

Experimental investigation on a thermoelectric cooler to evaluate the efficiency of a passive temperature harmonization device

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Abstract: This study evaluated the efficiency of a passive thermal homogenization device (aluminum tube) designed to optimize the temperature profile in a thermoelectric cooler (TEC) box. An experimental approach was considered, comparing a standalone TEC1-12706 Peltier module with a system integrated with an aluminum tube. Both configurations operated under natural convection with passive thermal management on the TEC hot side. The introduction of the aluminum tube led to a temperature reduction of 10°C inside the tube compared to 5°C in the rest of the enclosure, creating two distinct thermal zones. The results showed that the COP value increased from 35% to 250%, with an average gain of 80%, compared to the module without the aluminum tube. Although the absolute Coefficient of Performance (COP) remains lower than that of active systems, the incorporation of the aluminum tube significantly mitigates thermal stratification within the storage medium. These results underscore the potential of this approach for sustainable cooling applications in energy-constrained regions, primarily due to reduced mechanical complexity and enhanced system robustness.

Keywords: Aluminum tube, Heat sink, Passive homogenization, Temperature profile, Thermoelectric cooler.

1. Introduction

Thermoelectric devices have emerged as a focal point of research and development in recent years, garnering substantial attention for their promising applications in renewable energy and energy management. These devices can convert heat energy into electrical power and vice versa, making them applicable across various industries [1-4]. Based on their applications, thermoelectric devices can be classified into thermoelectric coolers (TEC) and thermoelectric generators (TEG) [5, 6]. Thermoelectric generators convert heat into electrical power and are used in military and aerospace systems for power generation, as well as for powering remote environmental monitoring sensors in locations without conventional power sources [7, 8]. Their reliability and ability to function in harsh environments make them highly valuable.

On the other hand, thermoelectric coolers (TECs) convert electrical power into heat energy. The Peltier effect, discovered by Jean Charles Athanase Peltier in the 19th century, describes the phenomenon where a voltage applied across two different conductors generates a temperature gradient [9]. This effect is the foundation of Peltier devices, commonly known as TECs, which are widely used for cooling sensitive electronic components, detectors, and medical equipment requiring precise temperature control [10]. These coolers are also employed in portable coolers, beverage chillers, and electronic devices requiring localized cooling or heating.

Thermoelectric modules can be integrated into heating, ventilation, and air conditioning systems for energy-efficient temperature control in buildings. In these systems, heat sinks play a crucial role in dissipating the heat generated by the hot side of the Peltier module. Research has focused on optimizing heat sink design, material selection, and surface area to enhance thermal conductivity [11, 12]. Studies have shown that incorporating heat pipes into heat sink designs significantly improves thermal dissipation, resulting in more efficient Peltier cooling [13]. Fluid cooling, using water or air, is another effective strategy to enhance heat dissipation in Peltier systems, with water offering higher thermal conductivity than air [14]. The integration of fans has also been extensively studied, further improving convective heat transfer and thermal management [14, 15].

In refrigeration systems, achieving effective temperature homogenization within an enclosure is critical for optimal performance and product preservation [16, 17]. While active methods like fans and forced-air circulation are commonly used, there is increasing interest in passive techniques for temperature regulation. Passive methods, which rely on natural convection and increased surface area, offer energy-efficient alternatives that avoid the complexities and energy consumption of active components [18-20]. Few studies have been conducted on passive components based on natural convection for cool-side heat dissipation and temperature homogenization in the cool box [21]. This study was conducted in the context of passive methodologies, with the primary objective of investigating the use of an aluminum tube as a passive component to homogenize temperature in a Peltier cooling box.

2. Materials and Methods

Thermoelectric modules are used as energy converters made of many thermocouples electrically connected in series. Thermoelectric coolers (TECs) consist of two dissimilar semiconductor materials that generate a thermoelectric cooling effect when an electric voltage is applied in the appropriate direction.

Thermoelectric modules generally operate with two heat exchangers attached to their sides to enhance heat exchange. Figure 1 shows actual pictures of the experimental setup components, including the heat sink attached to the cool and hot sides of the TEC used in this study.

