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Design and Experimentation of Peltier-Based Thermoelectric Cooling Vaccine Carrier Box

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***Abstract*—Vaccines are typically administered during routine immunization programs, with a critical focus on maintaining a cold chain system. The cold chain system plays a pivotal role in ensuring the efficacy of vaccines. In this paper, a portable solar-powered vaccine carrier box based on the Peltier Effect for effective vaccine cooling is designed and experimented with. The system has four 12V DC 3.5A Thermoelectric Cooler (TEC) Peltier Modules, with strategically positioned heat sinks outside the cooling box. Additionally, the setup incorporates a 12V 180W Solar Panel for daytime power generation and eight Rechargeable Li-Po 3.7V 4500mAh batteries for uninterrupted operation for 3 hours. The experimentation involved three distinct conditions. Firstly, a gradual temperature decrease was observed in the empty cooling box. Secondly, with the introduction of 10 sterile glass vaccine tubes filled with water, the temperature decreased more slowly, reaching 15°C in 62 minutes and 8°C after 90 minutes. Lastly, with 6 vaccine tubes, it took approximately 55 minutes to reach 15°C and about 90 minutes to achieve the desired 8°C temperature. The system exhibits a Coefficient of Performance of 0.42. The results emphasize the efficient cooling performance of the developed storage system, highlighting its capability to maintain temperatures below 15°C, a critical factor in preserving vaccines.**

***Index Terms*—Thermoelectric Cooler, Peltier Effect, Coefficient of Performance, Heat Sink, Solar Panel, Cold Chain System.**

I. INTRODUCTION

In rural areas of Pakistan, infectious diseases pose a significant threat to the lives and well-being of infants and young children, leading to high mortality rates and disabilities. The most cost-effective strategy for preventing these infectious diseases is through vaccination. Vaccines are typically administered during routine immunization programs, with a critical focus on maintaining a cold chain system. The cold chain system plays a pivotal role in ensuring the efficacy of vaccines. It involves properly storing and transporting vaccines from the manufacturer to the patient and maintaining a specific temperature range to keep the vaccines effective [1].

The traditional cold storage system faces operational challenges, including mechanical friction and power quality issues, leading to increased energy demand and greenhouse gas emissions [2]. The development of portable thermoelectric cooler facilities powered by renewable energy sources is essential to address these issues and ensure safe, energy-efficient vaccine transportation. These facilities can help mitigate climate change by reducing carbon emissions. Thermoelectric coolers, which operate based on the Peltier effect - a solid-state method of heat transfer using dissimilar semiconductor materials- offer advantages such as the absence of moving parts, no liquid circulation, and zero hazardous gas emissions [3]. Unlike conventional refrigeration systems, which rely on evaporators, condensers, and compressors, thermoelectric cooling systems operate with three main components: a cold junction, a heat sink, and a DC power source. Instead of a refrigerant, two dissimilar conductors are used, and heat is absorbed and transferred by the movement of electrons between semiconductor materials. N-type and P-type semiconductors with specific electron properties play a crucial role in this process. They transfer heat from hot to cold regions using semiconductor-based Peltier modules, which operate on the Seebeck effect principle, making them a solid-state method for heat transfer, typically using materials like bismuth telluride. This unique technology enables refrigeration without traditional refrigerants or mechanical devices, offering an efficient cooling method [4].

The thermoelectric cooling system, constructed from two dissimilar semiconductor materials, can provide cooling or heating by leveraging the temperature differential between their junctions when an electric current passes through them. This technology offers several advantages, including lower maintenance requirements, reduced environmental impact due to the absence of refrigerants, and greater energy efficiency in specific cooling applications [5]. Additionally, Peltier-based refrigeration systems can be compact and versatile, making them suitable for a range of scenarios, from portable coolers to medical equipment and electronics cooling, where precision temperature control is crucial. Consequently, thermoelectricity with Peltier modules holds the potential to revolutionize the refrigeration industry by offering a more sustainable and efficient cooling solution.

