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Performance of Peltier-Based Thermal Management System: Impact of Multiple Modules on Cooling Efficiency and Energy Consumption

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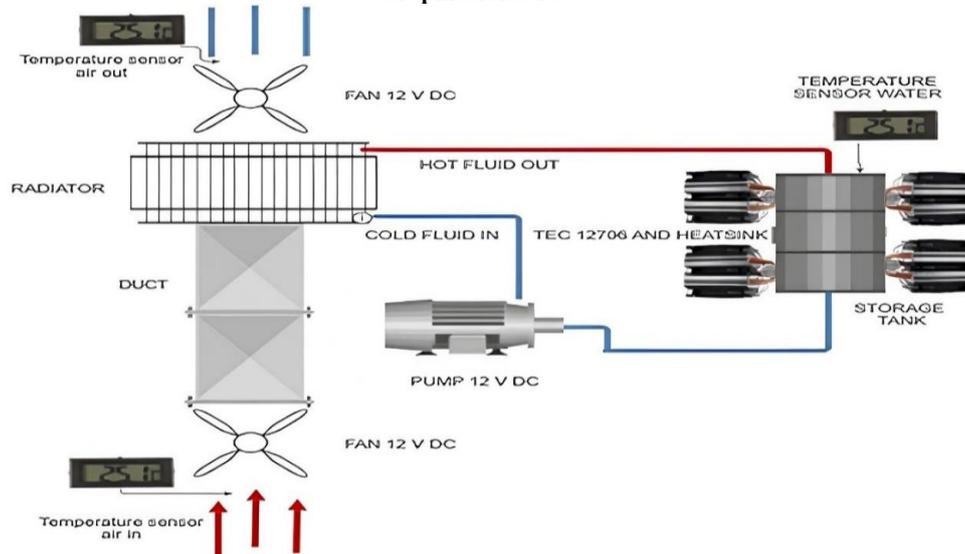| *PAPER INFO*	*ABSTRACT*
	The effectiveness of thermal management procedures is considered a crucial point for keeping the performance and longevity of electronic and electrical application boards. One of the solutions, which has gained increased interest from researchers and industrial institutes, is the use of a thermoelectric cooler (TEC), also known as a Peltier, which is made of two semiconductor materials for promising support of the traditional forced fan air-cooling. However, a more detailed investigation of the effect of using Peltier technology under operational and design change conditions is needed. In line with this, this study examines an experimental prototype model to analyze the impact of different numbers of Peltier units (1 to 4) and different refrigerants (Distilled water only, mono ethylene glycol and Distilled water 50:50) on thermal progress performance in terms of thermal absorption and energy consumption. Under variable real operations, the result appeared that the mixture (distilled water + mono ethylene glycol 50:50) outperformed distilled water only, achieved faster electrical cabinet temperature reduction, and a higher cooling performance (COP) in all Peltier configuration models. The highest COP of 3.75 was recorded using four Peltier units with a mixture of mono ethylene glycol. The findings emphasize the importance of the best refrigerant choice and system configuration for efficient thermal management, paving the way for future advancements in thermoelectric cooling technologies.

Graphical Abstract

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NOMENCLATURE

A	area of the pipe, (circular)	T	temperature
c	specific heat, kJ/kg C	Th	temperature of the hot side of the TEC
COP	coefficient of performance	Tc	temperature of the cold side of the TEC
I	electrical current, A	Tr	temperature of the air
Km	thermal conductivity of TEC, W/mC	TEC	thermoelectric cooler
ṁ	mass flow rate, kg/s	TEM	thermoelectric module
P1	input energy consumed TEM, W	V	voltage, V
P2	input energy consumed (pump +fans), W	**Greek Symbols**	
ρ	Density of air	αm	seebeck coefficient (V/C) of TEC
q	heat transfer rate, W	ΔT	temperature difference
qa	heat transfer rate between air fluid and cold surface of TEM	**Subscripts**	
qph	Peltier heating, W	a	air
qpc	Peltier cooling, W	c	cold
qj	Joule heating, W	con	Fourier heating
qcon	Fourier heating, W	h	hot
qc	cooling energy of TEM, W	j	Joule heating
qh	heating energy of TEM, W	max	Maximum
qr	heating energy of (pump + fans)	ph	Peltier heating
Rm	electrical resistance of TEC, Ω	pc	Peltier cooling
S	Speed of air	w	fluid

1. INTRODUCTION

Controlling the thermal load of electrical and electronic components is crucial for enhancing their efficiency and extending their operational lifespan (1). The flow of electrical current through conductive materials generates heat as a result of converting electrical energy into thermal energy, causing electrical components to produce heat during operation (2). To ensure the safe and reliable performance of these systems, it is essential to dissipate the generated heat efficiently from the components to the surrounding environment (3). With the rapid advancement in electronic device performance, effectively transferring accumulated heat within a limited time and space using conventional cooling methods become increasingly challenging. Consequently, energy consumption and heat dissipation have appeared as significant obstacles to further improving electronic device performance (4).

In this context, thermoelectric cooling devices based on the Peltier effect have gained considerable attention as effective solutions for thermal management in electrical, electronic, and mechanical systems (5). Temperature control systems are essential across various industries to keep the best operating conditions, enhance product quality, and improve energy efficiency (6). Peltier-based cooling systems offer several advantages, including compact size, low cost, and environmentally friendly design, making them particularly suitable for thermal management in electronic systems (7). This is especially beneficial in hot climates, such as the Middle East, where these systems can efficiently regulate running temperatures, ensuring the safe and reliable operation of electrical component (8).

