Power Engineering and Engineering Thermophysics
https://www.acadlore.com/journals/PEET

A Semiconductor-Based Refrigeration System for Cooling of Water: Design, Construction, and Performance Tests

Taiwo O. Oni[1,2*], Samuel J. Aliyu[2], Bernard A. Adaramola[3], Oluwasina L. Rominiyi[3]

[1] Department of Mechanical Engineering, Ekiti State University, 360001 Ado-Ekiti, Nigeria
[2] Department of Mechanical Engineering, Landmark University, 251103 Omu-Aran, Nigeria
[3] Department of Mechanical and Mechatronics Engineering, Afe Babalola University, 360001 Ado-Ekiti, Nigeria

[*] Correspondence: Taiwo O. Oni (taiwo.oni@eksu.edu.ng)

Received: 11-14-2022 **Revised:** 12-14-2022 **Accepted:** 03-09-2023

Citation: T. O. Oni, S. J. Aliyu, B. A. Adaramola, and O. L. Rominiyi, "A semiconductor-based refrigeration system for cooling of water: Design, construction, and performance tests," *Power Eng. Eng. Thermophys.*, vol. 2, no. 1, pp. 15-25, 2023. https://doi.org/10.56578/peet020102.

Abstract: Convectional refrigeration is one of the causes of global warming as carbon dioxide is emitted from its refrigerant to the environment. Semiconductor-based refrigeration is one of the alternative technologies that can lower the carbon dioxide emissions to the atmosphere as it uses electron gas instead of a refrigerant as its working fluid. The present work aims to design and construct a semiconductor-based refrigerator and test its performance. The refrigerator was designed to cool 4×10^{-3} m^{-3} of water from a temperature of 30℃ to 0℃. The tests performed on the refrigerator were retention time of the temperature of the water, change in the water temperature at different intervals of time, and the cooling rate of the water. The results of the tests indicated that the temperature of the water dropped from its initial value of 30℃ to 0℃ after 225 minutes, and maintained the temperature of 0℃ for 15 minutes. After the refrigerator was switched off, the temperature of 0℃ was retained for approximately 30 minutes, and then took 192 minutes to rise from 0℃ to its initial value of 30℃. The average cooling rate for the duration of 225 minutes was 0.133℃/min. The current work widens the studies on the use of alternative technologies for convectional refrigeration.

Keywords: Cooling rate; Performance; Refrigerator; Retention time; Semiconductor; Temperature

1. Introduction

The achievement and maintenance of a temperature of a product or space below that of its immediate surrounding, the intention being to cool the product or the space to the required temperature, is known as refrigeration. It involves the removal of heat from the product or the space, and the transfer of the heat to a region at a temperature higher than that of the product or the space [1-3]. Applications of refrigeration are found in many areas, which include food preservation, electronic cooling, chemical process engineering, medical science [4, 5], cryogenics, air conditioning [6], etc.

The accomplishment of refrigeration can be through vapour compression refrigeration systems, absorption refrigeration systems, or special refrigeration systems, such as thermoelectric refrigeration systems and thermo-acoustic refrigeration systems [4, 5]. Vapour compression refrigeration and absorption refrigeration systems make use of mechanical components, namely compressor, pump, condenser, evaporator, and expansion valve [4]. This makes vapour compression and absorption refrigeration systems hard to be developed into portable ones [6, 7].

It has been reported that vapor compression refrigeration and absorption refrigeration systems use refrigerants (that is, working fluids), like chlorofluorocarbon (CFC) and hydrofluorocarbons (HFC), which are parts of the major causes of global warming through their carbon dioxide emissions to the environment [5].

To sunset chlorofluorocarbon and hydrofluorocarbons used in refrigerators and thereby diminish global warming that contributes to climate change, some countries, at the 28th meeting of Parties to the Montreal Protocol held in Kigali, Rwanda in 2016, have committed themselves to lessen their use of chlorofluorocarbon and hydrofluorocarbons by 2019 [8]. Therefore, researchers have directed their attention to developing and improving alternative refrigeration systems that use environmentally friendly and dirt-free techniques [5].

A thermoelectric refrigeration system is one of the alternative technologies that can contribute to lowering carbon dioxide emissions to the atmosphere [9, 10]. It replaces the circulation of a refrigerant in a convectional refrigerator with electron gas, that is, electron gas (rather than refrigerant) serves as the working fluid to carry the heat [5, 11, 12]. The compressor, evaporator, and condenser in a convectional refrigerator are replaced with a power source, heat source, and heat sink, respectively, in a thermoelectric refrigerator [13-15].

Thermoelectric refrigeration systems work on the principle of the Peltier effect which was discovered in 1834 by a French physicist, Francis et al. [16]. The principle states that when an electric current is passed through an array of two unalike semiconductors, one of the junctions of the semiconductors becomes cold through the absorption of electrons as the electrons move from one semiconductor to another, and the other junction becomes hot [15, 17, 18]. Therefore, a thermoelectric refrigerator can be reasonably referred to as a semiconductor-based refrigeration system. Its schematic representation is shown in Figure 1.

