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Experimental study on the performance of Peltier TEC12706 as a cooling and heating media

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Abstract

The application of refrigeration spans a wide range of industries, from household needs to the oil and gas sector, employing various cooling methods. One rapidly developing approach is the use of Peltier devices, particularly the TEC1 12706 model, due to its compact size and widespread availability. It is essential for students to understand the application of Peltier technology, which necessitates the creation of practical tools for both educational and research purposes. Most existing research on Peltier devices focuses on air conditioning systems with fixed loads; therefore, it is imperative to explore their cooling and heating effects in dynamic environments. To address this gap, this study investigates the performance of Peltier modules as cooling and heating systems for moving media. A prototype of a cooling and heating module (heat pump) was developed using Peltier devices, and its performance was evaluated by varying the flow rates of hot and cold water (1.62/1.02; 1.2/0.8; and 0.9/0.68 L/min) and the number of operational Peltier elements (2, 4, 6). Calculations using the relevant formulas yielded the Coefficients of Performance (COP): COPc = 0.45, COPh = 1.37, and COPtot = 1.82. The results revealed that the cooling performance coefficient is lower than both the heating and total performance coefficients. Additionally, variations in flow rates and the number of installed Peltier devices showed minimal impact on cooling and heating performance coefficients.

Keywords:
COP, heating and cooling, heat pump, TEC1 12706.

1 Introduction

Refrigeration plays a critical role across various sectors, including households, industrial applications, and the oil and gas industry. In the oil and gas sector, cooling techniques are essential not only for human comfort but also for safeguarding equipment and optimizing processes. These techniques are employed in the production of Liquefied Petroleum Gas (LPG) and Liquefied Natural Gas (LNG), as well as in air drying for instrumentation at refineries and oil and gas fields. However, the use of traditional refrigerants, such as Freon and ammonia, in air conditioning systems poses significant environmental challenges, including harmful gas emissions and contributions to global warming. These issues can be addressed through the implementation of thermoelectric modules, which offer a more sustainable alternative. By utilizing efficient semiconductors, these modules reduce power consumption and minimize environmental impact. Additionally, thermoelectric modules are compact, lightweight, and highly reliable, with no working fluids or moving parts, distinguishing them from conventional refrigeration systems [1].

Analysis and experimental study of sustainable cooling using Peltier has been carried out by: [2],[3],[4],[5],[6],[7],[8],[9],[10],[11],[12]. Peltier module there with significantly reduced cost and power consumption. The use of Peltier as a cooling and heating medium has also been increasingly used as is the case with [1],[2], some of which use Arduino as a controller [13]. And selection of TEC12706 for air space cooling was found correct as the cooling load had been taken care of by the Peltier element [14]. This research concludes that the development of Peltier cooling technology is advancing rapidly. Most existing studies focus on air conditioning systems with fixed loads, highlighting the need for further investigation into the cooling and heating effects in dynamic environments. As an educational institution in the energy sector, PEM Akamigas Cepu recognizes the importance of equipping its students with both theoretical knowledge and practical skills in this area, enabling them to stay abreast of technological advancements. Furthermore, in the pursuit of energy efficiency, it is essential to explore the application of Peltier devices not only for cooling processes but also for utilizing waste heat. This necessitates a comprehensive study of their performance across various applications, including cooling, heating, and combined cooling-heating processes.

A cooling and heating prototype was developed using Peltier modules TEC1 12706 to evaluate their thermoelectric performance characteristics as both a cooling and heating medium. This prototype also serves as a practical facility for the refrigeration engineering course within the refinery mechanical engineering program at PEM Akamigas Cepu. The selection of the Peltier TEC1-12706 is justified by its widespread availability and diverse applications in the market. With compact dimensions of 40×40×4 mm and an optimal input power of 72 W when supplied with 12 Volt DC, this module is particularly attractive for cooling and heating processes. Additionally, this component can be reversed to function as a DC power generator (TEG-Thermoelectric Generator), further enhancing its utility.

2 Research Methods/Materials and Methods

The research method used in this study is to make a cooling and heating prototype and carried out the performance.

2.1 Prototype Setup

Several components, namely the thermoelectric cooler module, measuring instruments (electricity, temperature and others) were combined into a cooling and heating module (heat pump) with a thermoelectric cooler.

