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Otomotiv Termoelektrik Jeneratörünün Deneysel ve Sayısal Performansı

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ÖZET

Bu çalışmada, farklı egzoz sıcaklık değerleri altında termoelektrik modülün elektriksel güc hesabını sağlayan bir model geliştirilmiştir. Termoelektrik modüllerdeki etki, farklı motor devir sayılarında deneysel ve sayısal olarak araştırılmıştır. Ansys Termal Elektrik Programında kullanılan çalışma sınır koşulları deneysel çalışmalardan elde edilmiştir. Deneysel çalışmada 40 adet termoelektrik modül kullanılarak bir prototip oluşturulmuştur. Termoelektrik modüllerin her iki yüzeyinde oluşabilecek mikroskobik hava boşluklarını doldurmak ve ısı transfer dönüşümünü iyileştirmek için termal macun kullanımına gidilmiştir. Bu çalışma, motorun farklı çalışma koşullarının termoelektrik modüllerin elektrik üretimi üzerine olası etkilerini analiz etmeyi amaçlamaktadır. Atık ısı enerjisini elektrik enerjisine dönüştüren Otomotiv Termoelektrik Jeneratörü sisteminde maksimum devre voltajı 40 adet termoelektrik modül için 63 V olarak kaydedilmiştir. Termoelektrik modüllerin elektriksel güç değeri ortalaması alınarak belirlenmiştir. 1500, 2000, 2500, 3000 ve 3500 dev/dak çalıştırılan motorda sırasıyla bir termoelektrik modülün elektriksel gücü 0.26 W, 0.5 W, 1 W, 2.38 W and 3.75 W olmuştur. Aynı şartlar altındaki sayısal analizlerde elde edilen bu değer sırasıyla aynı motor devirleri için 0.42 W, 1.16 W, 2.17 W, 2.9 W ve 5 W olarak tespit edilmiştir. Deneysel ve sayısal analizlerdeki elde edilen bilgiler göstermektedir ki, termoelektrik modüllerdeki sıcaklık dağılımlarının uniform olmasının yanı sıra termal ve elektriksel bağlantılarda oluşan kayıplar modüllerin etkinliğinin azalmasına neden olmuştur.

Anahtar kelimeler: Motorlarda Atık Isı, Termoelektrik, Termal analiz

Experimental and Numerical Performance of Automotive Thermoelectric Generation

ABSTRACT

In this study, a model which allows the electrical power calculation of thermoelectric module under different exhaust temperature gradients was developed. The impact in thermoelectric modules was investigated both experimentally and numerically in different engine speed. The working boundary conditions used in Ansys Thermal Electric Program were obtained from experimental studies. In the experimental study, a prototype was created by using 40 thermoelectric module. Thermal paste was used in order to recover the heat transfer and fill the microscopic gases on two surfaces of thermoelectric modules. This study aims to analyze possible impacts of various engine operating conditions on thermoelectric modules and power generation of thermoelectric modules. Maximum circuit voltage in the Automotive Thermoelectric Generation system that transforms the waste heat energy into electrical energy was recorded as 63 V for 40 thermoelectric module. The value of electrical power of thermoelectric modules was described as average. The electrical power value for per thermoelectric module was 0.26 W, 0.5 W, 1 W, 2.38 W and 3.75 W in the engine speeds of 1500 rpm, 2000 rpm, 2500 rpm,3000 rpm and 3500 rpm, respectively. This values was obtained as 0.42 W, 1.16 W,2.17 W, 2.9 W,5 W in numerical analaysis under some conditions. The data obtained in experimental and numerical studies show that thermal and electrical connection losses as well as non-uniform temperature distribution in thermoelectric module caused the reduce of modules efficiency.