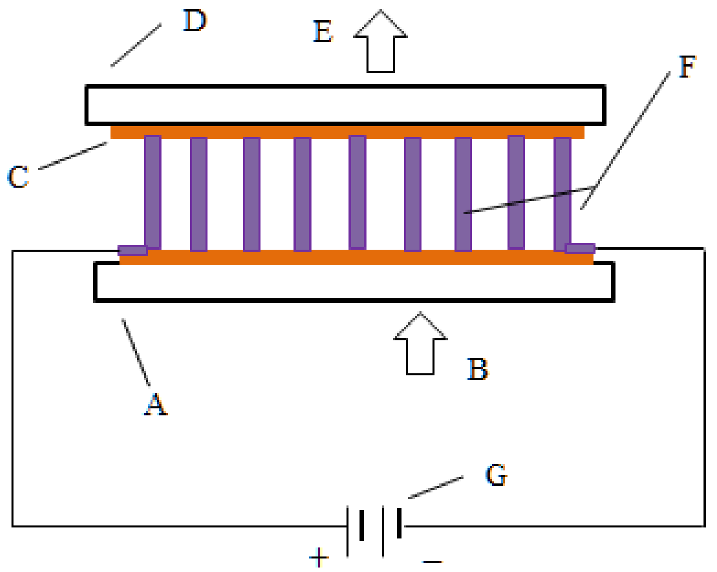


Figure 1. Schematic representation of a semiconductor-based refrigeration system (Key: A = heat source (cold), B = heat absorbed from a product or space, C = electrical insulator, D = heat sink (hot), E = heat rejected to environment, F = thermoelectric elements (semiconductors), G = power source)

Regardless of the fact that the coefficient performance of a semiconductor-based refrigeration system is not as high as for a vapour compression cycle, the characteristics of the semiconductor-based refrigeration system, which include noiselessness, high reliability [14, 15], light weight, low cost in bulk manufacturing, ruggedness [13, 15], vibration-free operation [15], compactness [19], longevity, low maintenance [20], and environmental friendliness [5, 21], have increased its acceptance among its users.

Semiconductor-based refrigeration has been applied in electronic components [22, 23], aerospace, automotive air-conditioning systems, submarines, surface vessels [22, 23], military, hotels, laboratory, scientific instruments, medical equipment [19], etc.

Investigations on semiconductor-based refrigeration have, before now, been carried out. Omer et al. [10] designed, fabricated, and tested a semiconductor-based refrigerator, and a phase change material was later integrated into it. The results showed that the integration of the phase change material improved the performance of the refrigerator.

A study on the performance of a cooling system that incorporated a thermoelectric module was reported by Naphon and Wiriyasart [24]. The system was applied for cooling a central processing unit of a computer and was found to have a good performance.

Awasthi and Mali [22] developed a thermoelectric cooler and used it to effect cooling. The cooler was able to remove heat from the product and transfer the heat to its immediate surrounding which was at a temperature higher than that of the product.

The performance parameter of a semiconductor-based refrigeration system, which was used to chill water, was analysed by Alomair et al. [5]. It was discovered that the coefficient of performance and the rate at which heat was removed by the system decreased with decreasing temperature of the water.

The investigation of the effect of different heat exchangers on the performance of a semiconductor-based refrigerator, which was carried out by Astrain et al. [25], showed that the most desirable design of the heat exchangers yielded higher values of coefficient of performance for the refrigerator.

Gökçek and Sahin [26] designed a small semiconductor-based refrigerator, used it to cool water, and carried out a performance analysis of the refrigerator. It was found through the assessment of its performance that the refrigerator could be relied upon to chill water.

Saifizi et al. [27] utilized a semiconductor-based refrigerator to store vaccines at a low temperature. Two different materials, namely stainless steel and aluminium, were used to hold the vaccines inside the refrigerator. It was revealed that the refrigerator with aluminium had a better cooling capacity than the one with stainless steel.

An evaluation of the comparison among semiconductor-based refrigeration, heat pipe, and vapour compression refrigeration systems for cooling of electronics was done by Liang et al. [7]. It was discovered that the semiconductor-based refrigeration system could be used for cooling electronics at lower temperatures, the heat pipe system was more suitable for cooling at higher temperatures, and the vapour compression refrigeration system could dissipate higher heat flux at lower temperatures.

A semiconductor-based refrigerator was used by Onoroh et al. [28] to reduce the temperature of the product that was put inside it, and the performance of the refrigerator was performed. It was reported that the refrigerator has a good performance. Kepekci et al. [29] and Xia et al. [30] have performed different investigations on thermoelectric refrigeration systems, and submitted that the systems can be reliably used achieve refrigeration.

Thus, it has been made known through the above pieces of literature and others that in a bid to effect cooling, various researches have been carried out on semiconductor-based refrigeration systems. In spite of these, extensive attention has not been paid to the retention time of the temperature of the products that are cooled by the refrigerator. This clearly indicates that more researches need to be done on semiconductor-based refrigeration. Therefore, in the present work, attention is on the design, construction, and performance test of a semiconductor-based refrigeration system for cooling water. The tests performed were retention time of the temperature of the water, change in the water temperature at different intervals of time, and the cooling rate of the water.

2. Design of the Refrigerator

2.1 Description of the Refrigerator

The semiconductor-based refrigerator being considered is designed to cool water. It comprises two chambers, namely the water chamber and module chamber, as shown in Figure 2. The water to be cooled is put inside the water chamber. Therefore, the water chamber can be referred to as the refrigeration chamber. The water chamber has a door that can be opened to allow water to be put inside it and closed later. The thermoelectric module is put inside the module chamber. Cables for the power supply are attached to the thermoelectric module. The refrigerator is placed on a stool.

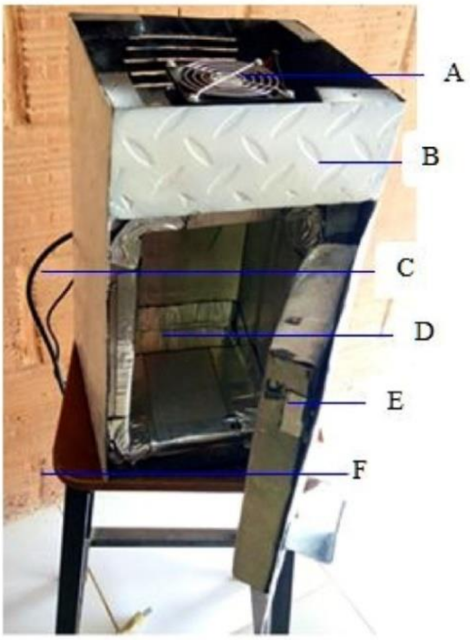


Figure 2. The refrigerator, showing its two chambers and other parts (Key: A = thermoelectric module, B = module chamber, C = cable for power supply, D = refrigeration chamber, E = door of the water chamber, F = stool on which the refrigerator sits)

2.2 Calculation of the Refrigerator Load

The two basic loads in the refrigerator are passive and active heat loads. Passive heat load considers the maintenance of a temperature difference between the ambient and the refrigeration chamber. It occurs as a result of heat transfers through the walls of the refrigerator. Active heat load arises from heat transfers through the products (that is, water in the case of the present work) put inside the refrigeration chamber.

