ISSN: 3048-9563

KT Journal of Mechanical Engineering

Key Tech Services Publication, India

http://www.ktjme.com
https://doi.org/10.64188/3048956325030
Vol.: 2, No. 4, 2025, Pages: 42-53

PERFORMANCE ANALYSIS OF A SINGLE STAGE COOLED THERMOELECTRIC REFRIGERATION SYSTEM

Kartik Kore[1], Sunny Loware[2], Bhagyashri Thakur[3], Bhakti Malshikare[4], Sagar G Mushan[5]

[1-5] School of Mechanical Engineering, MIT Academy of Engineering, Alandi, Pune

Abstract

Thermoelectric refrigeration systems offer an eco-friendly and compact alternative to conventional vapor compression systems due to the absence of refrigerants and moving parts. However, their practical application is limited by low cooling efficiency, primarily caused by ineffective heat rejection at the hot side. In this work, a single-stage water-cooled thermoelectric refrigeration system is designed, fabricated, and experimentally evaluated for small-scale cooling applications. The system employs TEC1-12706 thermoelectric modules, an insulated cooling cabinet, and a water-based heat rejection arrangement. Experimental studies are conducted under different water level conditions to analyze their effect on cooling performance. The results demonstrate that higher water levels significantly reduce the cooling time, with the fully filled condition achieving the target temperature of 20 °C in 1 h 36 min, compared to 2 h 41 min and 3 h 30 min for half-filled and pump-level conditions, respectively. Thermal analysis indicates a total heat load of 74.244 W, while the system operates with a total power consumption of approximately 152 W, achieving a coefficient of performance of 0.884. Furthermore, the feasibility of operating the system using a solar-based DC power supply is evaluated, demonstrating its suitability for off-grid and sustainable refrigeration applications. The outcomes of this study highlight the importance of effective hot-side cooling and support the potential of water-cooled thermoelectric refrigeration systems for portable and eco-friendly cooling solutions.

1. Introduction

Received:05.12.2024 Revised: 15.02.2025 Accepted: 04.04.2025 Published Online: 18.04.2025

Keywords: Thermoelectric refrigeration, Peltier module, water-cooled heat rejection, portable refrigeration, experimental analysis, solar-powered refrigeration, coefficient of performance

*Corresponding author name and email: Sunny Loware, sunny.loware@mitaoe.ac.in

How to cite this article: Kartik Kore, Sunny Loware, Bhagyashri Thakur, Bhakti Malshikare, Sagar G Mushan, Performance analysis of a single stage cooled thermoelectric refrigeration system, KT Journal of Mechanical Engineering, 2 (4) 2025,42-53. https://doi.org/10.64188/3048956325030

Refrigeration systems are essential in domestic, industrial, and medical applications for food preservation, thermal comfort, and temperature-sensitive storage. Conventional vapor compression refrigeration systems are widely adopted due to their high efficiency; however, they rely on refrigerants with high global warming potential and involve mechanically complex components that increase maintenance requirements [1]. Growing environmental concerns and the demand for compact and sustainable cooling technologies have motivated research into alternative refrigeration methods. Thermoelectric refrigeration, based on the Peltier effect, has emerged as an attractive alternative due to its eco-friendly operation, compact size, silent functioning, and absence of moving parts [7]. When a direct current passes through a thermoelectric module, a temperature difference is created between its hot and cold sides, enabling heat absorption and rejection. Despite these advantages, thermoelectric refrigeration systems typically exhibit low coefficient of performance, which restricts their application to low capacity and portable cooling systems [9]. Several researchers have reported that the performance of thermoelectric refrigerators is strongly influenced by the effectiveness of heat rejection at the hot side [1, 3]. Air cooled heat sinks often fail to maintain low hot-side temperatures, leading to reduced cooling capacity and efficiency. To overcome this limitation, water-cooled heat rejection systems have been proposed and experimentally validated, showing improved cooling performance and thermal stability [2, 5]. Studies conducted by Indian researchers have also confirmed that water cooling significantly enhances cabinet temperature reduction and system reliability in small-scale thermoelectric refrigeration systems [4, 6, 10]. Although water-cooled thermoelectric systems demonstrate superior performance, limited experimental work has focused on analyzing the effect of water level variation on cooling time and system efficiency. Most existing studies emphasize design optimization or numerical simulation, while integrated experimental investigations combining thermal performance, power consumption, and renewable energy feasibility remain scarce [8, 12]. Furthermore, with increasing interest in off-grid and sustainable energy solutions, the potential of operating thermoelectric refrigeration systems using solar-based DC power has not been sufficiently explored [15]. In this study, a single-stage water-cooled thermoelectric refrigeration system is designed, fabricated, and experimentally evaluated to investigate the influence of different water levels on cooling performance. The work includes thermal and electrical performance analysis, experimental validation of cooling behaviour, and an assessment of solar-powered operation feasibility. The outcomes of this research aim to contribute toward the development of efficient, portable, and environmentally sustainable thermoelectric refrigeration systems for small scale applications.