Keywords: Waste Heat in Engine, Thermoelectric, Thermal analysis

INTRODUCTION

Thermoelectric is the science that examines the electrical potential that is composed of the materials due to the temperatures of the liquid or solid materials. Thermoelectric is turn into from heat energy into electrical energy or electrical energy into heat energy. The waste heat recovery has become one of important ways in internal combustion engines (ICE) for energy saving. It is well known that the character of the combustion has an important effect on engine efficiency and waste heat recycling systems. (Balcı, 2011; Temizer and et al.,2012). The heat of exhaust gases is an important potential. (Goncalves and et al., 2010). For this reason, studies in the field of recovery of waste energy are gaining importance. Recently, thermoelectric has become an important research topic. Recovering of wasted heat and converting it into useful energy such as electrical energy can increase efficiency of energy conversion systems and reduce demand on fossil fuels and natural resources (Thacher and et al.,2006; Thacher and et al.,2007; Saqr and et al., 2008) Thermoelectric devices can be used for cooling, heating, power generation, and sensing. There are many advantages of thermoelectric generators such as, simple structure, no moving parts, silence in operation and no pollution (Bansal and Martin, 2000; Riffat and Ma, 2003).

The effect of thermoelectric modules on cooling capacity was analyzed to be used finite element method of TEM. Cooling power, electrical power and performance parameters were calculated (Antonova and et al., 2013). In another study, it was possible to analyze the calculation of thermoelectric devices using the finite element method (Li and et al., 2010). In the simulation study was created a TEG system that consists of 32 double leg was designed. Three different filling thickness values were used as 100, 500 and 1000 in order to analyze the effect of TEG geometry. Cubic and strays of the TEG modules were chosen as 2 mm. Different temperatures were determined for usage as 100, 300 and 500 ^{0} C. When the results of the experiment were examined, the temperature distribution that was not uniform (Admusu and et al., 2013). Significant improvements were obtained in vehicle waste heat recovery applications. The TEG made use of the Seebeck effect in semiconductors for the direct conversion of heat into electrical energy. The electrons in the n type materials that have the ability to move in semiconductors and metals, endures as the holler of the p-type materials load the carrier. These are alloys like Bi_2Te_3, PbTe, SiGe and BiSb. Bi_2Te_3 is the most preferable alloy because of its appropriate working heat and thermoelectric performance. The Seebeck coefficients of the p-type and n-type materials are a function of temperature. These semiconductors are placed between two ceramic layers. Thus, thermal conductivity, electrical insulation and mechanical strength could be provided (Kulbachinskii and Kaminskii, 2004;Hsu and et al., 2011). Some car companies (Orr and et al.,2015) have proven their interest in exhaust heat recovery, developing systems that make use of TEGs. Kim et al. designed an exhaust heat recovery using both TEGs and heat pipes. In their study was generated a maximum of 350 W using 112 TEGs (Kim and et al., 2011). Liu et al. investigated a thermoelectric energy generation system which the maximum electrical power output was 183.24 W (Liu and et al.,2015)

The exhaust gas system of an engine is used to discharge the expanded exhaust gas through the exhaust manifold. However, the design octagonal effect, which may also have significant impacts on the performance was ruled out in previous studies. Transforming the energy of waste heat into electricity that is the specific aim and innovation point of this research, as presented both experimentally and numerically. In this study, the effect of diesel engine that is operated in different speeds on the TEG system has been investigated.

Thermoelectric Analysis and Governing Equations

Finite Element Method (FEM) is a solution technique in both engineering and physics. FEM provides thermal and flow electromagnetic analysis and integrated analysis. Ansys coupled-field element type provides certain and effective analysis of devices for users. Ansys Finite Element Method has a wide element archive. An analysis can be conducted on the interactions between analysis types. For this reason, finite element method has become the solution technique for the fields of engineering and physics (Antonova and Looman, 2005).

The heat conduction and continuity equations of electric charge for TE analysis can be expressed as:

Heat flow in thermoelectric analysis is shown as;

$$\rho C\frac{\partial T}{\partial t} + \nabla . q = \dot{q} \quad (1)$$

The continuity of electric load is shown as;

$$\nabla.(\frac{\partial D}{\partial t} + \mathrm{J}) = 0 \quad (2)$$

When the thermoelectric analysis is combined with continuity equation it is shown as;

$$\vec{q} = [\Pi]\mathrm{J}\text{-}[\lambda]\boldsymbol{\nabla}\mathrm{T} \quad (3)$$

$$\vec{J} = [\sigma](\mathrm{E} - [\mathrm{a}].\nabla\mathrm{T} \quad (4)$$

$$\overrightarrow{D} = [\varepsilon]\vec{\mathrm{E}} \quad (5)$$

ρ is the density (kg/m^3), C is the heat capacity (J/kg.K), T is the temperature in Kelvin (K), is the heat production in the unit (W/m^3), heat is the flow vector, J is the electrical current density vector (A/m^2), E is the electrical field density vector (V/m), is the electrical flow density vector (C/m^2), λ is the thermal conductivity matrix (W/mK), is the electrical conductivity matrix (S/m), a is the Seebeck parameter (V/K) matrix, is the dielectrical conductivity matrix (F/m) (Antonova and Looman, 2005).

