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A Comparative Study on the Performance of Single-Stage and Cascade Thermoelectric Refrigerators

Djuanda[1], Muhsin Z.[2], Erniyani[3], Otniel M. Sariri[4]
[1,2,3,4]Mechanical Engineering Education, State University of Makassar, Makassar, Indonesia
Correspondent author: djuanda@unm.ac.id

Abstract**—** *This study aims to compare the performance of thermoelectric modules in terms of their coefficient of performance (COP) between single-stage and cascade configurations. A quantitative approach was employed using an experimental research design. Each configuration was tested under voltage variations of 3V, 6V, 9V, and 12V. Data were collected using a data acquisition system. The experiments were conducted at the Mechanical Engineering Education Laboratory, Faculty of Engineering, Makassar State University. The single-stage thermoelectric module was tested four times at voltage levels of 3V, 6V, 9V, and 12V. The results indicated that the highest COP for the single-stage configuration was 3.64 at 3V, followed by 1.43 at 6V, 0.72 at 9V, and 0.45 at 12V. Similarly, the cascade thermoelectric module was tested at the same voltage levels. The corresponding COP values were 1.87 at 3V, 0.64 at 6V, 0.22 at 9V, and 0.073 at 12V. Based on the experimental results and data analysis, it can be concluded that the single-stage thermoelectric module exhibits a higher COP compared to the cascade configuration under the tested conditions.*

Keywords**—***Thermoelectric, single-stage, cascade-stage, coefficient of performance.*

I. INTRODUCTION

The rapid advancement of technology in the field of alternative energy necessitates that technicians continually enhance their knowledge and skills to avoid being left behind amidst fast-paced technological progress (Sumarjo Jojo, 2017). In line with these developments, innovation is essential to support and drive practical applications in daily life, which begins with the generation of ideas prior to implementation (Simamora, 2019). Cooling systems, in particular, require continuous innovation and development to improve efficiency, practicality, and environmental sustainability.

A cooling machine is a system designed to produce low temperatures by transferring heat from within an insulated space to the external environment, thereby lowering the internal temperature relative to its surroundings. Common examples of cooling devices include refrigerators, freezers, and air conditioners (AC). The fundamental working principle of these machines is evaporation, where a refrigerant absorbs heat and undergoes phase change, leading to a cooling effect. During this process, heat from the surrounding air is absorbed and transferred, resulting in reduced temperatures (Ryanuargo, 2013). Cooling systems are widely used in commercial buildings, offices, and households. Among them, AC units not only provide cool air but also regulate humidity for human comfort. Similarly, refrigerators are used to preserve food, cool beverages, and perform other essential functions.

Currently, many cooling machines—particularly those designed for food and beverage storage—remain relatively large and heavy, even in their portable versions. This bulkiness poses a challenge for mobility due to the size and weight of the components involved. Furthermore, some conventional cooling machines still utilize refrigerants containing chlorofluorocarbons (CFCs), which are harmful to the ozone layer. These systems also typically consume large amounts of electrical energy, making them less energy efficient and environmentally sustainable. As a result, there is a growing need for cooling technologies that are cost-effective, energy-efficient, and eco-friendly. One promising solution is the thermoelectric cooling system (Mirmanto, 2018).

Thermoelectric coolers represent an innovative technology that converts electrical energy into a temperature gradient, enabling cooling without the use of traditional refrigerants. When supplied with a DC voltage of approximately 12–15 volts, one side of a thermoelectric module becomes hot while the other becomes cold (Amrullah et al., 2015). This method of cooling is environmentally friendly, durable, easy to maintain, and suitable for both large-scale and portable applications (Mirmanto, 2018).

Thermoelectric modules can be configured in series (multi-array) to enhance performance. Due to their dual-side nature—producing heat on one side and cold on the other—these modules can be arranged in a cascade or multi-stage configuration, where the cold side of one module is used to cool the hot side of another. This setup is particularly effective in applications such as water-cooling systems or portable cool boxes that utilize thermoelectric elements.

