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Design and Fabrication of Solar-Powered Portable Thermoelectric Refrigeration System for Thermolabile Pharmaceuticals

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Abstract: In order to maintain the therapeutic efficacy of thermolabile medicine and vaccines, electrical energy must be continuously supplied. For remote areas lacking access to electrical electricity, this poses a serious dilemma. The potency level of thermolabile medications and vaccines is decreased, particularly during last-mile delivery, which causes significant financial loss. In this study, we designed and developed a portable active refrigeration system that runs on solar photovoltaic cells for the refrigeration of thermolabile pharmaceuticals to be utilized in rural areas without access to electricity, especially to facilitate last-mile vaccination delivery. The system makes use of a thermoelectric refrigeration system that, when given electrical power, causes a temperature difference based on the Peltier effect. It will be demonstrated that a solar panel with a peak power of roughly 50W and batteries with a storage capacity of 10Ah are needed for a typical application for vaccine refrigeration. The developed refrigeration system has a 3-liter volume capacity and can store 150 vaccine ampules, each with a 10ml capacity, at temperatures between 2°C to 8°C using a Peltier cell (TEC), that consumes 66 W at 12V

***Keywords*: Therapeutic, Thermolabile, Thermoelectric, Peltier, Refrigeration.**

I. INTRODUCTION

Any nation must have access to basic healthcare, especially if it wants to improve circumstances for its citizens and ensure that infants survive. Vaccinations are given out as one of the basic medical services in this regard.

The percentage of people worldwide who have received the DTP-31 vaccine has increased to 78% [1], saving more lives and preventing more disease outbreaks. If the administered vaccines are not effective at the time of usage, the effect of this expanded coverage will be muted. The enormous effort made to reach children with immunization services will be in vain if vaccines are stored carelessly and suffer temperature-related harm. The inadequacy of the current cold chain in many nations is a result of improperly maintained or antiquated refrigerated equipment, poor adherence to cold chain protocols, insufficient monitoring, and a lack of awareness of the risks associated with vaccine freezing [2].

The majority of vaccinations are considered to be thermolabile products. Thermolabile medications are those that need certain storage conditions and often demand low temperatures (between 2 and 8 degrees Celsius). If these requirements are not met, the properties of these medications may deteriorate to varying degrees depending on the temperature attained and the time spent there. If the medication has already been given to the patient, this either entails a financial loss or therapeutic inactivity [3].

The logistics required to ensure temperatures between 2 and 8 °C from production to final administration for thermolabile medications is known as a "cooling chain" [4]. Refrigeration systems are essential for this purpose, which calls for continuously given electrical energy. However, in many developing nations, conventional electrical energy distribution systems have fallen short in terms of accessibility and dependability to meet the needs of rural health clinics [5].

Solar energy is a clean, non-polluting, renewable energy source that has been increasingly appealing over the past ten years for uses like cooling vaccines and medications in remote areas of developing nations. Thus, in this study, we design and construct a mobile active refrigeration system that uses solar photovoltaic cells to cool thermolabile drugs in rural areas utilizing thermoelectric refrigeration systems. Thermoelectric cells (TEC) have been developed over the past few decades to efficiently convert electrical energy into a heat flow (cooling). When electrical energy is applied to the junction of two distinct materials, the Peltier effect is used to create a temperature difference. Thermoelectric refrigerators have already been utilized for commercial and industrial goods as well as for instrumentation in the military and aerospace [6].

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Other authors have already studied thermoelectric coolers [7, 8], but in this work, we combine the design and development of the thermoelectric refrigerator with the photovoltaic system to achieve a self-sustaining cooling system without emitting greenhouse gases, as well as without the noise and maintenance issues typically associated with conventional refrigeration systems.

