Thermoelectric modular systems based on semiconductor elements of Peltier-Seebeck for vehicles

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Abstract. Elevations in technology of semiconductor materials allow for new vehicle systems use for improvement in the standard ones. One of the most promising materials for achieving an efficacy of more than 50% is polyaniline, which belongs to the class of conductive polymers that has semiconducting peculiarities. For instance, a new generation of semiconductor elements based on the Peltier-Seebeck effect makes it possible to use them to create thermoelectric generators, which means to use the thermal energy of the exhaust gases of internal combustion engines (ICE) to generate electrical power. The second area where Peltier-Seebeck semiconductor elements find application in automobiles are modular climate control systems. Due to the absence of moving parts and relatively small dimensions, they allow the creation of individual climatic zones in the car interior. An elegant design and technological solution is the placement of similar thermal semiconductor modules inside the driver's and passenger's seats, which makes it possible to transfer heat more efficiently and make climatic zones more apparent. The article considered engineering options for the design of climate control units based on Peltier elements and the creation of a prototype. The issues of integration into the vehicle on-board network and the features of power control are considered.

The studies and results of this paper can contribute to improving the energy efficiency and technosphere safety of vehicles.

1. Introduction
The development of technologies in the field of semiconductor materials allows them to be used for new motor vehicle systems or to improve the design of the conventionally used ones. For example, a new generation of semiconductor elements based on the Peltier-Seebeck effect can be used to create thermoelectric generators (TEGs) that convert the thermal energy of the spent exhaust gases into electric and increase the overall efficiency of the propulsion device. Thermoelectric modules implemented with the Peltier-Seebeck effect have high potential when used in climatic systems of vehicles.

A unit element of a thermoelectric module is a thermocouple consisting of two heterogeneous elements with p- and n-type conduction. The elements are connected together by means of a switching plate with a low internal resistance (e.g. copper). In a typical thermoelectric module (Figure 1) thermocouples are placed between two flat ceramic plates based on oxide or aluminum nitride and are connected rowley. The quantity of thermocouples can vary from units to hundreds of pairs, allowing for creation of thermoelectric modules of up to hundreds of watts or more [1].
Figure 1. Example of thermoelectric module basic structure.

The thermoelectric effect of Seebeck is associated with the emergence of electromotive force (EMF) at the ends of sequentially connected semiconductors of different materials, one of which is heated and the other is cooled. The EMF value at the ends of the conductors is directly proportional to the Seebeck-module E coefficient and the temperature difference $\Delta T$ between hot Th and cold Tc sides of the thermoelectric module [2]:

$$E_{\text{thermo-EMF}} = E \Delta T \quad (1)$$

If carried out vice versa thus EMF is applied to the ends of semiconductors, then at the point of their contact (junction point) heat will be absorbed (the surface will be cooled) or released depending on the direction of the EMF. The heat (Q) released or absorbed will be directly proportional to the difference of Peltier coefficients $\pi_{AB}$ for each of the materials, amperage I and time t:

$$Q = (\pi_A - \pi_B) \cdot I \cdot t \quad (2)$$

A typical Peltier module for cooling purposes is able to provide a significant temperature difference of several tens of degrees. It is worth mentioning that the acceptable efficiency of modules using the Peltier effect for cooling is feasible at low ambient temperature (up to +30° C). Subsequently the cooling possibilities are sharply reduced, and almost disappear at + 40 °C.

The general efficiency of the module depends on the type of the semiconductor materials of thermoelectric elements, which is customary to calculate through the adjustable ZT value - the coefficient of thermoelectric efficiency:

$$ZT = \frac{S^2 \sigma T}{\lambda} \quad (3)$$

where $S$ stands for the Seebeck coefficient, $\sigma$ stands for the conductivity coefficient, $T$-temperature measured in K (Kelvin) and where $\lambda$ is the coefficient of thermal conductivity.

Nowadays widespread thermoelectric semiconductor materials have $ZT \approx 1$. Low efficiency and high costs hinder the expansion of TEG implementation including the automotive industry. Thermoelectric module manufacturers are to solve three key problems: improving ZT quality, increasing the working range of materials to function at higher temperature differences and finally finding relatively inexpensive materials. In order to increase the ZT coefficient, it is essential to find or create a material that must have mutually exclusive properties — low thermal conductivity, but good electrical conductivity. It is predicted to receive as a result of laboratory research in the vast future materials with $ZT = 2$, in which the efficiency rate will be more than 10% with a temperature
difference of less than 200 K (Figure 2) [3]. One of the most promising materials that allows for achieving efficiency of more than 50% is polyaniline, which is classified as a class of conductive polymers that have semiconductor peculiarities. However, until the requested material is found acceptable in terms of efficiency - cost - temperature difference for the automotive industry, the development of thermoelectric technologies, using the Seebeck-Peltier effect will remain significantly limited.

