Proceedings of 8th IOE Graduate Conference
Peer Reviewed
ISSN: 2350-8914 (Online), 2350-8906 (Print)
Year: 2020 Month: June Volume: 8

Experimental analysis of free-surface single jet impingement on the performance of the thermoelectric cooler

Sandeep Dhakal [a], Yogesh Gautam [b], Bibek Pandeya [c],
Bibek Prajapati [d], Vishwa Prasanna Amatya [e]

[a, b, c, d, e] *Department of Mechanical and Aerospace Engineering, Pulchowk Campus, IOE, TU, Nepal*
Corresponding Email: [a] 073bme633@pcampus.edu.np, [b] 073bme648@pcampus.edu.np, [c] pandeyabibek@gmail.com, [d] bibekprajapati1@gmail.com, [e] amatya2003@hotmail.com

Abstract

Thermoelectric (TE) refrigeration is considered a promising system when lightweight, compactness, ease of maintenance, less power consumption, environmental friendliness, and portability are major concerns over high COP. TE refrigeration employs Peltier effect to produce a temperature gradient across two sides of the module. Most of the previous literature employed heat sinks on both sides of the module for effective heat exchange but the thermal interface between module and heat sink and thermal resistance of heat sinks hindered the cooling performance. This study presents a performance analysis of the TE refrigeration, when coolant is formed to impinge directly onto the surface of the module, eventually reducing thermal and contact resistance and improving the performance of the module. COP of a single-stage TE refrigerator was obtained to be 1.046 for the load of $5ml$ at $5V$, 0.730 for the load of $5ml$ at $12V$, 0.833 for the load of $10ml$ at $12V$ and 0.730 for the load of $15ml$ at $12V$. Although the COP of the system degraded with a corresponding increase in input voltage, the cooling capacity of the system increased considerably. Active hot side cooling with impinging jet not only ensured a high rate of temperature drop but also considerably decreased the minimum achievable temperature on the cold side of the module.

Keywords

Thermoelectric Cooler, TEC, Water Impingement, COP, Figure of Merit

1. Introduction

Refrigeration is one of the most crucial systems for many applications; ranging from household to freshen general-purpose goods, food manufacturing industry to keep the manufactured goods fresh in the inventory, electronic industry as a temperature controller and medical industry to ensure the prolonged use of vaccines and medicines. The refrigeration system employing the principle of vapor compression is already in commercial practice. The compression system tends to be more rigid employing mechanically moving parts and have a comparatively high Coefficient of Performance (COP). These systems are not suitable when lightweight, compactness, ease of maintenance, less power consumption, and portability are major concerns over high COP. Therefore, Thermoelectric (TE) refrigeration is considered a promising system when the above-mentioned criteria are more essential. However, the COP of TE refrigeration is much smaller than that of vapor compression refrigeration [1]. TE refrigeration is superior to the vapor compression refrigeration from an environmental point of view as well because of its clean features. Miranda et al. [2] envisaged the utilization of the TE as an air cooler for electrical automobiles from the economic and performance point of view. Consier et al. [3] investigated the production of cold and hot air by the TE module and deduced that the TE module can be employed for both heating and cooling application with acceptable COP.

A TE refrigerator consists of a thermoelectric cooler (TEC) module. TEC is a device that assimilates both electrical and thermal effects to convert electrical energy into the temperature gradient. TEC are solid-state devices operated by direct current (DC) power source that act as quiet heat pump to remove heat from a region thereby reducing its temperature. Saifizi et al. [4] ameliorated a hybrid TE refrigeration system employing a direct and air to air TE heat pump to ensure low temperature for vaccine storage. Lal and Kumari [5] demonstrated an experimental analysis of a low-cost TEC that illustrated a COP of 0.26 with a minimum attainable temperature of 2.3^0C. Shafee et al. [6] developed a cascade and integrated TE heating and cooling system that illustrated COP of 0.02 for cascade system and 0.294 for integrated systems. Although the performance of entire TE refrigertor improved in the cascade system, the performance of a particular stage degraded. Adeyanju et al. [7] developed a quick beverage chiller based on TEC that could chill a glass of water to 6^0C in 2 minutes. Tijani et al. [8] proposed a water cooling system employing multi-stage TEC powered by solar energy that illustrated a COP of 0.45 and a temperature gradient of $0.004^0C/s$ for a 5L storage tank. Alomair et al. [9] experimentally analyzed the solar-powered TE air cooler and achieved a maximum COP of 1.7 at around $1A$. It was also illustrated that the increment of the electrical current consequently reduced the COP.