The main components and their specifications used in this study include:

1. Peltier TEC1-12706 (6 pieces) for the cooling/heating module.
2. The heat sink uses a water block cooler (2 units, @ 2 pieces) for heat dissipation and absorption.
3. Power supply 12 Volt DC (@ 10 Ampere) for Peltier power supply.
4. Volt ammeter to measure the voltage and current of the power supply.
5. Booster pump (80 L/minute) and its piping system for circulating the working fluid flow.
6. Water flowmeter to measure the fluid flow capacity.
7. Thermometer to measure the temperature of the working fluid.
8. Tub for holding water/working fluid.
9. Hot hoses, pipes and fittings for water/working fluid installations.
10. Framework for the installation of equipment, with the equipment set-up diagram as shown in Fig. 1.

Two systems, each consisting of three Peltier TEC1-12706 modules flanked by two water blocks, will be interconnected to allow for the operation of two, four, or six Peltier modules simultaneously. The Peltier modules will be connected to a DC power source located on the side of the water blocks. A booster pump will facilitate the flow of water as a cooling and heating medium, while instrumentation equipment will be installed to measure fluid flow capacity, temperature, voltage, and current.

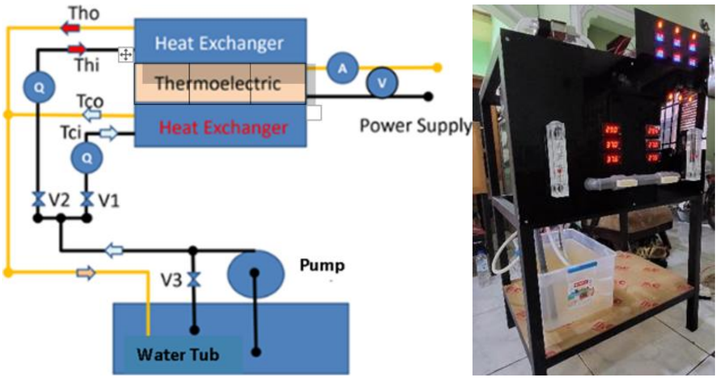

Fig. 1. System set up & prototype photos.

When electricity is supplied to the thermoelectric modules via DC current, a temperature differential will develop between the two surfaces: one will become hot while the other will remain cold. The cold side will absorb heat from the working fluid, resulting in a decrease in the fluid's temperature (refrigeration process). Conversely, the hot side will release heat into the heating medium until it reaches a predetermined temperature. The temperature difference between the hot and cold surfaces is affected by the type of thermoelectric module, the amount of electricity supplied, and the efficiency of the heat transfer processes occurring on both surfaces.

2.2 The Research of Cooling/Heating Performance

In this study, the research data were taken at variations of cold and hot fluid flowrate conditions: 1.62/1.02; 1.2/0.8; 0.9/0.68 liters/minute for each number of operating Peltiers from 2, 4 and 6. And from the measurement results, calculations will be carried out according to the applicable formula.

2.3 Formula

2.3.1 Thermoelectric Module

A thermoelectric module consists of a connection between two different metal ends. When Direct Current (DC) electricity is applied to one set of ends, the other ends will experience a temperature difference, resulting in a hot and cold junction. Fig. 2 illustrates a basic configuration of a typical thermoelectric material connection, featuring a P-N semiconductor junction that operates as an electricity generator.

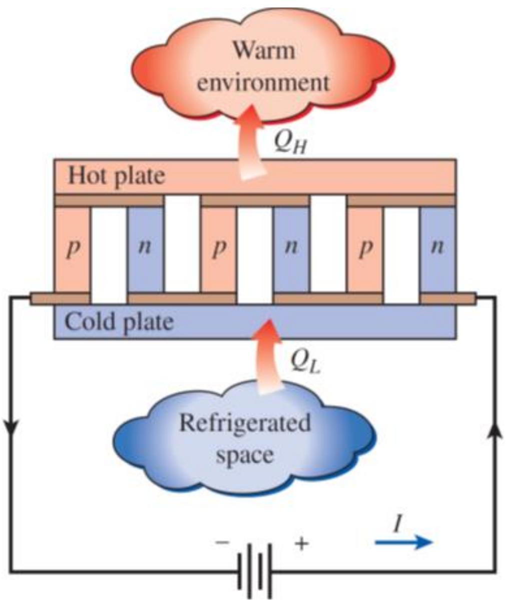

Fig. 2. A P-N semiconductor connection as an electricity generator [15].

