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Gemi Makinelerinde Egzoz Atık Isısının Geri Kazanımı İçin Bir Termoelektrik Sistemin Sonlu Elemanlar Yöntemiyle Tasarımı ve Analizi

Design and Analysis of a Thermoelectric System for Exhaust Waste Heat Recovery in Marine Engines by Finite Element Method

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Özet:

Termoelektrik jeneratör (TEG) literatür taraması sonucu içten yanmalı motorların egzoz sistemlerinden atılan ısının geri kazanımı üzerine geliştirme çalışması yapılmıştır. TEG teknolojisinin kullanımı atık ısının geri kazanılması için çevre dostu bir teknik olarak kabul edilir. Bu doğrultuda ele alınan literatürlerde, geçmişte yapılan atık ısı çalışmaları detaylı şekilde incelenmiştir. İçten yanmalı motorlar günümüzde taşıtlarda en yaygın olarak kullanılan tahrik yöntemi olmasına rağmen verimliliklerinin düşük olduğu bilinmektedir. Bu doğrultuda yapılan araştırmalar gösteriyor ki verimliliği %35 olan bir motorun, soğutma suyu ve sürtünme kayıpları yaklaşık %25 oranına sahipken, geri kalan %40'lık enerjinin egzoz gazı ile hiç kullanılmadan atmosfere atıldığı görülmektedir. Dolayısıyla egzoz geri kazanım sistemleri ile enerjiyi dönüştürüp yeniden kullanıldığında bu kayıp enerjinin yüzdesi düşürülmüş olacaktır. Bu konuda yapılmış çalışmalar incelendiğinde genellikle kara taşıtları üzerinde denemeler yapıldığı ve denizcilik sektöründe örneklerinin olmadığı görülmüştür. Çalışmalar incelendiğinde büyük ebatta termoelektrik jeneratöre rastlanmazken, sıcaklık değerlerinin gemi bacasında da yakalanabileceği görülmüştür. Bu nedenle çalışmalar yakından incelediğinde sistemin gemilerde de uygulanabilir olacağı düşüncesine varılmıştır. Gemilerdeki egzoz çıkış sıcaklıklarını incelendiğinde ise egzoz manifoldunda 500℃ olan sıcaklık, turboşarjer girişte 450℃, turboşarjer çıkışında 300℃ ve baca kazanı çıkışında ise yaklaşık 200℃ olduğu görülmüştür. Termoelektrik modülün çalışma sıcaklıklarına en uygun olacak yerin baca kazanı çıkışındaki silencer düzeneği olacağı düşünülmüş ve bununla ilgili detaylı teknik çizimler incelemeye alınmıştır.

Kelime Anahtarı: Termoelektrik Enerji, Egzoz Atık Isı, Gemilerde Enerji Verimliliği, Termoelektrik Jeneratör.

Abstract:

Following review of thermoelectric generator (TEG) literature, development study on recovery of heat released from internal combustion engine exhaust systems was conducted. TEG technology is regarded as an environmentally friendly waste heat recovery technique. Waste heat studies conducted in the past have been thoroughly examined in literature we have examined in this direction. Although internal combustion engines are the most commonly used propulsion method in vehicles today, their efficiency is well known. According to research in this area, an engine with a 35% efficiency has approximately 25% of cooling water and friction losses, while the remaining 40% of energy is thrown into the atmosphere with exhaust gas and is never used. As result, when we convert and reuse energy with exhaust recovery systems, we reduce percentage of this lost energy.

When studies on this subject are examined, it is discovered that trials are generally on land vehicles, with no examples in maritime sector. When studies were examined, it was discovered that, while no large thermoelectric generators were encountered, temperature values could also be captured in ship's chimney. As result studies, we concluded that system would also be applicable on ships. The exhaust outlet temperatures on ships are 500℃ at exhaust manifold, 450℃ at turbocharger inlet, 300℃ at turbocharger outlet, and around 200℃ at chimney boiler outlet. The silencer device at the exit of chimney boiler was thought to be the best location for thermoelectric module's operating temperatures, so detailed technical drawings were examined.

Keyword: Thermoelectric Energy, Exhaust Waste Heat, Energy Efficiency in Ships, Thermoelectric Generator.

1. Introduction

The production of electricity from flue gas, another application for thermoelectric devices, has been the subject of numerous investigations. By generating electrical energy from the waste heat produced by setting up an experimental setup, it was hoped to change the negative impacts of the gas discharged out of the chimney in a study. As a result, it was noted that the computations produced a gain of 12.2% (Goldsmid, 2009).