2.2.1 Heat load from the walls of the refrigerator

The materials used to design the walls of the refrigeration chamber of the refrigerator are mild steel sheet, expanded polystyrene foam, and aluminium sheet. These materials are used for the outer wall, insulation, and inner wall, respectively. The specifications of the materials are presented in Table 1.

Table 1. Specifications of the materials used for the refrigeration chamber of the refrigerator

Material	Thickness (m)	Thermal conductivity (W/m.K) [31]
Mild steel sheet	0.0010	51.9
Expanded polystyrene foam	0.0345	0.027
Aluminium sheet	0.0005	177

The refrigerator was designed to cool 4×10^{-3} m^3 of water. The inner dimensions of the water chamber are a height of 0.219 m, a breadth of 0.135 m, and a depth of 0.135 m. This amounts to an inner volume of 4×10^{-3} m^3 (that is, 4 liters) of the water chamber. Considering these inner dimensions of the refrigeration chamber and the thickness of its walls (given in Table 1), the outer dimensions of the refrigeration chamber are a height of 0.291 m, a breadth of 0.207 m, and a depth of 0.207 m.

The heat load through the walls of the refrigeration chamber is given by the relation,

$$Q_w = \frac{A_w.(T_h - T_c)}{\frac{x_s}{k_s} + \frac{x_p}{k_p} + \frac{x_l}{k_l}} \tag{1}$$

where, Q_w is the heat transfer through the walls (W); A_w is the area of the walls through which heat is transferred (m^2), T_h is the initial temperature of the water (K); T_c is the temperature to which the water is cooled (K); x_s, x_p, x_l is the thickness of mild steel sheet, expanded polystyrene foam, and aluminium sheet, respectively, (m); and k_s, k_p, k_l is the thermal conductivity of mild steel sheet, expanded polystyrene foam, and aluminium sheet, respectively, (W/m.K).

The area of the walls through which heat is transferred is,

$$A_w = 2(0.291\text{ m} \times 0.207\text{ m}) + 2(0.291\text{ m} \times 0.207\text{ m}) = 0.2409\text{ m}^2$$

The refrigerator was designed to cool water from a temperature of 30°C to a temperature of 0°C. Hence,

$$T_h = 30°\text{C} = 303\text{K, and } T_c = 0°\text{C} = 273\text{K.}$$

Appropriate substitution of the values of the terms in Eq. (1) gives,

$$Q_w = \frac{0.1813\text{ m}^2.(303\text{ K} - 273\text{ K})}{\frac{0.0010\text{ m}}{51.9\text{ W/m.K}} + \frac{0.0345\text{ m}}{0.027\text{ W/m.K}} + \frac{0.0005\text{ m}}{177\text{ W/m.K}}}$$

$$Q_w = \frac{0.2409\text{ m}^2.(303\text{ K} - 273\text{ K})}{1.278\text{ m}^2.\text{K/W}} = 5.66\text{ W}$$

2.2.2 Heat load from the water

The heat to be removed from the water in the refrigeration chamber (Q_r) is expressed by the relation [4]:

$$Q_r = m.c_r.(T_h - T_c) \tag{2}$$

where, m is the mass of the water (kg) and c_r is the specific heat capacity of the water (J/(kg.K)). The value of c_r is 4,178 J/kg.K [31]. That is,

$$m = \text{density} \times \text{volume}.$$
$$= 996.0\ \text{kg/m}^3 \times 4 \times 10^{-3}\ \text{m}^3 = 3.983\ \text{kg}.$$

Therefore,

$$Q_r = 3.983\ \text{kg} \times 4{,}178\ \text{J/kg.K} \times (303\ \text{K} - 273\ \text{K}) = 499.35\ \text{kJ}.$$

It has been made known that 4 hours is the average time it takes to cool water [32]. This means that the heat load from the water is $Q_r = 499.35\ \text{kJ}/4\ \text{hrs} = 34.68\ \text{W}$.

2.2.3 Refrigeration load

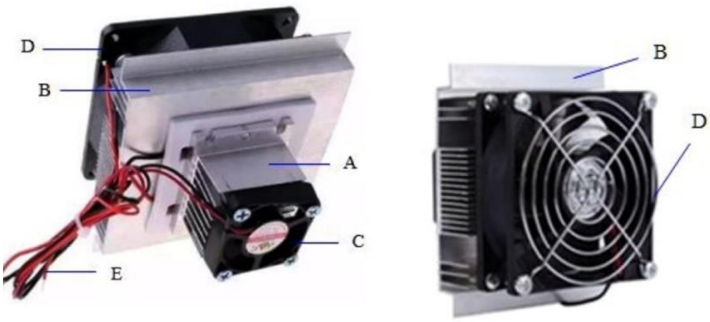
The refrigeration load is $Q_L = Q_w + Q_r = 5.66\ \text{W} + 34.68\ \text{W} = 40.34\ \text{W}$.

In order to make the design more reliable and considering the amount of the actual refrigeration load (which is 40.34 W), a safety factor of 1.23 [2] was introduced into the refrigeration load. Hence, the refrigeration load (Q_L) is $40.34\ \text{W} \times 1.23 = 49.62\ \text{W} \cong 50\ \text{W}$.