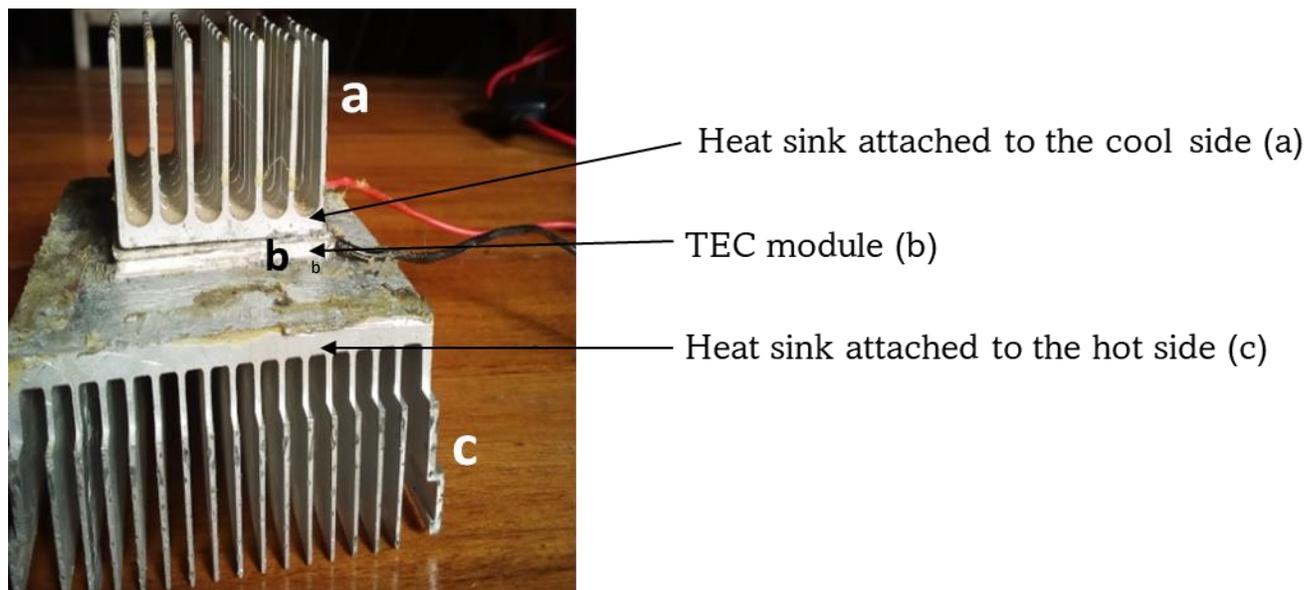


Figure 1.

Components of the experimental setup: (a) cool-side heat sink, (b) hot-side heat sink (water block), and (c) TEC1-12706 Peltier thermoelectric module.

The experiment was conducted using a thermoelectric cooling system consisting of a Peltier module (TEC1-12706) placed inside a laboratory refrigerator box made of Styrofoam sheets, with dimensions of $15 \times 10 \times 15$ cm. The cooling system was tested in two working conditions: one with the module alone and the other with an aluminum tube (dimensions 4×4 mm base, 150 mm height, and 1 mm thickness) attached to the cold side of the module. The hot side of the thermoelectric module was water-cooled using a passive system (water box) without any active water pumps or fans.

The operating voltage of the Peltier module was set to 12 V DC, with an operating current below 3 A. The system was tested at ambient temperature, and no external thermal load was applied during the experiments, conducted in a controlled environment to minimize external temperature variations.

The air inside the refrigerator box was assumed to be homogeneously distributed with no significant airflow restrictions. The water-cooling system was assumed to provide consistent cooling at the hot side of the Peltier module throughout the experiment. The aluminum tube was assumed to have minimal thermal resistance, allowing for efficient heat transfer and temperature homogenization.

Heat loss through the Styrofoam refrigerator walls was considered negligible due to the insulating properties of Styrofoam.

The refrigerator box was first assembled with Styrofoam sheets to ensure thermal insulation. In the first condition, the Peltier module was placed directly at the center of the bottom of the refrigerator box. The system was connected to a power source, and the temperature inside the box was monitored at regular intervals using thermocouples placed at different locations inside the box (Figure 2). In the second condition, the aluminum tube was placed on the cold side of the Peltier module (Figure 3). The system was powered, and the same temperature monitoring procedure was followed. Both experimental setups were run under the same conditions, and temperature data were recorded throughout the experiments. The temperature distribution, cooling rate, and coefficient of performance (COP) were calculated for both setups.

The water cooling for the hot side of the module was maintained using a passive water reservoir, with no active pumping or forced airflow. The cooling efficiency was measured based on the temperature at the hot side of the module. All experiments were repeated three times to ensure consistency and repeatability of results.

The core component of the experimental cooling system is a TEC1-12706 thermoelectric Peltier module, with its technical parameters and operating conditions summarized in Table 1. Unlike conventional active cooling systems, the hot side heat dissipation is managed by a passive water reservoir without forced circulation, while the cold side relies solely on natural convection enhanced by a finned heat sink and a passive aluminum tube. This configuration aims to minimize mechanical complexity and energy consumption.

Table 1.

Operating parameters of the TEC1-12706 Peltier module.

Peltier thermoelectric	Operating voltage	Operating current
TEC1-12706	12 V DC	<3A

Water has been used as a coolant for the hot side. The experimental results obtained have been compared for both conditions. Schematic views and pictures of the refrigerators are shown in Figure 2 for the module-only mode and Figure 3 for the aluminum tube mode.

