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Enhancing the coefficient of performance (COP) of mini refrigerators based on thermoelectric units (Peltier)

Abstract: Energy scarcity in the world and the pollutants resulting from excessive use of energy lead to an increase in global warming. There is a need to search for sustainable alternatives that use less energy to reduce environmental problems as well as alternatives to the use of Freon, which is harmful to the environment, one of the most dangerous pollutants, and increases the ozone hole.

The current research aims to investigate the performance of thermoelectric refrigerators with different operating conditions. A portable thermoelectric refrigerator was developed for those living in remote areas of Egypt off the electrical grid (e.g., deserts). The designed refrigerator is based on the Peltier effect using Peltier units. The refrigerator is designed, manufactured, and experimentally tested. Several variables were studied in fast cooling systems for different conditions to minimize

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time, decrease the cooling temperature, and increase the coefficient of performance (COP) by the response surface methodology (RSM) model.

The results reveal that the obtained maximum COP was 77.3%, at 4 V and 1.006 with a difference in cooling temperature (ΔT) of 8°C. The highest ΔT was 26.4°C at 10 V, 9.149 A, 91.49 W and COP 11.2%. The optimum condition was cooling temperature 12.7°C, COP 51.4% at 4 V, 3.445 A by using 4 Peltier, according to Response surface methodology (RSM) includes optimization procedures for the settings of factorial variables by design expert 13, such that maximum ΔT was 20.3°C and maximum COP 49.576% with 4 volts, 4 no. of Peltier and current 3.601 A in the value range. The results reveal that the obtained determination coefficient for ΔT and the COP adjusted R2 and R3 values 0.9286 and 0.9603 respectively.

Keywords: COP, efficiency of energy, environmental pollution, thermal storage, thermoelectric unit

Introduction

Because of the ever-increasing need for clean energy, energy conversion is becoming just as crucial as energy. To decrease environmental problems, energy-efficient green technologies are advancing quickly. Numerous research projects have considered different technologies of electrical energy generation from renewable energy sources (Góralczyk et al. 2016; Ibrahim et al. 2020).

In 1826, Seebeck demonstrated that the temperature differential between various metals can be converted to an electric current via the TE effect. the Seebeck effect's inverse viability by transforming the applied current to a temperature difference. In their definition of TE efficiency from 1911, they stated that low heat conductivity and strong electrical conductivity are characteristics of ideal TE materials (Seebeck 1826).

The advantages of employing TE devices are quiet operation, long lifespan, small design needs for fewer places, environmental friendliness, a lack of moving parts, working fluid, and a lack of maintenance, these factors make them the most popular choice. However, because they have poorer energy conversion efficiency than other typical systems, their uses are limited (Sajid et al. 2017).

There have been many TE cooling research investigations that combine theoretical and experimental data. To create a more effective heat exchanger, typical shell and tube heat exchangers were modified to use a tubular TE device composed of tilted multilayers of BST/Ni as the tubes, (Huang et al. 2000; Riffat and Ma 2003; Takahashi et al. 2013).

Astrain et al. (2016) performed a computational analysis on a thermoelectric refrigerator with an internal volume of 15 m^3 to determine the effect of the heat exchanger on its overall consumption and efficiency. The findings show that effective heat exchanger optimization can result in significant gains in TEC efficiency (Astrain et al. 2016).

Chen et al. (2012) presented a model of an internal and external irreversible thermoelectric generator-driven thermoelectric refrigerator. The COP is no longer constant and declines monotonically with an increase in the total number of thermoelectric devices, whilst the cooling load is less and no longer proportionate to the total number of thermoelectric units (Chen et al. 2012). In the same field of research, A. Çağlar designed a portable TE refrigerator and the temperature and COP of the TE refrigerator were examined for the best operational settings over sixty minutes using the orthogonal fractional factorial experiment design approach. Results reveal that although the COP lowered from 0.351 to 0.011, the air temperature inside the TE refrigerator dropped from 293 K to 254.8 K (Çağlar 2018).

Gökçek and Şahin (2017) performed several experiments that were run at various system voltages and cooling water flow rates in the mini channel. The findings indicated that at the end of a two-hour experiment, the internal temperature of a water-cooled, thermoelectric refrigerator was approximately 2°C for a flow rate of 0.8 L/min and approximately 0.1°C for a flow rate of 1.5 L/min. At the end of the 25-minute cooling period, the COP value of the thermoelectric refrigerator was 0.23 at 1.5 L/min and 0.19 at 0.8 L/min (Gökçek and Şahin 2017). In his research, Afshari proved that the average COP value of air-to-water mode is approximately 30–50% higher than that of air-to-air mode. In other words, an air-to-water thermoelectric cooling device operates more efficiently (Afshari 2021).

Manikandan et al. investigated the use modified TE cooler pulse operation to cool buildings. The outcome demonstrated that the thermoelectric cooling system can offer an average cooling power of 600 W with the COP of 1.01 for a typical working state with the modified pulse operation, which is 23.3% and 2.12% greater than the conventional mode of operation (Manikandan et al. 2017). Soprani et al. improved the functioning and created a TE cooler for cooling electronics by applying a topology optimization approach (Soprani et al. 2016).

Tipsaenporm et al. displayed the outcomes of tests performed to investigate the potential application of a direct evaporative cooling (DEC) system for improving the efficiency of a small thermoelectric air conditioner (TE). It raised the cooling capacity of the compact TE air conditioner from 53.0 W to 74.5 W. The 21.5 W increases (40.6%). Additionally, the DEC system can increase the coefficient of performance (COP) of the small TE air conditioner by up to 20.9% (Tipsaenporm et al. 2012). Similarly, Tan et al. used a simple evaporative cooling system, which increased COP by 20.9%. They proposed a phase change material (PCM) integrated TE cooling system for space cooling in which the PCM served as a heat sink during the daytime cooling phase to minimize the temperature of the hot side of the TE module and stored cold thermal energy at night (Tan and Zhao 2015).

Mirmanto et al. showed that the COP decreased with time, and the best position for the thermoelectric placement of this study was on the wall (Mirmanto et al. 2019).

Response surface methodology (RSM) shines as a powerful statistical tool for optimizing processes through experiment design, analysis and refinement. Within its diverse array of designs, the central composite design (CCD) reigns supreme in the literature for its ability to enhance and optimize various processes (Nechev et al. 2021). In essence, RSM acts as a statistical microscope, revealing the intricate relationships between input factors and output responses, including how multiple variables synergistically influence the outcomes. While the traditional "one variable at a time" approach requires numerous trials to explore response boundaries, RSM accomplishes this with significantly fewer runs. Moreover, unlike such limited methods, RSM can capture the combined effect of multiple variables on the final product, providing a holistic picture of the optimization landscape (Kolanowski 2021).

The power of RSM has captured the attention of researchers seeking to improve various features of convection cooling. Rejeb et al. (2020) used RSM to optimize a polynomial statistical model presented to forecast the electrical efficiency of a concentrated photovoltaic-thermoelectric system, achieving An excellent fitting between forecast values obtained from the statistical model and The numerical data provided by the three-dimensional numerical model. Similarly, Parlak et al. (2024). It has been investigated by the numerical model how the specified design parameters of the heat sink and thermoelectric module affect the cooling performance of the fluid flowing through the heat sink.

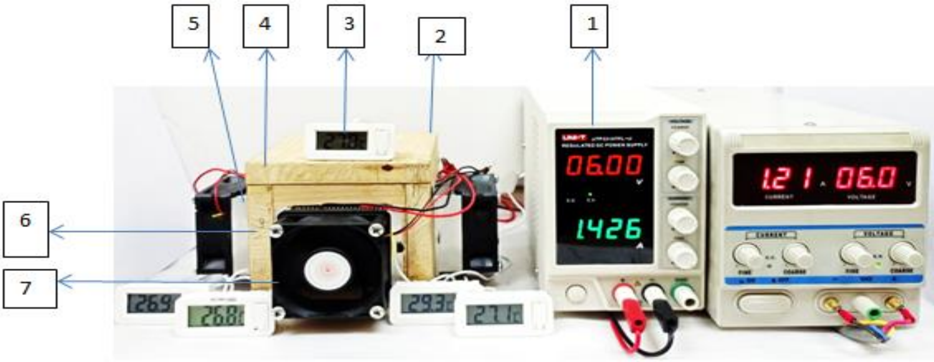
Response surface methodology (RSM) represents a statistical technique employed to design, analyze, and refine experiments within any given cycle. Among the various types of plans, the central composite design (CCD) stands out as a frequently utilized tool in the literature for enhancing and optimizing diverse processes (Chen et al. 2022). In statistics, RSM is thought to be a very useful tool for studying the relationship between input factors and output using models and how factorial variables affect the response. Utilizing the "one variable, once" procedure to enhance the boundaries needs countless trials, although RSM can achieve this with altogether fewer runs. Furthermore, the "one factor at a time" procedure can't expect the consolidated impact of at least two variables on the result, which is conceivable utilizing RSM (Tripathi et al. 2020).

The current study aims to improve the performance of the Peltier to reach the highest COP, obtain the shortest cooling time with the lowest cooling temperature, highest cooling temperature differences and decrease energy consumption. This will lead to a sustainable system that will indirectly help in decreasing energy production emissions.