Given the effectiveness of thermoelectric cooling in managing high-performance chips and components, it has been proposed as a promising alternative to conventional cooling techniques (9). A significant body of research focuses on the application of Peltier cooling systems, including portable air conditioning units (10) liquid heat exchangers with pumps (11) and portable O-REF (oven-refrigerator) applications (12). Additionally, thermoelectric technology is being explored for energy harvesting applications, such as gas turbine sensing and monitoring systems (13), as well as recovering waste heat from engines and vehicle exhaust systems for electricity generation (14, 15). Furthermore, researchers are investigating the impact of different electrical connection methods for multiple Peltier cells to enhance thermal performance efficiency, particularly in applications requiring more effective heat transfer (16, 17).

Several studies have explored the application of thermoelectric cooling technology in various cooling systems. Mirmanto et al. 2019 (18) focused on analyzing the impact of varying fluid flow rates on the cooling capacity and coefficient of performance (COP) of a thermoelectric cooling system. Two thermoelectric modules were used, with water as the working fluid. The experiment began at an initial water temperature of 25°C and was conducted over a period of 5 hours. During the experiment, water mass flow rates were set at 1 g/s, 1.5 g/s, and 2 g/s, with temperature measurements recorded every 10 seconds. The results indicated that the lowest temperature achieved was 19.43°C at a flow rate of 1 g/s. The study concluded that, while thermoelectric cooling systems offer certain advantages, their effectiveness in cooling flowing water is limited when compared to their performance with stationary (static) liquids. A cooling system developed using thermoelectric cooling chips to cool water and generate chilly air. The system, which incorporated two thermoelectric cooling chips, was evaluated over a five-minute operation period using three

different cooling media: water, water with 30% alcohol, and water with 50%. The findings showed that the water-alcohol mixture with 50% alcohol achieved the most significant temperature reduction, from 22.7°C to 19.1°C, proving the system's potential for energy-efficient cooling compared to conventional air conditioners. Mushonga et al. (19) successfully designed a thermoelectric cooling system that reduced the temperature of 10 liters of water from 30°C to 10°C within 20 minutes using four Peltier units. The study highlighted the system's efficiency in achieving rapid cooling while perfecting energy consumption, making it a practical solution for applications requiring localized high-efficiency cooling. Abdulghani (10) focused on improving the cooling efficiency of TEC-12706 thermoelectric air coolers by analyzing the effect of the number of units used. The study evaluated different numbers of chillers (1, 2, 3, and 4), along with the thermal performance of each case. The first temperature was 35°C, and a total of 16 tests were conducted to ensure accuracy. Each test lasted 10–30 seconds. The data obtained showed that the system was capable of achieving a temperature reduction of 10–15°C, depending on the number of chillers. Using four chillers achieved the best balance between thermal and economic efficiency, making this number best. The study concluded that increasing the number of chillers improves the coefficient of performance (COP) and reduces operating costs. However, beyond a certain point, economic returns may decline due to increased electrical energy consumption. Adref et al. (20) examined the performance of thermoelectric cooling units in reducing water temperature and storing cooling energy. Experiments conducted in a 10-liter water tank using three Peltier cooling units over 20 minutes proved that increasing the number of cooling units enhanced both temperature reduction and cooling efficiency. Specifically, with three cooling units, the water temperature dropped from 9.0°C to -10.0°C, highlighting the system's suitability for industrial and electronic cooling applications. Ab Rahman et al. (21) developed and evaluated a thermoelectric cooling box using two Peltier units connected in parallel to enhance cooling performance. The cooler reached its maximum cooling effect within 90 minutes and was evaluated under two conditions: empty and filled with soft drinks. The results showed that when empty, the cooler achieved a temperature reduction from approximately 30°C to 18°C, suggesting that increasing the number of Peltier units could further improve efficiency. Redho et al. (22) explored the impact of integrating ice packs into a Peltier-based cooler. The experiments, conducted over two hours, evaluated three configurations: Peltier-only cooling, Peltier combined with ice packs, and Peltier with ice packs and frozen food. The results showed that the combination of Peltier units and ice packs significantly

improved cooling efficiency, with temperatures reaching -6.7°C when operational and stabilizing at -3.5°C after being turned off. This study highlights the potential of hybrid cooling solutions for preserving perishable goods.

Traditional cooling methods struggle to manage heat in compact electronic circuits, particularly under high thermal loads. There is limited investigation into how varying the number of thermoelectric cooling (TEC) units and using different refrigerants affects thermal performance and energy efficiency under real-world conditions. The reviewed studies highlight the advantages of thermoelectric cooling (TEC), including high cooling efficiency, rapid response, low energy consumption, and compatibility with other cooling technologies to enhance performance. Its applications extend from electronics and industrial cooling and eco-friendly air conditioning, making it a promising solution for modern cooling challenges.

1. The current work differs from the work done by Mirmanto et al. (18) in that it uses a static coolant instead of a moving one.
2. The design in the current work consists of two parts: the first part cools the coolant, as reported in literature (10), and the second part cools the air.
3. In terms of coolant usage, this work differs from literature (20-22), which used only water. The current work uses different coolants based on distilled water and A 50:50 mixture of distilled water and mono ethylene glycol.
4. The current work is also similar to work conducted by Mushonga et al. (19) in terms of selecting the best number of thermoelectric coolers to achieve the best balance between thermal and economic efficiency.

Therefore, the current study will complement the features proposed by earlier studies and propose a new contribution to electrical and electronic circuits cooling technology. The most important feature of this proposed work is the use of a coolant that is mainly based on a mixture of mono ethylene glycol with distilled water in a 50:50 ratio. The study conducted a thermal analysis under realistic conditions to prove the effect of the TEC number and type of accompanying coolant refrigerant on the thermal performance system.

More details about this research are explained in the following sections: Section 2 is devoted to the proposed model and materials employed in the experiment. The mathematical formulation in section 3. Section 4 presents the results and discussion. Finally, section 5 concludes the paper.