Recent scientific research has placed significant emphasis on the design and development of Peltier-based thermoelectric cooling storage systems. In [6], the focus is on the geometric optimization of thermo-elements within a thermoelectric cooler to enhance cooling capacity and coefficient of performance. This optimization effort emphasizes the identification of optimal module thickness and operating current values, factors that are influenced by considerations such as overall heat dissipation and external thermal resistances. The adjustment of the cross-sectional area of pellets as a method to precisely regulate the operating current and voltage of a thermoelectric module is discussed in [7]. Several studies have proposed and tested different designs and configurations of thermoelectric cooling storage boxes using Peltier modules. The main factors that affect the performance and efficiency of the storage box are the size, shape, material, and arrangement of the Peltier module, the heat sink, the fan, the insulation, and the phase change material [8]. The experimental results show that the thermoelectric cooling storage box can achieve a temperature range of 5 °C to 25 °C, depending on the ambient temperature and the load [9]. Rudresha et al. in 2023 utilized ANSYS Workbench and CFD software to optimize thermoelectric refrigeration systems, emphasizing modifications in insulating materials and internal design, ultimately revealing a substantial 9.4 °C temperature difference for the sharp edge design with nickel insulation and underscoring the profound influence of design changes on system performance [10]. The impact of changing the cross-sectional area of the thermo-elements in the cooling box on both the maximum cooling capacity and the maximum achievable coefficient of performance is discussed in [11]. The study in [12] addresses several critical factors concerning thermoelectric cooler (TEC) design to employ a genetic search method to optimize the most optimum dimensions for the TEC, ultimately seeking to enhance TEC performance and efficiency. Siddique et al. in 2023 improved solid-state thermoelectric cooling by integrating phase change material (PCM), finding that its incorporation not only increased cooling capacity but also enhanced storage volume, presenting a promising performance for the advancement of thermoelectric refrigeration systems [13].

In [14], a small thermoelectric Peltier cooler (20 x 26 x 18 mm) is designed using a Peltier thermoelectric cell between external and internal heat sinks, allowing efficient heat removal from a refrigeration box. The cooler achieved a coefficient of performance (COP) exceeding 0.5, efficiently lowering the temperature within the cooler box from the ambient temperature to 18.5°C while dissipating 25W of heat. A thermoelectric refrigerator, utilizing the Peltier effect, was specifically designed to run on solar energy while effectively maintaining a temperature range between 2°C and 8°C, exhibiting an average COP value of 0.004 [15]. In 2021, Afshari conducted a comparative analysis of air-to-water and air-to-air thermoelectric coolers utilizing Peltier elements. His findings revealed that the air-to-water mode exhibited a superior Coefficient of Performance (COP) compared to the air-to-air mode, with a notable increase of 30–50% [16]. In [17], the design of a portable mini thermoelectric cooler is discussed that employs the Peltier Effect for optimizing the operational conditions, particularly fan voltages for the thermoelectric cooler, and conducts performance analysis, including the coefficient of performance (COP), to determine the most efficient operating conditions. A thermoelectric cooler (TEC) is utilized in [18] to directly control the temperature within a thermoelectric cooler by circulating cooling water through two aluminum blocks. The research centers on analyzing the impact of heat sink temperature, flow rate, and current via calculations, ultimately achieving a coefficient of performance (COP) of 0.73. The experimental data in [19] demonstrated the effectiveness of a thermoelectric cooling system when used as a cooling box, both with and without products to be cooled. In both scenarios, there was an average temperature difference of 4.86°C after 90 minutes. This study in [20] explores the performance of a portable thermoelectric cooler (TEC) box using the Peltier effect and air-cooling heat sink, with a cooling capacity of 22 litres. The research investigates the thermal performance of the TEC under varying input power levels (50.5W, 72.72W, and 113.64W) and cooling loads (1440 mL and 2880 mL at 113.64W input power). The results indicate that as input power increases, the box temperature decreases, albeit at the cost of reduced coefficient of performance (COP), as higher input power absorbs more energy. In terms of cooling load, a greater cooling load leads to longer temperature stability in the box, as more energy is required to lower the box's temperature.

This paper discusses the design of a portable solar-powered vaccine carrier box, emphasizing utilizing the Peltier Effect for effective vaccine cooling. The first step involved assessing the cooling capacity required for this application, considering the availability of Thermoelectric Cooling (TEC) Modules with varying voltage, current, and heat extraction capabilities. To cool the hot side of the vaccine holder, a heat sink and fan assembly were employed, chosen over water cooling due to size and complexity considerations. An efficient heat exchanger was deemed essential for effectively cooling the TEC Module's hot surface. The design also encompassed a solar power supply, featuring photovoltaic panels, a charge controller, and batteries. The design of the cooling holder was developed in SolidWorks, with thermal analysis in Flow Simulation. MATLAB simulations were used to determine the exact dimensions of the prototype before finalizing the design in Solid Works.