2. Literature Review

Thermoelectric refrigeration has gained attention as an ecofriendly alternative to conventional vapor compression systems due to its compact design and absence of refrigerants [1, 7]. However, the performance of thermoelectric refrigerators is highly dependent on effective heat rejection at the hot side. Riffat and Ma [1] reported that liquid-cooled heat sinks significantly enhance cooling performance compared to air-cooled systems. Several experimental studies have demonstrated the advantages of water-cooled thermoelectric refrigeration systems. Patel and Parmar [2] and Naphon and Wiriyasart [3] reported improved cabinet cooling and lower hot-side temperatures when water cooling was employed. Indian researchers such as Sharma and Yadav [4] and Singh and Kumar [6] further confirmed that effective hot-side cooling improves system reliability and cooling efficiency in small scale thermoelectric refrigerators. Astrain and Aranguren [5] highlighted that liquid-based heat rejection reduces thermal resistance and improves heat transfer effectiveness. Recent studies by Verma and Gupta [10] and Zhang and Li [11] also demonstrated enhanced performance of water-cooled thermoelectric systems over air-cooled configurations. Although previous research establishes the benefits of water-cooled thermoelectric refrigeration, limited experimental work focuses on the effect of water level variation on cooling time and performance. Moreover, the integration of thermal analysis, power consumption evaluation, and solar-powered operation remains insufficiently explored, which forms the basis of the present study. Most existing studies focus on comparing air cooled and water-cooled thermoelectric refrigeration systems, while the specific influence of water level variation on cooling performance is not adequately investigated. Limited experimental research is available on single-stage water-cooled thermoelectric refrigerators operating under different practical water availability conditions. Many reported works emphasize simulation or heat sink optimization, whereas integrated experimental studies combining thermal performance and cooling time analysis are relatively scarce. The combined evaluation of heat load, coefficient of performance, and electrical power consumption under real operating conditions is insufficiently addressed. The feasibility of operating thermoelectric refrigeration systems using solar-based DC power sources for off-grid applications has not been extensively explored.

3. Methodology

The present work involves the design, fabrication, and experimental evaluation of a single-stage water-cooled thermoelectric refrigeration system to study the effect of water level variation on cooling performance. The system consists of two TEC1-12706 thermoelectric modules mounted between a cold-side heat sink and a hot-side water cooled heat sink. The cold side is placed inside a polystyrene-insulated cabinet to reduce heat gain, while the hot side is connected to a water circulation arrangement for efficient heat rejection.

