The Impact of Different Electric Connection Types in Thermoelectric Generator Modules on Power

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***Abstract*— *Recently, there is a need for increase in energy efficiency and more energy due to increase in the human population and increased production with the development of technology. This pushes scientists to search for alternative energy. In this respect, interest in renewable energy sources is increasing day by day due to the fact that it is clean energy. Thermal sources have some advantages when compared to other sources, which is why they are at the forefront of renewable energy sources. Today we make use of thermal sources in many fields ranging from greenhouse, fish breeding, thermal facilities, city heating and electricity production. When generating electricity from geothermal electricity conventional methods such as steam turbine-generator cycle are used as well as innovative methods such as semiconductor thermoelectric modules. In the light of developing technologies and researches, we know that we can produce electricity using the heat that the thermal energy gives out while it is being transmitted from one place to another. In this study, in order to shed light on the technological developments in electricity generation using thermal sources, Thermoelectric Coolers (TEC) which convert heat energy into electricity have been used. Two different TEC1-12706 and TEC1-12710 materials from the market were used. The effects of the serial and parallel connections of these materials on the generated power have been observed. Following the experimental studies, the reactions of the different connection types of the TECs to the load were examined. It was observed that the power values obtained from different TECs used varied according to the connection types, both loaded and unloaded.*

***Keywords*— Electricity generation, Output power and efficiency, Renewable energy sources, Thermoelectric generator, Thermoelectric modules.**

I. INTRODUCTION

Energy is one of the main factors that reflect the economic and social development potential of a country because it has an important place in production. In order to meet the increasing need for electricity energy with the developing technology, efforts are being made to obtain energy from alternative energy sources all over the world. These studies aim to achieve clean, cheap and efficient energy. Fossil sources such as coal, oil, natural gas, LPG, wood, which we use widely today, both cause harm to the environment as well as are expected to be consumed in the near future. Nuclear energy, which has started to be used as an alternative to these, has a dangerous production method that requires attention in production and recycling. Due to these reasons, the use of renewable energy sources such as biogas, hydrolic, wind, sun, tidal wave energy, thermal, geothermal has become inevitable in today and in the future. Renewable energy sources differ in terms of efficiency, cheapness, damage to the environment and advanced technologies. Among these energy sources, geothermal energy is more advantageous in that it is efficient, cheap, does not cause damage to the environment and can be utilized at any time of the year, and recently attracts more attention from scientists.

Although today it does not have the potential to be used as the major source of energy production, geothermal energy stands out as a non-polluting, renewable, sustainable and environmentally friendly energy when appropriate technologies are used. Several studies have been carried out on generating electricity with TEC from various waste heat [1-5]. In this study, in order to shed light on the technological developments in electricity generation using thermal sources, Thermoelectric Coolers (TEC) which convert heat energy into electricity have been used. Two different TEC1-12706 and TEC1-12710 materials from the market were used. The effects of the serial and parallel connections of these materials on the generated power have been observed. Following the experimental studies, the reactions of the different connection types of the TECs to the load were examined. It was observed that the power values obtained from different TECs used varied according to the connection types, both loaded and unloaded.

II. THERMOELECTRIC GENERATOR (TEG)

As shown in Fig. 1, a load is attached to the +/- ends of the TEMs and if one of the two surfaces of the ceramic is subjected to high heat and the other low heat, the temperature difference (ΔT) between the two surfaces is formed and DC current is generated by the movement of electrons along P and N type semiconductors as a result of heat flow. In the P type semiconductor part, the holes move to the cold surface of the part, while in the N type semiconductor parts, the electron flow moves to the cold surface of the part. As shown in Fig. 1, the module generates DC current and thus a thermoelectric power generator (TEG) is obtained. There are technologically advanced and commercially viable TEGs or TECs. TECs have maximum COP (Coefficient of Performance) and cooling efficiency in small temperature differences (ΔT) between two surfaces while TEGs have the maximum efficiency in great temperature differences (ΔT) [6-9]

