World Journal of Advanced Engineering Technology and Sciences
eISSN: 2582-8266
Cross Ref DOI: 10.30574/wjaets
Journal homepage: https://wjaets.com/

(Research Article)

Experimental assessment of precision temperature control electronic architecture for solar-powered TEC refrigerator

Rutvik Mehenge [1,*] and Vindya Prasad [2]

[1] *Department of Mechanical Engineering, Trinity College of Engineering and Research, Pune, India.*
[2] *Department of Electronics and Communication Engineering, PES University, Bangalore, India.*

World Journal of Advanced Engineering Technology and Sciences, 2023, 10(01), 030–039

Publication history: Received on 29 July 2023; revised on 09 September 2023; accepted on 12 September 2023

Article DOI: https://doi.org/10.30574/wjaets.2023.10.1.0251

Abstract

This study presents experimental research concerning an active thermoelectric cooling control architecture applied to portable, solar-powered medical refrigerators. A specialized Electronic Control Unit (ECU) has been devised for regulating thermoelectric cooling, enabling users to define operational thresholds for the thermoelectric coolers through the system's architecture. The TEC1-12706 thermoelectric cooling system was employed. The system is engineered to swiftly cool the medical refrigerator's storage cabinet by up to 6 °C within 30 minutes and maintain a critical temperature range of 2 °C to 8 °C, vital for safeguarding thermolabile vaccines and medications. The control unit design encompasses a closed-loop control approach utilizing an Arduino Nano, a Linear voltage regulator, and a solar-powered battery charging setup. The Arduino issues signals based on preset points through sensors, thereby regulating the refrigeration system's desired temperature, while a relay module serves as an ON-OFF controller for temperature management. Preliminary results affirm that, in conjunction with a heat sink and DC fan, the thermoelectric cooler successfully achieves the intended temperature range, demonstrating promising cooling capabilities.

Keywords: Thermoelectric; Refrigeration; Thermolabile vaccines; Medications; Arduino-Nano; Linear Voltage Regulator

1. Introduction

The DTP-31 vaccination is now administered to 78% of the population worldwide [1], averting more disease outbreaks and saving more lives. The impact of this increased coverage will be lessened if the provided vaccines are ineffective when they are used. It will be ineffective to reach children with immunization services if vaccines are improperly maintained and suffer damage from temperature fluctuations. The current cold chain is insufficient in many countries due to outdated or inadequately maintained refrigeration equipment, poor adherence to cold chain standards, inadequate monitoring, and a lack of knowledge about the dangers of vaccine freezing [2].

A large percentage of vaccines are regarded as thermolabile compounds. Thermolabile drugs are those that frequently require low temperatures (between 2 and 8 degrees Celsius) and specific storage settings. If these conditions are not met, depending on the temperature reached and the duration spent there, the characteristics of these medications may deteriorate to varied degrees. Since maintaining a consistent temperature is crucial for the storage and delivery of thermolabile products, an effort has been made to develop a closed-loop electronic cooling control architecture for portable medical refrigerators that are powered by solar energy. The Peltier module, which consists of pairs of semiconductors that, by imposing a direct current, creates a heat flow and subsequently a temperature difference across the two sides to achieve cooling [3]. The use of Peltier cells as temperature control elements is growing in recent years due to their small size and ease of use, among other conceivable uses [4], such as setting medical cooling kits for blood or vaccine storage [5], car seats [6,] and electronics [7].

* Corresponding author: Rutvik Mehenge

Many cooling technologies have been described in the literature by various researchers. According to six technical assessment criteria (state-of-the-art, complexity, size and weight, maintenance, useful life, and efficiency) with regard to their use in various refrigeration applications (domestic air conditioning, commercial air conditioning, mobile air conditioning, domestic refrigeration, and commercial refrigeration), Gauger et al. [8] evaluated several alternative refrigeration technologies. They came to the conclusion that none of the alternative refrigeration technologies were as alluring as converting vapor compression refrigeration to non-CFC refrigerants at the time of their research. The possibility to lessen the environmental impact of refrigeration in the food business was explored by Tassou et al. [9] who also looked at developing cooling technologies. They found that the primary obstacles to the widespread use of thermoelectric and Stirling cycle refrigeration were these technologies' lesser efficiency and greater prices as compared to vapor compression refrigeration.

Kretinin et al. introduced a simulation model for TECs in the ANSYS Program [10]. Shaojing et al. [11] created an adaptive proportional-integral-derivative (PID) neural network technique to control the temperature of thermoelectric systems. Yunfei et al. [12] proposed a cooling/heating technique for charge-coupled device (CCD) detectors. The goal of their research was to build a CCD detector box with a broad temperature range. The study uses both linear and pulse width modulation (PWM) controllers to maintain varying temperatures. A thermal cooling electronic control unit was proposed by Sanver et al. [13].

The paper designs and assesses an active thermoelectric cooling control architecture for mobile, solar-powered medical refrigerators.