2.3.2 Caloric Calculation

In a cooling system utilizing a Peltier device, heat is generated as a result of the electric current flowing through the system. This current extracts heat from the cooled medium, transferring it from the cold side to the hot side of the Peltier module. Consequently, a heat dissipation process occurs on the hot surface. Fig. 3 illustrates a heat process diagram for the Peltier device.

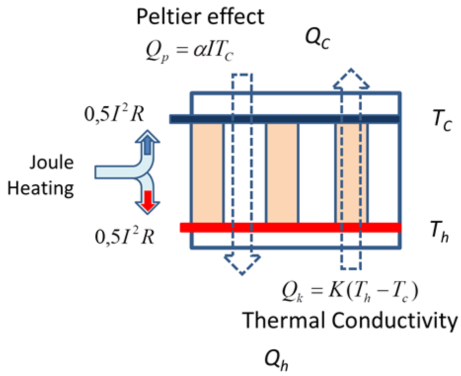

Fig. 3. Heat transfer in thermoelectrics [16].

2.3.3 Heat Pumped by the Peltier Effect

The amount of heat pumped by the Peltier effect is the heat absorbed in the cooling process on the cold side of the thermoelectric surface based on the thermoelectric properties. The amount of heat can be calculated by the Eq. 1 [16].

$$Q_p = \alpha I T_c \quad (1)$$

Where: Q_p = heat pumped by the Peltier effect (W), α = Seebeck coefficient (V/K), T_c = cold side temperature (K), I = electric current supplied to Perltier (A).

2.3.4 The Joule Heating Effect

The Joule heating effect caused by electric current can be calculated with the Eq. 2 [16].

$$Q_j = \frac{I^2.R}{2} \quad (2)$$

Where: Q_j = Joule heating effect (W), R = electrical resistance (Ω).

2.3.5 Heat Transferred

The amount of heat transferred due to thermal conductivity can be calculated by the Eq. 3 [16].

$$Q_k = K\Delta T \quad (3)$$

Where: Q_k= heat transfer due to thermal conductivity (W), K = thermal conductivity (W/K), ΔT = temperature difference between the hot side and the cold side (K).

2.3.6 Absorbed Calories

The amount of heat transferred to the side of the thermoelectric cold surface of the cooling load is the balance of the heats mentioned by Eq. 3, whose magnitude is Eq. 4-Eq. 5 [16].

$$Q_c = Q_p - Q_k - Q_j \quad (4)$$

$$Q_c = \alpha I T_c - 0.5 I^2 R - K\Delta T \quad (5)$$

Where: Q_c = heat absorbed on the cold side (W).

2.3.7 Released Calories

The amount of heat released from the side of the thermoelectric hot surface is a balance of the heats mentioned in the Fig. 3, the magnitude of which is Eq. 6 [16].

$$Q_h = \alpha I T_c + 0,5 I^2 R - K\Delta T \quad (6)$$

Where: Q_h = heat released on the hot side (W).

2.3.8 Properties of Materials

The properties of thermoelectric materials that affect the performance of the cooling system with this Peltier are: Seebeck effect (Seebeck coefficient), thermal conductivity, electric resistance, figure merit.

1. Seebeck coefficient

The magnitude of the Seebeck coefficient can be determined by the Eq. 7 [17].

$$\alpha = 2\alpha_m N \tag{7}$$

Where: α = Seebeck Peltier effect (W/K), $\alpha_m = \alpha_0 + \alpha_1 T_{ave} + \alpha_2 T_{ave}^2$, α_m = Seebeck coefficient effect elements (V/K) [16], α_0= 2.2224×10^{-5}, α_1 = 9.306×10^{-7}, α_2 = -9.905×10^{-10}, T_{ave} = the average temperature of the cold and hot sides (K), N = the number of connection elements in the Peltier (TEC1-12706 = 127).

