



Numerical Analysis of the Effect of Peltier Modules on the Thermal Performance of a Thermoelectric Icebox

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ABSTRACT

The increasing prevalence of diseases and epidemics, particularly in recent years, such as the COVID-19 pandemic, has highlighted the challenges associated with transporting temperature-sensitive medicines and medical supplies to remote areas. Maintaining these products within specified temperature ranges while ensuring portability is essential for preserving their quality and effectiveness. Therefore, this study aims to design, develop, and analyze a portable thermoelectric refrigeration system for the storage and transportation of medical supplies under controlled temperature conditions. The proposed system provides a mechanism for maintaining medical supplies at suitable temperatures to ensure optimal storage conditions. Different configurations were investigated to achieve lower internal temperatures, with particular emphasis on varying the number and arrangement of thermoelectric coolers (TECs) based on Peltier modules. Changes in the Peltier configuration resulted in substantial variations in the internal temperature of the storage box. The reported temperature reductions were 113% for the first model, 95% for the second model, 108% for the third model, and 106% for the fourth model. The study further investigates the effect of the number of Peltier thermoelectric coolers on the thermal performance of the system and evaluates their potential for reducing electrical energy consumption. ANSYS simulation software was employed to analyze heat transfer and temperature distribution within the storage box, as well as the transient flow behavior of the cooling air. The findings provide insights into the influence of TEC configuration on the cooling performance of portable thermoelectric refrigeration systems for temperature-sensitive medical supplies.

1. Introduction

A thermoelectric (TE) unit, also known as a Peltier cooler or thermoelectric cooler (TEC), is a semiconductor-based electrical device that functions as a heat pump by transferring heat from one side of the device to the other, thereby producing a heating or cooling effect. TEC units are commonly fabricated using bismuth telluride (Bi_2Te_3), a thermoelectric material suitable for compact and environmentally friendly cooling applications that do not require conventional refrigerants. Bismuth telluride-based TEC modules can provide effective thermal performance through semiconductor

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elements positioned between two ceramic plates. The thickness and properties of these ceramic layers can influence thermal stress distribution and consequently affect the reliability of the module [1].

The Peltier effect has been widely applied in thermal analysis, calorimetry, calibration, and heat-flow correction. Peltier-based cooling technologies have also been incorporated into microcalorimeters and cooling systems for computer processors [2]. Previous experimental studies have investigated thermoelectric refrigerators powered by solar cells and examined the thermomechanical performance of small-scale TE cooling systems [3]. However, Joule heating generated by the electrical current supplied to a thermoelectric module can significantly influence its performance and reliability. At high input currents, substantial temperature gradients may develop across the thermoelectric legs and contact layers, potentially increasing thermal stresses and reducing the reliability of the TEC module [4].

Conventional cooling and cold-chain systems are available in many developing countries, but their installation and operation can be relatively expensive. Thermoelectric cooling provides an alternative for applications in which compactness, portability, and precise temperature control are important. Refrigerated vehicles are commonly employed for long-distance transportation between cities, while insulated transport systems may incorporate thermoelectric devices or conventional mechanical refrigeration to maintain the required temperature. Thermoelectric systems can be designed to accommodate different temperature requirements by determining an appropriate operating range, integrating suitable cooling components into the storage compartment, and evaluating the resulting cooling performance [5].

Compared with conventional refrigeration systems, thermoelectric cooling offers several advantages:

- i. Thermoelectric devices operate based on thermoelectric phenomena in semiconductor materials. Depending on the mode of operation, temperature differences can be converted into electrical energy, while the application of direct current can generate a temperature difference across the module.

- ii. Thermoelectric cooling is driven directly by direct-current (DC) electricity. Because the system contains no conventional moving mechanical components, it can provide quiet, vibration-free, and potentially reliable operation.

- iii. TEC modules are compact and can operate without conventional refrigerants such as chlorofluorocarbons (CFCs). Their compact solid-state construction also provides flexibility in installation and orientation.

- iv. Their relatively simple construction can shorten system-development cycles and potentially reduce maintenance and operating requirements [6].

The solid-state architecture of thermoelectric systems enables compact system design, precise temperature control, and reversible heating and cooling by changing the direction of the electrical current. These characteristics make thermoelectric devices attractive for applications requiring localized and controlled thermal management [7,8]. Peltier modules are particularly suitable for small-scale refrigeration systems. When the cooling capacity of a single module is insufficient, multiple thermoelectric modules can be integrated to increase the overall cooling capacity. Nevertheless, the number and arrangement of TEC modules must be optimized because increasing the number of modules also increases electrical consumption and the heat-rejection requirements on the hot side [9].

Heat-sink design is therefore an important factor affecting the thermal performance and efficiency of thermoelectric cooling systems. Effective removal of heat from the hot side of the TEC is necessary to maintain the required temperature difference and achieve satisfactory cooling

performance. Thermoelectric technology has attracted increasing attention for specialized applications, particularly in the medical sector. Peltier cooling systems have been investigated for patient temperature management, localized skin cooling, medical devices, laboratory equipment, and other temperature-sensitive applications. Previous studies have also examined the economic and thermal performance of air-cooling systems incorporating different numbers and configurations of Peltier modules [10–13], including experimental investigations of thermoelectric cooling performance [14,15].