Based on these considerations, this study aims to compare the performance of single-array and multi-array thermoelectric cooling systems in terms of efficiency and effectiveness.

Thermoelectric devices function as tools for the direct conversion of thermal energy into electrical energy—known as thermoelectric generators (TEGs)—or, conversely, for converting electrical energy into a temperature gradient—referred to as thermoelectric coolers (TECs). These devices operate based on the Seebeck effect, which was first discovered by Thomas Johann Seebeck in 1821. The Seebeck effect states that when two dissimilar conductors or semiconductors are joined at two junctions maintained at different temperatures, a voltage is generated, causing an electric current to flow in a closed circuit. The magnitude of

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the generated voltage is directly proportional to the temperature difference between the two junctions.

The thermoelectric phenomenon was further developed by Jean Charles Athanase Peltier, who discovered in 1834 that when an electric current passes through a thermocouple, it can either absorb or release heat at the junctions, depending on the direction of current flow. Thermoelectric cooling is built on this effect. The junction between an N-type semiconductor and a P-type absorbs heat when current flows from the N-type to the P-type, creating a cooling effect. Conversely, when current flows from the P-type to the N-type, heat is released, generating a heating effect. The interconnections in a Peltier module are made of conductive materials that allow bidirectional current flow, in contrast to diodes, which only permit unidirectional current flow (Umboh et al., 2012).

Thermoelectric modules typically employ semiconductor materials, utilizing solid-state technology. They are made up of a variety of N-type components (materials with an excess of electrons) and P-type components (materials with a deficiency of electrons). Heat is absorbed on one side of the module and dissipated on the other when a temperature difference is applied across the module. This heat transfer induces a voltage across the thermoelectric junction, with the magnitude of the generated electrical voltage being proportional to the temperature gradient (Ryanuargo, 2013).

In refrigeration applications, thermoelectric devices offer several advantages, including the absence of moving parts and circulating fluids, compact size, and ease of integration into various system designs. Their main drawbacks, though, are the comparatively high cost of system deployment and the relatively poor energy conversion efficiency.

There are currently two types of thermoelectric devices available. The first is the Thermoelectric Generator (TEG), which is typically used to generate electrical energy by utilizing the temperature difference between two different semiconductor materials. The second type is the Thermoelectric Cooler (TEC), which is commonly used to produce cooling effects, such as in water dispensers. (Andrapica et al., 2017)

a. The Thermoelectric Generator (TEG) is a power generation device based on the Seebeck effect, first discovered in 1821 by Thomas Johann Seebeck. This effect explains that when two different conductive materials (typically semiconductors) are joined and subjected to a temperature gradient, an electric current or electromotive force is generated (Nandy et al., 2009). When applied to a solar radiation collector, the temperature difference between the collector plate and the surrounding environment can be utilized to generate electrical energy, which can subsequently be stored in a battery. The voltage produced by a TEG is directly proportional to the temperature difference between the two junctions; hence, a larger temperature gradient results in a higher generated voltage.
b. Thermoelectric Cooling (TEC) is a solid-state cooling device that operates based on the Peltier effect, which is the reverse of the Seebeck effect. The Peltier effect occurs when an electric current is passed through a circuit composed of two different conductive materials, resulting in a temperature difference at the junctions—one side absorbs heat (cold side), while the other side releases heat (hot side) (Pangestu et al., 2019). Currently, thermoelectric devices are commonly applied on a small scale, such as in water dispensers, cool boxes, and mini refrigerators. However, recent developments have extended their application to larger-scale systems, including thermoelectric-based air conditioning units.

The Seebeck effect refers to the generation of an electromotive force (EMF) or electric current when two dissimilar metals are joined and their junctions are maintained at different temperatures. This phenomenon is caused by the diffusion of charge carriers from the hot side to the cold side of the junction (Rafika, 2016). In contrast, the Peltier effect, which is often considered the reverse of the Seebeck effect, involves the creation of a temperature difference when an electric current is passed through a junction of two different metals.