2. Equipment thermal conductivity

The amount of thermal conductivity can be calculated by the Eq. 8 [17].

$$K = 2K_m NG \tag{8}$$

Where: K_m = element thermal conductivity (W/cm.K) [16] = $K_0 + K_1 T_{ape} + K_2 T_{ave}^2$, K_0 = 6.2605×10^{-2}, K_1 = -2.777×10^{-4}, K_2 = 4.131×10^{-7}, G = element geometry factors (0.121 cm) (AZTEC software v3.1, [17]).

3. Electrical resistance

The amount of electrical resistance can be determined by the Eq. 9 [17].

$$R = \frac{2\rho N}{G} \tag{9}$$

Where: ρ = element electrical resistance (Ωcm) [16] = $\rho_0 + \rho_1 T_{ave} + \rho_2 T_{ave}^2$, ρ_0 = 5.112×10^{-5}, ρ_1 = 1.634×10^{-6}, ρ_2 = 6.279×10^{-9}, T_{ave} = the average temperature of the Peltier hot and cold sides (K).

4. Figure of merit

The figure of merit (Z) is a key parameter used to assess the efficiency of thermoelectric materials. A high value of Z indicates a strong thermoelectric performance. The figure of merit is influenced by the material's thermoelectric properties as a function of temperature. The value of Z can be calculated using the Eq. 10 [18].

$$Z = \frac{\alpha_m^2}{\rho . K_m} \tag{10}$$

Where: Z = figure of merit (1/K).

2.3.9 Performance

Process performance (COP) of cooling and heating with Peltier can be calculated by the Eq. 11-Eq. 13.

1. Cooling process

$$COP_c = \frac{Q_c}{P} \tag{11}$$

$$Qc = m_c \times Cp \times (Tci\text{-}Tco)$$

2. Heating process

$$COP_h = \frac{Q_h}{P} \tag{12}$$

$$Qh = mh \times Cp \times (Tho - Thi)$$

3. Cooling and heating process (both of heat taking and releasing are utilized)

$$COP_t = \frac{Q_c + Q_h}{P} \tag{13}$$

$$P = V \cdot I$$

Where: Q_c = heat absorbed from the medium on the cold side, Q_h = heat released in the medium on the hot side, P = electrical power supplied to the Peltier (W).

3 Results and Discussion

By varying the flow rate and number of Peltiers, the results obtained from this study are shown in Table 1 and the results obtained will be calculated using a predetermined formula, the calculation results are shown in Table 2.

Tabel 1. The relationship between constant flowrate and variation in the number of Peltiers

No	Hot	Cold	Th1	Ths	Th2	Tc1	Tcs	Tc2	1		2		3		4		5		6	
	LPM	LPM	C	C	C	C	C	C	V	A	V	A	V	A	V	A	V	A	V	A
Rata-rata	1.62	1.02	28.42	31.6	29.6	28.2	27.22	27.64	12	4.01	12	3.92								
Rata-rata	1.62	1.02	29.37	33.267	31.65	29.25	27.55	28.03	12	3.96	12	3.87	11.9	4.04	12.05	3.78				
Rata-rata	1.6	1.02	30.54	34.9	33.92	30.34	28.06	28.44	12	3.92	12	3.85	11.9	3.98	12	3.73	12	3.86	11.9	3.92
Rata rata	1.2	0.8	31.54	37.04	36.02	31.32	28.48	29	12	3.88	12	3.8	11.9	3.93	12	3.68	12	3.81	11.9	3.88
Rata rata	1.2	0.8	32.32	37.22	35.36	32.08	29.08	30.54	11.94	3.88	12	3.8	11.9	3.95	12	3.71				
Rata rata	1.2	0.8	33.12	36.76	34.68	32.9	30.22	32.06	11.9	3.91	12	3.82								
Rata-rata	0.9	0.68	33.86	38.08	35.8	33.62	30.86	32.68	11.92	3.88	12	3.81								
Rata-rata	0.9	0.68	34.62	40.22	38.34	34.34	30.74	32.58	12	3.82	12	3.74	11.9	3.89	12	3.66				
Rata-rata	0.9	0.68	35.44	41.88	41.1	35.2	30.86	32.54	12	3.79	12	3.71	11.9	3.83	12	3.6	12	3.73	11.9	3.77

