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Experimental investigation of thermoelectric self-cooling system for the cooling of ultrasonic transducer drivers

Ultrasonik sürücülerin soğutulması için termoelektrik kendinden soğutma sisteminin deneysel incelenmesi

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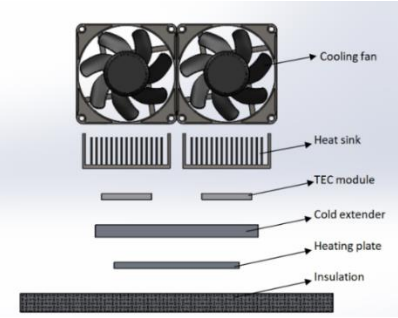
Experimental Investigation of Thermoelectric Self-Cooling System for the Cooling of Ultrasonic Transducer Drivers

Highlights

- *The cooling of any heat generating device without electricity consumption is possible with a thermoelectric self cooling system.*
- *Cold expanders used in these systems increase the performance of the thermoelectric self-cooling system.*

Graphical Abstract

This paper presents the experimental analysis of a Thermoelectric self-cooling (TSC) which provide the cooling of any heat-generating device without electricity consumption.



Şekil. 4 **/Figure.** 4

Aim

To investigate the effect of cold extender thickness on the cooling performance of thermoelectric system

Design & Methodology

An experimental setup is designed on a 275W push-pull ultrasonic driver circuit.

Originality

The investigation of the the effect of thickness of the cold extender on the performance

Findings

The fans' activation time increases with increases thickness of cold extender.

Conclusion

A high heat capacity block called cold extender can be placed between the thermoelectric module and heat sink to increase performance of overall system

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Experimental Investigation of Thermoelectric Self-Cooling System for the Cooling of Ultrasonic Transducer Drivers

(This study was presented at ULIBTK 2019 conference. / Bu çalışma ULIBTK 2019 konferansında sunulmuştur.)

Araştırma Makalesi / Research Article

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ABSTRACT

Electronic driver circuits are used for the driving of ultrasonic transducer systems. Due to the high frequency switching, thermal management is the main problem that has a significant effect on the reliability of the driver. Different applications are being studied to solve such overheating problems. In this study, the designed thermoelectric self-cooling system dissipates the excess heat generated in the push-pull drive circuit and improves system performance. Thermoelectric self-cooling (TSC) is a new thermoelectric application which provide the cooling of any heat-generating device without electricity consumption. This paper presents the experimental analysis of a TSC system. An experimental setup is designed on a 275W push-pull ultrasonic driver circuit. In this study, it has been shown how the performance of the thermoelectric system changes with the use of cold extender of different thicknesses. 5 and 10 mm thickness cold extenders have had a positive effect on the cooling performance of both the hot and cold surfaces of the self-cooling system. However, when the thickness of the cold extender is increased beyond the threshold, the heat capacity of the cold extender has prevented the temperature between the cold and hot surfaces to reach critical temperature differences which enables the fan to operate.

Keywords: Thermoelectric, self-cooling, energy harvesting.

Ultrasonik Sürücülerin Soğutulması için Termoelektrik Kendinden Soğutma Sisteminin Deneysel İncelenmesi

