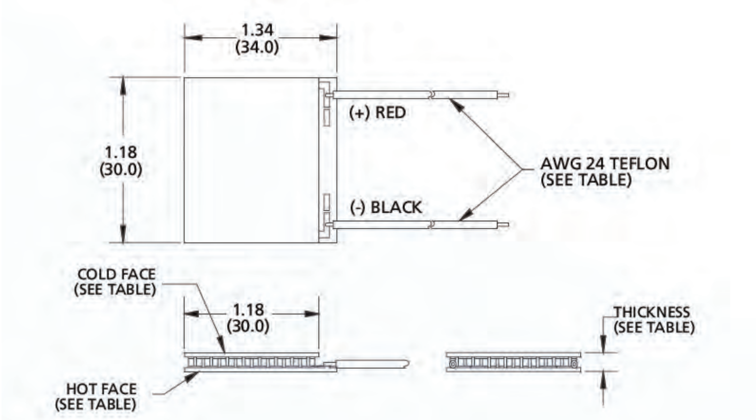

Fig. 1 Dimensions of Peltier module HT4, 12 [10]

Subsequent research regarding energy recycling using a TEG have been conducted in the „ECOTEC X18XE engine" research station in The Faculty of Automotive and Construction Machinery Engineering of the Warsaw University of Technology, in Integrated Laboratory of the Mechatronics System of Vehicles and Construction Machinery.

The disjoint elements of the exhaust draining system have been used and temperatures have been measured, starting at measurement points on the exhaust collector and ending with the end silencer, in order to locate a component being heated, in order to perform the research. The results have been presented in [6, 9]. The research station of a single cell has been presented in Fig. 2. The research station of the TEG team during the recycling of energy has been presented in Fig. 3, in various work variants and in varying environments.

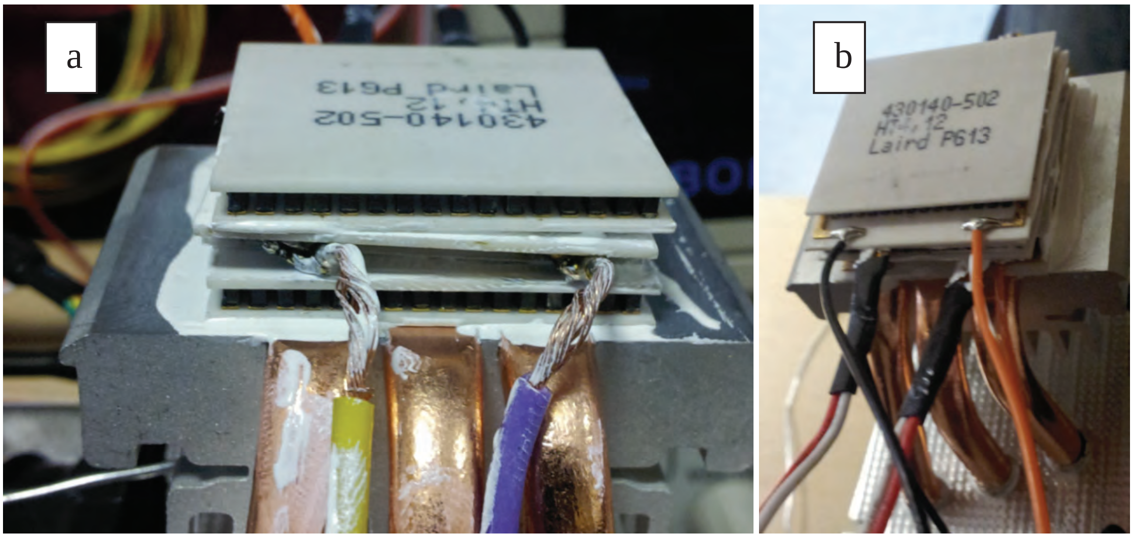

Fig. 2. Photograph of the research station measuring the properties of a singular TEG: view from the front of the TEG „stack“, b) view from above the TEG system

On the surface of the exhaust pipe, Peltier elements have been installed. A multimeter has been added to the terminals of the TEG, in order to measure the voltage generated by TEG. The measurements have been conducted for two states, for idle operation 800 rpm as well as for a constant 2000 rpm.

