# Thermoelectric generators of motor vehicle powertrains, problems and prospects

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**Abstract.** At present, considerable efforts of vehicle manufacturers are directed towards improving efficiency and reducing emissions. For example, a system of energy recuperation during braking is often used in electric and hybrid vehicles. It improves energy efficiency, but a significant part of the energy released from the fuel by the internal combustion engine, forming a component of a hybrid power plant or used to recharge the batteries of an electric vehicle, is lost in its cooling system and discharged with the exhaust gases. This energy can be converted into electricity and used to recharge the batteries. This paper provides an analysis of the development of direct exhaust gas heat to electricity conversion systems, used in hybrid vehicles and, more generally, in any vehicle with an internal combustion engine, where energy recovery will reduce the load on the generator. Currently, considerable efforts of vehicle manufacturers seek to improve their efficiency and reduce emissions. For example, in vehicles with electric and hybrid powertrains often applicable system of energy recuperation during braking, which improves energy efficiency, but the internal combustion engine, a component of the hybrid powertrain or used to recharge the battery electric vehicle, a significant part of the energy consumed in the fuel is lost its cooling system and is discharged with the exhaust gases. This energy can be converted into electricity and is used for recharging the batteries. This article provides an analysis of the development of systems of direct conversion of thermal energy of exhaust gases into electricity, in vehicles with hybrid powertrain and, more generally, in any vehicle with the engine, where energy recovery will reduce the load on the generator.

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## Introduction

Modern automotive industry is on the verge of a major paradigm shift, similar to the late 19th century, when electric drive was a rule rather than exception. Sales of hybrid vehicles combining electric motors and internal combustion engines reached the level of millions.

At the same time, a substantial part of vehicle manufacturers' R&D budgets is spent on improving the environmental and economic performance of hybrid vehicles. Systems to recover energy during braking become widely used. Another possible way to reduce fuel consumption and toxic emissions is direct conversion of thermal energy, contained in exhaust gases of the internal combustion engine, into electricity, which can be used by the primary drive of the vehicle.

## Heat balance of the vehicle

Analysis of the external heat balance of ICE [1], in particular a spark ignition engine, reveals that up to 40% of the energy released during combustion of the fuel is carried away with the exhaust gas. Much of this energy can be used for various purposes. Besides, some energy is dissipated by the engine cooling system and spent to overcome friction and inertial forces.

The optimal methods to recover thermal energy from exhaust gases among many options possible for hybrid vehicles are those to produce electrical energy, which, in turn, can be immediately directed to the traction motor.

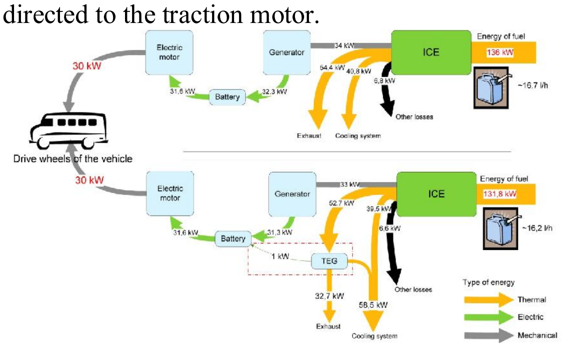



**Figure 1. Changes of heat balance of the hybrid vehicle after introduction of a thermoelectric generator.**

Figure 1 shows the change of the heat balance of a hybrid vehicle, when a thermoelectric generator is installed. The main point of comparison of the two heat balances was equality of the amounts of energy spent by the drive wheels (30 kW). The efficiency of all drive systems of the hybrid vehicle remained unchanged. The above diagrams demonstrate that introduction of a thermoelectric generator with efficiency of 5%, which converts about 2% of the exhaust gas thermal energy into electricity, the fuel consumption drops by approximately 3%.

**Thermoelectric materials**

The efficiency of the exhaust gas heat recovery depends on the properties of the chosen material of the thermoelectric generator unit.

The first description of direct heat to electricity conversion was made by Thomas Johann Seebeck in 1821. However, he explained the thermoelectric effect, named after him, by polarization of materials under the influence of temperature difference, which was disproved later.