Module cooling performance is generally specified as a function of the operating voltage and temperature difference across the two sides of the TEC module. TEC module is generally employed for practical application with heat sinks on both module faces for effective heat transfer. An extensive study of air-cooled heat sinks applied on both, hot and cold sides of the TEC module is administered in many studies [10, 11, 12]. Tipsaenporm et al. [13] administered direct evaporative cooling to the hot side of TE module and enhanced the cooling capacity of the module from $53W$ to $74W$. Nagy and Buist [14] modeled the performance of a TEC and illustrated that thermal resistance of heat sink can play a critical factor in degrading the performance of TEC. Zhu and Yu [15] illustrated that the cold side of the TE module is unable to work efficiently unless the temperature of the hot side of the TE module is maintained at a logical low value. Hence, an effective cooling system must be employed for efficiently extracting heat from the hot side of the TE module. Astrain et al. [10] concluded that the contact resistance between the heat sink and the TEC module is often about $0.03K/W$. Hence, to realize maximum cooling performance, the thermal interface between module and heat sink and the thermal resistance of heat sinks must be minimized. If coolant is formed to impinge directly onto the surface of the module, low thermal resistance is often achieved thereby reducing the contact resistance to zero.

Impinging jets are often broadly classified into the submerged jet and free-surface jet. Within the case of a single impinging jet, Behnia et al. [16] concluded that submerged and free-surface jets performed indistinguishably in terms of the heat transfer coefficient. Hence, the objective of this study includes;

- Design and development of a low-cost TE refrigerator employing single impinging jet to extract excess heat from the hot side of the TEC module
- Analyzing the performance of the TE refrigeration system for varying load in terms of Coefficient of Performance (COP) and Cooling Capacity (Q_c)
- Analyzing the variation in rate of cooling for varying load and differing input voltage

2. Materials and Methods

2.1 Thermoelectric Module (TEC)

Figure 1: TEC1-12706

A TEC module is composed of an array of semiconductors that have been doped such that one type of charge carrier (i.e., either electron or hole) carries majority of the current. The semiconductors are assembled such that, they are electrically connected in series, thermally in parallel, and enclosed in a ceramic substrate (generally Alumina). When a DC voltage is applied across two terminals of the module, the charge carriers in the semiconductor absorb heat energy from one substrate surface rendering it cold and releases it to the substrate at the opposite surface making it hot. The direction of the polarity of DC voltage supply across the module terminal determines the hot and cold side.

TEC1-12706, as shown in figure 1, is used in the current study. Specification of TEC1-12706, as indicated in table 1, have been taken into consideration for designing single-stage TE refrigerator.

Table 1: Specification of TEC module [17]

Model: TEC1-12706	
Hot Side Temperature (^0C)	25
$Q_{max}(W)$	50
$\Delta T_{max}(^0C)$	66
$I_{max}(A)$	6.4
$V_{max}(V)$	14.4
Module Resistance (σ)	1.98
Number of Thermocouple	127
Dimensions	
Width (mm)	40
Length (mm)	40
Thickness (mm)	3.9

Figure 2 illustrates the ΔT vs V performance curve of TEC1-12706 at 25^0C that can be utilized to compute the current flowing through the TE material for a particular voltage and temperature gradient across the sides of the module.

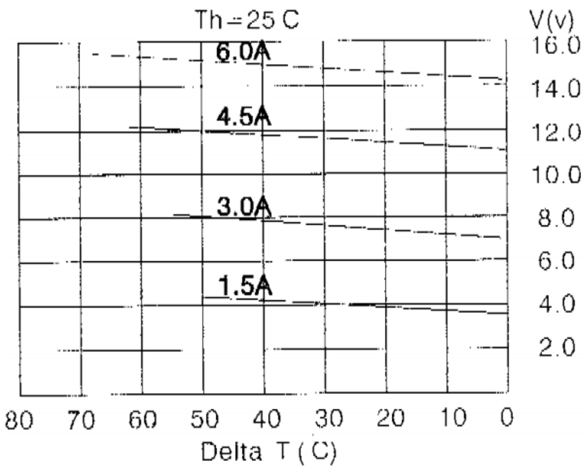

Figure 2: Performance curve: ΔT vs V at 25^0C [17]

2.2 Experimental Setup

A general schematic diagram of the experimental setup is illustrated in figure 3. It consists of a plastic container, a TEC, a mini submersible pump, copper container, FLIR C2, mercury thermometer, power supply, and cotton and glass wool for insulation purposes. A plastic container as an outer wall and copper container as an inner wall with cotton and glass wool in between the wall was used as a cooler box. 230 W ATX switching computer power supply was employed to ensure the desired potential difference across the module terminal.