2.3 Selection of an Appropriate Thermoelectric Module

Before an appropriate module was selected for the refrigerator, the refrigeration load was considered. The space available for the thermoelectric module was also taken into consideration. Based on the refrigeration load of 50 W calculated above, a thermoelectric module with a cooling capacity of 50 W was selected. The module chamber inside which the thermoelectric module is placed is on top of the refrigeration chamber (see Figure 2 above). Therefore, the outside dimensions of the refrigeration chamber calculated in section 2.2.1 point out that the module chamber has dimensions of a breadth of 0.207 m and a depth of 0.207 m. The dimensions of the selected thermoelectric module are height, breadth, and depth of 0.10 m, 0.12 m, and 0.08 m, respectively. This shows that the breadth and depth of the thermoelectric module are not greater than those of the module chamber, which is an indication that the dimensional requirement is met by the thermoelectric module.

The model of the thermoelectric module is XH-X200. It comprises thermoelectric elements, a heat source and a heat sink (made of aluminium), a fan (made of plastic) attached to each of the heat source and heat sink, and cables for the power supply. The thermoelectric module has a power supply of voltage of 12 V and current of 6 A. Its picture is shown in Figure 3.



(a) (b)

Figure 3. Thermoelectric module: (a) Thermoelectric module; (b) View of the fan of the heat sink of the thermoelectric module (Key: A = heat source, B = heat sink, C = fan of the heat source, D = fan of the heat sink, E = cables for power supply)

3. Construction of the Refrigerator

The refrigerator is shown in Figure 2. Its refrigeration chamber was constructed from a 0.001m-thick mild steel sheet, which was cut by a shearing machine into the required different parts of different sizes. An electric arc welding machine was used to join the parts together. A pair of butt hinges was used to attach the door to the refrigeration chamber. The handle of the door was folded by a folding machine and was attached to the door by rivets. Expanded polystyrene foam, whose thickness is 0.0345 m, was laid on the inner surface of the mild steel sheet, and an aluminium sheet of 0.0005 m thickness was laid on the expanded polystyrene foam. The expanded polystyrene foam and aluminium sheet prevent heat loss from the refrigeration chamber. To prevent leakage of heat from the gaps between the walls of the refrigeration chamber, the gaps were filled with silicone paste.

The module chamber of the refrigerator was constructed from a 0.001m-thick mild steel sheet and was attached to the top of the refrigeration chamber. Neither the polystyrene foam nor the aluminium sheet was laid on the surface of the module chamber because it (the module chamber) is not needed for refrigeration.

A slot was cut on the interface between the top of the refrigeration chamber and the bottom of the module chamber. The slot is a passage through which the heat source of the thermoelectric module enters the refrigeration chamber. The thermoelectric module was placed inside the module chamber, and the gaps between the slot and the heat source of the module were filled with silicone paste.

Considering the height of the thermoelectric module (which is 0.10 m) and the need for the height of the module chamber to be greater than that of the thermoelectric module, the height of the module chamber was made to be 0.140 m. Thus, the dimensions of the module chamber are a height of 0.140 m, a breadth of 0.207 m, and a depth of 0.207 m.

4. Conduct of the Experiments

The set-up of the experiments is shown in Figure 4. Water in a quantity of 4×10^{-3} m^{-3} (that is, 4 liters), at a temperature of 30℃, was put inside the refrigeration chamber of the refrigerator, and a thermocouple (PATOS DE-305 Type-K) was inserted in the refrigeration chamber. The ambient temperature was 30℃. After the water has been put inside the refrigeration chamber, its door was closed, and the power source of the refrigerator was switched on.

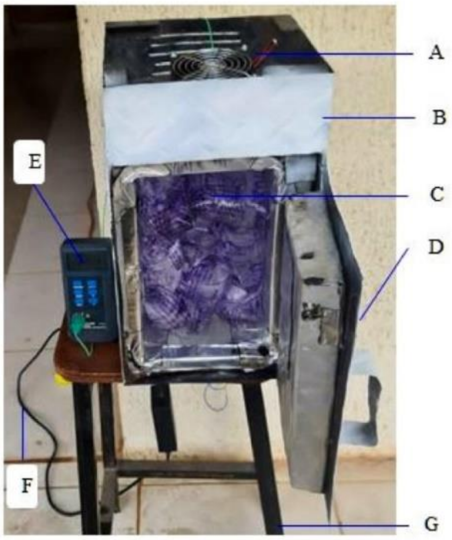


Figure 4. Set-up of the experiments on the refrigerator (Key: A = thermoelectric module, B = module chamber, C = water inside the water chamber, D = door of the refrigeration chamber, E = thermocouple, F = cable for power supply, G = stool)

The temperature of the refrigeration chamber was allowed to be stable at 30℃ (which was its temperature when it was put inside the refrigeration chamber) before the start of the reading and recording of its temperature. The temperature of the water was taken and recorded at intervals of 15 minutes up to the time that it was 0℃. A digital stopwatch was used to record the time. After the water in the refrigeration chamber has reached a temperature of 0℃, the power source of the refrigerator was switched off, and the time taken for the water to retain the temperature of 0℃ and the time taken to return to its initial temperature of 30℃ were recorded by the digital stopwatch.

5. Calculation of Coefficient of Performance

The ratio of the heat load absorbed by the semiconductor-based refrigerator (that is, refrigeration load) and the electrical input power (P) of the thermoelectric module is referred to as the coefficient of performance (COP) of the refrigerator [15]. As mentioned above, the refrigeration load (Q_L) is 50 W, and the module has a power supply of voltage of 12 V and a current of 6 A. This means that the COP of the semiconductor-based refrigerator can be calculated to be $\mathrm{COP} = \frac{Q_L}{P} = \frac{50\ \mathrm{W}}{12\ \mathrm{V}\times 6\ \mathrm{A}} = \frac{50\ \mathrm{W}}{72\ \mathrm{W}} = 0.70$.

According to Adeyanju [33], a semiconductor-based refrigerator has 0.90 < COP < 1.20, but is less than 0.90 in some cases. For example, Alomair et al. [5] obtained 0.37 < COP < 0.88, but that of Chavan et al. [15] was 0.44.

