MATHEMATICAL MODELING of THERMOELECTRIC GENERATOR by REGRESSION ANALYSIS

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Abstract

Abstract - As countries grow, their need and demand for energy grow as well. The development of the technology and industry, which come to exist due to the growth of the country, a brings about a rise in energy consumption, as well as increasing the damage to the environment. Therefore, as the environmental and energy-related issues started to emerge more and more, we have seen an increase in the number of studies on energy production and its effects on the environment. Such studies highlight the renewable energy sources among the non-polluting alternative energy sources. Geothermal energy, particularly, shines out among the other renewable energy sources. It is a clean energy source that has been sustained since the Earth was formed. This study focuses on the design of a device named thermoelectric generator (TEG) that converts a renewable energy source, geothermal energy, directly into electric energy. Hence, we ran a simulation of a regression analysis and mathematical model on the thermoelectric modules TEC1-12706 and TEC1-12710, which can easily be found on the market, and then crosschecked the simulation results of different temperature, pressure, and water flow with experiments. The values for current, voltage, power, hot and cold surface temperatures, and the temperature difference between hot and cold surfaces were

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constantly monitored and recorded. The results of the experiment were compared using the regression analysis method. For the device TEC1-12706, error percentage of 9 experiments was 16.52% while it was 9.70% for TEC1-12710. At 90°C temperature difference, for TEC1-12706, output voltage was Vmax = 2.03V, output power Pmax = 2.17W, and efficiency 32.15%. For TEC1-12710, output voltage was Vmax = 2.11V, output power Pmax = 3.42W, and efficiency 38.53% [1,2].

Keywords: Geothermal Energy, Thermoelectric Generator (TEG), Modeling, Regression Analysis

1. Introduction

In our current decade, where energy preservation gained such importance, especially the developed countries form their energy policies so that at least 10% of their energy demand can be provided using renewable energy sources. As the environment and energy-related issues increase worldwide in the recent years, the number of studies focusing on energy consumption and its effects on the environment have also increased. For this reason, many countries started to favor the geothermal energy sources among renewable sources. Geothermal energy have existed for a really long time, and it provides a clean and cheap energy source. Every year, new geothermal energy sources are detected all over the world and the use of this energy source also increases rapidly. Since we need devices to produce megawatts of electricity and we need to import the solar panels and wind turbines needed from developed countries, this ends up being very costly for Turkey. Thanks to the studies and investments on the subject, it is apparent that the power deficit resulting from ever growing demand for power can be quenched using the residual heat from energy conversion. If we look back in time, we can see that we have used our energy sources inefficiently. We need to rethink the necessity of energy usage in many industries to fix this[3,4,5]. As the thermoelectric modules (TEM) have many advantages such as being durable, not requiring maintenance, being quiet, not having moving parts, and having a simple structure, the importance of these modules and the thermoelectric (TE) semiconductors have increased swiftly ever since the production of electric energy using residual heat energy became more popular[6,7,8,9,10].

This study focuses on the design of a thermoelectric generator (TEG) that converts a renewable energy source, geothermal energy, directly into electric energy. We used common thermoelectic modules that can easily be found on the market. During the experiments, the thermal liquid in TEGs was operated at different temperature, pressure and speed options. Upon conducting the experiments, we did a TEG modeling using the data we have collected. This paper inspects the small power TEG design model. As we have aimed to build bigger systems in the future, we designed the prototype so that it would be similar to the bigger systems within the bounds of possibility.

2. Materials and Methodology

We put the common thermoelectric coolers in copper blocks that had water tunnels inside. As can be seen from figure 1, TECs can be purchased from the market in a square shape with the size of 40x40 mm.