In a related study, waste gas is used to heat the hot thermoelectric generator surface and various water flow rates are used to cool the cold surface. With the aid of this illustrative mechanism, it has been demonstrated that energy can be produced from the waste gases formed in industrial enterprises by heating the heated surface with the waste gas from the pipes of the stoves used in homes (Çengel and Boles, 2012).

Alfred et al. In their review study, they stated that most of the existing TEGs have low operating temperatures, which limits their commercial use, and stated that their efficiency varies between 5% and 10%. They said that the temperature of the cold side of the TEG module has a greater effect on the power output than the temperature of the hot side. Various geometric optimization methods, such as fins under natural convection and heat emitters, have been found to result in an increase in TEG power output of 129% and 42%, respectively. They made recommendations for further research alternatives such as SiGe alloys, clathrates, skutterudites and complementary metal oxide semiconductors with better temperature ranges and values (Ochieng, Megahed, Ookawara, Hassan, 2022).

Song et al. performed thermoelectric generator (TEG) optimization for electric motor (EM) vehicle. They achieved an 11.6% increase in power density by improving the electrical charge resistance and configuration compared to the previously designed TEG. When they compared their studies with the TEG developed for the conventional fuel vehicle, they achieved a 1.7% improvement in fuel consumption. Their results demonstrated the importance of developing

TEGs applied to EMs (Lan, Stobart and Wang, 2022).

Sharma et al. carried out an experimental study to recover the heat dissipated from the exhaust of a diesel engine. In the experiment, they used a conventional type diesel engine with four cylinders with a power of 7.4 kW. They used a square stainless steel pipe to recover heat from the exhaust. They placed TEG on both sides of the pipe and observed the energy production of the system with the help of the refrigerant. According to the results, as the load of the engine increased, the power and efficiency of the TEG increased. When the machine load reaches the maximum 6 kg; TEG produced 37W of power. It has been stated that the total thermal efficiency of the machine can be increased by using different materials (Sharma et al, 2021).

Luo et al. developed a software to analyze the performance of TEGs with refrigerant used in automobile exhaust systems and to simulate the results obtained when different parameters are entered. This forecasting model, which can run on the COMSUL platform, is based on multiphysical laws. When full geometry, temperature-dependent material properties, TEG's topological connections, and impedance matching data are entered into the system, it can simulate real operating conditions. The model also takes into account the exhaust gas temperature and the exhaust mass flow at different speeds. In addition, it can calculate the power losses of the refrigerant pump it uses to cool itself and the effect of weight. The margin of error in comparing the estimation method with real experience is only 5.74%. In addition, it has been noted that the energy produced and the conversion efficiency increase in direct proportion to the speed of the car (Luo, Sun and Wang, 2022).

Meng et al., for the first time, developed a thermoelectric generator that takes into account multiphysics laws to take advantage of automobile exhaust waste heat. In this study, it has been taken into account that the temperature difference between thermoelectric units is not uniform. It has also been shown that the flow direction affects the system performance. The counter-flow cooling model has been accepted as a more reliable system since it reduces temperature irregularity. However, it was also stated that it did not increase the total output power compared to the parallel flow system (Meng, Wang and Chen, 2016).

Huang et al. proposed circular thermoelectric generators (DTEGs) to adapt exhaust pipe geometry for use in automobiles to recycle waste heat. They created a model to measure the performance of DTEGs in automobile exhaust. They compared their model with the widely used automotive exhaust flat plate thermoelectric generators (DPTEGs). They found that the performance of DTEGs outperformed DPTEGs by an average of 1.1% in power. With the increase of the cooling medium flow rate, the net power starts to decrease after the maximum. They preferred a flow rate of 0.05 kg/s to compromise coolant temperature rise and tank volume. Since there is a temperature drop from the exhaust to the generator, they placed a hollow cylinder in the heat exchanger, resulting in a 214.0% increase in net power. However, this decreases significantly with increasing exhaust flow rate. They recommended the use of a cylinder with a dimensionless diameter of 0.8 for gasoline cars (Huang and Shen, 2022).