The result of Sujith et al.[34] yielded a COP of 0.124, Gastelo-Roque and Morales-Acevedo [21] achieved a COP of 0.61, and Onoroh et al. [28] got a COP of 0.34. A comparison of these COPs with the one in the present work indicates that the COP obtained in the present work (which is 0.70) falls within the range of the COP of semiconductor-based refrigerators.

6. Results and Discussions of the Performance Test of the Refrigerator

6.1 Temperature of the Water

When the refrigerator was switched on, an electric current passed through the semiconductor of the thermoelectric module. The heat source of the thermoelectric module absorbed heat from the water in the refrigeration chamber and rejected it to the heat sink of the thermoelectric module. As a result of these, the water in the refrigeration chamber became cold.

The temperature of the water at various times is depicted in Figure 5. The water temperature (*T*) and cooling time (*t*) can be expressed by a functional relation.

$$T = -[4(10^{-8})(t^4)] + [2(10^{-5})(t^3)] - 0.0029t^2 - 0.0648t + 30 \quad (3)$$

In the first 15 and 30 minutes of cooling, the temperature of the water reduces from 30℃ to 29 and 25.7℃, respectively. In the further 75 minutes, the temperature reduces to 9℃. The temperature of the water reaches a value of 2℃ at the time of 165 minutes and drops to 0℃ at the time of 225 minutes. This confirms that the refrigerator was able to cool water to a temperature of 0℃, for which it was designed. The temperature of 0℃ is maintained up to the time of 240 minutes.

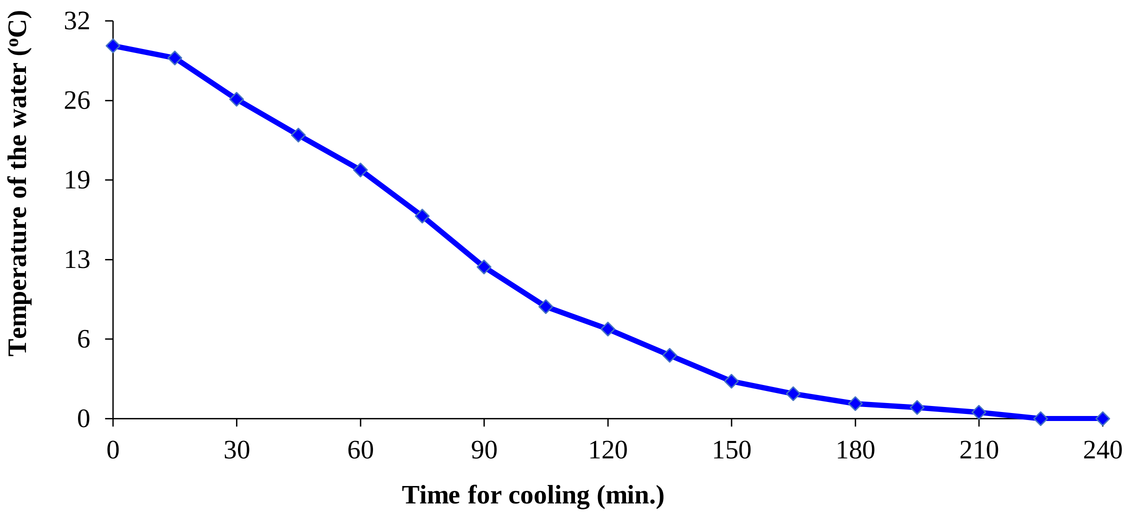


Figure 5. Temperature of the water

6.2 Retention Time of the Water Temperature

Another criterion for knowing the performance of the refrigerator is its retention time of temperature. The retention times considered are the time during which the water in the refrigeration chamber retained the temperature of 0℃ after the refrigerator was switched off, and the time that was taken by the water to rise from the temperature of 0℃ to its initial value of 30℃ after the refrigerator was switched off.

The left part of Figure 6 is the cooling of the water and the right part represents the retention time. It should be noted that the water cools to 0℃ at the time of 225 minutes and maintains it till the time of 240 minutes. The refrigerator was switched off at the time of 240 minutes and that time (that is, 240 minutes) was used as the start of the retention time. The temperature of 0℃ was retained for approximately 30 minutes after the refrigerator was switched off, as its value increases from 0℃ at the time of 240 minutes to 0.3 and 0.5℃ at the time of 255 and 270 minutes, respectively. The temperature of the water is 27℃ at 420 minutes and rises to its initial value of 30℃ at 432 minutes. Thus, the time taken for the water to rise from 0℃ to its initial value of 30℃ after the refrigerator was switched off is 192 minutes.