Temperature-controlled transportation is particularly important for medical materials with limited storage lifetimes or strict thermal requirements. Medical transport containers must maintain appropriate environmental conditions during transportation while remaining sufficiently compact and portable. Thermoelectric air-cooling systems provide a potential solution because they operate without the compressors and rapidly moving mechanical components typically associated with conventional refrigeration systems. Consequently, they can reduce vibration, which may be advantageous for the transportation of sensitive medical materials. Furthermore, TEC modules operate using direct current and can provide either heating or cooling depending on the direction of current flow [16].

In this study, a temperature-controlled thermoelectric medical storage box was designed, fabricated, and analyzed. The system employs Peltier thermoelectric modules to maintain controlled internal temperatures for the transportation and storage of temperature-sensitive materials, including organs, blood products, vaccines, and other medical supplies. The study evaluates the thermal performance of the proposed system with particular emphasis on the influence of Peltier-module configuration on cooling performance and energy consumption.

2. Literature Review

Peltier cooling devices have undergone substantial improvements in efficiency, thereby expanding their potential applications, particularly in the medical sector and thermoelectric power generation. The performance of thermoelectric materials is commonly evaluated using the dimensionless figure of merit (ZT), and considerable research has focused on enhancing ZT through approaches such as alloying and nanostructuring. Heat-sink design has also received significant attention, as effective heat dissipation is critical to the overall thermal performance and efficiency of thermoelectric modules.

Liu *et al.* [17] reviewed recent developments and challenges in thermoelectric cooling technology, with particular emphasis on advances in thermoelectric materials, device configurations, and practical applications. The study examined key factors influencing thermoelectric cooling performance and discussed applications in electronic thermal management, electric vehicles, medical treatment, and refrigeration. The authors emphasized that further improvements in thermoelectric materials and device design are essential for achieving higher cooling capacity and energy efficiency.

Pamula *et al.* [18] developed and experimentally evaluated a compact thermoelectric cooling system for transporting temperature-sensitive biological samples using unmanned aerial vehicles (UAVs). The proposed system incorporated Peltier cooling modules into a lightweight, insulated container designed to maintain controlled thermal conditions during transportation. Experimental tests were conducted under different operating conditions to assess the cooling performance of the system. The results showed that the system could achieve temperatures as low as -10°C , demonstrating the feasibility of Peltier-based cooling for transporting temperature-sensitive biological materials, including organs, vaccines, and other medical samples.

Khan *et al.* [19] designed and experimentally investigated a portable Peltier-based thermoelectric cooling system for vaccine storage. The system employed four 12-V DC Peltier modules coupled with external heat sinks and was powered by a solar panel and rechargeable batteries. Experimental tests were performed under different cooling loads, including an empty storage compartment and vaccine tubes filled with water. Under loaded conditions, the system reached a temperature of 8°C after approximately 90 min and achieved a coefficient of performance (COP) of 0.42. These findings demonstrated the feasibility of Peltier-based thermoelectric cooling as a portable solution for maintaining the temperature requirements of vaccine storage.

Sankaran *et al.* [20] developed an Internet of Things (IoT)-based medical container for transporting organs and other temperature-sensitive healthcare products using UAVs. The proposed system integrated a Peltier cooling module with temperature sensing, monitoring, and control components to maintain suitable thermal conditions inside the container throughout transportation. Real-time temperature monitoring and control were incorporated to enhance the reliability of the portable medical transportation system. The study demonstrated the potential of combining thermoelectric cooling with IoT-enabled monitoring and control to maintain controlled thermal conditions during the transportation of organs and other temperature-sensitive healthcare products.

3. Numerical Analysis

The boundary conditions and geometric configuration of the refrigerated container considered in this study are illustrated in Figure 1. The figure presents the container geometry, insulation materials, and airflow conditions used in the analysis. The container was designed in a rectangular box configuration with dimensions of 36.5 cm × 36.5 cm in the x- and y-directions and a depth of 56 cm along the z-axis.

Following the design and fabrication of the container, temperature measurements were recorded on both the hot and cold sides of the Peltier modules. The electrical current drawn by each module was also measured to evaluate the relationship between electrical input and cooling performance. The primary objective of the analysis was to optimize the temperature distribution within the refrigerated container to provide suitable conditions for the storage and transportation of temperature-sensitive medical materials. The assessment included evaluating the ability of the container to maintain the required internal temperature, identifying potential thermal leakage through the insulation and container walls, and defining the relevant properties of the container and insulation materials.

Computational Fluid Dynamics (CFD) analysis was employed to investigate the temperature distribution, heat transfer, and airflow behavior within the refrigerated container. However, the interpretation of the numerical results should consider the complexity of the underlying heat-transfer and fluid-flow phenomena, as well as the assumptions and limitations associated with the CFD model. The geometry and principal boundary conditions adopted for the numerical analysis are presented in Figure 1.