2. Design Consideration

The refrigeration system's hardware was created. We used a wooden frame design with two sections; one section has the electronics system, and the other section has a cold storage chamber with a capacity of three liters that is firmly insulated with polyurethane foam and glass wool for thermal isolation from the surroundings.

The electronic control unit, power system, battery packs, and PV voltage stabilizers and regulators with battery drain indicator circuit make up the electronic section. There are three electrical energy sources for the proposed refrigerator. The system is made compatible with solar panels to charge batteries, which in turn provide the required DC energy to the thermoelectric refrigerator. Another source is the external power supply of 12 Volts via an adapter. During mobile applications, the onboard batteries can be used to power Peltier modules. Cooling is provided by a Peltier cell, which makes use of the module's electrical energy. Table 1 lists the specifications of the selected Peltier module.

Table 1 Characteristic parameters of the selected Peltier module

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

An electrical closed-loop control system is used to maintain a constant temperature between 2 and 8 degrees Celsius, and a heat sink is used to reject heat to the atmosphere. On a temperature monitoring display, end users can log and monitor the cabinet temperature in real-time. Figure 1 depicts the energy flow through the entire system.

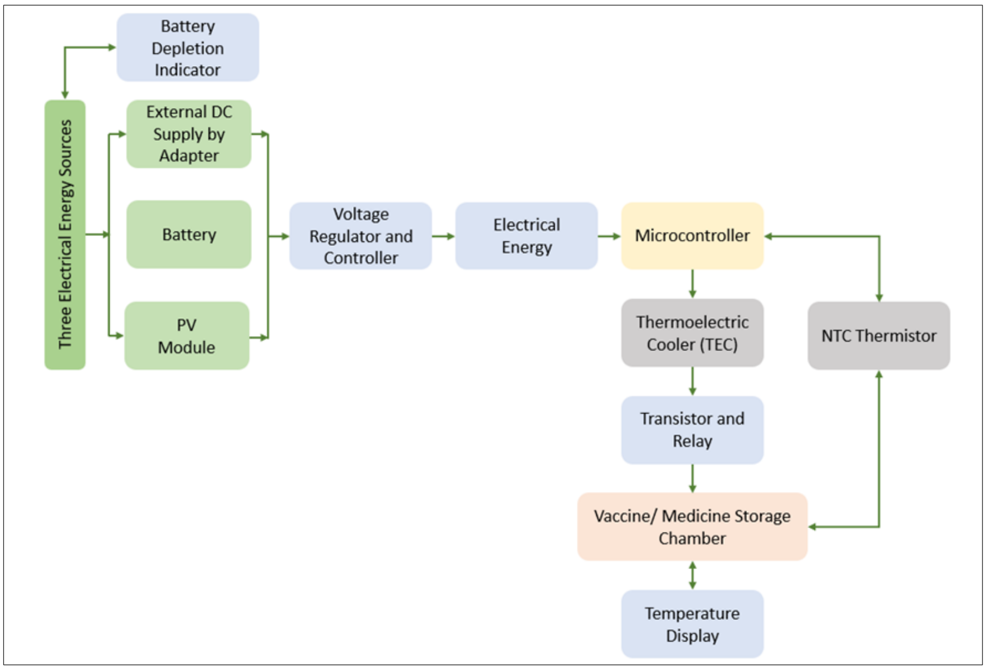


Figure 1 Thermoelectric refrigeration system energy Flow

3. Design of Electronic Control System

The electronic control unit (ECU) in the refrigerator will manage the energy supply in accordance with temperature data. When the internal temperature hits about 2 °C, the refrigerator enters an "unfreezing" phase, at which point the electrical energy supply is interrupted. When the temperature reaches 8 °C, the refrigerator will begin the "freezing" phase, and the ECU will reconnect the electrical energy source at that time. The controller design and power subsystem are covered in detail in the section.

3.1. Design of Controller

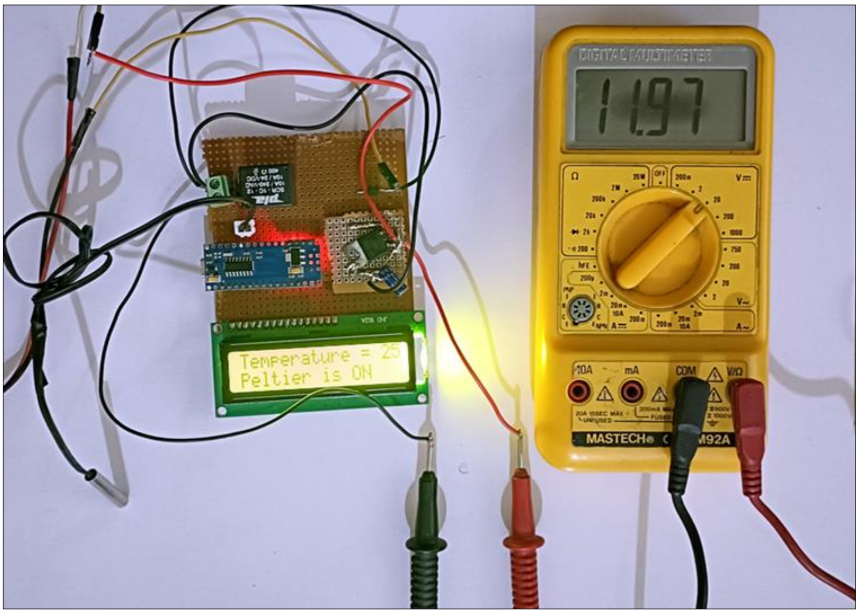


Figure 2 Experimental controller design and arrangement showcasing output voltage of 12 V at ON operation

