DOI: 10.63527/1607-8829-2025-2-49-59

Dipak Bhoge[1] (https://orcid.org/0000-0003-3942-9915),
Avinash Kamble[1] (https://orcid.org/0009-0009-1188-3826),
B.K. Sonage[1] (http://orcid.org/0000-0002-6106-1355),
Neeraj Agrawal[2],
Swami Prasad[1],
Damdare Shridhar[1]

[1]N. K. Orchid College of Engineering & Technology, Solapur, Maharashtra, India;
[2]Dr. Babasaheb Ambedkar Technological University, Lonere, Maharashtra, India

Corresponding author: Dipak Bhoge, e-mail: *dipakbhoge@orchidengg.ac.in*

An Experimental Study of a Thermoelectric Cooling Unit Powered by Solar

Solar-powered Thermoelectric Refrigeration (TER) provides a promising alternative to conventional cooling methods, reducing dependence on traditional electricity sources and mitigating environmental impact. The TER system boasts an extended lifespan and minimal maintenance requirements. Positioned as an economical solar-powered solution, TER is an accessible refrigeration option for individuals and in remote desert regions where grid electricity is unavailable. This study focuses on assessing the performance of TER.

The research introduces a novel portable solar-powered thermoelectric refrigerator with a 30-liter capacity. The thermoelectric module's cooling effect is harnessed to create a refrigerated space, and the system is engineered to achieve a temperature of 16 °C in the cold chamber for effective refrigeration. Experimental findings indicate thermoelectric cooling unit successfully reaches the temperature 16 °C within 105 minutes, under room temperature of 29 °C. The system hot side maintains a temperature of around 35 °C with a water-cooled heat exchanger. This performance demonstrates the viability and efficiency of the proposed solar thermoelectric refrigerator for providing sustainable and reliable refrigeration in environments lacking conventional power infrastructure. The maximum COP obtained is 0.31. A solar-powered thermoelectric refrigerator offers eco-friendly cooling by utilizing renewable energy, reducing carbon emissions and dependence on conventional electricity.

Keywords: TER, solar, heat exchanger, thermoelectric, refrigerator.

Dipak Bhoge, Avinash Kamble, B.K. Sonage, Neeraj Agrawal, Swami Prasad, Damdare Shridhar (2025). An Experimental Study of a Thermoelectric Cooling Unit Powered by Solar. *Journal of Thermoelectricity*, (2), 49–59. https://doi.org/10.63527/1607-8829-2025-2-49-59

1. Introduction

Maintaining indoor thermal comfort in residential buildings is getting more costly and destructive to the environment. In the majority of countries, the cooling mechanism uses a lot of energy and produces more carbon dioxide emissions [1]. Refrigeration and HVAC systems are important; they account about 15 % of the world's electrical energy production. The air conditioner and refrigeration system together contribute to global warming and air pollution [2]. Thermoelectric modules directly convert electrical energy into cooling and heating or waste heat into electricity because of their unique mix of thermal, electrical, and semiconducting characteristics [3]. For heating and cooling, therefore, an alternative technology is needed to reduce the impact on the environment [4].