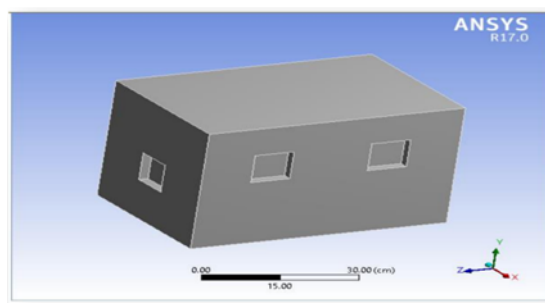


Fig. 1. Geometry of the icebox in ANSYS program

ANSYS software was used to simulate the temperature distribution and airflow characteristics inside the refrigerated container. The governing equations for continuity, momentum in the three coordinate directions, and energy were solved numerically. A total of 200 computational iterations were performed to obtain a converged solution for the velocity field, airflow behavior, and temperature distribution within the computational domain.

The numerical analysis was conducted to investigate the effects of different container configurations, including single- and two-level arrangements, on internal airflow and temperature distribution. The CFD model was also used to evaluate temperature variations along the container walls under specified thermal and airflow boundary conditions. These simulations provide insight into heat-transfer mechanisms and air circulation within the refrigerated compartment.

Experimental measurements were conducted using temperature sensors to determine the temperatures on both the hot and cold sides of the Peltier modules. The electrical current drawn by each Peltier module was also measured to evaluate its operating performance. In addition, the internal temperature of the container was monitored using a display system integrated with the Thingier.io platform. These measurements were used to evaluate the cooling performance of the system and to establish the relationship between temperature variation, operating time, and container dimensions.

Table 1

Thermophysical properties of the container wall material and the internal and external air [18]

Parameter	Polyurethane	Fluid(Air Exterior)	(Internal Air container)
Density(Kg/m ³)	50	1.184	Perfect gas
Specific heat (J/kg. K)	950	1007	1007
Thermal conductivity (K)(W/m. K)	0.025	0.02551	0.02551
Viscosity coefficient (Kg/m. s)		1.849×10^{-5}	1.849×10^{-5}
Flow rate(Kg/s)		5	0.00281

The locations of the Peltier modules were subsequently determined based on the container configuration, as illustrated in Figure 1. For the CFD analysis, the input and outlet boundary

conditions, wall properties, insulation-material specifications, and internal and external airflow conditions were defined in ANSYS. The principal parameters and boundary conditions employed in the numerical model are summarized in the following table [17].

4. Ansys Mesh

The ANSYS Meshing tool was used to discretize the three-dimensional solid model of the refrigerated container into a finite number of computational elements and nodes. This discretization process converts the continuous geometric domain into a numerical mesh that can be used to solve the governing equations for heat transfer and fluid flow.

Mesh size, particularly the characteristic element edge length, is an important parameter affecting both numerical accuracy and computational cost. In general, a finer mesh can provide a more detailed representation of temperature and airflow variations; however, it also increases computational time and memory requirements. Therefore, an appropriate balance between solution accuracy and computational efficiency must be established. Different mesh sizes were considered, and a suitable mesh resolution was selected to provide reliable numerical results within a reasonable computational time.

After developing the geometric model, the locations of the Peltier modules were defined and the cooling container was discretized using the selected mesh configuration. Appropriate boundary surfaces, including the container walls, Peltier interfaces, air inlet and outlet regions, and external surfaces, were identified and assigned corresponding boundary names to facilitate the subsequent CFD setup.

The experimentally measured temperatures on the hot and cold surfaces of the Peltier modules were incorporated into the numerical model as thermal boundary conditions where applicable. Other relevant initial and boundary conditions were subsequently specified in ANSYS based on the experimental configuration.

The numerical analysis was performed to investigate temperature distribution throughout the refrigerated container and across its walls, including the external wall surfaces. The influence of different internal levels or compartment configurations on cooling performance was also examined. In addition, the airflow velocity distribution within the container was analyzed to determine the circulation characteristics of the cooled air. Temperature and velocity contours were subsequently generated to visualize the thermal and airflow behavior within the computational domain and to evaluate the overall cooling performance of the proposed system.