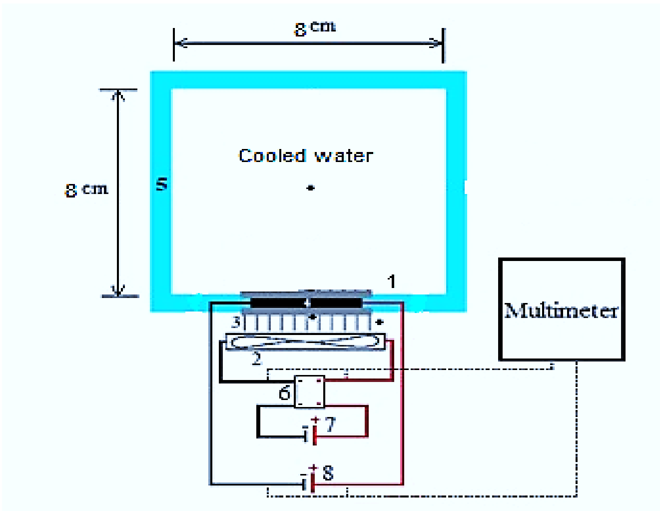
1. Materials and method

1.1. Materials

The photographic picture and schematic of the experimental configuration are shown in Figure 1 (a, b). The system consists of a refrigerator box (RB) with dimensions 8×8×8 cm and four thermoelectric units (TU) placed on the walls of the four sides of the refrigerator box (Mirmanto et al. 2019). RB is constructed from two boxes; the outer box is made from wood and the inner box is made from stainless steel with thermal insulation foam located between them to prevent cooling leakage. The TU are combined from Peltier unit, heat sinks, and fan. The hot side of the Peltier unit must be completely cooled to achieve low temperatures on the cold side. As a result,



a)



b)

Fig. 1. Photograph and schematic diagram of experimental setup
a) photographic picture of experimental setup: 1 – power supply, 2 – S.S. box, 3 – sensor, 4 – wooden box, 5 – heat sink, 6 – Peltier unit, 7 – fan; b) schematic diagram of experimental setup: 1 – S.S. box, 2 – fan, 3 – heat sink, 4 – Peltier unit, 5 – foam box, 6 – voltage regulator, 7 – power supply

Rys. 1. Zdjęcie i schematyczny diagram układu doświadczalnego

a fan is typically utilized on the hot side of the Peltier unit. Finally, the measure device is a digital millimeter that is used to measure voltage and current. The temperature is measured using a digital thermometer.

1.2. Material and characteristics of experimental components

1.2.1. Peltier unit

Peltier unit TEC1-12706 is used to achieve cooling. N-P junction semiconductors are often welded to a copper conductor. The Peltier unit is seen in Figure 2a. The performance requirements for this type of Peltier are listed in Table 1.

1.2.2. Heat sink (plate fins)

The fins of the heat sinks are made of aluminum, Figure 2b Shows a photograph of the heat sink.

1.2.3. Fan

Figure 2 (c) shows a photograph of the fan; its dimensions are 6.5×6.5×2.5 cm.

a) Peltier unit **b) Heat sinks (6.8×6.6×3.6 cm)** **c) Fan 6.5×6.5×2.5 cm**

Fig. 2. Peltier unit, heat sinks and fan

Rys. 2. Jednostka Peltiera, radiatory i wentylator

Table 1. Performance specifications of Peltier TEC1-12706 (Elngar et al. 2018)

Tabela 1. Specyfikacje wydajności Peltiera TEC1-12706

Model and Trade name	Size [mm]	Power, Q_{max} [W]	Current I_{max} [A]	Voltage V_{max} [V]
TEC1-12706	40 × 40	50	6.4	14.4

Figure 3 shows the performance curve of the Peltier TEC1-12706 as the relation between temperature difference and voltage at T_h = 25°C at various values of current, I = 1.5, 3.0, 4. 5, and 6.0 A.

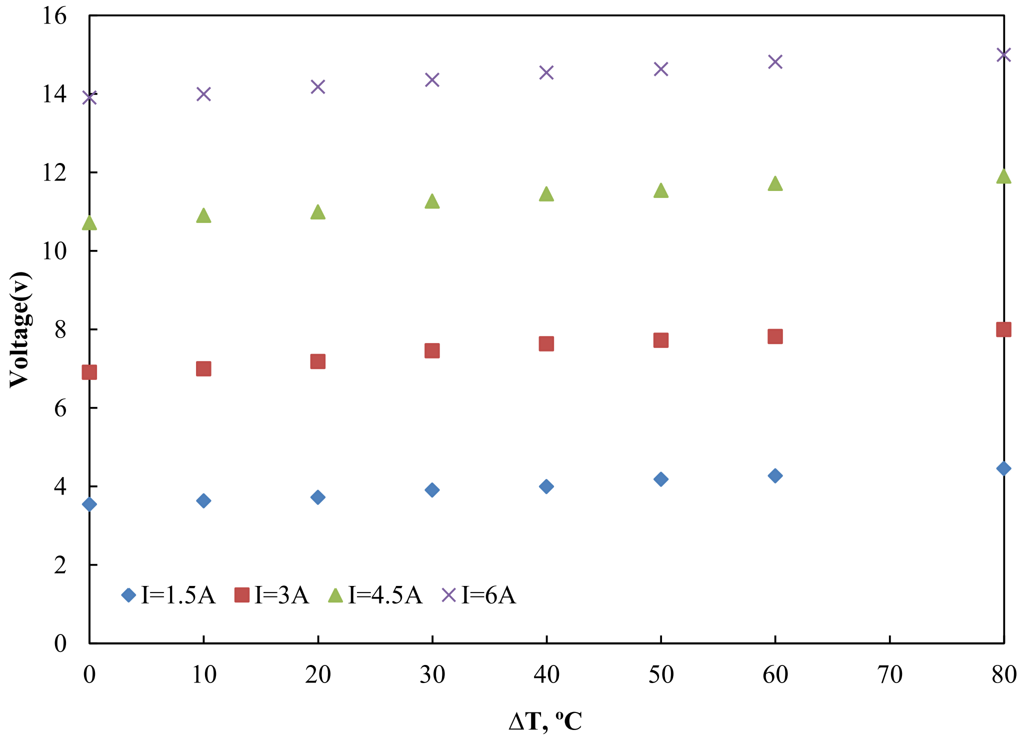


Fig. 3. Performance specification curves ΔT vs. voltage for Peltier

Rys. 3. Krzywe specyfikacji wydajności ΔT w funkcji napięcia dla modułu Peltiera

1.3. Method

1.3.1. Experimental procedure

The TE refrigerator consists of a Peltier unit, an S.S. box with dimensions of 8 × 8 × 8 cm, heat sinks (plate fins are made of aluminum) and fans. The heat sinks and fans are mounted on the Peltier module for easy heat dissipation. The hot side of the Peltier module must be well-cooled to achieve lower temperatures on the cold side. Figure 4 shows the relationship between voltage and current for a Peltier module with fan and fan only at racer time. Once the fans are set to a certain voltage, the current becomes constant and does not change over time. However, the Peltier unit current decreases in the first minute of the experiment until stability is reached. Before starting the experiments, 0.25 liters of water were put in the box and its temperature was recorded, the voltage was set at a specific value from 4 to 14 V and the ambient temperature and the current of the Peltier unit and fans were recorded. The water temperature, hot side of the Peltier, and current were recorded every 5 mins. The duration of the experiment was 45 mins. Several experiments were performed using a variable voltage of 4:14 V, a number of Peltier units of 1:4, and an initial temperature.

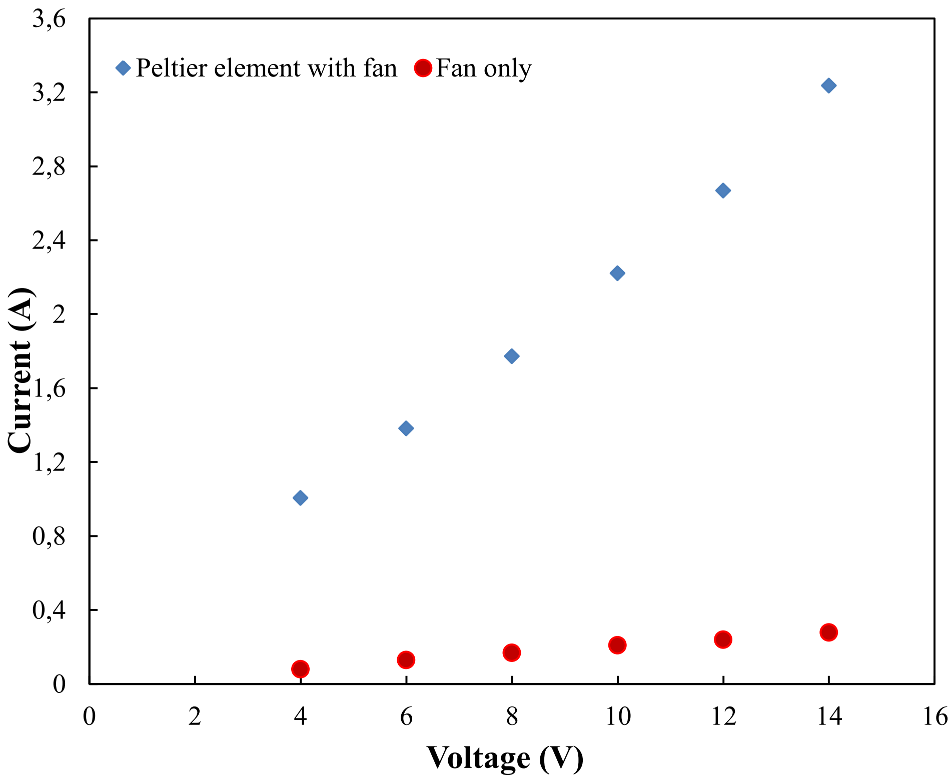


Fig. 4. Relationship between V & I for Peltier unit with fan and fan only at constant time

Rys. 4. Zależność między V i I dla modułu Peltiera z wentylatorem i tylko wentylatorem w stałym czasie

1.3.2. Modeling study

The Peltier effect was used to design and build a TE refrigerator in this study. The Peltier unit variable voltage, current, and ambient temperatures were the components of the design. The COP of the refrigerator system was the ratio of heat produced by Peltier unit to energy supplied. The equations used to get the COP of the refrigerator system are as follows:

$$COP = \frac{Q}{w} \tag{1}$$

where

Q – cooling capacity, which can be determined by using the following equation:

$$Q_{cooling} = mC_p \Delta T \tag{2}$$

where

ΔT – the temperature difference between the initial temperature and cooling temperature which it is equals,

$$\Delta T = T_i - T_c \tag{3}$$

W is the amount of energy required to working power the Peltier unit, V is the voltage, I is the electric current, and t is the time by using the following equation:

$$W = V \cdot I \cdot t \tag{4}$$

1.3.3. Modeling and optimization

The Box-Behnken design, which is a powerful tool from the response surface methodology (RSM) in Design Expert 13, was used in this work. This design enabled us to model and study the effect of two critical factors voltage and no of Peltier on the cooling temperature differences (ΔT) and COP. A comprehensive statistical analysis of variance (ANOVA) was performed to evaluate the importance of each factor and its interactions with the COP and ΔT. In addition, numerical optimization was used in Design Expert to obtain optimal operating parameters that provide maximum COP with maximum ΔT. Table 2 shows twenty-four experimental runs; the values between the lower and upper bounds for each factor in Table 2 were suggested by Design Expert version 13. Using equation (5), the COP was calculated as shown in column 6 in Table 2. The optimum condition at minimum volt, minimum no. of Peltier, minimum current, minimum cooling temperature, maximum cooling temperature differences and maximum COP.