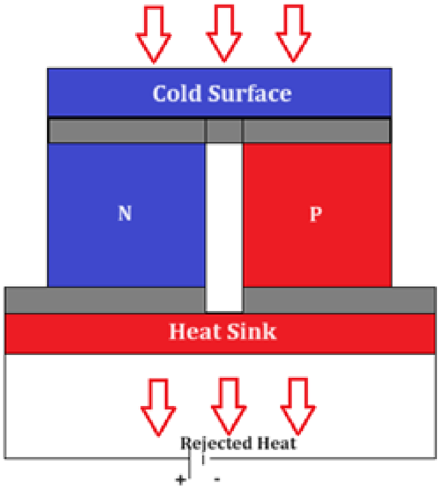

Fig. 1. Principle of Working of TEM

TE cooling unit has several benefits than traditional refrigeration systems, like being driven by direct current, having no working fluid or mechanical moving parts, being lightweight, highly reliable, and having an easy way to convert between heating and cooling modes [5]. Thermoelectric modules (TEM) represent semiconductor-based electronic devices functioning as solid-state heat pumps [6]. Operating on the principles of the Peltier effect, these modules establish distinct cold and hot surfaces. The core structure of a TEM (Fig. 1) comprises an array of semiconductor pallets engineered with doping, wherein either positive or negative charge carriers dominate the current flow. Sets of n-type and p-type pallets are strategically organized to configurations. Metalized ceramic substrates serve as the foundational platform for these pallets, with small conductive tabs interconnecting them. The fundamental operation of a TEM involves the passage of a direct current (DC) through the module, facilitating the transfer of heat and generating a temperature disparity across the ceramic substrates. Consequently, one side of the TEM surface becomes hot, while the other side becomes cold. This mechanism constitutes the direct conversion of electric voltage into thermal differentials, making thermoelectric modules efficient tools for manipulating temperature gradients in a wide range of applications. The investigation in thermoelectric refrigeration is outlined below. The researchers made diverse efforts to enhance the efficiency of thermoelectric modules.

Y. Koysa (2018) studied TEG module having maximum open circuit capacity of 1.423 V and achieved is 0.942 V for the obtained temperatures [7]. Building Integrated Photovoltaic Thermoelectric (BIPVTE) integrates solar cooling with an active photovoltaic façade. The findings showed that BIPVTE has an energy-saving ratio of about 480% in Hong Kong and that installing BIPVTE in six other cities can save energy about 29.19 to 62.94 kW·h per m^2 per year [8]. Solar powered TEM technology can serve the needs of refrigeration and air conditioning applications and also it is environmentally safe [9]. The thermoelectric module can use free, emission-free solar energy or clean energy sources than Grid electricity. A solar-assisted thermoelectric module is small, light, incredibly dependable, and runs on sustainable energy [10]. Its quick-switchable cooling and heating modes and lack of operating fluid and mechanical parts make it a better choice than a traditional refrigerator. In the previous research, it is observed various performance analyses (Comparison of TEM with VCRS, Comparing TEM with Grid electricity and solar-powered) used to check the performance of TEM, and very few attempts were made to compare the Solar-powered TEM with an air-cooled and water-cooled heat sink. The heat from hot side of surface of Peltier can be removed in different ways i.e. natural convection, forced convection, and water-cooled Heat sink.

<u>*Table 1*</u>

Significant Study related to Thermoelectric Refrigerator

Author	Methodology	Result
Atrain et al. [11]	Domestic hybrid refrigerator that combines VCR and thermoelectric technology for the cooler and freezer.	Observed improvement in performance and hybrid system consumes less energy [11].
A. Wahab et al. [12]	Study on the small solar powered thermoelectric colling unit.	Researcher observed the 22 °C drop in temperature in 44 min from 27 °C and COP = 0.6.
Zhao et. al. [13]	Thermoelectric colling unit combined with PCM for cooling.	Researcher observed the 7 °C drop in temperature in 2 hour and COP = 1.22
Gokçek et.al. [14]	An experimental evaluation of the performance of a Mini channel water cooled TER.	COP = 0.41.
D Enescu et al. [15]	Performance of TER unit.	The COP = 0.5 with a temperature drop of 20 °C.
Alam at al. [16]	Reducing the thermal conductivity of the material.	Improves the performance of thermoelectric material.
E Fenton et al. [17]	Phase change material (PCM) based Thermoelectric (TE) food storage refrigerator.	The COP = 0.69 with a temperature achieved below 5 ^{0}C.

From the above literature, it is observed that the COP is ranging from 0.16 to 1.22 for various systems. And the Minimum temperature reached up to –7.4 °C.

The main emphasis of this study is to foster a functioning model of a Solar powered thermoelectric cooling unit to cool a volume of 30 liters that uses the Peltier impact through TEM and also to check the performance with and without water cooled heat exchanger.