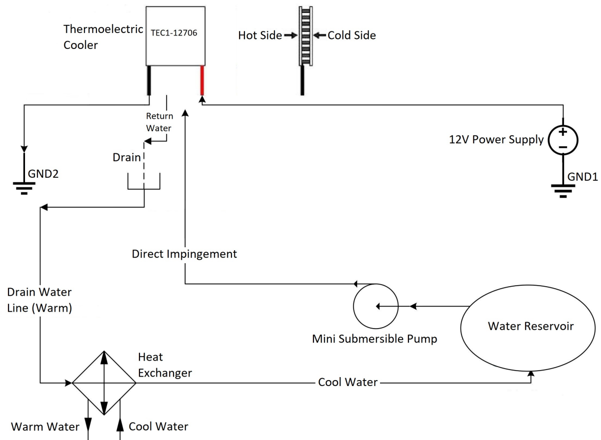

Figure 3: Schematic diagram of test rig

The temperature of the cold side of TEC was measured employing FLIR C2 infrared thermal imaging camera. Subsequently, the temperature of the impinging water jet was monitored using a mercury thermometer. FLIR C2 infrared camera detects infrared rays and generates a calibrated electrical signal which is then processed into an image or video with embedded temperature information. Embedded feature of the camera was employed to detect and record minimum temperature of the water as the load placed on the cold surface of the module. It operates with an accuracy of $\pm 2^0C$ ($\pm 3.6^0F$) or 2%, whichever is greater, at 25^0C. The optimum object temperature range for the FLIR C2 thermal camera is -10^0C to $+150^0C$ (14^0F to 302^0F) and it operates within the temperature range of -10^0C to $+50^0C$ (14^0F to 122^0F). The thermal sensitivity of the camera is $< 0.10^0C$.

Separate cooling system for effective heat removal from the hot side of the module is illustrated in figure 3. In the heart of the system, a mini submersible pump was employed to deliver a single impinging jet of $5mm$ diameter onto the hot side of the TEC module. It was operated at $6V$ with a flow rate of $120L/hr$. Relatively warm water collected after impingement was then cooled employing a heat exchanger to maintain the temperature of impinging jet constant.

2.3 Mathematical Model

Assuming that the temperature variation does not affect the device parameters, the methodology proposed by Riffat and Ma [18] is utilized in the current study to evaluate cooling capacity (Q_c) and COP of the TEC. Operation of TEC is based on the Peltier effect and thermoelectric cooling effect is given by

$$Q_{sb} = \alpha I T_c \quad (1)$$

Where α is the Seebeck coefficient $(V/^0C)$ of the TE material, I is current supplied to the TE couple, and T_c is the temperature of the cold junction.
Joule heat on the sample is produced because of the current flowing in the TE material which is given by

$$Q_j = I^2 R \quad (2)$$

Where, R is the net resistance of the TE module.
During the operation, back flow of thermal current occurs i.e., the heat is conducted from the hot end to the cold end through TE material. Heat conducted from the hot end to the cold end is computed as

$$Q_{cd} = k(T_h - T_c) = k\Delta T \quad (3)$$

Where, k is the thermal conductance of TE material, T_h and T_c indicate the temperature of the hot and cold side of TE module. Equation 3 indicates that the heat conduction increases with the increase in temperature difference across the module.
Cooling capacity (Q_c) equation is obtained by combining equations 1, 2 and 3 as

$$Q_c = \alpha I T_c - 0.5 I^2 R - k\Delta T \quad (4)$$

Above equation 4 is the governing equation for computing the cooling effect. The electrical energy consumed by the TEC can be estimated as

$$Q_E = I^2 R + \alpha I \Delta T \quad (5)$$

Coefficient of Performance (COP) of TEC is defined as the ratio of the cooling capacity (Q_c) to the electrical power consumed (Q_E) and can be computed from equations 4 and 5 as

$$COP = \frac{Q_c}{Q_E} = \frac{\alpha I T_c - 0.5 I^2 R - k\Delta T}{I^2 R + \alpha I \Delta T} \quad (6)$$