$$\rho\mathrm{C}\frac{\partial T}{\partial t}{+}{=}\ \overrightarrow{\nabla}([\Pi]\mathrm{J}) - \vec{\nabla}\ ([\lambda]\vec{\nabla}\mathrm{T}) = \dot{q} \quad (6)$$

$$\overrightarrow{\nabla}([\varepsilon]\vec{\nabla}\frac{\partial\phi}{\partial t} + \overrightarrow{\nabla}([\sigma][\mathrm{a}]\nabla\mathrm{T}) + \overrightarrow{\nabla}\big([\sigma]\overrightarrow{\nabla}\phi\big) = 0 \quad (7)$$

Thermal-Electric option facilitates determination of the features of thermoelectric materials in Ansys Workbench. First of all, material selection, mesh and limit conditions were determined for the model. Bismuth tellurium materials were used in Thermal-Electric in Ansys Workbench. Some features like isotropic thermal conductivity, thermal conductivity, isotropic resistance, isotropic Seebeck parameters were loaded to the copper conductivity that is modeled in 3 dimensions. We may range these steps as follows:

-Physical structure

-Creating a model, network and assign physical features to the area in the model

-Applying the limit conditions and loads

-Forming solutions

The boundary condition was created for 3 dimensional thermoelectric solution using the ANSYS Workbench simulation software. This model was transferred into the ANSYS Workbench software. Rectangular mesh network was the assumed method for mesh operation. Outer edge surface of the copper material was selected as the external electrical load to simulate the system in the open circuit voltage (V) and low potential limit condition. Likewise, the other outer edge surface of the copper conductive material was selected as the external electrical load for high potential limit condition. Figure 1 illustrates the TEG module with 252 pairs of TE legs employed in this application.

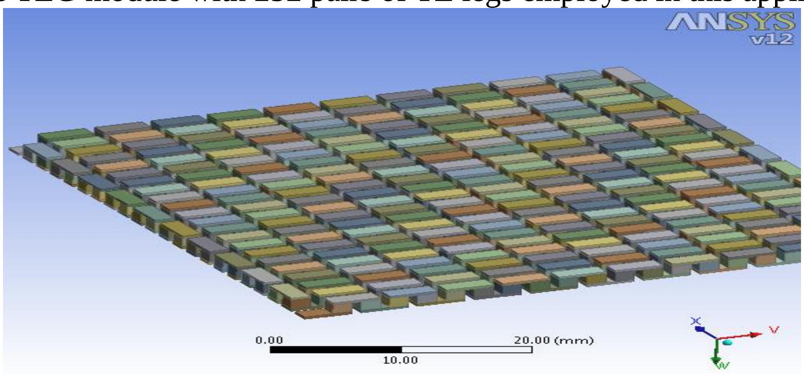


Figure 1. Finite element model of the TEM

Bismuth Tellurium material was selected for semiconductive elements(p and n). Physical properties of Bismuth tellurium material may change based on the temperature (Gao and et al., 2011; Chen and et al.,2012).
The following assumptions were made to simplify the modelling

- •Surfaces of the TEG are exposed to the ambient temperatures,
- •Ideally insulated,
- •The gap between the thermoelectric legs are ignored,

The semiconductor material used in the fabrication of the pellets was selected according to the position of the TEG in the exhaust system. Another important issue is the temperature of the cooling water. High-temperature gases passing along exhaust pipe can be used to heat the "hot side" of the TEGs while the "cold side" is created using water-filled pipes. Also, the cold side of the TEM can cooled by refrigerant or air.