In this study, the voltage regulator 785CT is used to regulate the TEC. The thermoelectric temperature with the 7805CT is predicted to be controlled by a microcontroller linked to a PC. In the experiment, a TEC1-12706 thermoelectric cooling system and a 7805CT linear voltage regulator are connected to an Arduino Nano microcontroller. In order to show the thermoelectric performance, a thermistor (395025 10k NTC thermistor) installed inside the cold storage chamber and connected to the microcontroller was utilized to measure the temperature, the sensor also relayed temperature reading values to the controller for operation of closed loop system. The temperature data was displayed in the serial monitor of the Arduino IDE 2.1.1 program, which was connected to the microcontroller. Refer to Figure 2 for the experimental controller arrangement.

A constant output voltage of +5 volts is provided by the integrated circuit (IC) known as the 7805 CT voltage regulator. It is not designed with pulse width modulation (PWM) applications. Despite not being directly responsible for producing or controlling PWM signals, the 7805CT can be utilized to provide a variety of electronic circuits with a stable 5-12 V power supply. In addition to thermal shutdown and safe area compensation, these regulators use internal current limiting. With adequate heatsinking, they can deliver output currents of greater than 1.0 A. The integrated circuit (IC) is safeguarded by the 7805's built-in thermal protection, which causes it to shut down if the internal temperature increases too much. Using a linear voltage regulator, we were able to provide a controlled output voltage to power the TEC.

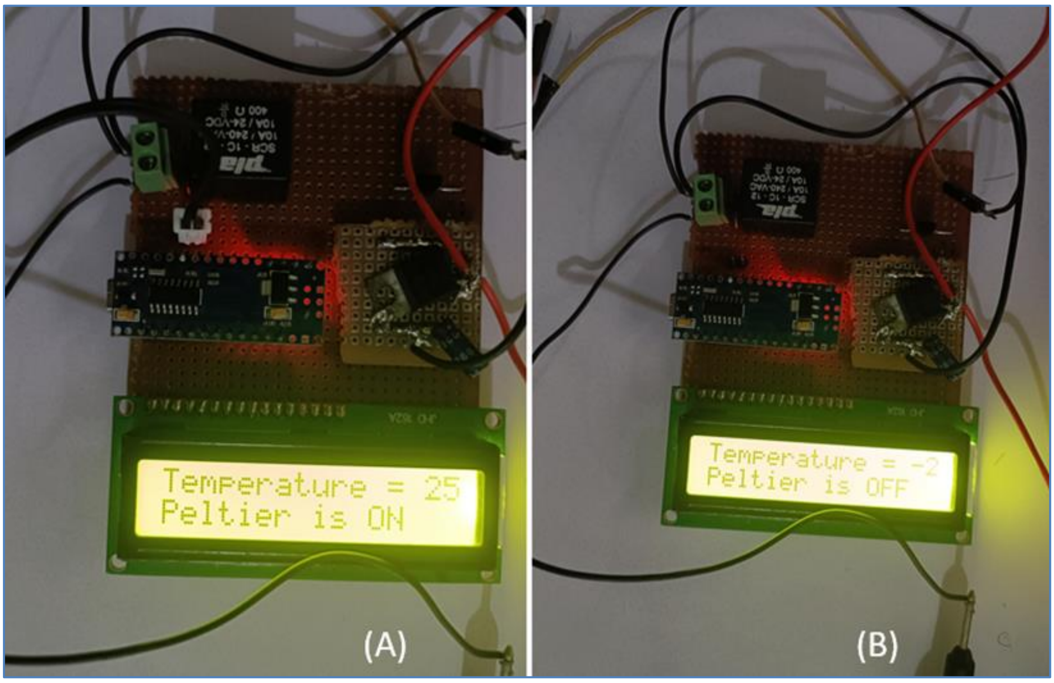


Figure 3 (A) System in ON state to drive Peltier on the feedback of thermistor. (B) System in OFF state to drive Peltier on the feedback of thermistor to accomplish controlled cooling between 2 °C and 8 °C

The single thermistor in the current control design, which also functions as a feedback sensor, is used to operate the system in a closed loop. The thermistor will act as feedback and detect the load temperature if, for example, we wish to accomplish controlled cooling between 2 °C and 8 °C. It then sends signals to the Arduino microcontroller in accordance with those signals, which Arduino uses to effectively drive the Peltier by adjusting the output liner voltage by 7805CT by ON and OFF operation, refer to Figure 3**.** Figure 4 shows the schematic circuit diagram using an Arduino and a 7805CT to operate a TEC device.