To ascertain the crucial design factors of circular thermoelectric generators (A-TEGs) incorporated into heat exchangers, Zaher et al. created an analytical model. The design optimization of the A-TEG system for greatest power generation has been presented using a new dimensionless design factor (β). The power output from the A-TEG system is always maximized in this design factor, which uses a mix of diameter and fill ratios. To optimize the A-TEG design utilizing the design factor (β), they created and validated a thorough analytical model to simulate an integrated heat exchanger. A parametric case study revealed that by lowering the diameter and fill ratios, the material volume of A-TEGs may possibly be lowered by 75%, with only an 11% decrease in maximum power at the ideal design factor. The study's conclusions demonstrated that A-TEGs are a practical tool for directing successful and affordable designs for waste heat recovery systems (Zaher, Abdelsalam and Cotton, 2021).

According to Zhao et al., the internal combustion engine exhaust thermoelectric generator's efficiency is constrained by the poor heat transfer performance in the exhaust duct. According to them, the generator's thermoelectric performance is enhanced by the exhaust duct's better heat transmission and the consequent rise in exhaust back pressure. They suggested a brand-new design of thermoelectric generator with fluid circulation for heat transmission. A heat transfer fluid replaces the exhaust after it has exchanged heat with the generator's exhaust. They claimed that the high heat transfer coefficient of the heat transfer fluid in the generator could be used to increase the thermoelectric performance of the system without modifying the exhaust duct. The physical characteristics of the module, as well as its reliance on system architecture, power usage, and temperature, have all been taken into account when developing a mathematical model of the new system. This model was used to examine how structural and heat transmission fluid characteristics affected thermoelectric performance. They discovered that while the number of modules could be decreased by 83.2%, the peak net output power of the new generator could be enhanced by 77.5% when compared to the conventional generator. As a result, they were able to configure the exhaust heat exchanger in the best way possible to increase the system's overall net output. The outcomes also include technical details on the thermoelectric generator's design and operational requirements (Zhao et al, 2021).

Two main sources of heat removal for the internal combustion engine currently account for around 65-70% of its energy input, according to an examination of energy distribution. These are the radiator (30%) and the exhaust gas system (between 35 and 40%). The overall thermal efficiency will increase if some of this wasted heat is partially recovered. Thermoelectric generators provide a number of advantages over alternative thermal energy recovery techniques including the Organic Rankine Cycle and mechanical or electric turbo coupling, among others. Environmentally friendly, without moving parts, minimal to no noise or vibration, no need for working fluid, high reliability (operating temperatures are not exceeded), low maintenance, scalable, modular, able to operate in a wide range of transient temperature conditions, and capable of directly converting thermal energy into electrical energy. The goal of this is to provide a thorough review of the usage of thermoelectric generators for internal combustion engine waste heat recovery in order to aid researchers and engineers in the development of effective systems. This will be accomplished by outlining two thorough summaries of both experimental and simulation results, which could cover efficiency improvements, fuel consumption decreases, power output increases, and losses, among other things. A description of the heat exchanger design is also provided (eg external shape, internal structure, material, test temperature and gas flow rate, etc.). The usage of thermoelectric generators mounted on exhaust systems and other locations (radiator and exhaust gas recirculation) that can generate heat for power has thus been thoroughly explained (Burnete et al, 2022).

A new thermoelectric generator concept for recovering exhaust waste heat from a gas-fired propane spark-ignition (SI) engine was experimentally studied by Gürbüz et al. They sought to raise the T temperature differential in their new design by allowing the evaporation of propane and enhancing the cold surface activity of TEG by incorporating copper pipes into the rectangular exhaust heat exchanger. As a consequence, the propane input TEG generated a maximum of 90.2 W DC electrical power and 3,02% energy conversion efficiency at an engine speed of 4500 rpm. Additionally, they discovered a strong link between experimental and numerical results and engine speed variations of 3% to 15%. (Gürbüz, Akçay and Topalcı, 2022).

A thermoelectric generator that can be used with a ship's main engine exhaust system is designed in the prepared design. A mathematical model was developed for this planned system, and the design parameters were established. By designing the system in accordance with the determined parameters, thermal analyzes were carried out and appropriate thermoelectric modules were selected. In order for the system to work efficiently, the thermoelectric module is positioned in the chimney part of the exhaust system. The reason for this is that the cold surface is in contact with the air outside the ship for cooling, and the temperature of approximately 200°C is measured after the chimney boiler in the heating of the hot surface. As a result of the analyzes made, it is aimed to obtain the power required to operate the electrical components of the ship.