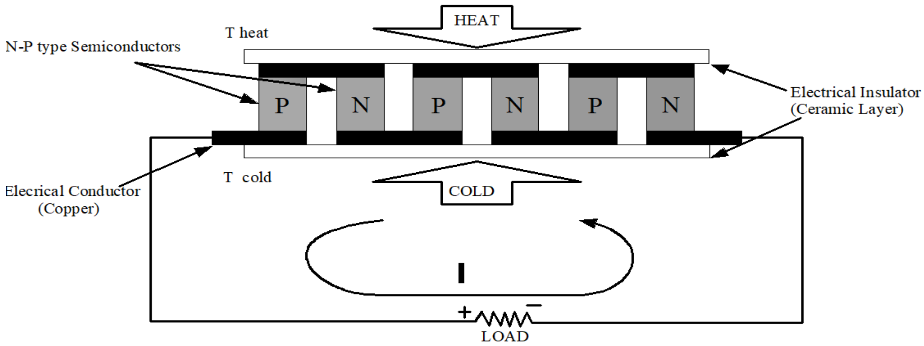

FIGURE 1. THERMOELECTRIC GENERATOR (TEG)

III. MATERIAL AND METHOD

A closed hot-cold water circulation system was designed and the TEMs were operated as TEG in the laboratory environment in this study. Electricity has been produced by making various electrical connections among 8 TECs in each. Hot-cold water was passed through plates with dimensions of 10x10x20 mm in the experimental setup designed as a closed system. In order to increase heat conduction, 4 TECs were placed on the surface of the plates using thermal paste. Thus, cold and hot water is passed through the two plates that formed the blocks designed to have 4 TECs between the two plates. Thus, the impacts of the temperature difference (ΔT) between the surfaces of the TEMs and the types of electrical connections of the TEMs on the power produced in the TEMs have been determined [10-12][10-12]. In addition, two different thermoelectric modules which were coded TEC1-12706 and TEC1-12710, were used during the experiment and their effects on different TECs were examined.

3.1 Thermoelectric Generator (TEG) Module

In the system, two different TECs with the sizes of 40 * 40 * 3.8 mm were used with the codes of TEC1-12706 ve TEC1-12710 in order to generate heat energy from temperature difference. The parameters of the TECs used are given in Table 1.

TABLE 1
TEC1-12706 AND TEC1-12710 CHARACTERISTICS

Performance characteristics	TEC1-12706			TEC1-12710	
Hot Side Temperature (°C)	25	50		25	50
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

3.2 Design of the plates on which TECs were placed and placement of TECs

In the design of the plates, the article "The plate design for obtaining maximum energy with thermoelectric generator" was utilized [13]. TEC1-12710 and TEC1-12706 were placed on the plates shown in Fig. 2 using thermal paste. In addition, a thermocouple temperature sensor was installed between the TECs to measure surface temperatures.

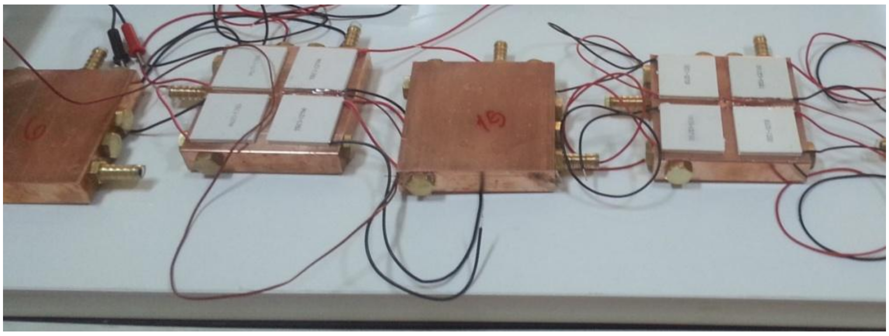

FIGURE 2. IMAGE OF TEC MODULES PLACED ON THE PLATE

IV. EXPERIMENTAL SETUP

The experimental setup used to pass the thermal water from the blocks is given in Fig. 3. In the design of this system, the article "Electrical Conduction with Thermoelectric Generator" from the previous work of the authors were utilized [14].

In the experimental setup shown in Fig. 3, two independent closed systems for hot and cold water circulation were designed. In the designed system, the temperature of hot / cold water entering and exiting the plates can be continuously measured with sensors.