II. SYSTEM CONFIGURATION

The proposed refrigeration has three electrical energy sources. If we have 240 volts of ac power, we can connect the refrigeration directly by using an SMPS (switch mode power supply) to convert 240 volts to 12 volts. If we don't have power, we can use batteries to power Peltier modules or solar panels to charge batteries, which in turn provide the necessary DC energy to the thermoelectric refrigerator. The thermoelectric refrigerator has a 3-liter overall capacity and is designed to hold about 150 vaccine ampules, each with a 10ml capacity. A Peltier cell, which utilizes the electrical energy from the module, provides cooling.

We employed a wooden frame design to keep the cabin box cold, and a cooling chamber that is highly insulated with polyurethane foam and glass wool for thermal isolation from the surroundings. The storage chamber features a thin layer of aluminium foil for even temperature distribution and is equipped with a phase change material (PCM) to lessen thermal fluctuations during logistics. A closed-loop electronic control system is employed to keep the temperature firmly between 2°C and 8°C and a heat sink is used to reject heat to the atmosphere. End users can record and view the cabinet temperature in real-time on a temperature monitoring display. The overall thermoelectric system's energy flow is shown in Fig. 1.

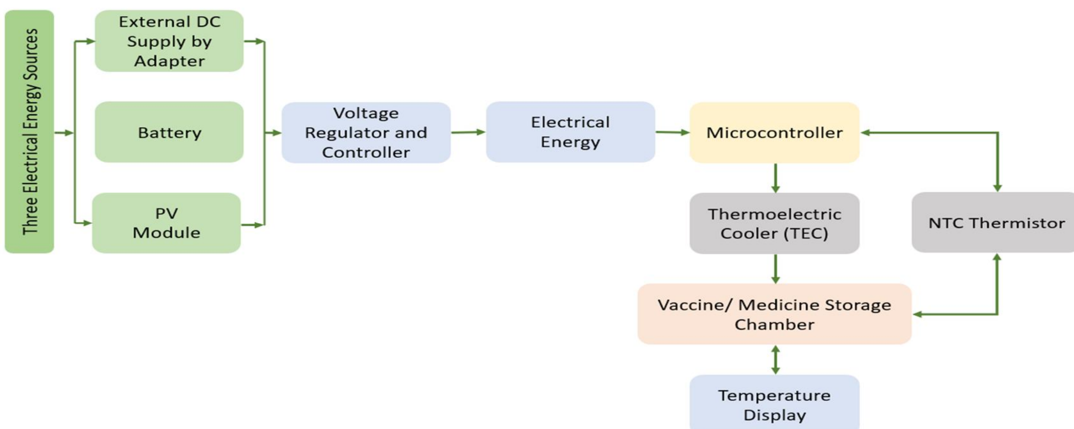


Fig. 1. Thermoelectric Refrigeration System Energy flow

A schematic representation of the system to be created is shown in Fig. 2. It consists of sufficient cabinet storage capacity, batteries, an electronic control system, insulation materials, and the refrigerator itself.