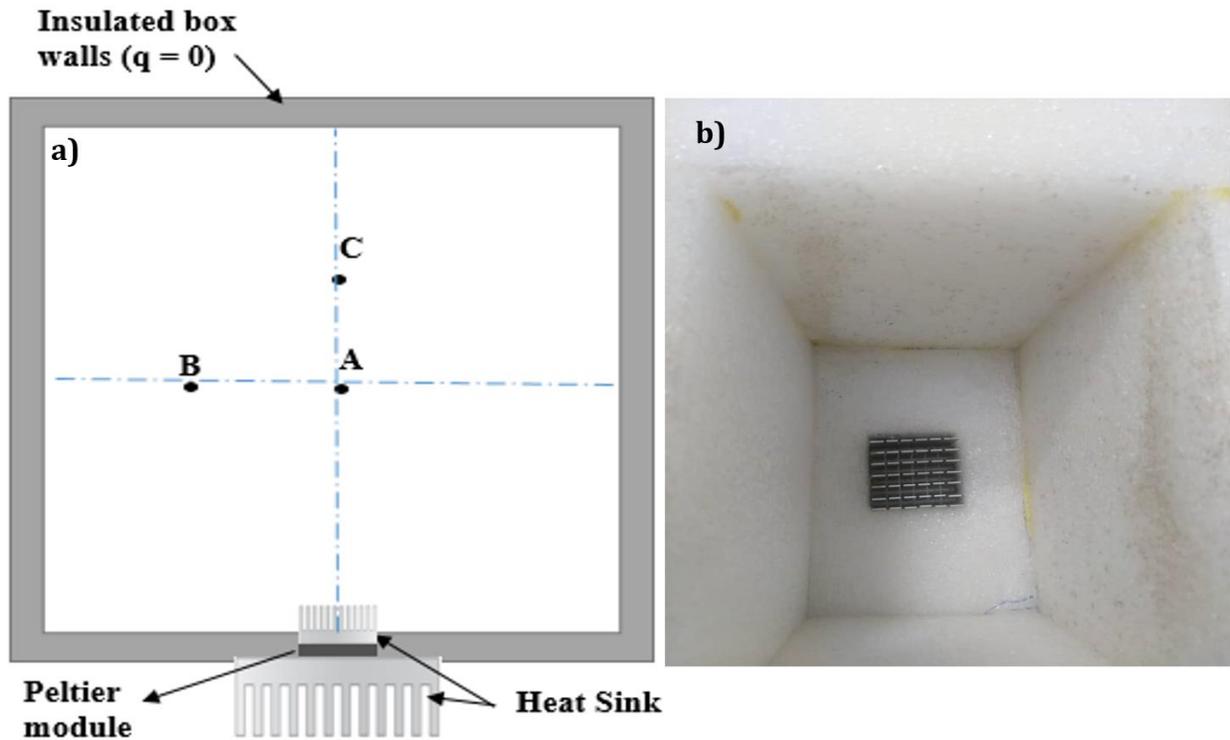


Figure 2. Configuration of the standalone module system (control mode). (a) Sectional schematic showing thermocouple placement at points A, B, and C, (b) Photographic view of the Styrofoam enclosure.

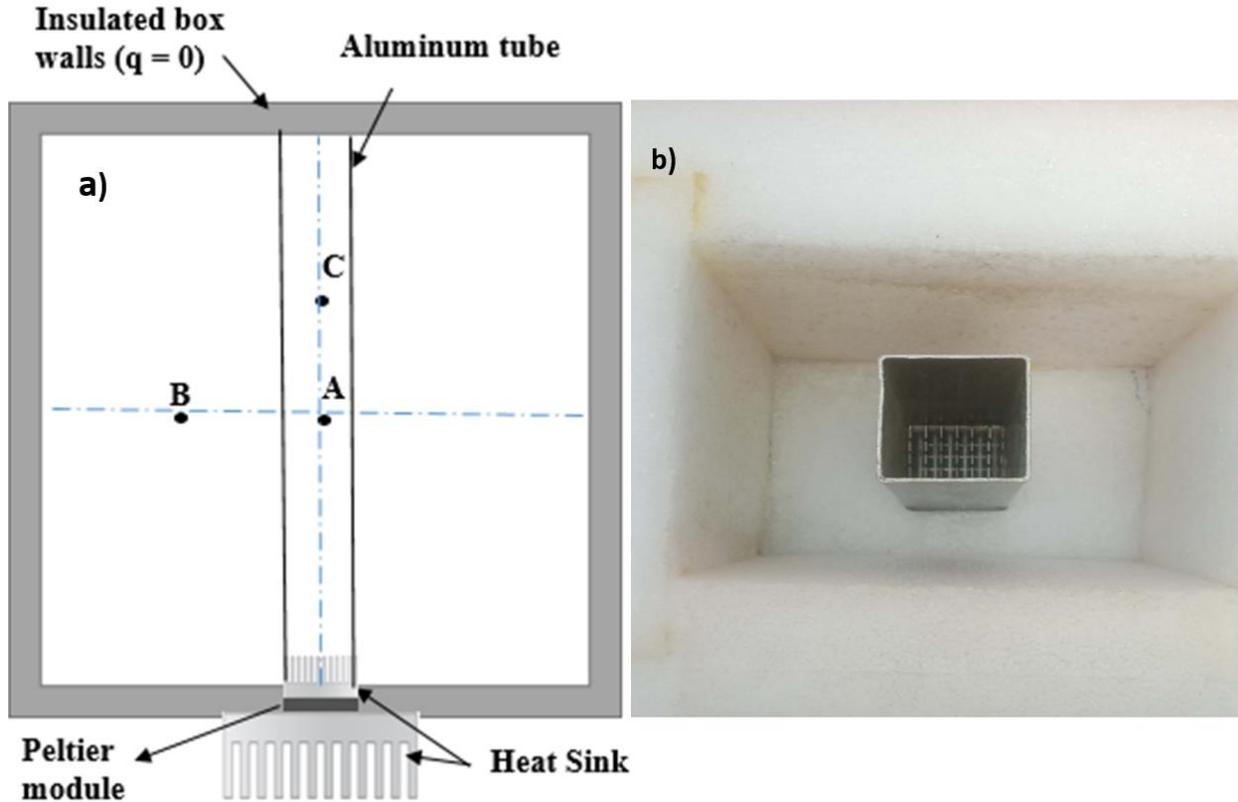


Figure 3. Configuration of the aluminum tube system (experimental mode). (a) Sectional schematic showing the tube placement and thermocouple positions at points A, B, and C; (b) Photographic view of the thermal management device.