2. Thermoelectric Generators

Thermoelectric generators are thermoelectric components that, depending on the temperature difference between their two surfaces, can produce direct current. These thermoelectric components make it simple to produce electrical energy everywhere there is a temperature differential. If various temperature values have an impact on the junction sites in a closed circuit made up of two distinct metals, the Joule effect, Peltier effect, and Seebeck effect come into play between these surfaces. The structure of the thermoelectric generator is depicted in Figure 1.

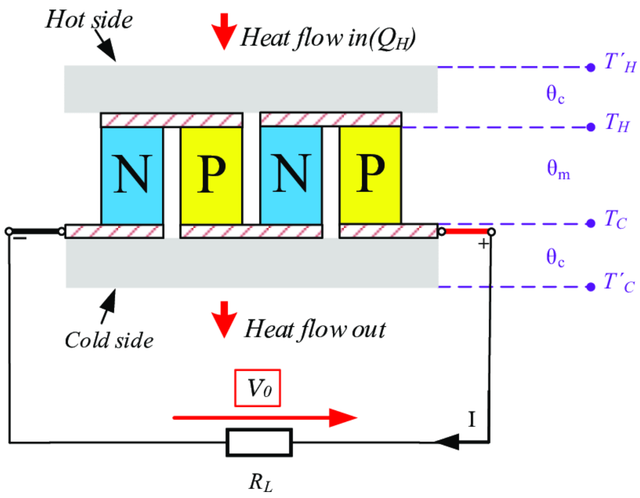

Figure 1. Structure of the thermoelectric generator

2.1. Thermoelectric Module

When a direct current electrical energy is applied to both ends of thermoelectric modules, direct current electrical energy is obtained from the ends when a temperature difference is created between the surfaces (Çengel and Boles, 2012). Thermo elements formed in N and P type semiconductor pairs are placed between ceramics in electrical series and thermally parallel (Kraftmakher, 2005).

A thermoelectric cooling module consisting of an N and P semiconductor pair is shown in

Figure 2.

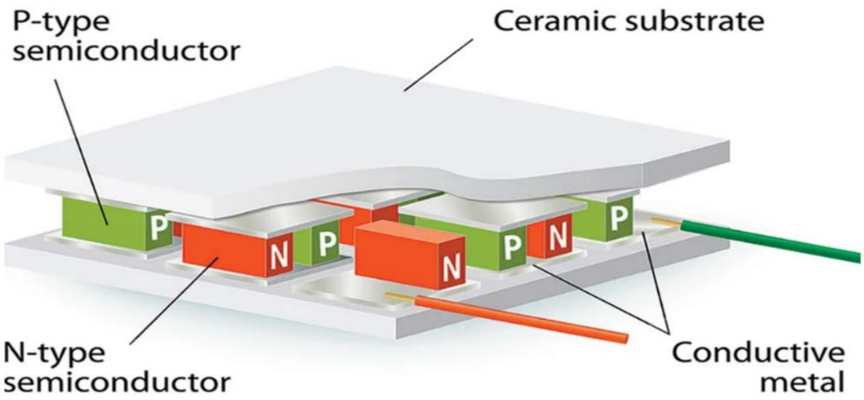

Figure 2. Internal Structure of Thermoelectric Module

In the structure in the figure, the circulating of the direct current from each N and P type semiconductor pairs through the lower and upper contacts causes the temperature to move (Goldsmid, 2009). 2 While the current flows from the low-energy P-type semiconductor to the high-energy N-type conductor, the electrons receive the energy from the cold surface and leave the hot surface. The electrical power supplied from the outside will provide the energy required for the electrons to move within the system and will enable the heat to be transferred as they move between the changing energy levels (Çengel and Boles, 2012).

Thermoelectric modules used for heating, cooling and electrical power generation have many advantages. Among them; they are light and small in size, have no moving parts, do not vibrate and make noise, can be easily controlled for temperature, are harmless to the environment, can work smoothly in different gravity conditions, etc. like this. The most important disadvantages are that they are low in yield and expensive (Antonova and Looman, 2005). The circuit consisting of a semiconductor, which has both electrical and thermal effects, is called a thermoelectric circuit. Thermoelectric effects, which form the basis of the conversion of heat energy to electrical energy and electrical energy to heat energy, have been known for more than 150 years (Smoot, 2017). Three different thermoelectric events, called Seebeck, Peltier and Thomson, occur in thermoelectric modules (Solbrekken, 2008).

