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Theoretical and experimental studies of heat recovery from exhaust gases of an automotive engine to generate electricity in a thermoelectric generator

Nghiên cứu lý thuyết và thực nghiệm về thu hồi nhiệt từ khí thải của động cơ ô tô để tạo ra điện trong máy phát nhiệt điện

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Abstract

Thermal energy from fuel combustion released into the environment with the exhaust gases of the internal combustion engine accounts for up to half, and in some cases, up to two-thirds, of the total internal energy of the injected fuel. Therefore, utilizing this waste heat energy is always focused on research and improvement by researchers and engine manufacturers. Utilizing heat for turbocharging has been widely applied. In addition, some older internal combustion engines do not yet have turbocharging, and even when using turbocharging, the thermal energy of the exhaust gas behind the gas turbine remains high. It can be utilized in the rankine or organic rankine cycle by evaporating water. This technology is challenging to apply in automobiles due to the limited space in the engine room layout. Using the Thermoelectric Generator (TEG) to produce electricity by taking advantage of engine exhaust heat energy has many advantages, such as “non-mechanical” energy conversion, no moving parts, no working noise, automatism and high reliability, long life, convenience in operation, small inertia, easy adjustment, and stable parameters. The article introduces the thermoelectric module and its applications, the model of the thermoelectric generator, and some experimental results investigating the application of the generator installed on the exhaust pipe of the Toyota 7K-E engine to take advantage of exhaust heat energy turned into electricity, creating additional power for the vehicle's electrical system.

Keywords: Heat recovery; exhaust gas; thermoelectric module; thermoelectric generator; automotive engine; cold side; hot side.

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Tóm tắt

Nhiệt năng từ quá trình đốt cháy nhiên liệu thải ra môi trường với khí thải của động cơ đốt trong chiếm tới một nửa, và trong một số trường hợp, lên đến hai phần ba, tổng năng lượng bên trong của nhiên liệu được phun. Do đó, việc tận dụng nguồn nhiệt thải này luôn được các nhà nghiên cứu, nhà sản xuất động cơ chú trọng nghiên cứu và cải tiến. Sử dụng nhiệt để tăng áp đã được áp dụng rộng rãi. Ngoài ra, một số động cơ đốt trong cũ chưa có tăng áp, và ngay cả khi sử dụng tăng áp, nhiệt năng của khí thải phía sau tuabin khí vẫn ở mức cao. Nó có thể được sử dụng trong chu trình rankine hoặc rankine hữu cơ bằng cách làm bay hơi nước. Công nghệ này là thách thức để áp dụng trên ô tô do không gian hạn chế trong bố trí phòng máy. Sử dụng TEG để sản xuất điện bằng cách tận dụng năng lượng nhiệt thải của động cơ có nhiều ưu điểm, chẳng hạn như chuyển đổi năng lượng "phi cơ học", không có bộ phận chuyển động, không có tiếng ồn làm việc, tự động hóa và độ tin cậy cao, tuổi thọ cao, thuận tiện trong vận hành, quán tính nhỏ, dễ dàng điều chỉnh và thông số ổn định. Bài viết giới thiệu mô-đun nhiệt điện và các ứng dụng của nó, mô hình của máy phát nhiệt điện và một số kết quả thí nghiệm điều tra ứng dụng của máy phát điện được lắp đặt trên ống xả của động cơ Toyota 7K-E để tận dụng năng lượng nhiệt thải biến thành điện, tạo thêm năng lượng cho hệ thống điện của xe.

Từ khóa: Thu hồi nhiệt; khí thải; mô-đun nhiệt điện; máy phát nhiệt điện; động cơ ô tô; mặt lạnh; mặt nóng.

1. Introduction

In piston internal combustion engines (ICE), the process of converting the thermal energy of fuel combustion into useful mechanical energy is accompanied by a loss of up to 40–65% of heat energy into the environment with exhaust gases [1,2]. Although technological advancements have significantly reduced the fuel consumption of ICE, the peak thermal efficiency of a 4-stroke Otto cycle engine is about 35%, which means that 65% of the energy released from the fuel is lost as heat. High-speed diesel engines perform better; the peak thermal efficiency is around 45%, meaning 55% of the fuel's energy is rejected as heat.