2. Experimentation

The experimental setup (Fig. 2) consists of several major components: solar panel, MPPT controller, battery, thermoelectric module, heat sink, cooling fan, insulated container of 30 liters, and a water pump. The Peltier module in the project has the specification TEC1-12710 – size 40 × 40 mm, voltage 12 V, current 10 A, max power 120 W is the part of the system. The heat sink fixes on the hot side of the TEM and mounts on the hot and cold side of the Peltier module for dissipating the heat. To intensify the level of heat transfer, a fan preferably of 12 V and 0.3 A current is used.

The water pump, specified as Make: PREET, Model: MGP 5510 with an 18 W capacity and a maximum pumping height of 1.7 meters, is integrated into the system to facilitate the circulation of cooling water, enhancing the overall thermal management.

The 60 A solar charge controller, also known as MPPT, ensures that the power output from the solar panel is efficient. It makes sure that the maximum possible power from the solar panel is tapped to charge the battery efficiently. This electrical energy stored in the 12 V, 120 A·h Autobat battery makes it possible for the entire refrigeration system to run, during low solar intensity or even at night.

This experimental setup uses solar power to run a thermoelectric cooling system, equipment including the Peltier module, heat sink, fan, and water pump. Combined with a solar charge controller and a reliable battery, the technology provides stable and effective cooling that fits the idea of usage in remote or off-grid conditions.

The cold side of the TEM is utilized for cooling applications; it provides cooling by natural convection in a space. The heat from the hot side of the module is rejected by using forced convection heat sinks and water-cooled heat sinks.

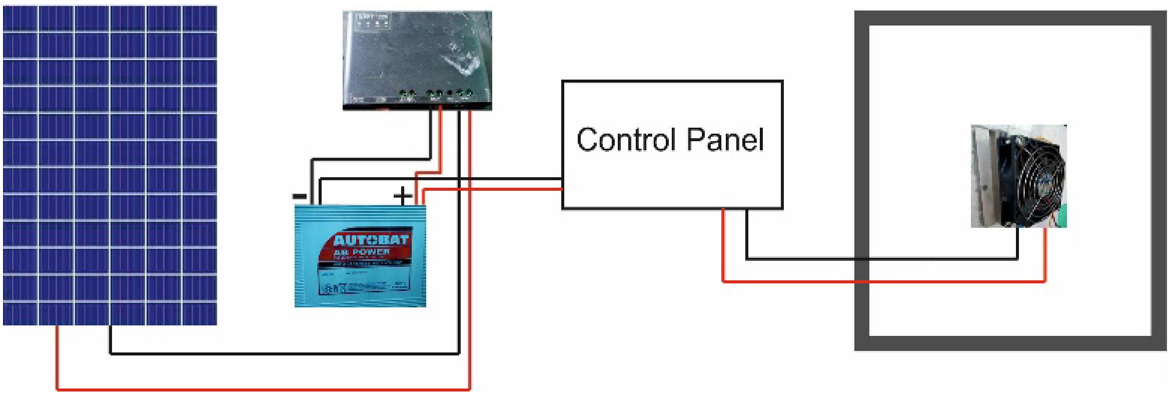

Fig. 2. Block Diagram of Experimental Setup

The TEC1-12710 Peltier modules have a capacity of 120 W. The heat exchangers of aluminum with fins attached. The specifications of inside and outside fins are 60 mm × 45 mm × 20 mm with 9 fins and 120 mm × 100 mm × 20 mm with 21 fins.

The dimensions for the inside and outside heat exchangers were 60 mm × 45 mm × 20 mm with 9 fins and 120 mm × 100 mm × 20 mm with 21 fins, respectively. The dimensions of the fins on the outside heat exchanger were 100 mm × 20 mm × 1 mm and those on the inside were 45 mm × 20 mm × 1 mm. Heat transfer between the aluminum heat exchangers and their surroundings was assisted by forced air convection provided by a brushless D.C. fan (3.6 W) attached to the outside heat exchangers. And water-cooled heat exchanger of 40 mm × 40 mm × 5 mm size. Seven K-type thermocouples are used to measure cold side fin temperature, inside room temperature, atmospheric temperature, temperature between the water sink and TEM at cold and hot side, and water inlet and outlet temperature. Temperature is measured with ±3% accuracy.