The temperature variations were measured with T-type thermocouples placed at three points named A, B, and C; the average temperature of the box was obtained.

Electrical power consumption was also calculated by recording current and voltage values obtained by using a voltage/ampere meter.

In scientific studies on TEC refrigerators, performance evaluations are conducted by different methods. In the present study, the power consumption of the module was calculated to estimate the Coefficient of Performance (COP) of the TEC cool box. The COP value estimated in experimental studies is calculated taking into account the electrical power consumption of the Peltier module, water pump, and fan. In the present study, a passive natural convection system was used to homogenized temperature in the box, and a back of water was applied to regulate the temperature of the hot side of the module. No water pump or fan was used during this study. Then the total COP value of this passive system can be written as follows:

$$COP_{tot} = \frac{Q}{W_{pel}} \quad (1)$$

The amount of absorbed heat from the enclosed environment within the box can be calculated by the following equation:

$$Q = mC_{P,air}(T_2 - T_1) \quad (2)$$

where T_2 and T_1 are the first and last temperatures of the refrigerator box, and m is the air mass inside the box. The mass of air contained in the refrigerator box can be obtained from the volume of the refrigerator box and the density of the air using the following equation:

$$m = \rho V \quad (3)$$

Consumed electrical power by the Peltier module can be calculated from recorded current (I) and voltage (U) values as:

$$W_{pel} = IUt \quad (4)$$

3. Results

Figure 4 shows the experimental results for temperature variation over the test time (1200 s) for the two tested modes. The results indicate that the aluminium tube configuration enables faster temperature reduction and achieves lower final temperatures.

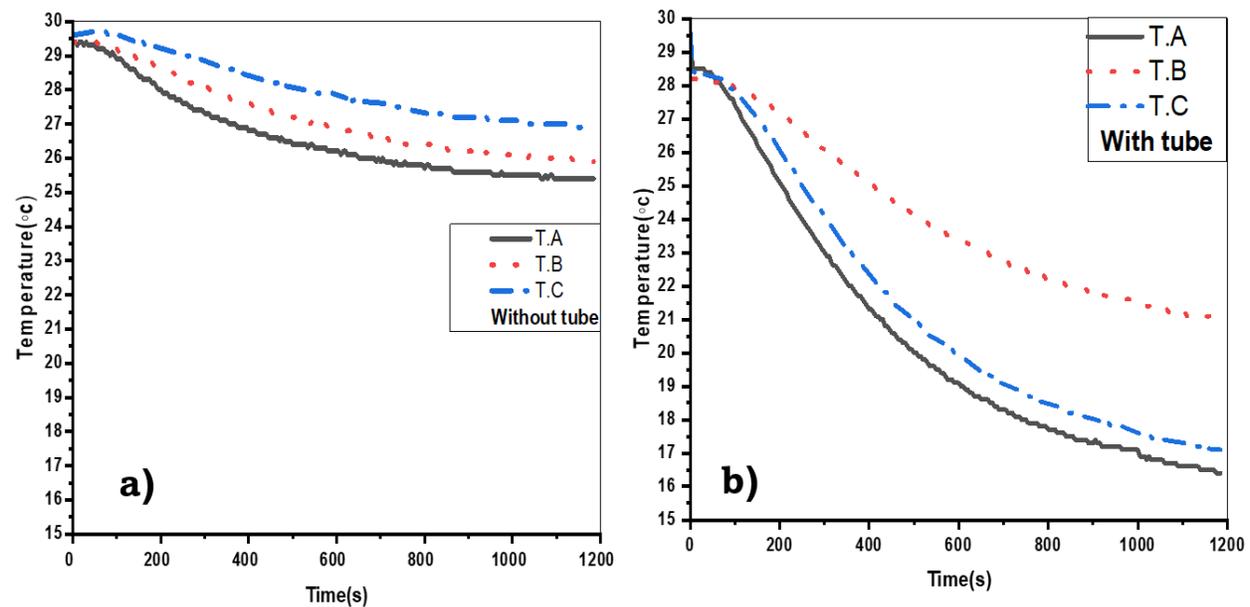


Figure 4. Temperature of refrigerator boxes with respect to test time at two modes: a) without tube, b) with tube.

For improved comparison, the temperature profiles at each measurement point were analyzed for both operating modes. Figure 5 illustrates the temperature evolution recorded at the three locations. Examination of the thermal profiles reveals that a temperature decrease of 10 °C was achieved inside the tube, compared with a 5 °C reduction outside the tube (within the cool box). The introduction of the tube not only enhanced the overall temperature drop but also led to the formation of two distinct thermal zones: a colder region inside the tube and a relatively cooler region outside it.