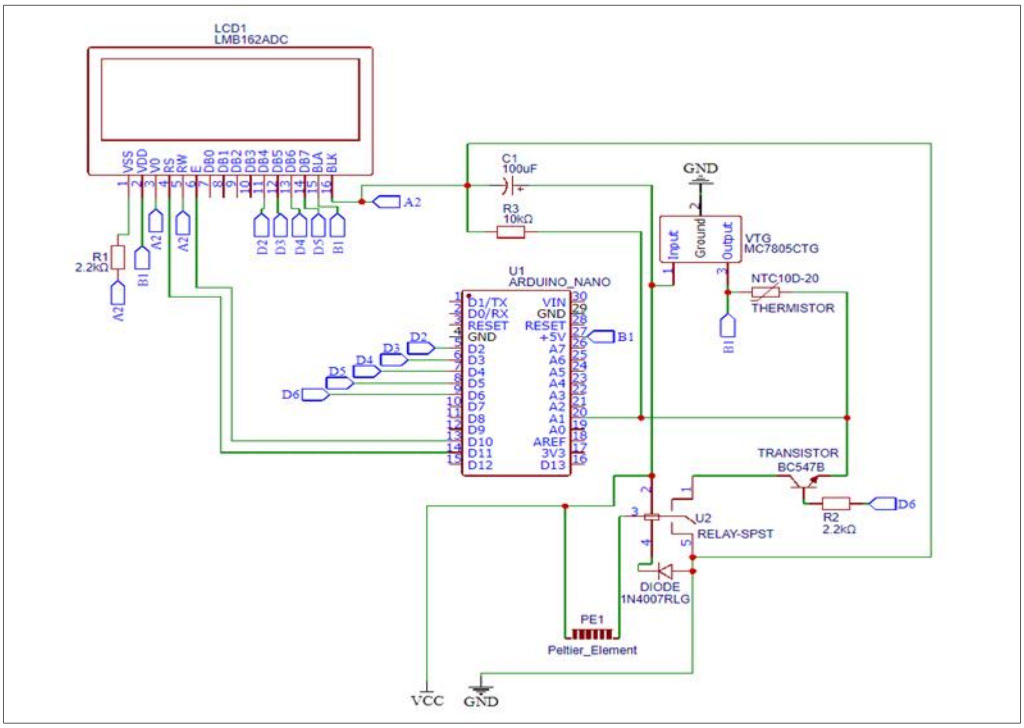


Figure 4 Schematic Controller circuit diagram using an Arduino and a 7805CT to operate Peltier

3.2. Power System

The Peltier cell and battery pack can be powered by solar panels that can be integrated into the refrigeration system. We employed two solar panels with a combined output of 30 watts for our application. In order to meet the power requirements of the module, it was determined that a lead acid battery with a maximum voltage of 12 V and a maximum amperage of 6Ah would be more appropriate for the study. The onboard solar panels would be used to refuel the batteries during outdoor activities. The main challenge with using solar cells for charging is that the output voltage and current greatly depend on the sun's ray strength. Another issue is that nighttime discharge from the lead acid battery into the solar charger must be prevented. Furthermore, lead acid battery overcharging needs to be automatically stopped.

The simplest technique to recharge a lead acid battery is to keep a 15-volt current flowing across the terminals while controlling the charging current with a series resistor. The issue with this situation in terms of solar charging is evident, since how is this current to be maintained continuously with changing weather conditions. The charger must draw the appropriate amount of electricity in order to produce maximum power for any given light intensity. A drop in terminal voltage caused by using too much current from the solar charger will make it take considerably longer to charge the lead acid battery. To ensure that the solar battery is being charged to its full potential, it is necessary to continuously modify the circuit input impedance, as shown in Figure 5. The charging circuit should ideally be able to sense the proper amount of current while maintaining 14 V across the lead acid battery despite variations in the solar battery.

The simplest solar panels consist of a series of solar cells. One of the first things we need is a voltage doubler to boost the voltage from the solar battery because, during cloudy daytime hours, the solar battery's output voltage is low (less than 12 V). The issue of overcharging a lead acid battery is brought up by this device. The solution to this issue is some type of artificial load that, when the battery is full, immediately switches on to take up the charging current and, when the battery is being charged, automatically turns off. With a 1N4002 rectifying diode and a constant 15 V Zener diode placed across the lead acid battery, an excellent fake load may be created. The zener begins to switch on as the battery's terminal voltage progressively increases as it gets close to being at full capacity. Any additional current will subsequently be absorbed by the Zener diode.