3. Material and Method

By effectively converting the thermal energy that has been left in the environment without being used into electrical energy, this study aims to partially address the energy shortage. In order to achieve this, a mathematical model of the designed model was developed in accordance with the laws of heat transfer, and this model's analysis was done in a computer environment utilizing the Thermal-Electric and Thermal modules of the ANSYS Workbench 16.0 software. According to specific temperature circumstances, the results of these analyses' current, voltage, and power values were recorded. In this study, it is aimed to reduce the energy deficit to some extent by efficiently converting the heat energy left to the nature without being used into electrical energy. For this purpose, the mathematical model of the designed model was created in accordance with the heat transfer principles, and the analysis of this model was carried out in the computer environment, using the Thermal-Electric and Thermal modules in the ANSYS Workbench 16.0 software program. The current, voltage and power values obtained as a result of these analyzes were recorded depending on certain temperature conditions.

3.1. Relationships Used in Thermoelectric Generator Design

The dimensions of each component utilized in this model, which is intended to actualize power generation, as well as the material properties chosen in accordance with the design parameters, are determined by ideal thermoelectric equations. The Seebeck effect, Joule heat, and conduction heat are the basis for the ideal thermoelectric equations employed in this context (İslamoğlu, 2018). To generate these ideal equations employed in the model's construction, some assumptions have been made:

• When the intended thermoelectric generator is mounted on the exhaust, the temperature of the exhaust gas traveling through that part is 200 °C (473 °K).

• The generated thermoelectric generator has a uniform temperature distribution.

• The thermoelectric module's cool surface is in close proximity to a heat sink. Convectional contact occurs between the environment and the heat sink.

• Thermal and electrical contact resistances are neglected.

• Temperature has no effect on a material's characteristics. The Thomson effect has so been disregarded.

• For the semiconductor thermoelectric feet in the thermoelectric module, convection and radiation are disregarded.

• It is assumed that the connection points are perfectly within the model.

The dimensions of the hexagonal block in the design, which is used to transmit the exhaust gas temperature to the hot surface of the thermoelectric module under desired conditions, and its heat transfer coefficient were determined using standard heat transfer formulas. The thermoelectric generator received heat from the exhaust gas,

$$Q = m\,c\,\Delta T \text{ (W)} \tag{1}$$

calculated by the formula. The exhaust gas' thermophysical characteristics employed in this formula are listed in Table 1.

Table 1. Exhaust gas thermophysical properties

Temperature (K)	Core Heat (kj/kgK)	Density (kg/m³)	Thermal Conductivity (W/mK)
400	1.106	0.912	23.6
450	1.114	0.810	29.1
500	1.126	0.729	35
550	1.140	0.662	36.6
600	1.070	0.607	48

In order to find the size of the hexagonal block, which is a part of the design, and the heat transmission coefficient of the material to be used, according to the calculated heat amount

$$Q = K\,\Delta T \text{ (W)} \tag{2}$$

formula is used. Here K is the total heat transfer coefficient. Its unit is W/K. It is calculated according to the formula below.

$$K = \frac{kA}{L} \text{ (W/K)} \tag{3}$$

The following equations are used to determine the voltage, current, resistance, and power values that should be produced from the thermoelectric power generating module, the internal construction of which is illustrated in Figure 3.

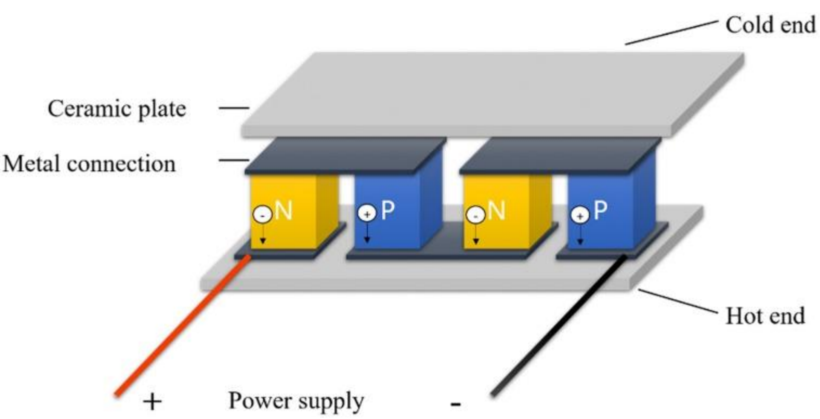

Figure 3. Internal structure of the thermoelectric module

Voltage value;

$$V = \frac{N\,S\,(T_H - T_L)}{\frac{R_L}{R}+1}\left(\frac{R_L}{R}\right) \quad (V) \tag{4}$$