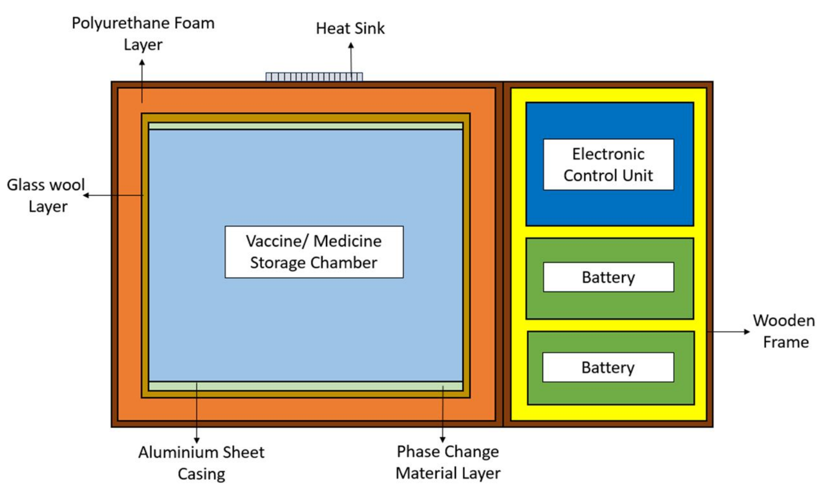


Fig. 2. Schematic representation of the Refrigeration system

III.DESIGN OF TEC REFRIGERATOR

A. Thermal Load Calculation

The total thermal load (Q_t) must be understood as the initial stage in the refrigerator design process. Here, we compute the heat absorbing load (Q_a) inside the cabin and the heat rejection load (Q_r) through the heat sink fan outside. Eq. 1. provides the total heat load. The amount of heat that must be evacuated to maintain a specific temperature within the refrigerator is known as (Q_a). The following Eq. 2. can be used to determine the thermal load from the product that needs to be cooled:

$$Q_t = Q_a + Q_r \qquad 1$$

$$Q_a = \frac{mC_p(T_1 - T_2)}{t} \qquad 2$$

T1 is the beginning temperature of the vaccines, T2 is the final temperature of storage for the vaccines, and t is the amount of time it takes for the temperature of the vaccines to change from initial temperature to final temperature, wherein m is the mass and c is the specific heat of the products.

Vaccines must adhere to the "cooling chain" so that when the refrigeration cycle is started, the vaccines will be at a maximum temperature of 6°C and the refrigerator will only slightly lower the temperature. Vaccines are commonly stored at temperatures between 2°C and 8°C. The vaccination temperatures will be between 4 and 6°C in this refrigerator, and they will be at 6°C when they are first placed inside. A 3-liter storage capacity is available in the refrigerator's cabinet. The total thermal load for the product to be cooled is determined to be 66W-h by applying Eq. 1. For a 3 cubic meter volume box to attain 6°C, we, therefore, needed a total 66-watt heat-absorbing load.

B. Peltier Module Selection

The basic element of our refrigerator is a Peltier cell (TEC), which converts electrical energy into extracted heat flow. We can select the proper TEC (or TECs) by determining the specific characteristics that define the Peltier cell. In order to do this, we used the universal performance curve suggested by Buist [9] in accordance with the method described by Tan et al. [10]. Equation 1's computed thermal load value led us to choose two Peltier modules with equal ratio capacities. Each Peltier requires 33 watts of load to cool up to 6°C. The following details of the chosen TEC are listed in Table 1:

Parameter	Value	
Hot Side Temperature	25°C	50°C
Q_{max} (Watts)	50	57
Delta T_{max} (°C)	66	75
I_{max} (amps)	6.4	6.4
V_{max} (Volts)	14.4	16.4
Module Resistance (Ohms)	1.98	2.30

Table 1: Characteristic parameters of TEC

C. Electronic Control Unit and Temperature Sensor

The refrigerator will have an electronic control unit (ECU) that will regulate the energy supplied in line with the temperature readings. The refrigerator enters a "unfreezing" phase when the interior temperature reaches close to 2°C, at which point the electrical energy supply is cut off. The refrigerator will start the "freezing" phase when the temperature hits 8°C, at which point the ECU will reconnect the electrical energy source. To regulate the operation of the refrigerator, we used an Arduino UNO with a linear voltage regulator. A thermistor (395025 10k NTC thermistor) was chosen as one of the temperature sensors, and it was installed inside the cooling chamber space to detect the temperature and provide a signal to the controller. According to the sensor's input temperature value, the controller would send output current to the Peltier module to provide refrigeration of 2° to 8°C inside the cabinet. The system has a digital display that allows users to see the temperature inside the storage cabinet for vaccines and medications.

D. Heat Sink and Fan

A black anodized heat sink fan assembly (Model No. TDEX6015/TH/12/G, R_{th} =1.157 °C/W) has been employed to improve heat dissipation from the hot side of the thermoelectric cooling module. A single heat sink fan assembly would be needed since both Peltier modules would be stacked on the same heat sink. We choose a 0.5-ampere 12-volt heat sink fan, and the maximum power required to reject heat is 6 watts, or heat rejection load (Q_r).