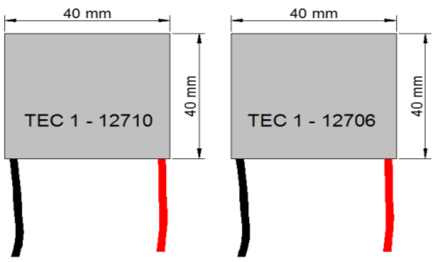


Figure 1. TEC1-12706 and TEC1-12710 Thermoelectric Coolers

When negative and positive DC voltage is applied to the black and red cables of the module, they work in a peltier way. During this process, the PNP and NPN semiconductive materials inside go through electron movements. When these electrons move from one place to another, the temperature of the surfaces change according to the movement direction of the electrons. While one of the surfaces get cold, the other one gets warm and this allows the device to cool small areas such as vehicle refrigerators or mini refrigerators. There are studies still underway to use this method in human clothing, shoes, car seats, etc. [11,12].

If you apply high temperature to one of the ceramic surfaces and low temperature to the other one instead of applying DC energy to the cables, the electrons in PNP and NPN series semi conductors, which are thermally parallel and electrically series with copper sticks, will start moving and you will receive DC voltage from the red and black cable ends of the module. This process is called thermoelectric generator (TEG) practice.

To generate energy from temperature difference in the system, two different TECs coded as TEC1-12706 and TEC1-12710 with size of 40*40*3,8 mm were used. The parameters for the used TECs are listed in Table 1 [11,5].

Table 1. TEC1-12706 and TEC1-12710 specifications

Performance characteristics	**TEC1-12706**			**TEC1-12706**	
Hot Side Temperature (°C)	25°C	50°C		25°C	50°C
Qmax (Watt)	50	57		85	96
ΔTmax (°C)	66	75		66	75
Imax (Ampere)	6,4	6,4		10,5	10,5
Vmax (Voltage)	14,4	16,4		15,2	17,4
Modul Resistance (Ohm)	1,98	2,30		1,08	1,24

As can be seen from Figure 2, TECs are placed between plates that have water tunnels inside.

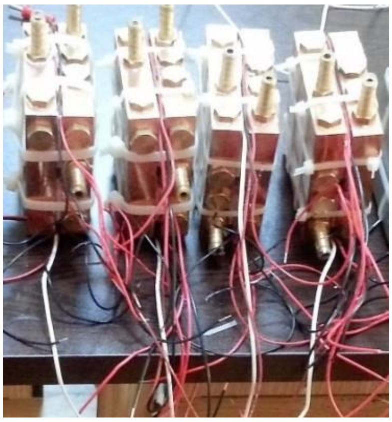


Figure 2. Placement of TEC1-12706 and TEC1-12710 in Thermoelectric Cooling Blocks

The TECs that are placed in copper blocks are connected electrically as shown in Figure 3.

Different temperatures are applied to the thermoelectric modules' surfaces by running hot or cold water through water tunnels as shown in Figure 4 [13].

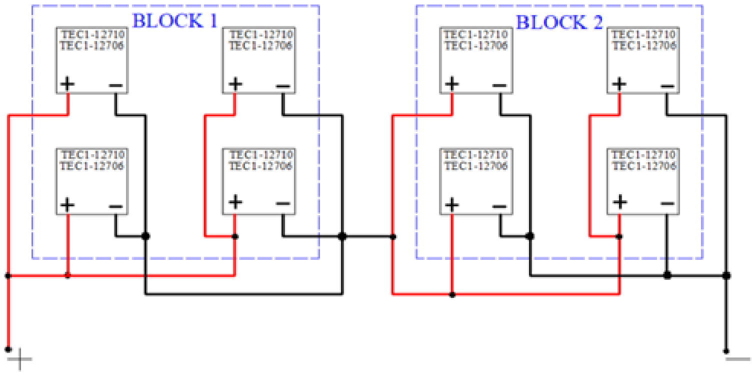


Figure 3. Electrical Wiring of TEC1-12706 and TEC1-12710 in Thermoelectric Cooling Blocks.