2. PROPOSED MODEL

The increase in energy consumption of conventional air conditioning systems highlights the need for more sustainable and efficient cooling solutions. Earlier

studies have shown the importance of finding innovative alternatives to address this issue. Promising solutions include the use of Peltier units, which have proven their efficiency by adding more units, improving thermal insulation, using cooler cooling water, and using alcohol in cooling systems, as they can enhance cooling efficiency while keeping temperature stability and reducing fluctuations. Aluminum radiators and water-cooled systems have also been shown to be essential elements for improving thermal efficiency and providing better performance for thermoelectric cooling units. In this context, this research proposes the design of an air conditioning system using different numbers of Peltier elements instead of a compressor, in addition to using two types of liquids instead of gases used in conventional air conditioning systems. The cooling ability and coefficient of performance of this proposed system will be calculated, with an attempt to reduce electrical energy consumption.

2. 1. Materials Employed in the Experiment
This section delineates the components utilized in the fabrication of the air conditioning system, which fundamentally comprises a thermally insulated aluminum reservoir with a capacity of 1000 ml of liquid, a heat exchanger, fans for the intake of hot air and the expulsion of cold air, and thermoelectric units for liquid cooling. It functions within a closed-loop system and is powered by a 12-volt, 50-amp power source, as shown in Figure 1.

All tests were conducted manually to determine the optimal coolant type and the requisite number of cooling units that maximize performance while minimizing
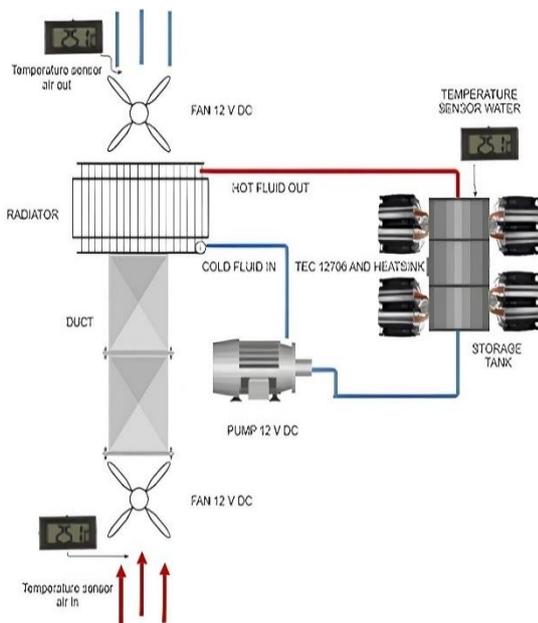
energy usage. Subsequently, the automatic control process is transitioned to a selected controller that precisely regulates the temperature. Programmable logic controllers were used due to their high precision and rapid reaction to temperature regulation.

2. 1. 1. Cool Box   The cooling box used in the design consists of dimensions (40 cm, 30 cm, 21 cm). It is designed for electrical and electronic applications, in addition to two pipes with a diameter of 59.4 mm to draw hot air from inside the electrical and electronic distribution board and push cold air. The dimensions of the box were chosen to be compatible and sufficient for all components of the air conditioning device, as shown in Figure 2.

2. 1. 2. Supply Unit   The electrical power supply the single phase power supply which is passes through the switched mode power supply. The unit is used for the rectification of 230 volt AC power supply into 12 and 24 volt DC power supply. For the 12 V DC power source as shown in Figure 3, it is used to operate the (TEC- 12706) and the rest of the system components.

2. 1. 3. Thermoelectric Cooling Module   When Alessandro Volta discovered that temperature changes can produce thermoelectric forces in 1794, the idea of thermoelectric cooling was born (23, 24). TECM is a device based on the "Peltier effect", discovered in 1834, where he discovered that when a direct current source is applied to thermometers. There is a temperature
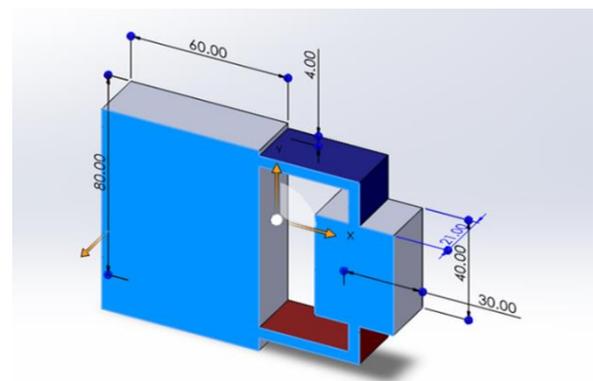

Figure 2. SolidWorks modeling design

Figure 1. Description of the proposed method

Figure 3. Power supply

difference between the n and p junctions. Whenever there is a flow of electricity, heat is absorbed from one side called the cold part, and is released in the other side called the thermal junction (25, 26) as shown in Figure 4 and Table 1.

2. 1. 4. Type of Heat Sink and Fan Heat sinks are an important part of the electrical circuit operation, microelectronics, and thermal management that affect the heat dissipation of the environment. In the present work, the hot side of the Peltier was cooled by copper tubes distributed on the hot wall and connected to aluminum heat sinks. The heat exchanger consists of a finned radiator around a tube charged with a refrigerant, it is a passive heat exchanger designed to has a large surface area so that the air is contacting with the surrounding cooling medium. The flow of the cooling medium through the structure of the heat sink vanes helps to improve the setup and thus decrease the resistance and allow more air to pass through the heat sink. The performance of the heat sink is also governed by the shape and design of its fans, as optimizing the shape and size of the fins helps maximize heat transfer density, as demonstrated in Figure 5. The fan has dimensions of (9 cm * 9 cm * 2.5 cm). These fans operate on a 12V DC voltage and a current rate of 0.24 A, where fans that dissipate hot air.

