Chapter 10

Prospects and Problems of Increasing the Automotive Thermoelectric Generators Efficiency

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Additional information is available at the end of the chapter

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Abstract

The chapter considers the current state and trends in the field of heat recovery units for vehicles with internal combustion engines (ICE), including thermoelectric generators for cars, motorcycles, ships and railway transport. Based on the analysis of literature data, mathematical modeling and experimental studies, this chapter presents various designs of such generators. This research considers a heat exchange between exhaust gas (EG) and thermoelectric modules (TEM), as well as how their usage affects ICE operation. Furthermore, the chapter profoundly explores the challenges of installing thermoelectric generator (TEG) on vehicle system. In addition, the ways of increasing overall system efficiency, by optimizing the flow channel and reducing electrical power losses, are presented.

Keywords: thermoelectric generator, Seebeck effect, internal combustion engine, internal combustion engine vehicles, thermal contact resistances, heat exchange structure, automatic power management

1. Introduction

Internal combustion engines are currently the main power source for most vehicles. A significant change in the ICE share can hardly be expected in the short or medium term [1].

In 1988, in order to improve the road transport's environmental performance, the United Nations Economic Commission for Europe introduced emission standards regulation (Euro-0) that required reducing the level of carbon monoxide, nitrogen oxide and hydrocarbons in the exhaust gases. Since then, the environmental standards are progressively becoming more stringent (Euro-6 standard is in force since 2015). In addition, the international efforts to reduce the rate of global warming resulted a new law Standard No 443/2009 by European Union, which prescribes the reduction emission of CO_2 up to 130 g/km for new passenger cars till 2015 and up to 95 g/km by end of 2021. With the passage of time every year, new restrictions are being advocated by tax policies which take into account a vehicle's environmental performance level, encourage automakers to work towards finding effective solutions to reduce harmful emissions into the atmosphere.

The activity in this area takes two directions: optimization of processes in a combustion chamber and neutralization of exhaust gases [1]. However, these developed methods can partially solve the problem of reducing harmful emissions. At the same time, the average fuel consumption for vehicle operation is 35% [2], while approximately 37% is dissipated as EG [3], which means that great potential is available for heat recovery technology.

At present numerous technical solutions are being developed for heat recovery systems. Among the most promising are the Rankine cycle, thermoelectric generator and a turbo-compound engine. All these solutions have their own merits and drawbacks [4, 5]. Numerous authors believe [6–8] that up to now the thermoelectric generator is the least developed technology. However, due to the absence of moving parts, potentially high reliability, compactness and the prospects in new thermoelectric materials over the past 20 years [9], this technology has great practical potential as an exhaust heat recovery system for ICEs.

2. ATEG research review

One of the first published works on a thermoelectric generator for vehicles was done in 1913 [10] where a thermoelectric cell based on a thermocouple wire powers lighting and ignition systems. This generator was meant to eliminate the need for a standard electromechanical alternator, thus making the electric power supply system less complex and expensive.

The first research in this area was conducted in 1961–1963 at Clarkson University (USA) by Bauer [11] and Tomarchio [12]. Bauer considered the possibility of using $PbTe$-based thermoelectric generators to recover heat in the automobile cooling system and came to the conclusion that a noticeable electric power requires a lot of thermoelectric material. Tomarchio investigated the possibility of replacing an alternator with a thermoelectric generator in the automobile exhaust system and concluded that the desired power levels in the 20–50 mph (32–80 km/h) speed range. Speeds below 20 mph require new, more efficient materials.

In the mid-1950s, research by Goldsmid [13] and Ioffe [14], the subsequent development of thermoelectric materials based on bismuth telluride solid-state solutions achieved significant development in the applications of thermoelectric effect. However, these technologies were adopted in automobile generators only in the late 1980s and early 1990s, which was apparently caused by the changes in environmental policies of different countries (the EU environmental guidelines were formulated in 1987 in The Single European Act (SEA)).

In 1988, Birkholt et al. [15]. developed automotive thermoelectric generator (ATEG) and tested on Porsche 944. It had a peak power of 58 W at 800°C temperature for hot-side heat exchanger.

Temperature difference between hot and cold side of heat exchanger was 490°C. $FeSi_2$ was used as the thermoelectric material.

Hi-Z Technology, Inc. (Hi-Z) funded by the U.S. Department of Energy (DOE) began a large-scale of research in this direction in 1987 with the aim of obtaining sufficient electric power to eliminate the need of engine driven alternators in trucks. Different locations were purposed for the TEG installation to enable heat recovery; among them were the exhaust manifold, the internal combustion engine, the intercooler and the lubrication system. The conclusion was made that the exhaust gases have the best potential for ATEG [16]. Thermoelectric materials were analyzed in terms of their effectiveness in solving this problem and the optimal materials were selected. In 1994, Hi-Z presented test results for 1 kW ATEG installed on the Cummins NTC 325 and NTC 30 engines [17]. The obtained power was 1068 W for a 300 hp. engine at 1700 rpm. The ATEG used 72 thermoelectric modules (Hi-Z-13) based on bismuth telluride with 4.5% efficiency, the hot and cold side temperatures constituted 230 and 30°C, respectively. The authors concluded that special attention must be paid to the heat exchanger configuration because of the increased sensitivity to the temperature difference between its various components and their mean temperature.

In 1998, Nissan Motor group presented ATEG test results for a 3000 mL gasoline engine with $SiGe$-based thermoelectric modules that demonstrated maximum power 35.6 W at 60 km/h on hill-climb mode with 1141°C exhaust gas temperature [18]. The total efficiency η_t of heat exchanger constituted 11% and the heat flow through the modules was converted into electricity with generated power η_p 0.9% efficiency. It was noted that by increasing 50% η_t and 5% η_p, the alternator's power would reach 950 W. It is worth to mention that a bypass was used to regulate the heat flow during the experiment.

In 1999, this group created and tested generator for 2 and 3 L gasoline engines with Hi-Z-14 modules based on Bi_2Te_3. This system demonstrated maximum power 193 W under the same operating conditions; with η_t constituting 37% and η_p 2.9% [19].

The early research in ATEG was devoted to the following issues: the total heat to electricity conversion efficiency, the dependence of the output power on the engine rpm (obtaining the maximum power at the maximum rpm), and the key directions for further work. Along with the development of more efficient thermoelectric materials, special emphasis is laid on the intensification of heat transfer processes in ATEG, especially the heat recovery in a gas heat exchanger.

In 2012, Amerigon (now Genterm) in collaboration with BMW and Ford, and the financial support from DOE presented results of their project in ATEG launched in 2004 [20]. A prototype ATEG for two passenger cars (BMW X6 and Lincoln MKT) was constructed and installed into the exhaust system behind the catalytic converter. The project focused on the effect the ATEG with an integrated bypass had on various car systems. Static and dynamic experiments were carried out, including the US06 drive cycle. Fuel efficiency was found to be 1.2% at 110 km/h. The maximum peak power for BMW X6 at 125 km/h in the stationary and dynamic modes constituted 605 and 450 W, respectively.

Between 2011 and 2015, Genterm in cooperation with BMW and Tenneco, continued work on ATEG. The aim of the new project was to achieve 5% reduction in fuel consumption over US06 cycle with the potential for efficient commercialization [21]. In the end, the average fuel saving was 1.2% (9.2 g/mil CO_2 emission reduction) for a Ford F350 (6.2 L SOHC V8 flex fuel engine) with maximum 1160 W and average 470 W generator power over US06 cycle. At the same time, CO_2 emission increased by 0.2 g/mil for a BMW X3 28i with the ATEG. CO_2 emission increasing was explained by automobile weigh increasing and requiring more power for cooling system. These results confirm the necessity of TEG and all car systems optimization.

ATEG with Bi_2Te_3-based TEMs was developed as part of the HeatReCar [22, 23] project with Fiat and Chrysler collaboration. The system was installed onto an IVECO Daily light-duty truck with a 2.3 l diesel engine, and showed a 2.2% increase in fuel efficiency (6.7 g/km reduction in CO_2 emission) over NEDC cycle and 3.9% increase in fuel efficiency (9.6 g/km reduction in CO_2 emission) over WLTP cycle. The project also developed and tested skutterudite-based TEM for high-temperature applications.

The RENOTER project, launched in 2008 by Renault Trucks and Volvo, was aimed at creating ATEG for diesel (100–300 W depending on the driving cycle) and gasoline (up to 500 W) passenger cars, as well as for large trucks (up to 1 kW) with 0.3–1.3 $/W cost of generated electricity [24]. Apart from the heat exchanger design optimization, the project focused on the development of effective, cheap and reliable thermoelectric materials and their installation onto generators (Mg_2Si- and $MnSi_{1.77}$-based materials).

The analysis of the ATEG projects over the past 15 years reveals the drive to reduce fuel consumption or CO_2 emission, to make the design solutions economically efficient and to meet the reliability indicators. This has the following implications: ATEG must be investigated in dynamic as well as in stationary modes; tests over various operating cycles must be conducted, cheaper; less toxic materials must be used for TEM; reliability must be evaluated and maintained. Even though the projects do not always achieve their goals in full, the great potential in optimizing individual design and technological solutions is obvious.

The analysis of publications shows that the number of papers dealing with various aspects of the ATEG development is growing every year (**Figure 1**).

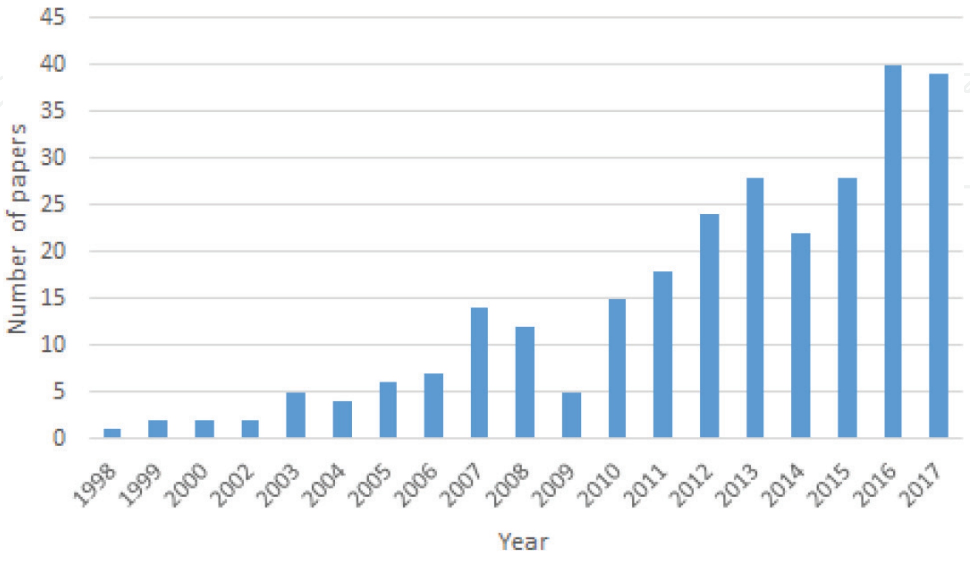


Figure 1. Research papers in ATEG (SCOPUS).