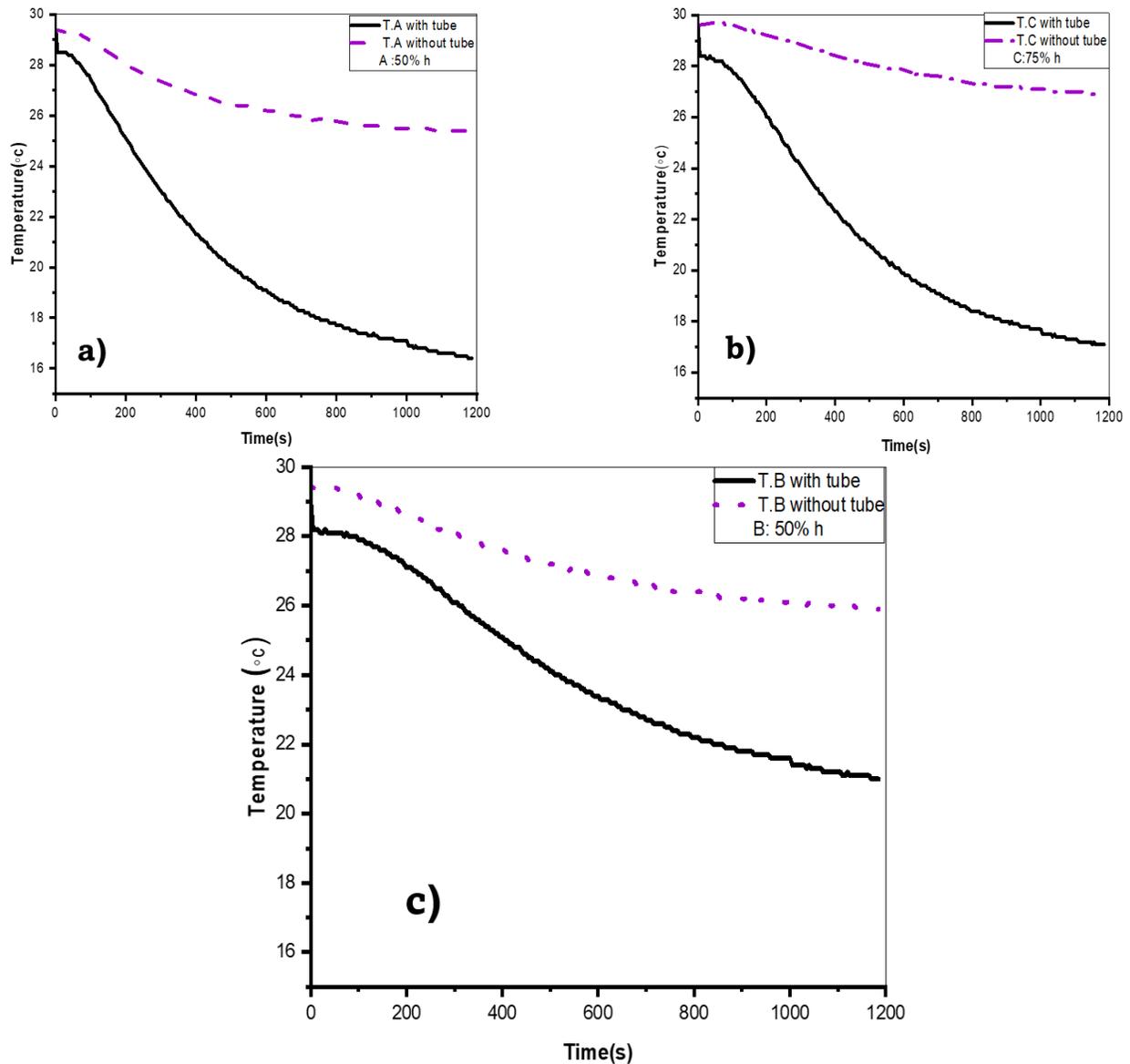


Figure 5. Time-dependent temperature evolution at points A, B, and C without and with aluminum tube configurations.

To calculate the total COP values, the amount of power consumed by the TEC module has been measured. The consumed electrical power was obtained from the continuously recorded voltage and current values using a digital volt-ampere meter. In all experiments, it was revealed that the power consumption in both modes was approximately equal. However, a decrease of 0.47% in the average was recorded in the aluminum tube mode.

Additionally, at the beginning of the experiments, the power consumption was lowest in the aluminum tube mode but increased gradually over time. In module-only mode, this value was high at the beginning and decreased, and fixed at a constant value toward the end of the test time. Figure 6 presents the power consumption values over time for both modes.