ÖZ

Elektronik sürücü devreleri ultrasonik transdüser sistemlerinin sürülmesinde kullanılır. Yüksek frekans nedeniyle, termal yönetim sürücünün güvenilirliğini önemli ölçüde etkileyen ana sorundur. Bu tür aşırı ısınma problemlerini çözmek için farklı uygulamalar üzerinde çalışılmaktadır. Bu çalışmada, push-pull sürücü devresindeki fazla ısıyı dağıtmak ve sistem performansını artırmak için bir termoelektrik kendinden soğutma sistemi tasarlanmıştır. Termoelektrik kendinden soğutma (TSC), herhangi bir ısı üreten cihazın elektrik tüketimi olmadan soğutulmasını sağlayan yeni bir termoelektrik uygulamadır. Bu makale, bir TSC sisteminin deneysel analizini sunmaktadır. Deneysel bir kurulum 275W push-pull ultrasonik sürücü devresinde tasarlanmıştır. Bu çalışmada, termoelektrik sistemin performansının farklı kalınlıklarda soğuk genişletici kullanımıyla nasıl değiştiği gösterilmiştir. 5 ve 10 mm kalınlığındaki soğuk genişleticiler, kendi kendini soğutma sisteminin hem sıcak hem de soğuk yüzeylerinin soğutma performansı üzerinde olumlu bir etkiye sahiptir. Bununla birlikte, soğuk genişleticinin kalınlığı eşik değeri geçtiğinde, soğuk genişleticinin ısı kapasitesi, soğuk ve sıcak yüzeyler arasındaki sıcaklığın fanın çalışmasını sağlayan kritik sıcaklık farklarına ulaşmasını engellemiştir.

Anahtar Kelimler: Termoelektrik, kendinden soğutma, enerji hasadı.

1. INTRODUCTION

Thermoelectric materials can be used for the conversion of electrical energy to thermal energy. Conversion of electrical energy to thermal energy and thermal energy to electrical energy can be done by using thermoelectric materials. Direct conversion between these two energies is possible due to the two thermoelectric effects, called Peltier effect and the Seebeck effect. The basic principle that thermoelectric cooling devices rely on is the Peltier effect which is discovered by James Peltier in 1894. Peltier effect is the phenomenon that when electrical current is passed through a composite material that consist of two different materials, the heat absorbed from one side of that material dissipate from the other side. Thermoelectric cooling systems have many advantages, such as the small size and light weight, the absence of moving parts and working fluids. And, the flow of heat can be controlled by the direction of current and they are

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suitable for operating under direct current (DC) electrical sources [1]. The use of thermoelectric cooling devices is rapidly increasing due to all these advantages. There are many applications in portable coolers, dehumidifiers, satellites, thermoelectric household refrigerators, mini air conditioners [2-4]. Besides Joule heating ($Q=RI^2$), there is a linear relationship between Peltier heat (Q_p) and the current.

$$Q_p = P\, q \quad (1)$$

where q is the load (q = I t) through the junction and P is the Peltier coefficient. The Peltier coefficient depends on the type of contact material and the contact temperature. Peltier coefficient is a function of Seebeck coefficient and junction temperature.

$$P = \alpha\, T \quad (2)$$

Where, α is defined as the Seebeck coefficient and T is the connection temperature in Kelvin. As a result of the temperature difference on the two surfaces of a thermoelectric material, an electric current is formed. This is defined as the Seebeck effect. This effect was discovered by Thomas Seebeck in 1821. In his invention, he determined that two different semiconductor materials, A and B, which are connected each other electrically in series and thermally in parallel, generate electric current when subjected to temperature difference [5].

A thermoelectric module is produced by connecting any number of semiconductor thermocouples in series between two ceramic plates as shown in Fig 1. With the current applied to the module, one of the ceramic plates heats up and the other side cools down. The temperatures obtained from the surfaces vary depending on the amount of current to be applied. The plate we want to cool or heat is determined by changing the current direction. The type, number and size of the semiconductor thermal pairs determine the cooling capacity of the thermoelectric module. Depending on the number of stages, different types of TEC modules are used.

According to the working principle of thermoelectric modules, in the cold junction, energy (heat) is absorbed by electrons and transferred from the p-type semiconductor (low energy) to the n-type semiconductor (high energy). Energy is supplied from a power source to activate the electrons. As the electrons passing through the hot side move from the n-type semiconductor to the p-type semiconductor, they transfer the energy that absorbed into a heat well [6].