When two different metals are connected at one end and the opposite ends are subjected to different temperatures, a voltage difference is produced between the ends. This phenomenon, first discovered by Thomas Johann Seebeck, is known as the Seebeck effect and forms the basis of thermocouple technology. The magnitude of the generated voltage is directly proportional to the temperature difference between the two junctions.

Peltier thermoelectric elements consist of P-type and N-type semiconductor materials connected in a closed electrical circuit that includes a load. The temperature difference at the junctions of each semiconductor induces electron movement from the hot side to the cold side, generating a thermoelectric effect.

A Peltier element, also known as a thermoelectric cooler, is a device that creates a temperature difference between its two sides when a direct current is applied across its terminals. In cooling applications, the primary advantages of Peltier elements include the absence of moving parts and circulating fluids, as well as their compact size and ease of integration into various designs. However, their main disadvantages are relatively low energy efficiency and high design and production costs (Wirawan, 2012).

The Peltier element consists of an array of two types of semiconductors, namely P-type and N-type, arranged in series. Each pair of semiconductors is connected via metal (typically copper) conductors. These metal connections are positioned at the base of each semiconductor unit, while an upper conductor serves to dissipate heat and a lower conductor function to absorb heat. Both the top and bottom surfaces of the element are typically covered with ceramic plates, which serve to concentrate and distribute the heat effectively.

A temperature difference is created across the semiconductor junctions of the Peltier element when an electric current is applied. The junction absorbs heat, creating a cooling effect, if the current flows from the N-type to the P-type semiconductor. Conversely, when the current flows from the P-type to the N-type semiconductor, the junction releases heat, resulting in a heating effect.

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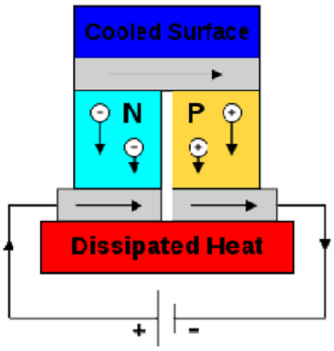

Fig. 1. Peltier element supplied with electric current (Umboh, R. et al. 2012)

The interconnection between semiconductors in a Peltier element consists of a conductor that allows current to flow in both directions, in contrast to a diode, whose interconnection permits current flow in only one direction (Umboh, 2010).

The working principle of thermoelectric cooling is based on the Peltier effect. When a direct current (DC) is applied to a Peltier element—comprising multiple P-type (semiconductors with lower energy levels) and N-type (semiconductors with higher energy levels) semiconductor cells—heat is absorbed on one side of the element, resulting in a cooling effect, while the opposite side releases heat and becomes hot. The side that becomes hot or cold depends on the direction of the current flow, as illustrated in Fig. 2.

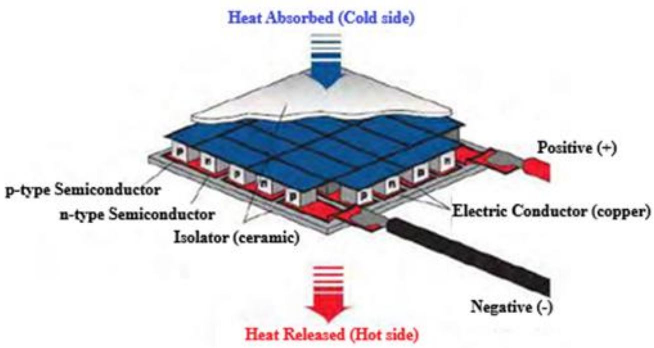

Fig. 2. Peltier flow scheme (Ryanuargo, et.al. 2013)

The Peltier element's chilly side experiences cooling as electrons move from a lower to a higher energy level, particularly from the P-type semiconductor to the N-type semiconductor. Since the P-type material has a lower energy level, electrons must absorb heat from the surroundings to make this transition, resulting in a cooling effect on that side. In contrast, electrons move from the N-type semiconductor (higher energy level) to the P-type semiconductor (lower energy level) at the Peltier element's hot side. During this process, excess energy is released as heat into the surrounding environment, producing a heating effect.