Over the past 5 years, China has become the leader in the number of publications in this field, with Wuhan University of Technology being the most active at ATEG research. In terms of publications total, the US holds the first place, with Caltech having the highest number of publications. The following organizations are playing an active part in the ATEG research: German Aerospace Center (DLR), TU Berlin, Loughborough University (UK), AGH University of Science and Technology (Poland) and Chungbuk National University (Korea). In Russia, Bauman Moscow State Technical University and Moscow Polytech are working on ATEG.

3. ATEG design

3.1. Features of technical requirements for ATEG in comparison with stationary TEGs

The increase in the electrical power of on-board equipment cannot always be achieved by installing a more efficient alternator due to the high density of the layouts of modern ICEs (this is especially true for small vehicles, for example, motorcycles). In this case, the TEG installation on the EG system can be the way out.

At the same time, in contrast to TEGs operating in stationary conditions with a constant heat flux, the effective use of TEGs for vehicles requires the solution of a number of specific tasks which must ensure:

- durability of device under variable thermal and mechanical loads associated with frequent changes in engine operating modes and vehicle vibrations;
- minimization of electric losses during various operating conditions of internal combustion engine and varying electric load;
- technological solutions must be compatible with mass production;
- optimal layout of ATEG with certain mass and dimensional constraints;
- effective convective heat transfer of TEG hot heat exchanger with a limited heat exchange surface area with low hydraulic resistance.

The solution of these problems requires a rational arrangement of TEG, parametric optimization of the quantitative TEG models taking into account multiple accompanying physical processes as well as carrying out experimental studies for quantitative verification of models and prototype tests.

3.2. General requirements for ATEG design

As a rule, ATEG has a hot heat exchanger coming through the EG and one or more TEM sections, cold heat exchanger to drain the heat into the hydraulic cooling system or directly into the external environment, the voltage stabilization system for the on-board power supply system (12 V).

ATEGs must be connected to the exhaust, power and hydraulic cooling systems of the vehicle and effectively operate with them. However, there are challenges of all these points implementation during ATEG design.

General technical requirements for ATEG:

- technological design for series production;
- reliability with frequent changes in pressure and temperature of EG;
- limitation of weight and dimensions;
- high efficiency of heat removal and heat transfer;
- low hydraulic resistance;
- no resonance frequencies in the range of 15–200 Hz.

Technical requirements differ significantly in a wide range depending on the type of vehicle. For example, the limitation for mass and dimensions for trucks is much softer, while the requirement for air resistance is much stricter than for a motorcycle.

There are conflicts of design goals. The most challenging issue is that high efficiency of heat removal can be achieved due to fins and turbulators of the EG flow, but they increase the air resistance.

Below, in this section, the known technical solutions and the structural elements used in them and requirements to them are described.

3.3. ATEG quality characteristics

The integral TEG quality characteristics are

- electric power supplied by the TEM W_{TEM};
- electric power consumption W_{need} for the operation of TEG auxiliary systems;
- total electric power produced by TEG W_{teg};
- drop pressure of a hot heat exchanger Δp_{teg};
- the efficiency of TEM η_{TEM};
- the efficiency of TEG η_{teg};
- TEG weight m_{teg}.

But these parameters can only be determined for a given engine with a selected operating mode or as the function of the flow, temperature of the EG, the flow and temperature of the liquid in the cooling system and the resistance of the electrical load R_{load} applied to the TEG.

When TEG and ICE are simultaneously considered, the quality characteristics are:

- measuring the fuel consumption of the internal combustion engine while maintaining the shaft power Δq_{fuel};
- increment of the ICE shaft power ΔW_{mech} while maintaining fuel consumption q_{fuel};
- the change in the content of toxic impurities in the EG;
- the change in the level of acoustic vibrations in the EG stream.

These values must be measured for certain operating modes of the ICE. For example, the fuel consumption and emissions into the atmosphere from passenger cars are regulated by the standards: In Europe NEDC, in US EPA Federal test FTP72/75 and JC08 in Japan. Recently, the transition to the unified standard Worldwide harmonized Light vehicles Test Procedure (WLTP) is planned. These standards describe the sequence of changes in the speed of a vehicle in typical operating modes ("Urban driving Cycle", "Extra-urban driving Cycle" and "Combined"), which is installed on a test stand. Similar standards exist for other types of vehicles.

3.4. Hot heat exchanger

Much attention is paid to the design of the ATEG hot exchanger. As a rule, the resistance of convective heat transfer is the largest in the thermal circuit of ATEG or comparable to the resistance of TEM. For example, the thermal resistance of convective heat transfer was 39–76% of the total resistance in the thermal circuit of TEG, decreasing with the growth of engine rotation n_e (**Figure 2**) in the mathematical model for TEG with hexagonal heat exchanger and longitudinal finning described in [25]. The design of the TAG is similar to the one described in article [26], but the contact resistance of the joints was also taken into account which are also very significant.

To obtain acceptable contact resistance of joints, the following actions are required: increase of holding pressure on the surface area, surface treatment of heat exchanger with low roughness and shape deviations, elimination of corrosion and thick oxide films and application of high-temperature thermal grease.

The hot TEG heat exchanger should have a large area for the installation of serial flat TEMs. Constructions with 2 [27], 4 [28] and 6 [25, 26, 29, 30] external faces are known. In **Figure 3**, the elements of TEG with such constructions are marked: 1 - hot heat exchanger; 2 - TEM; 3 - cold heat exchanger; 4 and 5 - diffuser and conceiver. Diffuser and conceiver are needed for uniform heat exchange and reduction of hydraulic resistance. The displacer 6 and the heat fins 7 serve to intensify the heat exchange.

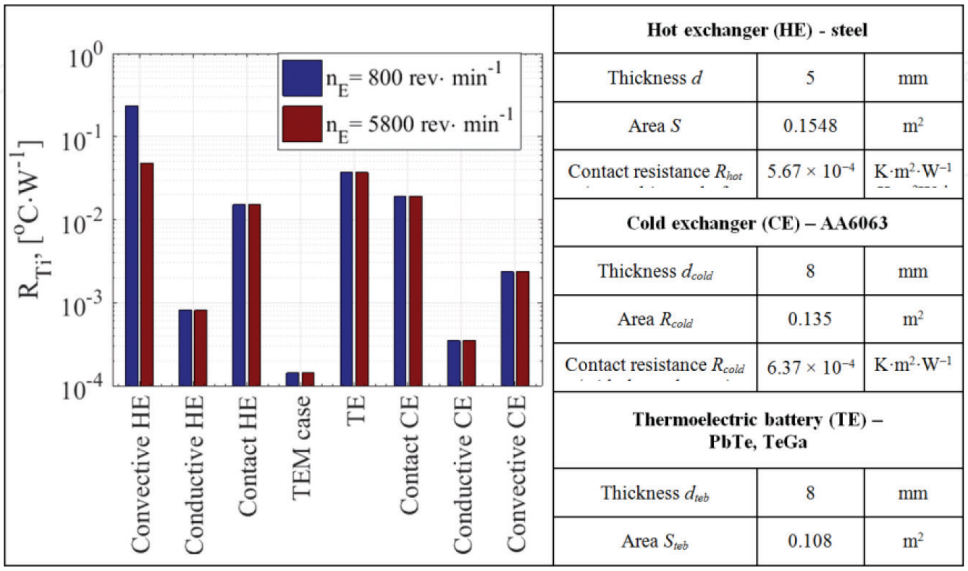
There are known TEG versions made with several modular heat exchangers of a flat [33] or cylindrical [21] shape (**Figure 4**), the number of which must be selected for different cars, based on the consumption of EG. This greatly simplifies the design of the TEG, because the heat exchange module, with the hot and cold heat exchanger, and thermoelectric elements have been optimized in advance. The designs with flat heat exchangers involve the use of serial TEMs and can easily be adapted to other exhaust gas temperatures by changing the TEM. The design with cylindrical modules requires manufacturing special thermocouples and is more difficult to be adapted to other temperatures. Constructions with cylindrical heat exchangers (**Figure 4b**) have a larger ratio of the area of the hot heat exchanger to the area of the cold heat exchanger, but its disadvantage is reduction of pressure in a contact area, in the case if this area is heated.

To intensify convective heat transfer in a hot heat exchanger, longitudinal [25] or oblique [29] fins and a displacer [25, 29, 30] are used, although they increase the hydraulic resistance. To reduce the length of the thermal way, the fins must run perpendicular to the plane of the heat exchanger, but in terms of manufacturability, it is convenient to make the fins in the form of folded plates [34–36] (**Figure 5a**). The heat exchanger shell can be made from cast iron or by connecting steel billets. If the fins are made from individual blanks, they must be welded to reduce thermal resistances.

The EG temperature reduces as it moves inside the hot heat exchanger. If several sections of the same TEM are used in the TEG, in order to equalize their heat flux through the different sections, it is necessary to increase the heat flux for the TEM sections located closer to the outlet. To do this, increase the area and thickness of the heat fins located closer to the outlet (**Figures 3a** and **5a**) or include water cooling towards the EG flow.

Despite the fact that the models of gas heat exchangers have been thoroughly studied [37, 38], complex geometry of the structure and nonlinearity of heat transfer in turbulent motion require the optimization of the flow channel with the use of finite volume method [27, 29] for estimating the heat flow and hydraulic resistance.

The approximate values of the pressure differences for some of the considered TEG heat exchangers for passenger cars are given in **Table 1**. The length of heat exchanger L is with lengths of diffuser and conceiver. D_p is an inside diameter of the inlet branch pipe.



Hot exchanger (HE) - steel		
Thickness d	5	mm
Area S	0.1548	m^2
Contact resistance R_{hot}	5.67×10^{-4}	$K \cdot m^2 \cdot W^{-1}$
Cold exchanger (CE) – AA6063		
Thickness d_{cold}	8	mm
Area R_{cold}	0.135	m^2
Contact resistance R_{cold}	6.37×10^{-4}	$K \cdot m^2 \cdot W^{-1}$
Thermoelectric battery (TE) – PbTe, TeGa		
Thickness d_{teb}	8	mm
Area S_{teb}	0.108	m^2

Figure 2. Resistance of the components of the thermal circuit in [25], HE, hot exchanger; TE, thermoelectric element; CE, cold exchanger.

These drop pressures are quite large and can lead to a drop in the efficiency of the engine, which suggests the need for careful optimization of the flow channel taking into account its resistance to exhaust gas flow and its effect on the ICE.

According to RANS turbulent model usage [27], it is defined that the presence of numerous dimples in comparison with a flat wall allows increasing the Nusselt number Nu by 1.17–1.4 times with an increase of the Reynolds number Re from 10,000 to 25,000, but at the same time fanning friction factor f grows in 1.05–1.25 times. A single quality parameter is selected in [27] taking into account the intensification of heat exchange and the increase in friction factor:

$$P = \frac{Nu}{Nu_0}\left(\frac{f_0}{f}\right)^{1/3} \tag{1}$$

where Nu and f_0 are Nusselt number and the friction factor flow for a heat exchanger with a flat wall. According to parameter P, the heat exchanger with dimples turned out to be better than two designs with straight fins.