The energy of the ICE exhaust gases can be partially recovered by turbocharging, that is, using the exhaust gas stream to drive a gas turbine mechanically linked to the compressor. The purpose of turbocharging is to increase the engine's volumetric efficiency and power density. This is an effective measure to strengthen and reduce engine size. Today, almost 100% of diesel engines are turbocharged; most gasoline engines are also turbocharged [3].

However, even with turbocharging, much residual heat energy remains in the vehicle's exhaust, creating a promising energy source. Besides, waste heat recovery technology can be based on the rankine cycle and the organic rankine cycle. The Rankine cycle system evaporates pressurized water using a steam generator located in the exhaust pipe. Due to the heating of the exhaust gases, the liquid turns into steam. The steam then drives the Rankine engine's expander, which can be either a turbine or a piston engine. This expander can be connected directly to the crankshaft of the ICE or linked to a generator to generate electricity. In a study [4], researchers concluded that waste heat from light vehicle engines in the steam power cycle can save fuel from 6.3% to 31.7%, depending on the mode of operation. Up to now, one of the effective methods to increase the efficiency of thermal energy due to fuel combustion is still to take advantage of heat energy from engine exhaust, such as using exhaust gas to rotate compressor turbines [5], using boilers to use heat, etc. For automobiles in particular and road vehicles in general, taking advantage of heat in the Rankine cycle when using boilers is impossible.

Recently, researchers have focused on using thermoelectric generators (TEG). This waste heat recovery technology uses a thermoelectric generator based on the Seebeck effect. Although this technology has many advantages, such as TEG not having moving parts so it does not make noise and a slight heat source can still generate electricity, this technology has hardly been practically applied in cars today. Besides, there are still laboratory studies [6]. However, this is one of the effective methods to utilize emitted heat energy, especially in automobiles.

With the above analysis, in this article, we conduct research on the principle of thermoelectric modules and TEG; research the theoretical basis for calculating and designing TEG for an automotive engine; and design, manufacture, and experiment to determine the power obtained for a simple TEG model applied to the Toyota 7K-E gasoline engine.

2. The principle of thermal power generation

According to published literature [7] and [8], the thermoelectric process takes place in three ways: Seebeck, Peltier, and Thomson, among which there is a reversible connection. The TEG is a type of device that works on the principle of the Seebeck effect: if two semiconductor wires made of different materials are connected into a closed circuit and the connector is subjected to different temperatures (T1 and T2), then the electromotive force (EMF) appears in the circuit (Figure 1). These two different semiconductor wires are called “thermocouples” [9]. The electromotive force is proportional to the temperature difference between the two connectors.

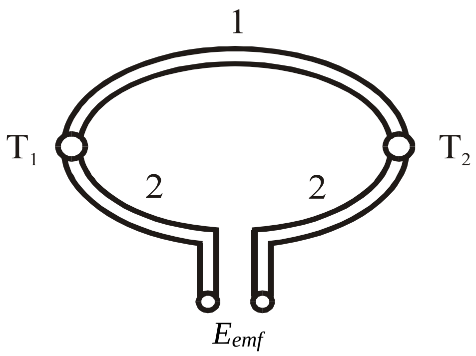


Figure 1. Diagram of the Seebeck effect

$$E_{emf} = \left(\alpha_{S1} - \alpha_{S2}\right) \cdot \Delta T, \text{ V} \quad (1)$$

Where $\Delta T = T_1 - T_2$ (K), $\alpha_{S1,}\ \alpha_{S2}$ are the Seebeck coefficient of semiconductors 1 and 2, (V/K).