Evaluating $\frac{\delta COP}{\delta I} = 0$, optimum current for maximum COP is given by

$$I_{opt} = \frac{\alpha \Delta T / R}{(\sqrt{1 + Z T_m} - 1)} \quad (7)$$

Where, $T_m = (T_h + T_c)/2$ Substituting the value of I_{opt} from equation 7 to equation 6, we obtain the maximum achievable COP.

$$COP_{opt} = \frac{T_c \sqrt{1 + Z T_m} - T_h}{\Delta T (\sqrt{1 + Z T_m} + 1)} \quad (8)$$

Where $Z = \alpha^2 / kR$ is the figure of merit and depends on Seeback coefficient (α), thermal conductance (k) and electrical resistivity (ρ) of the TEC module. Above equation 8 indicates that the optimal COP is dependent on Z, ΔT and T_m.

3. Result and Analysis

3.1 Performance of single-stage TEC module

Figures 4, 5, 6 and 7 illustrate the temperature variation of the cold side of the TEC module with respect to time at varying load conditions. It can be observed that the temperature curve followed a straight line initially that eventually stabilized over a period of time.

The eminence of cooling the hot side of the module is evident from the performance curve of the TEC module. Without active hot side cooling, the performance of module degraded after 10^0C. On the contrary, with active hot side cooling, minimum temperature of -15^0C, -40^0C, -37^0C and -40^0C was achieved on the cold side of the TEC module with a load of $5ml$ at $5V$, $5ml$ at $12V$, $10ml$ at $12V$ and $15ml$ at $12V$, respectively. Active hot side cooling with single impinging jet not only ensured a high rate of temperature drop in the cold side but also considerably decreased the minimum attainable temperature on the cold side.