Table 2. Accomplishment of experimental run designs

Tabela 2. Realizacja projektów eksperymentalnych

Run	F1	F2	R1	R2	R3
1	4	1	1.006	8	77.3
2	4	2	1.833	12.5	66.3
3	4	3	2.663	15.7	57.3
4	4	4	3.445	18.2	51.4
5	6	1	1.387	8.3	38.8
6	6	2	2.518	13.7	35.3

Run	F1	F2	R1	R2	R3
7	6	3	3.854	17.6	28.4
8	6	4	5.251	23	24.8
9	8	1	1.773	8.7	23.9
10	8	2	3.815	16.2	20.6
11	8	3	5.568	20.7	18.1
12	8	4	7.192	25.5	17.2
13	10	1	2.222	9.2	16.1
14	10	2	4.596	16.9	14.3
15	10	3	6.849	20.4	11.6
16	10	4	9.149	26.4	11.2
17	12	1	2.668	11.2	13.6
18	12	2	5.548	18.2	10.6
19	12	3	8.184	18.7	7.4
20	12	4	10.771	24.2	7.3
21	14	1	3.237	9.1	7.8
22	14	2	6.478	17.9	7.7
23	14	3	9.397	19.3	5.7
24	14	4	11.729	22.4	5.3

* F1: Factor 1 (Volt, V); F2: Factor 2 (number of Peltier); R1: Response 1 (Current, A); R2: Response 2 (Temperature Difference ΔT, °C); R3: Response 3 (COP %).

2. Results and discussion

The results of all the experiments are classified into four groups: effect of variable voltage 4:14 V with step 2 V by the using No. of Peltier unit 1:4 on the cooling temperature and the COP.

2.1. Coefficient of performance optimization and ANOVA analysis

COP was evaluated across various experimental runs. Design Expert 13 software generated models to analyze the relationships between process factors and the key responses. To assess the quality and significance of these models, an analysis of variance (ANOVA) was conducted at a 96.72% confidence level, focusing on F-values. The COP model was best represented by the quadratic model. However, some terms within these models lacked statistical significance (p-values > 0.1). Therefore, the models were optimized by removing these insignificant terms, resulting in more concise and accurate representations of the process. Equations (5) and (6) describe the model obtained by Design Expert software for the cooling temperature difference and the COP. Tables 3 summarizes the results of the ANOVA analysis for the temperature difference and the COP for the refrigerator box. It is worth mentioning that Equations (5) and (6) are used for the factor ranges shown in Table 3 and Table 4.

For temperature difference:

$$Temperature\ Difference(\Delta T) = -5.11190 + 2.24866 \cdot Volt + \\ + 4.52333 \cdot No.\ of\ Peltier - 0.104687 \cdot Volt^2 \tag{5}$$

Table 3. ANOVA Analysis for the response of the temperature difference

Tabela 3. Analiza ANOVA dla odpowiedzi różnicy temperatur

Source	Sum of Squares	df	Mean Square	F-Value	P-Value	
Model	677.16	3	225.72	100.74	< 0.0001	Significant
A- (Volt)	62.74	1	62.74	28.00	< 0.0001	
B- (No. of Peltier)	613.82	1	613.82	273.94	< 0.0001	
A^2	26.19	1	26.19	11.69	0.0027	
Residual	44.81	20	2.24			
Cor Total	721.97	23				
R^2 = **0.9379**	Adjusted R^2 = 0.9286					

For **COP%**:

$$\mathbf{COP\ \%} = +147.38548 - 20.73670 \cdot Volt - 9.51676 \cdot No.\ of\ Peltier + \\ + 0.673714 \cdot Volt \cdot No.\ of\ Peltiers + 0.7765 \cdot Volt^2 \tag{6}$$

Table 4. ANOVA Analysis for the response of the COP

Tabela 4. Analiza ANOVA dla odpowiedzi COP

Source	Sum of Squares	df	Mean Square	F-Value	P-Value	
Model	9,167.06	4	2,291.76	140.04	< 0.0001	Significant
A (Volt)	8,373.32	1	8,373.32	511.66	< 0.0001	
B (No. of Peltier)	470.64	1	470.64	28.76	< 0.0001	
AB	158.86	1	158.86	9.71	0.0057	
A^2	1,440.89	1	1,440.89	88.05	< 0.0001	
Residual	310.94	19	16.37			
Cor Total	9,477.99	23				
R^2 = **0.9672**	Adjusted R^2 = 0.9603					

Statistical tests confirmed the suitability of the chosen model to predict improvements in the temperature difference and the COP within the range of variables studied (A: volts, B: number of Peltier). This is supported by the high coefficients of determination (R2, R3) for the temperature difference and the COP model, which were 0.9379 and 0.9672, respectively. These values indicate a strong fit between the model and experimental data, indicating reliable predictions within the studied range.

Further validation came by comparing the actual experimental results with model predictions regarding temperature difference and the COP as shown in Figure 5 and Figure 6. The close agreement between the two demonstrates the accuracy of the model and confirms the strong association between the independent variables and the desired responses. In addition, the high adjusted R2 and R3 values (0.9286 and 0.9603, respectively) provide additional evidence of the robustness of the model and reduce the influence of non-significant terms.

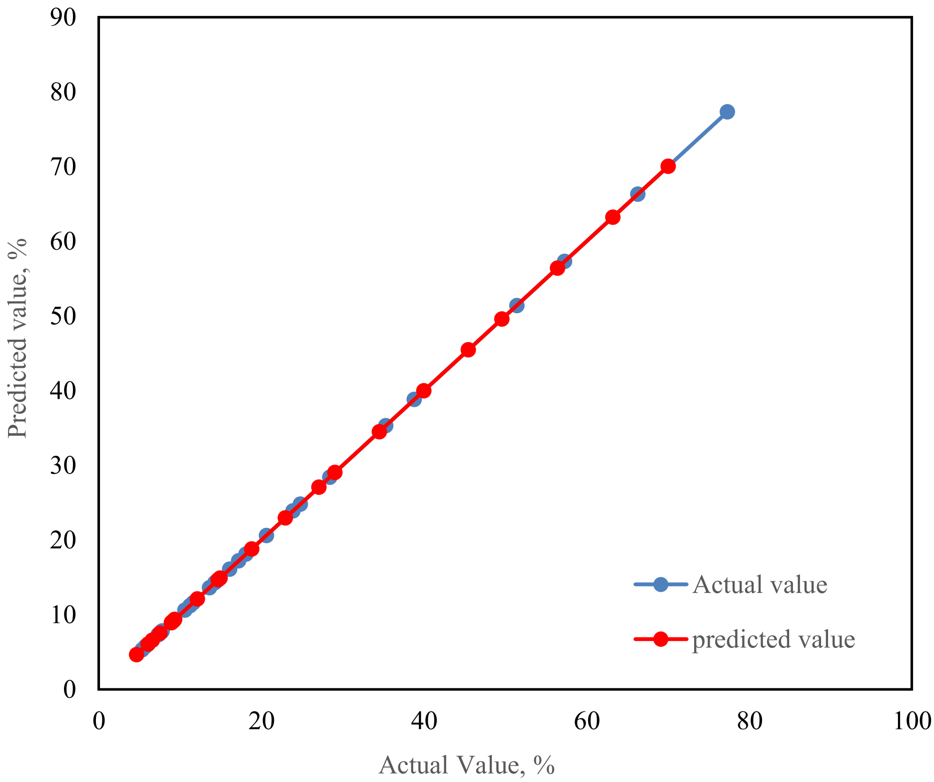


Fig. 5. Actual and predicted values for the cooling temperature difference model

Rys. 5. Rzeczywiste i przewidywane wartości dla modelu różnicy temperatur chłodzenia