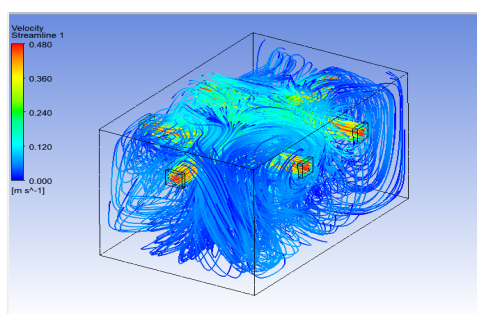


Fig. 2. Velocity distribution contours for Model 1

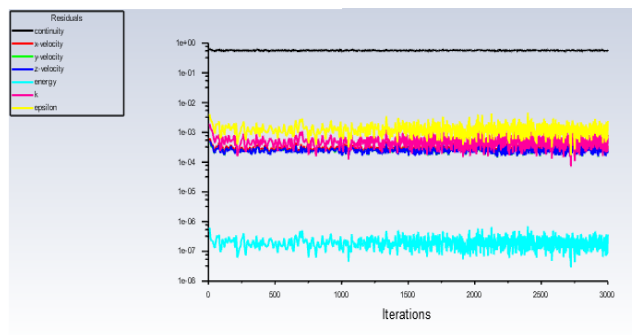


Fig. 3. Convergence histories of continuity, energy, and velocity components in the x-, y-, and z-directions as a function of the number of iterations for Model 1

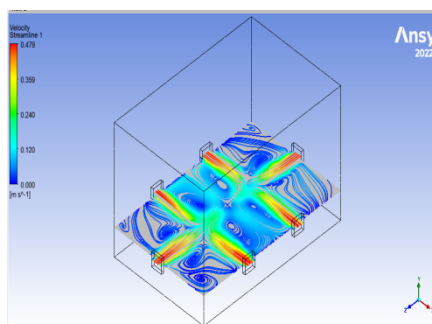


Fig. 4. Velocity distribution contours for Model 2

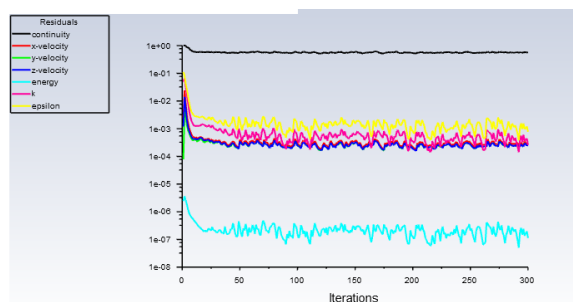


Fig. 5. Convergence histories of continuity, energy, and velocity components in the x-, y-, and z-directions as a function of the number of iterations for Model 2

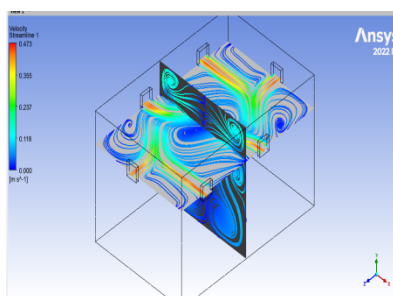


Fig. 6. Velocity distribution contours for Model 3

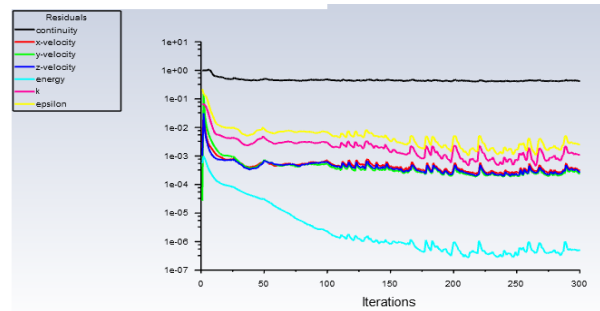


Fig. 7. Convergence histories of continuity, energy, and velocity components in the x-, y-, and z-directions as a function of the number of iterations for Model 3

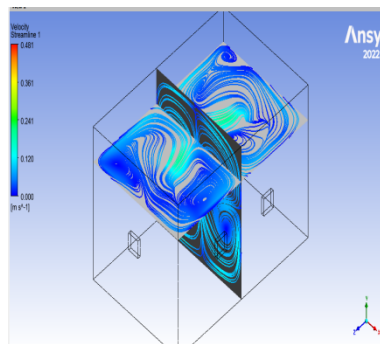


Fig. 8. Velocity distribution contours for Model 4

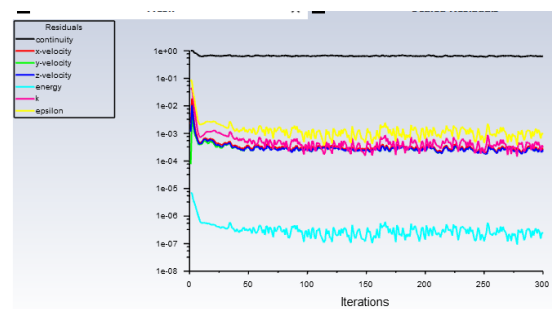


Fig. 9. Convergence histories of continuity, energy, and velocity components in the x-, y-, and z-directions as a function of the number of iterations for Model 4

5. Mathematical Equations

$$Q_{\text{active}} = I^2 R \quad (1)$$

$$Q_{\text{conduction}} = K \times A \times \frac{dT}{dX} \quad (2)$$

$$Q_{\text{convection}} = h A (T_0 - T_c) \quad (3)$$

$$Q_{\text{radiation}} = F_s \times \epsilon \times \sigma \times T_o \times T_c \quad (4)$$

$$Q_{\text{total}} = Q_{\text{active}} + Q_{\text{cond}} + Q_{\text{conv}} + Q_{\text{rad}} \quad (5)$$

$$Ex = -Q_H \left(1 - \frac{T_o}{T_c}\right) \quad \text{Exergy Equation} \quad (6)$$