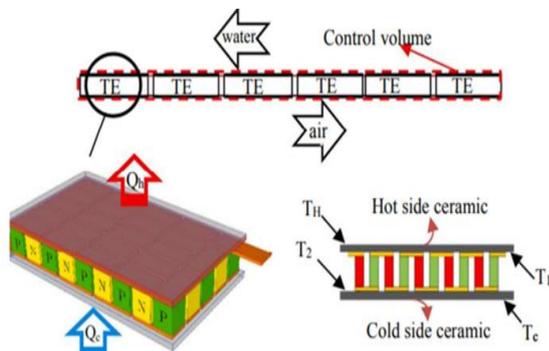**2. 1. 5. Fluid Pump** In this work, a DC water pump was used, which is a low-voltage electric pump, is quiet

Figure 4. Thermoelectric Cooling Module

TABLE 1. Peltier's Specifications (27)

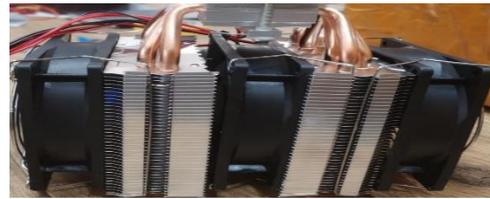| Model	TEC1-12706
Operating Voltage	12 V (DC)
V_{MAX}	15V (DC)
I_{MAX}	4-6 A
ΔT_{MAX}	67 °C
Dimension	4*4*3.9 cm
Qc $_{(max)}$	48-72 W

Figure 5. Heat Sink and fans

and uses little power, and is designed to transfer fluids efficiently. It usually features brushless motors, which provide longer life and reliable performance, as shown in Figure 6.

2. 1. 6. Type of Fluid

2. 1. 6. 1. Distilled Water It is used in many vital and industrial fields because it is free of impurities, salts, and minerals that may affect the performance of processes or the quality of the product.

2. 1. 6. 2. Fluid (Distilled Water and Mono Ethylene Glycol 50:50) It is a widely used industrial chemical compound, also known as ethylene glycol. It is a 50:50 mixture of ethylene glycol with deionized water plus advanced chemical inhibitors and laser dyes to protect against freezing, overheating, rust, and corrosion. It provides effective protection for all metal surfaces in engine radiators and cooling systems, including those made of aluminum. It comes in ready-to-use form.

2. 2. Method and Conditions of the Experiment and Testing When integrating all the components, a functional cooling system is built, as shown in Figure 7, which shows the complete integration of the proposed system. Briefly, the process starts with filling the liquid from the hose into the right storage tank, where the liquid flows through the water pump and enters the water tank. In this tank, the cooling process is mainly performed by the Peltier element. The cooled liquid exits the tank and flows through the heat exchanger (radiator). This cycle runs continuously, with a temperature sensor inside the tank to check the current temperature during system operation. When the temperature of the liquid inside the tank reaches the target temperature, both the pump and fans are turned on to cool the main parts of the electrical

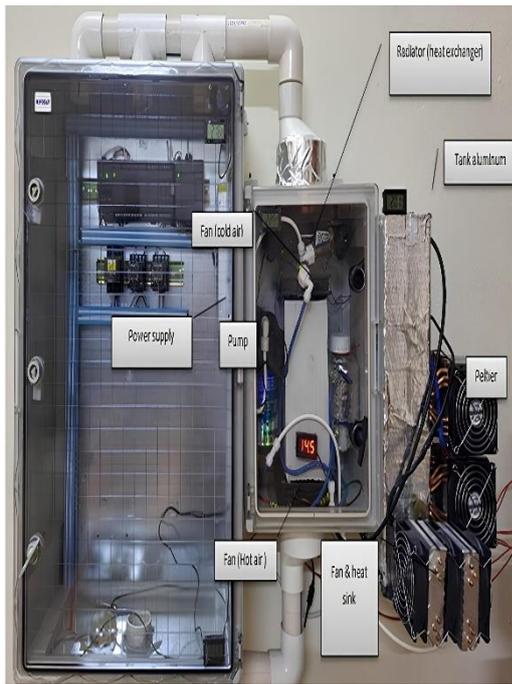| Description product	
Size	8 cm *17 cm
Voltage	12 V DC
Max pump output	120 PSI
Min inlet	30 PSI
Size	8 cm *17 cm

Figure 6. Fluid pump

Figure 7. Complete Setup of the Thermoelectric Cooling Chamber with Components

and electronic distribution board. The temperature data is recorded every minute to accurately measure the amount of its decrease.

Using the proposed design, an experiment was conducted to cool 1000 ml of various liquids, including distilled water only and a coolant having mono ethylene glycol and distilled water 50/50, using different numbers of Peltier elements electrically connected in parallel. The target temperature of the liquids was set at 8 °C, and the experiment focused on achieving the main goal of reducing the temperature of the electrical and electronic distribution board to below 50 °C. Readings were recorded at regular intervals of 1 minute to evaluate the efficiency of the system and the extent to which the desired goals were achieved.