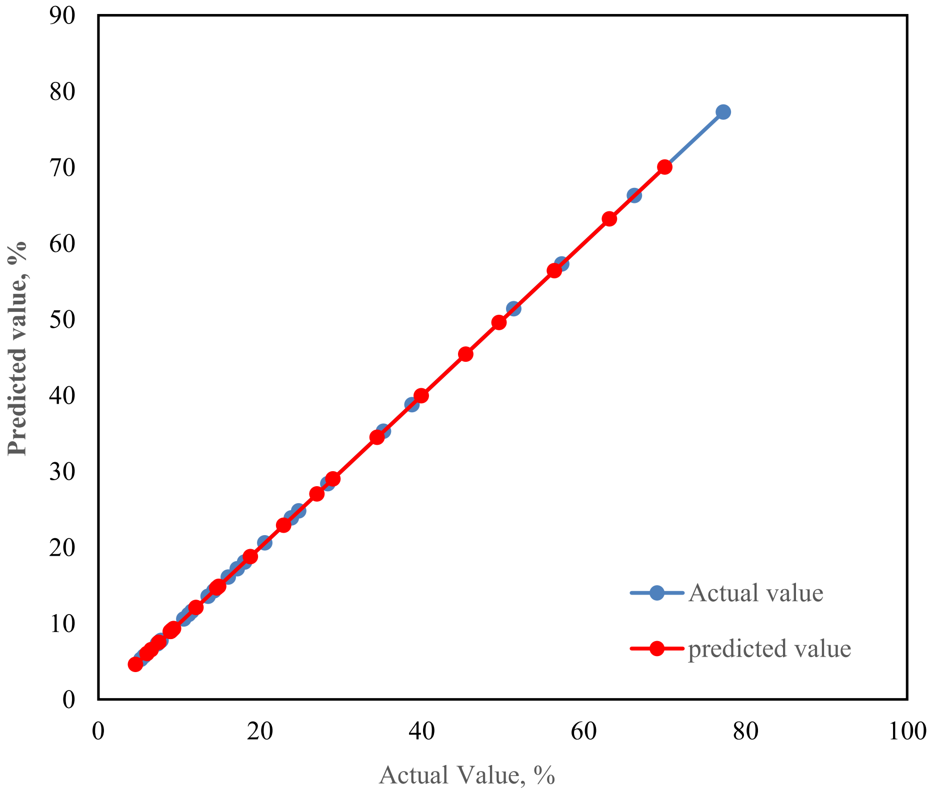


Fig. 6. Actual and predicted values for the COP model

Rys. 6. Rzeczywiste i przewidywane wartości dla modelu COP

2.2. The effect of variable voltage on power and cooling temperature using one Peltier

Figure 7 depicts the variation in temperature and power consumption by using one Peltier unit operating at a varied voltage of 4:14 V with steps of 2 V. The temperature decreased with increasing time for all tested voltages. The power started as high power and after five minutes changed to a steady state case like a constant relationship. The best difference cooling temperature (ΔT) was 11.2 °C at 12 V and 2.668 A with COP 13.6%, but this wasn't the best on power consumption because Peltier uses high voltage and current. The maximum COP was 77.3%, at 4 V and 1.006 with ΔT 8 ºC A which was the best power consumption because of the use of low voltage and current for a cooling period of 45 min.

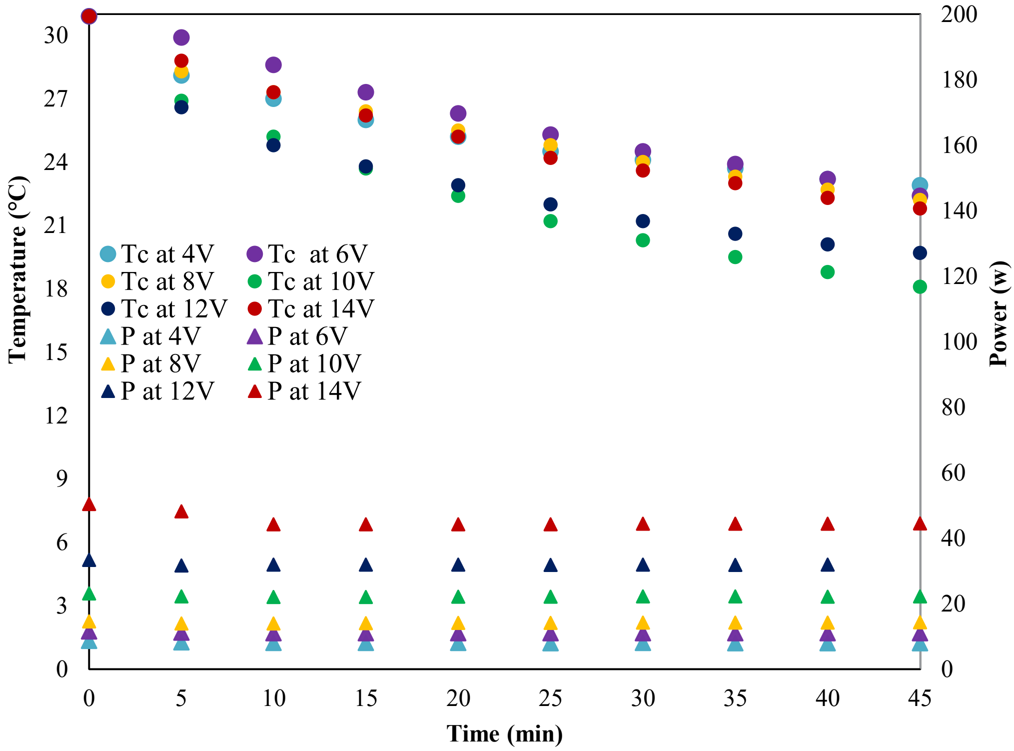


Fig. 7. Variation of temperature and power by using one Peltier unit

Rys. 7. Zmiana temperatury i mocy przy użyciu jednego modułu Peltiera

2.3. Effect of variable voltage on power and cooling temperature using two Peltier units

The variation of temperature and power consumption are displayed in Figure 8 by using two Peltier units at variable voltages of 4, 6, 8, 10, 12, and 14 V. The maximum COP was 66.3% at 4 V, 1.833 A, 7.332 w, and ΔT 12.5°C (cooling temperature =18.4°C). The temperature decreased with increasing time for all tested voltages from room temperature 30.9°C to the cooling temperature. The power was started at high power, and after five minutes was changed to a steady state as a constant power. It was noticed that the highest difference in cooling temperature was 18.2°C (cooling temperature =12.7°C) At 12 V, 5.548 A, 66.57 w, and COP was 10.6%.

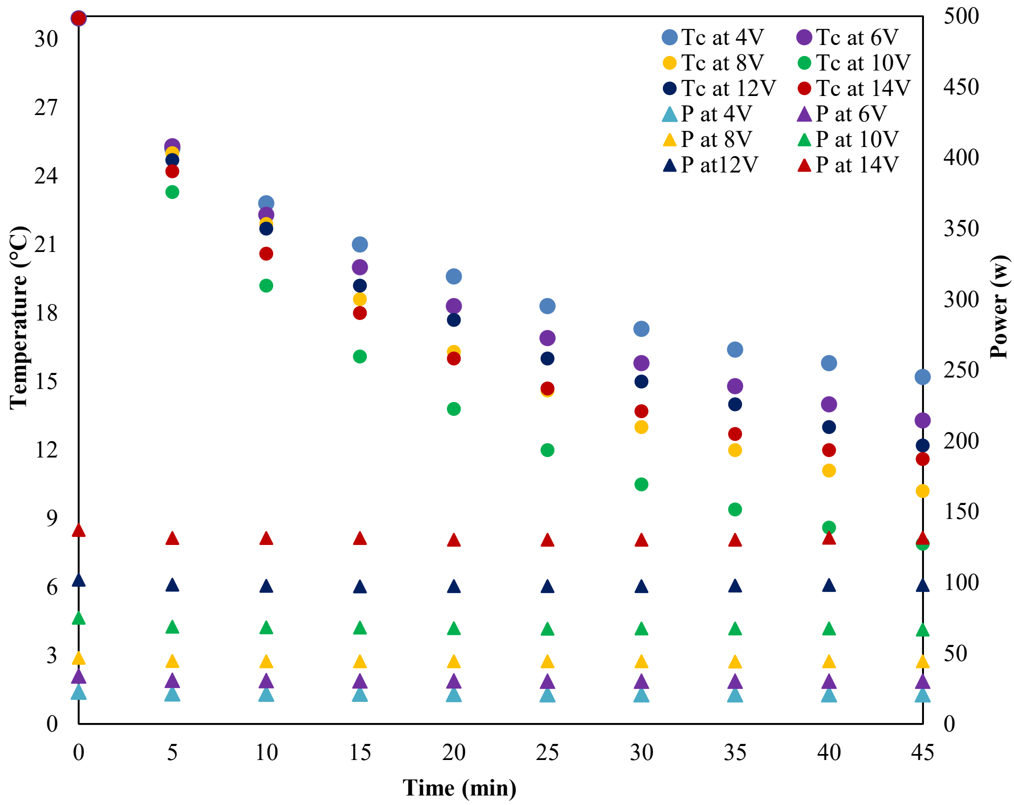


Fig. 8. Variation of temperature and power by using two Peltier units

Rys. 8. Zmiana temperatury i mocy przy użyciu dwóch modułów Peltiera

2.4. Effect of variable voltage on power and cooling temperature using three Peltier units

Figure 9 exhibits the variations in temperature and power usage when three Peltier units with variable voltage of 4, 6, 8, 10, 12, and 14V were used. The temperature decreased with increasing time for all tested voltages. The highest difference cooling temperature was 20.7°C at 8 V and 5.568 A with COP 18.1% this was low efficiency due to high voltage and current. The maximum COP was 57.3%, with ΔT 15.7 ºC at 4 V and 2.66 A which was the best power consumption due to using low voltage and current for a 45-minute cooling period.