The negative sign in the law indicates heat gain

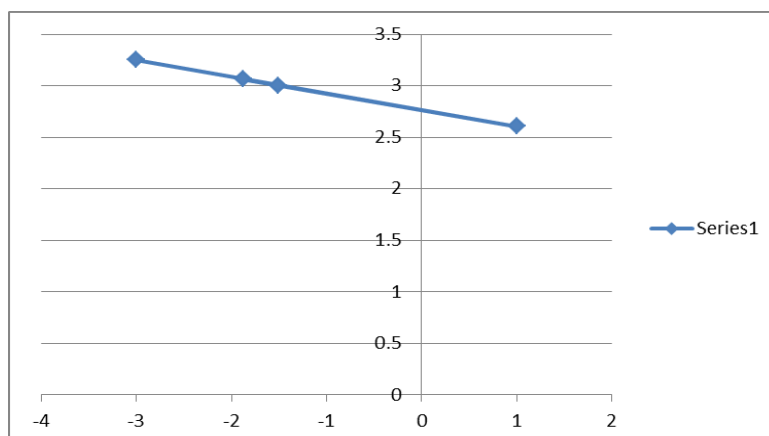


Fig. 10. Relationship between exergy and the cold-side temperatures obtained for the four models

6. Results And Discussion

This study investigates four thermoelectric cooling configurations for the developed cooling box. In each model, the positions of the Peltier modules are varied to evaluate their influence on the temperature distribution and overall cooling performance. Numerical simulations are performed using ANSYS to analyze the thermal behavior of each configuration.

Model 1

In Model 1, the Peltier modules are positioned at the top of the cooling box. Numerical analysis is performed using ANSYS to evaluate the resulting temperature distribution. During operation, natural convection causes warmer air to rise toward the upper region of the box, while colder air moves downward. Consequently, the Peltier modules located at the top remove heat from the warmer air accumulating in this region, promoting cooling throughout the enclosure.

The numerical results show that the maximum temperature inside the box is approximately 292 K, while the minimum temperature reaches approximately 270 K. These results demonstrate the effect of the top-mounted Peltier configuration on the internal temperature distribution and provide a basis for comparison with the other three configurations.

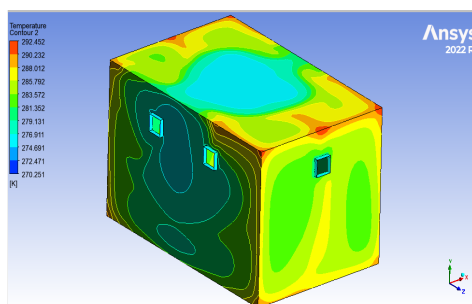


Fig. 11. Temperature gradients across the external surfaces of the cooling box

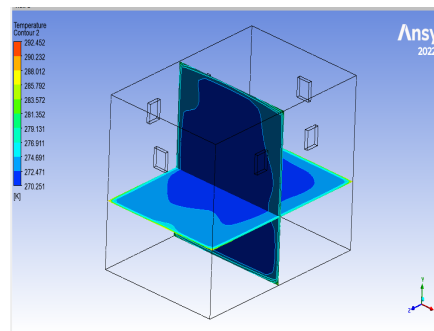


Fig. 12. Internal temperature distribution within the cooling box

Model 2

In Model 2, the Peltier modules are positioned at the bottom of the cooling box. The numerical results indicate that warmer air naturally rises toward the upper region of the enclosure, while colder air generated by the Peltier modules remains concentrated near the bottom. Consequently, the upper region maintains a relatively higher temperature, resulting in a less uniform temperature distribution throughout the box.

The numerical analysis shows that the maximum temperature inside the box is approximately 296 K, while the minimum temperature is approximately 274 K. Compared with Model 1, this configuration produces higher minimum and maximum temperatures, indicating that positioning the Peltier modules at the bottom is less effective in achieving uniform cooling throughout the enclosure.

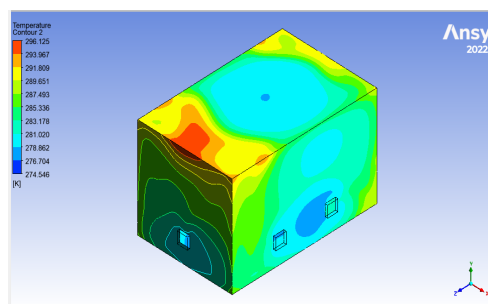


Fig. 13. Temperature gradients across the external surfaces of the cooling box

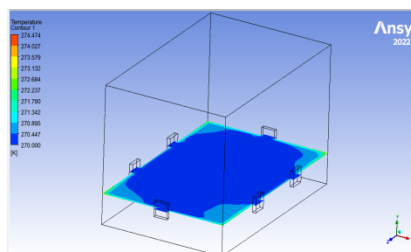


Fig. 14. Internal temperature distribution within the cooling box

Model 3

In Model 3, the Peltier modules are positioned asymmetrically within the cooling box. The numerical results indicate the formation of vortices in the central region of the enclosure. These vortices produce zones with limited circulation of cooled air, resulting in regions that are not cooled

effectively. Consequently, the asymmetric arrangement leads to a less uniform temperature distribution within the box.