Thus, heat absorption occurs at the cold side and is subsequently released at the hot side. The total heat released on the hot side is equal to the sum of the heat absorbed at the cold side and the electrical energy provided to the thermoelectric module, which can be expressed by the following formula:

Qhot = Qcold + W

Where:

- Qhot is the heat released at the hot side,
- Qcold is the heat absorbed at the cold side,
- W is the electrical energy input to the module.

II. Research Method

This research is classified as experimental, utilizing a quantitative approach to examine the influence of independent variables on dependent variables under controlled conditions. The study aims to compare the coefficient of performance (COP) between a single-stage thermoelectric system and a cascade-stage thermoelectric system.

Data collection was carried out by measuring temperatures at several points, as well as recording the current and voltage supplied to the thermoelectric modules. Additionally, the water flow rate at the cold and hot sides of the water block was measured. Temperature measurements were conducted using Type-K thermocouples, and data were recorded through a data acquisition (DAQ) system. An voltmeter and an ammeter were used to measure voltage and current, respectively. In order to evaluate the system's performance, the water flow rate on both the hot and cold sides of the thermoelectric modules was also measured.

The schematic diagrams of the experimental circuits for the single-stage and cascade-stage thermoelectric systems are presented in Figures 3 and 4, respectively.

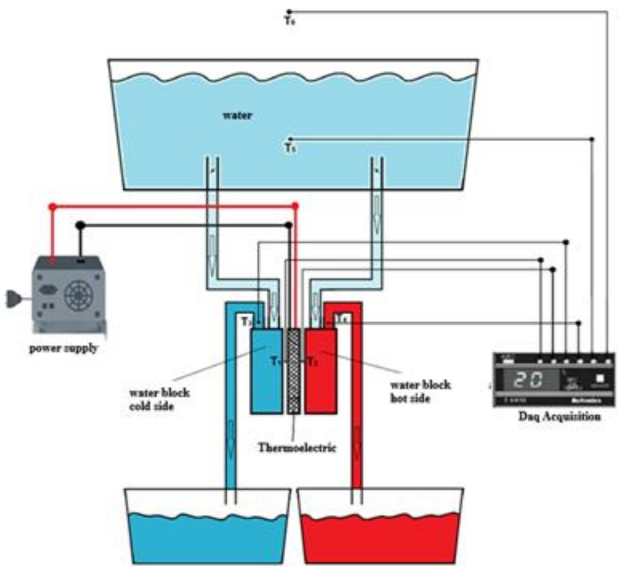

Fig. 3. Single stage thermoelectric system scheme

Thermoelectric modules were supplied with electric current under varying voltages of 3 V, 6 V, 9 V, and 12 V. The application of electric current generated a temperature gradient across the two surfaces of the thermoelectric module, namely the cold side and the hot side. To quantify the amount of energy transferred, water was circulated through water blocks attached to both surfaces of the thermoelectric module. The inlet and outlet temperatures of the water, along with the surface temperatures of the thermoelectric module, were measured using K-type thermocouples connected to a data

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acquisition system. Additionally, the thermoelectric voltage, the input current, and the water flow rate via the water block were measured.