Internal resistance value;

$$R = \rho \frac{L}{A} \quad (\Omega) \tag{5}$$

Current value;

$$I = \frac{S(T_H - T_L)}{R_L + R} \quad (A) \tag{6}$$

Power value;

$$W = \frac{N\,S^2\,(T_H - T_L)^2}{R}\,\frac{\frac{R_L}{R}}{(1+\frac{R_L}{R})^2} \quad (W) \tag{7}$$

The thermoelectric power generator module chosen in accordance with these relations has the following efficiency.

$$\eta = \frac{W}{Q_H} \tag{8}$$

The chosen thermoelectric module's performance criterion (FoM) is determined as follows.

$$FoM = \frac{S^2}{\rho k} \quad (1/K) \tag{9}$$

3.2. Finite Element Method

In many engineering applications, the finite element method (FEM) is a crucial solution technique. Additionally, FEM offers unified analytic options for numerous investigations, including thermal, flow, and electromagnetic evaluations. Additionally, it develops analyses of physics abilities that are integrated, such as thermal-structural, fluid-structural, electromagnetic-thermal, and thermal-electric.

The analysis of thermoelectric devices can be done completely and successfully using the ANSYS analysis package. The analyses carried out using FEM additionally take into account the Seebeck, Peltier, and Thomson effects in addition to the Joule heating effect. The analysis of thermoelectric cooler and generator devices makes use of these effects (Antonova and Looman, 2005).

3.3. Modeling of Thermoelectric Generator

Today's technological advancements have made it possible to design in many different fields thanks to simulations created in a computer environment. One of these simulation tools, the SolidWorks drawing program, which was employed in the creation of this model, offers simplicity of use, design effectiveness, etc. Depending on the features, it is a program that is frequently used in the design and assembly of parts. Additionally, the ANSYS Workbench 16.0 program, another simulation tool employed in this project's part analysis, when used in conjunction with FEM-based software enables the design and analysis of systems through simulations.

The ANSYS finite element program is a highly favored tool since it has a huge archive and permits use of interaction between analysis modules. This model is made up of a hexagonal block, six thermoelectric modules, six heat sinks, and six aluminum plates. Its design was completed in a computer environment, and all proportions were precisely planned. The model in Figure 4 also includes some glass wool to prevent the silicon component of the thermoelectric modules from being harmed at high temperature values, a two-part outer casing to ensure assembly of the designed thermoelectric generator to the ship's main engine exhaust system and to shield it from the outside environment, and to keep the created design together. Connectors can be found.

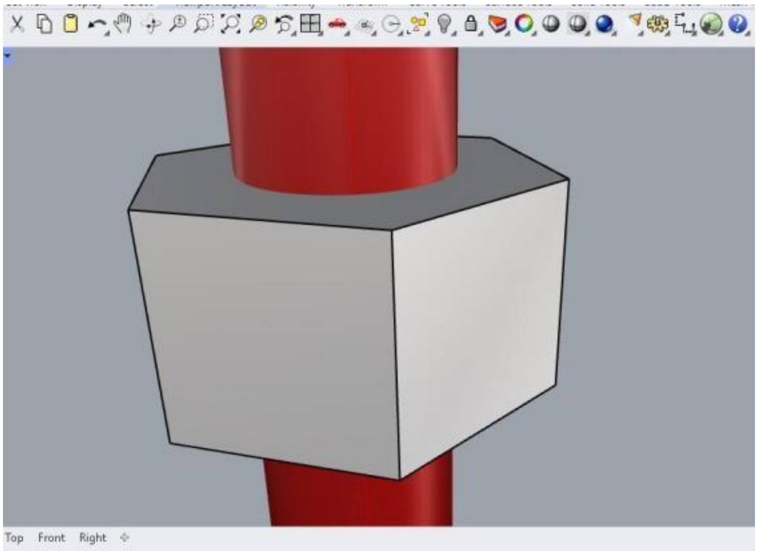

Figure 4. Thermoelectric generator design in Solidworks program

The high temperature factor is one of the main issues that can arise in the design of a thermoelectric generator suitable with such a system. Since the thermoelectric modules that will be utilized in the thermoelectric generator can function effectively up to specific temperature values. The designed system cannot achieve the specified efficiency if the thermoelectric modules don't burn. In this case, a ceramic block in the shape of a hexagon with a low thermal conductivity coefficient was created to make sure that the hot surface of the thermoelectric modules is not affected by temperatures that are lower than the exhaust gas temperature. As stated in Section 2.1, this block, which is 90 cm broad and 45 cm thick, lowers the temperature value of 200℃ (473 °K) to a temperature value at which the thermoelectric module can function.