The Seebeck effect is caused by electromotive force generated in the contacts of a closed circuit consisting of dissimilar conductors, when a temperature difference exists. However, the EMF occurring in the circuit made of two dissimilar conductors, does not exceed a few millivolts, which is sufficient for temperature measurements, but not for generation of electricity. In order to improve the efficiency of both the direct conversion of thermal energy into electricity and the reverse, thermoelectric elements consisting of p and n type semiconductors electrically connected in series and thermally connected in parallel were created. The design of a thermoelectric generator module is shown in Figure 2.

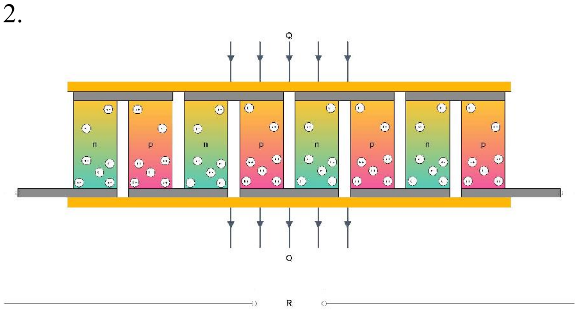


**Figure 2. Principle of operation and construction of thermoelectric generator module**

The resulting temperature of both sides of the thermoelectric module and voltage in the circuit at a constant heat flux and load consist of the contribution of three fundamental thermoelectric effects: Seebeck, Peltier and Thompson.

Performance of a thermoelectric generator can be estimated by the efficiency value (2), which depends not only on the material used, but also on the temperature difference between the cold and hot junctions. To evaluate the efficiency of thermoelectric material the concept of merit factor ZT (1) is used. The merit factor of the thermoelectric material and its efficiency can be calculated as follows:

$$ZT = \frac{\sigma \times \alpha^2}{\lambda} \Delta T \qquad (1)$$

$$\eta = \frac{\sqrt{1+ZT}-1}{1+ZT+\frac{T_C}{T_H}} \times \frac{T_H - T_C}{T_H}, \qquad (2)$$

Where: $\sigma$ – *specific conductivity, S/m;*
$\alpha$ – *thermo – EMF coefficient;*

$\lambda$ – *specific thermal conductivity, W/(m * K);*
*ΔT - temperature difference between hot ($T_H$) and cold ($T_C$) of the element, K.*

It follows from the definition of the thermoelectric material's merit factor, that along with high thermal EMF it must have high electrical conductivity and low thermal conductivity, which is impossible for any single material. Therefore, the search for an effective thermoelectric material is reduced to a compromise for a given operating conditions.

Figure 3 shows some thermoelectric materials, both currently in use and perspective developments since the middle of the 20th century.

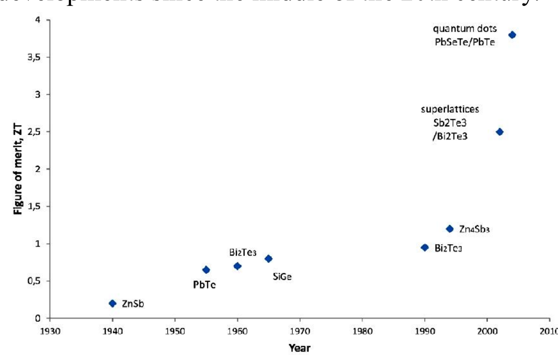



**Figure 3. Progress in thermoelectric materials figure of merit, ZT.**

Zinc antimonide (ZnSb), used by Seebeck in his experiments, has an extremely low merit value of 0.2. Due to its low efficiency the first thermoelectric generator using zinc-antimony with composition close to stoichiometric, presented in 1867 found no practical application.

Since 1960s the most widely spread thermoelectric elements are based on lead and bismuth tellurides. The main reason for the widespread use of lead telluride (PbTe), in spite of its low value of thermoelectric merit factor of about 0.6 - 0.7, was its cheapness. Later it was fully replaced with bismuth telluride ($Bi_2Te_3$), which has ZT of approximately 1.0 corresponding to 5-7% efficiency at temperatures up to 230°C, but significantly less at higher temperatures. In the following decades the efficiency of thermocouples based on bismuth telluride was steadily increasing, but the barrier of ZT

= 1 has never been exceeded. Along with the above mentioned tellurides, silicide germanium (SiGe) found some use, limited due to its high cost.

The interest to the use of zinc antimonide in generator modules reappeared after the discovery of thermoelectric properties of $Zn_4Sb_3$ alloy, which by far exceed those of tellurides. High, about 1.2 [2], thermoelectric merit of this material is largely due to inhomogeneities of its crystal lattice, which reduce thermal conductivity.