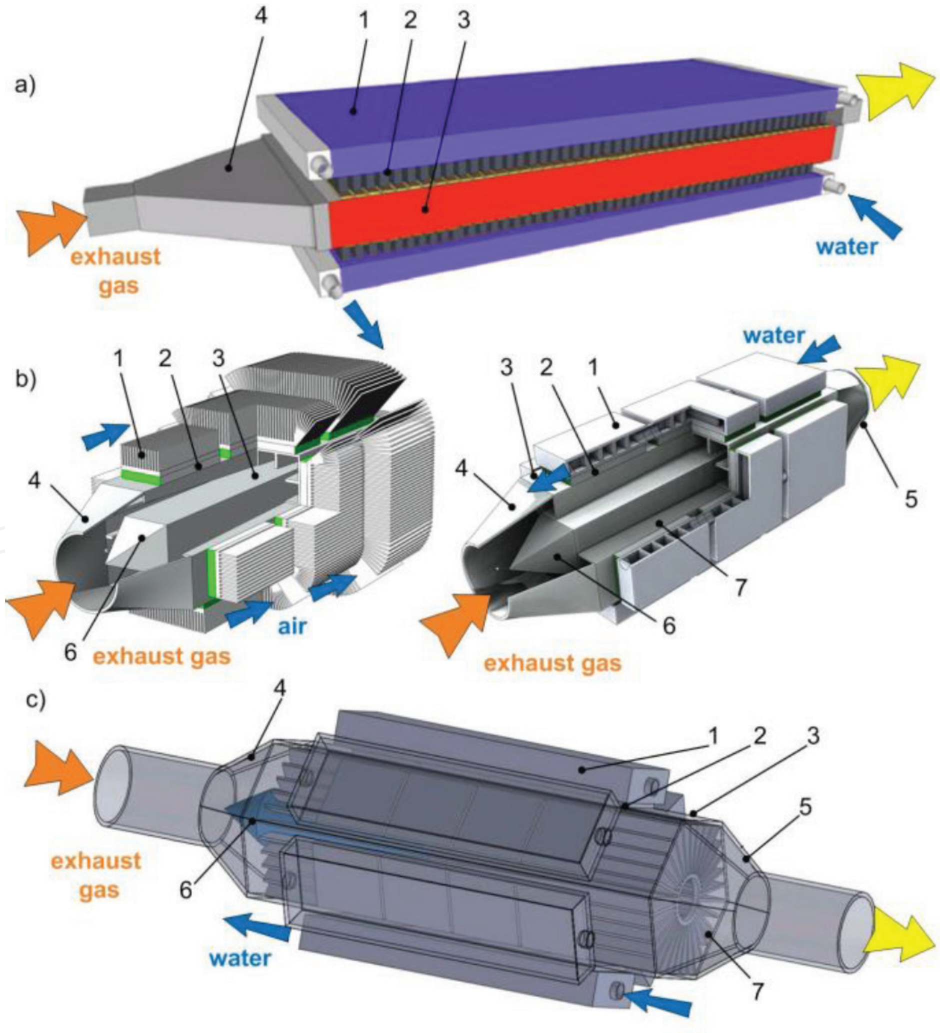


Figure 3. Constructions with flat walls of hot heat exchanger: (a) with two flat walls [31, 32]; (b) with four flat walls [28]; (c) with six walls [25, 33].

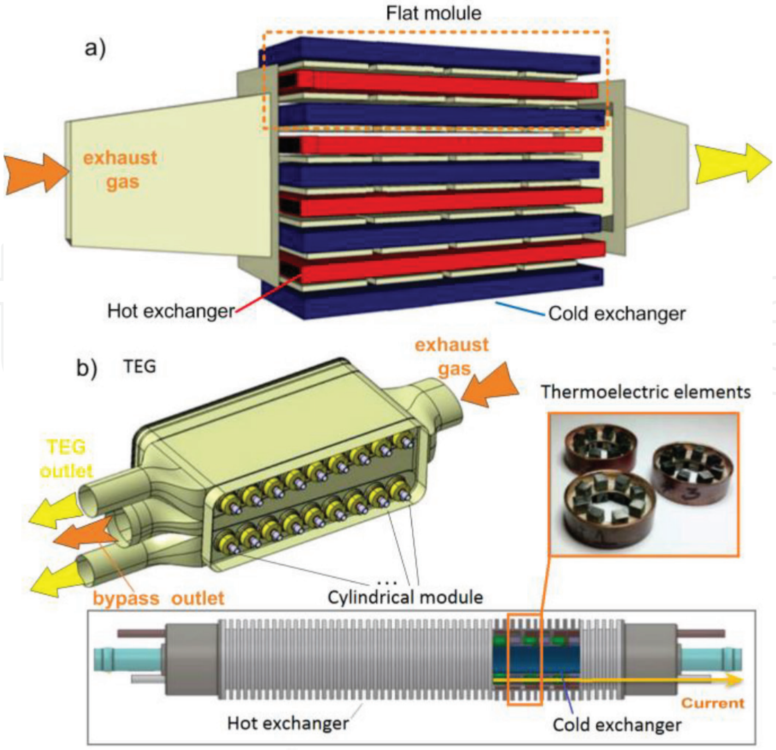


Figure 4. TEG constructions with several hot heat exchangers: (a) with flat modules [33]; (b) with cylindrical modules [21].

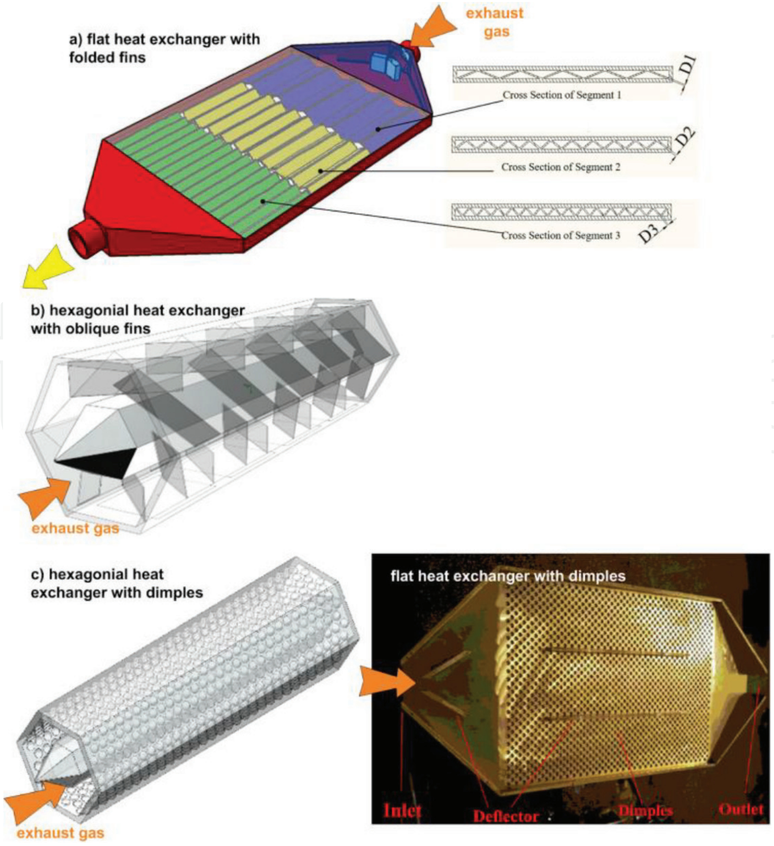


Figure 5. Thermal heat exchange intensifiers: (a) fins in the form of folded plates [35]; (b) oblique fins [29]; (c) dimpled surface [27].

Drop pressure Δp_{eg}, Pa	Flow EG Q_{eg}, L/min	Inlet EG temperature T_{EG}, K	TEM heat flow Q, W	Cross-section of heat exchanger, mm	Methods of convection intensification
100–700	1800	600	500–750	Rectangle 295 × 12 (inner sizes) $L = 625$, D_p=35	Flat heat exchangers with fins and dimples (**Figure 5c**) [27]
4800–5360	3920	570–870	—	Rectangle 310 × 22 (outer sizes) $L = 696$, D_p=50	Flat heat exchangers with folded fins (**Figure 5a**) [35]
250–450	2730	350–760	500–4200	Hexagon (side 63) $L = 408$, $D_p = 50$ inner hexahedral dispergator (side 20, length 174)	Hexagonal heat exchanger with longitudinal fins [39]
960	3650	1073	5300	Hexagon (side 62) $L = 593$ D_p=45 with inner hexahedral dispergator (side 29, length 513)	Hexagonal heat exchanger with flat walls [29]
1920	3650	1073	7550		Hexagonal heat exchanger with longitudinal fins [29]
2360	3650	1073	7200		Hexagonal heat exchanger with oblique fins and heat exchange intensifiers in the form of pits [29]
6420	3650	1073	8640		

Table 1. Comparison of pressure differentials in various works.

In [29], eight designs of hexagonal heat exchangers with different combinations of longitudinal, oblique fins and also with dimpless are compared based on finite volume method quantification with the use of Lam-Bremhorst $k-\varepsilon$ turbulence model. As a generalized criterion, a parameter of:

$$P = \frac{Nu}{Nu_0}\frac{\varepsilon_0}{\varepsilon} = \frac{Nu}{Nu_0}\frac{f_0}{f} \tag{2}$$

where ε is loss factor.

However, such approaches do not allow to take into account the actual drop in the engine power from the pressure drop, therefore it is necessary to introduce the ICE model and consider the mutual behavior of the internal combustion engine and ATEG, as was done in [21, 25, 30]. For this purpose, approximate dependencies of the power drop of the internal combustion engine on the volume flow EG and additional hydraulic resistance of the exhaust pipe was constructed.

Convection intensification of heat exchanger can provoke the oxidation of products due to incomplete fuel combustion (hydrocarbon and volatile organic compound), but the authors of this section are not acquainted with the quantitative studies on this issue.

Thus, the technical requirements for the hot heat exchanger are:

- low hydraulic resistance;

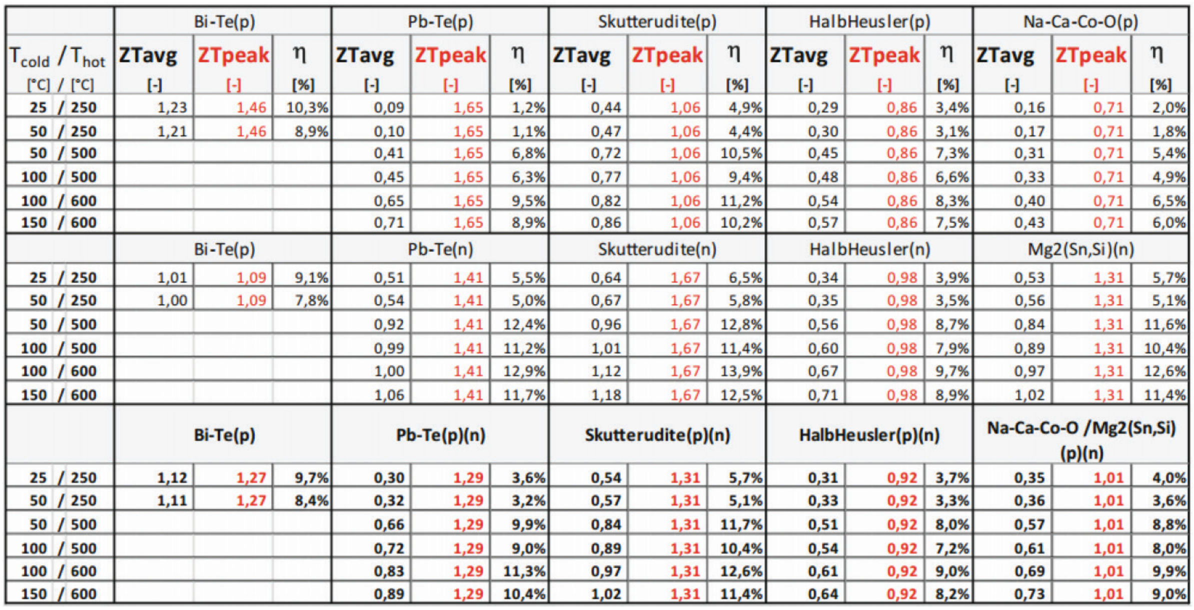
- ability to work at EG temperature up to 700–1000°C without corrosion and loss of load-bearing capacity;
- high efficiency of convective heat sink;
- possibility of clamping TEM with considerable efforts without heat bridges;
- it is desirable to have elastic expansion bends for temperature deformations in the heat exchanger itself and (or) in the TEM system clamping.