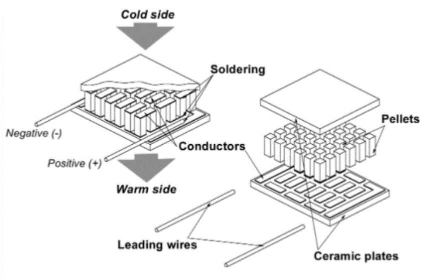

Figure 1. Single-stage Module Construction [7]

Hot side temperature (*T_h*), cold side temperature (*T_c*) and temperature difference (*ΔT*) between both surfaces are important factors for thermal analysis. If the system is expected to achieve the desired performance, the temperature difference between the two surfaces must be well determined. The calculation of the temperature difference (*ΔT*) is as shown below.

$$\Delta T = T_h - T_c \quad (3)$$

The temperature difference between the hot and cold sides of the thermoelectric module is called the actual temperature (*ΔT*) difference. This temperature difference is a different concept from the temperature difference of the system. The temperature difference of the system is defined as the temperature difference between the ambient temperature and the load to be cooled. The temperature values in a thermoelectric system are as shown in Figure 2.

Determination of the amount of heat removed from the cold surface (Q_c) of TEC is very difficult and important. Q_c can be calculated by finding the mass flow rate of air, specific heat of air and temperature difference. Here the temperature difference is temperature difference of the system. The mathematical equation of Q_c is as shown as below.

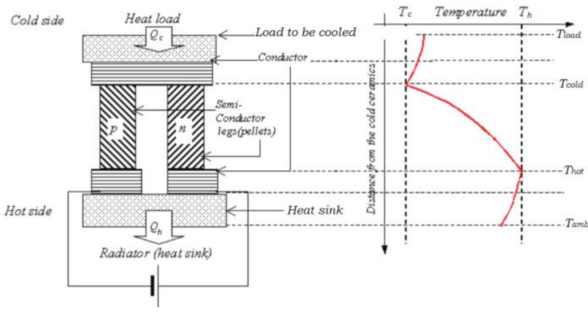

Figure 2. Simplified Scheme of TE Module and the Temperature Differential Relations [7]

$$Q_c = m\, C_p\, \Delta T \quad (4)$$

The average power of the thermoelectric module is calculated as follows.

$$W_m = V_m\, I_m \quad (5)$$

where, V_m is the voltage that the module draws, I_m is current through the module. Similarly, the power of the fan is calculated as follows.

$$W_f = V_f\, I_f \quad (6)$$

where, Vf is the voltage that the fan draws, I_m is current of fan. W is the TEC power which is the sum of W_m and W_f. The thermal efficiency of the thermoelectric system is shown as the coefficient of performance (COP). COP is the ratio of the heat drawn from the load to be cooled to the electrical power spent to drive the thermoelectric module (Eq 7) [6].

$$COP = Q_c / W \quad (7)$$

As mentioned before, Seebeck Effect refers to an electrical potential occurring in a semi-conductive material when a temperature difference is applied, so it is also an electromotor force. Thus, a thermoelement consists of two different thermoelectric materials which are electrically connected. If there are different temperature levels at both junctions, voltage occurs as a function of the applied temperature difference:

$$\alpha = V / \Delta T \tag{8}$$

where α is the Seebeck coefficient, ΔT the temperature difference and V is the Seebeck voltage [8].

In recent years, researches on thermoelectric energy harvesting systems have increased. The new thermoelectric materials, TEGs, which work according to the Seebeck effect for energy harvesting systems, are developed and are becoming more and more efficient. Specific thermoelectric generators (TEG) have been developed for using in aerospace and aviation industries. Nowadays, new research studies focus on recovering particularly low amounts of waste heat to produce electrical energy [9]. In their study, Janak and Singule examined the different application possibilities of energy harvesting methods for aerospace [10]. Similarly, Chottirapong et al. proposed a combined thermoelectric and photovoltaic energy collection system for an organic fertilizer plant with a power output of 290 mW [11]. Leonov examined the thermoelectric energy collection system that produces 0.5 to 5 mW of power from body temperature through wearable sensors [12]. Ota et al. used cascaded TEG and obtained 4 kW power with thermoelectric power generation system developed for industrial furnaces [13].