TESTING SET

A prototype that works in accordance with the working principles of thermoelectric generator was applied to an internal combustion diesel engine's exhaust system. Two different fluids were used in the systems in order to create different temperatures that are the working conditions for TEM. One of these was the exhaust gases used to create a hot surface. In this study, two different fluids were used as exhaust gases and cooling water. 40 thermoelectric modules which were connected as series to each other electrically placed on an octagonal structure with aluminum alloy material. The TEMs were worked between the exhaust pipe and cooling water unit. Aluminum plate that cut in the measurement of 300x480x2 mm was turned into an octagonal structure in a special bending machine in order to make achieve an the angle of 135 degrees. The dimensions of the TEG system are given in Table 1.

Table 1. The dimension of TEG

System Components	Dimensions
Nozzle	Length:150 mm, Shrinkable cross-sectional diameter:57 mm, Height:144.8mm, Thickness: 2mm
Octagon channel	Length: 300 mm, Height: 14.48 mm, Thickness: 2mm
Cylinder tube	Length: 300 mm, İnner diameter: 180 mm, Thickness: 15mm
TEM	56 mm x 56 mm x 5 mm (Width, Length and Thickness)

Totally, 40 TEMs were connected to each other as 5 pieces in each surface in the experiments. The system consisted of the TEM's, the inlet and outlet pipes of the exhaust gases and the water inlet and outlet. The waste heat recovery system shown in Figure 2 was designed for use with the exhaust pipe of engine.

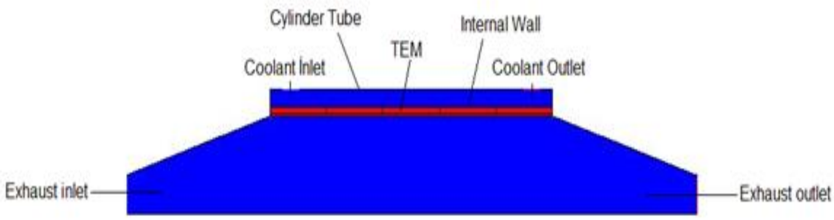


Figure 2. Two-dimensional view of the TEG System

In this study, the effects of internal combustion diesel engine that operated in different speeds and loads on TEG system was investigated. One of the most important issues was the design of the TEG system as the design of the system directly affects the efficiency of TEG systems. From this point, the important aspects in the design of the system were as follows:

- •Thermal forces need to have the ability to distribute and manage heat as comparable to a more planar design.
- •The wall surface is applied to the cold side in order to ensure thermal conductivity, electrical insulation and water tightness.
- •Exhaust gases have edge length that will not increase the surface and the opportunity to benefit from TEM.
- •The input and output nozzles are created in order to ensure the entry and exit of the exhaust gas flow. In this way, the danger of sudden contraction and expansion is prevented.
- •The similarity of cylindrical properties are considered to be important parameter in the selection of this geometry.

In the experiments, the plate and cylinder tube consisting of 6061 T4 aluminum material were used. The material selection was built by considering the machinable features, corrosion resistance, lightness, flexibility and heat transfer parameters. The heat of exhaust gases in the octagon channel allow creation of hot surface of the TEM. Water was used in order to create the cold surface of TEM in the system. The ınternal wall was created with a thickness of 0.4 mm galvanized sheet between TEMs using cold water that flows parallel with the exhaust gas flow. The objective is to prevent the damage of TEM by preventing its contact with the water. Thermal paste was used in order to enhance the heat transfer and fill the micro-void on the surfaces of TEM. TEG cooling system consists of cooling radiator, hoses, tank and electric pump with 12 V DC voltages. The input speed of cooling water was stable and 2 m/sec. in all working conditions. The one changing feature of cooling water was the input heat. The DC-DC converter was in between TEG and battery as an electric circuit. DC-DC converter under the brand of Mean Well brand with the number of SD-1000L-12 providing charge to the battery in a certain voltage was used to prevent electrical fluctuations and transfer the electrical power. Then, electric power was generated due to the temperature difference between the two sides of the thermoelectric modules and stored in batteries. Thermocouple type k was used in the heat measurements. The electric current generated by the modules was measured with a multimeter. The test set was comprised of Cussons P8602 brand engine dynamometer (test cell) bench and Fiat Doblo 1.9 Multijet brand diesel engine with 4–cylinders and 4-stroke. Injection system is common rail 1400 bar. In particular, the 1.9 Multijet is equipped with a variable geometry turbocharger. Hydraulic dynamometers that controls the speed and load values of diesel engine is connected in order to determine the performance of TEG system placed between the exhaust manifold and the muffler. Hydraulic dynamometers are used as loading units (Nm) in the engine. Testing set used in the workshop of Automotive Engineering Department of Technology Faculty in Firat University is shown in Figure 3. The objective is to determine the effect of engine on TEM's. The output and input temperatures of exhaust gases were recorded by measuring TEM top and low surface temperatures and voltage and current values. The features of internal combustion diesel engine connected to the test stand are given in Table 2.