In thermoelectric modules (TM) using semiconductors of different thermal conductivity (n- and p-types), their Seebeck coefficients have approximately equal absolute values. Formula (1) can be expressed as:

$$E_{emf} = \left(\left|\alpha_{S1}\right| - \left|\alpha_{S2}\right|\right) \cdot \Delta T = \left(\alpha_{S1} - \left(-\alpha_{S1}\right)\right) \cdot \Delta T$$

or

$$E_{emf} = 2 \cdot \alpha_S \cdot \Delta T, \text{ V} \quad (2)$$

Where is the average absolute value of the Seebeck coefficient for n- and p-(V/K) semiconductors? The principal scheme of thermoelectric modulation is shown in Figure 2 [10]. These modules are composed of p-n pairs (e.g., p-PbTe, n-75% PbTe, and 25% SnTe) placed in two ceramic plates. Depending on the size of the module and the properties of the constituent materials, they have different electromotive powers.

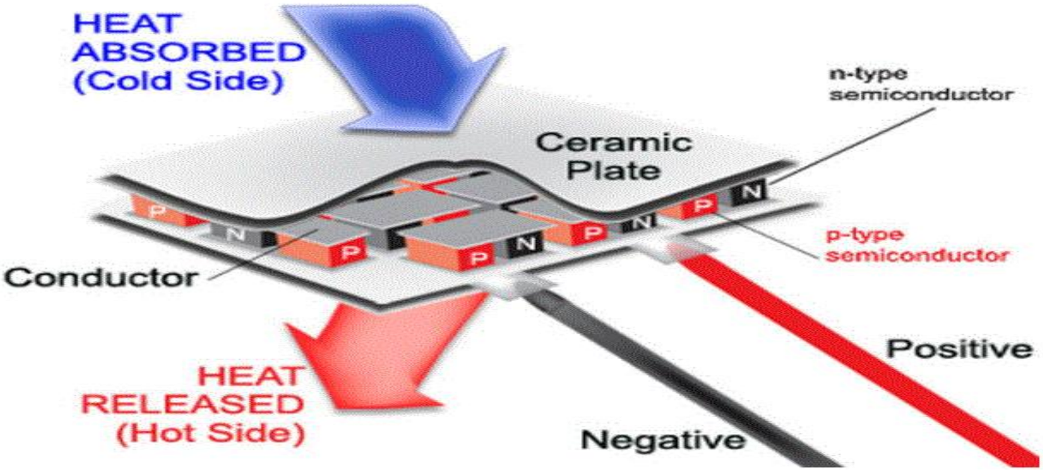


Figure 2. Structure of thermoelectric module

In Table 1, some characteristics of common thermoelectric modules are introduced: in working mode, hot side 150°C, cold side 50°C (temperature difference 100°C). The highest working temperature on the hot side is 300–380°C. These modules range in length from 40 mm to 58 mm in width and 3.8–4.2 mm in thickness [8, 9]. Along with achievements in the field of thermal power (creating new materials, developing nanotechnology, etc.), there is an interest in the application of thermal power technology to generate electricity. The company “BMW AG” has installed on some car engines (BMW 5 series Sedan) thermoelectric generating equipment (Figure 3). The power of the complex with TEG increases by 15% when using a complex drive system [10] (according to each operating mode, some or all of the suspension is driven by the energy generated by TEG).

Table 1. Characteristics of some types of thermal power modules of Kryotherm [11][12]

Type	Geometrical Dimensions, mm			Cold end: 50°C; Hot end: 150°C					
				Internal Resistance	Heat Resistance	Voltage	Current	Power	Efficiency
	A	B	H	Ohm	K/W	V	A	W	%
TGM-127-1.0-0.8	30	30	3.1	2.41	1.40	1.83	0.76	1.38	2.3
TGM-127-1.0-1.3	30	30	3.6	3.92	2.27	2.18	0.56	1.21	2.7
TGM-127-1.0-2.5	30	30	4.3	7.53	4.36	2.55	0.34	0.86	3.2
TGM-127-1.4-1.5	40	40	3.9	2.46	1.43	2.25	0.91	2.05	2.8
TGM-127-1.4-2.5	40	40	4.8	3.84	2.23	2.50	0.65	1.63	3.2
TGM-199-1.4-0.8	40	40	3.2	1.93	0.45	2.19	1.14	2.49	1.8
TGM-199-1.4-1.2	40	40	3.6	2.89	0.68	2.69	0.93	2.50	2.2
TGM-199-1.4-1.5	40	40	3.9	3.85	0.91	3.03	0.79	2.39	2.4
TGM-287-1.0-1.3	40	40	3.6	8.85	1.00	4.54	0.51	2.33	2.5
TGM-287-1.0-1.5	40	40	3.8	10.20	1.16	4.77	0.47	2.23	2.7
TGM-287-1.0-2.5	40	40	4.8	17.00	1.93	5.49	0.32	1.77	3.1