The thermoelectric generation technology can convert thermal energy directly to electricity using a thermoelectric generator consisting of p-type and n-type semiconductors. It has no moving parts and is compact, quiet, reliable and environmentally friendly [14]. The waste heat from working systems not only reduces energy efficiency, it also increases the operating temperature of the devices and reduces the performance of the devices. In order to improve the performance of operating systems, forced convection cooling devices are installed in systems. Electric power is required for the operation of this kind of cooling systems. Therefore, the cooling process causes more energy consumption.

The major disadvantage of TEG modules, which are specially developed for energy harvesting systems and which have some advantages such as higher power output and resistance to high operating temperatures compared to TEC modules, is the high cost of these modules. The average TEG price is about 10 to 20 times the TEC price. Due to this high initial investment cost, TEC module will be used in our study.

The need for a new system has arisen in line with all this information. This system is thermoelectric self-cooling system that can be defined between TEC and TEG. The thermoelectric self-cooling system is used when there is a device that produces a certain amount of heat and needs to be cooled. The thermoelectric modules are used to convert the produced heat into electrical energy. The resulting electrical energy also activates the device used for cooling. With the temperature difference between the surfaces of the module, both electricity can be produced and cooling can be done.

This study was conducted to investigate the use of thermoelectric self-cooling (TSC) system, which is a special application, in applications for cooling ultrasonic transducer drivers. In the coming years, TSC technology is expected to replace the forced convection cooling systems in order to save electricity. This expectation is the main reason of this study.

Martinez et al., investigated experimentally and analytically the operation of devices with thermoelectric self-cooling system. The experimental and analytical results show that the thermal resistance between the heat source and the environment decreases by 25-30% after the installation of the thermoelectric self-cooling system. With these results, this technology can be applied promisingly to devices that produce large amounts of heat [5]. Liu et al., establish a thermoelectric self-cooling device test setup to investigate application techniques. The effects of heat sink on thermoelectric self-cooling process were investigated [14]. Cai et al., examined thermoelectric cooling systems and especially self-cooling systems, and gathered general information about systems and previous studies [15]. Cooke, a new self-powered thermoelectric car seat cooler is presented. In that study, both power generation and cooling were carried out together with the same thermoelectric device [16]. Kiflemariam and Lin worked on the thermoelectric self-cooling system. In their study, the effects of different parameters applied in geometry on cooling performance were examined. According to the results, when the highest heat input is applied, a decrease of 20-40% was observed in the device temperature [17]. As a result of the studies conducted by Wang and Bar-Cohen, it has been observed that thermoelectric self cooling application applied locally on germanium chips can reduce the temperature rise in micro heat sources. Under optimized geometric and electrical conditions, 600μm × 600 μm the germanium micro-cooler provided 4.5 °C cooling on a 100 μm-thick chip [18].

Besides all these, Saber et al., worked on a cooling technique called "sustainable self-cooling framework". In this technique, the hot area is cooled by means of TECs placed on this area and the electrical power required for the TECs is provided by the TEGs. The results obtained in 3D modeling showed that this technique is useful in cooling the hot zone [19].

2. MATERIAL AND METHODS

Thermoelectric Self Cooling Device

Thermoelectric self-cooling systems that will be used for the removal of excess heat generated in electronic devices will both generate electricity remove heat from the system. The temperature differences between cold and hot surfaces of thermoelectric self-cooling system generates voltage. This voltage is used to activate fans. The aim of these fans to remove overheat and to cool the surface of ultrasonic transducer drivers. For this purpose, a TSC system was installed as shown in the Figure 3.

Figure 3. Photograph of the prototype of TSC system

The test system consists of two thermoelectric cooling modules (TEC), two aluminum heat sinks, two fans, heat source plate, insulation panels, cold extender of different thicknesses and temperature probes (Figure 3-4).