3.5. Thermoelectric materials and modules

The TEM is a key element of ATEG, in which, through the Seebeck effect, there is a direct conversion of the heat into electricity. The output electric power of the TEM depends on the heat flux, the temperature difference of its thermocouples, the thermal and electrical resistances in its construction, the geometry of the thermoelements which must be optimized for the given temperature conditions, the consistency of the internal resistance with the load resistance and the ZT-factor of used semiconductor materials. Moreover, ZT under optimal design is a key parameter of TEM efficiency.

Figure 6 shows the required (green line) and achievable electrical power of ATEG when it is installed in different parts of the exhaust system (close-coupled position or away from the engine). The data are given for different materials/modules for different types of cars with efficiency of the hot heat exchanger η_t of 50, 66 and 75% (C/D - mid-range class, E/F - upper/luxury class and M/J - multi-van, SUV, utilities). **Table 2** shows the efficiency of the most promising materials for use in ATEG.

The analysis of **Figure 6** shows that for achieving the required electrical power, the efficiency of the thermoelectric module, using a heat exchanger of 50%η_t, should be at least 8.2%. Increasing the



	Bi-Te(p)			Pb-Te(p)			Skutterudite(p)			HalbHeusler(p)			Na-Ca-Co-O(p)		
T_{cold} / T_{hot} [°C] / [°C]	ZTavg [-]	ZTpeak [-]	η [%]	ZTavg [-]	ZTpeak [-]	η [%]	ZTavg [-]	ZTpeak [-]	η [%]	ZTavg [-]	ZTpeak [-]	η [%]	ZTavg [-]	ZTpeak [-]	η [%]
25 / 250	1,23	1,46	10,3%	0,09	1,65	1,2%	0,44	1,06	4,9%	0,29	0,86	3,4%	0,16	0,71	2,0%
50 / 250	1,21	1,46	8,9%	0,10	1,65	1,1%	0,47	1,06	4,4%	0,30	0,86	3,1%	0,17	0,71	1,8%
50 / 500				0,41	1,65	6,8%	0,72	1,06	10,5%	0,45	0,86	7,3%	0,31	0,71	5,4%
100 / 500				0,45	1,65	6,3%	0,77	1,06	9,4%	0,48	0,86	6,6%	0,33	0,71	4,9%
100 / 600				0,65	1,65	9,5%	0,82	1,06	11,2%	0,54	0,86	8,3%	0,40	0,71	6,5%
150 / 600				0,71	1,65	8,9%	0,86	1,06	10,2%	0,57	0,86	7,5%	0,43	0,71	6,0%
	Bi-Te(p)			Pb-Te(n)			Skutterudite(n)			HalbHeusler(n)			Mg2(Sn,Si)(n)		
25 / 250	1,01	1,09	9,1%	0,51	1,41	5,5%	0,64	1,67	6,5%	0,34	0,98	3,9%	0,53	1,31	5,7%
50 / 250	1,00	1,09	7,8%	0,54	1,41	5,0%	0,67	1,67	5,8%	0,35	0,98	3,5%	0,56	1,31	5,1%
50 / 500				0,92	1,41	12,4%	0,96	1,67	12,8%	0,56	0,98	8,7%	0,84	1,31	11,6%
100 / 500				0,99	1,41	11,2%	1,01	1,67	11,4%	0,60	0,98	7,9%	0,89	1,31	10,4%
100 / 600				1,00	1,41	12,9%	1,12	1,67	13,9%	0,67	0,98	9,7%	0,97	1,31	12,6%
150 / 600				1,06	1,41	11,7%	1,18	1,67	12,5%	0,71	0,98	8,9%	1,02	1,31	11,4%
	Bi-Te(p)			**Pb-Te(p)(n)**			**Skutterudite(p)(n)**			**HalbHeusler(p)(n)**			**Na-Ca-Co-O /Mg2(Sn,Si) (p)(n)**		
25 / 250	**1,12**	**1,27**	**9,7%**	**0,30**	**1,29**	**3,6%**	**0,54**	**1,31**	**5,7%**	**0,31**	**0,92**	**3,7%**	**0,35**	**1,01**	**4,0%**
50 / 250	**1,11**	**1,27**	**8,4%**	**0,32**	**1,29**	**3,2%**	**0,57**	**1,31**	**5,1%**	**0,33**	**0,92**	**3,3%**	**0,36**	**1,01**	**3,6%**
50 / 500				**0,66**	**1,29**	**9,9%**	**0,84**	**1,31**	**11,7%**	**0,51**	**0,92**	**8,0%**	**0,57**	**1,01**	**8,8%**
100 / 500				**0,72**	**1,29**	**9,0%**	**0,89**	**1,31**	**10,4%**	**0,54**	**0,92**	**7,2%**	**0,61**	**1,01**	**8,0%**
100 / 600				**0,83**	**1,29**	**11,3%**	**0,97**	**1,31**	**12,6%**	**0,61**	**0,92**	**9,0%**	**0,69**	**1,01**	**9,9%**
150 / 600				**0,89**	**1,29**	**10,4%**	**1,02**	**1,31**	**11,4%**	**0,64**	**0,92**	**8,2%**	**0,73**	**1,01**	**9,0%**

Table 2. Efficiency of thermoelectric materials and modules on their basis [40].

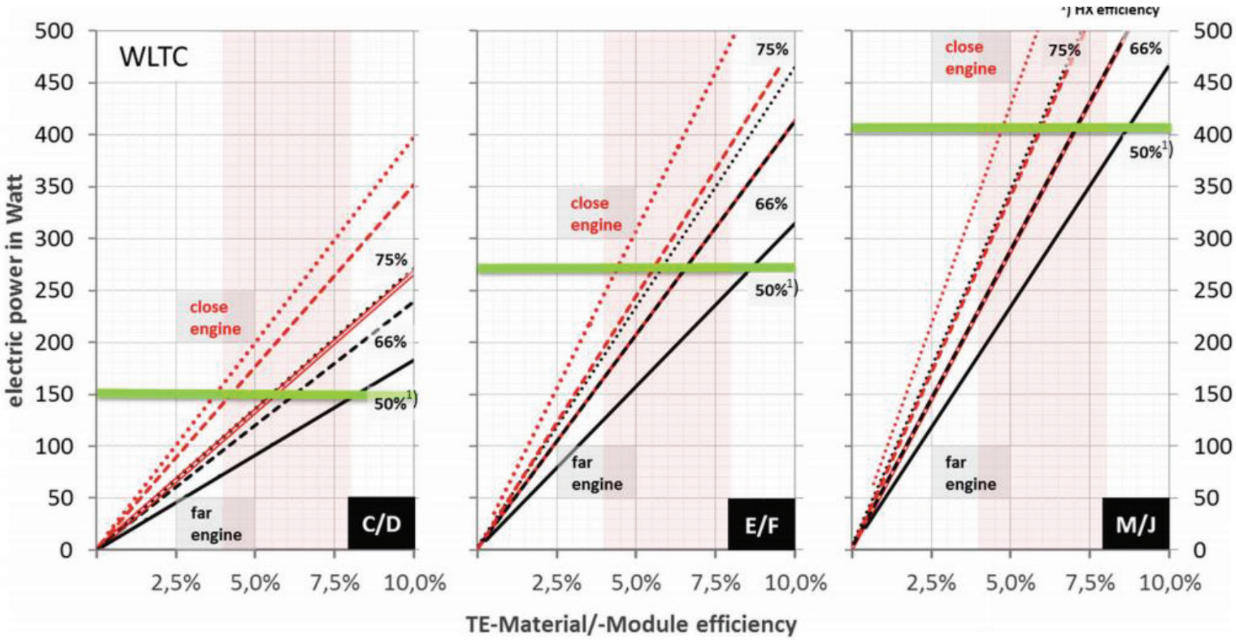


Figure 6. Necessary material/module efficiency [41].

efficiency of the heat exchanger and installing ATEG closer to the output manifold can reduce this requirement up to 5% or less. At the same time, on the basis of classical materials for which large-scale serial production is currently established (Bi_2Te_3, *PbTe*, *SiGe*), it is quite capable to satisfy these requirements. In addition, the large-scale serial production also imposes on us the friendly environmental production, non-toxic, reliability and low cost of ($/W energy) which unfortunately does not fully match with the materials above. The latter requirement is paramount. If the estimated the cost of current TEMs is 5 $/W, then economically it is necessary for ATEG, to increase the prospect of its commercialization, achieve 1 $/W [40].

Among the most promising materials—which are being actively developed and persistently being used in ATEG are the silicide, skutterudite or half-Heusler materials [40].

General technical requirements for TEMs used in ATEG can be presented:

- compactness;
- efficiency (TEM should convert as much heat as possible);
- mechanical strength in conditions of cyclic operation (heating/cooling, not less than 10,000 cycles);
- chemical stability under given temperature variables;
- shock and vibration durability in the range of 15–200 Hz;
- manufacturability and low production costs for serial production.

Existing developed ATEG mock-ups (prototypes) basically use TEMS with flat structure which thermoelectric elements are connected in series by conductor tabs commutation and clamped between two insulating ceramic or polymer plates (**Figure 7a**). Those plates are

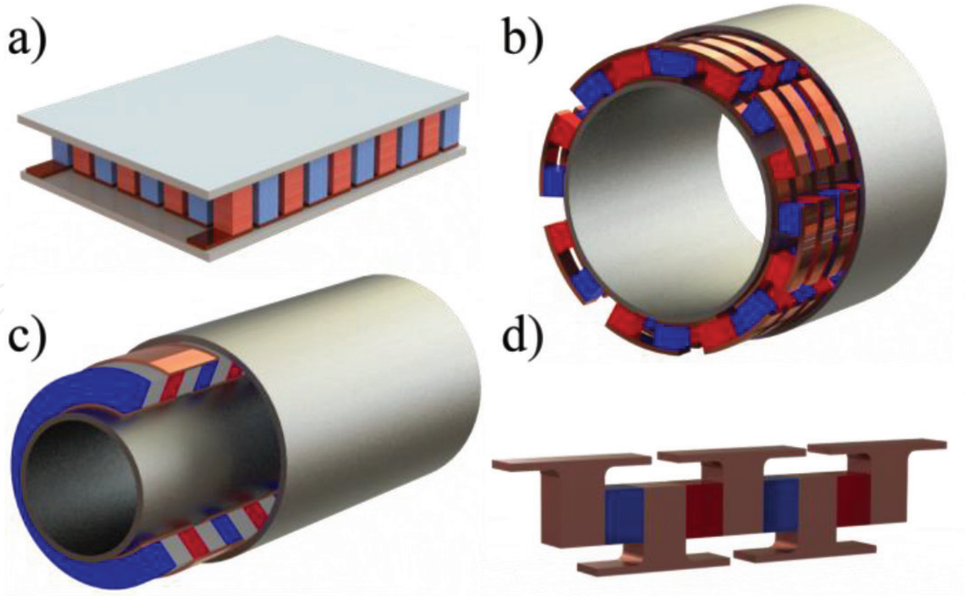


Figure 7. TEM designs: (a) with flat legs; (b) with cylindrical shape; (c) with disc shape; (d) with T-shaped conductive layers.