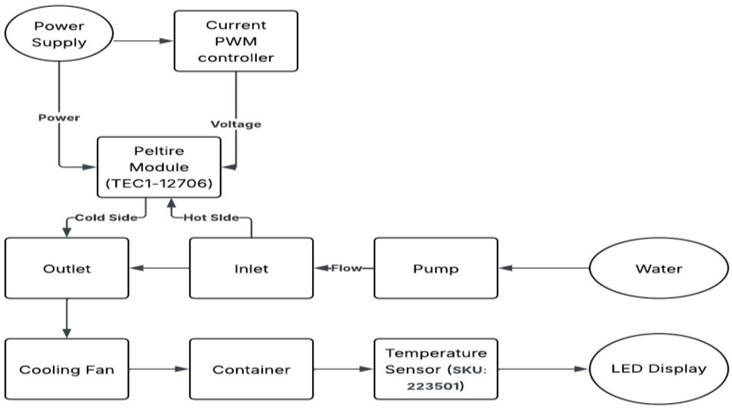

Fig.1: Block Diagram Representing Flow

A DC power supply provides electrical energy to the system through a PWM controller, which regulates the voltage and current supplied to the thermoelectric modules. A DC water pump circulates water from the reservoir through the hot side heat exchanger, allowing heat absorbed at the hot side to be removed effectively. Cooling fans are used to enhance heat transfer and maintain uniform temperature distribution within the cabinet. A temperature sensor is installed inside the cabinet to continuously monitor the temperature, and the readings are displayed for real-time observation. Experimental testing is conducted under three different water level conditions, namely fully filled, half-filled, and water filled up to pump level. For each condition, the cabinet temperature is recorded at regular intervals until the target temperature of 20 ºC is achieved. The cooling time is analyzed along with thermal and electrical performance parameters, including heat load, power consumption, and coefficient of performance. This methodology enables a systematic evaluation of the influence of water level on thermoelectric refrigeration performance and supports the assessment of solar-based DC operation feasibility.

B. System Requirement The thermoelectric refrigeration system is designed to operate as a low-voltage DC, single-stage water-cooled cooling unit suitable for small-scale experimental analysis. The system is required to achieve a target temperature reduction from ambient conditions (26 ºC) to 20 ºC within a reasonable time while maintaining stable operation under different water level conditions. The system must support continuous operation, allow temperature monitoring, and be compatible with solar-based DC power supply for future integration.

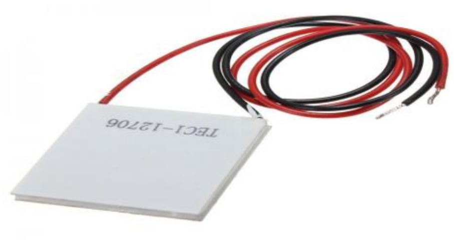

Fig. 2: TEC1-12706 Peltier Module

The core requirement of the system is the use of thermoelectric cooling based on the Peltier effect, with sufficient heat rejection capability at the hot side to maintain effective cooling. The system must accommodate controlled water circulation, ensure proper thermal contact between components, and operate safely within electrical and thermal limits.

Fig. 3: Cooling Fan

Hardware requirements include two TEC1-12706 thermoelectric modules operating at 12 V DC, a water-cooled heat sink on the hot side, a cold-side heat sink inside an insulated cabinet, two 6 V DC cooling fans, and a 12 V DC water pump. The refrigeration cabinet must be insulated using polystyrene or thermocol to minimize heat gain. A DC power supply capable of delivering approximately 12 V and 13 A is required to operate the system. Temperature sensors and a digital display are required for monitoring cabinet temperature during experimentation.

Fig. 4: Water Pump

The system must be capable of operating under three different water level conditions: fully filled, half-filled, and water filled up to pump level, to evaluate the effect of water availability on cooling performance. Electrical components must be compatible with solar-based operation, allowing integration of a 250 W, 12 V solar panel, battery, and charge controller for off-grid functionality.

Fig. 5: AC to DC Power Supply

4. Design and Analysis

A. Design and Dimension: The thermoelectric refrigeration system is designed as a single-stage, water-cooled unit for small-scale and portable cooling applications. The design is based on the Peltier effect and focuses on enhancing hot-side heat rejection to improve system performance while operating on low voltage DC power

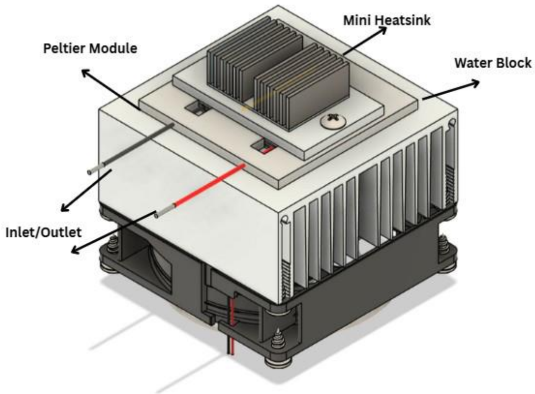

Fig. 6: Fan and Heat Sink Assembly

The system employs two TEC1-12706 thermoelectric modules mounted between a cold-side heat sink inside an insulated cabinet and a hot-side water-cooled heat sink. The refrigeration cabinet is insulated using polystyrene to minimize heat gain, with internal dimensions of 255 mm × 215 mm × 245 mm.