In the experimental setup, the natural convection heat sink at the cold side and forced convection heat sinks as shown in Fig. 3 or water heat sinks as shown in Fig. 4 at the hot side are used. The heat from the hot side of TEM is rejected by an air-cooled heat sink, fins, and fan. the heat from the hot side of tem is rejected by the water-cooled heatsink, fins, and fan. The heat is absorbed by the water at the hot end of TEM and it is rejected into the atmosphere by natural convection by spraying the water into the atmosphere as shown in Fig. 4. The average heat dissipated from the hot side was 135.13 W.

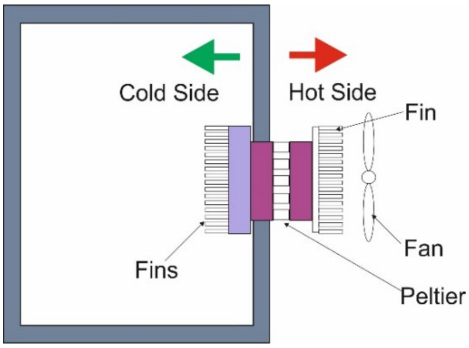

Fig. 3: TEM and Air-Cooled Heat Sink

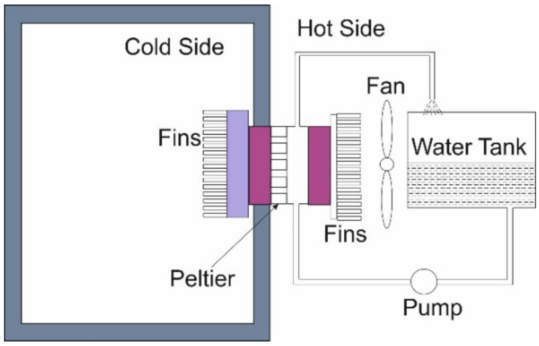

Fig. 4. TEM and Water-Cooled Heat Sink

3. Performance calculation

The system analysis is performed by using the first law of thermodynamics (Fig. 5) and the following is the procedure adopted for the analysis.

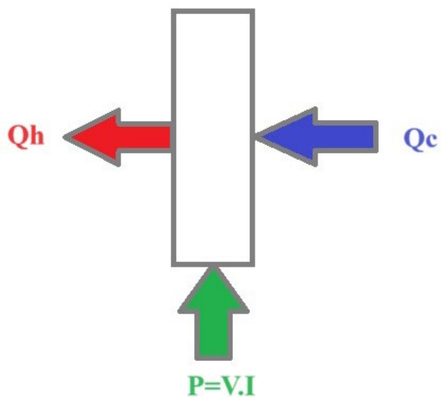

Fig. 5. Energy balance according to the First law

Heat rejected (Q_h) at the hot side is given by

$$Q_h = \dot{m} C_w \Delta T, \quad (1)$$

where $\dot{m}$ – rate mass flow (kg/sec), C_w – specific heat of water, (J/kg·K), ΔT – temperature difference (°C).

Heat absorbed at the cold side (Qc) i.e. cooling capacity

$$Q_c = Q_h - P \quad (2)$$

where

$$P = V \cdot I \quad (3)$$

P – electric power (W), V – voltage (V), I – current (A).