2. 3. Performance Indicator   This section proposes a simplified ideal equation for thermoelectric coolers, along with various theories to realize their potential. The largest parameters include maximum current, temperature difference between hot and cold junctions, maximum cooling capacity, maximum voltage, and coefficient of performance (COP) analysis, the equations for heating and cooling of TEM are introduced, and then it is explained how the required parameters of those equations can be estimated from the characteristics found in commercial datasheets of TEM. Thermoelectric consists of a series of 2 N pellets of two different semiconductor materials (p and n type), consisting of N thermoelectric couples that are connected

electrically in series and thermally in parallel, the air-cooled system is analyzed using a simple method to decide the heat transferred theoretically and experimentally, where the energy consumed by the system and the maximum performance factor can be calculated (28). The amount of heat transferred from the cold surface (qc) of the Peltier unit (TEC) is of immense importance. qc can be calculated by finding the mass flow rate of the fluid, the specific heat capacity of the fluid, and the temperature difference. The temperature difference is the temperature difference between the cooling part of the Peltier unit and the energy consumed by the Peltier unit, four main types of heat transfer processes, including Peltier heating (qph), Peltier cooling (qpc), Joule heating (qj), and Fourier heating (qcon) involved in thermal evaluations of TEM, which are calculated in Equations 1-19.

$$q_{pc} = \alpha_m \times I \times T_c \tag{1}$$

$$\alpha_{ph} = \alpha_m \times I \times T_h \tag{2}$$

$$q_j = R_m \times I^2 \tag{3}$$

$$q_{con} = \frac{1}{\theta m}(T_h - T_c) \tag{4}$$

The energy balance between Equations can calculate the cooling and heating ability of any individual TEM. 1-4 (29).

$$q_c = q_{pc} - \frac{1}{2}q_j - q_{con} = \alpha_m \times I \times T_h - \frac{1}{2}R_m \times I^2 - \frac{1}{\theta m}(T_h - T_c) \tag{5}$$

$$q_h = q_{ph} - \frac{1}{2}q_j - q_{con} = \alpha_m \times I \times T_h + \frac{1}{2}R_m \times I^2 - \frac{1}{\theta m}(T_h - T_c) \tag{6}$$

It requires α_m (Average Seebeck coefficient of the module), Rm (Electrical resistance of the module), and (thermal resistance of the module), thermal resistance of the module parameters in Equations 5 and 6. N, Imax, Vmax, qmax, ΔTmax, and Tref are specifications usually adopted in commercial datasheets. ΔTmax is the maximum temperature difference (ΔTmax) that can be achieved between the cold and hot sides of a thermally insulated TEC for a specified Tref value (temperature of hot side) Imax and Vmax are the input current and voltage that produce the ΔTmax across a TEC. qmax = is the maximum amount of Heat (W) that can be absorbed in a cold plate of TEC at Imax and ΔT = Zero. It should be noted that qmax is not the largest possible amount of heat that can be managed by TEC. Qmax is only the heat flow corresponding to the current qmax. α m, Rm, and can be evaluated from the equations below, and then can be used in Equations 5 and 6.

$$\alpha_m = \frac{V\,max}{T\,h\,(ref)} \tag{7}$$

$$R_m = \frac{Vmax}{I\,max} \times \frac{(Th - \Delta\,Tmax)}{Th\,(ref)} \quad (8)$$

$$\theta m = \frac{1}{Km} = \frac{\Delta T\,max}{Vmax\,Imax} \times \frac{2\,T\,h}{Th\,(ref) - \Delta T\,max} \quad (9)$$

Other parameters, including surface temperatures, DC voltage, and electrical current, inlet/outlet temperatures, flow rates, and so on, were directly measured during the experiments. Hence, the amount of qc, qh, Tc, and Th for the entire system is evaluated from the following equations, in which the index "i" stands for any individual TEM module. qci and qhi are calculated by Equations 5 and 6 (30).

$$T_c = \frac{\sum_{i=1}^{n} Tci}{6} \quad (10)$$

$$T_h = \frac{\sum_{i=1}^{n} Thi}{6} \quad (11)$$

$$q_c = \sum_{i=1}^{n} q_{ci} \quad (12)$$

$$q_h = \sum_{i=1}^{n} q_{hi} \quad (13)$$

"P_1" is the input energy consumed by TEM and can be found from Equations 14.

$$P_1 = I \times V \quad (14)$$

Heat transfer rate absorbed/dissipated by fluid flows can be calculated from Equations 15 (31).

$$q_{w,\,cold\,side} = \dot{m}_{w,\,cold\,side} \times C_{p,\,fluid} (T_{w,\,inlet} - T_{w,\,outlet}) \quad (15)$$

In addition to calculating Qair by finding the mass flow rate of air, the specific heat of air, and the temperature difference. Here, the temperature difference is the difference in air temperature and the amount of energy consumed (for fans and pumps) (32).

"P2" is the input energy consumed by (pump + fans) and can be found from Equation 16.

$$P_2 = I \times V \quad (16)$$

Heat transfer rate absorbed and dissipated by fluid flows can be calculated from Equations 17 and 18 (23).

$$\dot{m}_{a(Mass\,flow\,rate\,of\,air)} = S \times \rho \times A \quad (17)$$

$$q_r = \dot{m}_r \times C_{p,\,air} (T_{r,\,inlet} - T_{r,\,outlet}) \quad (18)$$

The coefficient of performance of any cooler is defined by Equation 19 (33).

$$COP_{total} = \frac{qw + qr}{p1 + p2} \quad (19)$$

3. RESULTS AND DISCUSSION

3. 1. Effect of Distilled Water with Several Peltier Units   The cooling performance was studied using different Peltier configurations (1, 2, 3, and 4) with two types of fluids: distilled water only and Coolant

containing mono ethylene glycol and distilled water 50:50. The results showed a large variation in cooling rates and system behavior, which affected performance efficiency and energy consumption. When using 1000 ml of distilled water to reduce its temperature from 21.5 °C to 8 °C, it was found that one Peltier unit did not achieve the target even after three hours, as the maximum temperature that could be reached was 12.8 °C, leading to its exclusion. Using two Peltier units, the desired temperature was reached in 40 minutes at a cooling rate of 0.3375 °C/min, demonstrating moderate performance with an energy consumption of 323.712 kJ. Using three units, the time was reduced to 30 minutes at a cooling rate of 0.45°C/min with an increase in energy consumption of 364.176 kJ. With four units, the target temperature was reached in 20 minutes at a faster cooling rate of 0.675 °C/min, with an energy consumption of 323.712 kJ, Figure 8 shows the three cases of distilled water cooling operations.