Tabel 2. Capacity and COP calculation data

Jumlah	Hot	Cold	Temperatur (T, C)						Q (J/s)			COP		
Peltier	LPM	LPM	Th1	Ths	Th2	Tc1	Tcs	Tc2	Qin	Qcold	Qhot	COPC	COPH	COPTot
2	1.62	1.02	28.42	31.6	29.6	28.2	27.22	27.64	95.1	39.6	132.5	0.42	1.39	1.81
4	1.62	1.02	29.367	33.27	31.65	29.25	27.55	28.033	188.1	77.8	280.7	0.41	1.49	1.91
6	1.6	1.02	30.54	34.9	33.92	30.34	28.06	28.44	188.1	99	247	0.53	1.31	1.84
2	1.2	0.8	33.12	36.76	34.68	32.9	30.22	32.06	188.1	91.9	258.2	0.49	1.37	1.86
4	1.2	0.8	32.32	37.22	35.36	32.08	29.08	30.54	186.9	84.8	247	0.45	1.32	1.78
6	1.2	0.8	31.54	37.04	36.02	31.32	28.48	29	186.9	84.8	258.2	0.45	1.38	1.84
2	0.9	0.68	33.86	38.08	35.8	33.62	30.86	32.68	186.9	77.8	247	0.42	1.32	1.74
4	0.9	0.68	34.62	40.22	38.34	34.34	30.74	32.58	187.5	86	256.3	0.46	1.37	1.83
6	0.9	0.68	35.44	41.88	41.1	35.2	30.86	32.54	278.9	127.2	377	0.46	1.35	1.81

3.1 The Research Result of Constant Hot/Cold Flowrate for Each Number of Operating Peltiers

From the table of data calculation results, a graph can be made.

3.1.1 Flowrate of Hot/Cold Water: 1.62/1.02 liters/minutes

From the table of data calculation results, a graph flowrate of hot/cold water: 1.62/1.02 liters/minutes can be made as shown in Fig. 4.

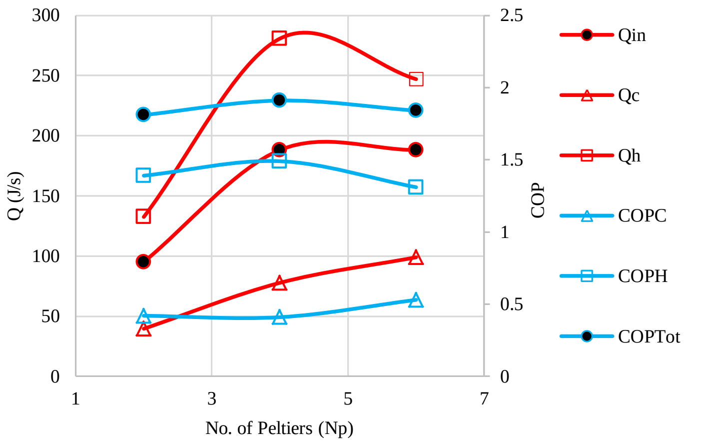

Fig. 4. Graphs of Np, Q and COP at mh = 1.62 & mc = 1.02 LPM.

3.1.2 Flowrate of Hot/Cold Water: 1.2/0.8 liters/minutes

From the table of data calculation results, a graph flowrate of hot/cold water: 1.2/0.8 liters/minutes can be made as shown in Fig. 5.

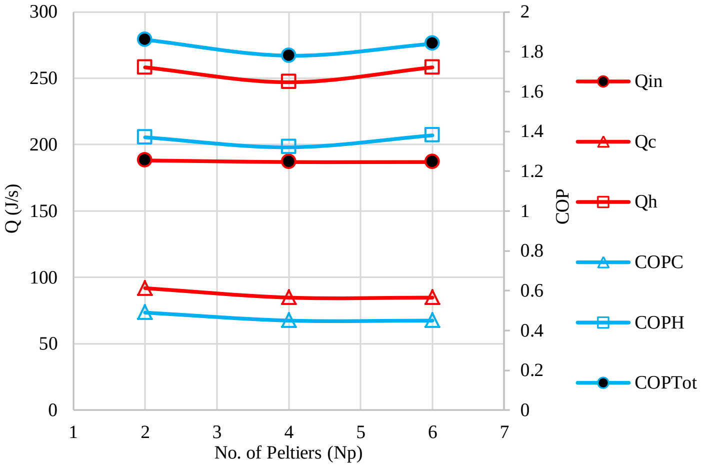

Fig. 5. Graphs of Np, Q and COP at mh = 1.2 & mc = 0.8 LPM.