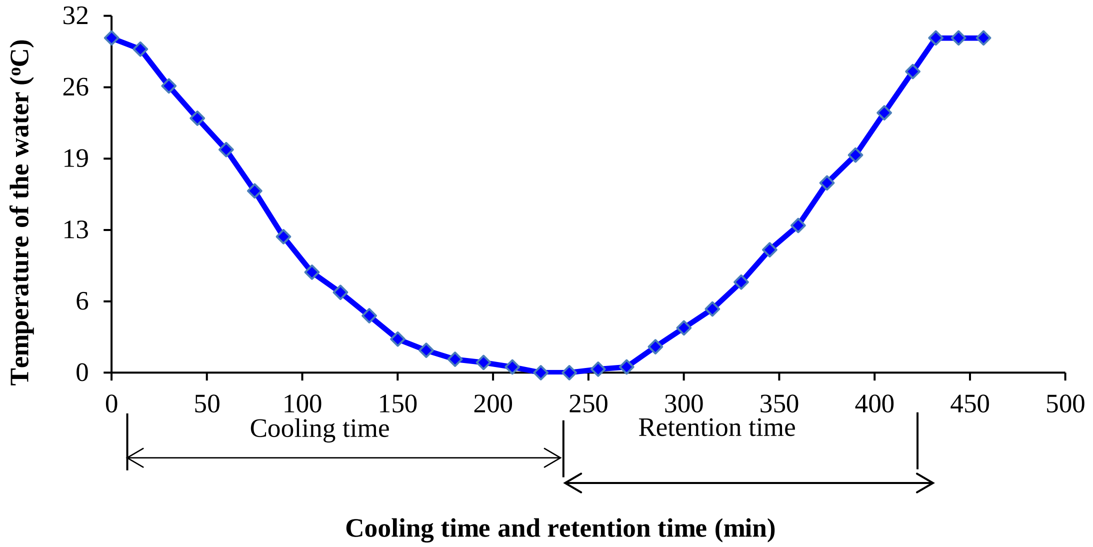


Figure 6. Retention time of the temperature of the water

6.3 Cooling Rate of the Water Temperature

The cooling rate of the water is presented in Figure 7. The cooling rates at the time of 15, 30, 45, and 60 minutes are 0.067, 0.220, 0.193, and 0.187℃/min, respectively. This translates to an average cooling rate of 0.167℃/min in the first 60 minutes of cooling the water. In the second 60 minutes (that is, from 75 to 120 minutes), the average cooling rate is 0.213℃/min, which is 27.7% higher than the first 60 minutes. The average cooling rate of 0.100℃/min in the third 60 minutes is 53.1% lower than the second 60 minutes. The cooling rates at the time of 195, 210, and 225 minutes are 0.020, 0.027, and 0.033℃/min, respectively, which is equivalent to an average cooling rate of 0.027℃/min. The average cooling rate for the cooling period of 225 minutes is 0.133℃/min.

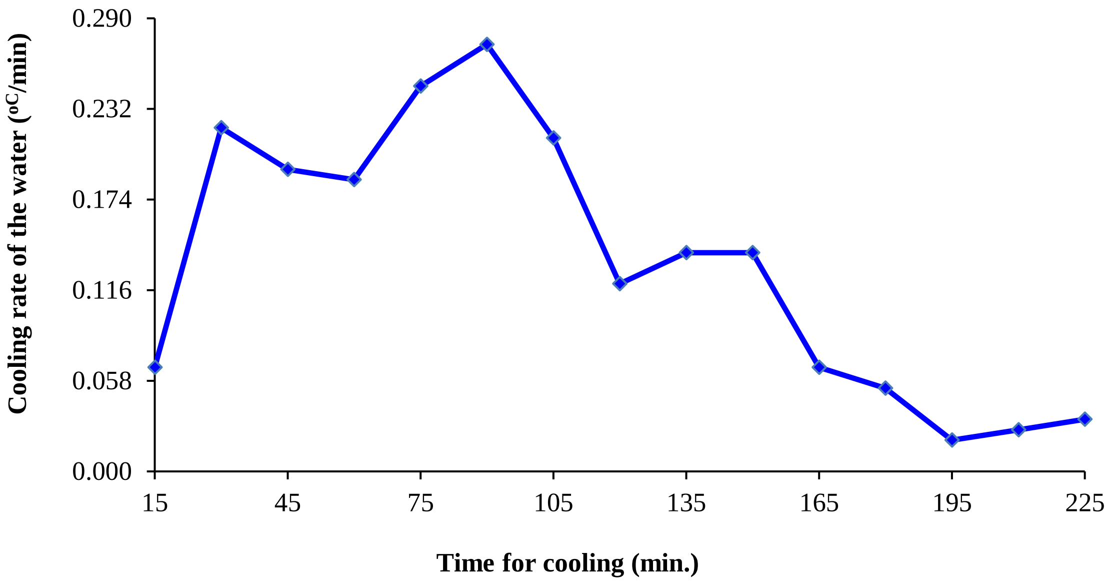


Figure 7. Cooling rate of the water

6.4 Change in the Water Temperature at Different Intervals of Time

The change in water temperature at different intervals of time is shown in Figure 8. During the first five time intervals, that is 15, 30, 45, 60, and 75 minutes, the changes in the temperature of the water are -1, -3.3, -2.9, -2.8, and -3.7℃, respectively. The changes in the temperature of the water are -4.1, -3.2, -1.8, -2.1, and -2.1℃ during the time intervals of 90, 105, 120, 135, and 150 minutes, respectively. During the last five time intervals, that is 165, 180, 195, 210, and 225 minutes, the changes in the temperature are -1, -0.8, -0.3, -0.4, and -0.5℃, respectively.

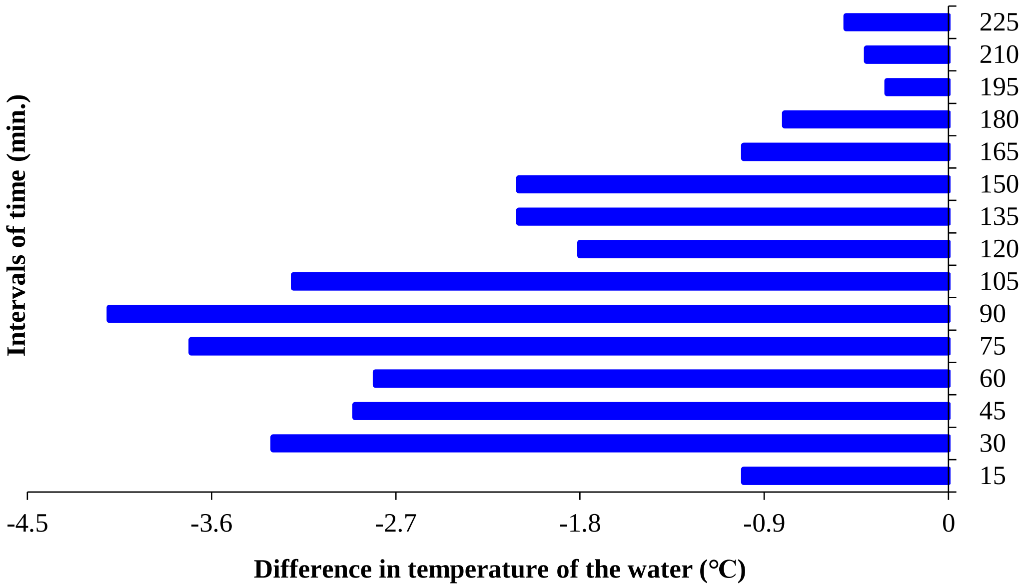


Figure 8. Change in water temperature at different intervals of time

7. Conclusions

A semiconductor-based refrigeration system, which is an alternative technology that can lower the carbon dioxide emissions to the atmosphere, was looked into in the current work.