The numerical analysis shows that the maximum temperature inside the box is approximately 293 K, while the minimum temperature reaches approximately 271.12 K. These results indicate that the positioning of the Peltier modules significantly influences airflow patterns and temperature distribution. Therefore, minimizing stagnant or poorly cooled regions should be considered when determining the optimal arrangement of Peltier modules.

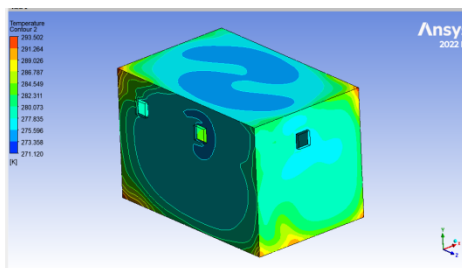


Fig. 15. Temperature gradients across the external surfaces of the cooling box

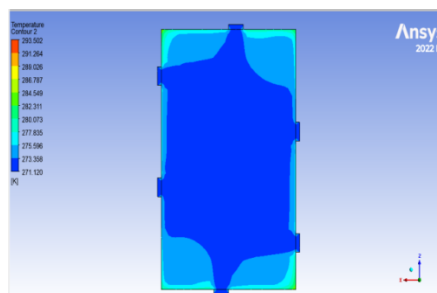


Fig. 16. Internal temperature distribution within the cooling box

Model 4

In Model 4, the Peltier modules are positioned opposite each other on the sides of the cooling box. This arrangement promotes a more balanced airflow pattern within the enclosure. Unlike the asymmetric configuration in Model 3, no significant vortex formation is observed, allowing the cooled air to circulate more uniformly throughout the internal space.

The numerical analysis shows that the maximum temperature inside the box is approximately 293 K, while the minimum temperature reaches approximately 271.49 K. The absence of significant vortices suggests that the opposing Peltier configuration provides a more stable airflow pattern and reduces the formation of poorly cooled regions within the enclosure. Therefore, this arrangement may provide a more uniform internal temperature distribution compared with the asymmetric configuration.

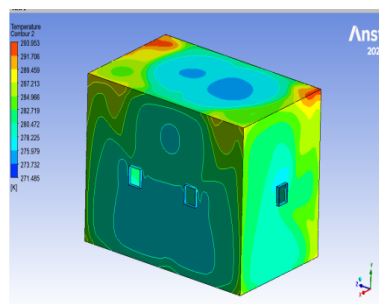


Fig. 17. Temperature gradients across the external surfaces of the cooling box

After analyzing and comparing the thermal performance of the four configurations, the final design of the thermoelectric cooling box was developed. The selection of the Peltier module arrangement was based on the numerical results obtained from the ANSYS simulations, particularly the internal temperature distribution, airflow characteristics, vortex formation, and minimum and maximum temperatures. The resulting design aims to achieve effective and relatively uniform cooling while minimizing poorly cooled regions within the enclosure.

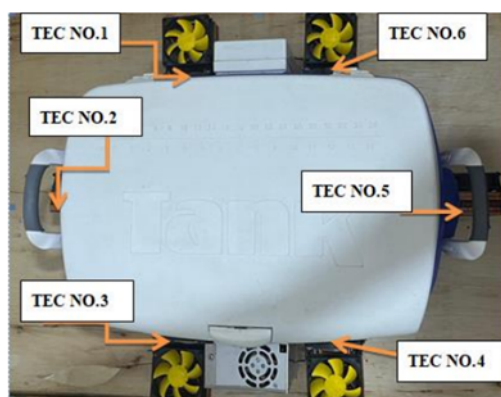


Fig. 18. Design of the cooling box showing the locations of the Peltier modules

To provide sufficient cooling capacity, the system consists of an insulated cooling box equipped with six thermoelectric cooling (TEC) modules. Each Peltier module is coupled with two heat sinks: an internal heat sink installed on the cold side and assisted by a fan to enhance heat transfer and cold-air circulation, and an external heat sink installed on the hot side to dissipate the heat transferred from the enclosure. The locations and arrangement of the Peltier modules within the cooling-box design are illustrated in Figure 16.