(cold and hot heat sides) perpendicular to heat flow. To protect from the sublimation process at high temperatures, the module can be placed in a sealed shell or coated with heat-resistant protective enamels. The use of such TEMs in ATEG presupposes the presence of flat surfaces on heat exchangers, and also requires careful study of the clamping design in order to ensure a constant and uniform effort throughout. The inability to provide such a clamp and, as a consequence, large thermal resistances forced the development of ATEG in the framework of the DOE No. DE-FC26-04NT42279 to move from a flat construction to a cylindrical one on its 4th stage [20].

The cylindrical design of ATEG with radial heat flow requires the use of tubular TEMs, in which the thermoelements can be utilized in the cylindrical (**Figure 7b**) or disc (**Figure 7c**) shapes [41]. Analogues of flat TEM with a cylindrical surface as heat exchangers can also be made. It should be noted that such TEMs will be considerably less technologically advanced than flat modules.

In view of the fact that ZTs of individual thermoelectric materials are significantly dependent on the temperature, there is a practice to use segmented thermoelements in TEMs for improving their efficiency [42, 43]. At the same time, the use of different materials with different physic-mechanical properties in the design of a thermoelement results in the need to harmonize, for example, the cross-sectional area for different materials and their thermal linear expansion coefficient (TLEC). The latter is especially important for ATEG operating under conditions of constantly changing heat flow, and also relates to the coordination of the TLEC of the p- and n-type elements and the conductive tabs for multi-segment TEMs.

An interesting design of the TEM, partially solving the problem of coordinating the material properties, was proposed in D.T. Crane et al. [44, 45]. This design with T-shaped conductive layers (**Figure 7d**), also playing the role of heat conductors, makes it possible to apply different thicknesses of elements and their different geometries, and to vary the thickness of individual segments, providing an optimal thermal operating mode for each material, therefore maximum efficiency. At the same time, attention is drawn to the stress state of the contact between thermoelement and conductive tab, due to the fact that during compression of such thermoelement between hot and cold heat exchangers minimum thermal resistances should be ensured.

3.6. Cooling system

ATEG for heat removal must be connected to the cooling system of the car or use its own cooling system.

In the first case, the load on the regular car cooling system is increasing. In most cars, the air intake area cannot be increased without significant design changes. This circumstance limits the thermal power passing through the TEG and the electric power it generates. This obstacle can be overcome for new models of cars that would be developed taking into account the possibility of installing TEG.

In the second case, the autonomic TEG cooling system can be designed in different ways.

An independent liquid cooling system with forced circulation is relatively complex and increases mass and dimensions. The air cooling of the ribbed cold heat exchanger with an oncoming airflow can be comparable to forced liquid cooling. So in the article [28] when considering TEG models for motorcycles and snowmobiles with Yamaha WR450F motorcycle engine (a volume 0.449 mL), the values of the generated electric power of 80–105 W have been obtained at speeds of more than 40 km/h. But the protruding air radiators will inevitably degrade the aerodynamic characteristics of the vehicle.

Thermoelectric generators for internal combustion engines on water transport or snowmobiles can be installed without large and protruding cold heat exchangers due to the high efficiency of cooling by water and snow.

It should be noted that the use of an independent forced liquid cooling system requires additional energy costs for pumps, fans and valves operations. In the case of the ATEG integration into the car cooling system there is a need in the additional power for increasing cooling system productivity. In this way, the electricity generated by ATEG partly expend on the operation of the ATEG itself.

The paper [21] presents the results of the evaluation of the ATEG various components and parameters influence on CO_2 emissions for two generators installed on BMW X3 and Ford F350 cars. The energy consumption of the ATEG cooling system on the BMW X3 (**Figure 8**) averages 5.7 W in the cycle US06 (0.2 g CO_2/ mil emission increase) with an average generator power of 19.8 W. The cooling system of FORD F350 requires 25 W (0.5 g CO_2/mil emission increase) with an average generator power of 470 W under the same conditions.

In the same article [21], 23 concepts of ATEG integrating into the car cooling system are developed according to the following criteria:

- influence on engine warm-up;
- influence on engine cooling;
- influence on transmission warm-up;

- influence on transmission cooling;
- influence on TEG cooling;
- influence on warm-up of cabin heating;
- electric power consumption;
- weight and
- expected costs.

As a result, the authors choose the most optimal solution (**Figure 9**), the main idea of which is that the designer should use the extracted exhaust heat for accelerate engine warm-up, without influencing the original warm-up strategy of the cooling system.

When using forced liquid cooling (general or independent), it is necessary to provide for the regulation of the flow rate of the liquid in order to reduce the energy loss when pumping the liquid in the conditions of low thermal power passing through the TEG (for example, idling).

3.7. Cold heat exchanger

A cold heat exchanger must remove heat from the TEG into the water cooling system or directly into the external environment. The second option can be very simple and effective when cooling with snow (for snowmobiles) or with water (for hydrocycles) when the heat transfer coefficient $a_{cold} > 1000$ W/(m^2 K). Cooling by external ambient air requires the installation of numerous ribs, since in this case $a_{cold} = 20$–100 W/(m^2 K), and this strongly depends on the speed of the ambient air [28]. Installing an external ribbed air heat exchanger can increase the aerodynamic resistance of the vehicle. Even if it is a small increase in resistance—this phenomenon can offset the reduction in fuel consumption from electricity generation.

The geometry of the water heat exchanger is paid much less attention, since due to the high heat transfer coefficient there is very favorable heat removal conditions (**Figure 2**).

As an example, there are the results of ATEG calculations with air and forced water cooling, considered in the article [28] (**Figure 10a**, **b**) for Yamaha WR450F IC engine (volume 0.449 L, 9000 revmin^{-1}). **Figure 10** shows: 1 – hot heat exchanger; 2 - TEM with the height b_{te} of the thermoelement; 3 – cold heat exchanger. The air heat exchangers are considered in a motorcycle operating conditions (air flow temperature $T_{air} = +20$°C and speed V_{air}) and snowmachine mode ($T_{air} = -20$°C and speed V_{air}).

The gas heat transfer calculations are performed with free air flow around ATEG without taking into account the geometry of the vehicle.

The different heights of thermoelements calculations allows choosing the optimal value $b_{te} = 17$ mm for the developed ATEG (**Figure 10d**). The generated ATEG power W_{TEG} greatly decreases with air speed V_{air} decreasing and air temperature T_{air} increasing.

At $T_{air} = -20$°C and $V_{air} = 100$ km h^{-1} ATEG with air cooling has comparable power W_{TEG} with water cooled ATEG (**Figure 10d**). In this case, averaged in time electric power which supplies cooling systems $W_{need} = W_{TEM} - W_{TEG}$ is about 10 W or about 10% of the power produced by the optimal design.

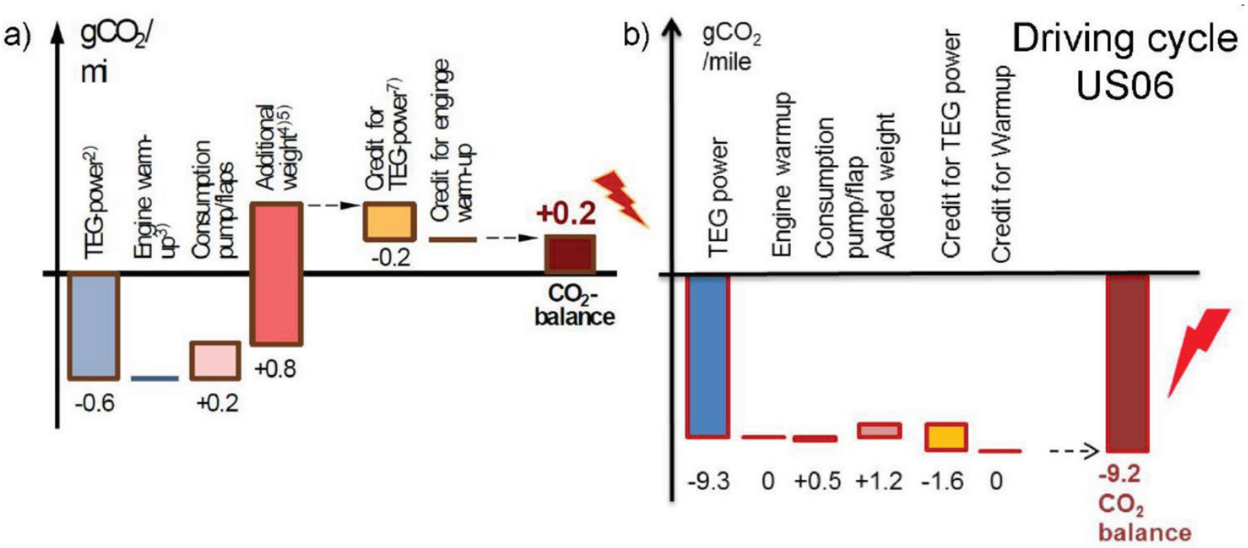


Figure 8. The results of the evaluation of the ATEG various components and parameters influence on CO_2 emissions for BMW X3 (a) and Ford F350 (b) ATEGs [21].

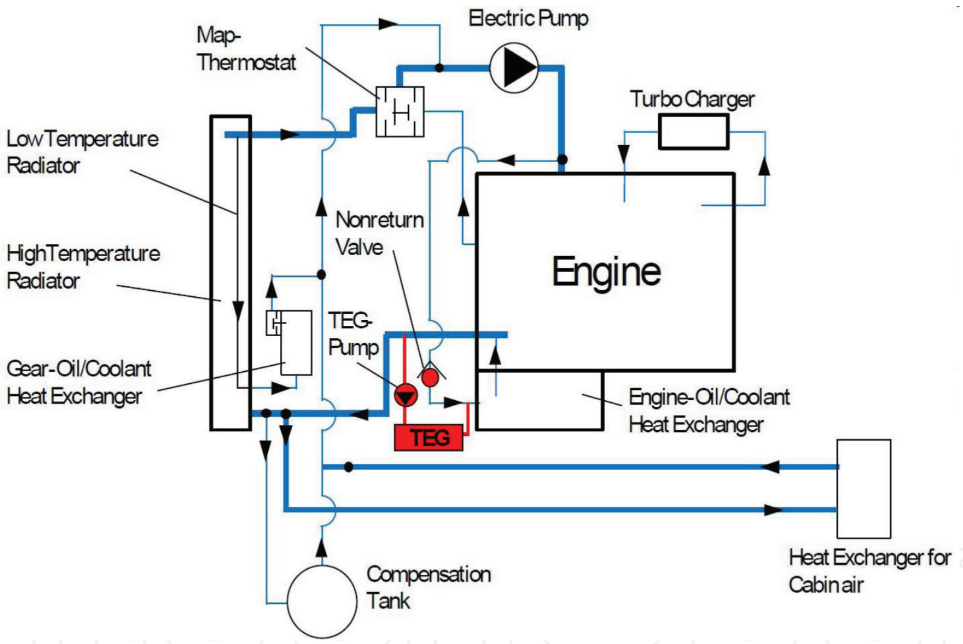


Figure 9. Coolant system of X3 xDrive28i with automatic transmission and selected concept for coolant integration [21].