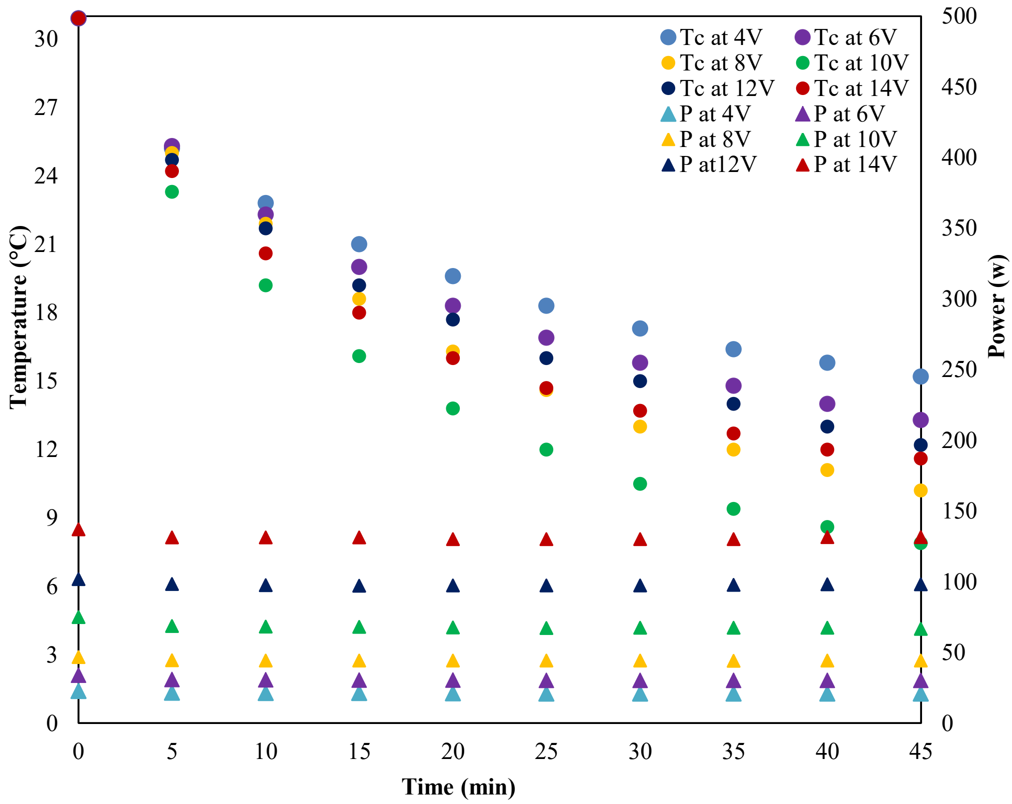


Fig. 9. Temperature and power variations over time for operation with three Peltier units

Rys. 9. Zmiany temperatury i mocy w czasie pracy z trzema jednostkami Peltiera

2.5. Effect of variable voltage on power and cooling temperature using four Peltier

Figure 10 displays the temperature, power consumption and cooling time variation of the cooled box using four Peltier units at different voltages of 4, 6, 8, 10, 12, and 14V. The temperature decreased with increasing time for all tested voltages. The power started at high power after five minutes goes to a steady state case like a constant relationship. The result was that the highest difference in cooling temperature was 26.4°C at 10 V, 9.149 A, 91.49 W, and COP 11.2%. The difference in cooling temperature was the greatest cooling difference but COP wasn't the best because of the high voltage and current. The level of 51.4% was the maximum COP at 4 V, 3.445 A, and 13.78 W, which also had the best power consumption, low voltage, and current. The level of 5.3% was the minimum COP at 14 V, 11.72 A, and 164.2 W, which also had the highest power consumption, high voltage, and current at the same cooling period of 45 min.

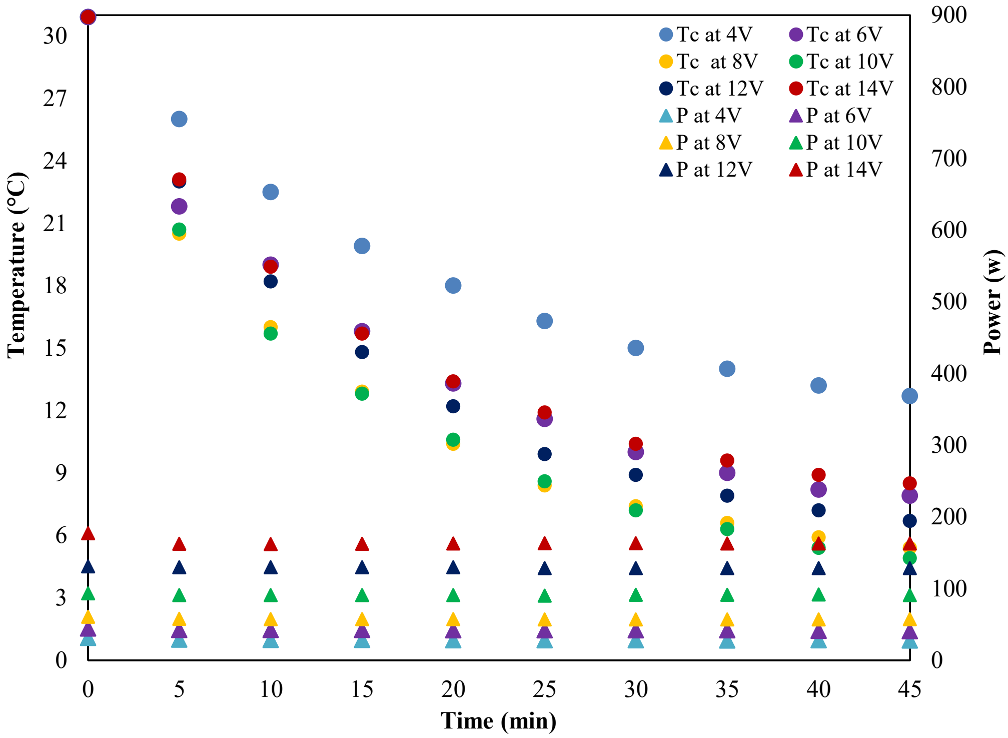
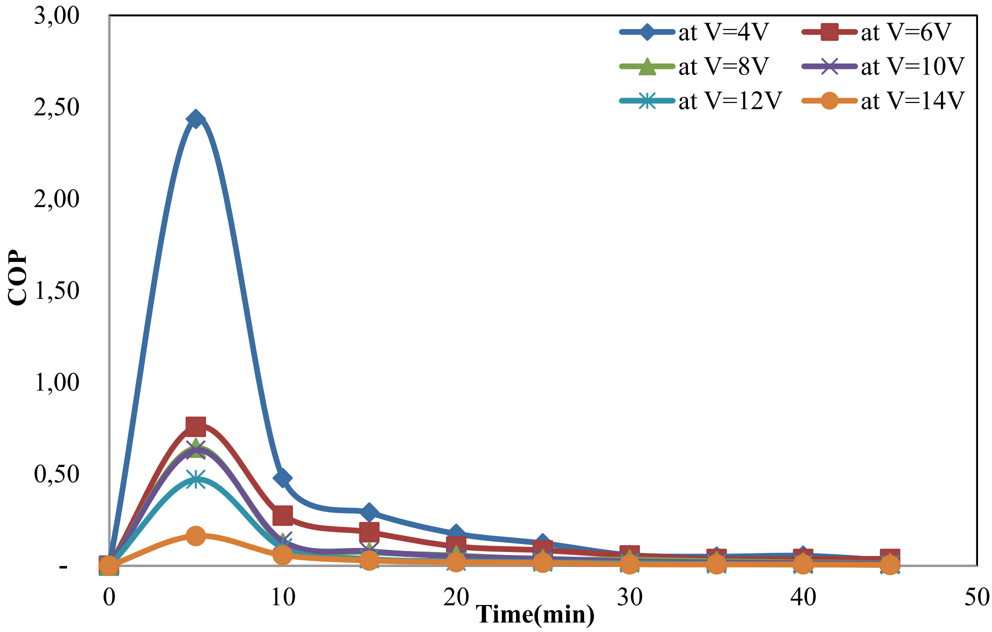


Fig. 10. Temperature and power variations over time for operation with four Peltier units

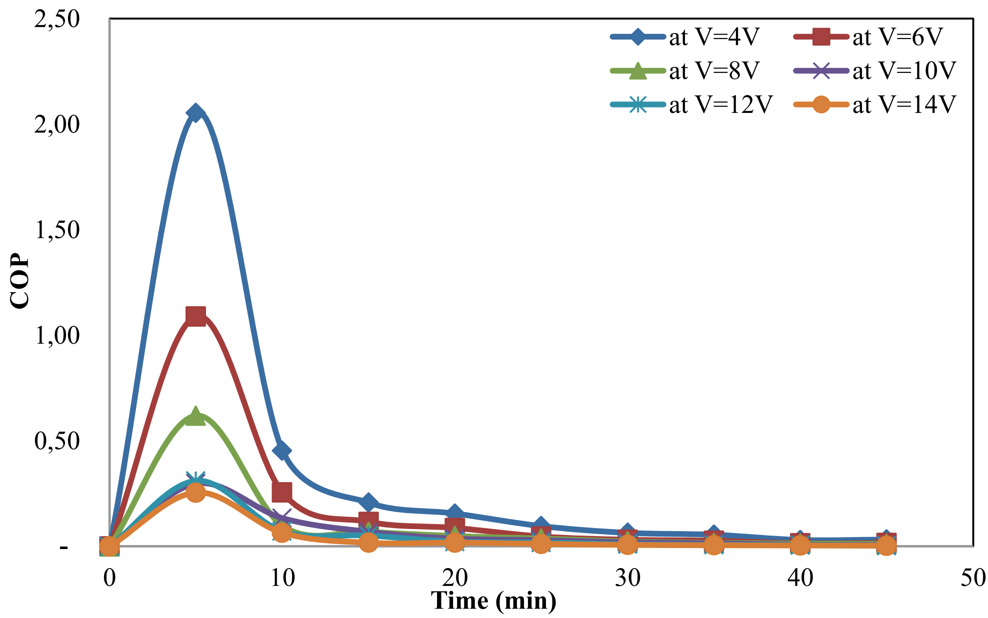
Rys. 10. Zmiany temperatury i mocy w czasie pracy z czterema jednostkami Peltiera