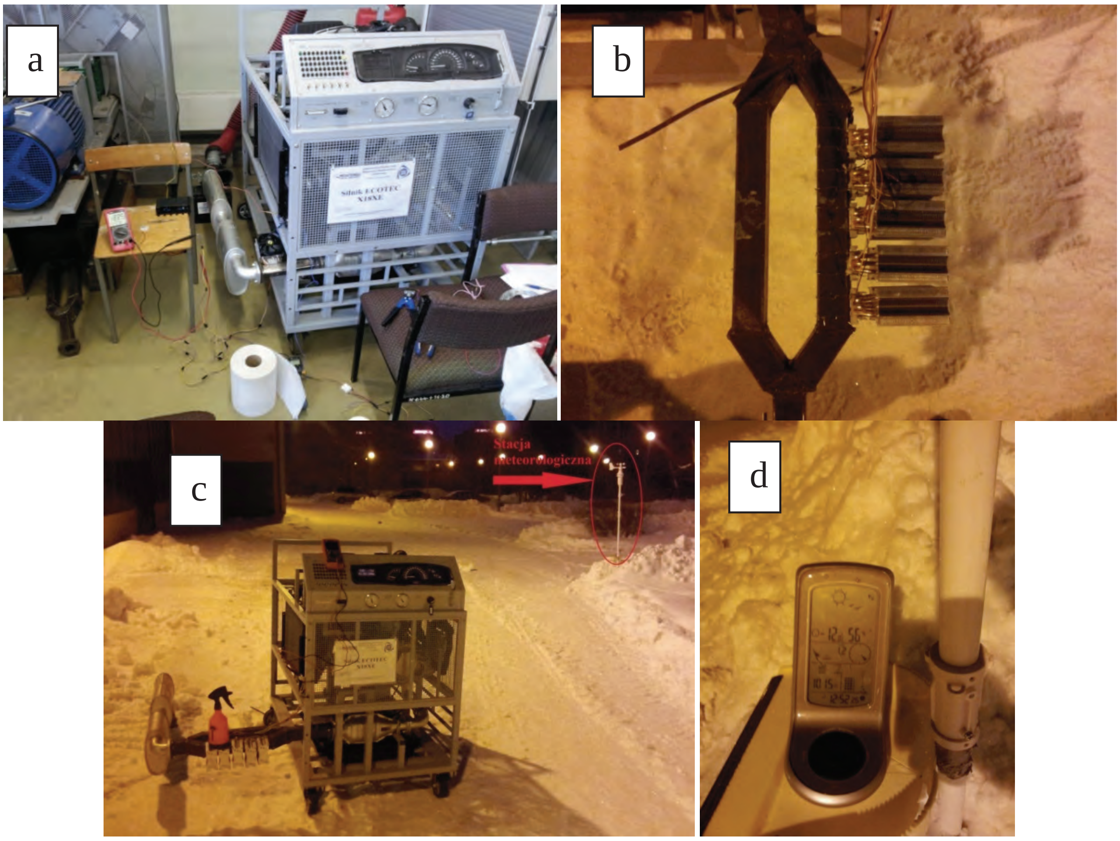

Fig. 3. Photograph of the research station Engine ECOTEC X18XE: a) in a laboratory, with ambient temperature 25ºC, b) view of a modified exhaust system, with a control compartment and an installed TEG, c) photograph of a research station during operation, with ambient temperature -12ºC, d) photograph of the meteorological station

4. Result of the research and computer simulations

Before the research studies, the whole Peltier element has been modelled using ANSYS software, and the following simulations have been conducted: temperature flow, electric current flow, energy recycled. The results of the survey of voltage properties of TEG have been presented in the form of a set of parameters. A sample sheet has been presented in Fig. 4.