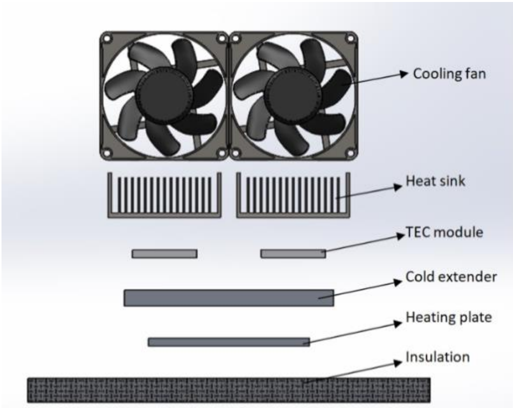

Figure 4. Thermoelectric self-cooling (TSC) system

The power generation unit is composed of two thermoelectric modules (TEC 12706) in series. The properties of the TEC module obtained from the product datasheet are shown in Table 1.

Table 1. Specifications of the TEC module

TEC 12706			
Dimensions	40x40x3.9 mm	$\mathbf{U_{max}}$	16.4 V
$\mathbf{T_h}$	50 °C	$\mathbf{R_i}$	2.3 Ω
$\mathbf{\Delta T_{max}}$	75 °C	$\mathbf{Q_{max}}$	57 W
$\mathbf{I_{max}}$	6.4 A		
Number couples		127	
Thermoelectric material		Bi_2Te_3	
Ceramic material		Al_2O_3	
Solder material		BiSn (138 °C)	

On the heating plate with a power of 275 W, different thickness aluminum cold extender plates were placed. These cold extenders increase difference between TEC modules and heating plates to prevent any thermal bridge that reduce the power generation. Two TEC modules were positioned on top of these plates so that heat sinks were placed on them. Two temperature probes that contacted surfaces were located to measure the upper and lower surface temperatures of TEC modules. Two heat sinks were placed on two peltiers and probes were placed to measure the temperature of both the heat sink and the heating plate. Data collection was carried out using the Testo 454 data logger and the LabView software. Data processing was done in Matlab program. The test procedure was performed in all experiments in the same way. After the heating plate was opened, the work continued until the plate was in the thermal equilibrium with environment.

5. RESULT

An experimental setup has been designed for the study of cooling performance of the proposed self cooling system. A 275 W heater plate representing the driver was mounted on the insulation material. Cold extenders of different thickness, TEC modules, heat sinks and cooling fans were placed on over the heating plate from bottom to top respectively. Experiments using four different thickness cold extender (5mm, 10mm, 15mm and 4mm) were repeated and the performance of the self-cooling system was examined. The material of the cold extender is aluminum. During the experiments, cold extender top surface (T_{Al}), TEC module hot surface (T_h), TEC module cold surface (T_c) and heat sink base (T_f) temperatures were measured at 2 s intervals and recorded in the datalogger. Figure 5 shows the results of the experiment done using a 5 mm thick cold extender.

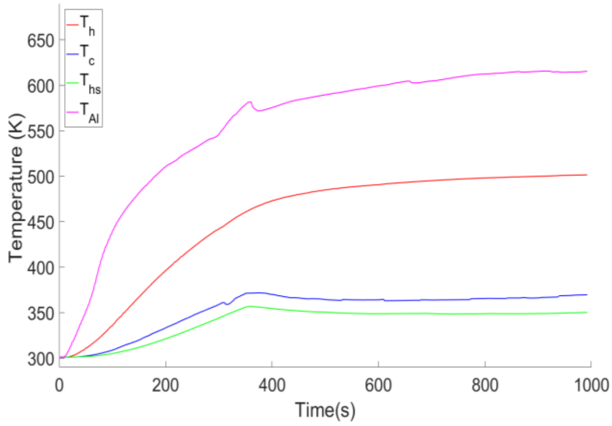

Figure 5. 275W heating plate - 5 mm cold extender - TEC - heat sink - cooling fan

The highest temperature values are in cold extender due to contact with the heating plate. The expected temperature difference between the hot and cold surfaces of the TEC module causes voltage to build up.

The base temperature of the heat sink is the lowest because of the amount of heat thrown into the air.

Approximately between 300 and 400 seconds, the required voltage values are reached and the fan is activated. By this time, the slope of temperature curve tends to decrease.