The refrigerator was designed and constructed to cool 4×10^{-3} m^3 of water from a temperature of 30°C to 0°C. The tests of its performance were carried out. The tests were retention time of the temperature of the water, change in the water temperature at different intervals of time, and the cooling rate of the water.

A comparison of the coefficient of performance (COP) of the present work with those of previous works indicates that the COP obtained in the present work falls within the range of the COP of semiconductor-based refrigerators.

The refrigeration system was able to cool the water to a temperature of 0°C, for which it was designed. The time taken for the water to rise from 0°C to its initial value of 30°C after the refrigerator was switched off is 192 minutes. The average cooling rate for the time of 225 minutes is 0.133°C/min.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] I. Dincer, *Refrigeration Systems and Applications*. WS, UK: John Wiley & Sons Ltd., 2017. https://doi.org/10.1002/9781119230793.

[2] V. Ananthachar, "Retail facilities," In 2019 ASHRAE Handbook - Heating, Ventilating, and Air-Conditioning Applications, H. E. Kennedy (Ed.), Atlanta, GA, USA: ASHRAE, 2019, pp. 22-24, 2019.

[3] T. O. Oni, J. B. Awopetu, S. A. Adeleye, D. C. Uguru-Okorie, A. A. Adeyanju, and N. E. Olukayode, "Development of a latent heat thermal energy storage material-based refrigeration system," *Int. J. Heat Technol.*, vol. 39, no. 2, pp. 469-476, 2021. https://doi.org/10.18280/ijht.390216.

[4] D. A. Andrew, H. T. Carl, and F. B. Alfred, *Modern Refrigeration and Air Conditioning*. Illinois, IL, USA: The Goodheart-Willcox Company Inc, pp. 664-664, 2004.

[5] Y. Alomair, M. Alomair, S. Mahmud, and H. A. Abdullah, "Theoretical and experimental analyses of solar-thermoelectric liquid-chiller system," *Int. J. Ref.*, vol. 56, pp. 126-139, 2015. https://doi.org/10.1016/j.ijrefrig.2015.01.003.

[6] S. Vijayarengan, R. Sooriyaraj, G. Vinithraj, C. Venkatesan, and A. Vinoth, "Design and fabrication of thermoelectric solar refrigerator," *Int. J. Emerg. Technol. Eng. Res.*, vol. 6, no. 4, pp. 142-148, 2018.

[7] K. Liang, Z. Li, M. Chen, and H. Jiang, "Comparisons between heat pipe, thermoelectric system, and vapour compression refrigeration system for electronics cooling," *Appl. Therm. Eng.*, vol. 146, pp. 260-267, 2019. https://doi.org/10.1016/j.applthermaleng.2018.09.120.

[8] "The Kigali Amendment to the Montreal Protocol: HFC phase-down," United Nations Environment Programme, 2016, https://wedocs.unep.org/20.500.11822/26589.

[9] S. B. Riffat, S. A. Omer, and X. L. Ma, "A novel thermoelectric refrigeration system employing heat pipes and phase change material: An experimental investigation," *Renew. Energy*, vol. 23, no. 2, pp. 313-323, 2001. https://doi.org/10.1016/S0960-1481(00)00170-1.

[10] S. A. Omer, S. B. Riffat, and X. L. Ma, "Experimental investigation of a thermoelectric refrigeration system employing a phase change material integrated with thermal diode (thermosyphons)," *Appl. Therm. Eng.*, vol. 21, no. 12, pp. 1265-1271, 2001. https://doi.org/10.1016/S1359-4311(01)00010-2.

[11] F. Meng, L. Chen, and F. Sun, "Performance optimization for two-stage thermoelectric refrigerator system driven by two-stage thermoelectric generator," *Cryogenics*, vol. 49, no. 2, pp. 57-65, 2009. https://doi.org/10.1016/j.cryogenics.2008.11.005.

[12] N. Le Pierrès, M. Cosnier, L. Luo, and G. Fraisse, "Coupling of thermoelectric modules with a photovoltaic panel for air pre-heating and pre-cooling application: An annual simulation," *Int. J. Energy Res.*, vol. 32, no. 14, pp. 1316-1328, 2008. https://doi.org/10.1002/er.1439.

[13] H. Sofrata, "Heat rejection alternatives for thermoelectric refrigerators," *Energy Convers. Manage.*, vol. 7, no. 3, pp. 269-280, 1996. https://doi.org/10.1016/0196-8904(95)00189-1.

[14] G. Min and D. M. Rowe, "Experimental evaluation of prototype thermoelectric domestic-refrigerator," *Appl. Energy*, vol. 83, no. 2, pp. 133-152, 2006. https://doi.org/10.1016/j.apenergy.2005.01.002.

[15] D. S. Chavan, S. V. Pawar, M. S. Dhamal, S. K. Kute, P. B. Borade, and G. S. Dhumal, "Thermoelectric refrigeration system running on solar energy," *Int. J. Mech. Recent Res. Civil Mech. Eng.*, vol. 2, no. 1, pp. 140-148, 2015.

[16] O. Francis, C. J. Lekwuwa, and I. H. John, "Performance evaluation of a thermoelectric refrigerator," *Int. J. Eng. Innov. Res. Technol.*, vol. 2, no. 7, pp. 18-24, 2013.