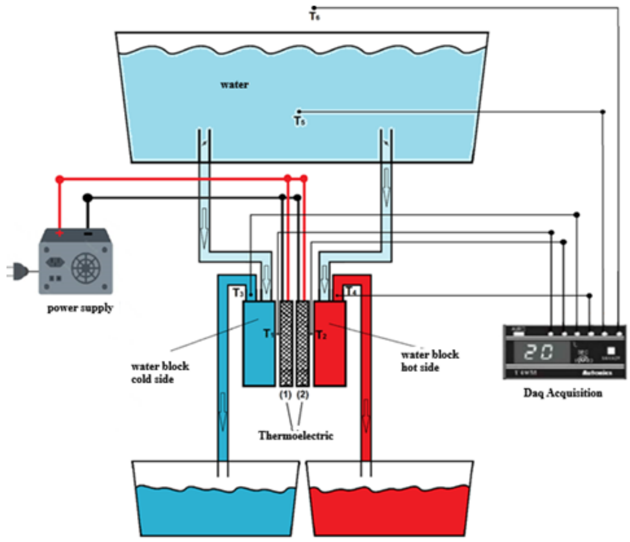

Fig. 4. Cascade stage thermoelectric system scheme

A similar procedure was applied to the cascade thermoelectric configuration. In this setup, two Peltier elements were connected such that the hot side of the first module was cooled by the cold side of the second module. Voltage variations of 3 V, 6 V, 9 V, and 12 V were applied to both elements. Measurements of temperature, voltage, electric current, and water flow rate through the water block were conducted in the same manner as in the single thermoelectric configuration.

III. Result and Discussion

This study employs a 12706-type thermoelectric module integrated into a 40 × 40 mm water block. Two testing configurations are conducted: a single thermoelectric module and a multistage thermoelectric module mounted on the water block. Each configuration is tested under four voltage variations, specifically 3 V, 6 V, 9 V, and 12 V. Data collection is carried out using thermocouples and a data acquisition system to record temperature measurements. Additionally, a voltmeter and an ammeter are utilized to measure the voltage and current supplied to the thermoelectric module.

The performance evaluation is carried out by calculating the Coefficient of Performance (COP) of the thermoelectric cooling device. The COP is determined using the following equation:

$$COP = qc / Pin$$

where:
qc = heat absorbed on the cold side of the module (W)
Pin = electrical power supplied to the module (W)

Fig. 5 presents the results of temperature measurements on the hot side of the thermoelectric module under various voltage conditions.

Graph 5(a) illustrates the relationship between the hot-side temperature and testing time for a single thermoelectric module under voltage variations of 3V, 6V, 9V, and 12V. Initially, prior to voltage application, the hot-side temperature is at ambient room temperature. Once voltage is applied, the temperature increases accordingly. At 3V, the hot-side temperature reaches 32.6°C; at 6V, it reaches 35.6°C; at 9V, it reaches 37.4°C; and at 12V, it reaches 40.7°C. These results indicate that the hot-side temperature of a single thermoelectric module increases with increasing applied voltage.

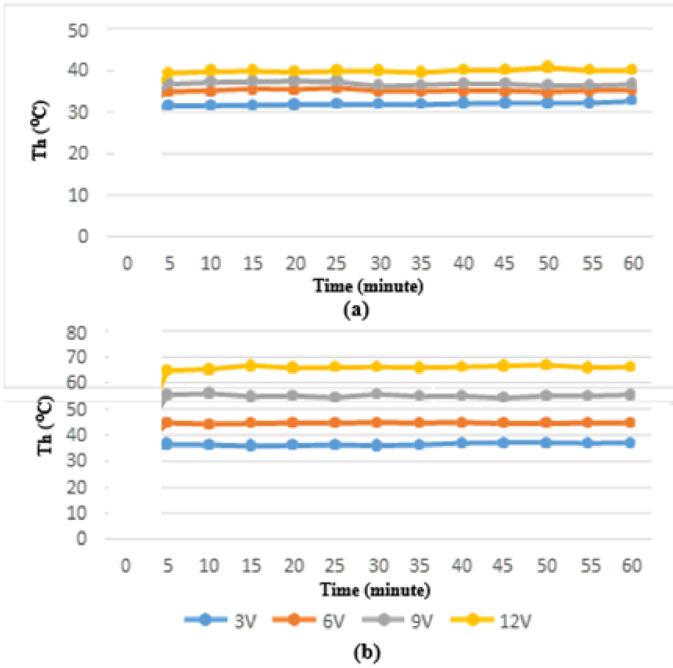

Fig. 5. Temperature of the hot side of thermoelectric module (a) single, (b) Cascade

Meanwhile, graph 5(b) presents the relationship between the hot-side temperature and testing time for a cascade thermoelectric configuration under the same voltage variations. At 3V, the temperature reaches 36.7°C; at 6V, it reaches 44.5°C; at 9V, it reaches 55.7°C; and at 12V, it reaches 66.7°C. These findings demonstrate that in a cascade thermoelectric system, the hot-side temperature increases more significantly with rising voltage compared to a single module setup.