2.6. The best conditions for different temperatures, power variations, and No. of Peltier

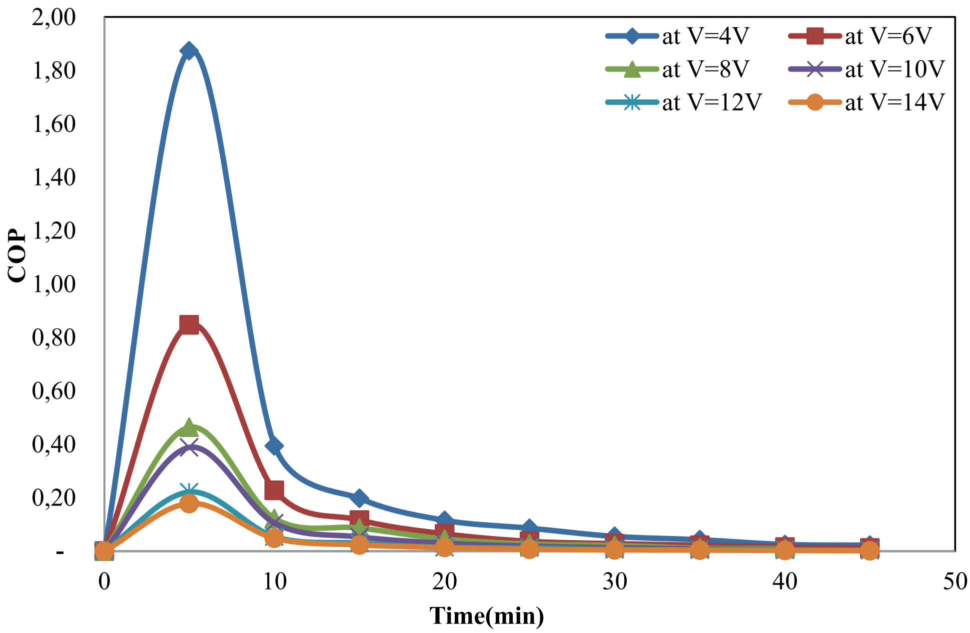
As COP is the major comparison parameter for refrigeration systems, it was used as the quality characteristic for the best. The voltages of the Peltier unit and the fans as well as the ambient temperature are operating factors that have a substantial impact on the COP of the system. These parameters have varying influence on the COP and should thus be the best. Table 2 displays the voltage for the Peltier and fan experiments, as well as the initial temperature and calculated COP values. Where V is the total voltage for the Peltier and the fan, I is the average current, and T is the temperature difference. Finally, the COP is computed. The best COP is 77.3%, which was the highest COP in the experimental study by using one Peltier at 4V. The temperature decreased from 30.9 to 4.5°C by using 4 Peltier units at 10V, at 45 min and at COP 11.1%. Figure 11 (a, b, c, d) show the effect of the number of Peltier units on COP. The results showed that the COP decreased with time, and the best number of the thermoelectric was one Peltier at 4 V. The best performance of the Peltier unit is within 15 mins from the start of use. The COP increased sharply near the starting point, then achieved the peak and went down.



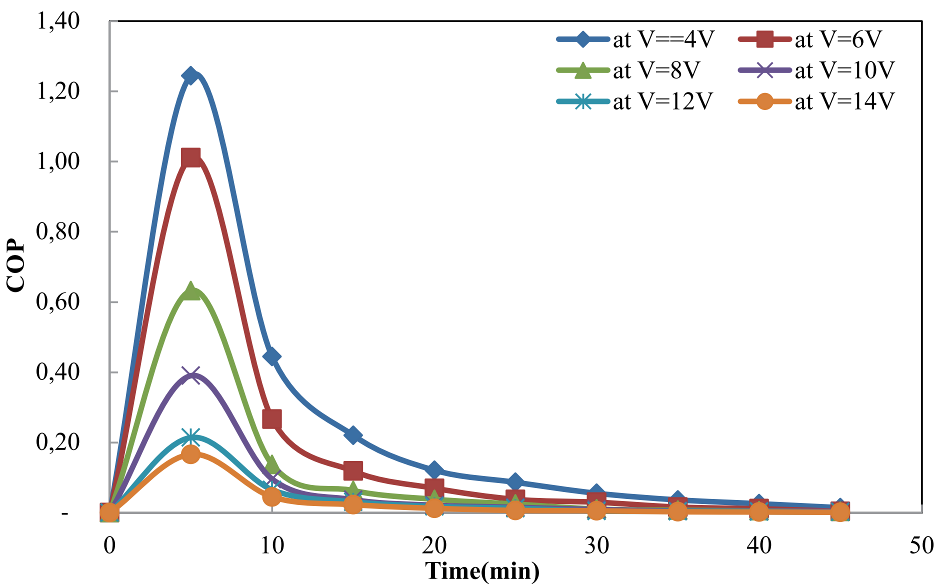
a) Effect of one Peltier on COP over time at different voltage



b) Effect of two Peltier units on COP over time at different voltage



c) Effect of using three Peltier units on COP over time at different voltage



d) Effect of using four Peltier units on COP over time at different voltage

Fig. 11. Effect of one, two, three, and four Peltier on COP over time at different voltage

Rys. 11. Wpływ jednego, dwóch, trzech i czterech ogniw Peltiera na współczynnik COP w czasie przy różnym napięciu

2.7. Influence of variation of voltage and number of Peltier on temperature difference and the COP

2.7.1. Effect of number of Peltier units and voltage on temperature difference (ΔT) %

Figure 12 (a) shows the relationship between voltage, number of Peltier units and temperature difference on a 3D curve. The x-axis represents A: voltage (V) and the y-axis represents B: Peltier axis. The z number represents C: temperature difference (°C). It is noted from the figure that there is an inverse relationship between voltage and different temperatures. This decrease in voltage led to an increase in the temperature difference. It is also clear that the relationship between the number of Peltier units and temperature is a direct relationship, as the lower the Peltier number leads to a lower temperature difference. The highest temperature difference was achieved using four Peltier units at 10 volts.

2.7.2. Effect of number of Peltier units and voltage on COP %

Figure 12 (b) unveils the relation between voltage, number of Peltier units and COP on a 3D curve. The x axis represents A: voltage (V) and the y axis represent B: Peltier axis. The z number represents C: COP (%). From this figure, there is an inverse relationship between voltage and COP. Increasing voltage led to a decrease in the COP. the same for the number of Peltier units the increase in the number of Peltier units led to a decrease in the COP. The highest COP was achieved using one Peltier unit at 4 volts.

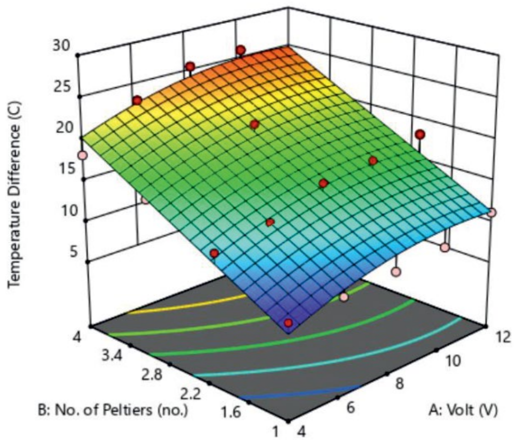
2.7.3. The beast and optimum condition for COP and ΔT

The best and optimum conditions for COP and ΔT are presented in Table 5. The highest COP was 77.3% at 4 V, one Peltier unit, 1.006 A Current, and ΔT 8°C. The highest ΔT was 26.4°C at COP 11.2%, 10 V, four Peltier units, and 9.149 A Current. The Optimum conditions at four Peltier units and 4 volts were (3.445 A Current, ΔT 18.2°C and COP 51.4%) for Experimental and (3.601 A Current, ΔT 20.3°C and COP 49.576 %) for Calculations by RSM.

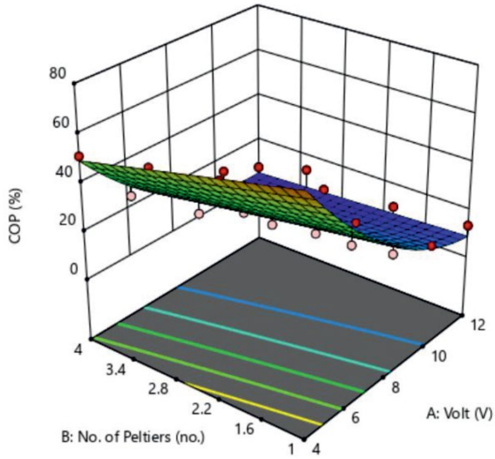
Table 5. The best and optimum condition for COP and ΔT

Tabela 5. Najlepsze i optymalne warunki dla COP i ΔT

Volt V	No. of Peltier	Current A	ΔT [°C]	COP [%]	Notes
4	1	1.006	8	77.3	Highest COP
10	4	9.149	26.4	11.2	Highest ΔT
4	4	3.445	18.2	51.4	Optimum (Experimental)
4	4	3.601	20.3	49.576	Optimum (Calculations RSM)



a) Effect of number of Poltier units and voltage on temperature difference



b) Effect of number of Poltier units and voltage on COP%

Fig. 12. 3D response surface plot illustrating interaction effects on temperature difference and COP

Rys. 12. Trójwymiarowy wykres powierzchni odpowiedzi ilustrujący efekty interakcji na różnicę temperatur i współczynnik wydajności (COP)

2.8. Optimization results

The optimization process aimed to obtain the best temperature difference with maximum COP under the ranges of the studied operating factors. Maximum COP was achieved from Design Expert software using the numerical optimization type presented in Table 6. The optimal values of the two studied factors that give maximum COP with the best temperature difference were determined. It was found that the maximum COP was 49.576% with a temperature difference of 20.301°C. These values were achieved at a voltage of 4 V, four Peltier units, and a current of 3.601 A, as shown in Figure 13. The red dots in the figure indicate the optimal input factor values, while the blue color signifies the maximum outcome value. At voltage in range (4–14) V, the number of Peltier units in range (1–4), the response of current in range (1.006–11.7) A, the response of temperature difference maximum and COP% maximum.