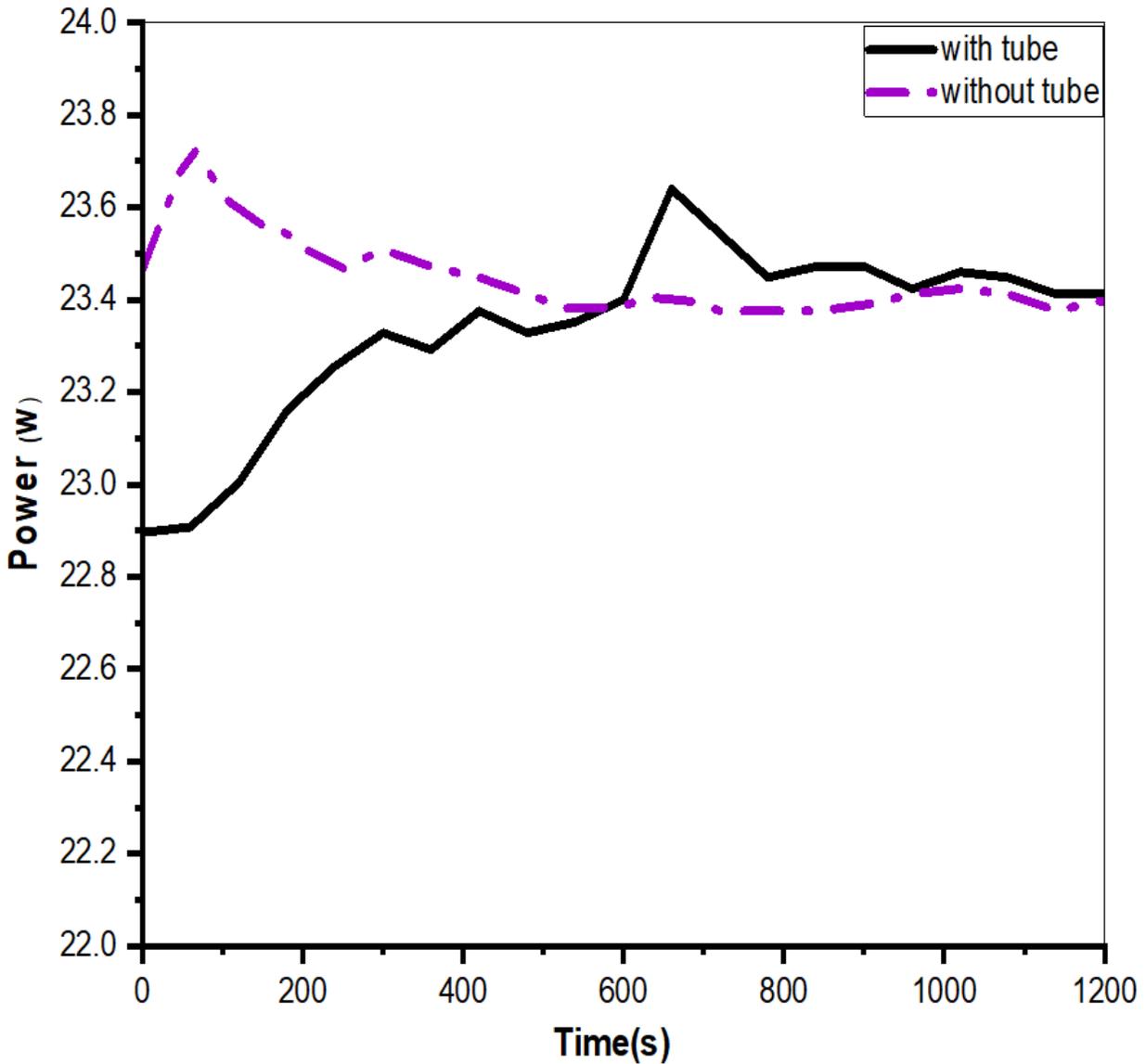


Figure 6. Power consumption with respect to test time at two modes (without and with aluminum tube).

Using the temperature profile and power consumption, the COP results calculated from Equations (1 - 4) for the studied TEC systems are shown in Figure 7 for both modes. The results revealed that the aluminum tube mode has the best performance. At the beginning, the COP values of the module-only mode are noticeably higher than those of the aluminum tube mode. However, its value decreases gradually over test time and becomes less than aluminum tube mode at the end of the experiments.