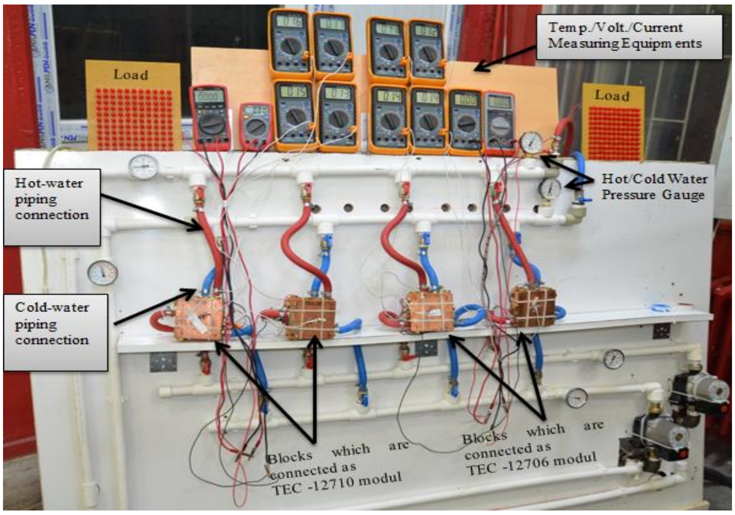

FIGURE 3. CONNECTION IMAGE OF THE DESIGNED SYSTEM

In the designed system, two heat sources were utilized by connecting two heat exchangers in series for hot water. This allowed the hot water in the system to reach the desired value more quickly. Because of the fineness of the thermoelectric modules and because the plates from which hot and cold water were conveyed were impacted, the fan heat exchanger was used to cool the cold water and the air temperature was kept at a certain temperature [15].

The temperature values on the plates, voltage generated by thermoelectric modules and current values were measured using measuring tools. T he load is also connected to the output of the system in order to measure the loaded and unloaded voltages of the system.

V. CONDUCTION THE EXPERIMENTS

Since the power produced by the thermoelectric modules (TEM) alone is often insufficient for the receivers, Thermoelectric generators (TEGs) were made in a variety of ways between the two blocks of the same block contents, as well as the connections between the same types of TECs, and their power and efficiency were noted. Thus, the most efficient connection method was tried to be determined. Fig. 4 to 11 show these connection methods and Tables 2 to 9 show the data from the connections.

In the type of connection shown in Fig. 4, although the voltage generated by TEC1-12706 at $\Delta T \sim 54\,°C$ when it is unloaded is higher than that of TEC1-12710, the current and voltage needed by the load were not provided when the load is connected to the output. The TEC1-12710 provided very low power when loaded.

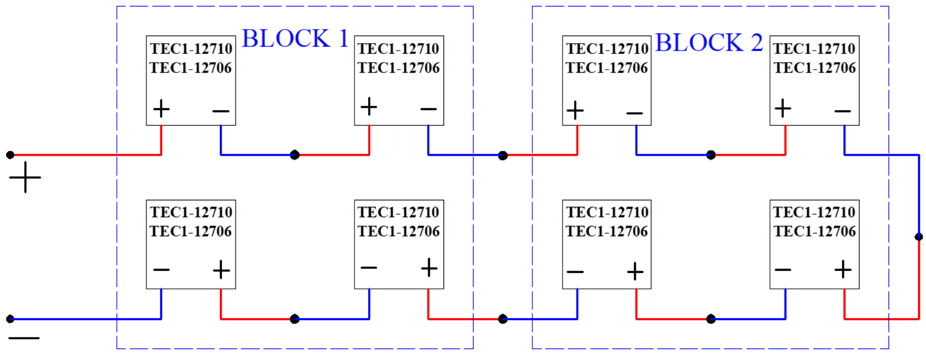

FIGURE 4. SERIAL CONNECTION IMAGE OF ALL TEC1-12706 AND TEC1-12710 THERMOELECTRIC MODULES

TABLE 2
THE DATA TABLE OF THE CONNECTION SCHEME IN FIG. 4

TEC1-12706							
1.BLOCK		2. BLOCK		No-Load State	Loaded State		
Heat	Cold	Heat	Cold	Voltage (V)	Voltage (V)	Current (A)	Power (W)
70	19	73	19	15,56	?	?	?
TEC1-12710							
1.BLOCK		2. BLOCK		No-Load State	Loaded State		
Heat	Cold	Heat	Cold	Voltage (V)	Voltage (V)	Current (A)	Power (W)
74	19	75	19	12,03	0,13	0,5	0,065

In the type of connection shown in Fig. 5, although the voltage generated by TEC1-12706 at $\Delta T \sim 53\ ^{\circ}C$ when it is unloaded is higher than that of TEC1-12710, TEC1-12710 thermoelectric module produced 14.8% more power when the load is connected to the outlet.