Table 6. The optimization for temperature difference and COP

Tabela 6. Optymalizacja różnicy temperatur i współczynnika COP

Type	Volt [V]	No. of Peltier	Current [A]	Δ*T* [°C]	COP [%]	Desirability [%]
Experimental	4	4	3.445	18.2	77.3	64.8
Calculations	4	4	3.601	20.3	49.576	

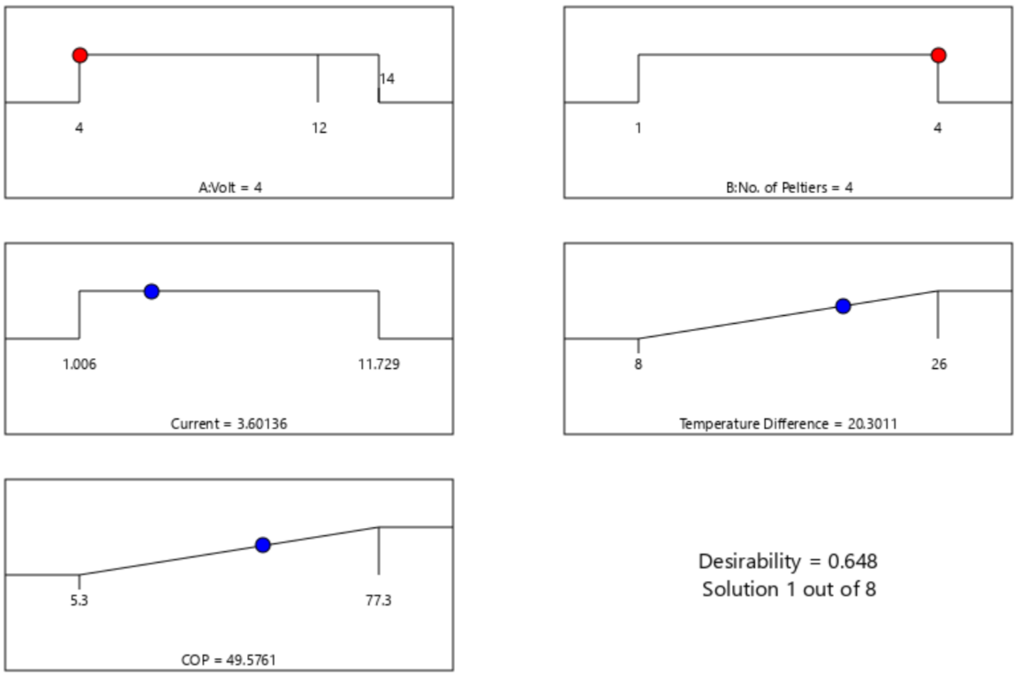


Fig. 13. Maximum temperature difference and COP at optimal experimental factors

Rys. 13. Maksymalna różnica temperatur i współczynnik COP przy optymalnych czynnikach eksperymentalnych

2.9. Comparison of the present work with different previous works on thermoelectric cooling systems

Table 7 presents the comparison between the published work and the present work. In the present research, a portable refrigerator 8 × 8 × 8 cm based on the Peltier principle for the domestic purpose was considered. Using four Peltier units at different voltages gave the best power of 4.024 W, cooling 8°C and COP 0.773, The temperature was reduced from 30 to 4°C in 45 min by using four Peltier units for 0.25 L water.

Table 7. A comparison of the present work with different previous works on thermoelectric cooling systems

Tabela 7. Porównanie obecnej pracy z różnymi poprzednimi pracami na temat układów chłodzenia termoelektrycznego

Authors	Refrigerator type and applications	Methodology	Findings		COP	Variations in temperature
			Power (W)	Cooling (W)		
Present results by the authors	Portable refrigerator based on the Peltier principle for domestic purpose (8 · 8 · 8 cm)	Using four Peltier at different voltage	4.024	3.11	0.773	The temperature was reduced from 30 to 4°C in 45 min by using four Peltier (0.25 L water)
Biswas and Kandasamy 2021	Portable solar thermoelectric cooler for storage of perishable foods	Solar PV system related to the TEC, which consist of TEM, heat sink-fan. The PV and store battery power were utilized in day and nighttime, respectively.	53.5	23.8	0.44	The cold side temperature decreased to 5±0.2°C in 180 min and hot side temperature increased to 40.2°C. The temperature of fish fillets dropped to 6.5°C
He et al. 2013	Solar thermoelectric cooling system for room cooling (size: 0.125 m^3)	The solar cells were connected with thermoelectric device, heat exchanger and water tank which was installed in an experimental room.	36	19.7–20.9	0.45	The room temperature was reduced to 17°C. The COP of 0.45 was obtained with thermal and electrical efficiency of 12.06 and 10.27%, respectively
Mirmanto et al. 2019	Thermoelectric cooler box with several positions (size: 215 · 175 · 130 mm^3)	The cooling system of the cooler box was comprised of a thermoelectric module model TEC1-12706	38.08		0.3	The experiment was conducted for about 18,000 s at the open ambient temperature
Abdul-Wahab et al. 2009	Portable solar thermoelectric refrigerator for domestic purpose (23 · 18 · 32 cm)	Solar PV cells were connected to a set of 10 TEMs. Each module consumed maximum power of 9.5 W.	95	15.33	0.16	The temperature was reduced from 27 to 5°C in 44 min without load, and from 26 to 4°C in 50 min with load (0.5 L canned drink)

Conclusions

A thermoelectric (TE); based on the Peltier principle, was built and tested. A stainless-steel tank was designed, and insulated and four Peltier units were placed on the sides of the tank. The results showed that.

1. The best voltages of the fan and Peltier element for maximum cooling are determined as 10 V, 8 V, and 6 V respectively.

2. The voltage and number of Peltier units were the main effect on COP by the opposite relation. The maximum value of COP at 4 V was 77.3% when the COP was measured for 4V, 6V, 8V, 10V, 12Vand 14V.

3. The lowest COP was 5.3% by using four Peltier units at 14 V and the highest current consumption was 11.729 A.

4. The highest cooling was obtained when the temperature decreased from 30.9 to 4.5°C using 4 Peltier units at 10 V and the maximum cooling temperature difference was 26.4°C for 45 min.

5. The best continuously working time for Peltier units is found to be 15 min and the steady state of the Peltier is reached after 30 min. Peltier units may fail after 45 minutes of continued working. The best working condition for Peltier is running for 15 minutes and stopping minutes with another Peltier.

6. The obtained maximum COP was 77.3%, at 4 V and 1.006 with the difference in cooling temperature of 8°C.

7. The highest difference in cooling temperature was 26.4C at 10 V, 9.149 A, 91.49 W, and COP 11.2%.

8. The optimum condition was cooling temperature 12.7°C, COP 51.4% at 4 V, 3.445 A by using four Peltier units, according to response surface methodology (RSM) includes optimization procedures for the settings of factorial variables by Design Expert 13, such that maximum cooling temperature difference was 20.3°C and maximum COP 49.576% with 4 volts, four Peltier units and a current of 3.601 A in the value range. The results reveal that the obtained determination coefficient for different temperature differences and the COP adjusted R2 and R3 values of 0.9286 and 0.9603, respectively.

Abbreviations

TE	– Thermoelectric
TEC	– Thermoelectric cooler
TEG	– Thermoelectric generator
TU	– Thermoelectric unit
COP	– Coefficient of performance
Cp	– Specific heat of water [J kg^{-1} K^{-1}]
CFCs	– Chlorofluorocarbons
PV	– Photo voltaic
$\dot{Q}$	– Heat transfer rate [W]

Nomenclature

Ti	– Initial temperature [°C]
cp	– Specific heat of water [J kg^{-1} K^{-1}]
I	– Electric current [A]
m	– Mass of water [kg]
$\dot{Q}$	– Heat transfer rate [W]
Tc	– The temperature of cold junction,
Th	– The temperature of hot junction [°C]
t	– Time [s]
$\dot{W}$	– Power consumption [W]

Tc	– The temperature of cold junction [°C]	T	– Temperature [°C]
Th	– The temperature of hot junction [°C]	V	– Voltage [V]
RB	– Refrigerator box		
TU	– Thermoelectric unit		
S.S.	– Stainless steel		
ΔT	– The cooling temperature difference		
PCM	– Phase change material		
DEC	– Direct evaporative cooling		

The Authors have no no conflicts of interest to declare.

References

Abdul-Wahab et al. 2009 – Abdul-Wahab, S.A., Elkamel, A., Al-Damkhi, A.M., Al-Habsi, I.A., Al -Rubai'ey', H.S., Al-Battashi, A.K., Al-Tamimi, A.R., Al-Mamari, K.H. and Chutani, M.U. 2009. Design and Experimental Investigation of Portable Solar Thermoelectric Refrigerator. *Renewable Energy* 34(1), pp. 30–34, DOI: 10.1016/j.renene.2008.04.026.

Afshari, F. 2021. Experimental and Numerical Investigation on Thermoelectric Coolers for Comparing Air-to-Water to Air-to-Air Refrigerators. *Journal of Thermal Analysis and Calorimetry* 144(3), pp. 855–868, DOI: 10.1007/s10973-020-09500-6.

Astrain et al. 2016 – Astrain, D., Aranguren, P., Martínez, A., Rodríguez, A. and Pérez, M.G. 2016. A Comparative Study of Different Heat Exchange Systems in a Thermoelectric Refrigerator and Their Influence on the Efficiency. *Applied Thermal Engineering* 103, pp. 1289–1298, DOI: 10.1016/j.applthermaleng.2016.04.132.

Biswas, O. and Kandasamy, P. 2021. Development and Experimental Investigation of Portable Solar-Powered Thermoelectric Cooler for Preservation of Perishable Foods. *International Journal of Renewable Energy Research* 11(3), pp. 1292–1293.

Çağlar, A. 2018. Optimization of Operational Conditions for a Thermoelectric Refrigerator and Its Performance Analysis at Optimum Conditions. *International Journal of Refrigeration* 96, pp. 70–77, DOI: 10.1016/j.ijrefrig.2018.09.014.