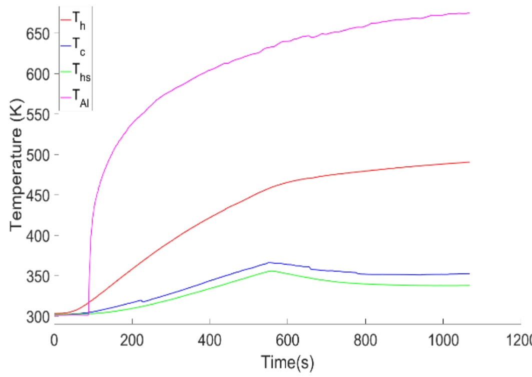

Figure 6. 275W heating plate - 10 mm cold extender - TEC - heat sink - cooling fan

Figure 6 shows the results of the experiment done using a 10 mm thick cold extender. Between 500 and 600 th seconds, the required voltage values are reached, and the fan is activated. In this experiment, due to the increase in the thickness of the cold extender, the temperature of above the extender remained constant at first and then increased rapidly. By this time the base temperature of the heat sink and the cold surface temperature of the TEC module increased but after that time the temperatures decreased. According to both experiments, the increase in cold extender thickness has delayed the formation of sufficient voltage and consequently the activation of the fan.

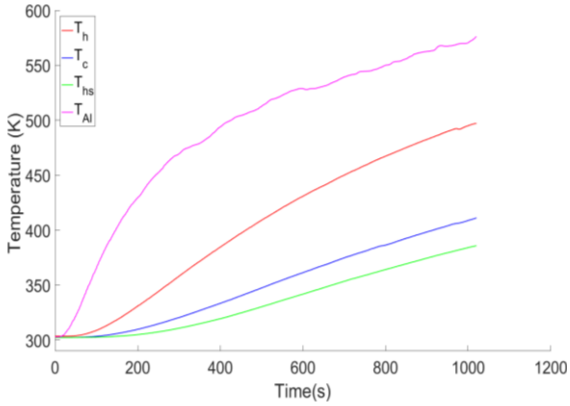

Figure 7. 275W heating plate - 15 mm cold extender - TEC - heat sink - cooling fan

Figure 7 shows the results of the experiment done using a 15 mm thick cold extender. By using a cold block of 15 mm thickness, it was observed that the four temperatures of the system were also continuously increasing. Since there is not sufficient temperature difference between the TEC module surfaces, the voltage value required to operate the fans has not been reached. For this reason, fans did not work and cooling could not be performed.

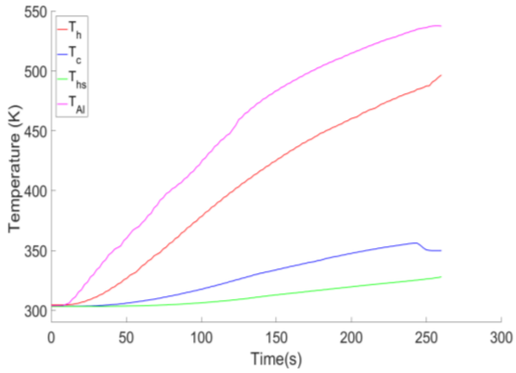

Figure 8. 275W heating plate - 4 mm cold extender - TEC - heat sink - cooling fan

Figure 8 shows the results of the experiment done using a 4 mm thick cold extender. In this experiment, sudden temperature increases are observed due to the use of very thin cold blocks. In a very short period of time, the temperature values on the system increased and the module burned because the temperatures exceeded the operating temperatures of the TEC module.

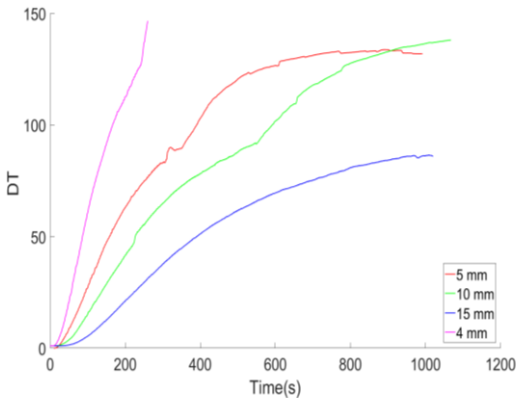

Figure 9. Temperature difference between both side of thermoelectric module

It is shown in the Figure 9 that the fans start at 305 and 553 seconds for the sizes of 5 and 10mm cold extenders.