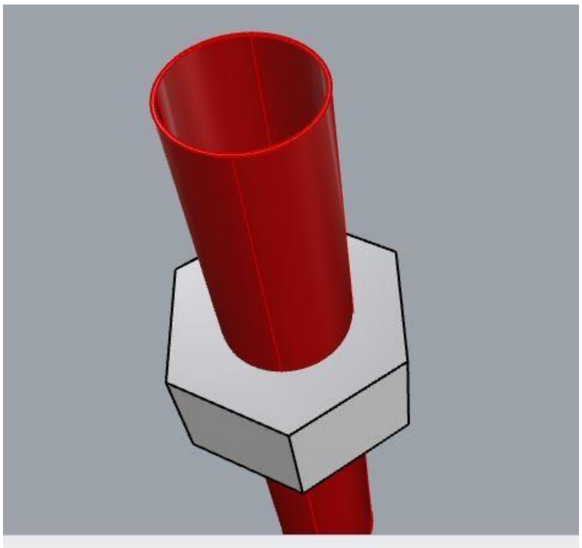

Figure 5. Hexagon Block

The hexagonal block contains the thermoelectric modules that were employed in the design. This is done for several reasons, including to make sure that the temperature values affecting the hot surface of the thermoelectric modules are more uniform, to make the most of the little work area, and to maintain the modules' stability while the tractors are moving. In addition, the exceptionally low heat transmission coefficient of the glass wool employed in these blocks is intended to protect the silicon components of the thermoelectric modules from the high temperature.

For the thermoelectric modules to function properly, the desired voltage, current, and power values must be attained, thermal analyzes of the hexagonal ceramic block were made using the ANSYS Workbench 16.0 analysis program. This model, which was designed in SolidWorks program, was transferred to ANSYS Workbench 16.0 program. Following these steps, the mesh operation is used to connect all of the model's features and make them dependent on one another. In order to ensure a uniform temperature distribution in the hexagonal block, certain node number, element number, and element size values were chosen during the mesh construction process in the most suitable manner for the current, voltage, and power values to be obtained depending on the performance characteristics of the computer.

The number of elements and nodes varies depending on the size of the elements. In Table 2, the number of nodes and the number of elements are given depending on the element dimensions.

Table 2. Thermoelectric Module properties

Size (m^2)	Number of Elements	Number of Loops
0,02	5772	23088

The exhaust gas temperature for the hexagonal ceramic block was defined as 200℃ (473 °K) in the thermal study, and the air temperature value that would effect the model was found to be 28 ℃. Additionally, as it is natural convection, the air convection coefficient is set at 18 W/m^2K. Based on these criteria, the results of the thermal analysis were seen. Thermoelectric module, another material included in the design, has been selected for power generation. The thermoelectric module, whose theoretical calculations are shown in Section 2.1. is shown in Figure 6.

Figure 6. Thermoelectric power generator module type SP1848-27145

Temperatures of up to 150 ℃ can be withstood by the SP1848-27145 type thermoelectric module, which has dimensions of 40 mm x 40 mm x 3.4 mm and is appropriate for high power generation. Table 3 provides the voltage and current numbers that the thermoelectric module will produce based on the temperature differential. 6 of the SP1848-27145 type thermoelectric modules whose properties are specified are used and all of them are connected in series.

Table 3. SP1848-27145 type thermoelectric module specifications

Temperature Difference ΔT	Voltage (V)	Current (mA)
20	0.97	225
40	1.8	368
60	2.4	469
80	3.6	558
100	4.8	669

In this system, where the cooling process is carried out by natural convection, a needle fin heat sink is preferred in order to increase the air flow direction and the surface area in contact with the air.

Temperatures of up to 150 ℃ can be withstood by the SP1848-27145 type thermoelectric module, which has dimensions of 40 mm x 40 mm x 3.4 mm and is appropriate for high power generation. Table 3 provides the voltage and current numbers that the thermoelectric module will produce based on the temperature differential.