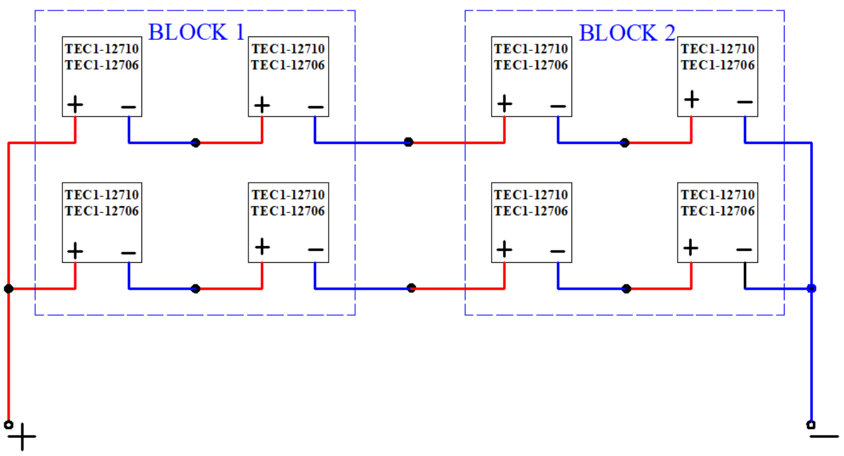

FIGURE 5. PARALLEL CONNECTION IMAGE OF 4 SERIAL SERIES OF TWO GROUPS TEC1-12706 AND TEC1-12710 THERMOELECTRIC MODULES

TABLE 3
THE DATA TABLE OF THE CONNECTION SCHEME IN FIG. 5

TEC1-12706							
1.BLOCK		2. BLOCK		No-Load State	Loaded State		
Heat	Cold	Heat	Cold	Voltage (V)	Voltage (V)	Current (A)	Power (W)
74	21	74	22	8,2	0,09	0,35	0,032
TEC1-12710							
1.BLOCK		2. BLOCK		No-Load State	Loaded State		
Heat	Cold	Heat	Cold	Voltage (V)	Voltage (V)	Current (A)	Power (W)
71	19	72	21	5,56	0,24	0,9	0,216

In the connection type of Fig. 6, TEC1-12710 at ΔT ~ 54°C produced close values to the connection type in Fig. 5. However, in this type of connection, while the unloaded TEC1-12706 produced voltage at values close to the connection type in Fig. 5, when the load is connected to its ends, it produced 20% more power.

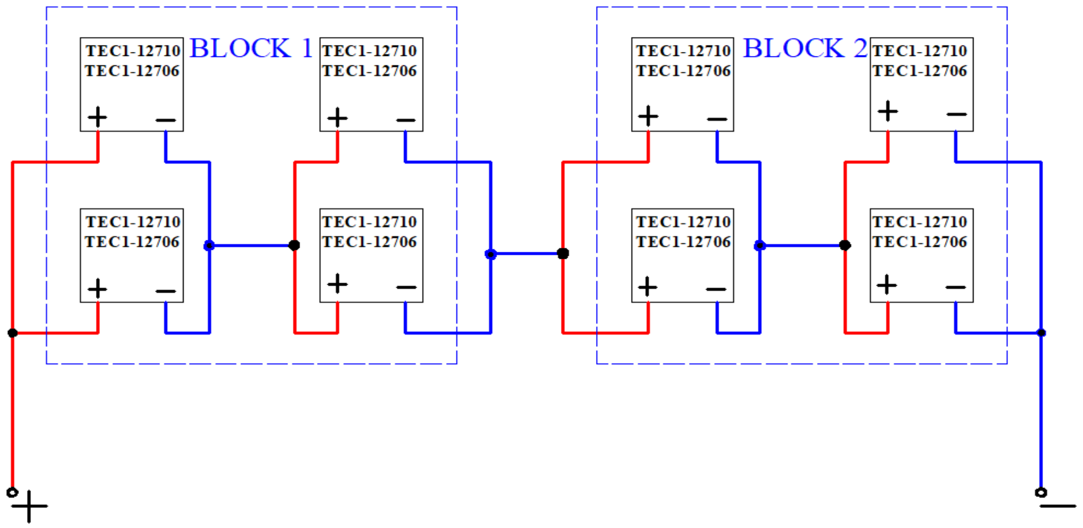

FIGURE 6. SERIAL CONNECTION IMAGE OF 2 PARALLEL SERIES OF GROUPS TEC1-12706 AND TEC1-12710 THERMOELECTRIC MODULES

TABLE 4
THE DATA TABLE OF THE CONNECTION SCHEME IN FIG. 6

TEC1-12706							
1.BLOCK		**2. BLOCK**		**No-Load State**	**Loaded State**		
Heat	Cold	Heat	Cold	Voltage (V)	Voltage (V)	Current (A)	Power (W)
73	19	71	19	8,96	0,22	0,72	0,158
TEC1-12710							
1.BLOCK		**2. BLOCK**		**No-Load State**	**Loaded State**		
Heat	Cold	Heat	Cold	Voltage (V)	Voltage (V)	Current (A)	Power (W)
71	19	71	19	5,79	0,27	0,97	0,262