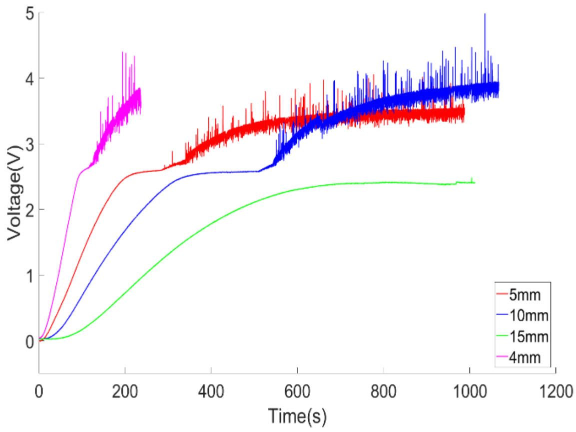

Figure 10. Time-dependent voltage variations in four experiments

The voltage values obtained in the experiments are shown in Figure 10. In the experiments using cold block 5 and 10 mm thickness, a rapid increase in voltage is observed in the first seconds and then this increasing decreases. When the voltage magnitudes reach to the running value of the fan, a fan activated and then the second fan activated. There is a sudden increase in voltage values by the activation of the fans. This is due to the cooling effect of fans. As a result of cooling, the temperature difference between the module surfaces increases. When a 15 mm cold extender was used, the voltage value did not reach the desired level and the fans did not activate. When the 4 mm cold extender was used, the increase in the voltage values was realized in a very short time. After stabilization, a sudden increase in voltage values was observed with the operation of the fans. Due to high temperatures, the fans could not cool the system and the module burned, the system switched off.

6. CONCLUSION

Self – cooling thermoelectric systems are based on a heat sink with a fan which the required electric power to run is generated by thermoelectric modules that is placed between the heat source and bottom plate of heat sink. A high heat capacity block called cold extender can be placed between the thermoelectric module and heat sink to increase performance of overall system. In this study, a series of experiments have been done with different size of cold extender at fixed heat load of 275W. For the sizes of 5 and 10mm, the positive effect of self-cooling system on the cooling performance is apparent both on the hot surfaces and cold surfaces. But, when the size of cold extender is increased, heat capacity of cold extender prevents the temperature between cold and hot surfaces to reach the critical temperature difference that allows fan to work. Thus, temperature on cold and hot surfaces tend to rise parallel despite of the case that fan is activated. Although, the highest temperature achieved with 15mm cold extender is almost equal to 10 mm cold extender at the end of experiment duration, the time constant of system is decreased drastically. So, temperature tends to increase, and the highest temperature will be greater than other cases.

SYMBOLS

Q_p The peltier heat [W]

Q_c Heat remove from the cold surface [W]

P Peltier coefficient

q The charge

α Seebeck coefficient

T The junction temperature[K]

ΔT Temperature differences of between the surfaces of thermoelectric [K]

T_h Hot surface of thermoelectric module [K]

T_c Cold surface of TEC [K]

U_{max} Voltage applied to the module at ΔT_{max}

I_{max} DC current through the modules at ΔT_{max}

V Voltage [V]

I Current [A]

COP Coefficient of Performance

DECLARATION OF ETHICAL STANDARDS

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Mert ŞENER: Performed the experiments, analyzed the results, and wrote the manuscript.

Feyzullah Mertkan ARSLAN: Performed the experiments.

Barış Oğuz GÜRSES: Wrote the manuscript.

Gökhan GÜRLEK: Performed the experiments, analyzed the results, and wrote the manuscript.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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