Further search for high-efficiency thermoelectric materials is aimed at reducing thermal conductivity while maintaining low electrical resistance through creation of various nanostructures in an alloy of semiconductor materials. At present, the work to create materials with superlattices (ZT 2.5) and quantum dots (ZT 3.8) [3, 4] is underway.

Table 1 shows the main properties of thermoelectric materials, used in modern mass-produced generating modules.

**Table 1. Properties of thermoelectric materials**

| Title | Composition | Type of semiconductor | Optimum operating temperature, °C | Merit ZT | Manufacturing technology |
|---|---|---|---|---|---|
| Germanium silicide | $Si_{0,8}Ge_{0,2}$ | n | 730 | 1,00 | Hot pressing |
| | $Si_{0,8}Ge_{0,2}$ | p | 730 | 0,70 | Hot pressing |
| Lead telluride | PbTe | n | 230-577 | 0,70 | Hot pressing |
| Zinc antimonide | $Zn_4(Sb_{0.97}Sn_{0.03})_3$ | p | 230-480 | 1,00 | Plasma sintering |
| | $Zn_4Sb_3$ | p | 230-480 | 1,22 | Plasma sintering |
| Telluride / bismuth selenide / antimony | $Bi_xTe_y/Sb_xSe_y$ | p/n | 180-250 | 0,3-1,01 | Hot pressing |

A good example of a modern commercially available generator module is the 2411G-7L31-15CX1 model, produced by Custom Thermoelectric. Its features are shown in Figure 4 below.

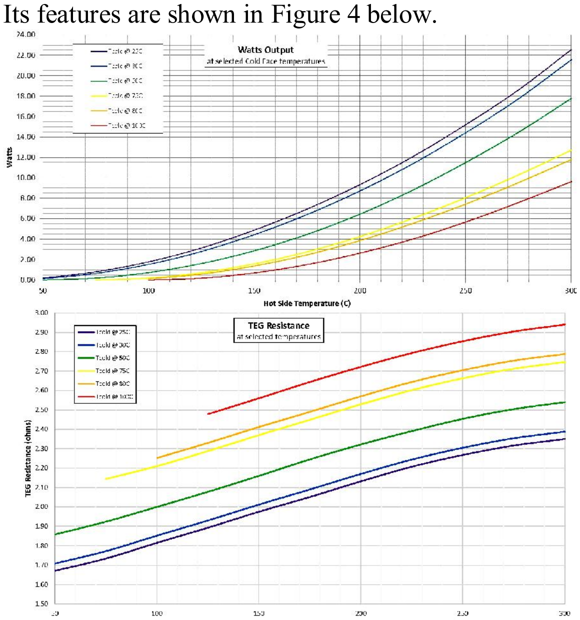


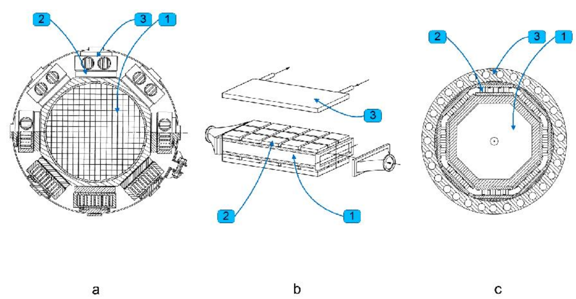

**Figure 4. Watts Output and TEG Resistance at selected temperatures [5]**

Thus, if the current thermoelectric generator modules using bismuth telluride (III), with ZT <1 can convert heat from exhaust gases, carried away with the exhaust of an internal combustion engine, with efficiency of 5-7%, the use of prospective thermoelectric materials allows to raise this figure up to 20-24%.

However, a thermoelectric materials intended for use in vehicles must satisfy additional requirements, such as environmental safety and accessibility, i.e. low cost. Currently, few thermoelectric materials that meet all these requirements are in mass production. One such example is bismuth telluride (III) $Bi_2Te_3$.

**Requirements for a vehicle thermoelectric generator**

Besides thermoelectric merit of the material, the design of a thermoelectric generator also significantly affects efficiency of the exhaust gas recycling. The use of a thermoelectric generator for recuperating thermal energy in a motor vehicle was first proposed in Automotive Engineers Community journal in 1963 [6].




1 – body with a channel for the exhaust gases; 2 – thermoelectric generator module; 3 – heat exchanger.