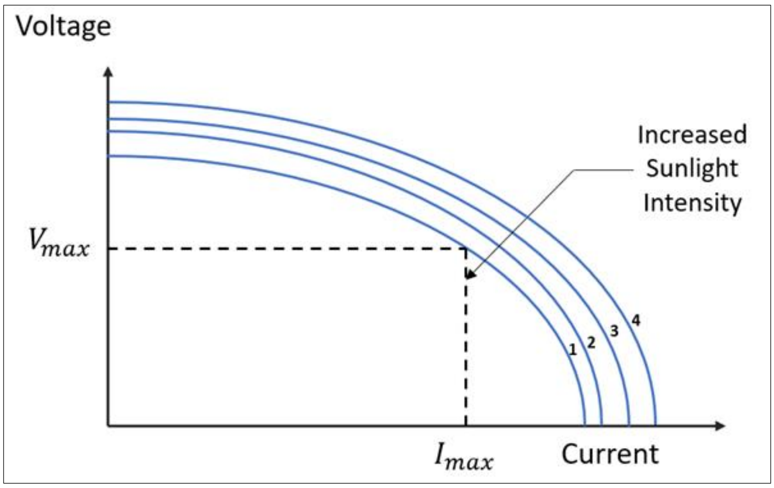


Figure 5 Voltage and current output at various light intensities

Taking a look at Figure 5, we can see that in order to get the most energy out of the solar battery, a different quantity of current at a different light intensity will need to be drawn. This is automatically ensured by the zener diode. Considering a case where the amount of sunshine increases, the solar cell's voltage grows, and more volts are applied across the lead acid battery as a result. In consequence, according to Ohm's law, the battery will absorb greater current. The curve in Figure 5 indicates that the solar battery will produce less voltage as a result of this additional strain. As a result, there is a decrease in voltage across the lead acid battery, which reduces the current flow. This algorithm automatically stops at the point where the product of voltage and current rent yields the highest value. The settling point is continuously revised in accordance with the fluctuating intensity of the sun.

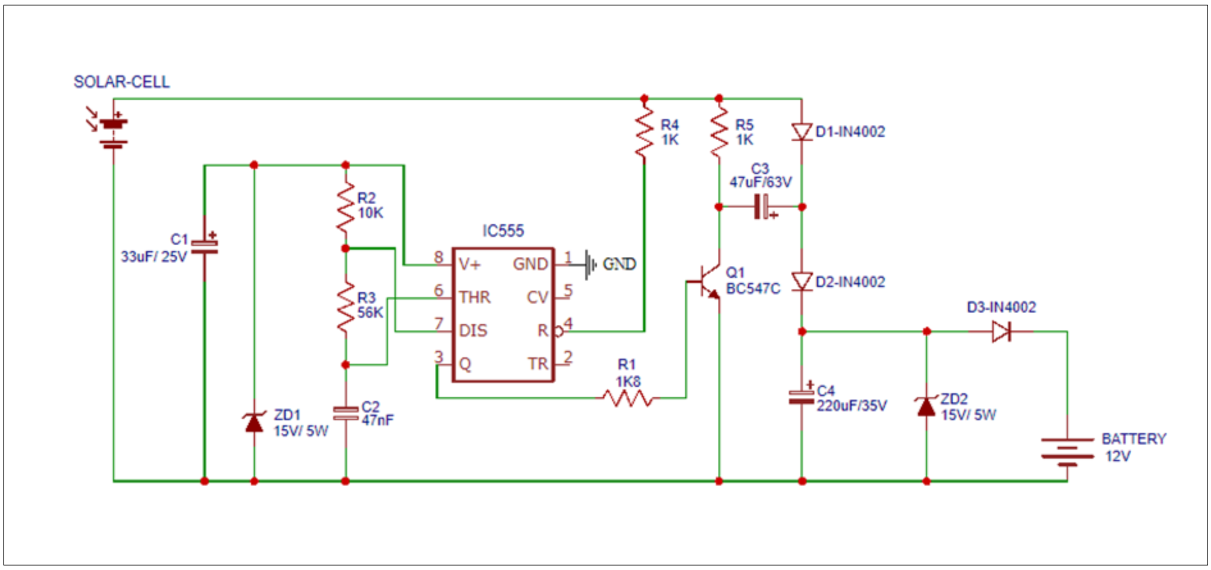


Figure 6 Schematic diagram of the solar power regulator

The solar battery's voltage output is quite low when there is little sunlight present. The output voltage might not be sufficient to replace the lead acid battery, even with the assistance of the voltage doubler. Everything stops at night, with the exception of the diode connected in series with the lead acid battery, which prevents the battery from being discharged. The diode's function will automatically continue on the following sunny day, allowing for maintenance-free charging. The oscillator that makes up the voltage doubler itself is used. We chose to use a CMOS 555 timer because it uses extremely little current, allowing the battery to be charged with every last bit of energy from the solar panel. Refer to Figure 6 and Figure 7 for comprehensive schematics of the solar power regulator and the fabricated solar regulator circuit, respectively. The lead acid battery will be charged consistently by the solar regulator.