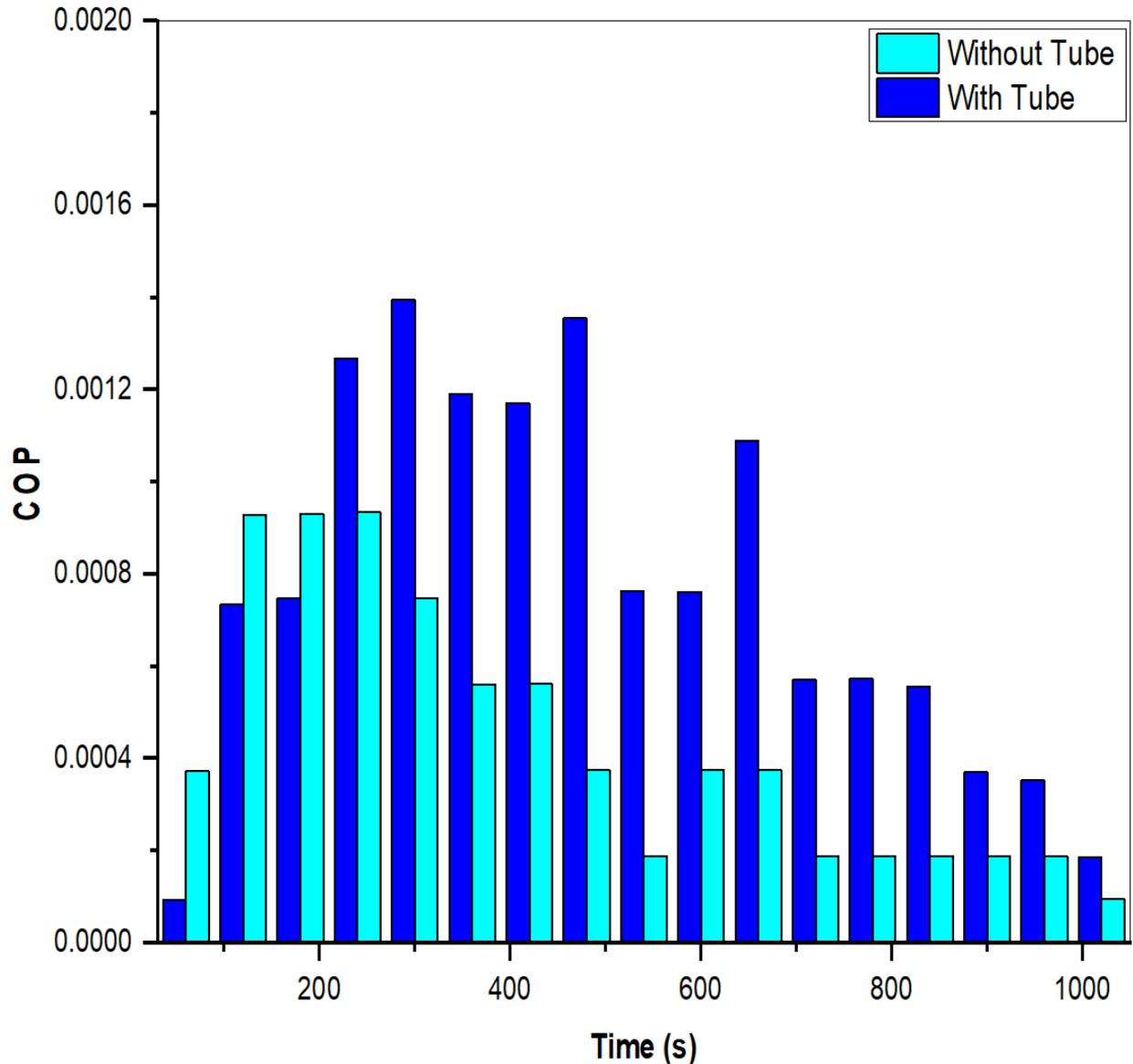


Figure 7.
COP values versus test time for two modes (without, with tube).

The results revealed an improvement ranging in 35–250% in the aluminum tube mode. However, at the beginning during the 180 s the module mode presented higher COP values than those of the tube mode. This phenomenon would probably be due to the fact that at the beginning, the energy generated on the cold side propagates much more quickly by conduction in the body of the aluminum tube. When this tube enters into dynamic equilibrium with the cold surface of the module, it in turn begins to cool the air surrounding it by convection. Aluminum has a high thermal conductivity (approximately 237 W/m.K) [22], which facilitates rapid heat dissipation along its surface. When used as a tube in contact with the cold side of the Peltier module, this conductivity allows heat to spread evenly across the aluminum's surface, reducing temperature gradients. The Peltier module operates by creating a temperature differential across its sides, but without sufficient heat dissipation, certain areas can experience localized heating, or "hot spots." Aluminum's conductivity mitigates this by quickly

transporting heat away from concentrated areas on the cold side, distributing it uniformly. This leads to more efficient operation since the Peltier module can maintain its designed temperature gradient without localized overheating. A uniformly cool surface enables more effective thermal transfer to the surrounding environment or to any thermal management system, resulting in improved performance.

The maximum COP value reported in the present study is 0,0014 in the aluminum tube mode. The obtained maximum COP value is very low compared to that reported by many authors [12, 14, 21, 23, 24]. Figure 8 presents the average COP for the Booth tested modes.

For better comparison, the average COP values were also calculated and compared. The results from the average COP have shown an important improvement of 80% in the aluminum tube mode.