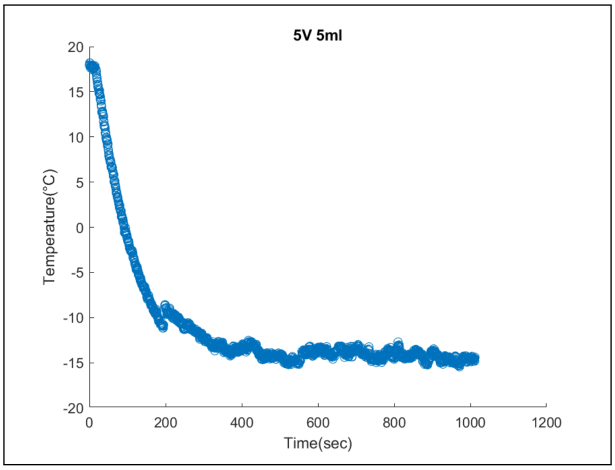

Figure 4: Performance of TEC for $5ml$ load at $5V$

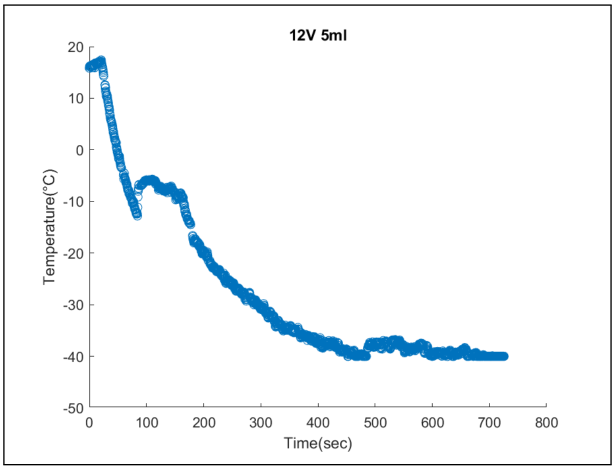

Figure 5: Performance of TEC for $5ml$ load at $12V$

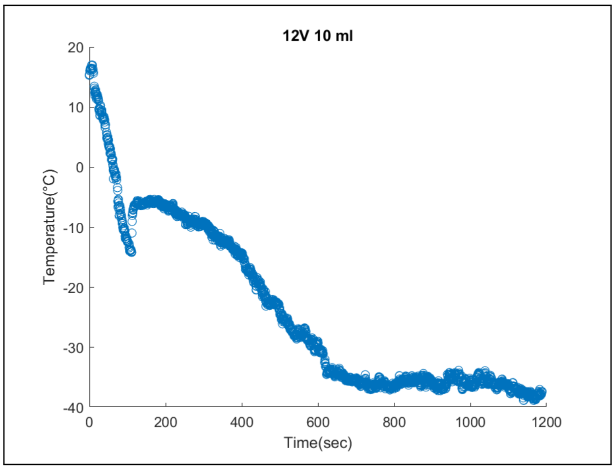

Figure 6: Performance of TEC for $10ml$ load at $12V$

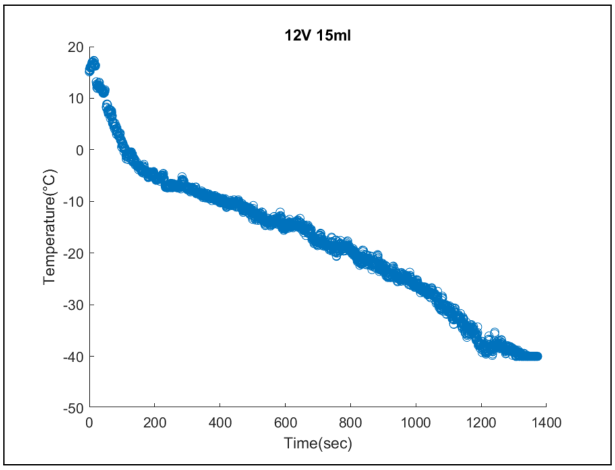

Figure 7: Performance of TEC for $15ml$ load at $12V$

The sudden increment in the temperature during transition from initial linear region to the final stable region is because of the complex physical process associated with freezing. Water has a tendency to cool to a temperature well below their melting point before the occurrence of ice nucleation [19]. There are basically two types of nucleation; ice is formed in homogeneous nucleation without any predefined nucleation site. In homogeneous nucleation, pure water freezes at temperature below -30^0C [19]. In actual practice, heterogeneous nucleation is encountered, when impurity or irregularity in the container acts as the nucleation site for the ice formation. In the subsequent process, previous interface is partially destroyed releasing some energy, eventually raising the supercooling point to be near the melting point.

From table 2, COP of single-stage TE refrigerator was obtained to be 1.046 for the load of $5ml$ at $5V$, 0.730 for the load of $5ml$ at $12V$, 0.833 for the load of $10ml$ at $12V$ and 0.730 for the load of $15ml$ at $12V$. Hence, the proposed system performed efficiently in comparison to the single-stage TE refrigerator [5]. Hence, it can be concluded that the overall COP of TE refrigerator improved considerably when hot side of the module was cooled with impinging jet.

Table 2: Parameter computation for varying load

Parameters	Load (ml)			
	5	5	10	15
V	5	12	12	12
Time (s)	1000	700	1200	1400
$T_h(K)$	290	289	289	289
$T_c(K)$	258	233	236	233
$\Delta T(K)$	32	56	53	56
$T_m(K)$	274	261	262.5	261
I	1.92	4.5	4.5	4.5
$k(W/mK)$	1.2	1.2	1.2	1.2
$\rho(\sigma m)$	0.352	0.352	0.352	0.352
$\alpha(V/K)$	0.156	0.214	0.226	0.214
$Z(K^{-1})$	0.058	0.109	0.121	0.109
$Q_{sb}(W)$	77.40	224.67	240.45	224.67
$Q_j(W)$	7.29	40.09	40.09	40.09
$Q_{cd}(W)$	38.4	67.2	63.6	67.2
$Q_c(W)$	35.35	137.43	156.80	137.43
$Q_E(W)$	33.79	188.19	188.19	188.19
COP	1.046	0.730	0.833	0.730

Also, the cooling capacity of $35.35W$, $137.43W$, $156.80W$ and $137.43W$ was achieved for the load of $5ml$ at $5V$, $5ml$ at $12V$, $10ml$ at $12V$ and $15ml$ at $12V$, respectively. Although the COP of the system degraded with corresponding increase in input voltage, cooling capacity of the system increased considerably.