Fig. 6 shows the variation in the cold-side surface temperature of the thermoelectric module at different voltage levels for both the single-stage and cascade thermoelectric configurations.

Fig 6(a) illustrates the relationship between the cold-side temperature and the testing time of a single thermoelectric module under voltage variations of 3 V, 6 V, 9 V, and 12 V. Initially, the cold-side temperature is at room temperature and decreases upon the application of voltage. At 3 V, the cold-side temperature reaches 27.6°C; at 6 V, it reaches 26.2°C; at 9 V, it reaches 25.8°C; and at 12 V, it reaches 25.3°C. These results indicate that applying a voltage of 12 V yields the lowest cold-side temperature in the single thermoelectric configuration.

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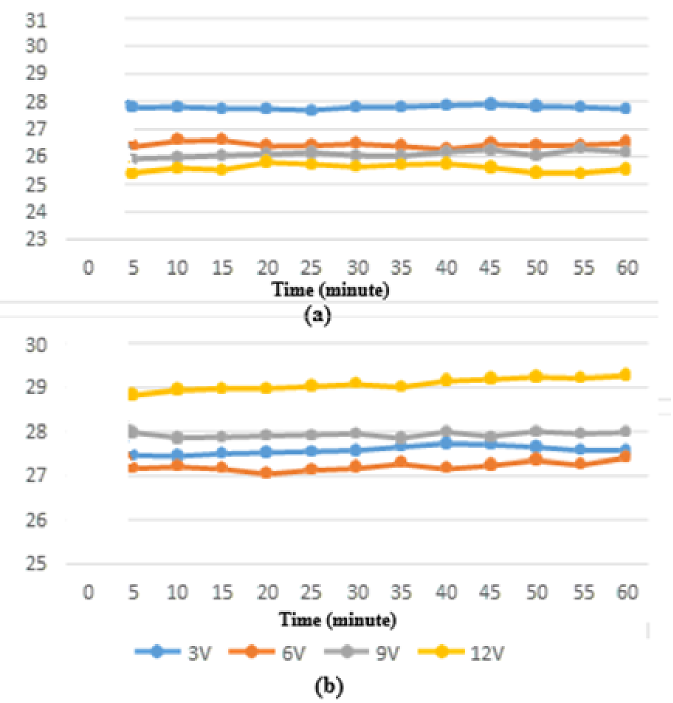

Fig. 6. Temperature of the cold side of thermoelectric module (a) single, (b) Cascade

Meanwhile, Fig. 6(b) shows the relationship between the cold-side temperature and the testing time of a cascade thermoelectric module with voltage variations of 3 V, 6 V, 9 V, and 12 V. Initially, the cold-side temperature is at room temperature and changes as voltage is applied. At 3 V, the cold-side temperature reaches 27.4°C; at 6 V, it reaches 27.04°C; at 9 V, it reaches 27.8°C; and at 12 V, it reaches 28.8°C. These findings suggest that in the cascade thermoelectric configuration, the lowest cold-side temperature is achieved at a voltage of 6 V.

In both tests, it was observed that increasing the voltage supplied to the thermoelectric circuit resulted in higher electrical power consumption. When comparing the two types of thermoelectric circuits, the single-stage circuit consumed less electrical power, whereas the cascade thermoelectric circuit exhibited the highest power consumption, reaching 61.32 watts at an input voltage of 12 volts.

To compare the performance of single and cascade thermoelectric systems under various voltage conditions, the Coefficient of Performance (COP) was calculated based on the experimental data. The results of the COP calculations are presented in Fig. 7.