![Figure 2](image.png)

**Figure 2.** Dependence of ZT efficiency value in thermoelectric materials (including theoretical forecasts).

The advantages of thermoelectric modules include: noise-cancellation, absence of moving parts and working fluids, functioning in any spatial position, small size and mass of the system and also relatively simple control [2]. Analysis of modern materials are shown in Table 1 [2, 4, 5, 6, 7].

A separate high of significance engineering task is to optimize structures that use thermoelectric modules. For example, with a standard size tolerance to the height of the thermoelectric module ±0.02 mm and a non-parallelism tolerance of ±0.02, the gap between the surface of the heat exchanger and the thermoelectric module a lower height can reach a value of 0.06 mm in the middle of a thermoelectric module measuring 40 × 40 mm. In the case of using a widely used thermal conductive paste with a thermal conductivity coefficient of 0.8 W/m*K and heat flow through a 50W thermoelectric module, 2.3°C will be wasted at this gap [8].

| Material /specification | $ZT_{\text{max}}$ | $\Delta T, K$ | $T_{\text{max}}$ | Status                |
|-------------------------|-------------------|---------------|------------------|-----------------------|
| Half-Heusler (semi-alloy)| 1                 | 500           | 600              | laboratory tests      |
| P-type tetrahedral      | 1.05              | 300           | 600              | available             |
| magnesium silicide      |                   |               |                  |                       |
| Silicon based alloys    | 1.2               | 500           | 600              | available             |
| Bi2Te3                  | 1.4               | 300           | 300              | available             |
| Skutterudite            | 1.6               | 394           | 504              | laboratory tests      |
| BiTe–PbTe               | 1.7               | 320           | 360              | available             |
| PANI                    | 2.7               | 340           | 370              | laboratory tests      |
Thermal contact improvements of thermoelectric modules surfaces with heat exchangers can be achieved by applying individual heat exchangers (instead of one conventional) for each thermoelectric module while ensuring the required purity of surface treatment in contact with the thermoelectric module [8]. The use of individual heat exchangers for each thermoelectric module eliminates the influence of their technological spread in height and non-parallelism of the sides. Increasing the surface temperature difference of thermoelectric modules can be achieved ceteris paribus by using flat springs, which tighten the surfaces between which the thermoelectric modules are located.

The purpose of this work was an analytical and engineering study of the evaluation of prospects of thermoelectric modules using the Peltje-Seebeck effect in modern vehicles.

2. Theoretical studies of an automotive thermoelectric generator based on the Seebeck’s effect

One of the applications of Seebeck's effect for semiconductor modules is the conversion of thermal energy of the engine exhaust gas into electrical energy. Modern internal combustion engines have average efficiency of about 25-30%. The thermal energy of the exhaust gas is about 30% (Figure 3). The thermal energy of the exhaust gas can be converted to electric and used to reduce fuel consumption or to apply new electrical and electronic systems of the vehicle [1], [2]. Some developers were able to implement a thermoelectric generator (TEG) design and obtain a power output of more than 1 kW of electricity [2,7]. For comparison, the standard car synchronous generator on average has a power output of 2-2.5 kW and increases fuel consumption by about 2-4% depending on the operating modes.

Potential possible generated TEG power is estimated from several hundred watts to about 2.5-3 kW for a passenger car depending on the type of internal combustion engine and motion cycle vehicle [10]. Theoretical possible figures are comparable to the power of most used generator sets. However, to obtain this amount of energy, a larger number of thermoelectric semiconductor modules will be required. Thus, the cost, mass and overall dimensions of the TEG will be tremendous. Increasing the overall dimensions degrades the layout and requires additional fasteners, and adding a TEG mass to the vehicle increases fuel consumption. In the researchers [10] conducted by the authors showed that when driving a medium class vehicle with a diesel engine on the NEDC cycle leads to an increase in energy consumption of 12.1 W/kg. In other words, the use of TEG on vehicles implemented with semiconductor materials with efficiency of approximately 5% is energetically beneficial and plausible when generating a power significantly greater than 12.1 W/kg.

Figure 3. Electric power balance chart in ICE [9].
The current level of pilot development of the TEG is approximately 100-200 W/kg depending on the type of materials and taking into account the additional mass of DC/DC converters, changes in the cooling system. It is possible to make a forecast that the TEG will receive when achieving a specific capacity comparable to the generator sets 350-400 W/kg and with the TEG cost reduction to a comparable level of prices with automotive alternators.

In order to research the applicability of the TEG on the car and to identify design and technological features in the integration into existing car systems, the authors started a project on the implementation of the model installation. In Russia, such works are represented only in insufficient quantities and a real project has been started in order to develop scientific and engineering experience. In the first phase a functional scheme was drawn up (Figure 4). According to this scheme, a mathematical model was developed in the Simulink modeling environment.