Table 2. The engine's features used in the experiments

Engine	Diesel P8602 Fiat Doblo
Engine technology	Multijet 2,Turbocharged
Fuel System	Common Rail
Number of cylinders	4
Cylinder volume	1.91
Maximum torque	2000 rpm, 280 Nm

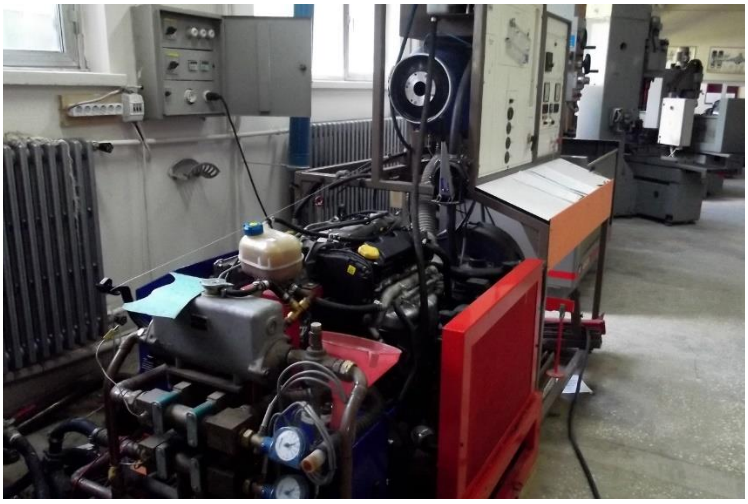


Figure 3. Experimental Setup

RESULTS AND DISCUSSION

The experimental section presents a description of the experimental setup and testing method to validate the new idea proposed. The TEG system was in connection with the engine exhaust system and measurement device was built and ready to operate. The measurements were in the range of 1500, 2000, 2500, 3000 and 3500 rpm engine speed and 75 Nm engine load. The effects of changing both engine speed and engine loads on TEG system were observed. The maximum TEM surface temperature was measured as 240 ^{0}C in hot surface and 95^0 C in cold surface when the engine ran in 3500 rpm. Due to experimental difficulties, there only two different surface temperatures of the first thermoelectric module could be measured. The main goal was to calculate the performance of the module the maximum difference in temperatures. In the study, temperature measurements were recorded with the help of thermocouples placed on the surfaces of TEM. The temperature on the hot surface of TEM and the speeds of 1500,2000,2500,3000 and 3500 rpm were measured respectively 89 ^{0}C, 134 ^{0}C, 170 ^{0}C, 200 ^{0}C and 240 ^{0}C and this value was measured as respectively 44 ^{0}C, 60 ^{0}C, 69 ^{0}C, 83 ^{0}C and 95 ^{0}C in cold surfaces. The speed and unit time of the internal combustion engines increased as the piston speed increased. Based on these increase the exhaust gas temperature and flow rate increased. In the experimental studies, the temperature was in proportion with the engine speed number.