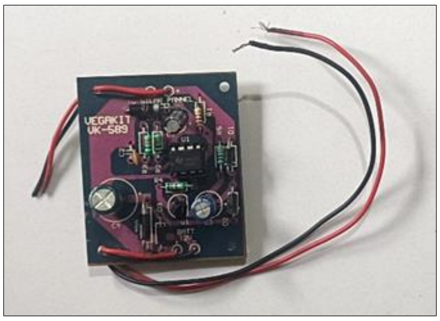


Figure 7 Fabricated solar regulator circuit

A battery depletion indicator circuit is also included for the end user to keep track of the battery's charge level. Refer to Figure 8 for the constructed circuit for the Battery drain indicator. This little circuit displays the charge level of dry cells as well as rechargeable lead acid or Ni-Cd batteries. Dot/bar display driver IC LM 3914 is utilized in dot mode, which implies pin 9 of the IC is open. Pin 5 of the IC is connected as an input via the positive battery terminal. The LED current is controlled by the resistor R2 connected between pins 6 and 8. Between pin & and ground is where the chip's reference voltage is located. By using a preset PI, the reference can be altered. R3 serves as a potential divider and is resistor RI.

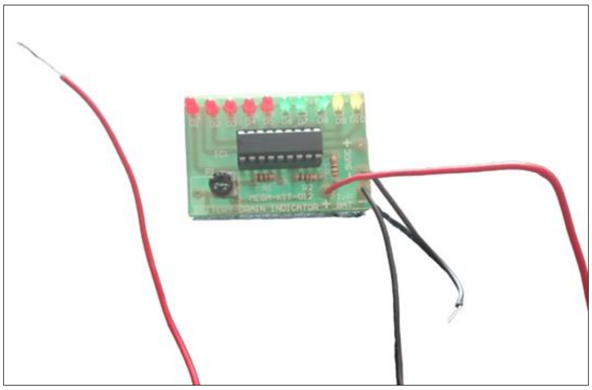


Figure 8 Constructed circuit for the Battery drain indicator

The LM 3914 drives 10 LED arrays that illuminate in 10 equal stages of the selected full scale. The next LED will turn on for each fluctuation of 1.5 volts by setting the full scale to 15 volts. Red LEDs in the D1 to D5 range will display the battery's discharge state. The health of the battery will be indicated by D6 to D8 green LEDs. The battery's overcharge state will be shown by the blue LEDs on D9 and D10. Refer to Figure 9 for a detailed Schematic circuit diagram of the battery drain indicator.

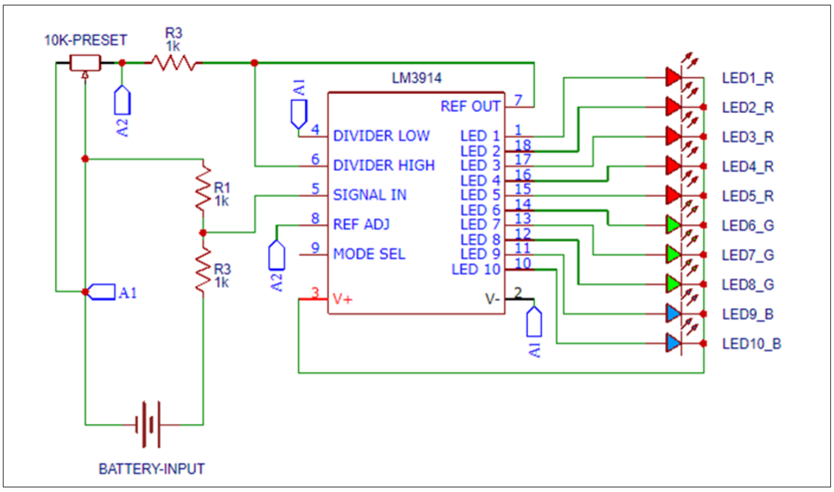
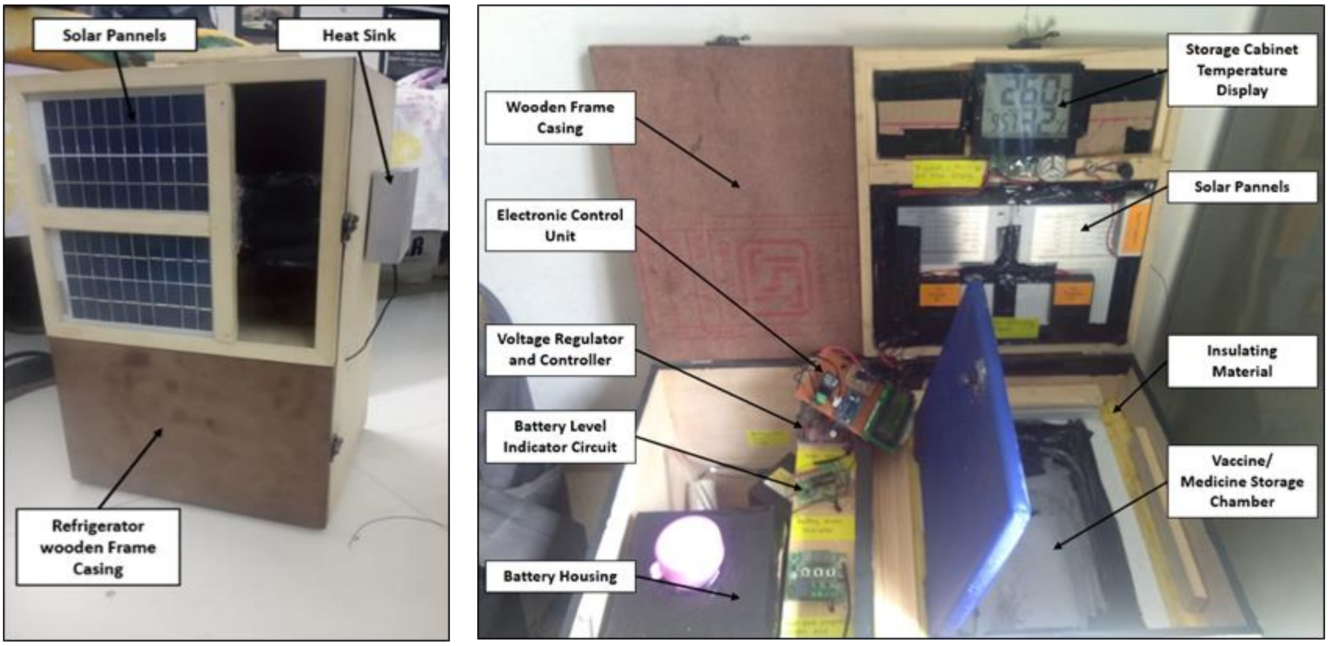