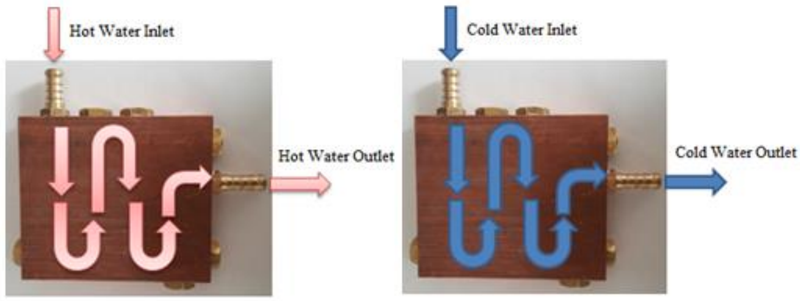


Figure 4. Hot and Cold Water Running Through the Copper Blocks.

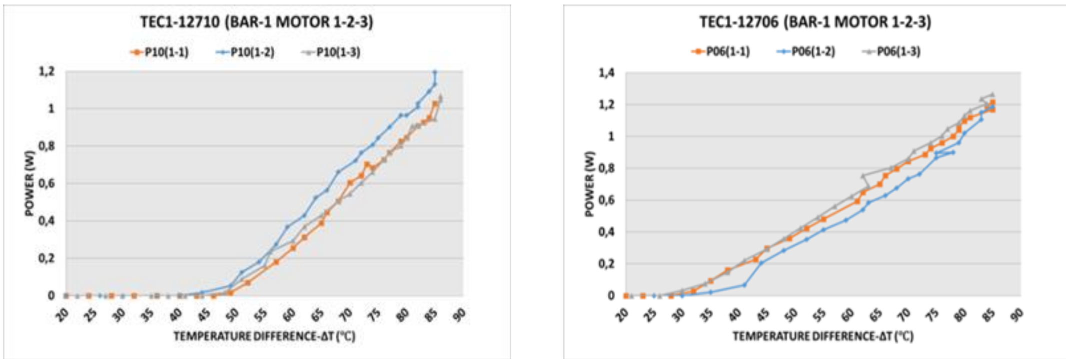
In the experimental setup, we built two independent close systems so that cold and hot water can run separately. We flushed cold and hot water in the closed systems and set the pressure between 1 and 3.5. We conducted several experiments with different pressures. The temperature of the inbound water and the temperature of the outbound water along with the pressure levels are monitored constantly using sensors. We also measured the temperature and the amount of electricity generated using the measuring devices on the blocks or on the cables of TEGs. Since most of the geothermal sources in Turkey have a lower temperature and the heat resistance level of the TECs were 120°C at max, we stopped the experiments when we reached 85-90°C difference.

3. Results and Discussion

3.1. Discussion

We conducted experiments with 3 different pressure and 3 different water levels, then monitored the amount of energy and power generated. We conducted 9 experiments for each of the machines, using different bar pressures (1, 2.5 and 3.5 bar) and water pump power options (at 1st, 2nd and 3rd option).

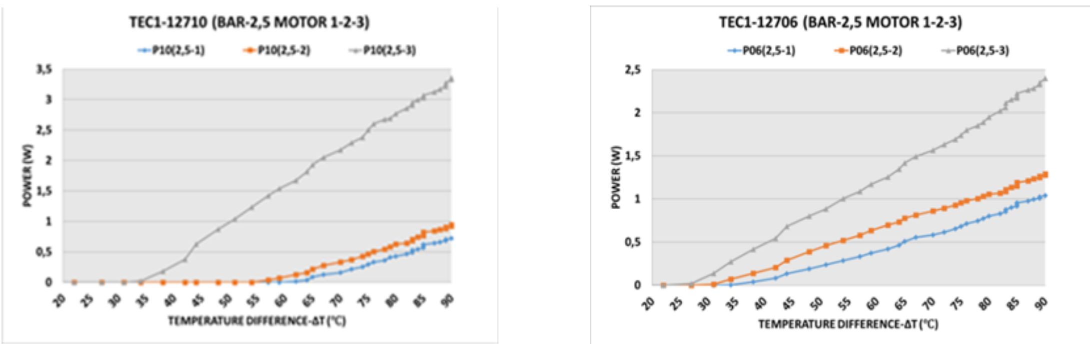
In experiments conducted at 1 bar pressure and 3 different water levels, in TEC1-12706 TEMs produced more power when the water levels increased, as can be seen in Figure 5. TEC1-12710, however, worked better at medium water level. In all three experiments, TEC1-12706 TEMs generated more power than TEC1-12710 TEMs at lower temperatures, and throughout the experiment, TEC1-12706 TEMs continued generating more power than TEC1-12710 TEMs.