II. LITERATURE REVIEW

The design of a portable solar-powered thermoelectric cooler should incorporate essential attributes for an effective cold chain delivery system. The schematic representation of the Thermoelectric Cooler Module in the proposed system is depicted as a flow chart in Fig. 1.

The design process involves several key steps, including calculating electrical power, conducting heat transfer calculations, determining the Coefficient of Performance (COP), using a mathematical model and accurately sizing the storage box dimensions. When designing the thermoelectric module, selecting material with a high Seebeck coefficient, electrical conductivity, and low thermal conductivity is crucial to achieve a high Figure of Merit (ZT) and power factor. Heat transfer losses often occur due to inadequate insulation distribution, leading to temperature loss. Therefore, optimal design selection requires choosing materials that exhibit chemical, thermal, and mechanical stability to ensure durability and environmental safety.

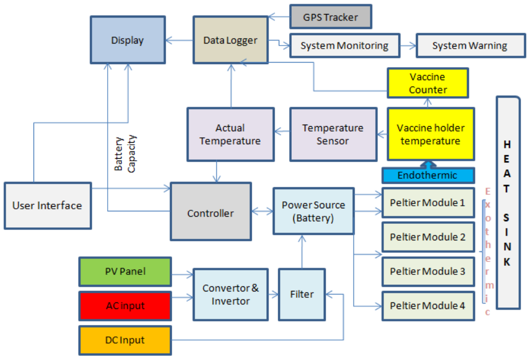

Figure 1: Functional flow diagram of Thermoelectric Cooler Module.

A. *Mathematical Model of Thermoelectric Module*

A Peltier Module is a semiconductor device composed of specific P-type and N-type materials, typically made from Bismuth Telluride (Bi2Te3). It operates by applying a DC power supply to create a temperature difference between its two sides. One side of the chip is kept at a lower temperature, while the other is maintained at a higher temperature. To enhance the efficiency of this thermoelectric cooling system, special heat exchangers and heat sinks are connected to the hot side of the chip. These components serve the dual purpose of dissipating excess heat generated during the cooling process and improving thermal efficiency.

The thermoelectric effect encompasses a collection of phenomena, which include the Seebeck effect, Peltier effect, Thomson effect, Fourier's law of heat conduction, and Newton's law of cooling.

- The Seebeck effect manifests when a temperature gradient across the junction of two distinct conductive materials generates an electromotive force (EMF) or voltage. This voltage can be harnessed to generate an electric current once the junction is electrically connected.
- Conversely, the Peltier effect is the converse of the Seebeck effect. It includes the transfer of heat from one side to the other when an electric current traverses the junction of two diverse conductive materials. This effect is instrumental in thermoelectric cooling systems for establishing a temperature differential between the two sides of the device.
- The Thomson effect characterizes the thermal changes that occur within a conductor as an electric current course through it. This phenomenon is intertwined with the Seebeck and Peltier effects and plays a role in influencing the efficiency of thermoelectric devices.
- Fourier's law of heat conduction formulates the principles governing how heat is conducted through a material. It posits that the rate of heat transfer is directly proportional to the temperature gradient and the material's thermal conductivity.
- Newton's law of cooling defines the rate at which heat dissipates from a surface to its surroundings, contingent upon a temperature difference. It frequently finds application in calculations related to heat exchange and contributes to the efficacy of heat sinks and heat exchangers integrated with thermoelectric chips.

To optimize the efficiency of a thermoelectric cooling system, specialized heat exchangers and heat sinks are affixed to the module's hot side. These components perform a dual role by effectively dissipating excess heat generated during the cooling process and enhancing the overall thermal efficiency of the cooling system. Through efficient heat management, the thermoelectric device can uphold a consistent temperature difference between its hot and cold sides, rendering it suitable for diverse cooling applications, including refrigeration and electronic device temperature control. The cooling capacity (QL) and Input power P of a Peltier thermoelectric cooler are given by (1) and (2) [21].

$$Q_L = \alpha I T_L - \frac{1}{2} I^2 R - K_t (T_H - T_L) \qquad (1)$$

$$P = \alpha I (T_H - T_L) + I^2 R \qquad (2)$$

Where

I^2R shows joule heating effect and it is irreversible,
α is the seebeck coefficient,
K_t is total thermal conductivity,
T_H is the hot end temperature of the module,
T_L is the cold end temperature of the module