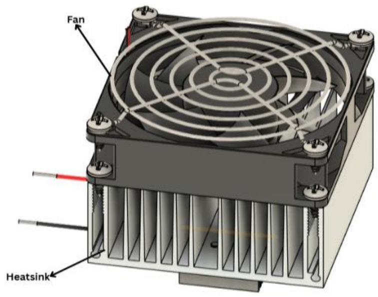

Fig. 7: Peltier Cooling System Assembly

A water circulation system comprising a reservoir, tubing, and a 12 V DC water pump is used to remove heat from the hot side. The system supports different water level conditions to facilitate experimental evaluation. The electrical design operates at 12 V DC and includes cooling fans and temperature sensors, allowing future integration with a solar-based power supply.

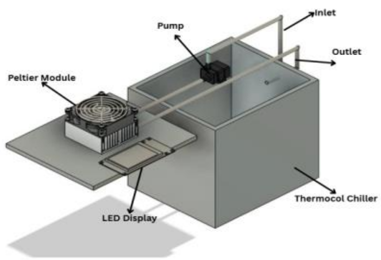

Fig. 8: Final Assembly

Table 1: Dimensions of Major System Components

Component	Dimension
Thermoelectric module (TEC1-12706)	40 mm × 40 mm × 3.8–4 mm
Refrigeration cabinet (internal)	255 mm × 215 mm × 245 mm
Hot-side water block	40 mm × 40 mm × 12 mm
Hot-side heat sink (air assisted)	40 mm × 40 mm × 25 mm
Cooling fan	40 mm × 40 mm × 10 mm
Mini DC water pump	45 mm × 43 mm

B. Analysis: The performance analysis of the single-stage water-cooled thermoelectric refrigeration system is carried out based on thermal load estimation, electrical power consumption, and experimental cooling behaviour. The analysis focuses on evaluating whether the selected thermoelectric modules and cooling arrangement are adequate for the desired temperature reduction. The internal volume of the refrigeration cabinet is calculated using the relation $V = L \times W \times H$. With internal dimensions of 255 mm, 215 mm, and 245 mm, the cabinet volume is obtained as 0.01343 m^3. This confirms that the system is designed for small-scale cooling applications. The temperature difference across the cabinet walls is determined from the ambient temperature of 26 ºC and the target internal temperature of 20 ºC, resulting in a temperature difference of 6 ºC. Polystyrene insulation with a thermal conductivity of 0.033 W/m· K and thickness of 0.03 m is used to minimize heat ingress. The total surface area of the cabinet is calculated using $A = 2(LW + WH + LH)$, which gives a surface area of 0.340 m^2 Heat transfer through the cabinet walls is then estimated using the conduction equation $Q = (k \times A \times \Delta T) / d$,resulting in a wall heat load of 2.244 W.

Additional heat loads due to stored items and internal components are considered as 60 W and 12 W, respectively. The total heat load acting on the system is calculated as the sum of these contributions, yielding a total heat load of 74.244 W. Based on this heat load, two TEC1-12706 thermoelectric modules are selected to provide sufficient cooling capacity. Electrical analysis shows that each thermoelectric module operates at 12 V and 6 A, consuming 72 W. With two modules, the total thermoelectric power consumption is 144 W. Including the power consumption of the cooling fans and water pump, the overall system power consumption is approximately 152 W. Using these values, the coefficient of performance of the system is calculated as COP = Qtotal /Pinput, which gives a COP of 0.884.

Table II: Summary of Calculated and Experimental Parameters

PARAMETER	VALUE
Cabinet volume	5L
Ambient temperature	26 °C
Target temperature	20 °C
Temperature difference	6 °C
Total surface area	0.340 m^2
Heat transfer through walls	2.244 W
Heat load from stored items	60 W
Internal heat load	12 W
Total heat load	74.244 W
Total power consumption	~152 W
Operating voltage	12 V DC
Operating current	~13 A
Coefficient of performance	0.884
Cooling time (5 L water)	1 h 36 min
Cooling time (2.5 L water)	2 h 41 min
Cooling time (1.3 L water)	3 h 30 min
Recommended solar panel	250 W, 12 V

A. Result: The experimental performance of the single-stage water cooled thermoelectric refrigeration system was evaluated by measuring the time required to reduce the internal temperature from ambient conditions (26 ºC) to the target temperature of 20 ° C under different water level conditions. The temperature variation with time is presented using a Temperature vs Time graph, which clearly illustrates the cooling behaviour of the system.