(a) (b)

Figure 5. The power generated by TEC1-12710 (a) and TEC1-12706 (b) at 1 bar pressure and with 3 different water levels.

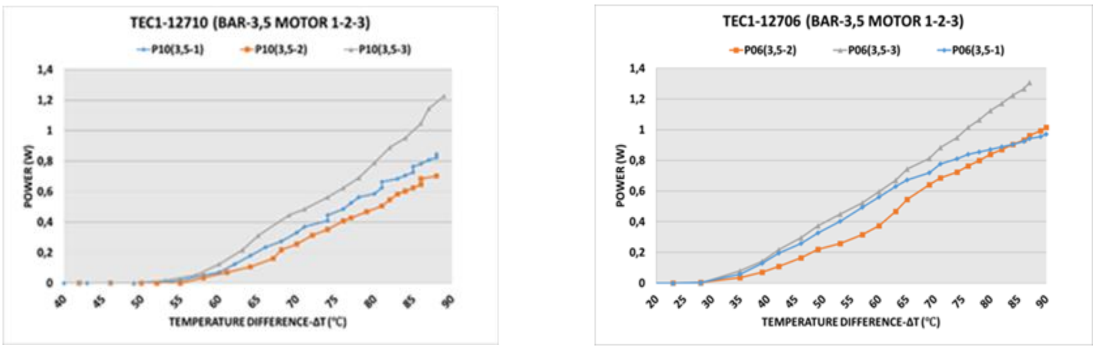
In experiments with 2.5 bar pressure and 3 different water levels, if the water levels rise, the amount of power generated also increase. Moreover, as the water level increased, they produced more power at temperatures at which they started to generate power. In all three experiments, TEC1-12706 TEMs started generating power at lower temperatures compared to TEC1-12710s. This can be seen in Figure 6 in a graph.



(a) (b)

Figure 6. The power generated by TEC1-12710 (a) and TEC1-12706 (b) at 2.5 bar pressure and with 3 different water levels.

In experiments at 3.5 bar pressure and with 3 different water levels, if the water pressure is constant, the amount of power generated increases proportionately to the water levels. Moreover, as the water levels increased, they started producing more power at lower temperatures. This can be seen in Figure 7 in a graph.



(a) (b)

Figure 7. The power generated by TEC1-12710 (a) and TEC1-12706 (b) at 3.5 bar pressure and with 3 different water levels.

3.1.1. Accuracy of TEG Modeling

Accuracy denotes how close the calculated data was to the measured data. Equation 1 is used for every data value to determine the error percentage between the calculated value and the measured value.

$$\delta_i = \frac{|R_a - R_a^0|}{R_a} 100 \qquad (1)$$

In this equation, δ_i: each value's error, R_a: estimated results, R_a^0 : experiment results, and i denotes data value.

To calculate the total error rate of the whole model, we use Equation 2.

$$\Delta = \frac{1}{n} \sum_i^n \delta_i \qquad (2)$$

In this equation Δ: estimated accuracy of the model and n : number of values.

We used Equation 1 and Equation 2 to determine the accuracy of the three recommended methods to model the induction change in segmental ARMs.

Error rates between the voltage values obtained from the 9 experiments and the regression analysis can be seen in Table 3.

