Comparison between two-stage and three-stage Peltier thermoelectric coolers driven by pulse width modulation

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Abstract. Thermoelectric device is one of electronic devices commonly used as temperature sensors, electrical generators, and cooling devices. Peltier thermoelectric cooler as a promising device offers greater performance in terms of electronic cooler, especially for computer components. However, the performance of single-stage thermoelectric cooler is limited. For certain optoelectronic devices, it cannot achieve a desired temperature to pump heat from the devices. In addition, to drive temperature of the thermoelectric coolers, a complex interface circuit should be made. In this research, two-stage and three-stage cascaded Thermoelectric Coolers driven by Pulse Width Modulation using Arduino and H-bridge Motor Driver were examined. The three-stage Peltier thermoelectric cooler showed better performance than the two-stage, where it achieved higher temperature difference between hot and cold. Both cascaded thermoelectric coolers had distinct temperatures in each interstage connection, with increasing values from near cold side to near hot side.

1. Introduction
Thermoelectric device is a device with transducers that can be used for heating and cooling, usually utilized in industrial and medical field[1]. This device converts electricity to heat, where the electricity passes through semiconductors and conductors and eventually result in temperature difference between two junctions, known as Peltier effect, or vice versa, known as Seebeck effect. Some advantages that thermoelectric module provides are low weight, small volume, no moving part, gas-free, no chemical reaction, environmental friendly, lengthy life spam, fast response[2,3]. With broad applications, thermoelectric device has successfully become a reliable device since many advantages can be reached with only one thermoelectric module. The cold side of a commercial TEC1-12706 thermoelectric cooler may reach a temperature of -55 ºC. Despite this, many researches are trying to improve its performance, depending on specific applications.

According to literature study, there are many applications that nowadays researches have examined thermoelectric coolers for, such as freshwater generation from atmosphere[4], air conditioning systems for vehicles[5], cooling system of cryosurgery device[6] and computer chip coolers[7,8]. As over heat often occurs in electronic components, cooler systems are commonly used in order to pump the heat out of CPU. However, heatsink is not enough capable to pump the heat. Also, conventional refrigeration, in general, needs more space to work, or in other words, the cooling affects the entire components in CPU package that do not need to be cooled. Unlike any other cooling systems,
thermoelectric coolers (TECs) can pump the heat from specific hotspot without affecting the other components. To develop its performances, thermoelectric cooler system is designed in cascade, two or more thermoelectric coolers stacked. This kind of cooler is expected to be able to increase the heat absorbed to the cold side of the TECs which is proportional to the temperature difference between the hot and cold side, proved by calculations[9].

In this research, we examined two-stage cascaded Peltier thermoelectric cooler, or TEC, with simply stacking the commercial TECs, and compared it to the three-stage cascaded TEC. These TECs were driven by Pulse Width Modulation (PWM) method. With this comparison, we expected that appropriate stage of cascaded TECs can be selected for suitable applications.

2. Experimental

2.1. Preparation of Cascaded Thermoelectric Coolers

In this research, two-stage and three-stage cascaded Thermoelectric Coolers (TECs) were built by stacking TEC1 - 12706 Peltier Thermoelectric Cooler Modules on each other. The parameters of the TECs are shown on Table 1. Thermistors (SEMITECH 104JT-050) were placed between the sides of thermoelectric coolers to measure the temperatures while the TECs working, shown on Figure 1. As shown, thermal pad, with a thickness of 1 mm and a thermal conductivity of 3.2 W/mK, was used for pasting the TECs, which could conduct the heat from one to another TEC, and was glued by thermal paste, with a thermal conductivity of 1.46 W/mK. On the bottom of TECs, water block was used to remove the heat from the hot side of the cascaded TECs to water station so that the heat could easily be liberated into atmosphere. The cascaded TECs were then placed into an acrylic box to slightly isolate them from atmosphere which is probably able to affect the measurement. The cascaded TECs were arranged where the hot side of a TEC was in contact to the cold side of another TEC until the top of the cascaded TEC was the hot side, and the bottom was the cold side. The purpose of this configuration was to yield higher temperature difference than only a single TEC.