Substituting the value $P = VI$ in equation 2 gives

$$V = \alpha (T_H - T_L) + IR \qquad (3)$$

Equation (3) is known as voltage balance equation of TEC. Whereas the total heat rejection equation is given by,

$$Q_H = P + Q_L$$

$$Q_H = \alpha I T_H + \frac{1}{2} I^2 R - K_t (T_H - T_L) \qquad \text{eq. (4)}$$

The Coefficient of Performance (COP) of a thermoelectric module using a Peltier module can be defined as the ratio of the heat transfer at the cold side to the electrical power input. It quantifies the efficiency of the cooling system. The COP can be expressed as:

$$COP = \frac{Q_L}{P_{in}} \qquad \text{eq. (5)}$$

$$COP = \frac{\alpha I T_L - \frac{1}{2} I^2 R - k_t (T_h - T_c)}{\alpha I (T_h - T_c) + I^2 R} \qquad \text{eq. (6)}$$

The Figure of Merit (*ZT*) for a thermoelectric module using a Peltier module is a critical parameter that quantifies its thermoelectric performance. *ZT* is a dimensionless quantity that reflects the efficiency of a thermoelectric material in converting heat into electrical power (or vice versa). A higher *ZT* value indicates better thermoelectric performance, as it suggests that the material is a more efficient heat-to-electricity converter. Achieving a high ZT value is a key goal in thermoelectric material research, as it leads to more efficient thermoelectric module. ZT is expressed as [22]:

$$ZT = \frac{\alpha^2 \sigma T}{K_t} \quad \text{eq. (7)}$$

Where,

α represents the Seebeck coefficient,
σ is Electrical conductivity,
T is the Absolute Temperature (in Kelvin), and
K_t is the Thermal conductivity.

B. Design of the Storage Box

The design of the storage box for the proposed thermoelectric cooling system considers a range of factors that ensure its optimal performance and suitability for the specific application. The design specifications for the storage box are detailed in Table 1 and visually presented in Fig. 2.

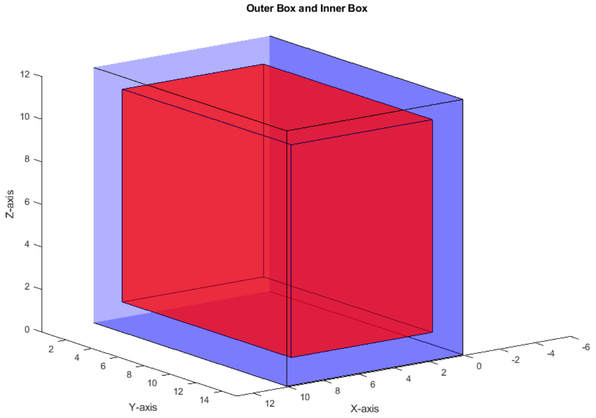

Figure 2: Dimensions of the box

Table I: Specifications of Rectangular Box

Specifications		Dimensions (cm)
Outer box dimensions	Width	10
	Height	15
	Depth	12
Inner box dimensions	Width	8
	Height	13
	Depth	10
Insulation	Width	2
	Height	2
	Depth	2

C. Experimentation

This project employs four 12V DC 3.5A Thermoelectric Cooler (TEC) Peltier Modules, known for their vibration-free and noise-free operation, with a maximum power consumption of up to 235W and a T_{max} of 70°C. These modules are used to convert electrical energy into cooling thermal energy, effectively maintaining the temperature of the vaccine stored in a polystyrene box.

To optimize cooling capacity, heat-sinks play a crucial role in efficiently dissipating heat from the Peltier modules, preventing overheating. In this system, all the Peltier modules are arranged in parallel and four heat-sinks are strategically positioned outside the cooling box to manage heat effectively.

The inner box serves as the primary storage space for items requiring cooling, reducing the loss of cool air. The power supply, a 24V Adjustable DC power supply with low ripple/noise, is the primary source of electrical energy to operate the system. Four CPU fans are further used to dissipate heat in the lightweight wooden casing, ensuring uniform heat extraction from the polystyrene box into the atmosphere. Thermal paste is employed as an adhesive medium to bond the Peltier modules, heat-sinks, and fans while facilitating heat transfer. Connecting wires establish the electrical circuit, linking the Peltier cooling elements to the power supply and connecting the power supply to the electrical energy source via a plug.

Additionally, a 12V 180W Solar Panel is integrated into the system to provide power during daylight hours. For backup power, eight Rechargeable Li-Po 3.7V 4500mAh batteries are included, ensuring uninterrupted operation of the thermoelectric storage box for 3 hours.