E. Battery Selection

A battery (bank) is required for a fully autonomous system for two reasons:

1) The PV module generates electricity that varies throughout the day. Any thermoelectric refrigerator cannot operate in this manner. A battery bank can offer constant voltage and current.
2) When the solar radiation from the PV module is insufficient to power the refrigerator during the night, certain parts of the day, or even for several days, a battery bank is necessary.

It is essential to have a power source with a high-power capacity and is lightweight at the same time in order to accomplish the goals of this study. Using Equation 1, a total heat load of 72W was determined. Each of the two thermoelectric modules (TEC1-12706) would require a 12v dc supply with a current of 2.75 amps. Equation 2 is used to determine that both Peltier modules utilize 66W of electricity. The formula for calculating battery capacity is: total load/battery voltage = 72/12 = 6 Ah. Based on battery capacity, we choose a 10 Ah battery to power this refrigerator.

Although known to be costly and constrained by their power capacity, lithium-ion batteries are lightweight, which meets the study's purpose. On the other side, a lead acid battery is larger than a lithium-ion battery but has a higher sustained power capacity. It was determined that lithium-ion batteries would not be practical for this study since it would not be efficient or cost-effective to use many batteries only to meet the module's high-power consumption. It was decided that a lead acid battery, with a maximum voltage of 12V and a maximum amperage of 10Ah, would be better suited for the study in order to handle the module's power demand.

F. Photovoltaic Cell and Solar charge Controller

The mechanism by which light is converted into electricity is known as the photovoltaic effect. This is employed when turning solar energy into electric energy straight away. Using photovoltaic cells, commonly known as solar cells or solar panels, it is possible to convert heat into energy. To make sure that the system will be able to sustain and energize itself through numerous tests, two 25W solar panels were employed to charge the lead acid battery. To prevent the batteries from being overcharged during the day, a solar charge controller was used to make sure that the power doesn't go back to the solar panels, preventing the batteries from being discharged overnight. The total power generated by the solar panels is 50W, with the controlled output power of the solar panels is 30W.

IV. CONSTRUCTION OF THERMOELECTRIC REFRIGERATOR

The setup's dimensions were predetermined in order to construct the prototype. The cold vaccine/medicine storage cabinet has a 3 Liter storage capacity, which can hold approximately 150 vaccine ampules, each with a 10ml capacity. The cabinet was built with a hardwood frame throughout. The hardwood frame was divided into two sections, one of which contains the battery housing and the entire electronics system, and another section includes the storage cabinet. The interior view of the refrigeration system with a wooden frame, which includes the electronics portion and storage cabinet part, is shown in Fig. 3.

The storage cabinet has thermal insulators that have an interior layer of glass wool and an outside layer of polyurethane. Using silicone guns, glue guns, and tapes, additional insulation was applied to the refrigerated space to prevent heat from entering. For even temperature distribution, a thin sheet of Aluminium metal is laid inside the cabinet. A Phase Change Material (PCM) that can be used for longer journey logistics can also fit in the cabinet. At phase transition, PCM releases/absorbs enough energy to deliver useful heat or cooling. The two Peltier modules are placed over a single heatsink, where the cold side of the Peltier module is put atop an aluminium sheet which is laid within the internal walls of the cold chamber, to uniformly cool it down and produce controlled cooling. The Peltier module's conductivity was improved for enhanced cooling efficiency using a thermal paste.

A fan assembly is positioned above the heat sink, which is outside the chamber, to use forced convection to reject additional heat to the atmosphere. An electronic control unit that employs an Arduino UNO and liner voltage regulators turns the Peltier on and off. A battery pack or an external DC power source can power the system. The refrigerators contain two solar panels that produce electricity to recharge the batteries when they are used outdoors. The voltage regulator regulates the solar panel's output voltage. The refrigeration system's solar-panel-based frame is depicted in Fig. 4.