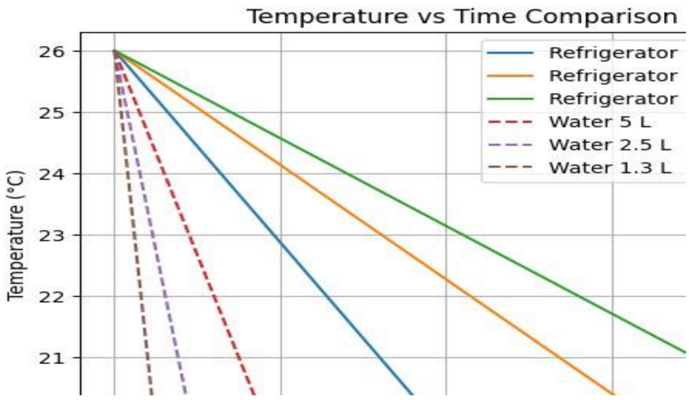

Fig. 9: Temperature Variation with Time for Different Water Levels

The results show that the cooling performance strongly depends on the water level in the hot-side cooling arrangement. When the water reservoir is fully filled, the system achieves the target temperature in the shortest time. As the water level is reduced to half-filled and pump-level conditions, the cooling time increases significantly. This trend confirms that improved hot-side heat rejection enhances thermoelectric refrigeration performance.

Table 3: Comparison of Cooling Time for Thermoelectric System and Conventional Refrigerator

SYSTEM / CONDITION	**WATER QUANTITY**	**TIME TO REACH 20 °C**
Thermoelectric system (fully filled)	5 L	1 h 36 min
Thermoelectric system (half-filled)	2.5 L	2 h 41 min
Thermoelectric system (pump-level)	1.3 L	3 h 30 min
Conventional refrigerator (estimated)	5 L	40–50 min
Conventional refrigerator (estimated)	2.5 L	20–25 min
Conventional	1.3 L	10–15 min

To further evaluate the effectiveness of the developed system, the cooling time of the thermoelectric refrigerator is compared with the estimated cooling time of water placed inside a conventional refrigerator operating under similar ambient and target temperature conditions.

B. Discussion: The experimental results confirm that effective heat rejection at the hot side is a critical factor in improving thermoelectric refrigeration performance. Increasing the water level enhances heat removal from the hot side, leading to reduced cooling time and improved temperature stability. The observed trends are consistent with findings reported in earlier studies on water-cooled thermoelectric systems. The electrical analysis shows that the total power consumption of the developed system is approximately 152 W at 12 V DC. This low-voltage DC operation makes the system suitable for integration with renewable energy sources. As a future modification, the system can be powered using a solar-based DC power supply consisting of a 250 W solar panel, a charge controller, and a battery. The solar panel can supply power directly to the thermoelectric modules, cooling fans, and water pump through the charge controller, while the battery ensures continuous operation during low solar availability. Since the system operates on DC power, the need for an inverter is eliminated, reducing energy losses. This modification enables off-grid operation and enhances the sustainability of the system. Overall, although the thermoelectric refrigeration system exhibits lower cooling performance compared to conventional refrigerators, its environmental benefits, portability, and compatibility with solar power make it a promising solution for small-scale and remote refrigeration applications.