a)

b)

Figure 3. Thermoelectric generator (a) and installation on BMW 5 series Sedan (b)

The company “General Motors” in the US is researching ways to increase the efficiency of TEG for automobile engines. TEG complexes are highly economical because they produce additional power and can reduce fuel consumption by up to 5% [13]. In 2009, the company “Komatsu, Ltd.” (Japan) successfully manufactured thermal power generators for diesel engines in construction. The working temperature of TEG is from 30°C to 380°C. The highest power generated from a module is 24 watts, dimensions of the module: 50x50x4.2mm [14].

Using TEG to generate electricity by utilizing engine exhaust thermal energy has many advantages, especially if applied to military motor vehicles, because this is a "non-motorized" energy conversion method: no moving parts, no noise in working, high automotiveness and reliability, long service life, convenience in mining, small inertia, easy to adjust, and stable parameters. Around the world, a number of universities and research institutes have started researching and applying TEG to ships and other motor vehicles because the heat energy of ship diesel engine exhaust (especially the main machine) is very large, promising to produce a large amount of electricity. Vietnam introduced the Law on Economical and Efficient Use of Energy in 2010. Therefore, taking advantage of energy sources discharged into the environment from vehicles is a necessary issue that needs to be researched, applied, and developed.

3. Objective and methods of research

With the advantages mentioned above, the use of TEG does not alter the exhaust system and is capable of utilizing the exhaust thermal energy of ICE to generate electricity, which is used for different purposes on military motor vehicles. Therefore, the Department of Engines has proposed the scientific topic “Research and application of power generation equipment on the basis of taking advantage of exhaust heat energy of internal combustion engines” for the purpose of researching and exploiting the practical capabilities of thermal power modules on the basis of taking advantage of exhaust heat of internal combustion engines. In the initial study, the selected subject was Kryotherm's TGM-287-1,0-1.5 thermoelectric module, whose parameters are shown in Table 2. To evaluate the actual power generation capacity of this module when taking advantage of the thermal energy of exhaust gases, the engine selected is a Toyota gasoline engine, model 7K-E, installed in the Engine Laboratory of the Institute of Vehicle and Energy Engineering, Le Quy Don University.

Table 2. Thermoelectric module parameters TGM-287-1.0-1.5

Parameter	t_c = 50°C	t_c = 100°C
	t_h = 150°C	t_h = 200°C
Volage, V	4,77	4,52
Current, A	0,47	0,43
Power, W	2,23	1,93
Dimension, length x width x height	40 x 40 x 3,8	
t_c – temperature of cold side; t_h – temperature of hot side		

Research methods are a combination of theoretical and empirical verifiability. On the basis of theoretical research on the survey of various types of thermoelectric modules, their application in internal combustion engines, the demand for electricity in military motor vehicles, the ability to take advantage of engine exhaust thermal energy, the calculation of parameters for the design of appropriate thermoelectric power generation equipment, and practical tests.