The graph above illustrates the relationship between the Coefficient of Performance (COP) and the voltage applied to both single and cascade thermoelectric modules. At an input voltage of 3V, the highest COP value is achieved by the single thermoelectric module, with a COP of 3.64949. Similarly, at 6V, the single thermoelectric module exhibits the highest COP of 1.37930. At 9V and 12V, the single module again shows superior performance, with COP values of 0.75490 and 0.43540, respectively. These results demonstrate that, across all tested voltage levels, the single thermoelectric consistently outperforms the cascade configuration in terms of COP.

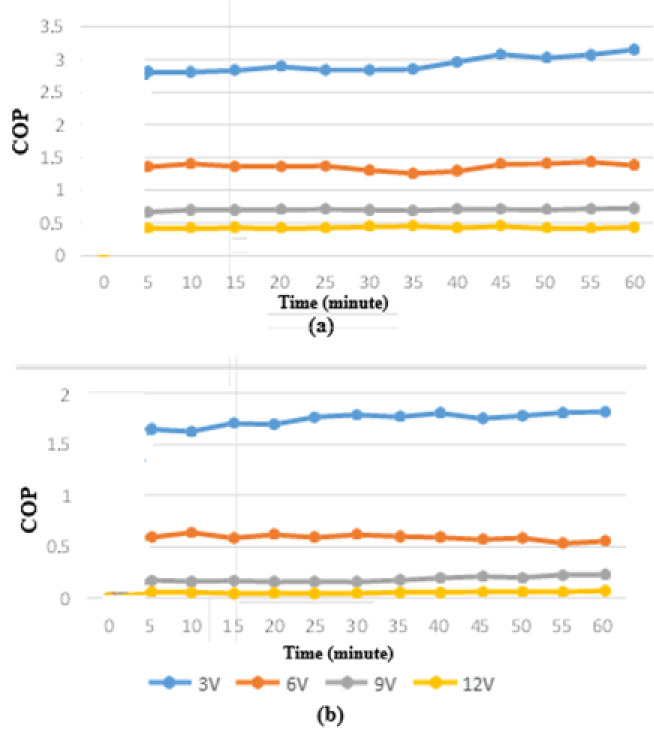

Fig. 7. Coefficient of performance (COP) of thermoelectric module (a) single, (b) Cascade

Based on experimental testing and subsequent analysis, the higher COP values observed in the single thermoelectric module can be attributed to its greater cooling capacity on the cold side compared to the cascade thermoelectric. This trend is evident in Table 4.1, which compares the absorbed power on the cold side for both configurations across all voltage variations. The single thermoelectric consistently exhibits higher cold-side absorption power.

In cascade thermoelectric systems, the lower absorption power can be explained by the configuration design, in which the hot side of the first thermoelectric module (TE1) is thermally connected to the cold side of the second module (TE2). The goal of this arrangement is to improve the thermoelectric effect by enabling TE2 to absorb heat from TE1's hot side. However, experimental findings indicate that TE2 is unable to effectively cool the hot side of TE1 due to the excessive heat load, resulting in suboptimal performance of TE1's cold-side absorption.

Furthermore, the lower COP values observed in the cascade thermoelectric configuration can also be attributed to significantly higher input power requirements compared to the single module. While COP is defined as the ratio of absorbed heat on the cold side (qc) to the input power (Pin), a substantial increase in input power without a corresponding increase in absorbed heat leads to a reduction in overall COP. Therefore, the inverse relationship between high input power and low heat absorption in the cascade configuration directly contributes to its reduced efficiency.

IV. CONCLUSION

Based on the research findings and discussion, it can be concluded that voltage variation affects the coefficient of performance (COP) of the thermoelectric cooling system. An increase in the applied voltage leads to higher electrical power supplied to the thermoelectric module. However, due to the inherent limitations of the module in transferring heat, this results in a decline in its performance. Furthermore, the study shows that the COP of the single-stage cooling system is superior to that of the cascade cooling system. This is attributed to heat transfer limitations between stages in the cascade configuration.

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