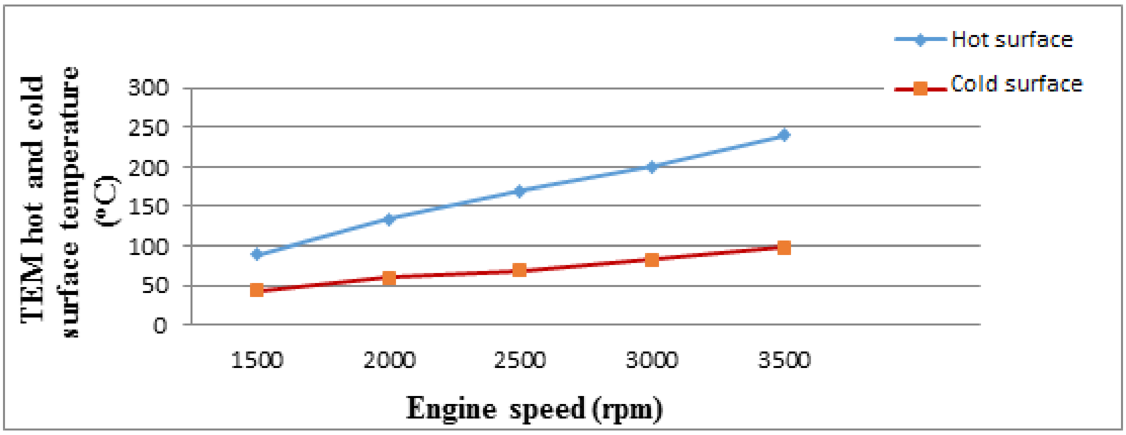


Figure 4. The temperatures on the surface of TEM

As shown in Figure 4, the increase in the speed of the engine increased both the top and bottom surface temperatures of the TEM. The temperature of the exhaust gases in TEG system decreased as a result of convectional heat transfer and cooling fluid flow in TEG system. But, exhaust gas temperatures in TEG systems increased with the increase of the speed. The important parameter for this system is the temperature of the cool side because the electrical power which produced with the increase of the difference temperature tends to increase, too. Therefore, the water circulated with the help of electrical pump in the system helped the cold surface temperature decrease. The increase of input temperature of the cooling water was prevented with the help of the cooling fan and heat exchanger. Exhaust gas temperatures caused to an increase in the temperatures of cooling water in parallel with the engine speed. Once the experimental results were examined, with the effect of the constant flow of cooling water, a part of the exhaust gas was cooled down and the outlet temperatures of exhaust gases decreased about 10-30 ^{o}C relative to it's inlet temperature. In the engine, the air's movements increased in parallel with the speed. Along with this increase, the engine torque and power values increased as well. The exhaust gas movement varies with the engine speed. It is thought that the exhaust gas speed was affected by the increase in combustion speed. This is why it is observed that the engine speed and the exhaust gas speed increased together. The Input temperatures of the cooling water are given in Table 3.

Table 3. The ınput temperatures of the cooling water

Engine Speed (rpm)	**The ınput temperatures of the cooling water**
1500	26^{o}C
2000	36,8^{o}C
2500	45^{o}C
3000	52^{o}C
3500	57,2^{o}C

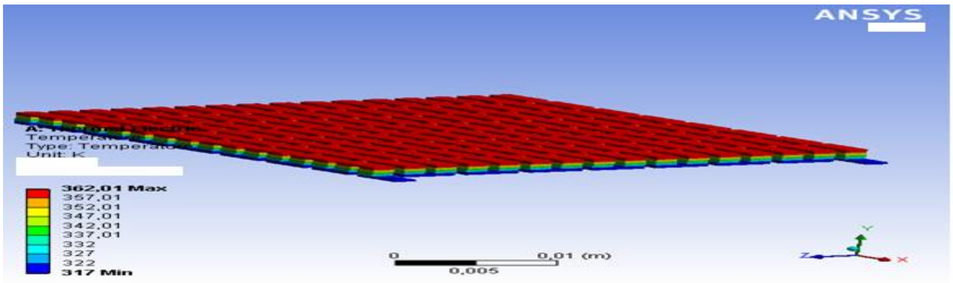
It is important to store the electrical power in maximum power of a battery. As in the alternator system, electrical circuit elements were needed to charge the battery in our study. Thus, the values of current and voltage were determined in the electrical load of the TEG system. The electrical energy obtained according to the difference in temperature values applied to the TEM was different. The battery charging process was achieved using a DC-DC converter. It was also used to reduce the DC voltage and stabilize the electrical energy. The system was connected to a 12 V car battery with the help of DC-DC converter. DC-DC converter requires setting the voltage to 14 V value in order to charge the battery. However, the output voltage of the TEG should be the value in the running range of the convertor in order to charge the battery. Maximum circuit voltage in the TEG system that transforms the waste heat energy into electrical energy was recorded as 63 V for 40 TEM. As shown in Table 4, when the engine speed and load increased, the value of the produced electrical energy increased. But this increase was not a linear one.