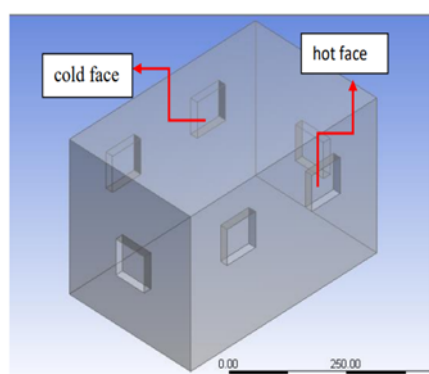


Fig. 19. Three-dimensional representation of the hot and cold surfaces of the thermoelectric cooling (TEC) modules

7. Conclusions

This study investigated four thermoelectric cooling configurations to determine the effect of Peltier module placement on the thermal performance of the developed cooling box. Numerical simulations using ANSYS were conducted to evaluate the temperature distribution and airflow characteristics for each configuration.

The results demonstrate that the location and arrangement of the Peltier modules significantly influence the cooling performance of the system. Among the four configurations, Model 1 exhibited the most favorable thermal performance, achieving a minimum temperature of approximately 270 K and a maximum temperature of 292 K. Positioning the Peltier modules at the top of the enclosure allows warmer air rising through natural convection to interact effectively with the cooling surfaces, while the cooled air subsequently moves downward through the enclosure.

In contrast, Model 2 exhibited the least favorable performance, with temperatures ranging from approximately 274 K to 296 K. When the Peltier modules were positioned at the bottom of the enclosure, the cooled air tended to remain concentrated in the lower region, while warmer air accumulated in the upper region. This resulted in a less effective and less uniform cooling process. Models 3 and 4 produced intermediate thermal performance. In Model 3, the asymmetric arrangement of the Peltier modules generated vortices that created regions with limited cold-air circulation, thereby reducing cooling uniformity. Model 4, in which the Peltier modules were positioned opposite each other, reduced significant vortex formation and produced a more balanced airflow pattern. Nevertheless, neither configuration achieved the minimum temperature obtained with Model 1.

The exergy analysis further supports the thermal-performance results. Exergy represents the maximum useful work that can theoretically be obtained from a system as it approaches equilibrium with its surroundings. Among the investigated configurations, Model 1 exhibited the highest exergy, whereas Model 2 exhibited the lowest. This indicates that Model 1 provides the greatest potential for effective utilization of the thermoelectric cooling system under the investigated operating conditions.

Overall, the findings demonstrate that Peltier module placement is a critical design parameter affecting temperature distribution, airflow behavior, and exergy performance. Based on the numerical and exergy analyses, Model 1 provides the most favorable configuration among the four investigated designs and is therefore selected as the preferred arrangement for the proposed thermoelectric cooling box.

References

- [1] Nagendra Singh Chauhan and Takao Mori, "Cooler, Stronger, Smaller: Improving Thermoelectric Cooling," *National Science Review* 12, no. 1 (2025): nwae445. <https://doi.org/10.1093/nsr/nwae445>.
- [2] Yihan Liu, Hao-Yuan Cheng, Jonathan A. Malen, and Feng Xiong, "Thermoelectric Active Cooling for Transient Hot Spots in Microprocessors," *Nature Communications* 15 (2024): 4275. <https://doi.org/10.1038/s41467-024-48583-9>.
- [3] Noor Alam, Mohammed Salman Ali, Syed Sajid, Deepak Sharma, and Zahir Hasan, "Experimental Investigation and Analysis of Cooling Performance of Solar Thermoelectric Refrigerator," *Solar Energy* 263 (2023): 111892. <https://doi.org/10.1016/j.solener.2023.111892>.
- [4] Lin Mu, Hu Zhang, Jiale Cui, Junfeng Zhao, Yan Shang, Hang Pu, and Ming Dong, "Numerical Study of Transient Supercooling Performance and Thermal Stress Analysis of Segmented Annular Thermoelectric Cooler," *Applied Thermal Engineering* 245 (2024): 122804. <https://doi.org/10.1016/j.applthermaleng.2024.122804>.