Figure 9 Schematic circuit diagram of the battery drain indicator

4. Control Method System

The controller is designed such that the desired temperature can be set from the control algorithm. Depending on the type of medication being stored, the temperature setting can be adjusted to satisfy the requirements. Since a wide range of vaccines and pharmaceuticals are commonly stored at temperatures between 2° and 8 °C, we set a temperature limit within that range for the current application. One of the temperature sensors, a thermistor (395025 10k NTC thermistor), was mounted within the cooling chamber area to measure the temperature and provide a signal to the controller. The controller would deliver output current to the Peltier module based on the sensor's input temperature value to produce refrigeration of 2° to 8 °C inside the cabinet. The system would be turned ON if the temperature value rose above 8 °C and shut OFF if the temperature value fell below 2 °C. The device incorporates a digital display that lets users check the temperature inside the vaccine and medication cabinet. For a thorough schematic block layout of the refrigeration setup, refer Figure 1. The refrigeration system outer frame with solar-panel- is depicted in Figure 10 (A) and the complete Peltier-based Refrigeration system setup utilized for testing is shown in Figure 10 (B).



(A) (B)

Figure 10 Refrigeration system outer frame with solar panel (A) and complete Peltier-based Refrigeration system architecture

5. Result and discussion

The refrigerator's temperature was monitored hourly for two days in both an indoor and an outdoor setting. The inner room's ambient temperature was about 25 °C, while the outside air temperature was 32 °C. Figure 11 shows graphically the temperature performance information for the created thermoelectric refrigerator. It compares the internal cabinet temperature of each graph with time. For interior settings, the system needed about 34 minutes on the first day to achieve a temperature decrease of about 5 °C, and about 42 minutes on the second day to achieve a temperature drop of about 7 °C. After the system was continuously run for 9 hours on both days, the designed Electronic Control unit for the thermoelectric refrigerator maintained the intended temperature range of 2 °C to 8 °C both indoors and outdoors. Additionally, the solar power regulator system effectively charged the battery with a consistent output voltage of 14 V. The graphs show that there were temperature variations over the course of the two testing days, but the electronic control unit maintained the storage cabinet's desired temperature by working in a closed loop.

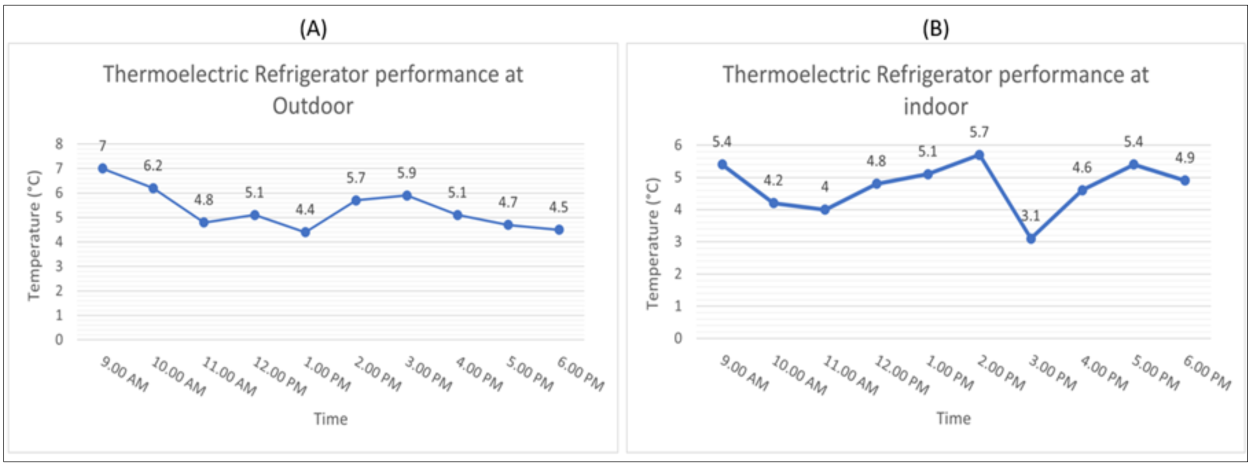


Figure 11 Comparison of internal cabinet temperature over time with the outdoor (A) and indoor system (B)