$$\mathrm{COP} = Q_c / P. \quad (4)$$

4. Result and discussion

4.1 Comparison of performance of Cooling unit with air cooled and water-cooled heat exchanger

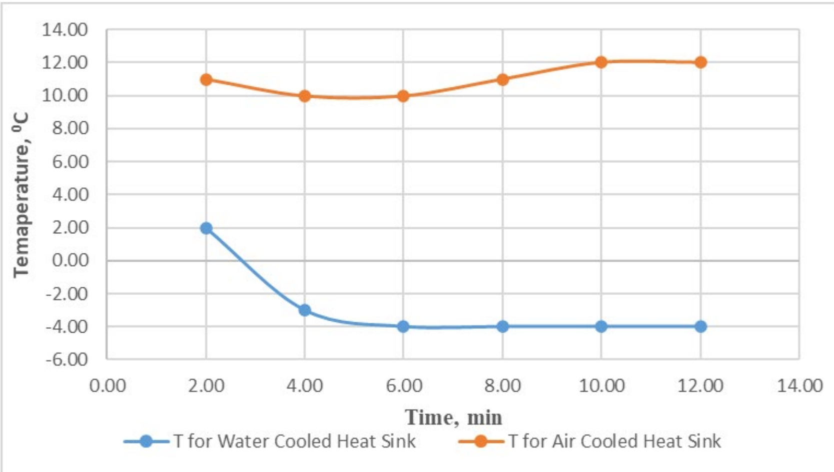

Fig. 6. Comparison of cold side surface temperature of TEM for air-cooled and water-cooled heat sink

From graph (Fig. 6) it is observed the cold side surface temperature of TE cooling unit for water cooled heat sink reached is –4 °C in 6min and for air cooled heat sink the cold temperature reached about 10 °C in 6 min. The cold temperature is achieved faster in a water-cooled heat sink; further detailed performance analysis of the Water-cooled TEM is done.

4.2 Cooling-time and temperature steadiness

The Figure 7 shows temperature progression in cold chamber and the temperature reach the 16°C during a period of 1 hour 45 minutes. At this time, the data shows a third order polynomial trend of temperature distribution with a good coefficient of determination (R2 Value 0.9659). Third order polynomial trend indicates a complex (nonlinear) dependence of temperature change due to the chamber, which may be attributed to different rates of heat transfer, thermal inertia, and other dynamic factors affecting the chamber environment. The polynomial equation better captures these variations than might a linear or quadratic model, and is thus a good way to predict temperature behavior in similar conditions. The high correlation proves that the temperature control mechanism is accurate, and our chamber is reaching 16°C in a repeatable fashion.