![Functional interaction of thermoelectric generator with the exhaust system and the cooling system of the ICE.](image)

**Figure 4.** Functional interaction of thermoelectric generator with the exhaust system and the cooling system of the ICE.

The model was developed on the condition that all materials are isotropic, the speed of heat propagation in all directions is the same, and semiconductor modules have the same height and are uniformly pressed for all areas. Relatively inexpensive and affordable for purchase in the Russian Federation TEG modules were chosen as subject of research. The specifications of the modules are presented on Figure 5. For research, the TEG with total output power - 200 W was chosen, which is planned to be collected from the TEG given in Table 2.

**Table 2.** Specification of modern thermoelectric materials.

| Thermoelectric parameters               | Units | Value   |
|----------------------------------------|-------|---------|
| Generated power, P                     | W     | 12.6    |
| $I_{\text{load}}$                      | A     | 4.1     |
| $U_{\text{load}}$                      | V     | 3.1     |
| Internal resistance                    |       |         |
| $R_{\text{ac}}$ (at 200 °C) ± 10%      | Ohm   | 0.75    |
| $R_{t}$ (heat resistance)              | K/W   | 0.69    |
| Operating/maximum temperature          | °C    | 200/220 |
According to this scheme on Figure 4, a mathematical model was developed taking into account the technical characteristics of TEG module TGM-127-2.0-1.3. The main purpose of the simulation was to establish the relation of the change in power output and voltage depending on external conditions and the warm-up rate of the catalytic converter (Figure 6).

![Figure 5. Output current (a) and efficiency (b) TEG module TGM-127-2.0-1.3.](image)

![Figure 6. General view of the TEG mathematical model. a - block of time simulation; b - graph of Tc change; c - graph of Th change; d - efficacy; e - variable of the number of TEG modules; f - subsystem for calculating TEG parameters; g - block for recording output parameters into the graphs; h - block of limitation of Th; i - block of Tc limitation.](image)

Experimental data on the relation of exhaust gas temperatures in the exhaust manifold and liquid cooling system (Figure 8) of the passenger car’s internal combustion engine at the base temperatures movement on the NEDC motion cycle (Figure 7).

On the external load $R_n$, the thermo-generator module creates a voltage $U$ equal to the Thermo-EMF, subtracted the voltage drop at the internal resistance $R$. Simultaneously $I$ in the circuit is determined by the expression (taking into account the expression (1)):

$$I = \frac{E_{\text{thermo. EMF}}}{R + R_H} = \frac{E_{\text{thermo. EMF}}}{R(1+m)}$$  

(5)
where $m = \frac{R_n}{R}$.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{exhaust_gas_heating_temperature_graph.png}
\caption{Exhaust gas heating temperature graph on a mathematical model cycle.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{coolant_temperature_change.png}
\caption{Dependence of the coolant temperature change from the start of ICE.}
\end{figure}

The voltage on the load is:

$$U = I \cdot R_\mu = E_{thermoelec} \cdot \frac{m}{1+m}$$

(6)

Thus, the power given to the external circuit can be calculated by the following formula:

$$P = I \cdot U = \frac{E^2 \Delta T^2}{R} \cdot \frac{m}{(1+m)^2}$$

(7)

The simulation results depict that the power output first increases due to a larger temperature difference. As the coolant heats up and the nominal value of 90 °C is reached, the output power reduces almost twice, and the output voltage becomes 13.2 V. On the hot side of the TEG, the operating temperature is 200 °C (the temperature from the exhaust manifold to hot TEG is reduced due to the additional heat exchanger) and the temperature change by almost 70 °C at initial temperature of 20 °C results in a significant reduction in the output power.
In this case, the relative change in coolant temperature will affect substantially less. In addition, it would reduce the requirements for a stabilizing DC/DC converter. Since significant output voltage drops are observed only when heating up the internal combustion engine and, therefore, the coolant, then in order to optimize the converting devices, the algorithm is advisable connection of the load to the TEG after having entered the operating mode for 30 seconds to a few minutes (depending on the ambient temperature). In addition, it is worth noting that a significant amount of heat is released on the hot side, which can cause a violation of the thermodynamic balance of the internal combustion engine. Thus, we have to either modify a regular liquid cooling system or apply a separate one, for example ultra-efficient air on the basis of a patent [8].