After achieving the target temperature, the air-cooling system was fully operated inside the electrical and electronic distribution board, which had an initial temperature of 50 °C. With two units, the air temperature dropped to 41.1 °C in the first minute and continued to drop to 33.3 °C in 4 minutes, with an energy consumption of 5.0976 kJ. After that, the temperature remained constant without change. With three units, the air temperature dropped sharply in the first minute to 40.1 °C, then gradually to 30.3 °C in 5 minutes, with an energy consumption of 6.372 kJ. With four units, the air temperature dropped significantly from 50 °C to 37 °C in the first minute, and continued to 30.1 °C in 8 minutes, with an energy consumption of 10.1952 kJ. Figure 9 shows the three cases of cooling operations of the electrical and electronic distribution board.

When calculating the total energy consumption, two Peltier units consumed 328.809 kJ, while three units consumed 370.548 kJ, an increase of 12.693%. In contrast, four units consumed 333.9072 kJ, a decrease of
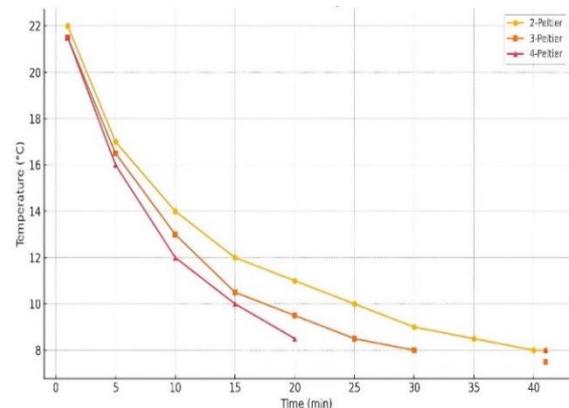

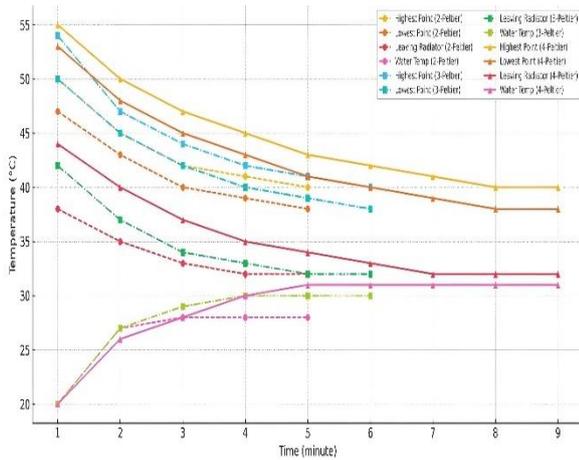**Figure 8.** Effect of Time on Distilled Water Using 2, 3, and 4 Peltier Modules

Figure 9. Effect of Time and Location on Temperature (Combined Peltier Units)

10.97% compared to three units. Figure 10 shows the relationship between energy consumption and the number of thermoelectric cooling units in terms of time.

The experiments showed a clear effect of the number of Peltier units on cooling rates and energy efficiency. Using two units, the water temperature decreased to 8 °C in 40 minutes and the air temperature to 33.3 °C with a coefficient of performance of 0.5792. Using three units, the performance improved, as the target temperature was achieved in 30 minutes with the air temperature decreased to 30.3 °C and the coefficient of performance increased to 0.6685. When using four units, the desired temperature was reached within 20 minutes and the air temperature dropped to 30.1°C, with a performance coefficient of 1.16496. These results confirm that increasing the number of Peltier units improves the cooling speed and performance efficiency, while taking into account the increased power consumption to achieve the desired balance.
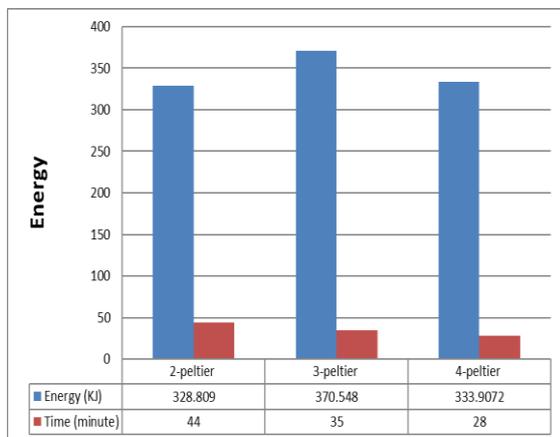
3. 2. Effect of Coolant Having (Distilled Water and Mono ethylene glycol 50:50) with the Number of Peltier Units

After draining the distilled water, the experiment was repeated using mono ethylene glycol and the same amount of liquid used previously (1000 ml) to reduce its temperature from 21.5 °C to 8 °C. It was found that a single Peltier unit did not achieve the target temperature even after three hours, as the maximum temperature reached was 10 °C, which led to its exclusion. Using two Peltier units, the desired temperature was reached in 23 minutes at a cooling rate of 0.586 °C/min, with an energy consumption of 186.1344 kJ. Using three units, the time was reduced to 17 minutes at a cooling rate of 0.7941 °C/min, with an increase in energy consumption of 206.346 kJ. With four units, the target was achieved in 14 minutes at a high cooling rate of 0.9642 °C/min, with an energy consumption of 226.5984 kJ. Figure 11 shows the three cases of cooling processes (distilled water and Mono Ethylene Glycol 50:50).

After achieving the target temperature, the entire air-cooling system inside the electrical and electronic distribution board was turned on, the first temperature of which was 50 °C. With two units, the air temperature dropped to 36.8 °C in the first minute, and later reached 31.3 °C in 7 minutes, and consumed 7.6464 kJ of energy.