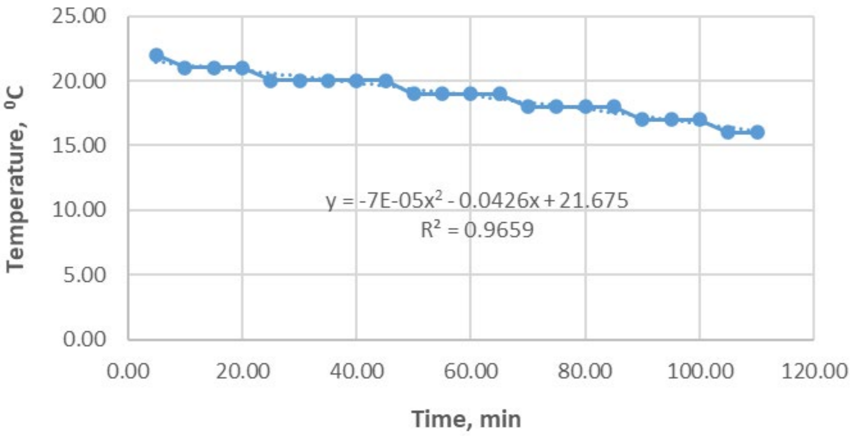

Fig. 7: Cooling-time and temperature steadiness

4.3 Performance of TER Cooling Unit with water cooled heat exchanger

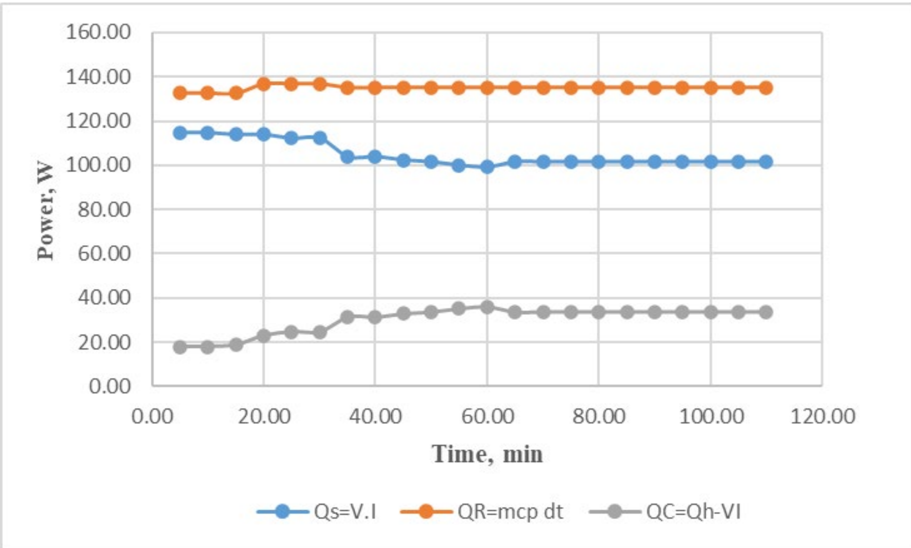

Fig. 8. Power input, cooling effect and heat rejected

Fig. 8 indicates after 40 minutes the unit has reached a steady state condition where the power input, cooling effect, and rate of heat rejected are all constant. Energy fluctuations have settled down at this stage providing for predictable operation. In this steady state on the other hand, the inputs and the outputs in the system balanced each other so the energy interactions in the system have reached equilibrium. According to the first law of thermodynamics which tells us that energy must be conserved, we should have power input to our system be equal to the combined energy of the cooling effect and the rate of heat rejected. This confirms that in steady state the system is in accordance to the energy balance equation. Validation is found that the system operates according to the thermodynamics, with its input power completely accounted for by heat flows to cool and remove waste heat. Data shown in Fig. 9 show that the system achieves a steady state having COP of 0.29 after around 65 minutes. A single thermoelectric module (TEM) in the system produces an average heat rejection of about 135 W at this steady condition. The module's efficient heat transfer, which is essential to reaching the system's intended temperature conditions, is reflected in this measured heat rejection capacity, making it crucial. Although modest, the COP value of 0.29 is consistent with conventional performance expectations for thermoelectric cooling systems, where adaptability and compact design are frequently weighed against efficiency.

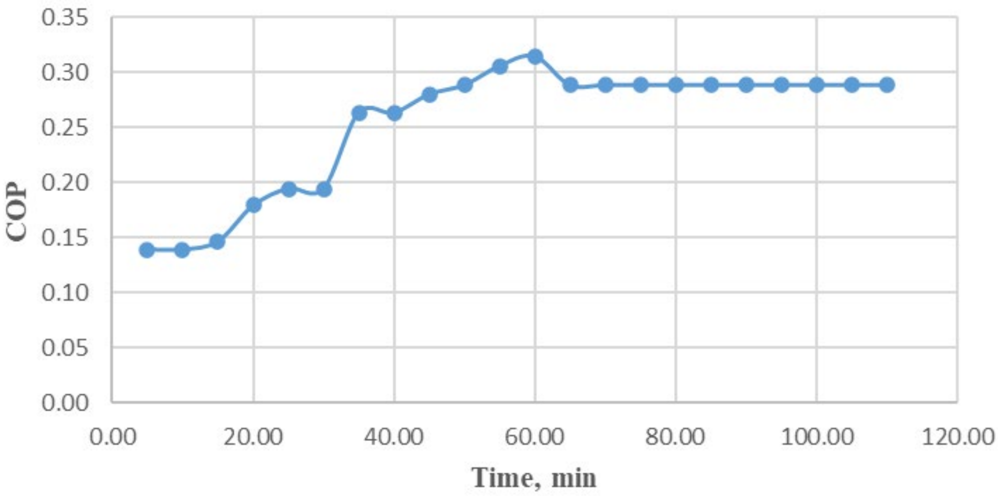

Fig. 9. COP vs time

Additionally, these experimental results support the thermoelectric module's dual-functional capabilities and are in good agreement with researchers D. Zhao (2014) and A. S. Patil (2021). The system's versatility and promise for energy-efficient applications across a range of thermal management scenarios are highlighted by its dual functionality as a cooling device and a heat source. The direction of electric current leads to, this dual functionality may fulfill varying temperature requirements, enabling optimal energy use in both heating and cooling scenarios. As a result, the system has potential for usage in applications that need controlled heating and cooling, such HVAC systems, environmental chambers, or localized heating and cooling in energy-sensitive environments, which increases its attractiveness for flexible and sustainable thermal management.