3.1.3 Flowrate of Hot/Cold Water: 0.9/0.68 liters/minutes

From the table of data calculation results, a graph flowrate of hot/cold water: 0.9/0.68 liters/minutes can be made as shown in Fig. 6.

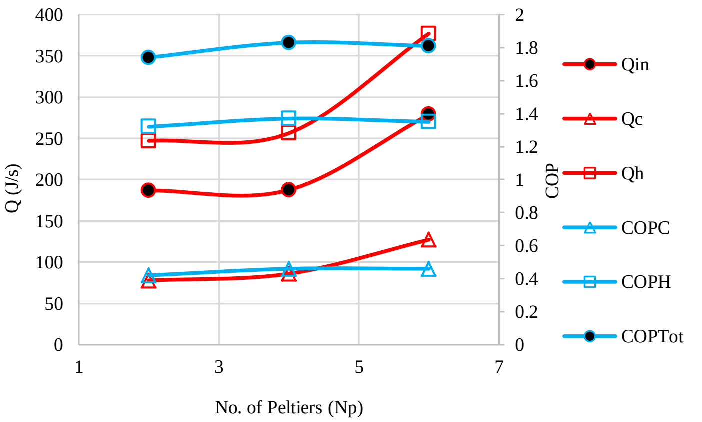

Fig. 6. Graph of the relationship between Np, Q and COP at mh = 0.9 & mc = 0.68 LPM.

From the graphs in Fig. 4-Fig. 6 it can be seen that:

1. Heat input increases according to the increase in the amount of Peltier (Np), this is in accordance with the equation that Q = Np (Volt) (Ampere), where Np is the number of Peltier used
2. The heat received by the hot fluid (water) tends to increase in accordance with the increase in the number of Peltiers
3. The heat released by cold fluid (water) tends to increase as the number of Peltiers increases
4. COPC and COPH tend to be constant (not affected by the amount of Peltier).

3.2 The Research Result of the Constant Number of Operating Peltiers for Each Variable of Hot/Cold Water: 1.62/1.02; 1.2/0.8; 0.9/0.68 liters/minutes

3.2.1 The Number of Operating Peltiers: 2

From the table of data calculation results, a graph of the research result of the constant number of operating Peltiers for each variable of hot/cold water: 1.62/1.02; 1.2/0.8; 0.9/0.68 liters/minutes can be made as shown in Fig. 7.

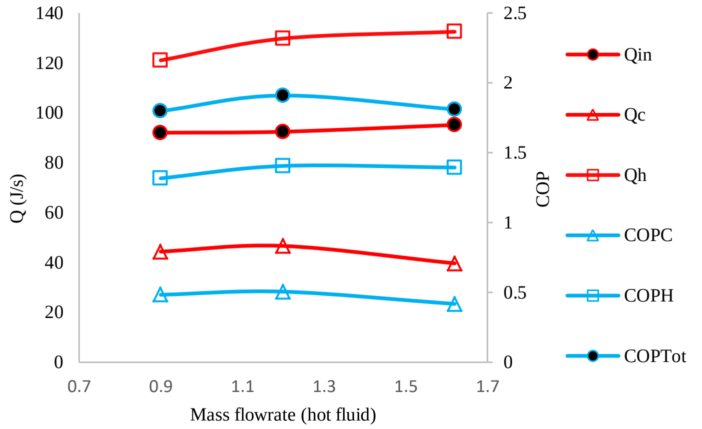

Fig. 7. Graph of the relationship mh, Q and COP at Np = 2 pieces.