Table 2. Mathematical Modeling and ANOVA Table.

Regression Statistics			**Parameters**	
Multi-R	0.915		Constant	0.897
R Squared	0.837		Engine Speed	0.022
Adjustable R Squared	0.836		Pressure	0.160
Standart Hata	0.233		Temperature Difference	0.021
Observation	321.000			

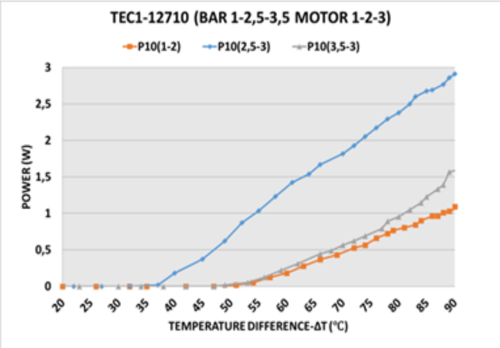
ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	88.291	29.43	544.081	0.000
Difference	317	17.147	0.054		
Total	320	105.438			

Table 3. Error rates in voltage values in experiments

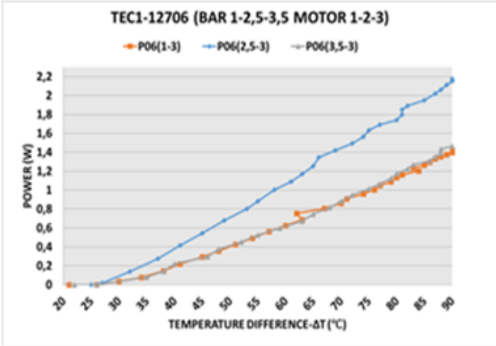
TEC1-12706				**TEC1-12710**			
Flow (rev/m)	**32.3**	**49.5**	**64.2**	**Flow (rev/m)**	**32.3**	**49.5**	**64.2**
Press. (bar)	%			*Press. (bar)*	%		
1	16.4	14.2	16.0	*1*	7.7	9.3	9.6
2.5	20.2	15.3	15.6	*2.5*	7.1	8.0	20.3
3.5	17.5	18.5	15.2	*3.5*	7.7	6.9	10.4
Average	**%16.52**			Average	**%9.70**		

3.2. Results

This study distinctively analyzed the TECs, different pressure settings, and different water levels using only one experiment setup. We designed a system where using hot-cold water level, pressure and temperature difference we could generate cheap, clean and easy electric energy.



(a)



(b)

Figure 8. Comparison of the best power generation levels of TEC1-12710 (a) and TEC1-12706 (b) TEMs at 1, 2.5 and 3.5 bar pressures and three different water levels

If we take into account the 9 experiments we've conducted, we can say that TEMs work the most efficiently at high pressure and with high water level. Their efficiency is pretty low at low pressure and with low water level. As can be seen from Figure 8, water level has a bigger effect on the efficiency than the pressure [11,14,15].

In thermoelectric modules, TEC1-12706 generates faster current and voltage at lower temperatures. In most of the experiments, TEC1-12706 generated more power than TEC1-12710. However, at high pressure and with high water levels, TEC1-12710 thermoelectric modules generated more power than TEC1-12706. This shows that while picking out the thermoelectric module, we should bear in mind the water level and the temperature difference in the water. Additionally, the data collected in these experiments were supported with mathematical modeling. Regression analysis shows that for voltage, TEC1-12706 has an error percentage of 16.52% in 9 experiments while TEC1-12710 has an error percentage of 9.70%. When TEC1-12706 thermoelectric modules are used as TEG, efficiency level for 9 experiments is 32.15%, while it is 38.53% for TEC1-12710 [1,2].

In future studies, the number of TEGs should be increased and the experiments should be conducted at higher temperatures. The experiments should also be conducted at one of the energy conversion systems in Turkey by building an experiment setup and should be supported with real practices on-site.

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