Hence, in order to operate the system at full load, TEC module should be operated near V_{max} for quick chilling. On the contrary, in order to operate the system at partial load, TEC module should be operated well below V_{max} for efficient operation.

3.2 Initial rate of cooling

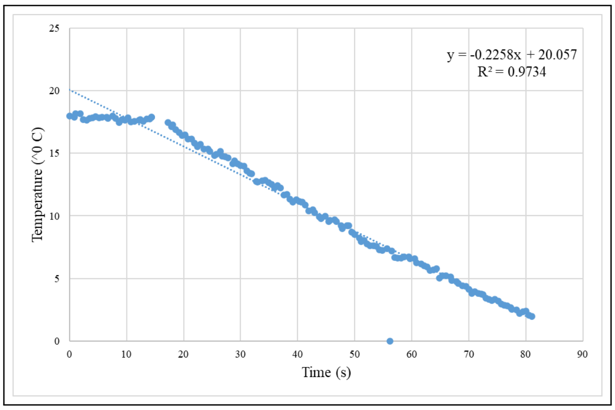

Figure 8: Initial rate of cooling for 5*ml* load at 5*V*

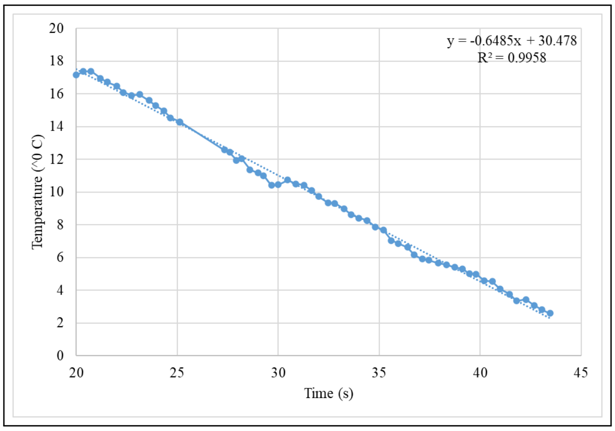

Figure 9: Initial rate of cooling for 5*ml* load at 12*V*

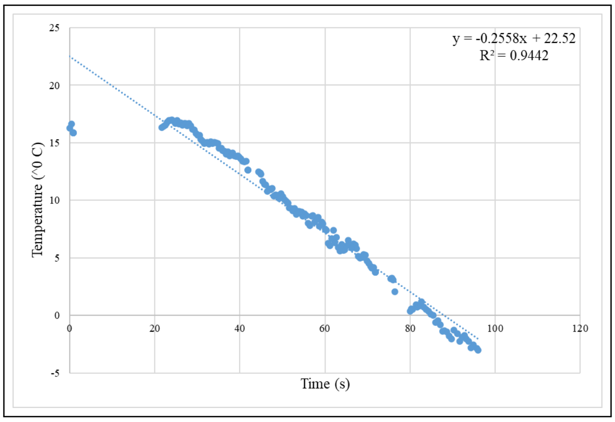

Figure 10: Initial rate of cooling for 10*ml* load at 12*V*

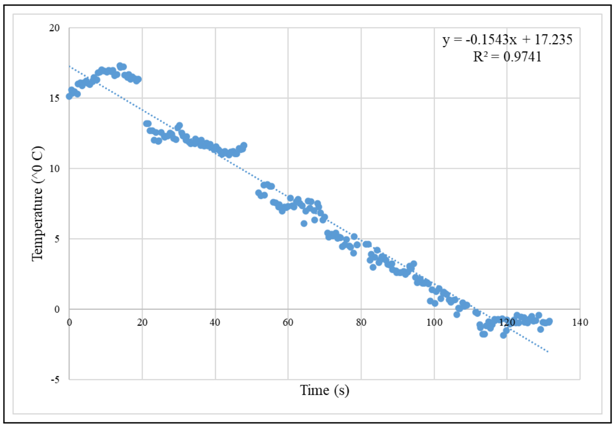

Figure 11: Initial rate of cooling for 15*ml* load at 12*V*

Figures 8, 9, 10 and 11 illustrate the initial linear temperature variation of the cold side of the TEC module with time. A trendline was then generated to incorporate the majority of the data point that would eventually indicate the initial rate of cooling. The coefficient of determination i.e., the R^2 value greater than 0.94 was observed for all parameter settings.