6. Conclusion

In conclusion, this research paper highlights the successful development and implementation of an innovative active thermoelectric cooling control architecture for solar-powered medical refrigerators. The study focused on the utilization of a specialized Electronic Control Unit (ECU) to regulate thermoelectric cooling, offering users the flexibility to set operational thresholds according to the system's design. A functional prototype of a thermoelectric refrigeration system was successfully developed. The device was successful in maintaining the 2 °C to 8 °C storage temperature range, which is necessary to keep insulin stable. The system's operational settings were designed to switch off at 2 °C and restart at 8 °C. A temperature drop of about 5 °C in about 34 minutes was seen when the system's cooling capability was assessed, and a temperature reduction of about 7 °C in about 42 minutes was seen when it was tested outside.

Because of the integrated batteries, which are made for a 12 V TEC (Peltier cell) type TE1-12706, the system can function independently for up to two days. This particular TEC module has the capacity to efficiently extract heat from a 3-liter refrigerator section and has enough space to carry 150 thermolabile vaccination ampules each of 10ml capacity, insulins, or pharmaceuticals. The battery was charged effectively by the solar power regulator circuit, which provided a steady output voltage of 14 V. Preliminary outcomes from the experimentation phase confirmed the system's ability to achieve and sustain the targeted temperature range, showcasing its promising cooling capabilities. The successful implementation of this active thermoelectric cooling architecture opens doors to enhancing the reliability and portability of solar-powered medical refrigerators, particularly for applications involving the safeguarding of temperature-sensitive medical supplies. As further research and optimization continue, this technology holds the potential to make a substantial impact on healthcare systems, ensuring the availability and effectiveness of vital vaccines and medications, even in challenging and resource-constrained environments.

Compliance with ethical standards

Acknowledgments

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Disclosure of conflict of interest

The authors declare no conflict of interest.

References

[1] Global Immunization Vision and Strategy (GIVS). Facts and figures, April 2005. http://www.who.int/vaccines/GIVS/english/Global imm. data EN.pdf.

[2] Protocol for evaluating freezing in the vaccine cold chain. Program for appropriate technology in Health, April 2003.

[3] G. A. Mannella*, V. La Carrubba, V. Brucato Peltier cells as temperature control elements: Experimental characterization and modeling, Elsevier - Applied Thermal Engineering 63, 2014, 234-245p.

[4] S.B. Riffat, X. Ma, Thermoelectrics: a review of present and potential applications, Appl.Therm. Eng. 23 (2003) 913-935.

[5] N.F. Guler, R. Ahiska, Design and testing of a microprocessor-controlled portable thermoelectric medical cooling kit, Appl. Therm. Eng. 22 (2002) 1271-1276.

[6] H.-S. Choi, S. Yun, K.-I. Whang, Development of a temperature-controlled car-seat system utilizing thermoelectric device, Appl. Therm. Eng. 27 (2007) 2841-2849.

[7] R. Chein, G. Huang, Thermoelectric cooler application in electronic cooling, Appl. Therm. Eng. 24 (2004) 2207-2217.

[8] Gauger DC, Shapiro HN, Pate MB. Alternative technologies for refrigeration and air-conditioning applications, United States environmental protection agency, Project Summary EPA/600/SR-95/066; 1995.

[9] Tassou SA, Lewis JS, Ge YT, Hadawey A, Chaer I. A review of emerging technologies for food refrigeration applications. Appl Therm Eng 2010;30:263–76.

[10] A.V. Kretinin, D.P. Shmatov, and E.E. Kulikova, Neural network simulation of multidisciplinary processes in thermoelectric devices, 2017 Second Russia and Pacific Conference on Computer Technology and Applications (RPC), Vladivostok, Russia, pp. 113-116, 25-29 Sept. 2017.

[11] S. Shaojing and Q. Qin, Temperature Control of Thermoelectric Cooler Based on Adaptive NN-PID, 2010 International Conference on Electrical and Control Engineering, Wuhan, China, pp. 2245-2248, 25- 27 June 2010.

[12] D. Yunfei, G. Wei, L. Mingwei, and F. Xuewu, Space High Precision Multi-thermoelectric Coolers Controller Design, 2013 Third International Conference on Intelligent System Design and Engineering Applications, Hong Kong, China, pp. 1276-1278, 16-18 Jan. 2013.

[13] U. Sanver, E. Yavuz, and C. Eyupoglu, “An electronic control unit for thermoelectric cooling,” in 2019 IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering (EIConRus), 2019, pp. 141–145.