- [5] Nazia Rodoshi Khan, Tasnuva Sharmin, Md. Azazul Haque, and Md. Hamidur Rahman, "Photovoltaic Thermoelectric Cooling System for Off-Grid Vaccine Refrigerator: An Experimental Study," *Transactions of the Canadian Society for Mechanical Engineering* 47, no. 4 (2023): 596–617. <https://doi.org/10.1139/tcsme-2023-0003>.
- [6] Chengjun Li, Yubo Luo, Wang Li, Boyu Yang, Chengwei Sun, Wenyuan Ma, Zheng Ma, Yingchao Wei, Xin Li, and Junyou Yang, "The On-Chip Thermoelectric Cooler: Advances, Applications and Challenges," *Chip* 3, no. 2 (2024): 100096. <https://doi.org/10.1016/j.chip.2024.100096>.
- [7] Lijun Wang, Xiao-Lei Shi, Yicheng Yue, Lvzhou Li, Chenguang Dong, Jing Guan, Jing Ding, Ningyi Yuan, and Zhi-Gang Chen, "Advances in Solid-State and Flexible Thermoelectric Coolers for Battery Thermal Management Systems," *Soft Science* 4 (2024): 32. <https://doi.org/10.20517/ss.2024.15>.
- [8] María Ibáñez-Puy, Javier Bermejo-Busto, César Martín-Gómez, Marina Vidaurre-Arbizu, and José Antonio Sacristán-Fernández, "Thermoelectric Cooling-Heating Unit Performance under Real Conditions," *Applied Energy* 200 (2017): 303–314. <https://doi.org/10.1016/j.apenergy.2017.05.020>.
- [9] Kun Liang, Zhaohua Li, Ming Chen, and Hanying Jiang, "Comparisons between Heat Pipe, Thermoelectric System, and Vapour Compression Refrigeration System for Electronics Cooling," *Applied Thermal Engineering* 146 (2019): 260–267. <https://doi.org/10.1016/j.applthermaleng.2018.09.120>.
- [10] Yao-Tsung Lin, Indra Permana, Fujen Wang, and Rong-Jie Chang, "Improvement of Heating and Cooling Performance for Thermoelectric Devices in Medical Storage Application," *Case Studies in Thermal Engineering* 54 (2024): 104017. <https://doi.org/10.1016/j.csite.2024.104017>.
- [11] Hamed Sadighi Dizaji, Samira Pourhedayat, Ali E. Anqi, Fayez Aldawi, Theyab R. Alsenani, and Hazim Moria, "Enhanced Peltier Refrigerator Using an Innovative Hot-Side Heat-Rejection Mechanism: Experimental Study under Both Transient and Steady-State Conditions," *Energy* 309 (2024): 133132. <https://doi.org/10.1016/j.energy.2024.133132>.
- [12] Jingshuang Zhang, Xiaohui Song, Junfeng Lei, Cheng Li, Yingjie Zhang, Lixian Sun, and Huadong Zhao, "Performance and Regression Analysis of Air-Cooled Thermoelectric Cooling System Using Response Surface Methodology and Numerical Simulation," *International Journal of Heat and Mass Transfer* 228 (2024): 125617. <https://doi.org/10.1016/j.ijheatmasstransfer.2024.125617>.
- [13] M. N. Abd-Al Ameer, Iman S. Kareem, and Ali A. Ismaeel, "Effect of Thermoelectric Cooler Arrangements on Thermal Performance and Energy Saving in Electronic Applications: An Experimental Study," *Energy Engineering* 123, no. 1 (2026): 24. <https://doi.org/10.32604/ee.2025.073437>.
- [14] A. Massaguer, E. Massaguer, M. Comamala, T. Pujol, L. Montoro, M. D. Cardenas, D. Carbonell, and A. J. Bueno, "Transient Behavior under a Normalized Driving Cycle of an Automotive Thermoelectric Generator," *Applied Energy* 206 (2017): 1282–1296. <https://doi.org/10.1016/j.apenergy.2017.10.015>.
- [15] Qimin Cao, Weiling Luan, and Tongcai Wang, "Performance Enhancement of Heat Pipes Assisted Thermoelectric Generator for Automobile Exhaust Heat Recovery," *Applied Thermal Engineering* 130 (2018): 1472–1479. <https://doi.org/10.1016/j.applthermaleng.2017.09.134>.
- [16] Lidong Chen, Ruiheng Liu, and Xun Shi, "Design and Fabrication of Thermoelectric Devices," in *Thermoelectric Materials and Devices* (2021), 221–267. <https://doi.org/10.1016/B978-0-12-818413-4.00007-7>.
- [17] Dongrui Liu, Qian Cao, Bingchao Qin, and Li-Dong Zhao, "Progress and Challenges for Thermoelectric Cooling: From Materials and Devices to Manifold Applications," *Materials Lab* 3, no. 1 (2024): 230032. <https://doi.org/10.54227/mlab.20230032>.
- [18] Ganapathi Pamula, Lakshmi Pamula, and Ashwin Ramachandran, "Design and Characterization of an Active Cooling System for Temperature-Sensitive Sample Delivery Applications Using Unmanned Aerial Vehicles," *Drones* 8, no. 6 (2024): 270. <https://doi.org/10.3390/drones8060270>.
- [19] Yousaf Khan, Taimur Ahmed Khan, Muhammad Ilyas, Malik Taimur Ali, and Sheeraz Ahmed, "Experimental Investigation of Peltier Based Thermoelectric Cooling System for Vaccine Storage," *Journal of Computing & Biomedical Informatics* 6, no. 2 (2024): 139–147. <https://doi.org/10.56979/602/2024>.
- [20] Vijayalakshmi Sankaran, Paramasivam Alagumariappan, Balasubramanian Esakki, Jaesung Choi, Mohamed Thoufeek Kanrar Shahul Hameed, and Pavan Sai Kiran Reddy Pittu, "Devising an Internet of Things-Based Healthcare Medical Container for the Transportation of Organs and Healthcare Products Using Unmanned Aerial Vehicles," *Engineering Proceedings* 58, no. 1 (2023): 16. <https://doi.org/10.3390/ecsa-10-16003>.