Table 4. The electrical volumes for different engine speeds and loads

Engine speed (rpm)	**Voltage (V)**	**Current (A)**	**Electrical Power (W)**
1500	14.6	0.73	10.65
2000	21.06	0.95	20
2500	31.2	1.29	40.2
3000	48.66	1.96	95.37

3500	63	2.38	150.3

The value of electrical power of TEM can be described as average. The electrical power value for per TEM was 0.26, 0.5, 1, 2.38 and 3.75 W in the engine speeds of 1500, 2000, 2500,3000 and 3500 rpm. The experimental study was also supported by numerical results. The properties obtained from experimental study are used ın Ansys Thermal Electric Program. These properties are surface temperatures and thermophysical properties of the modules. Figure 5 shows the temperature distribution obtained in the maximum temperature difference.



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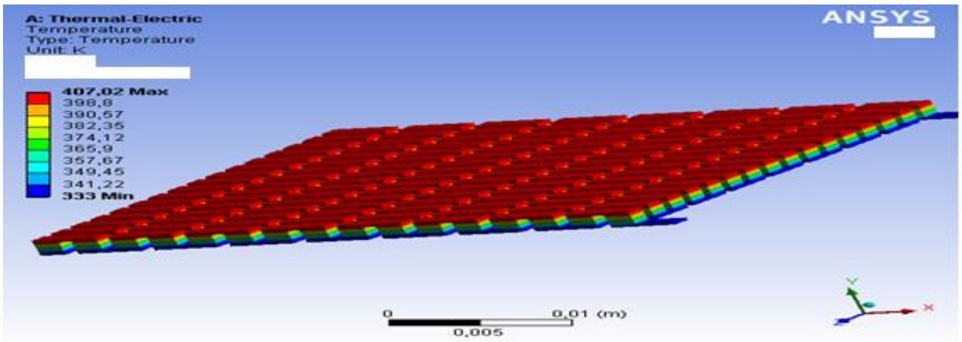

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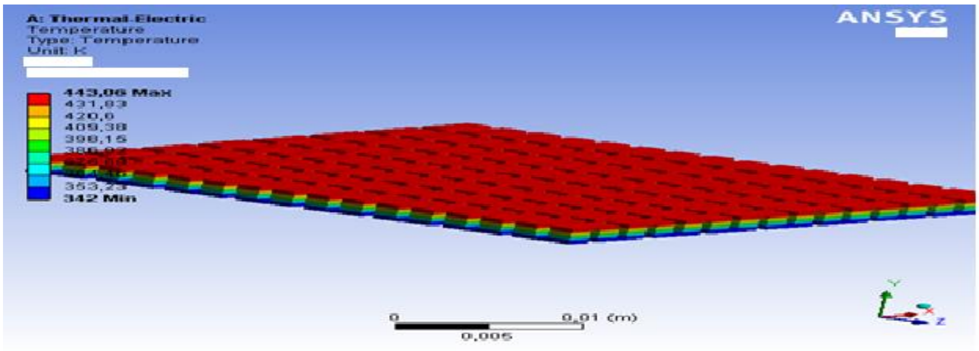

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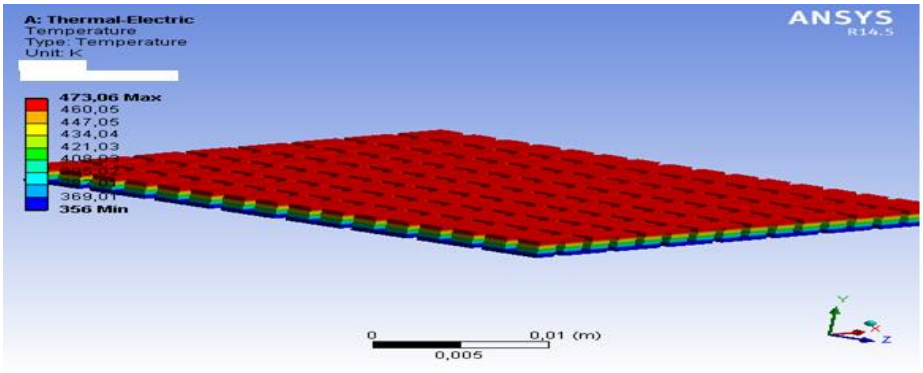