Technical requirements for the cold heat exchanger:

- insignificant contact thermal resistance;
- lightweight construction;
- amount of water should be precisely defined for required cooling;
- corrosion resistance and
- when using a heat transfer fluid, the possibility of boiling, leaks, and condensation on cold parts should be avoided.

3.8. Choice of heat exchanger material

Physical requirements for the material of heat exchangers:

- high corrosion resistance;
- high thermal conductivity of the material;
- good machinability of obtaining thermal surfaces with small roughness and deviations of a shape;
- low density and/or high durability for decreasing the weight.
- for hot heat exchangers, a melting point substantially higher than the temperature of EG (700–1000°C) is needed.

Table 3 compares the properties of the materials used with pure copper, which has the greatest thermal conductivity among structural materials. Adding impurities to copper or aluminum greatly reduces thermal conductivity, but increases strength and often corrosion resistance. The density of the material ρ affects the weight and cost. The coefficient of thermal expansion α is important in calculating thermal deformations and stresses.

The thickness of metallic heat exchangers walls is usually a few millimeters and their thermal resistance is negligible. But the finned gas heat exchangers are characterized by a long thermal path, therefore a high thermal conductivity is desirable for them λ.

Copper cannot be used in a hot heat exchanger because of its low corrosive resistance in the air against CO_2 vapors and water, without protective coatings (for example, nickel). Its application could be justified for external heat exchangers, but the issue is not enough density and high cost.

Aluminum can be applicable only for cold heat exchanger due to its low melting temperature characteristic. Also aluminum is cheap and has excellent corrosion resistance. Thermal conductivity of pure technical Aluminum is very high, but even insignificant amount of impurities can reduce conductivity by 1.5–2 times. So it is necessary to carefully select the fins size for finned aluminum air cold heat exchangers.

Steel has a high melting point and density. Low-carbon steels are prone to corrosion, and stainless steels have very low thermal conductivity, limited weldability and high cost. It is possible to use special stainless steels, for example, AICI 304, used for the manufacture of mufflers and hot air ducts. But the low thermal conductivity of this steel requires the production of hot heat exchangers with short and thick fins.

Cast iron makes it possible to create complex parts with good corrosion resistance. For example, cast radiators for heating systems were widely used before. The thermal conductivity of cast iron is strongly dependent on the shape and orientation of graphite inclusions having a thermal conductivity comparable to copper. The thermal conductivity of cast iron decreases with decreasing carbon content and increasing alloying additives, especially those that reduce graphitization (Mn,Cr). Grinding the size of graphite additives increases the strength, but reduces the thermal conductivity. For the manufacture of heat exchangers by casting, EN-JL1050 and the like grades can be used. However, it is desirable to avoid overheating of parts of cast iron heat exchangers in order to avoid ferritic-austenitic transformations (723°C).

Recommendations:

- cold water and air heat exchangers can be made from most of aluminum alloys.
- the finned hot heat exchangers are preferably made of low-carbon steel (possibly with anti-corrosion coatings) or cast iron (for example, Cast EN-JL1050).
- hot heat exchangers without fins or with short fins can be made by casting from cast iron or by welding from stainless steels, for example AICI 304.

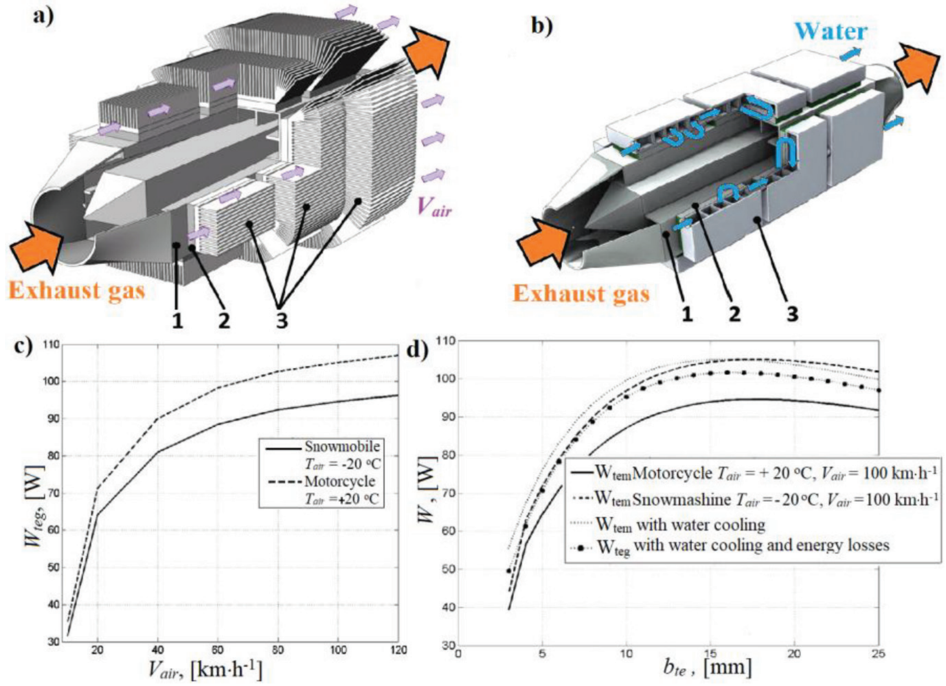


Figure 10. Comparison of TEG power with air cooling (a) and water cooling (b); temperature influence *T air* and air speed *V air* on power *W TEG* generated by ATEG (c); the influence of the thermoelement height *b te* on TEM generated power *W TEM*(d).

	Density ρ, kg·m-3	Thermal conductivity λ,W/(m·K)	Thermal expansion α ·106, 1/K	Melt point (soludus forallow) T, K
Pure copper	8933	400	17	1358
Pure aluminum	2702	240	24	933
Aluminum alloys	2600…2850	110–190	21–24	775–993
Low-carbon steel	7850	40–60	11–13	1425–1540
Stainless steel AICI 304	8000	17	17–18	1400
Cast EN-JL 1050	7250	42–44	13	1426

Table 3. Characteristics of materials for heat exchangers at T range 573–873 K.

3.9. Troubleshooting

This section provides general recommendations for troubleshooting issues that may occur when operating the ATEG.

Electrochemical corrosion is excluded by the selection of contacting materials with equal electrochemical potentials, qualitative isolation of electrical systems, using protective, electrically insulating or corrosion-resistant coatings and observing the pH of the coolant.

Excessive thermal deformations can lead to plastic deformation of parts and loss of flatness of contacts. It is possible to reduce the pressure force with the help of selecting the suitable materials as per their thermal expansion coefficients and using the elastic compensators for thermal deformations.

Fretting-wear occurs under the action of periodic tangential shifts on contacts. This process has not been fully studied. It can be eliminated by reducing the contact pressure (see paragraph above), using hardening or antifriction coatings or thermal grease.

The thermal contact resistance can increase due to several factors which are: oxidation, degradation of the thermal grease or reduction of the pressure during heating or cooling. Using of resistant materials, protective coatings and adjusting loads pressure can eliminate it.

Cleaning and monitoring of the pH of the coolant, selection of corrosion-resistant materials or coatings prevent heat exchangers pollution from corrosion, water deposits and soot.

4. Math modeling

It is necessary to conduct a number of tests to optimize the design of ATEG in order to increase the electric power it generates and its efficiency. Building a reliable mathematical model of the automotive thermoelectric system is the most rational solution to this problem. Detailed modeling can help to find the optimal combination of ATEG parameters. In addition, the estimation of various system parameters for existing driving cycles allows predicting the appropriateness of using a generator in a specific car model.

4.1. Structure of the mathematical model

In general, the mathematical model of ATEG should describe the behavior of a system consisting of the following components: car engine, hot heat exchanger, TEM unit, cold heat exchanger, cooling system, power control system (PCU) and consumption load. Block diagram showing the interaction of these subsystems is presented in **Figure 11**.

When simulating these subsystems, input, output impacts and parameters are set for describing the ongoing processes. The parameters include the data containing physical properties of the materials used and the geometry of system components.

As inputs to the ATEG: the temperature (T_{ex}^{in}) and mass flow (m_{ex}) of the exhaust gas emitted by the engine, the temperature (T_{cl}^{in}) and the mass flow of the cold-producing (m_{cl}).

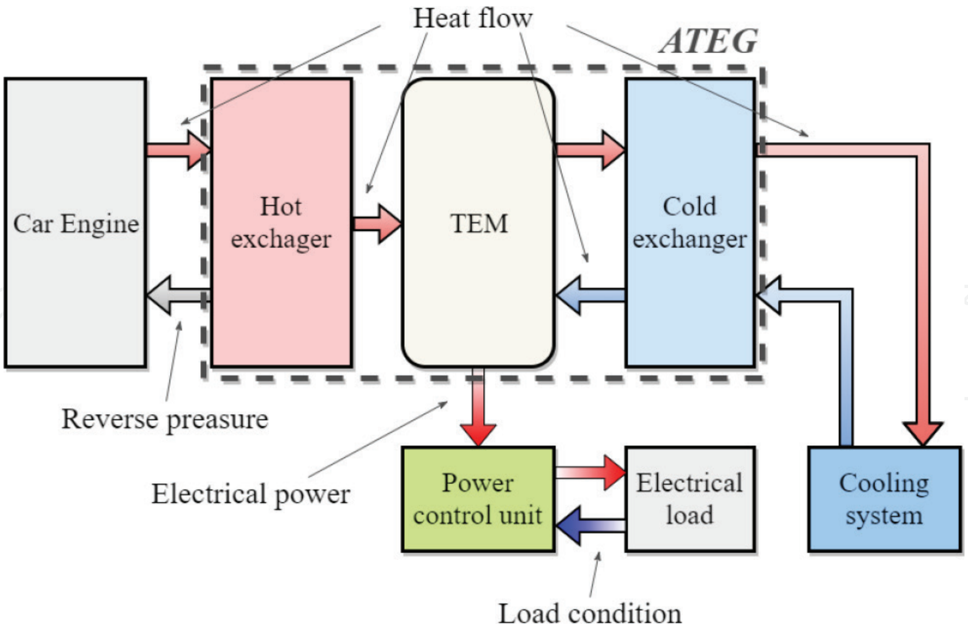


Figure 11. Structural scheme of mathematical model.