Conclusion

In conclusion, the current state of energy efficiency in thermoelectric refrigerators, utilizing existing materials and technology, remains somewhat lower than that of traditional compressor-based counterparts. Nevertheless, there is a viable avenue for creating a commercially viable thermoelectric refrigerator with an acceptable coefficient of performance (COP) when powered by solar energy. Furthermore, the potential exists for enhancing the COP by implementing thermoelectric modules for both cooling and heating applications. The coefficient of performance at steady state is 0.29 and heat rejected is about 135 W.

Despite the present efficiency gap, the environmental advantages of a thermoelectric refrigerator position it as an appealing alternative for environmentally conscious consumers. Those willing to invest slightly more for the benefits of quiet operation, precise and stable temperature control, and an extended lifespan may find the thermoelectric refrigerator a compelling choice. As technology continues to evolve, further advancements in materials and methodologies may contribute to closing the efficiency gap and expanding the appeal of solar-powered thermoelectric refrigeration solutions in the market.

Acknowledgments

The study presented here was funded by the La Fondation Dassault Systèmes and Nagesh Karajagi Orchid College of Engineering and Technology Solapur.

Authors' information

- Dipak Bhoge – Assistant Professor.
- Avinash Kamble – Assistant Professor.
- B.K. Sonage – Dr., Professor.
- Neeraj Agrawal – Dr., Professor.
- Swami Prasad – UG Student.
- Damdare Shridhar – UG Student.

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Submitted: 05.04.2025

Dipak Bhoge[1] (https://orcid.org/0000-0003-3942-9915),
Avinash Kamble[1] (https://orcid.org/0009-0009-1188-3826),
B.K. Sonage[1] (http://orcid.org/0000-0002-6106-1355),
Neeraj Agrawal[2],
Swami Prasad[1],
Damdare Shridhar[1]

[1]N. K. Orchid College of Engineering & Technology, Солапур, Махараштра, Індія;
[2]Dr. Babasaheb Ambedkar Technological University, Лонере, Махараштра, Індія

Експериментальне дослідження термоелектричного блоку охолодження, що живиться від сонячної енергії

Термоелектричне охолодження на сонячній енергії (ТЕО) є перспективною альтернативою традиційним методам охолодження, знижуючи залежність від традиційних джерел електроенергії і пом'якшуючи вплив на навколишнє середовище. Система ТЕО може пишатися тривалим терміном служби та мінімальними вимогами до обслуговування. Позиціоноване як економічне рішення на сонячній енергії, ТЕО є доступним варіантом охолодження для окремих осіб та у віддалених пустельних регіонах, де відсутня мережна електрика. Це дослідження сконцентровано на оцінці продуктивності ТЕО. Дослідження представляє новий портативний термоелектричний холодильник на сонячній енергії ємністю 30 літрів. Охолоджуючий ефект термоелектричного модуля використовується для створення охолодженого простору, система спроектована для досягнення температури 16 °C в холодильній камері для ефективного охолодження. Експериментальні результати показують, що термоелектричний блок охолодження успішно досягає температури 16 °C протягом 105 хвилин при кімнатній температурі 29 °C. Гаряча сторона системи підтримує температуру близько 35 °C за допомогою теплообмінника з водяним охолодженням. Ця продуктивність демонструє життєздатність та ефективність запропонованого сонячного термоелектричного холодильника для забезпечення сталого та надійного охолодження в середовищах, де відсутня звичайна енергетична інфраструктура. Максимальний отриманий холодильний коефіцієнт (COP) становить 0.31. Термоелектричний холодильник на сонячних батареях пропонує екологічно чисте охолодження за рахунок використання відновлюваної енергії, зменшення викидів вуглецю та залежності від традиційної електроенергії.

Ключові слова: термоелектричне охолодження, сонячний теплообмінник, термоелектричний холодильник.

Надійшла до редакції 05.04.2025