4. Research result

4.1. Calculation and design of power generation equipment using thermal power modules

The device consists of two main compartments, exhaust compartment 1 and cooling compartment 2. The exhaust gas chamber is machined as part of the exhaust pipeline and has flanges connected to the flange of the exhaust gas pipeline by bolts. When installing this cavity in the exhaust pipe of the engine, it is not necessary to carry out cutting of the exhaust pipe, but simply insert it between the flanges, which does not change the structure of the exhaust line of the engine. The cooling compartment is a box of defined, calculated dimensions in which coolant circulates. Between the two chambers is the thermoelectric module 3, which is placed on the fixed ledge. On the device are mounted sensors to measure the temperature of exhaust gases and cooling water. The coolant is taken from the engine cooler, which in this test uses a coolant circulation pump (which, in practical applications, can be obtained directly from the cooler without pumping).

4.2. Diagrams and devices used in testing

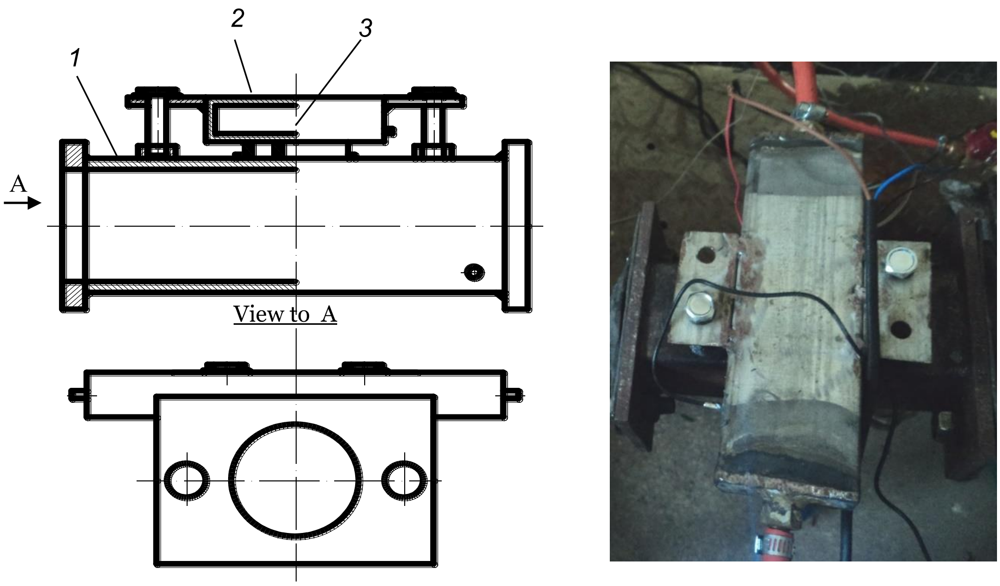
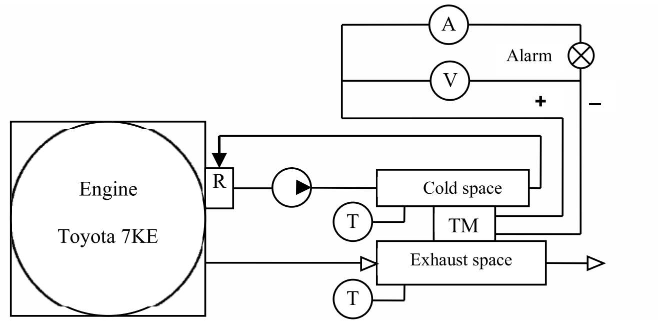


Figure 4. The TEG used in testing

Figure 5 introduces the test diagram, and Figure 6 - device on Toyota 7KE engine during testing.



T – thermometer; A – ampemeter; V – voltmeter; equipment.TM – thermoelectric module; R – safe