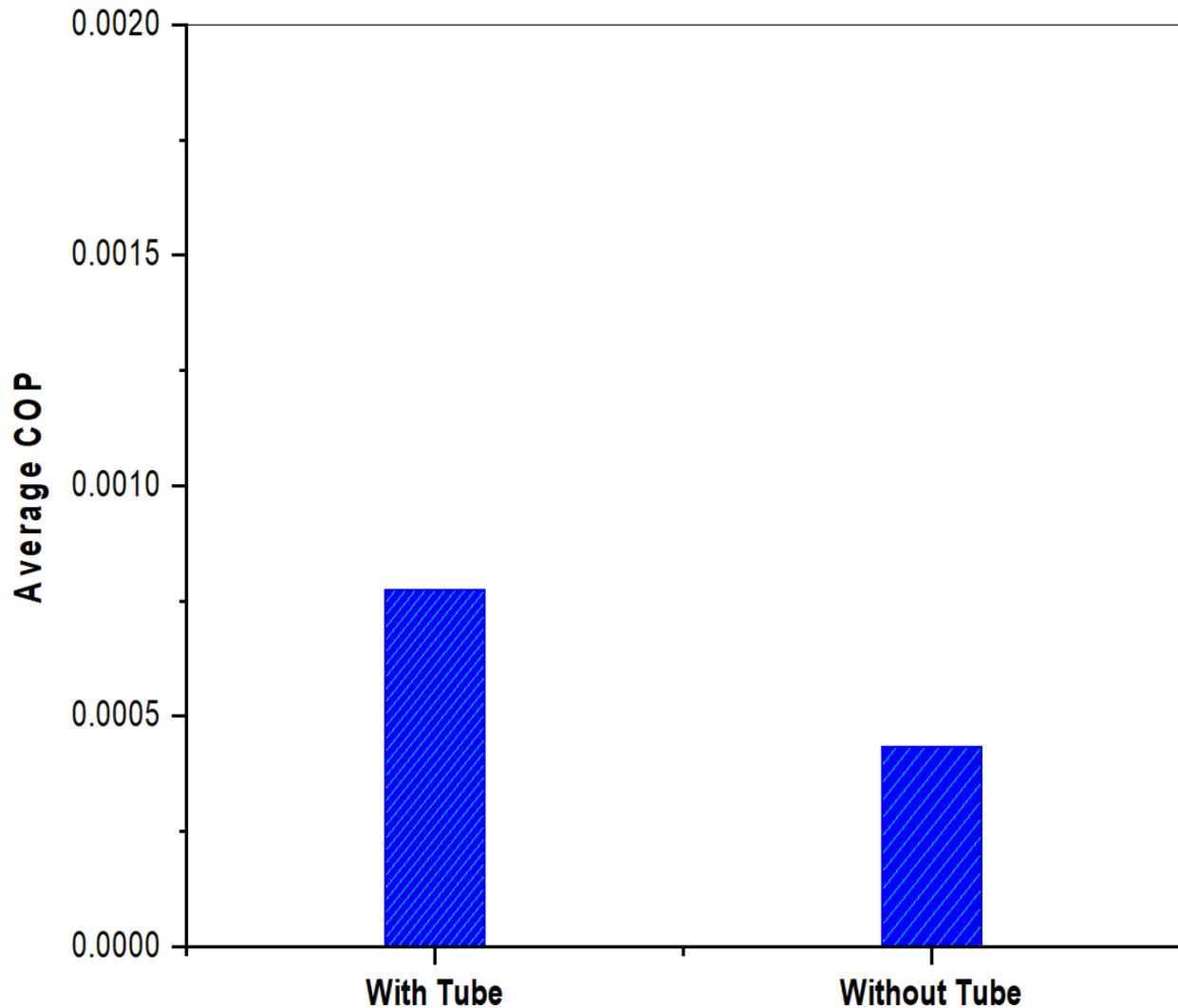


Figure 8.
COP values versus test time for two modes (without, with tube).

4. Discussion

The efficiency of thermoelectric modules is highly limited by heat dissipation at the hot end and heat extraction at the cold end. The exclusive use of natural convection (in the cold enclosure) and passive thermal management (water reservoir) on the hot side results in a very high thermal contact

resistance, reducing the COP value. Studies on active systems typically show COP values ranging from 0.3 to 0.7 [25]. The results of Chen et al. [21] on thermoelectric refrigerators operating under natural convection heat transfer confirm this issue. They specifically observed a high non-uniformity of temperature within the refrigerated box, with significant discrepancies between the cooler and the ambient air, notably up to a 7°C difference between the cold surface and the air temperature. Although the absolute COP reported in this work is lower (likely due to the entirely passive hot side heat dissipation), its contribution directly addresses the limitation of homogeneity raised by Chen et al. [21]. The aluminum tube acts as a passive palliative to the thermal stratification generated by natural convection. The aluminum tube serves as a passive mitigation mechanism for the thermal stratification induced by natural convection. Its effectiveness stems from the high thermal conductivity of aluminum (approximately 237 W/m·K), as reported by Zhang and Li [22], which enables rapid heat transfer and promotes a more uniform distribution of the cooling effect throughout the system. This strategy is consistent with the findings of Shabgard et al. [13], who demonstrated that the integration of passive heat transfer enhancement techniques can substantially improve the performance of thermoelectric systems by effectively reducing internal thermal resistance and promoting more efficient heat flow. Furthermore, studies of systems based on passive components generally reported COP values ranging from 0.01 to 0.14 [23]. The COP obtained in this study is even below this range, which highlights the predominant role of the thermal resistance of the passive water reservoir on the hot side. The electrical energy consumed by the module is thus primarily used to maintain the temperature difference across the thermoelectric junctions, rather than effectively extracting the internal heat load.

5. Conclusions

This study investigated the implementation of a passive device, specifically an aluminum tube, to enhance heat dissipation and promote temperature homogenization through natural convection in a refrigeration box equipped with a thermoelectric (TEC) module. The results demonstrated a substantial temperature reduction, with a decrease of approximately 5 °C outside and 10 °C inside the tube, leading to the formation of two distinct thermal zones. This configuration enhanced localized cooling and allowed more precise temperature reduction within the enclosure. Although the coefficient of performance (COP) and overall cooling capacity achieved with this passive approach were lower than those of active systems, such as fan- or pump-assisted configurations, the results remain promising. These findings highlight the potential of passive enhancement techniques as energy-efficient alternatives, particularly in applications where minimizing power consumption is a primary priority. Moreover, the absence of moving parts reduces mechanical complexity, maintenance requirements, and the likelihood of failure, thereby improving system reliability and extending operational lifespan. This approach aligns well with sustainable cooling strategies, as it limits energy demand and is especially suitable for off-grid or remote applications. Despite the comparatively lower COP values, the study emphasizes the promise of passive thermal management solutions and paves the way for further optimization and practical implementation in energy-constrained environments.

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Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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