**Figure 5. Schematics of different TEGs**

Currently, the leading automakers, such as General Motors, BMW and Toyota, have developed their own thermoelectric generators and conduct their tests, both in the labs and inside vehicles. Figure 5 shows examples of such generator designs [7-9]

All thermoelectric generators presented consist of three main parts:

- a body, which houses generator modules and has a channel to release the exhaust gases;
- thermoelectric generator modules;
- a cooler to transport the heat energy away from the generator modules.

Each of the presented thermoelectric generator designs has certain deficiencies that prevent their launch into production. For example, the thermoelectric generator shown in Figure 5a has an independent heat exchanger at each thermoelectric module, which increases the amount of hydraulic connections by an order of magnitude and reduces the general reliability of the generator. The design of generator shown in Figure 5b has less heat exchangers, but the generator modules are placed in the body unevenly and only on two sides, which can significantly reduce the efficiency of heat transfer from the exhaust gases to the coolant.

The last of these examples (Figure 5c) is seemingly free of the above problems, but its cartridge design of the cylindrical heat exchanger complicates and increases the cost of the generator assembly and also makes it completely unsuitable for repair.

Each part of a thermoelectric generator designed for use in a transport vehicle should both perform certain functions and meet specific requirements for in-vehicle applications.

The housing of a thermoelectric generator is designed to supply the heat from the exhaust gases to its thermoelectric generating modules. The heat flow through the generator modules must be maintained within predetermined limits in the entire operating range of the internal combustion engine despite any changes in the exhaust gas temperature and its mass flow rate. To achieve this it is necessary to increase the heat exchange area of the housing and turbulence of the exhaust gas stream. However, this would increase the hydraulic flow resistance of the exhaust system, which is unacceptable because of negative impact on the efficiency of the internal combustion engine. Therefore, the choice of the optimal thermoelectric generator housing design, material and manufacturing technology should be governed by both the above requirements, which remain largely contradicting each other.

The efficiency of converting the ICE exhaust gas heat into electrical energy by thermoelectric generator modules in all engine operating modes depends mostly on the choice of thermoelectric material [10]. Also, the design of generator modules should be tolerant to short-term overheating and ensure good performance under vibration, which is inevitable in a vehicle. On the other hand, overheating of the thermoelectric modules can be avoided by directing all or a part of the exhaust gas flow through a bypass channel in certain engine operating modes.

On the other hand, the heat flux through the generator modules depends not only on the efficiency of heat transfer from the exhaust gases, but also on the heat removal rate of the coolers. In a hybrid vehicle it is most appropriate to integrate the coolers of the generating modules with the cooling system of the internal combustion engine, which allows to maintain a constant temperature of about 900°C on the colder side of the module. It should be noted that this design solution may require changes in the engine cooling system, in particular increasing the heat dissipating capacity of the radiator.

In general, the thermoelectric generator intended for use in motor vehicles, including hybrid ones, must meet a number of special requirements, such as:

- compact size, which is important in a dense packaging of vehicle components and assemblies;
- low weight, particularly in the case of a hybrid vehicle, due to considerable weight of electric batteries;
- electromagnetic compatibility with other components of the electric drive;
- uniformity of parameters of its electrical output.

The last of the requirements listed above is worth considering in greater detail. A power plant of a hybrid vehicle uses both direct and alternating currents of different voltages. At the same time, the energy is usually stored by chemical DC sources. Thermoelectric generator modules produce direct current, but using it straightforwardly to charge the batteries is impossible because of direct dependence of the voltage and current from instantaneously changing temperature difference. This feature of thermoelectric generator modules necessitates introduction of an electric DC-DC converter and a control system.

As it is known [5], the maximum efficiency of a thermoelectric generator module is achieved when its own electrical resistance and the resistance of the electrical load are equal. In turn, the generator module's own electric resistance is largely dependent on the temperature and may vary by 15-40% within the operational temperature range. Therefore, the thermoelectric generator control system is required both to control the generator's condition and to adjust the AC converter's parameters in time to maximize the efficiency of direct exhaust gas heat to electricity conversion.

**Conclusion**

This paper provides a brief analysis of the development of direct exhaust gas heat to electricity conversion systems, used in hybrid vehicles, and possibilities of improving its efficiency through application of new thermoelectric materials.

We formulate the main technical requirements for constituent parts of thermoelectric generators, basing on the analysis of existing designs.

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