| Table 1. The TEC1-12706 parameters[10]. |
|----------------------------------------|
| **TE specifications**                  |
| Model                                  | TEC1-12706                            |
| Voltage                                | 12 V                                  |
| Vmax                                   | 15.4 V                                |
| Imax                                   | 6 A                                   |
| Qmax                                   | 92 W                                  |
| ΔTmax                                  | 75 °C                                 |
| Internal                               | 1.98 Ohm +/- 10%                      |
| Type                                   | Cooling cells                         |
| Seebeck coefficient                    | 53 mV/K[11]                           |
| Thermal resistance                     | 1.95 K/W[11]                          |

**Figure 1.** The design of (a) two-stage and (b) three-stage cascaded thermoelectric cooler
2.2. Electronic System

The experimental diagram is depicted on Figure 2. The TECs were controlled by the 2-channel L298n H-Bridge Motor Driver Modules, which are electrically connected to the Arduino MEGA Microcontroller. The temperatures measured by thermistors were read via serial monitor on Arduino IDE 1.8.9 software, and therefore the microcontroller was connected to PC. Each Motor Driver module was powered by a 12-volt power supply, with a maximum current of 5 A. The performance of the TECs was recorded for 30 minutes.

![Diagram of device setting](image)

**Figure 2.** The block diagram of the device setting

The cascaded TEC was basically driven by Pulse Width Modulation (PWM) method, where voltage pulse width was modulated by the Arduino MEGA microcontroller. Pulse Width Modulation, or PWM, is a technique commonly used for controlling the brightness of LED, speed control of DC motor and servo motor to get analog output with digital means. The Arduino digital pins either gives 5V (when turned HIGH) or 0V (when turned LOW), and the output is a square wave signal. The percentage of duty cycles shows how long the pins are turned HIGH and LOW in micro- or milliseconds. The PWM duty cycles given were varied, which range from 10% to 80%, and all of the thermoelectric coolers were in the same PWM duty cycles. The output voltage of thermistors was examined using Analog-to-Digital Converter (ADC) available in the Arduino through its analog pins. This method was for both two-stage and three-stage cascaded TEC.

3. Result and discussion

3.1. TEC Performance

The temperature of the TEC sides from the coolest to the hottest side was measured during process of cooling. It was expected that the surface temperature of the coolest side of the TECs should be extremely cool according to the thermoelectric properties. After measurement of two-stage cascaded TECs, it is clear that the TECs perform temperature distribution, both in interfaces of the TECs and in the hot side and cold side of the TECs. Figure 3 depicts the temperature values of three sides. As described before, T1 is the temperature in the hot side, T2 is the temperature in the interface and T3 is the temperature in the cold side. It can be seen from the graphs that, for PWM duty cycle 50%, the temperature difference of T1 until T3 is significant. T1 has the highest temperature, while T3 has the lowest.
Figure 3. The measurement of temperatures for the two-stage cascaded thermoelectric cooler with PWM duty cycle 50%

It was also showed that the TEC cooling can rapidly reach the lowest temperature before 1 minute. This rapid cooling is one of advantages of thermoelectric device which makes the TEC powerful as cooler compared to other methods. The temperature in the cold side was also influenced by the hot side, where it would appear from the graph that increase patterns of the temperatures are similar. The heat transfer from the hot side to the cool side could be the source of the temperature change. In addition, for all two-stage cascaded TECs performed, the temperature difference of the TECs increases proportional to the increase of PWM duty cycles. This indicates that the PWM can drive the cascaded TEC effectively at all duty cycles. The rise of the temperature difference occurs because the average voltage inclines and therefore adds more current flowing to the TECs which increases the heat flux. However, the temperatures of the modules were increased slowly by time. This is because the object and the cascaded TEC are not really isolated from atmosphere, and the heat transfer from the hot side to the cool side could be the source of the temperature change.