The backup time is calculated using equation i.e. Backup Time (in hours) = Battery Capacity (in Ah) × Input voltage (V) / Total Load (in Watts).

$$Backup\ time\ = (4.5 \times 8 \times 12)/133 = 3.2\ hours$$

Figure 3: Final Product of Peltier-Based Thermoelectric Cooling Module

III. RESULTS AND DISCUSSION

The experiment comprised three distinct conditions:

1. In the first condition, the cooling box was empty, with no load or contents placed inside.
2. In the second condition, 10 5ml sterile glass vaccine tubes filled with water were positioned inside the box.
3. The third condition involved placing 6 5ml sterile glass vaccine tubes filled with water inside the box.

Separate results were obtained for each of these conditions, and the outcomes are visually presented in Figure 4.

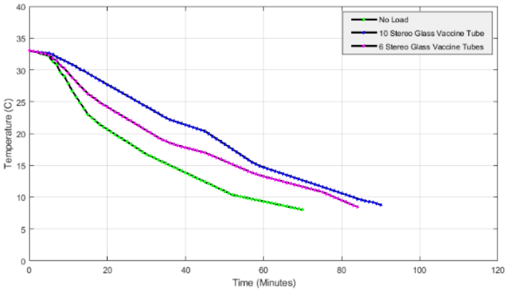

Figure 4: Temperature versus Time taken under all three load conditions.

Figure 3 provides insights into the cooling performance of the proposed storage system, highlighting its ability to consistently maintain temperatures below 15°C. Common to all scenarios, the cooling process exhibits a gradual start within the initial 15 minutes.

In a no-load condition, where the cooling box contains no vaccine tubes, the temperature experiences a slow initial drop. However, this phase is succeeded by a significant temperature decrease, spanning from 7°C to 18°C. Under these circumstances, it takes 38 minutes to reach 15°C, and the desired temperature of 8°C is attained after 62 minutes.

In cases where 5ml sterile glass vaccine tubes filled with water are placed inside the box, the thermoelectric cooler requires approximately 60 minutes to reach 15°C and roughly 90 minutes to achieve the desired temperature of 8°C.

The results for the Peltier module with the provided specifications are as follows:

- Number of Peltier Modules: 4
- Applied Voltage (V): 12 volts
- Total Current (I): 14 amperes
- Seebeck Coefficient (α): 0.02 V/K
- Electrical Resistance (R): 0.1 ohms
- Number of Peltier Elements (N): 4
- Thermal Conductivity (k): 0.1 W/(m*K)
- Hot Side Temperature (Thot): 33°C
- Desired Temperature (Tcold): 8°C

These results demonstrate the performance of the Peltier module under the specified conditions, including its electrical power consumption, heat transfer capacity, thermal resistance, and coefficient of performance (COP). The module's COP indicates its efficiency in transferring heat, and in this case, it's 0.42, which is a measure of how well it can achieve cooling. The results show that the Peltier module can transfer 70.00 W of heat while consuming 168.00 W of electrical power. The maximum achievable heat transfer is 77.84 W, which is close to the module's performance limit based on thermal resistance.

IV. Conclusion

A portable solar-powered vaccine carrier box that employs the Peltier Effect for efficient vaccine cooling is successfully designed and tested. The system incorporates four 12V DC 3.5A Thermoelectric Cooler (TEC) Peltier Modules, strategically positioned heat-sinks, a 12V 180W Solar Panel for power generation during the day, and eight Rechargeable Li-Po 3.7V 4500mAh batteries for continuous operation for 3 hours.

The experimentation involved three different scenarios, revealing the system's cooling capabilities. In an empty cooling box, a gradual temperature decrease is observed. When introducing 10 sterile glass vaccine tubes filled with water, the temperature decreased more slowly but still reached 15°C in 62 minutes and 8°C after 90 minutes. With only 6 vaccine tubes, it took approximately 55 minutes to reach 15°C and about 90 minutes to achieve the desired 8°C temperature. The system exhibited a coefficient of performance (COP) of 0.42, reflecting its efficiency in transferring heat. The results underscore the effectiveness of the storage system in maintaining temperatures below 15°C, a critical factor in vaccine preservation. Furthermore, the analysis of the Peltier module's performance, including its electrical power consumption, heat transfer capacity, thermal resistance, and COP, demonstrates its efficiency in achieving cooling.

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