In the type of connection in Fig. 7, both TEC types at ΔT ~ 57 ° C produced voltage, current and power at values close to the connection type in Fig. 6.

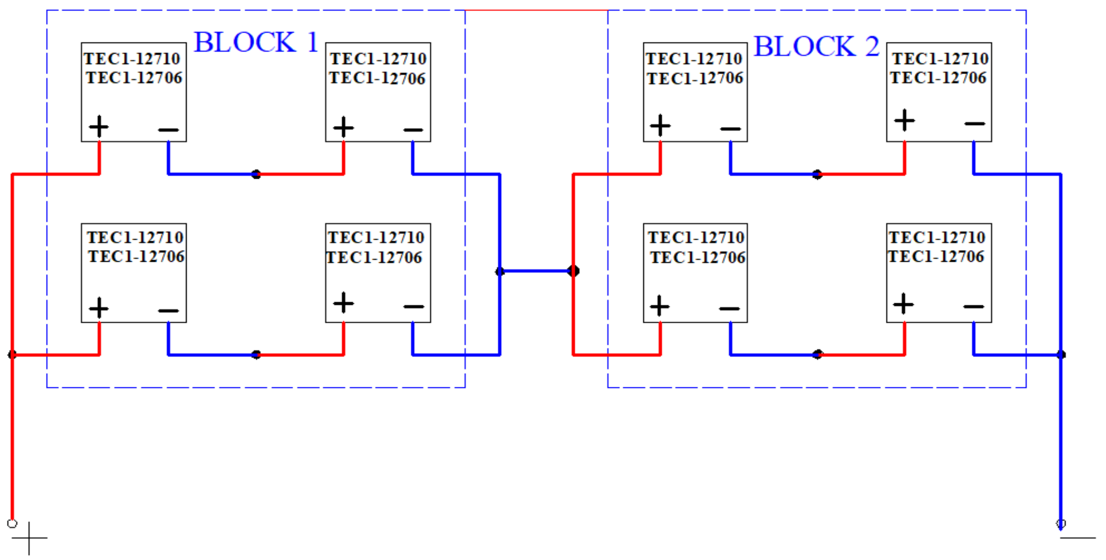

FIGURE 7. TWO SERIAL CONNECTIONS OF TEC1-12706 AND TEC1-12710 THERMOELECTRIC MODULES IN BLOCK AND THE PARALLELISM BETWEEN THEM AND THE SERIAL CONNECTION IMAGE OF THE TWO BLOCKS

TABLE 5
THE DATA TABLE OF THE CONNECTION SCHEME IN FIG. 7

TEC1-12706							
1.BLOCK		**2. BLOCK**		**No-Load State**	**Loaded State**		
Heat	Cold	Heat	Cold	Voltage (V)	Voltage (V)	Current (A)	Power (W)
72	15	73	16	9,24	0,2	0,78	0,156
TEC1-12710							
1.BLOCK		**2. BLOCK**		**No-Load State**	**Loaded State**		
Heat	Cold	Heat	Cold	Voltage (V)	Voltage (V)	Current (A)	Power (W)
71	18	73	16	6,4	0,28	1,05	0,294

In the type of connection in Fig. 8, although the voltage produced by both unloaded TEC types at $\Delta T \sim 52\ °C$ is less than the types of connections we mentioned earlier when loads are connected to their ends, they produced more power. Also, in this connection, the power produced by TEC1-12710 is 40% greater than the power produced by TEC1-12706.