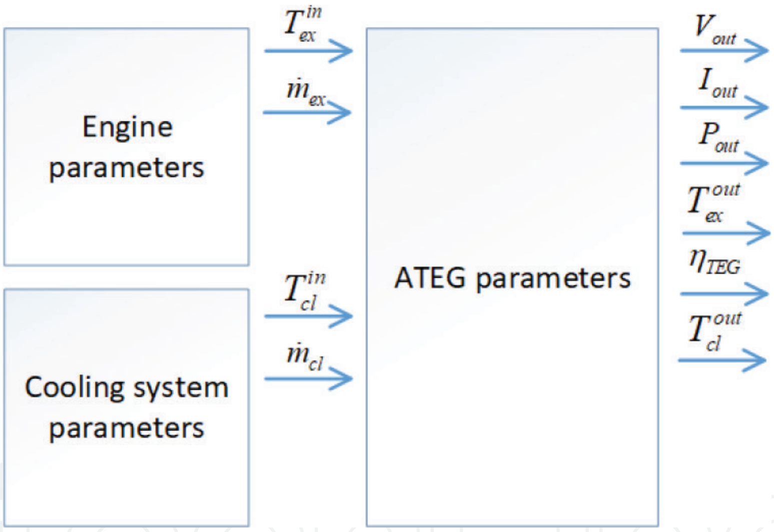


Figure 12. Input and output effects on ATEG.

The output ATEG model impacts, which can be calculated are: generated voltage, current and electrical power output, the temperature of exhaust gas at the exit of ATEG and efficiency (**Figure 12**).

4.2. Physical model ATEG

In general, ATEG consists of several sections through which a flow of hot gas and cold coolant flows. The physical model of the ATEG section contains the following basic elements (**Figure 13**): 1 and 4 - hot and cold heat exchangers; 2 - thermal contact resistances; 3 - thermocouples, 5 - TEM container.

The solution of operation modeling issue for the described system consists of thermal and electric circuits calculations taking into account thermoelectric processes.

The heat problem is solved by finding the distribution of thermal fluxes and temperatures over the entire cross-section of the ATEG section. For this purpose, the heat balance equations are used [46]. The electric current, voltage and power generated by the TEM can be calculated as a function of the electrical load using the Kirchhoff rules in accordance with the proposed electrical connection circuit for the thermoelements [47]. The amount of generated electricity is calculated using classical methods for determining the efficiency of thermoelectric conversion [48]. All characteristic values, such as the Seebeck coefficient, heat and conductivity coefficients, are taken into account.

Since the relationship between vehicle operation modes, the generated heat by exhaust gases and the generated electricity by ATEG are nonlinear, it is necessary to dynamically model these processes. To simulate the operation of ATEG under non-stationary operating conditions, the heat balance equations must be described in a differential form [45].

4.3. Tests of models, city cycles

The ATEG model allows estimating transient processes which makes it possible to use it The New European Driving Cycle (NEDC) is most often used to test the new work models ATEG. There are numerous scientific publications presenting measurements and calculations of thermoelectric generators used in cars on the basis of the NEDC [49]. It is extremely important to consider the dynamic behavior of the thermoelectric system in order to make realistic predictions of the performance of ATEG in the vehicle.

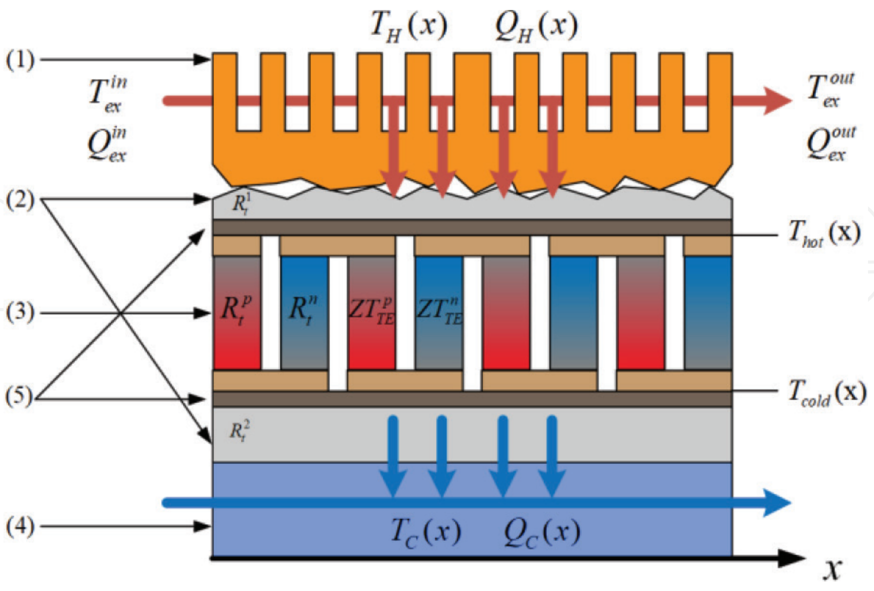


Figure 13. Functional diagram of ATEG section.

5. The ways of ATEG efficiency increasing

5.1. Adapting the design to variable operating modes

ATEG operation is accompanied by frequent volume flow differences and EG temperature changes, and vehicle electrical load is not constant. At the same time, it is necessary to ensure the optimum flow of EG through ATEG, when, on the one hand, there is sufficient intensive heat exchange in the ATEG, and on the other hand, the pressure drop EG is not too great.

Therefore, it is practical to use bypass for removing excessive EG through ATEG or a hot heat exchanger with variable hydraulic resistance of the flowing channel. For example, the patent [50] describes the construction of a heat exchanger using rotatable fins that allows intensifying heat transfer at low shaft speeds and reducing hydraulic resistance at high speeds. In **Figures 14**, 1- turning fins, 2- displacer, 3- TEM, 4- cold heat exchanger, 5- rotational blade-intensifier, 6 - control rod.

5.2. Application of heat pipes

One of the methods to increase the efficiency of ATEG can be the use of heat pipes in its structure [51, 52]. The reduction of the thermal resistance between exhaust gases and hot junctions allows increasing the hot junction temperature and also reduces the counter-pressure in the exhaust system in some cases. In addition, the heat pipes give the possibility of a more flexible approach towards the design of ATEG and there is no need to be limited to only the surface area of the hot heat exchanger. They also help to regulate the temperature of the hot junction by varying their length or by using variable conductance of heat pipes.

5.3. About materials with a phase transition

There is a need to select the operating point in the ATEG design. This fact connected with: variable heat flux through TEM under different operating conditions of the internal combustion engine, the dependence of the TEM semiconductor materials ZT on the junctions' temperature and the limitations on the peak temperature of the hot junction. Optimizing ATEG for obtaining maximum power at the extreme operating conditions of the internal combustion engine leads to low efficiency at low and medium rotational rates with low engine load. In the reverse situation, there is a need to use bypass for not overheating the TEM and not creating a counter-pressure in the exhaust pipe at high engine speeds. The solution to the problem of combining these two extreme situations and, consequently, increasing the efficiency of ATEG under different operating conditions of the ICE can be the use of materials with a phase transition that store heat at high loads on the ICE and give it to ATEG with a heat flux decrease in the exhaust line [53].

5.4. Temperature rise of EG

It is advisable to use EG at high temperatures for efficient ATEG operating which can be achieved through two technical solutions.

Firstly, installing the ATEG on ICE, which has the insulating combustion chamber with protective coatings. Such ICEs are increasingly being used in recent decades and are characterized as a high temperature of EG, low CO and residual hydrocarbons emissions, and fewer loads on the cooling system. Inside the ICE cylinders the operating gas reaches on its highest temperature which is about 2500°C. Mechanical work and temporary averaging of peak values reduce the temperature of the EG at the combustion engine output to 950–1000°C for gasoline internal combustion engines and 800–850°C for diesel engines.

Secondly, a precise thermal insulation of the collector and the exhaust pipe near the TEG location. For example, the authors of this chapter conducted experiments on ATEG which was connected to collector of 0.7 m long with a VAZ 21126 gasoline engine on a test stand. Its power was 72 kW and a volume of 1.6. The EG temperature measurements were made by using Kistler 4049B05DS1–2.0 sensor—installed at the entrance of the ATEG diffuser. It was noted that the insulation coating of the collector with basalt cloth increased the temperature of EG T_{eg} by more than 300°C (**Figure 15**).

Thirdly, to obtain the maximum temperature of EG, it is desirable to install ATEG directly after the internal combustion engine, in front of the catalyst, turbocharger and silencer.

5.5. Reduction of thermal resistance

The thermal resistance of the heat exchanger contacts can greatly reduce heat flow through ATEG [25, 54]. It is shown in [25] that neglect of contact thermal resistances during calculation leads to an overestimation of the generated TEM power by 25–30%. To reduce contact resistance, all possible methods should be taken, including:

- elimination of possible corrosion of contact joints.
- machining with minimal roughness and deviations from flatness.
- the use of graphite grease or high-temperature thermal grease for hot heat exchangers and conventional thermal grease for cold ones.
- installation of elastic expansion joints for temperature deformation to ensure a constant clamping force [54].

When operating ATEG on diesel engine, power may be reduced due to the deposition of soot in the hot heat exchanger. For example, Kajikawa describes an ATEG installed with a diesel engine [55]. During the first 100 h of operation, the heat flow through ATEG fell by 30%, reaching saturation levels due to soot formation, and further, remained almost unchanged for another 100 h. For gasoline engines, soot formation is much less critical.

5.6. Features of electrical load supply

The task of ensuring efficient transmission of TEG power to electrical consumers is significant. Usually, TEG consists of separate TEMs, which can be considered as conventional direct current (DC) sources. As all DC sources, each type of TEM has its own maximum power transfer condition. This condition can be simply described using the equivalent circuit (**Figure 16**).

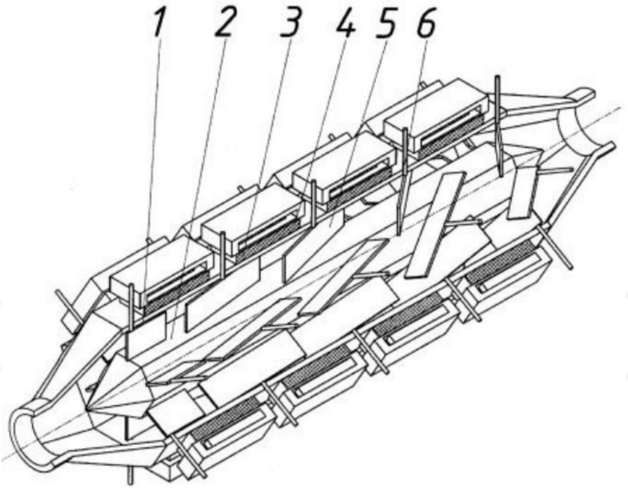


Figure 14. Constructions of hot hexagonal ATEG with variable angle of inclination of heat exchange intensifiers [51].