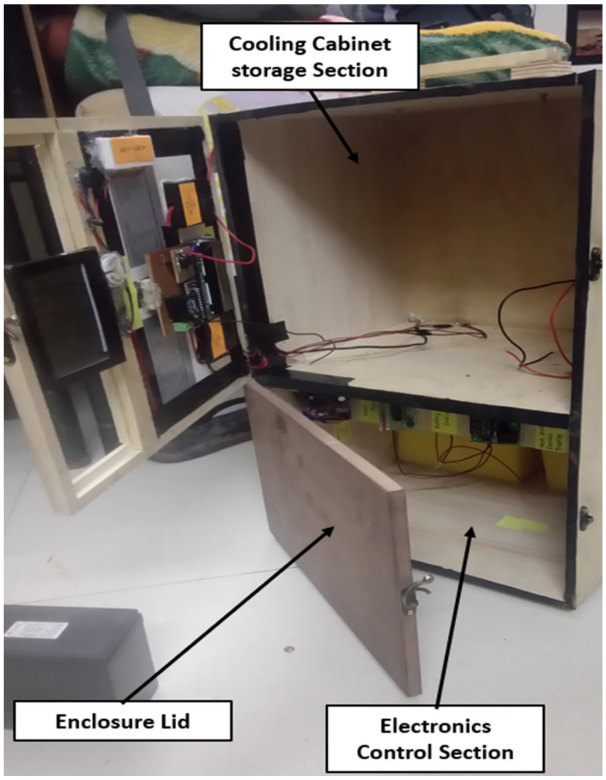


Fig. 3. Interior view of the Refrigeration system with a wooden frame

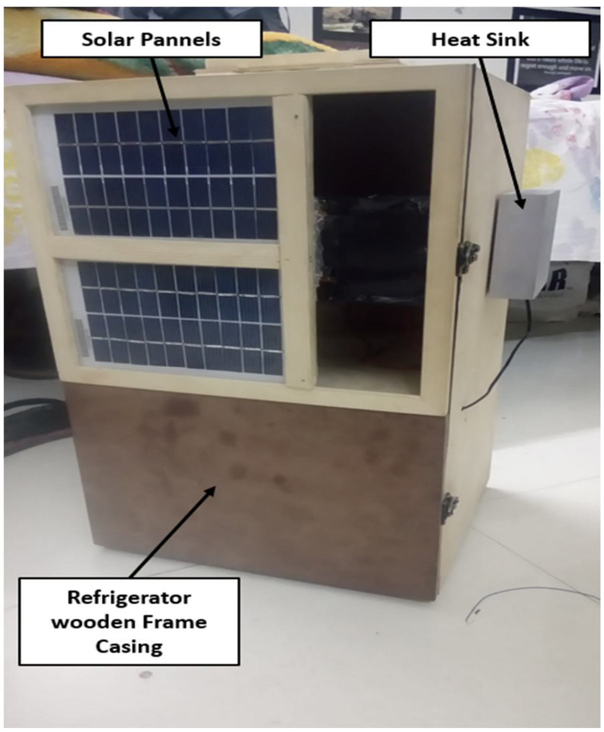


Fig. 4. Refrigeration system's solar-panel-based frame

The refrigeration arrangement contains a digital display for end users to show the storage cabinet's temperature data in real-time. A battery drain indicator is also installed to inform the user about the battery's charge level. The refrigerator was initially constructed, and its ability to achieve the specified temperature range was tested. The completed setup utilized for testing is shown in Fig. 5.