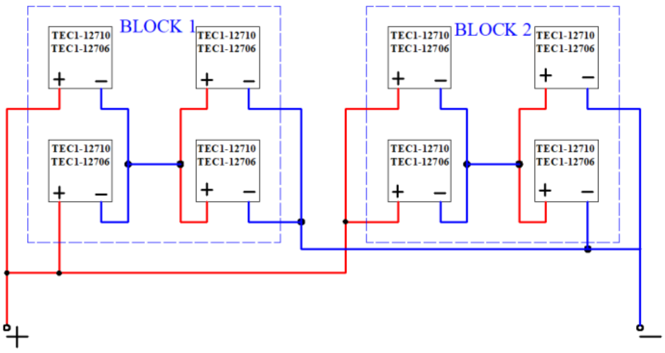

FIGURE 8. THE IMAGES OF SERIAL CONNECTION TO EACH OTHER AND PARALLEL CONNECTION TO THE OTHER BLOCKS OF PARALLEL GROUPS OF TWO IN TEC1-12706 AND TEC1-12710 THERMOELECTRIC MODULES IN THE SAME BLOCKS

TABLE 6
THE DATA TABLE OF THE CONNECTION SCHEME IN FIG. 8

TEC1-12706							
1.BLOCK		**2. BLOCK**		**No-Load State**	**Loaded State**		
Heat	Cold	Heat	Cold	Voltage (V)	Voltage (V)	Current (A)	Power (W)
71	19	74	19	4,11	0,29	1,08	0,313
TEC1-12710							
1.BLOCK		**2. BLOCK**		**No-Load State**	**Loaded State**		
Heat	Cold	Heat	Cold	Voltage (V)	Voltage (V)	Current (A)	Power (W)
70	19	71	21	2,67	0,41	1,55	0,636

In the type of connection of Fig. 9, at $\Delta T \sim 52\ °C$, when the TECs were both loaded and unloaded, they produced values very close to the connection type in Fig. 8.

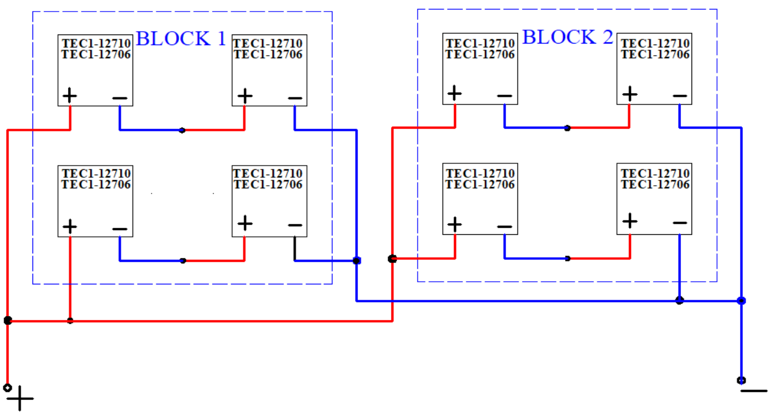

FIGURE 9. PARALLEL CONNECTION IMAGE OF 2 SERIAL SERIES OF TWO GROUPS TEC1-12706 AND TEC1-12710 THERMOELECTRIC MODULES

TABLE 7
THE DATA TABLE OF THE CONNECTION SCHEME IN FIG. 9

TEC1-12706							
1.BLOCK		2. BLOCK		No-Load State	Loaded State		
Heat	Cold	Heat	Cold	Voltage (V)	Voltage (V)	Current (A)	Power (W)
75	17	75	18	4,41	0,37	1,4	0,518
TEC1-12710							
1.BLOCK		2. BLOCK		No-Load State	Loaded State		
Heat	Cold	Heat	Cold	Voltage (V)	Voltage (V)	Current (A)	Power (W)
71	17	73	17	3,01	0,44	1,66	0,730

In the connection type of Fig. 10,at $\Delta T \sim 52$ ° C, the voltage produced by both unloaded TEC types is closer to the types of connections we mentioned earlier, while they produced more power when loads are connected to their ends. In addition, the power generated by TEC1-12710 in this connection is 51.6% more than the power generated by TEC1-12706