3. Climatic Module based on the Peltier Effect

In modern cars for the creation of drivers’ and passengers’ comfort implement several regulated climatic zones depending on the characteristics of each person and their current physiological states. The development of semiconductor technologies allow for change the approach to the organization of a comfortable climate environment. For example, to not implement the distribution of air flows from one central compressor, due to the regulation of the position of the dampers and fan speed, but to place individual climatic thermoelectric modules using the Peltier effect. In this case, when passing cur in one direction, the air can be cooled, and when the polarity changes, use the same module to heat the interior of the vehicle. The fan installed on the cold side takes air out of the atmosphere and passes through the heat exchanger, which in turn is cooled and cooled air is supplied to the passenger compartment. The fan installed on the other side takes heat from the hot side and releases it through the nozzles into the atmosphere outside the car (Figure 9). The relative compactness of thermoelectric modules allows them to be installed, directly in the exhaust air channels of the front panel of the car. This will reduce energy loss when transferring the flow of cooled air from the compressor of the air conditioner, through long air pipes, as in the standard scheme used now. In addition, one option may be to place climate modules directly in the passenger’s or driver’s seat of the vehicle [11].

Figure 9. Functional scheme of climatic module with the Peltier effect.
Using a climatic installation of Perltier elements instead of a compressor with belt drive will reduce the dynamic load on the internal combustion engine, adjust the power consumption and therefore achieve a reduction in harmful emissions and improve fuel consumption.

To examine the technical capabilities of a climatic installation with elements Peltier TEC — 12706, nominal supply voltage of 12 V. In order to minimize measurement errors, a closed system of the cooling part of the climate unit with a volume of 24 liters (Figure 1) was constructed and implemented in a separate space. It should be noted that the implementation of the project and the choice of components was limited due to strict quarantine restrictions due to COVID-19.

![Figure 10. Appearance of a breadboard construction climatic installation with Peltier elements.](image)

To develop a reliable, durable and functional climate installation, it is necessary to implement algorithms for smooth power regulation. First, discrete on/off semiconductor modules lead to a decrease in their resource by 2 or more times. This is due to the fact that with discrete control there are sharp changes in temperature and mechanical stresses arise between the plates of the module, and then micro deformations and cracks in the areas of adhesion with semiconductors. Peltier elements manufacturers rate the number of “on/off” cycles of modules about 5-6 thousand cycles at this level of technology development.

Secondly, the volt-amp characteristic of the Peltier module is nonlinear and with a slight change in voltage, the current changes more significantly. The characteristic also depends on the temperature of the surfaces of the module, which requires adjustment of control influences, since the cooling capacity of the Peltier element is directly proportional to the consumed electric current. Therefore, to stabilize the temperature, it is necessary to adjust the electrical power on the Peltier element. As a result, a smooth control algorithm was implemented using PWM and PID control based on the controller AVR Atmega328P, and temperature measurement was carried out with the help of 2 sensors DS18B20. Aluminum radiators of the type O221-60 were used as heat exchangers.

Experimental studies of the layout installation and control algorithms were carried out. The average efficiency value was measured and calculated from a series of 5 experiments under the same initial conditions. The data was processed according to error theory and normalized. The average efficiency rate of the installation in the smooth power control mode was 21.3 ± 1.1%.

Separately, studies of cooling intensity were carried out, the results of which are shown in Figure 11.

Estimated data analysis showed that within 10 minutes air volume 1 m³ will be cooled by 2.7° C, while the electric power of the climatic plant expended will be 1.05 kW. This means that a car with a compartment volume of 3 m³ will require about 10 similar climatic installations with the Peltier effect. Thus, the use of semiconductor elements in climatic installations is possible only with a significant increase in their efficiency (for example, due to improved materials technologies). It can be predicted that first of all, the use of such climate modules will be used in hybrid vehicles.
4. Conclusions
The study of the use of elements with the Seebeck effect in TEG showed a high potential for conversion due to a large amount of thermal energy, which is now simply dissipated into the atmosphere. The use of materials with a permissible operating temperature difference of more than 400 °C will reduce fluctuations in output electrical parameters and requirements for converting elements when connecting the TEG to the car's on-board network. Analytically it has been established that it is advisable to connect the generated electric power of the TEG after heating the coolant of the internal combustion engine.

Using a climatic installation of Peltier elements instead of a compressor with belt drive, will reduce the dynamic load on the internal combustion engine, adjust the power consumption and therefore achieve a reduction in harmful emissions and improve fuel consumption. The average efficiency of the mock climatic plant under normal climatic conditions was about 21%. The cooling of 24 liters of air volume of the climatic device requested 3831J/1C.

Contemporary semiconductor materials, taking into account economic constraints, do not allow for use of thermoelectric modules in vehicle systems. However, active work in this direction and improvement of efficiency by 3 times can significantly expand the scope of their application. Especially since prototype samples of such materials (for example, polyaniline) are obtained in laboratory conditions. A separate direction of improvement is the improvement of internal thermal insulation between the adhesions, the uniformity of pressing heat exchangers to the surface of the melting elements. A separate important direction of improvement is the use of efficient liquid and air heat exchangers. A fusion of design and technological solutions will make it possible to use environmentally friendly semiconductor modules with the Seebeck-Peltier effect on vehicles.

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