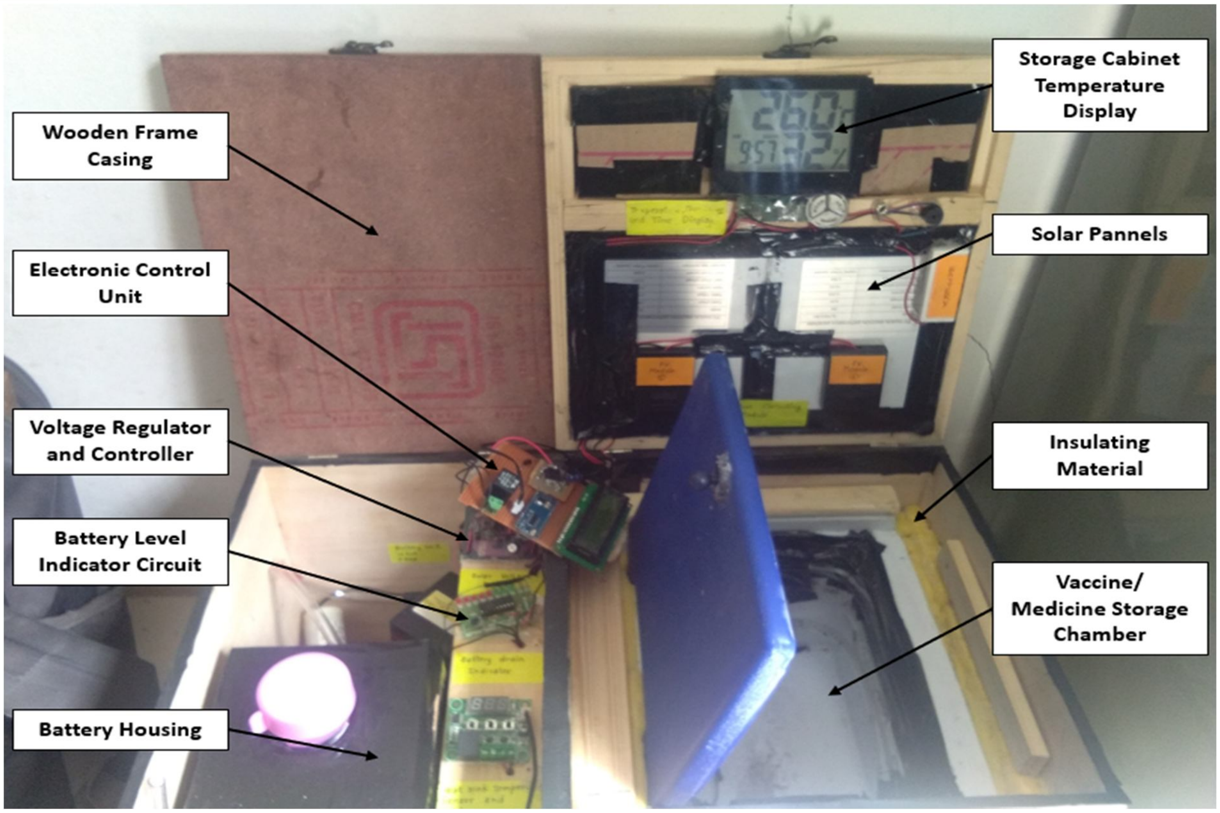
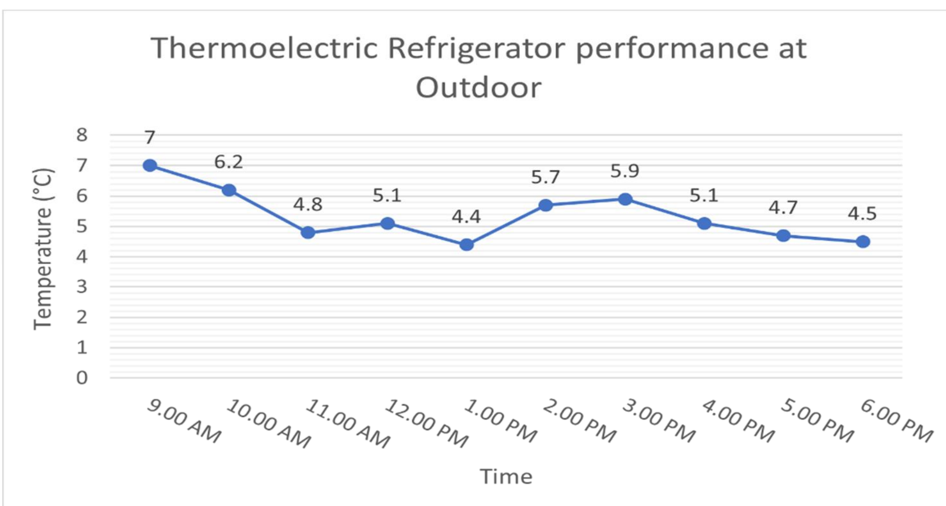