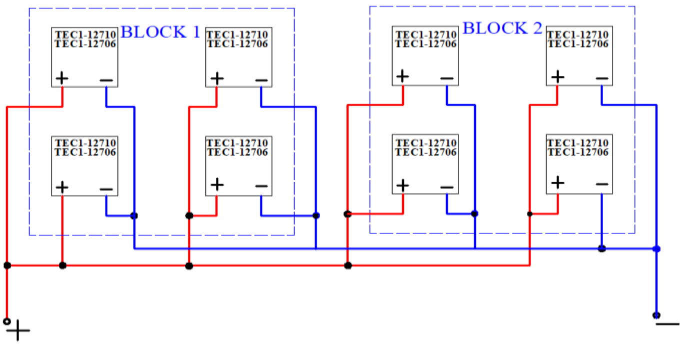

FIGURE 10. PARALLEL CONNECTION IMAGE OF ALL TEC1-12706 AND TEC1-12710 THERMOELECTRIC MODULES

TABLE 8
THE DATA TABLE OF THE CONNECTION SCHEME IN FIG. 10

TEC1-12706							
1.BLOCK		2. BLOCK		No-Load State	Loaded State		
Heat	Cold	Heat	Cold	Voltage (V)	Voltage (V)	Current (A)	Power (W)
71	19	72	19	4,29	0,36	1,34	0,482
TEC1-12710							
1.BLOCK		2. BLOCK		No-Load State	Loaded State		
Heat	Cold	Heat	Cold	Voltage (V)	Voltage (V)	Current (A)	Power (W)
78	18	80	18	3,1	0,51	1,83	0,933

In the connection type in Fig. 11, at $\Delta T \sim 55$ ° C, although both types of TEC produced voltage at the lowest value from the voltages that the connection types that we had tested up till then had produced, they produced the most power when the load was connected to their ends. In addition, the power produced by TEC1-12710 in this connection is 63% more than the power produced by TEC1-12706.

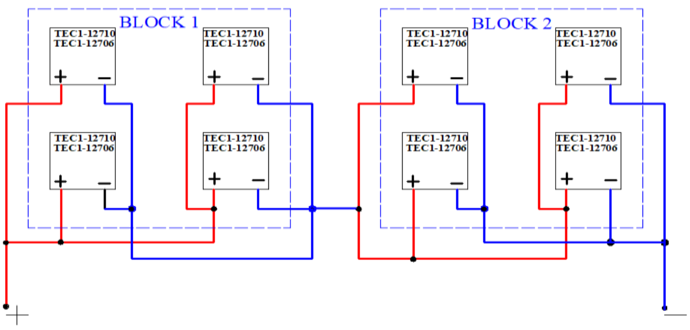

FIGURE 11. PARALLEL CONNECTION IMAGE OF TEC1-12706 AND TEC1-12710 THERMOELECTRIC MODULES IN THE SAME BLOCK AND THE SERIAL CONNECTION IMAGE OF THE THERMOELECTRIC MODULE GROUPS IN THE TWO BLOCKS

TABLE 9
THE DATA TABLE OF THE CONNECTION SCHEME IN FIG. 11

TEC1-12706							
1.BLOCK		2. BLOCK		No-Load State	Loaded State		
Heat	Cold	Heat	Cold	Voltage (V)	Voltage (V)	Current (A)	Power (W)
73	18	74	19	2,1	0,48	1,8	0,864
TEC1-12710							
1.BLOCK		2. BLOCK		No-Load State	Loaded State		
Heat	Cold	Heat	Cold	Voltage (V)	Voltage (V)	Current (A)	Power (W)
73	18	74	19	1,52	0,612	2,24	1,371

In the experiments, in the same hot and cold water circulation, 4 TECs were connected to 2 separate blocks and the voltage, current and power values they produced were compared. The connection type in Fig. 11 gave us the best values both in terms of current and voltage. Table 9 shows the data from this connection type. In this preliminary study, in the connection type in Fig. 11, TEC1-12706 thermoelectric module produces 2.1 V DC voltage at a temperature rise of $\Delta T = 55\ ^{\circ}C$ when unloaded and when it was loaded with 0,25 Ω load obtained by parallel connecting 4 resistors of 1 Ω, we could obtain 1.8 A current and 0.864 W power with 0,48 V DC voltage. Under the same conditions, TEC1-12710 thermoelectric module produced 1.52 V DC voltage when it was not loaded at $\Delta T= 55\ ^{0}C$ temperature difference while it produced 2,24 A current and 1,371 W of power with a voltage of 0,612 V DC when loaded.

VI. CONCLUSION

In the experimental setup prepared in this study, experiments were carried out with electrical connection between two types of TECs. According to these experiments, the type of electrical connection in Fig. 11 has been the type of connection that gave the best value for both TEC1-12706 and TEC1-12710 in terms of current and voltage ratio. Later, (T_H) module hot surface, (T_C) module cold surface, voltage (V), current (A) and power (W) values obtained from geothermal energy and time were measured starting from the operation of the system until the hot water reached 100 ◦ C at the third stage speed of the recirculation motor at 2.5 bar water pressure in this connection type closed system. When we look at the analysis graph of the voltage produced by TEC1-12706 and TEC12710 in Fig. 12, we can see that the values are very close to each other but TEC1-12706 produces more voltage at low temperature.