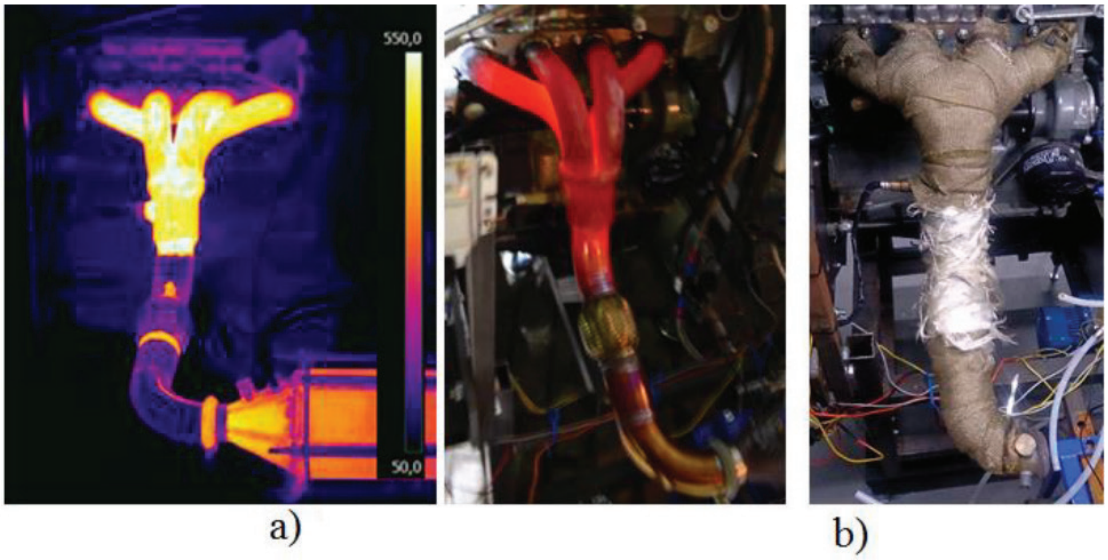


Figure 15. Manifold of the engine influence: (a) thermography and photo without insolation; (b) manifold with basalt fabric.

It is possible to represent the TEM as a power source (V_s) with an internal resistance (R_s). By Ohm's law maximum amount of power dissipates on load resistance (R_L) (Eq. (3)), when the value of the load resistance is exactly equal to the resistance of the power source (**Figure 17**).

$$P = I^2 \cdot R_L = \left(\frac{V_s}{R_S + R_L}\right)^2 \cdot R_L \tag{3}$$

Obtaining required output characteristics from TEMs array is ensuring by connecting TEMs in series or in parallel. The serial connection type is used in the case of increasing the output voltage. The parallel connection allows increasing total current. However, for each ATEG system the choice of connection type should be done attentively, according to modules electrical and temperature consistency.

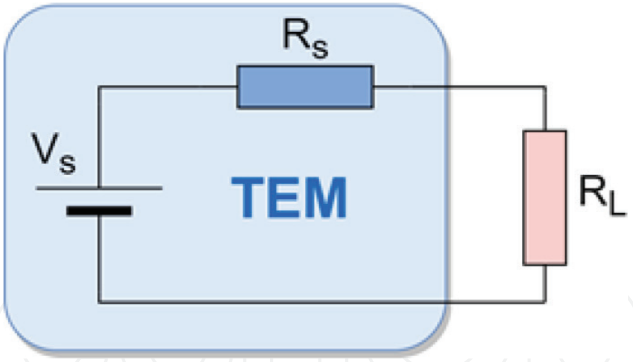


Figure 16. Equivalent circuit schema.

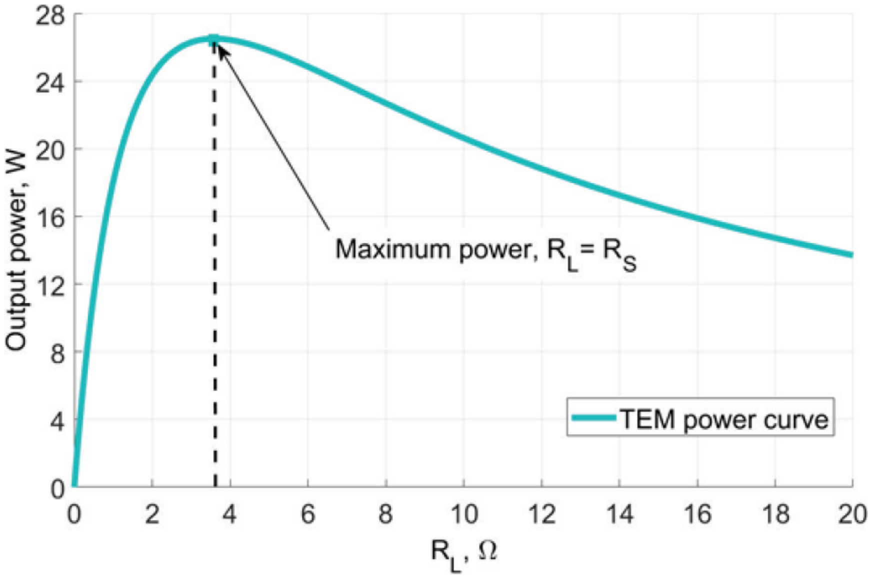


Figure 17. TEM power curve.

Also, heat flux distribution of the ATEG is often not the same all over its surface. Consequently, temperature states of various TEMs may differ. Thereby, it is correct to combine TEMs with equal temperature differences in one electrical circuit.

In the case of steady-state operating conditions, it is natural to connect TEG modules directly to the electrical load. The main parameter, which should be taken into account, is a match between summary electrical resistance of TEMs and a resistance of the electrical load. It allows harvesting maximum output power from TEG, as explained previously.

However, ATEG presents a transient system due to varying engine load conditions. Inconsistency in driving style, speed and torque can lead to changes in TEM temperature difference (**Figure 18**), which affects TEM internal resistance [56]. Consequently, a converter is required to continuously track ATEG power when the engine operates under various working conditions. The solution of this issue is connecting ATEG modules to the vehicle batteries and electrical loads through a DC/DC converter with maximum power point tracking (MPPT) algorithms.

MPPT method is mainly used in photovoltaic applications [57–60]. As solar panels, an operating point of TEM is rarely at peak power, as shown in **Figure 4**. MPPT technique executes continuous

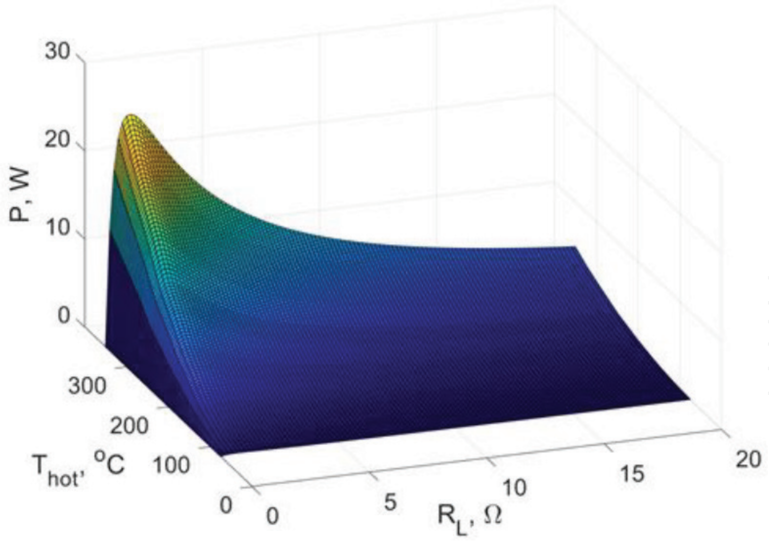


Figure 18. TEM power *P* versus hot-side temperature *T hot* and load resistance *R load* at cold side temperature *T cold* = 50°C.

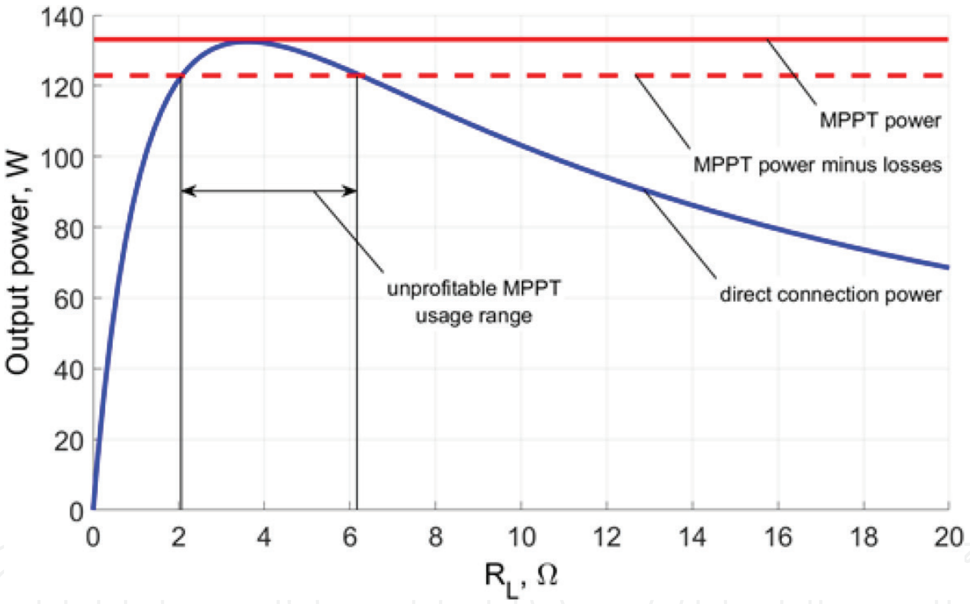


Figure 19. Conversion losses influence.

adjustment of the electrical system resistance to keep it operating at the peak power point under varying conditions. There are many different methods for tracking power point of TEG system: the constant voltage method [61], the perturbation and observation (P&O) method [62], the incremental conductance method [63], the ripple correlation control method [64], the dichotomy method [65] and the gradient method [66]. There are also combinations of several methods, for example, the aggregated dichotomy and gradient (ADG) method [67]. Intelligent methods, such as fuzzy logic [68] and neural network algorithms [69] are also developed for performance enhancement. The appearance and modifying of MPPT algorithms aim to obtain more rapid and accurate tracking of the power point. Some methods are more effective than others; some are easier to implement, but their main goal remains same. In this way, the usage of the DC/DC converter with MPPT function is necessary for such systems as ATEG.

However, ATEG electrical network has conversion losses, which decrease the total efficiency of the system. This fact should be considered while designing DC/DC converter. The function of switching on/off from general schema should be added to converter. When ATEG conditions nearby maximum power, converter with MPPT can be disconnected from ATEG and ATEG should transfer energy directly to the electrical load. It allows avoiding losses on the converter (**Figure 19**).

Also, the electrical network should be equipped with a vehicle battery. The battery provides a constant supply voltage in a range of 12–13 V. According to the principle that in a parallel circuit the voltage is same for all elements and that the voltage of vehicle electrical devices is also 12 V. Using the battery in the electrical network makes it possible to properly power all car systems.

6. Conclusion(s)

Summarizing the analysis of the ATEG development field and its current state, as well as the prospects for the commercial implementation of this technology, the significant progress in this direction, which occurred over the past 20 years, is noted. Many ATEG prototypes have been created. Tests of different vehicle classes with these prototypes in various driving cycles are carried out. That shows the possibility of achieving the specified requirements for reducing fuel consumption and CO_2 emissions, especially for trucks [40]. Developers are increasingly focusing to achieve the possibility of commercializing ATEG, to reduce the cost of electricity watt and to solve reliability issues. This makes them, along with the classic industrially produced TEM materials, consider new promising thermoelectric materials, sacrificing sometimes the efficiency of energy conversion. At the same time, optimization of the ATEG design and technological solutions can significantly reduce the requirements for these materials, and improve the weight and size of the ATEG.

The rapid progress in the development of new thermoelectric materials and the research advancement in this area let us hope that the technology for utilizing the heat of exhaust gases of internal combustion engines in ATEG is capable of reaching a broad practical implementation.

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