Figure 5. Test diagram

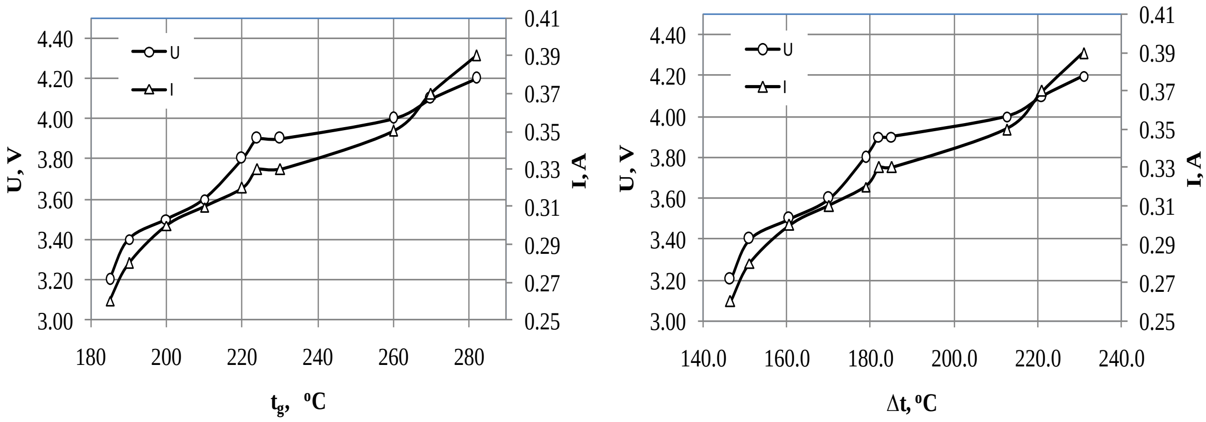
Figure 6. Engines and generator

4.3. Test results

Since experimental conditions do not allow measuring engine loads, the engine operates in idle mode, and the exhaust gas temperature is adjusted by changing the fuel supply to the engine. Visually, the current generated is observed by the brightness of the indicator lamp. To record the power generation parameters, use the Sannuo YX-960TR electricity meter. When the exhaust gas temperature t_g = 175°C and the cooling water temperature t_w = 37°C, the indicator light does not light up. When t_g = 185°C and t_w = 38.7°C, the indicator lights up. The results of the experiment are shown in Table 3 and represented in a graph in Figure 7.

Table 3. Preliminary results of thermal power generation equipment

t_g, °C	t_w, °C	$\Delta t = t_g - t_w$, °C	**U,** V	**I,** A
185	38.7	146.3	3.2	0.26
190	39.0	151.0	3.4	0.28
200	39.5	160.5	3.5	0.30
210	40.0	170.0	3.6	0.31
220	41.2	178.8	3.8	0.32
224	42.0	182.0	3.9	0.33
230	45.0	185.0	3.9	0.33
260	47.5	212.5	4.0	0.35
270	49.0	221.0	4.1	0.37
282	51.0	231.0	4.2	0.39



a) b)

Figure 7. Depends on the voltage and amperage of the device:

a) Enter the exhaust gas temperature;

b) Enter the temperature difference of exhaust gases and cooling water

Discussion:

- The voltage (U) and amperage (I) generated by the device increase with the increase in flue gas temperature. In addition, you and I depend on the temperature difference (for example, when the Δt is close to 182°C, you and I remain virtually unchanged while the exhaust and coolant temperatures at the respective points are different; (See Figure 7 b).

- The temperature difference between the exhaust gas and coolant is greater than the temperature difference required between the hot and cold sides of the TM, but the temperature difference you and I received is smaller than recommended by the manufacturer. This is explained by heat losses when passing through the device wall, as well as poor contact between the TM and the surface of the cavities of the device.

- In order to obtain a large power source, it is necessary to make a thermoelectric generator from many modules installed in series.

5. Conclusion

The use of power generation equipment on the basis of taking advantage of the thermal energy of engine exhaust is a promising application direction, especially for military motor vehicles. For large amounts of electrical power, multiple thermoelectric modules can be used. The test results show that the voltage and amperage obtained depend on the temperature difference between the flue gas temperature and the coolant temperature. Therefore, it is necessary to maintain a stable temperature difference so that the obtained thermoelectric parameters are stable. The next direction of the research is to calculate the optimal calibration of the parameters of the equipment, test the equipment at different load modes of the engine to get a more comprehensive picture of the generator equipment that takes advantage of the engine exhaust thermal energy, and calculate and determine a reasonable cooling mode for the TEG equipment. On the basis of the results obtained, when applying TEG to specific objects (cars, tanks, and ships), calculate the energy balance for the machine complex and develop a reasonable technological plan, such as installing an automatic adjuster to supplement the power supply for the consuming device or charging the battery so that the drive can be disconnected from the crankshaft of the engine for some suspension devices, aimed at increasing power and saving fuel for the machine complex.