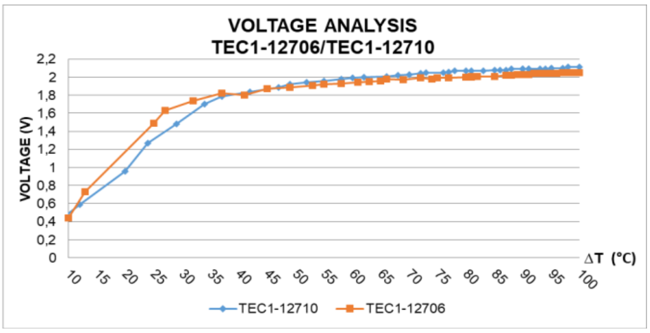

FIGURE 12. TEC1-12710 AND TEC1-12706 VOLTAGE (V) GRAPHIC

When we look at the graph of current analysis produced by TEC1-12706 and TEC12710 in Fig. 13, although TEC1-12706 provided current at lower temperature, at later temperatures, TEC1-12710 caught up and produced more current.

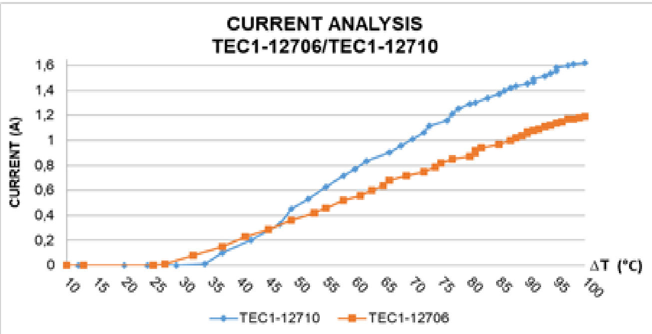

FIGURE 13. TEC1-12710 AND TEC1-12706 CURRENT (A) GRAPHIC

When we look at the graph of power analysis produced by TEC1-12706 and TEC12710 in Fig. 14, since the voltages produced by both TECs are very close to each other, the decisive element seems to be the current and although TEC1-12706 provided power for the current at lower temperature, at later temperatures, TEC1-12710 caught up and produced more power also.

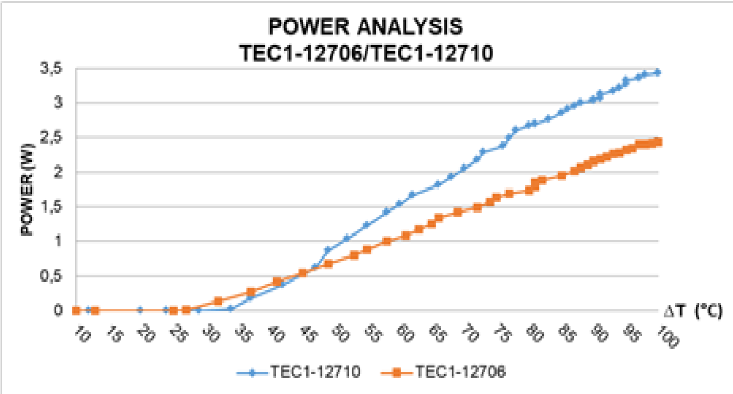

FIGURE 14. TEC1-12710 AND TEC1-12706 POWER (W) GRAPHIC

The graphs show that while TEC1-12706 thermoelectric modules provided system current and power at a temperature difference of about 27-28 °C, TEC1-12710 thermoelectric modules started to provide current and power at about 33-36 °C. However, when the surface temperature differences in both thermoelectric modules rose above 50 ^{0} C, TEC1-12710 thermoelectric module is more powerful than TEC1-12706 thermoelectric module due to the voltage-current it generates. At the end of the experiment, 71.2% difference between the power produced by the two modules emerged. In the direction of the experiment's purpose, it was determined that the TECs gave each other the highest current and voltage with the electrical connection shown in Fig. 11. Furthermore, comparisons between the two types of TEC have shown that TEC1-12706 was more efficient in places where the thermal temperature is below 50 ° C and TEC1-12710 was more efficient in places where the thermal temperature is above 50 ° C.

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