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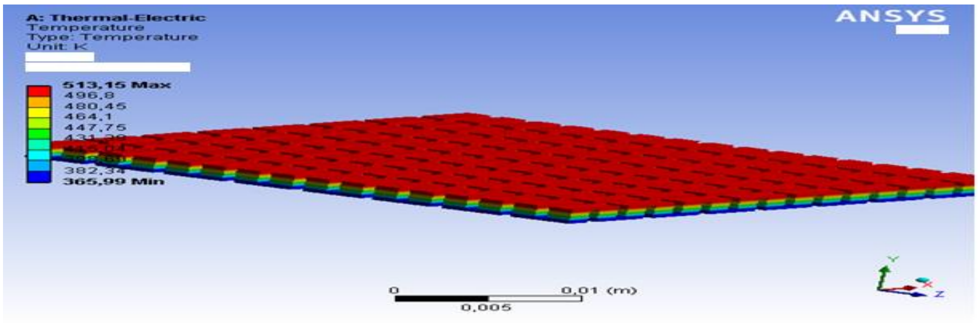

e.

Figure 5. The temperature distribution of the TEM system of the operation situation of the engines 1500 rpm (a), 2000 rpm (b), 2500 rpm (c), 3000 rpm (d) and 3500 (e) rpm

In both experimental and analysis results, the obtained electrical output data from a TEM are shown in Figures 6. Regarding the engine exhaust, it was aimed to obtain the dynamic results by changing the input of analysis of TEM that was exposed to different working temperatures. For instance, some physical features such as Seebeck, thermal conductivity, electrical conductivity that changed dependent on the temperature were described as working conditions for thermoelectric materials. Temperature distributions of the thermoelectric modules were calculated by steady-state thermal analysis. The temperature and electrical distribution are given in the following results. The different temperature gradient caused the heat to flow through entire module. Resulting heat flow caused different electrical output values of the TEM.

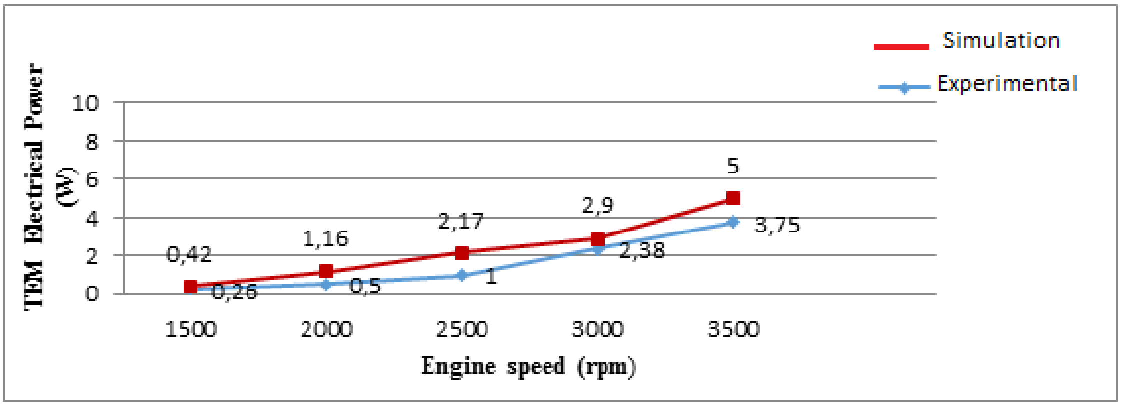

Figure 6. The obtained electrical output data

CONCLUSION

TEG systems can be more useful for utilization of the waste heat like vehicle radiators, stoves, natural hot springs, gas water heaters and sun rays. It can be thought as an alternative system for charging batteries in hybrid electrical vehicles. There are negative factors that affect power production performance of thermoelectric systems. The data obtained in experimental and numerical studies show that thermal and electrical connection losses as well as non-uniform temperature distribution in TEM decrease the efficiency of modules. It is thought that neglecting the heat losses, differences in Seebeck parameters and manufacturing errors and heat differences on TEM surfaces caused an increase in the values of analysis results. Additionally, voltage produced at the analysis was open-circuit voltage. This voltage measured while a current does not flow. For this reason, it caused an increase the output values in the analysis. TEG systems can be more useful for evaluation of the waste heat like vehicle radiators, stoves, natural hot springs, gas water heaters and sun rays.

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