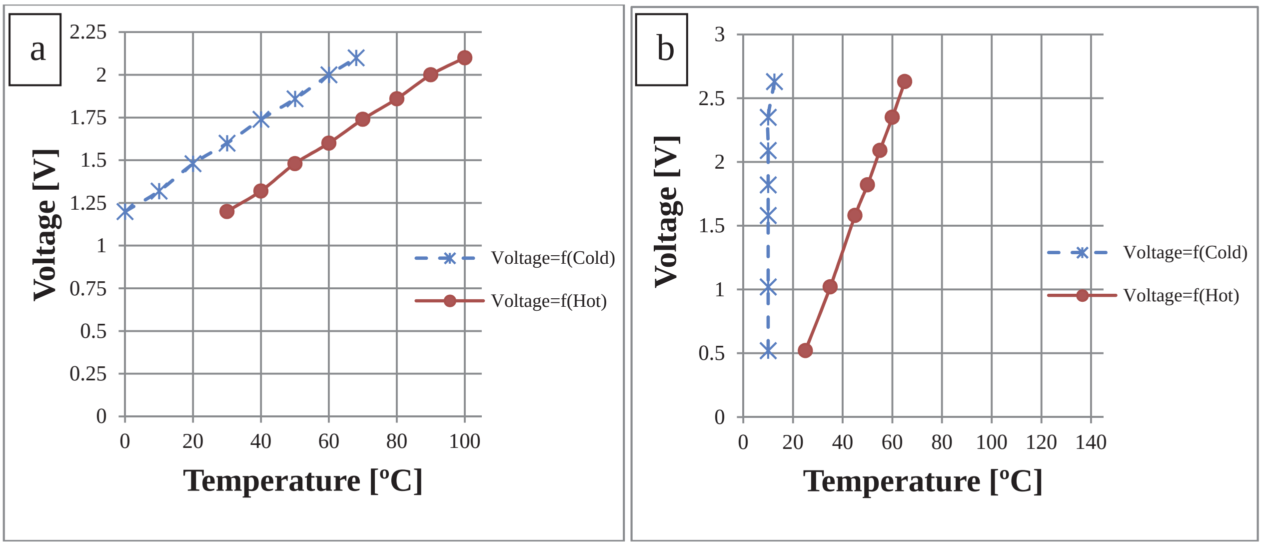

Fig. 4. Parameters of the surveyed TEG: a) for a constant temperature difference between the cold and hot side, ΔT=30ºC, b) for a constant temperature of the cold side Tc=10ºC and an increasing temperature of the hot side

During the analysis of the actual measurements of a single Peltier element, it was observed that the voltage did not rise in a linear manner. In academic literature, Seebeck coefficient is defined as a linear function, impacted primarily by material properties. The mathematical equations have been presented below:

$$V=\alpha*\Delta T, \tag{7}$$

where:
V – the difference of potential observed on the cell terminals in volts [V],
α – Seebeck coefficient in volts / degrees Celsius [V/ ºC],
ΔT – the difference in temperature.

$$\Delta T = T_h - T_c, \tag{8}$$

where:
T_h – the temperature of the hot side of the cell [ºC],
T_c – the temperature of the cold side of the cell [ºC].

Subsequently, the measured voltages in the process of energy recycling have been compared, for various environmental conditions and operation of the TEG system. The results have been presented in Tab. 1.

Tab. 1. Comparison of energy harvesting with different environments

	at temperature +28 [ºC]		at temperature -12 [ºC]	
	800 [rpm]	2000 [rpm]	800 [rpm]	2000 [rpm]
no the gas stream	1.4 [V]	2.5 [V]	0.9 [V]	1.44 [V]
with the gas stream	1.9 [V]	3.15[V]	1.14 [V]	2.24 [V]

The next stage of the measurement was the determination of the load characteristics, as well as the comparison of the results with computer simulations. After the simulations have been conducted for the assumed boundary conditions, the measurements of voltage and current values for the resistive load were taken. The results of the computer simulation and actual measurements have been presented in Fig. 6.