[17] T. Hara, H. Azuma, H. Shimizu, H. Obora, and S. Sato, "Cooling performance of solar cell driven, thermoelectric cooling prototype headgear," *Appl. Therm. Eng.*, vol. 18, no. 11, pp. 1159-1169, 1998. https://doi.org/10.1016/S1359-4311(98)00046-5.

[18] G. S. Nolas, J. Sharp, and H. J. Goldsmid, *Thermoelectric: Basic Principles and New Materials Development*, Berlin, BE, Germany: Springer Verlag, pp. 8-9, 2001. https://doi.org/10.1007/978-3-662-04569-5.

[19] A. Sharma, A. B. Agrawal, and N. Shrivastava, "Solar energy based refrigeration system using Peltier device," *Int. J. Theoretical Appl. Sci.*, vol. 10, no. 1, pp. 110-116, 2018.

[20] J. B. Dabhi, N. B. Parmar, and N. S. Mehta, "Consideration for design of thermoelectric refrigeration system," *Int. J. Adv. Eng. Res. Stud.*, vol. 1, no. 2, pp. 259-261, 2012.

[21] J. A. Gastelo-Roque and A. Morales-Acevedo, "Design of a photovoltaic system using thermoelectric Peltier cooling system for vaccines refrigeration," In 2017 IEEE MIT Undergraduate Reserach Technology Conference, (URTC), Cambridge, MA, USA, November 3-5, 2017, Cambridge: IEEE, pp. 1-4. https://doi.org/10.1109/URTC.2017.8284211.

[22] M. Awasthi and K. V. Mali, "Design and development of thermoelectric refrigerator," *Int. J. Mech. Eng. Robotics Res.*, vol. 1, no. 3, pp. 389-399, 2012.

[23] D. Astrain, J. G. Vián, and J. Albizua, "Computational model for refrigerators based on Peltier effect application," *Appl. Therm. Eng.*, vol. 25, no. 17-18, pp. 3149-3162, 2005. https://doi.org/10.1016/j.applthermaleng.2005.04.003.

[24] P. Naphon and S. Wiriyasart, "Liquid cooling in the mini-rectangular fin heat sink with and without thermoelectric for CPU," *Int. Commun. Heat Mass Transf.*, vol. 36, no. 2, pp. 166-171, 2009. https://doi.org/10.1016/j.icheatmasstransfer.2008.10.002.

[25] D. Astrain, P. Aranguren, A. Martínez, A. Rodríguez, and M. G. Pérez, "A comparative study of different heat exchange systems in a thermoelectric refrigerator and their influence on the efficiency," *Appl. Therm. Eng.*, vol. 103, pp. 1289-1298, 2016. https://doi.org/10.1016/j.applthermaleng.2016.04.132.

[26] M. Gökçek and F. Sahin, "Experimental performance investigation of mini channel water cooled-thermoelectric refrigerator," *Case Studies Therm. Eng.*, vol. 10, pp. 54-62, 2017. https://doi.org/10.1016/j.csite.2017.03.004.

[27] M. Saifizi, M. S. Zakaria, S. Yaacob, and K. Wan, "Development and analysis of hybrid thermoelectric refrigerator systems," *IOP Conf. Series: Mater Sci. Eng.*, vol. 318, no. 1, Article ID: 012036, 2018. https://doi.org/10.1088/1757-899X/318/1/012036.

[28] F. Onoroh, M. Ogbonnaya, O. N. Ezenwa, and E. O. Odubiyi, “Experimental and parametric analysis of a thermoelectric refrigerator,” *Int. J. Innov. Sustain. Dev.*, vol. 14, no. 2, pp. 125-141, 2020. https://doi.org/10.1504/IJISD.2020.106231.
[29] H. Kepekci, E. Kosa, and C. Ezgi, “Modeling and performance of a thermoelectric refrigerator,” In 5th International Anatolian Energy Symposium, Trabzon, TR, Turkey, March 24-25, 2021, Trabzon: Karadeniz Technical University, pp. 316-326.
[30] G. Xia, H. Zhao, J. Zhang, H. Yang, B. Feng, Q. Zhang, and X. Song, “Study on performance of the thermoelectric cooling device with novel subchannel finned heat sink,” *Energies*, vol. 15, Article ID: 145, 2022. https://doi.org/10.3390/en15010145.
[31] T. L. Bergman, A. S. Lavine, F. P. Incropera, and D. P. Dewitt, *Fundamentals of Heat and Mass Transfer*. New Jersey, NJ, USA: John Wiley & Sons, Inc, pp. 983-984, 2011.
[32] "Time for water to chill," Google, 2022, https://www.google.com/search?q=time+for+water+to+freeze&ei=fevKYvibA6KU9u8PucyT2Ag&ved=0ahUKEwi4zpP-zO74AhUiiv0HHTnmBIsQ4dUDCA4&uact=5&oq=time+for+water+to+freeze&gs_lcp.
[33] A. A. Adeyanju, “Experimental comparison of a thermoelectric refrigeration and vapour power compression refrigeration,” *J. Eng. Appl. Sci.*, vol. 5, no. 3, pp. 221-225, 2010. https://doi.org/10.3923/jeasci.2010.221.225.
[34] G. Sujith, A. Varghese, A. Achankunju, R. Mathew, R. George, and V. Vishnu, “Design and fabrication of thermoelectric refrigerator with thermosiphon system,” *Int. J. Scientific Eng. Appl. Sci.*, vol. 2, no. 4, pp. 373-379, 2016.

Nomenclature

A	area, m^2
c	specific heat capacity, $J.kg^{-1}.K^{-1}$
k	thermal conductivity, $W.m^{-1}.K^{-1}$
m	mass of water, kg
Q	heat transfer, W
t	time, s
T	temperature, K
x	thickness, m

Subscripts

c	cold
h	hot
l	aluminium sheet
L	refrigeration
p	polystyrene foam
r	water
s	mild steel sheet
w	wall