Fig. 5. Refrigeration system complete prototype

V. RESULT AND DISCUSSION

Over the course of two days, the refrigerator's temperature was recorded hourly in both an indoor and an outdoor environment. The ambient temperature for the interior battle was roughly 25°C, whereas the outside temperature was 32°C. The temperature performance data for the developed thermoelectric refrigerator is presented graphically in Fig. 4. It displays a comparison of each graph's internal cabinet temperature over time. The system required around 34 minutes on the first day to reach a temperature drop of around 5°C for indoor settings, and approximately 42 minutes on the second day to reach a temperature drop of 7°C for outdoor conditions. The thermoelectric refrigerator maintained the target temperature range of 2°C to 8°C both indoors and outdoors after the system was run continuously for 9 hours on both days. According to the graphs, there were temperature swings over the two days of testing, but the electronic control unit operated in a closed loop to ensure that the storage cabinet's desired temperature was maintained.



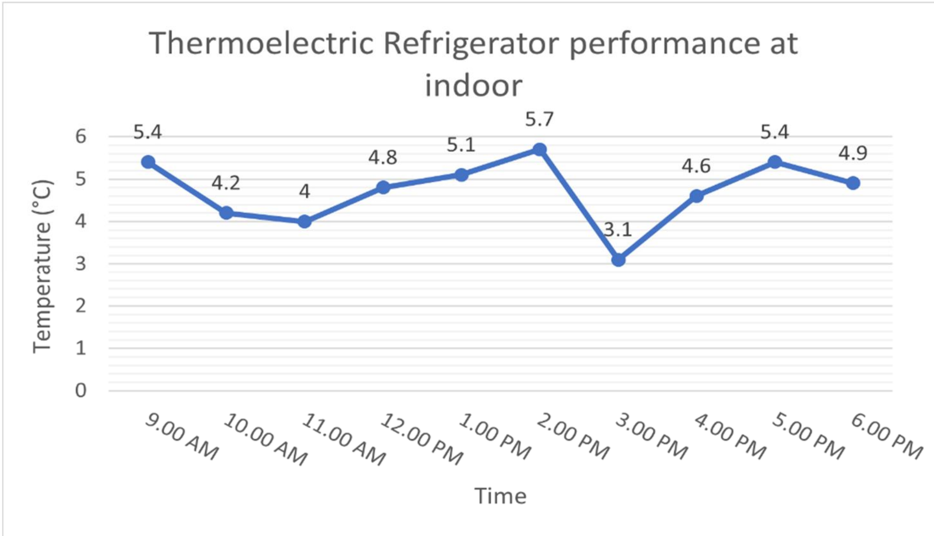


Fig. 6. Comparison of internal cabinet temperature over time with the outdoor and indoor system

VI. CONCLUSION

In this research, a functional prototype of a thermoelectric refrigeration system was successfully developed. The 2°C to 8°C storage temperature range, which is essential for keeping insulin stable, was successfully attained by the device. The system was built with operational settings that would shut down at 2°C and start up again at 8°C. The system's cooling performance was evaluated, demonstrating a temperature reduction of approximately 5°C within approximately 34 minutes in indoor settings, and a temperature reduction of 7°C within around 42 minutes under outdoor conditions.

The system may operate independently for up to 2 days due to the integrated batteries, which are designed for a 12 V TEC (Peltier cell) type TE1-12706 with a 66 W total power consumption. With the ability to efficiently draw heat from a 3-liter refrigerator section, this particular TEC module has enough room to hold 150 thermolabile vaccine ampules, insulins, or medications. The innovation is prepared for implementation in isolated rural locations lacking in electrical infrastructure. Thus, storing vaccines/ medications at an effective temperature to help improve the logistic chain, by accelerating access to immunization.