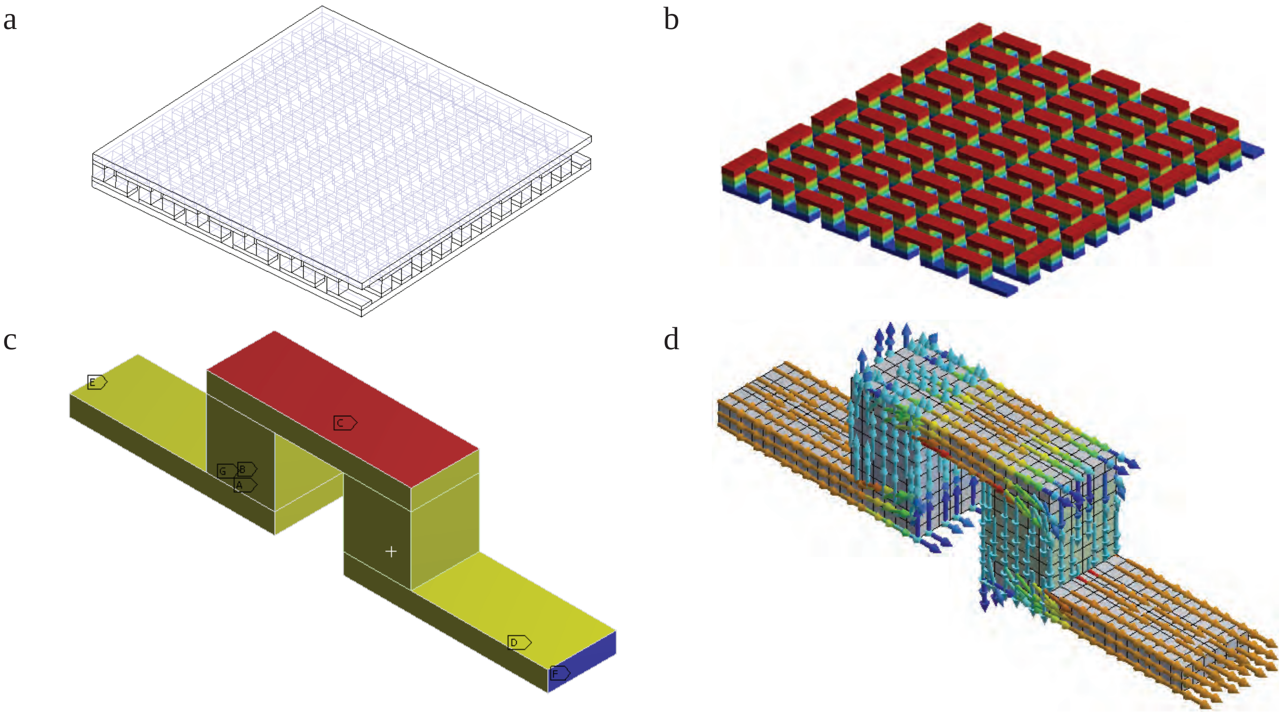

Fig. 5. Photographs of the computer TEG simulation: photograph of the TEG model, color photograph of temperature distribution, photograph of a single connector, photograph of the current flow through the connector

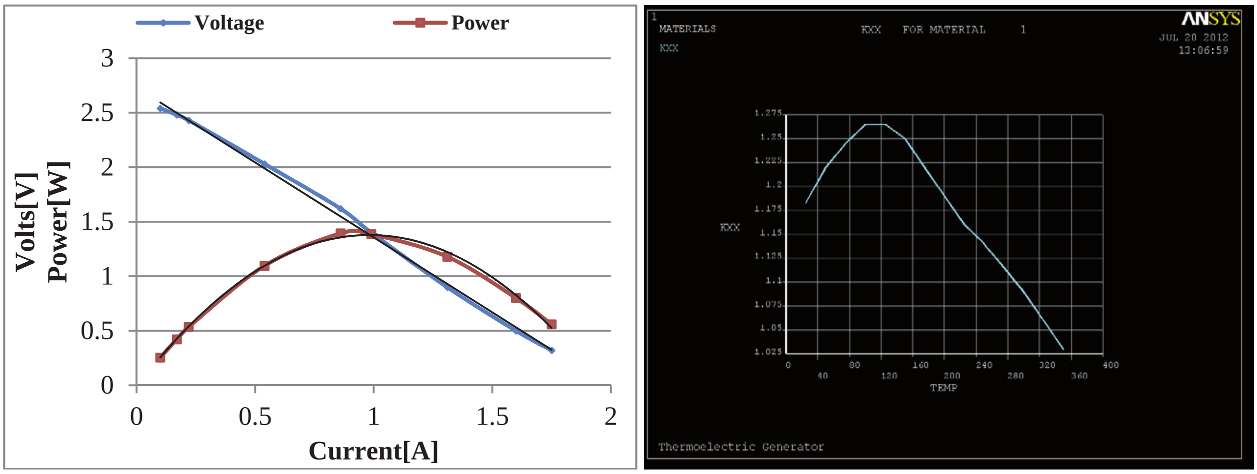

Fig. 6. load characteristics of a single TEG: a) the characteristic resulting from TEG research, b) photograph of the characteristics resulting from the computer simulation

5. Conclusions

Simulation-based research confirms the results obtained. It should be noted that the higher the temperature difference on the hot and cold side, the higher the resulting voltage. For simulation-based analyses, it is necessary to determine the impact of the Seebeck coefficient, and in particular the temperature difference on the linearity or its lack thereof in the parameters.

It is necessary to keep the maximum temperature within limits within which TEG may safely operate. After 140ºC is exceeded, there exists a significant probability of damaging the cell, and after 200ºC is exceeded, according to the information provided by the producer, semiconductor connectors that form the TEG get damaged.

The use of TEG requires a suitable, flat surface where the TEG may be installed. TEG is usable in the exhaust gas draining system at high temperatures, as well as in the cooling system of the engine, where the temperatures are lower. The specific determination of TEG usability in a vehicle requires additional research.

Overall, the minimum recycled energy from one TEG with fixed engine operation parameters (800 rpm) with no load is 1.4 W for a combustion engine with 1.8 dm^3 capacity and rated power 84.5 kW. The use of a larger number of TEGs in the exhaust system will significantly increase the amount of recycled energy. At the same time, it has been observed that the use of several TEG one after another results in a lower surface temperature of the exhaust system, which in turns impacts the energy recycled by another TEG.

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