3.2.2 The Number of Operating Peltiers: 4

From the table of data calculation results, a graph of the research result of the constant number of operating Peltiers for each variable of hot/cold water: 1.62/1.02; 1.2/0.8; 0.9/0.68 liters/minutes can be made as shown in Fig. 8.

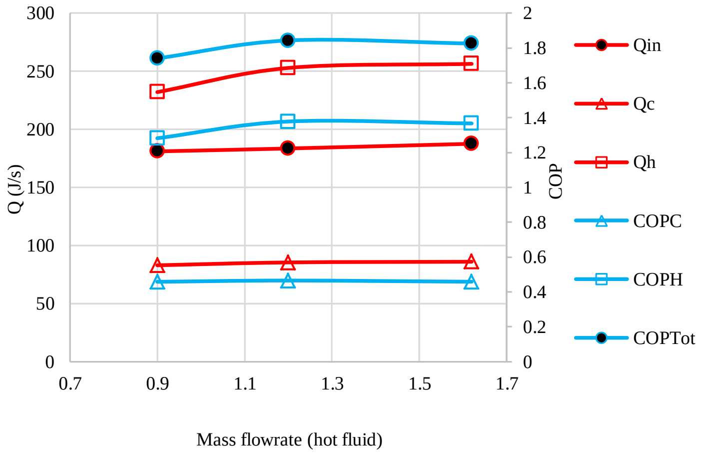

Fig. 8. Graph of the relationship mh, Q and COP at Np = 4 pieces.

3.2.3 The Number of Operating Peltiers: 6

From the table of data calculation results, a graph of the research result of the constant number of operating Peltiers for each variable of hot/cold water: 1.62/1.02; 1.2/0.8; 0.9/0.68 liters/minutes can be made as shown in Fig. 9.

The three graphs (Fig. 7-Fig. 9) show that:

1. The change in heat tends to be constant (not so much affected by changes in flowrate) for each number of Peltiers installed.
2. COP tends to be constant (not many changes to changes in flowrate) for each Peltier installed.
3. The COP for cooling is lower than the COP for heating.

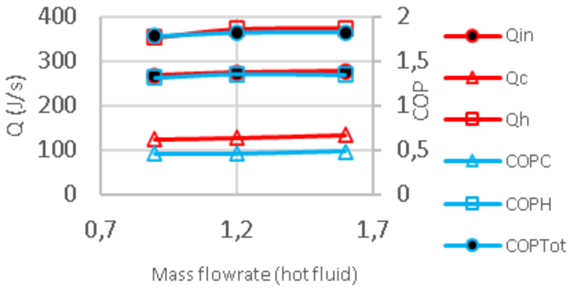

Fig. 9. Graph of the relationship mh, Q and COP at Np = 6 pieces.

3.3 Results

As for the results, in general it can be seen in the Table 3.

Table 3. Average COPs

No. of Peltiers	COP cooling (COPc)	COP heating (COPh)	COP total (COPtot)
2	0.443	1.36	1.803
4	0.44	1.39	1.83
6	0.48	1.35	1.83
Average	0.45	1.37	1.82

4 Conclusion

The findings of this study indicate that variations in flow rate and the number of installed Peltier devices do not significantly affect the performance coefficients for cooling or heating. Specifically, the cooling performance coefficient (COPc) is lower than the heating performance coefficient (COPh), as represented by the inequality COPc < COPh. This discrepancy arises because the heat released on the hot side of the Peltier is derived from the heat absorption process in the cold and hot fluids, which is powered by the electrical energy supplied to the Peltier. The total performance coefficient (COPtot) is the sum of the cooling and heating performance coefficients, expressed as COPtot = COPc + COPh. The average performance coefficients are: COPc = 0.45, COPh = 1.37, and COPtot = 1.82.

References

[1] A. S. Acharya, R. A. Fernandes, Preeti, and A. A. Sirsikar, “Peltier Module for Theremoelectric Heating and Cooling,” *Glob. Res. Dev. J. Eng.*, vol. 3, no. 4, pp. 79–83, 2018, [Online]. Available: www.grdjournals.com.

[2] S. Sahu, “An Experimental Study of Sustainable Cooling using Peltier Effect,” vol. 8, no. 09, pp. 579–585, 2019.