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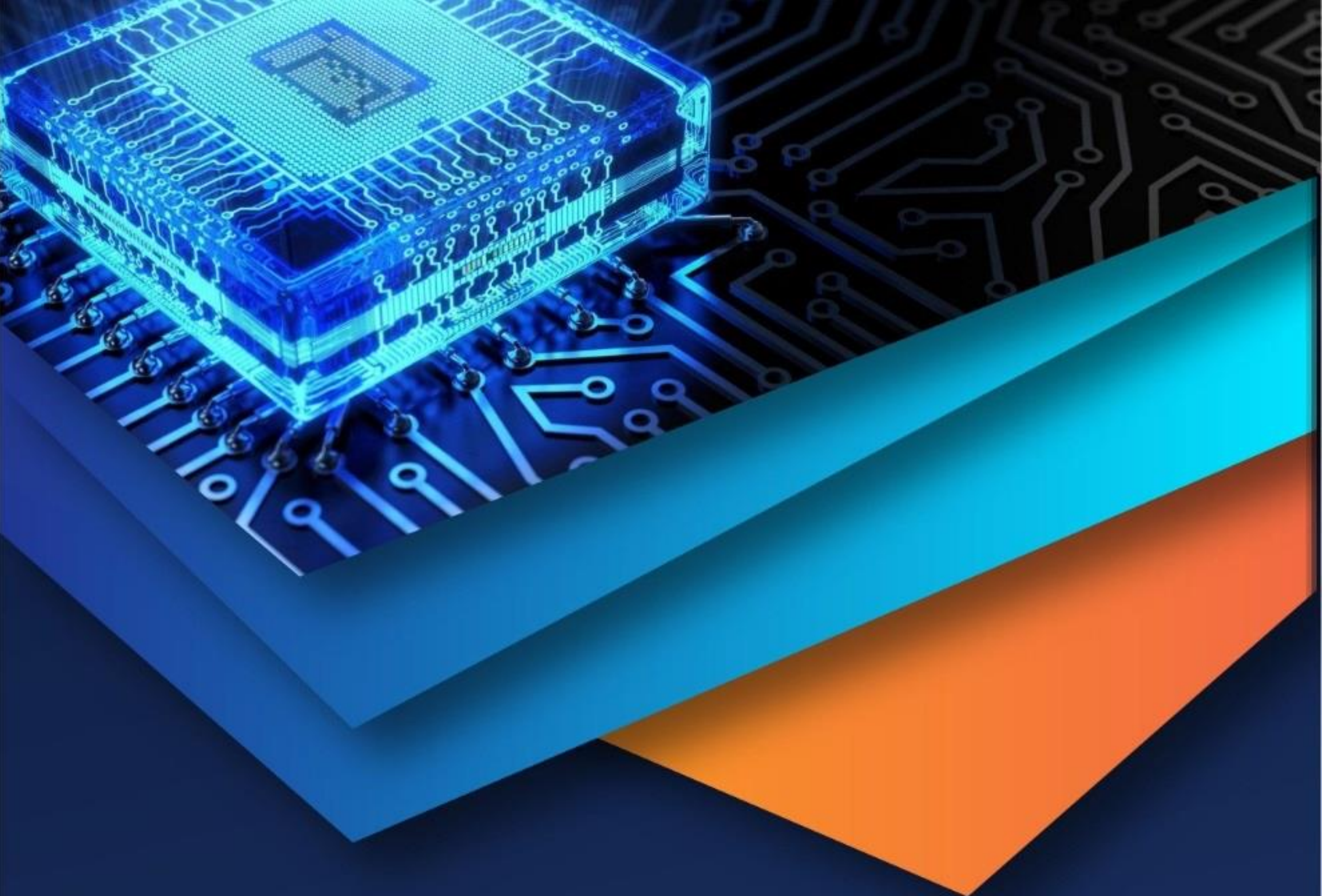

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