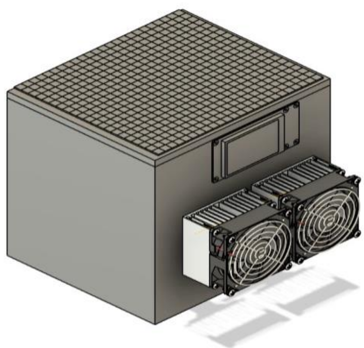

Fig. 10: Further Modification with Solar Panel

4. Conclusion

This study presented the design and experimental evaluation of a single-stage water-cooled thermoelectric refrigeration system for small-scale cooling applications. The results showed that effective hot-side water cooling significantly improves system performance by reducing the time required to reach the target temperature. Thermal and electrical analysis indicated a total heat load of 74.244 W and a power consumption of approximately 152 W, resulting in a COP of 0.884. Although the system exhibits lower cooling performance compared to conventional refrigerators, it offers advantages such as ecofriendly operation, compact design, and low maintenance. The feasibility of solar-based DC operation was also demonstrated, showing that the system can be powered using a 250 W solar panel with battery backup. This makes the proposed system suitable for portable, off-grid, and sustainable refrigeration applications.

Fig. 11: Final Model

References

1. S. B. Riffat and X. Ma, Thermoelectric refrigeration systems: A review of heat rejection techniques and performance improvement methods, Applied Thermal Engineering, vol. 130, pp. 1353–1365, 2018
2. V. K. Patel and H. J. Parmar, Experimental analysis of a single-stage water-cooled thermoelectric refrigerator, International Journal of Engineering Research and Technology, vol. 8, no. 6, pp. 742–747, 2019
3. P. Naphon and S. Wiriyasart, Experimental investigation of thermoelectric refrigerator with different cooling methods, International Communications in Heat and Mass Transfer, vol. 102, pp. 1–8, 2019.
4. Bhatkar V. W. Kriplani V. M., Awari G. K., Alternative refrigerants in vapour compression refrigeration cycle for sustainable environment: a review of recent research International Journal of Environmental Science and Technology, 10(4), 871-880, 2013. Doi 10.1007/s13762-013-0202-7
5. A. Sharma and R. Yadav, Design, and experimental investigation of a thermoelectric refrigeration system for small cooling applications, Journal of Thermal Engineering, vol. 6, no. 3, pp. 235–243, 2020
6. Bhatkar V.W., A. Sur, An experimental analysis of liquid air jet pump, Frontiers in Heat and Mass Transfer, 17 (12), 1-7, 2021. DOI: 10.5098/hmt.19.15
7. D. Astrain and P. Aranguren, Optimization of heat sinks for thermoelectric refrigeration systems, Energy Conversion and Management, vol. 210, 112733, 2020.
8. P. Singh and M. Kumar, Experimental performance analysis of thermoelectric refrigeration system using different cooling arrangements, Materials Today: Proceedings, vol. 46, pp. 10234–10239, 2021
9. Bhatkar V. W., Sur Anirban, Ramesh Kumar, Study of Refrigeration System with Minichannel Condenser using R1234ze, R134a, R152a, R600a, R290 and a Mixture of R290 and R600a (50/50), Journal of Process Mechanical Engineering, Vol. 239, No 2, 2023, https://doi.org/10.1177/09544089231193923
10. W. He, G. Zhang, and X. Zhang, Recent advances in thermoelectric cooling technologies and applications, Renewable and Sustainable Energy Reviews, vol. 141, 110800, 2021

11. A. R. Patel and N. K. Mehta, Experimental study on cabinet cooling performance of a thermoelectric refrigerator, International Journal of Mechanical Engineering and Technology, vol. 12, no. 4, pp. 56–63, 2021
12. S. Maneewan and S. Chindaruksa, Investigation of operating conditions of thermoelectric refrigerators for low-capacity applications, Energy Reports, vol. 8, pp. 421–429, 2022
13. Bhatkar V.W., Anirban Sur, A. Roy, Exergy analysis of a refrigeration system with a minichannel condenser using R134a refrigerant, Frontiers in Heat and Mass Transfer, 19 (15), 1-7, 2022. DOI: 10.5098/hmt.19.15
14. Indian Patent IN 202221045678 A, Compact water-cooled thermoelectric refrigeration system for portable applications, Indian Patent Office, 2022
15. U.S. Patent US 20210287541 A1, Thermoelectric cooling system with liquid-cooled heat rejection, United States Patent and Trademark Office, 2021
16. R. Mishra and S. Tiwari, Experimental analysis of a single-stage thermoelectric refrigerator for small-scale cooling applications, Journal of Cleaner Production, vol. 412, pp. 137402, 2024