[3] W. Lyskawinski and W. Szelag, “Analysis of cooling and heating system with Peltier cell,” *ITM Web Conf.*, vol. 19, p. 01032, 2018, doi: 10.1051/itmconf/20181901032.

[4] P. Jagadeesh, S. Harish, M. K. Nawinespravin, M. Prakash, and P. Sathiyaraj, “Water cooling system by using Peltier,” vol. 12, no. 6, 2022.

[5] F. Afshari and F. Afshari, “A Review Study On Peltier Cooling Devices; Applications And Performance,” *Proc. 3nd Int. Conf. Technol. Sci. December 18-20, 2020 Fig.*, no. December, 2020, [Online]. Available: https://www.researchgate.net/profile/Faraz-Afshari/publication/348169128_A_REVIEW_STUDY_ON_PELTIER_COOLING_DEVICES_APPLICATIONS_AND_PERFORMANCE/links/5ff205cfa6fdccdcb82950a9/A-REVIEW-STUDY-ON-PELTIER-COOLING-DEVICES-APPLICATIONS-AND-PERFORMANCE.pdf.

[6] K. Domke and P. Skrzypczak, “Peltier modules in cooling systems for electronic components,” *WIT Trans. Eng. Sci.*, vol. 68, pp. 3–12, 2010, doi: 10.2495/HT100011.

[7] M. Hammad, M. Firasat, A. Zahed, M. A. Hafeez, and M. A. Sohail, “Cooling of Water using Peltier Effect,” vol. 6890, no. 6, pp. 163–166, 2017.

[8] A. C. Sulaiman, N. A. M. Amin, M. H. Basha, M. S. A. Majid, N. F. B. M. Nasir, and I. Zaman, “Cooling Performance of Thermoelectric Cooling (TEC) and Applications: A review,” *MATEC Web Conf.*, vol. 225, pp. 1–10, 2018, doi: 10.1051/matecconf/201822503021.

[9] K. Irshad, “Performance improvement of thermoelectric air cooler system by using variable-pulse current for building applications,” *Sustain.*, vol. 13, no. 17, 2021, doi: 10.3390/su13179682.

[10] A. K. Mainil, A. Aziz, and M. Akmal, “Portable Thermoelectric Cooler Box Performance with Variation of Input Power and Cooling Load,” *Aceh Int. J. Sci. Technol.*, vol. 7, no. 2, pp. 85–92, 2018, doi: 10.13170/aijst.7.2.8722.

[11] A. Kabeel, M. Mousa, and M. Elsayed, “Theoretical study of thermoelectric cooling system performance,” *J. Eng. Res.*, vol. 3, no. 3, pp. 10–19, 2019, doi: 10.21608/erjeng.2019.125472.

[12] K. Teffah, Y. Zhang, and X. L. Mou, “Modeling and experimentation of new thermoelectric cooler-thermoelectric generator module,” *Energies*, vol. 11, no. 3, 2018, doi: 10.3390/en11030576.

[13] L. N. Codner and J. D. Sutton, “Personal heating and cooling system,” vol. 3, no. 5, pp. 208–211, 2016.

[14] M. K. R. Alam, H. Fitriawan, F. . A. Setyawan, and U. Murdika, “Design of Cooling and Heating Tool Using Thermoelectric Peltier Based On Arduino Uno,” *Elkha*, vol. 13, no. 1, p. 41, 2021, doi: 10.26418/elkha.v13i1.44421.

[15] M. J. Moran, H. N. Shapiro, D. D. Boettner, and M. B. Bailey, *Principles of Engineering Thermodynamics*. Wiley India, 2015.

[16] R. N. M. Al-kaby, “Study of Thermal Performance of Thermoelectric Cooling System,” no. May, pp. 1–17, 2009.

[17] Laird, “Product Information Assembly Information Performance and Properties,” *Thermoelectr. Handb.*, pp. 13–15, 2020.

[18] G. J. Snyder, M. Soto, R. Alley, D. Koester, and B. Conner, “Hot spot cooling using embedded thermoelectric coolers,” *Annu. IEEE Semicond. Therm. Meas. Manag. Symp.*, vol. 2006, pp. 135–143, 2006, doi: 10.1109/stherm.2006.1625219.