References

[1] Ramy Y.Dahham, Haiqiao Wei & Jiaying Pan. (2022). Improval Thermal of Internal Combustion Engine Efficiency: Recent Progress and Remaining Challenge. *Energie*, 15(7),6222. https://doi.org/10.3390/en15176222.

[2] Jerald A Caton. (2017).Maximum efficiencies for internal combustion engines: Thermodynamic limitations. *International Journal of Engine Research*,19(10). https://doi.org/10.1177/1468087417737700.

[3] D. Di Battista, M. Di Bartolomeo, R. Cipollone. (2022). Full energy recovery from exhaust gases in a turbocharged diesel engine, *Energy Conversion and Management*, Volume 271, 116280, ISSN 0196-8904, https://doi.org/10.1016/j.enconman.2022.116280.

[4] Hounsham, S., Stobart, R., Cooke, A., and Childs, P. (2008). *Energy Recovery Systems for Engines*, *SAE Technical Paper* 2008-01-0309, 2008, https://doi.org/10.4271/2008-01-0309.

[5] Zhibin Wang*, Xiaobing Pan, Wei Zhang, Yu Zhao, Haiming Li and Peng Liu. (2020). The Development Trend of Internal Combustion Engine. *International Conference on Electrical Automation and Mechanical Engineering*, 1626 (2020) 012139. doi:10.1088/1742-6596/1626/1/012139.

[6] Stuart Birch. (2012-02-03). *Temperatures rise in BMW's work to recover engine waste heat*, http://www.bmw.com

[7] Fernández-Yáñez, P.; Romero, V.; Armas, O.; Cerretti, G. (2021). Thermal management of thermoelectric generators for waste energy recovery. *Applied Thermal Engineering*. 196: 117291. doi:10.1016/j.applthermaleng.2021.117291.

[8] Murtdha S. Imran and Hasan.T. Hashim. (2020). A Heat Recovery Method of Internal Combustion Engine Using a Thermoelectric Generator, *IOP Conference Series: Materials Science and Engineering, Volume 671, 3rd International Conference on Engineering Sciences 4–6 November 2019, Kerbala, Iraq*. DOI: 10.1088/1757-899X/671/1/012134

[9] Andrzej Ziolkowski. (2017). *Automotive Thermoelectric Generator impact on the efficiency of a drive system with a combustion engine. MATEC Web of Conferences 118, 00024 (2017). VII International Congress on Combustion Engines.* DOI: 10.1051/matecconf/201711800024.

[10] Karol Sztekler*, Krzysztof Wojciechowski, Maciek Komorowski. (2016). The thermoelectric generators use for waste heat utilization from conventional power plant. E3S Web of Conferences 14 ,010 (2017*), Energy and Fuels.* DOI: 10.1051/ 71401032 2016 E3S Web of Conferences 14 e3sconf/201.

[11] *Generating Thermoelectric Modules by Kryotherm*, https://www.eureca.de/1215-1-Kryotherm.html (accessed 25 Jan 2024).

[12] *Thermoelectric coolers and related subsystems. Kriotherm catalog*. https://www.eureca.de/files/pdf/ cooling/kryotherm/Kryotherm_catalog.pdf (accessed 25 Jan 2024).

[13] *BMW provides an update on waste heat recovery projects; Turbosteamer and the Thermoelectric Generato*r. https://www.greencarcongress.com/2011/08/bmwthermal-20110830.html (accessed 25 Jan 2024)

[14] *Technical Report: Development of Cost-Competitive Advanced Thermoelectric Generators for Direct Conversion of Vehicle Waste Heat into Useful Electrical Power*. https://doi.org/10.2172/1414341.