The air temperature values used in the thermal analyses for the heat sink were accepted as 28 ℃, and the air's heat transfer coefficient was accepted as 18 W/m^2K.

Table 4 provides the heat transfer coefficients of the materials employed in the developed model.

Table 4. Heat transfer coefficients of the materials used

Material Name	Thermal Conductivity Coefficient (W/mK)
Ceramic	4
Aluminium	237.5
Glass Wool	0.035
Thermal Paste	11

4. Conclusion and Results

Thermal analyses were performed in this study for the heat sink and hexagonal block that were constructed. The operating circumstances of the used thermoelectric modules were examined in accordance with the temperature values produced as a result of these thermal analyses, and the voltage, current, and power values obtained from the thermoelectric modules were discovered.

The temperature values arriving to the hot surface of the thermoelectric module and the temperature values impacting the silicon sections of the thermoelectric modules were discovered in the thermal analyses performed on the hexagonal block. The temperature values of the area where the hexagonal block in Figure 7 makes contact with the hot thermoelectric module surface are specified in this context.

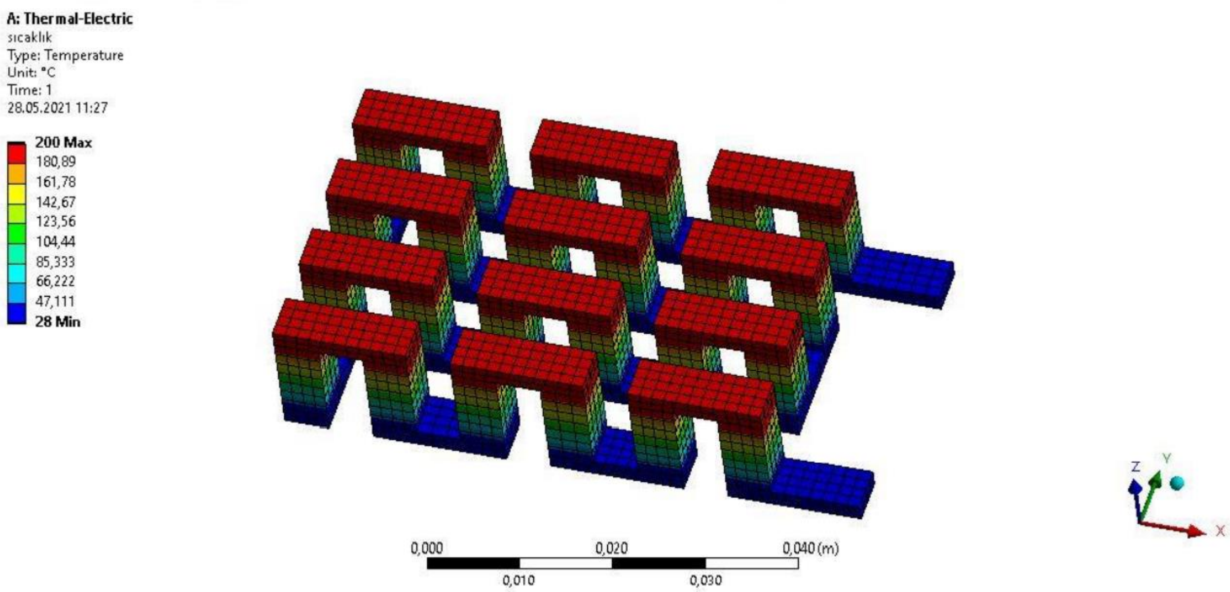

Figure 7. Temperature values coming to the hot surface of the thermoelectric module

A temperature value of roughly 113.51 ℃ was found at the center of the hot surface of the thermoelectric module in the hexagonal model with the uniform temperature distribution shown in Figure 8. Additionally, it has been noted that this temperature value steadily drops from the thermoelectric module's hot surface's center to its edge regions.

It is dependent on the outdoor working temperatures, the circumstances in which the ship's main engine exhaust system is employed, the exhaust gas temperature values, etc. Numerous factors influence the temperature differential. Six thermoelectric modules yielded a total of 5.43 V voltage, 3.77 A current, and 20.5 W power values. Therefore, this power value, which can be used immediately or stored, will enable the main engine exhaust system of the ship's electrical components to operate well.

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