Chen et al 2012 – Chen, L., Meng, F. and Sun, F. 2012. Effect of Heat Transfer on the Performance of Thermoelectric Generator-Driven Thermoelectric Refrigerator System. *Cryogenics* 52(1), pp. 58–65, DOI: 10.1016/j.cryogenics.2011.10.007.

Chen et al. 2022 – Chen, W.H., Carrera Uribe, M., Kwon, E.E., Lin, K.-Y.A., Park, Y.-K., Ding, L. and Saw, L.H. 2022. A Comprehensive Review of Thermoelectric Generation Optimization by Statistical Approach: Taguchi Method, Analysis of Variance (ANOVA), and Response Surface Methodology (RSM). *Renewable and Sustainable Energy Reviews* 169, DOI: 10.1016/j.rser.2022.112917.

Elngar et al. 2018 – Elngar, A.E.M., Rehim, Z.S.A., Refai, W.M., El-Bayoumi, N. and Marzouk, A.L. 2018. Modeling and Power Control for Integrated System of Photovoltaic and Thermoelectric Element. *Journal of Scientific and Engineering Research* 5(12), pp. 202–210. [Online] https://jsaer.com/download/vol-5-iss-12-2018/JSAER2018-05-12-202-210.pdf [Accessed: 2023-10-16].

Gökçek, M. and Şahin, F. 2017. Experimental Performance Investigation of Minichannel Water Cooled -Thermoelectric Refrigerator. *Case Studies in Thermal Engineering* 10, pp. 54–62, DOI: 10.1016/j.csite.2017.03.004.

Góralczyk et al. 2016 – Góralczyk, S., Marchenko, W., Karnkowska, M. and Podgórzak, R. 2016. Technology of Electrical Energy Production from Renewable (*Technologia produkcji energii elektrycznej z odnawialnych źródeł*). *Polityka Energetyczna – Energy Policy Journal* 19(4), pp. 87–100 (*in Polish*).

He et al. 2013 – He, W., Zhou, J., Hou, J., Chen, C. and Ji, J. 2013. Theoretical and Experimental Investigation on a Thermoelectric Cooling and Heating System Driven by Solar. *Applied Energy* 107, pp. 89–97, DOI: 10.1016/j.apenergy.2013.01.055.

Huang et al. 2000 – Huang, B.J., Chin, C.J. and Duang, C.L. 2000. A Design Method of Thermoelectric Cooler. *International Journal of Refrigeration* 23(3), pp. 208–218, DOI: 10.1016/S0140-7007(99)00046-8.

Ibrahim et al. 2020 – Ibrahim, S.M.A., Abed, K.A., Gad, M.S. and Abu Hashish, H.M. 2020. "Experimental Study on the Effect of Preheated Egyptian Jatropha Oil and Biodiesel on the Performance and Emissions of a Diesel Engine. *International Journal of Mechanical & Mechatronics Engineering IJMME-IJENS* 20(1), pp. 59–69.

Kolanowski, W 2021. Salmonids as Natural Functional Food Rich in Omega-3 PUFA. *Applied Sciences* 11(5), DOI: 10.3390/app11052409.

Manikandan et al. 2017 – Manikandan, S., Kaushik, S.C. and Yang, R. 2017. Modified Pulse Operation of Thermoelectric Coolers for Building Cooling Applications. *Energy Conversion and Management* 140, pp. 145–156, DOI: 10.1016/j.enconman.2017.03.003.

Mirmanto et al. 2019 – Mirmanto, M., Syahrul, S. and Wirdan, Y. 2019. Experimental Performances of a Thermoelectric Cooler Box with Thermoelectric Position Variations. *Engineering Science and Technology, an International Journal* 22(1), pp. 177–184, DOI: 10.1016/j.jestch.2018.09.006.

Nechev et al. 2021 – Nechev, J.T., Edvinsen, G.K. and Eilertsen, K.E. 2021. Fatty Acid Composition of the Lipids from Atlantic Salmon – Comparison of Two Extraction Methods without Halogenated Solvents. *Foods* 10(1), DOI: 10.3390/foods10010073.

Parlak et al. 2024 – Parlak, Z., İslamoğlu, Y. and Parlak, N. 2024. Performance Evaluation of an Integrated Heatsink and Thermoelectric Module by Two-Way Coupled Numerical Analysis. *International Journal of Thermal Sciences* 197, DOI: 10.1016/j.ijthermalsci.2023.108809.

Rejeb et al. 2020 – Rejeb, O., Shittu, S., Ghenai, C., Li, G., Zhao, X. and Bettayeb, M. 2020. Optimization and Performance Analysis of a Solar Concentrated Photovoltaic-Thermoelectric (CPV-TE) Hybrid System. *Renewable Energy* 152, pp. 1342–1353, DOI: 10.1016/j.renene.2020.02.007.

Riffat, S.B. and Ma, X. 2003. Thermoelectrics: A Review of Present and Potential Applications. *Applied Thermal Engineering* 23(8), pp. 913–935, DOI: 10.1016/S1359-4311(03)00012-7.

Sajid et al. 2017 – Sajid, M., Hassan, I. and Rahman, A. 2017. An Overview of Cooling of Thermoelectric Devices. *Renewable and Sustainable Energy Reviews* 78, pp. 15–22, DOI: 10.1016/j.rser.2017.04.098.

Seebeck, T.J. 1826. On the magnetic polarization of metals and ores by temperature difference (*Ueber Die Magnetische Polarisation Der Metalle Und Erze Durch Temperatur-Differenz*). *Annalen der Physik* 82(2), pp. 133–160, DOI: https://10.1002/andp.18260820202 (*in German*).

Soprani et al. 2016 – Soprani, S., Haertel, J.H.K., Lazarov, B.S., Sigmund, O. and Engelbrecht, K. 2016. A Design Approach for Integrating Thermoelectric Devices Using Topology Optimization. *Applied Energy* 176, pp. 49–64, DOI: 10.1016/j.apenergy.2016.05.024.

Takahashi et al. 2013 – Takahashi, K., Kanno, T., Sakai, A., Tamaki, H., Kusada, H. and Yamada, Y. 2013. Bifunctional Thermoelectric Tube Made of Tilted Multilayer Material as an Alternative to Standard Heat Exchangers. *Scientific Reports* 3, DOI: 10.1038/srep01501.

Tan, G. and Zhao, D. 2015. Study of a Thermoelectric Space Cooling System Integrated with Phase Change Material. *Applied Thermal Engineering* 86, pp. 187–198, DOI: 10.1016/j.applthermaleng.2015.04.054.

Tipsaenporm et al. 2012 – Tipsaenporm, W., Lertsatitthanakorn, C. Bubphachot, B., Rungsiyopas, M. and Soponronnarit, S. 2012. Improvement of Cooling Performance of a Compact Thermoelectric Air Conditioner Using a Direct Evaporative Cooling System. *Journal of Electronic Materials* 41(6), pp. 1186–1192, DOI: 10.1007/s11664-012-1909-9.

Tripathi et al. 2020 – Tripathi, M., Bhatnagar, A., Mubarak, N.M., Sahu, J.N. and Ganesan, P. 2020. RSM Optimization of Microwave Pyrolysis Parameters to Produce OPS Char with High Yield and Large BET Surface Area. *Fuel* 277, DOI: 10.1016/j.fuel.2020.118184.

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Poprawa współczynnika wydajności (COP) minilodówek opartych na jednostkach termoelektrycznych (Peltiera)

Streszczenie

Niedobór energii na świecie i zanieczyszczenia wynikające z nadmiernego zużycia energii prowadzą do wzrostu globalnego ocieplenia. Istnieje potrzeba poszukiwania zrównoważonych alternatyw, które zużywają mniej energii w celu zmniejszenia problemów środowiskowych, a także alternatyw dla stosowania freonu, który jest szkodliwy dla środowiska, jednym z najniebezpieczniejszych zanieczyszczeń i zwiększa dziurę ozonową.

Obecne badania mają na celu zbadanie wydajności lodówek termoelektrycznych w różnych warunkach pracy. Przenośna lodówka termoelektryczna została opracowana dla osób mieszkających w odległych obszarach Egiptu poza siecią elektryczną (np. pustynie). Zaprojektowana lodówka opiera się na efekcie Peltiera z wykorzystaniem jednostek Peltiera. Lodówka została zaprojektowana, wyprodukowana i przetestowana eksperymentalnie. Zbadano kilka zmiennych w systemach szybkiego chłodzenia dla różnych warunków, aby zminimalizować czas, obniżyć temperaturę chłodzenia i zwiększyć współczynnik wydajności (COP) za pomocą metodologii powierzchni odpowiedzi (RSM).

Wyniki pokazują, że uzyskany maksymalny współczynnik COP wynosił 77,3% przy 4 V i 1,006 przy różnicy w temperaturze chłodzenia (ΔT) wynoszącej 8°C. Najwyższa ΔT wynosiła 26,4°C przy 10 V, 9,149 A, 91,49 W i COP 11,2%. Optymalnym warunkiem była temperatura chłodzenia 12,7°C, COP 51,4% przy 4 V, 3,445 A przy użyciu 4 Peltierów, zgodnie z metodologią powierzchni odpowiedzi (RSM) obejmującą procedury optymalizacji ustawień zmiennych czynnikowych przez eksperta ds. projektowania 13, tak że maksymalna ΔT wynosiła 20,3°C i maksymalny COP 49,576% przy 4 V, 4 nr Peltiera i prądzie 3,601 A w zakresie wartości. Wyniki pokazują, że uzyskany współczynnik determinacji dla ΔT i COP skorygowane wartości R2 i R3 odpowiednio 0,9286 i 0,9603.

Słowa kluczowe: COP, efektywność energetyczna, zanieczyszczenie środowiska, magazynowanie ciepła, jednostka termoelektryczna