With three units, the air temperature dropped sharply to 36.5 °C in the first minute, and later reached 29.4 °C in 11 minutes, and consumed 12.744 kJ of energy. With four units, the air temperature dropped to 35.1°C in the first minute, then to 26.9°C in 18 minutes, consuming 22.9392 kJ of energy. Figure 12 shows the three cases of cooling operations of the electrical and electronic distribution board.

When calculating the total energy consumption, two Peltier units consumed 193.780 kJ, while three units consumed 219.09 kJ, an increase of 13.0612%. In contrast, four units consumed 249.537 kJ, an increase of
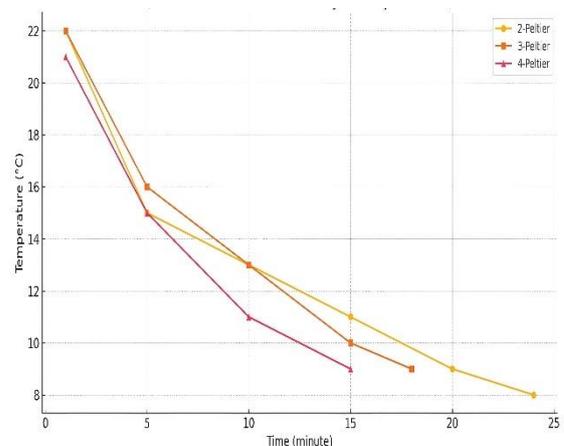

Figure 10. Relationship of energy consumed with the number of thermoelectric cooling units in terms of time (distilled water)

Figure 11. Effect of Time on Temperature (Distilled Water and Mono Ethylene Glycol 50:50)

13.897% compared to three units. Figure 13 shows the relationship between energy consumption and the number of thermoelectric cooling units in terms of time.

The experiments showed a clear effect of the number of Peltier units on cooling rates and energy efficiency. With two units, the water temperature dropped to 8°C in 23 minutes and the air temperature to 30.3°C with a coefficient of performance of 1.5402. With three units, performance improved, with the target temperature achieved in 17 minutes with the air temperature dropping to 29.4°C and a coefficient of performance increasing to 2.2231. With four units, the target temperature was achieved in 14 minutes with the air temperature dropping to 26.9°C, with a coefficient of performance of 3.75811. These results confirm that increasing the number of Peltier units improves cooling speed and performance efficiency, considering the increased energy consumption to achieve the desired balance.

3. 3. Cooling System Performance Using Distilled Water Compared to (Distilled Water and Mono ethylene glycol 50:50)   Overall, performance
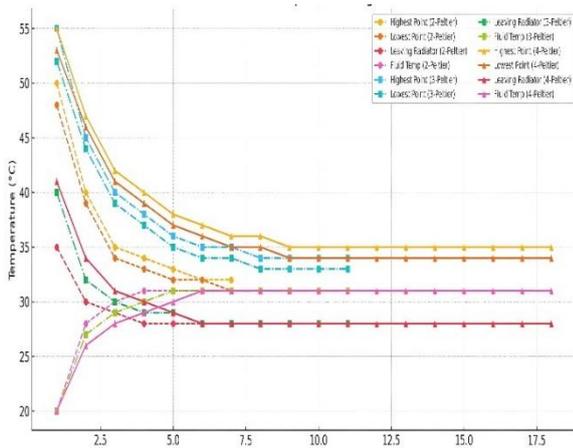

Figure 12. Effect of Time and Location on Temperature using 2, 3, and 4 Peltier Units.
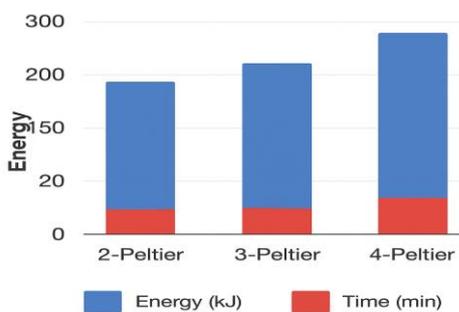

Figure 13. Relationship of energy consumed with the number of thermoelectric cooling units in terms of time (Distilled Water +Mono ethylene glycol 50/50)

than Coolant, having mono ethylene glycol, especially when measuring cooling rate, performance factor, and energy consumption. Using a solution containing mono ethylene glycol has a lower specific heat capacity than water, but it offers greater thermal stability and better resistance to boiling and freezing. This combination provides a balance between rapid heat absorption and its ability to transfer heat to the Peltier cooling unit without significant loss. This helps reduce heat loss and stabilize system performance. Increasing the number of Peltier units improves cooling speed and lowers air temperatures, but keeps average performance efficiency, except when using four units, in addition to noting that the energy consumption for using three Peltier units is higher than using four units with a low performance factor. In terms of overall performance using mono ethylene glycol, mono ethylene glycol outperforms pure water in terms of cooling speed, energy efficiency (performance factors), and energy consumption, as shown in Figure 14.

Increasing the number of Peltier units with mono ethylene glycol significantly improves performance, making it the preferred choice for applications that require fast and efficient cooling, as shown in Figure 15.
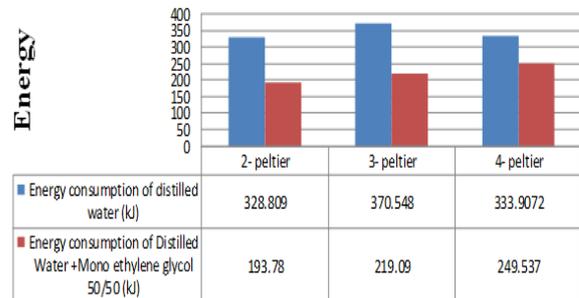

Energy	2- peltier	3- peltier	4- peltier
Energy consumption of distilled water (kJ)	328.809	370.548	333.9072
Energy consumption of Distilled Water +Mono ethylene glycol 50/50 (kJ)	193.78	219.09	249.537