Table 3: Initial rate of cooling for varying load

Parameters	Load (*ml*)			
	5	5	10	15
V	5	12	12	12
R^2	0.9734	0.9958	0.9442	0.9741
$^0C/s$	0.2244	0.6485	0.2558	0.1543

From table 3, it can be observed that the rate of cooling increased considerably from $0.2244^0C/s$ to $0.6485^0C/s$ with the corresponding increase in the input voltage from 5*V* to 12*V* at constant load. On the contrary, the rate of cooling decreased continually from $0.6485^0C/s$ to $0.2558^0C/s$ and then to $0.1543^0C/s$ with the corresponding increase in the load from 5*ml* to 10*ml* and then to 15*ml* at constant input voltage. Hence, the rate of cooling was found to increase with the corresponding increase in the input voltage for constant load while the rate of cooling was found to decrease with the corresponding increase in the load for constant voltage.

Although the initial rate of cooling and the cooling capacity increased with the corresponding increase in the input voltage, the COP of the system degraded. Hence, a balance must be achieved during practical operation in terms of the cooling capacity required and the COP.

3.3 Comparison of performance at varying load

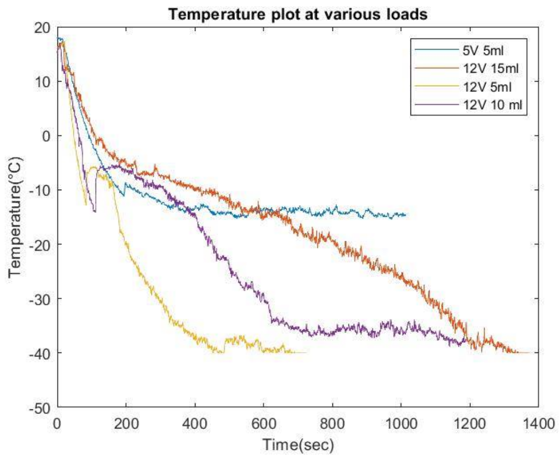

Figure 12: Performance comparison at varying load

Figure 12 illustrates that the TE system required less time to reach a stable temperature for the smaller load as expected. The load of $5ml$ at $12V$ reached a stable temperature of -40^0C at 400 seconds while the load of $10ml$ at $12V$ reached a stable temperature of -37^0C at about 650 seconds. Similarly, the load of $15ml$ at $12V$ reached a stable temperature of -40^0C at about 1200 seconds. Also, the temperature gradient across the sides of the TEC module was affected by the voltage applied across the terminal of the module. For the input voltage of $5V$, the stable temperature of the cold side of the TEC module was about -15^0C. Consequently, for the input voltage of $12V$, stable temperature further decreased to about -40^0C.

4. Conclusion

This paper presented the performance analysis of a proposed single-stage thermoelectric cooling system employing a free-surface single impinging jet to regulate the temperature of the hot side of the TEC module. The system was successfully configured and evaluated for cooling water from temperature above ambient condition to the temperature well below the freezing point of water.

From the performance evaluation results, COP was obtained to be 1.046 for the load of $5ml$ at $5V$, 0.730 for the load of $5ml$ at $12V$, 0.833 for the load of $10ml$ at $12V$ and 0.730 for the load of $15ml$ at $12V$. The temperature gradient across the two sides of the TEC module was affected by the voltage applied across the terminal of the module. For the input voltage of $5V$, the final stable temperature of the cold side of the TEC module was about -15^0C. Consequently, for the input voltage of $12V$, final stable temperature further decreased to about -40^0C. Active hot side cooling with single impinging jet not only ensured a high rate of temperature drop but also considerably decreased the minimum achievable temperature on the cold side.

The rate of cooling increased considerably from $0.2244^0C/s$ to $0.6485^0C/s$ with a corresponding increase in input voltage from $5V$ to $12V$ at a constant load. On the contrary, the rate of cooling decreased continually from $0.6485^0C/s$ to $0.1543^0C/s$ with a corresponding increase in load from $5ml$ to $15ml$ at a constant input voltage.

In the current study, the COP of a single-stage TE refrigeration system was improved considerably by employing a single jet impingement technique to extract excess heat from the hot side of the TEC module. Despite the fact that TE refrigeration is not as efficient as vapor compression refrigeration, the application of TE refrigerator is increasing because of controllability, portability, the high initial rate of cooling and partial load operation capability.