Fig. 4 shows the temperatures of four sides. The first TEC is the module which is attached on the water block, the second TEC is upside the first TEC and the third TEC is upside the second TEC. The most significant fact that stand out from the graph is that, for all PWM duty cycles, the temperature difference of T1 until T3 is not adequately comparable. T3, T2 and T1 are respectively the equilibrium temperature between the cold side of the second TEC and the hot side of the third TEC, the cold side of the first TEC and the hot side of the second TEC and the hot side of the first TEC and water block which was removing the heat. Due to this, T1, T2 and T3 had temperatures far from T4, where T4 is the equilibrium temperature between the coolest side of the cascaded TECs and the object which is air with room temperature.
Figure 4. The measurement of temperatures for the three-stage cascaded thermoelectric cooler with PWM duty cycle 50%

3.2. Comparison between two-stage and three-stage cascaded TECs

The temperatures distribution of three-stage cascaded TECs were measured in the same setting as the two-stage TECs. As a result, the three-stage TECs perform the same temperature distribution, that the cold side became the lowest temperature, and the temperature near the hot side became higher. However, the three-stage TECs show higher temperature difference between the hot and cold side than the two-stage as shown in Figure 5. The average of temperature differences was calculated after 20 minutes of measurement.

Figure 5. Comparison of temperature difference of two-stage and three stage cascaded thermoelectric coolers
From the graph, it can be seen that the increase trendlines of temperature difference of both are similarly linear because of the same thermoelectric property. However, it is obvious that the temperature difference of the three-stage TEC is higher than the two-stage. It indicates that the three-stage TEC absorbs more heat to coolest side. As expected, the heat flux of cascaded TEC will increase when adding more thermoelectric coolers. It is also needed to be known that the three-stage cascaded TEC needs more power. Therefore, the selection of stage number is worth to be considered.

4. Conclusion
The research with a topic of Comparison between two-stage and three-stage Peltier Thermoelectric Coolers driven by Pulse Width Modulation has been examined. Three-stage cascaded Thermoelectric Coolers absorb more heat than the two-stage. However, three-stage cascaded TECs need more power to work. Therefore, the application of these TECs should be considered.

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References

[1] Al-shehri S and Saber H H 2019 Experimental investigation of using thermoelectric cooling for computer chips J. King Saud Univ. - Eng. Sci. 0–8

[2] Aranguren P, DiazDeGarayo S, Martínez A, Araiz M and Astrain D 2019 Heat pipes thermal performance for a reversible thermoelectric cooler-heat pump for a nZEB Energy Build. 187 163–72

[3] Li W-K, Chang J-H, Amani M, Yang T-F and Yan W-M 2019 Experimental study on transient supercooling of two-stage thermoelectric cooler Case Stud. Therm. Eng. 14 100509

[4] Hand C T and Peuker S 2019 An experimental study of the influence of orientation on water condensation of a thermoelectric cooling heatsink Heliyon 5 e02752

[5] Pourkiaei S M, Ahmadi M H, Sadeghzadeh M, Moosavi S, Pourfayaz F, Chen L, Pour Yazdi M A and Kumar R 2019 Thermoelectric cooler and thermoelectric generator devices: A review of present and potential applications, modeling and materials Energy 186 115849

[6] Putra N, Ardiansyah, Sukyono W, Johansen D and Iskandar F N 2010 The characterization of a cascade thermoelectric cooler in a cryosurgery device Cryogenics (Guildf). 50 759–64

[7] Wiriyasart S, Hommalee C and Naphon P 2019 Thermal cooling enhancement of dual processors computer with thermoelectric air cooler module Case Stud. Therm. Eng. 100445

[8] Liu D, Zhao F Y, Yang H X and Tang G F 2015 Thermoelectric mini cooler coupled with micro thermosiphon for CPU cooling system Energy 83 29–36

[9] Karimi G, Culham J R and Kazerouni V 2011 Performance analysis of multi-stage thermoelectric coolers Analyse de la performance des refroidisseurs `lectriques multie ` tage ` s thermoe Int. J. Refrig. 34 2129–35

[10] Mirmanto M, Syahrul S and Wirдан Y 2018 Experimental performances of a thermoelectric cooler box with thermoelectric position variations Eng. Sci. Technol. an Int. J. 6–13

[11] Dymytrov Y Y and Kubov V 2017 Simple method of thermoelectric cooler ( Peltier device ) parameters determination based on datasheet and modeling results. Version 2 8–10