Figure 14. Relationship of energy consumption to the number of thermoelectric cooling units in terms of fluid type
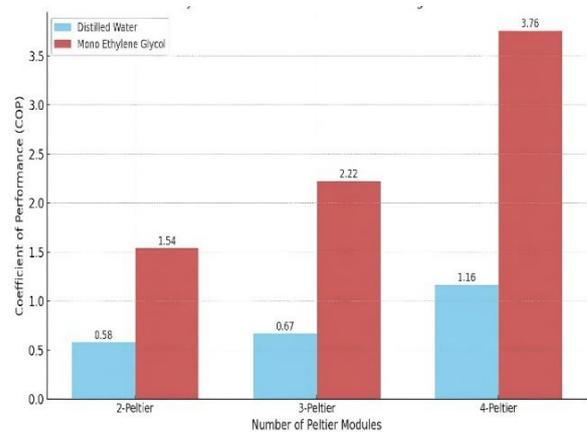

Figure 15. Relationship of the coefficient of performance with the number of thermoelectric cooling units in terms of fluid type

4. CONCLUSIONS AND FUTURE PERSPECTIVES

In this study, the use of a 50:50 mixture of distilled water and mono ethylene glycol proved superior cooling efficiency and energy consumption compared to distilled water, resulting in faster temperature drops and higher performance factors in all tested configurations. These findings underscore the significant impact that coolant choice has on the thermal performance of the system. Furthermore, the results show that increasing the number of Peltier units enhances cooling rates and reduces the time needed to reach target temperatures, highlighting the need for optimization to balance cooling ability with energy efficiency. These results are consistent with findings, who proven that increasing the number of TEC modules improves the efficiency of the cooling system and the COP up to a certain point, after which the benefits decline. This agreement with earlier studies reinforces the current study's findings, which emphasize the need to balance the number of modules and the COP. The cooling process showed two distinct phases: a rapid first temperature drops within the first minute, followed by a more gradual decline. This pattern was consistent across all configurations, emphasizing the critical role of first cooling rates in deciding the overall performance of the system. Systems using a 50:50 mixture of mono ethylene glycol and distilled water consistently outperformed those using distilled water alone, particularly when using four Peltier modules, where the coefficient of performance peaked at 3.75811. The study underscores the importance of perfecting both the coolant and the system configuration to achieve the desired thermal performance. Based on these results, a 50:50 mixture of mono ethylene glycol and distilled water is recommended for applications requiring higher efficiency and faster cooling. However, if cost constraints or reduced system complexity are prioritized, distilled water may be a suitable alternative, provided the number of Peltier modules is increased to compensate for the reduced performance.

The Peltier effect cooling system exhibited enhanced performance using a greater quantity of TEC modules and a 50:50 blend of distilled water and ethylene glycol; nonetheless, significant concerns remain inadequately solved. The study overlooked the issues associated with heat dissipation from the hot side of many Peltier modules, a characteristic that can considerably affect long-term performance and stability. Emphasis was placed on the cold side; yet, from a financial standpoint, There is a significant difference. The produced chiller is priced at $40, but traditional chillers have a market worth over $200. This is an essential analysis to evaluate economic viability as the quantity of modules escalates. Consequently, more research must concentrate on alleviating these constraints to enhance reproducibility,

broaden the range of application, and attain an improved equilibrium between performance and energy economy.

Future research should focus on exploring alternative coolants, advanced thermal management systems, and conducting detailed energy consumption analyses to further enhance system efficiency. Additionally, further optimization of system configurations could offer added insights into improving the balance between performance and energy usage.

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Persian Abstract

چکیده

اثربخشی رویه‌های مدیریت حرارتی، نکته‌ای حیاتی برای حفظ عملکرد و طول عمر بردهای الکترونیکی و الکتریکی محسوب می‌شود. یکی از راه‌حل‌هایی که توجه محققان و مؤسسات صنعتی را به خود جلب کرده است، استفاده از خنک‌کننده ترموالکتریک (TEC) است که با نام Peltier نیز شناخته می‌شود و از دو ماده نیمه‌هادی برای پشتیبانی امیدوارکننده از خنک‌کننده هوای فن‌دار سنتی ساخته شده است. با این حال، بررسی دقیق‌تری از تأثیر استفاده از فناوری Peltier در شرایط تغییر عملیاتی و طراحی مورد نیاز است. در همین راستا، این مطالعه یک مدل نمونه اولیه تجربی را برای تجزیه و تحلیل تأثیر تعداد مختلف واحدهای Peltier (۱ تا ٤) و مبردهای مختلف (فقط آب مقطر، مونو اتیلن گلیکول و آب مقطر ۵۰:۵۰) بر عملکرد پیشرفت حرارتی از نظر جذب حرارتی و مصرف انرژی بررسی می‌کند. تحت عملیات واقعی متغیر، نتیجه نشان داد که مخلوط (آب مقطر + مونو اتیلن گلیکول ۵۰:۵۰) عملکرد بهتری نسبت به آب مقطر به تنهایی دارد، کاهش دمای کابینت الکتریکی سریع‌تری را به دست آورد و عملکرد خنک‌کننده (COP) بالاتری را در تمام مدل‌های پیکربندی Peltier به دست آورد. بالاترین ضریب عملکرد (COP) معادل ۳٫۷۵ با استفاده از چهار واحد پلتیر با مخلوطی از مونو اتیلن گلیکول ثبت شد. این یافته‌ها بر اهمیت انتخاب بهترین مبرد و پیکربندی سیستم برای مدیریت حرارتی کارآمد تأکید دارند و راه را برای پیشرفت‌های آینده در فناوری‌های خنک‌کننده ترموالکتریک هموار می‌کنند.