Acknowledgments

The authors are grateful to Center for Energy Studies [CES], Institute of Engineering [IOE] for providing necessary facilities to complete the study.

References

[1] SB Riffat and Guoquan Qiu. Comparative investigation of thermoelectric air-conditioners versus vapour compression and absorption air-conditioners. *Applied Thermal Engineering*, 24(14-15):1979–1993, 2004.

[2] AG Miranda, TS Chen, and CW Hong. Feasibility study of a green energy powered thermoelectric chip based air conditioner for electric vehicles. *Energy*, 59:633–641, 2013.

[3] Matthieu Cosnier, Gilles Fraisse, and Lingai Luo. An experimental and numerical study of a thermoelectric air-cooling and air-heating system. *International journal of refrigeration*, 31(6):1051–1062, 2008.

[4] M Saifizi, MS Zakaria, Sazali Yaacob, and Khairunizam Wan. Development and analysis of hybrid thermoelectric refrigerator systems. In *IOP Conference Series: Materials Science and Engineering*, volume 318, page 012036. IOP Publishing, 2018.

[5] Shiv Lal and Emarti Kumari. Performance analysis of a low price thermoelectric cooler: An experimental approach. In *Int Conf Expo*, pages 76–82, 2017.

[6] Shafee SM, K Gnanasekaran, and S Johnson Samuel. Performance study on thermoelectric cooling and heating system with cascaded and integrated approach. *International Journal of Chemical Studies*, 6(1):1348–1354, 2018.

[7] AA Adeyanju, E Ekwue, and W Compton. Experimental and theoretical analysis of a beverage chiller. *Research Journal of Applied Science*, 5(3):195–203, 2010.

[8] Ismaila B Tijani, Ahmad AA Al Hamadi, Khaled ASS Al Naqbi, Rashed IM Almarzooqi, and Noura KSR Al Rahbi. Development of an automatic solar-powered domestic water cooling system with multi-stage peltier devices. *Renewable energy*, 128:416–431, 2018.

[9] Muath Alomair, Yazeed Alomair, Shohel Mahmud, and Hussein A Abdullah. Theoretical and experimental investigations of solar-thermoelectric air-conditioning system for remote applications. *Journal of Thermal Science and Engineering Applications*, 7(2), 2015.

[10] D el Astrain, JG Vian, and M Domınguez. Increase of cop in the thermoelectric refrigeration by the optimization of heat dissipation. *Applied Thermal Engineering*, 23(17):2183–2200, 2003.

[11] Yuanyuan Zhou and Jianlin Yu. Design optimization of thermoelectric cooling systems for applications in electronic devices. *International journal of refrigeration*, 35(4):1139–1144, 2012.

[12] SB Riffat, SA Omer, and Xiaoli Ma. A novel thermoelectric refrigeration system employing heat pipes and a phase change material: an experimental investigation. *Renewable Energy*, 23(2):313–323, 2001.

[13] W Tipsaenporm, C Lertsatitthanakorn, B Bubphachot, M Rungsiyopas, and S Soponronnarit. Improvement of cooling performance of a compact thermoelectric air conditioner using a direct evaporative cooling system. *Journal of electronic materials*, 41(6):1186–1192, 2012.

[14] Michael J Nagy and Richard J Buist. Effect of heat sink design on thermoelectric cooling performance. In *AIP conference proceedings*, volume 316, pages 147–149. American Institute of Physics, 1994.

[15] Lin Zhu and Jianlin Yu. Optimization of heat sink of thermoelectric cooler using entropy generation analysis. *International Journal of Thermal Sciences*, 118:168–175, 2017.

[16] M Behnia, S Parneix, Y Shabany, and PA Durbin. Numerical study of turbulent heat transfer in confined and unconfined impinging jets. *International Journal of Heat and Fluid Flow*, 20(1):1–9, 1999.

[17] Hebei I.T. (Shanghai) Co., Ltd. *Thermoelectric Cooler*.

[18] Saffa B Riffat and Xiaoli Ma. Thermoelectrics: a review of present and potential applications. *Applied thermal engineering*, 23(8):913–935, 2003.

[19] G John Morris and Elizabeth Acton. Controlled ice nucleation in cryopreservation–a review. *Cryobiology*, 66(2):85–92, 2013.