pISSN 1229-3008 eISSN 2287-6251
Progress in Superconductivity and Cryogenics
Vol.23, No.3, (2021), pp.55~59
https://doi.org/10.9714/psac.2021.23.3.055

Transient cooling operation of multistage thermoelectric cooler (TEC)

Jiho Park*, a, and Sangkwon Jeong[b]

[a] *Korea Institute of Machinery and Materials, Daejeon, Rep. of Korea*
[b] *Korea Advanced Institute of Science and Technology, Daejeon, Rep. of Korea*

(Received 21 June 2021; revised or reviewed 23 July 2021; accepted 24 July 2021)

Abstract

A thermoelectric cooler (TEC) is promising as an alternative refrigeration technology for the sake of its inherent advantages; no-moving parts and refrigerant-free in its operation. Due to the compactness, reliability and excellence in temperature stability, TECs have been widely used for small cooling devices. In recent years, thermoelectric devices have been attractive technologies that not only serve the needs of cooling and heating applications but also meet the demand for energy by recycling waste heat. In this research paper, multistage TEC is proposed as a concept of demonstrating the idea of transient cooling technology. The key idea of transient cooling is to harnesses the thermal mass installed at the interfacial level of the stages. By storing heat temporally at the thermal mass, the multistage TEC can readily reach lower temperatures than that by a steady-state operation. The multistage TEC consists of four different sizes of thermoelectric modules and they are operated with an optimized current. Once the cold-part of the uppermost stage is reached at the no-load temperature, the current is successively supplied to the lower stages with a certain time interval; 25, 50 and 75 seconds. The results show the temperatures that can be ultimately reached at the cold-side of the lowermost stage are 197, 182 and 237 K, respectively. It can be concluded that the timing or total amount of the current fed to each thermoelectric module is the key parameter to determine the no-load temperature.

Keywords: multi-stage, thermoelectric cooler (TEC), transient cooling

1. INTRODUCTION

Thermoelectric effect refers to the process of converting energy between heat and electricity. When there is a temperature difference between both ends of the thermocouple, electrons inside the device move, thereby generating an electromotive force. It can be divided into two major effects; i.e., *Seebeck effect*-a potential difference occurs due to the temperature difference and *Peltier effect*-one side generates heat and absorbs heat at the other side when a current is applied to both ends. Among these, a thermoelectric cooler (TEC) harnesses the Peltier effect to create a heat flux at the junction of two different types of materials. Although its main application is cooling, it can be utilized either for heating or for cooling.

The TEC is advantageous in that it has a very fast thermal response and does not require refrigerants in its operation. A significant benefit of the TEC is the lack of mechanical moving parts. For the sake of the compactness, reliability and excellence in temperature stability, TECs have been widely utilized for small cooling devices. A non-dimensional number, a figure of merit (FOM) can be expressed as follows;

$$ZT = \frac{\alpha^2}{\rho k} T \tag{1}$$

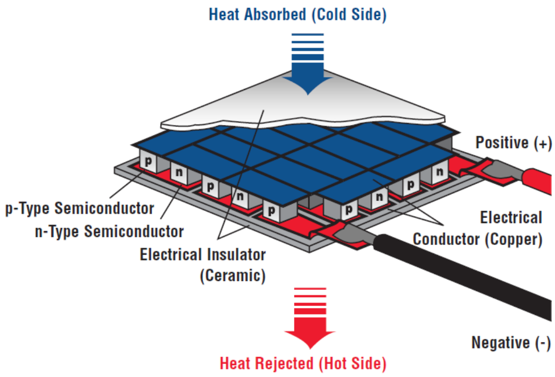
* Corresponding author: jh8809@kimm.re.kr

Where, α is the Seebeck coefficient (V K^{-1}), ρ is the electrical resistivity (Ω m), k is the thermal conductivity (W m^{-1} K^{-1}), and T is the temperature (K). The thermoelectric materials are commonly compared using the above equation as a measure of the TEC's efficiency. The equation implies that the materials should have a combination of low thermal conductivity and low electrical resistivity suitable for high efficiency TECs. It is a well-known fact that ordinary metals obey the Widemann-Franz law.

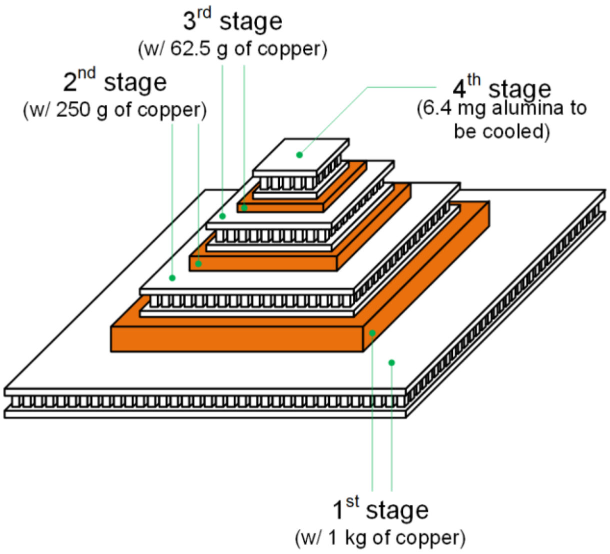
$$L_0 T = \rho k \tag{2}$$

Where, L_0 is the Lorentz constant. The law says the product of electrical resistivity and thermal conductivity remains constant at the fixed temperature condition. This fact signifies there exist drawbacks to increasing the FOM of thermoelectric materials. Recently, many researchers have been working towards increasing the FOM by artificially manipulating the crystal structure of the material [1–3].

In recent years, the demand of refrigeration, i.e., air-conditioning, bio-regents and food preservation, as well as vaccine storage and its cold-chain especially for COVID-19, has been ever increasing and it had led to producing more electricity and releasing more CO_2, simultaneously. The accelerated excavation and ongoing use of fossil fuels have been recognized to create serious



(a)



(b)

Fig. 1. Schematic diagrams of (a) a thermoelectric module and (b) multistage TEC with thermal masses.

environmental problems. For these reasons, thermoelectric devices are promising in the view of not only refrigeration utilizing a refrigerant-free cycle but micro-power generation by recovering waste heat [4, 5].

In this research paper, an innovative idea is proposed to extend the temperature range of the TEC by staging thermoelectric modules. The multistage TEC includes thermal masses that provides a thermal buffer to temporarily store heat dumped from the lower stage. The mass allows the multistage TEC to operate with transient cooling. As a concept of the multistage TEC, a parametric study of the transient cooling effect is being carried out.

2. METHODOLOGY

2.1. Strategy for transient cooling

By constructing thermoelectric modules in multiple stages, it is intended to obtain a lower temperature than using a single thermoelectric module. Except for the thermoelectric module installed at the 1^{st} stage, the thermoelectric modules at the remaining stages aim to reach a temperature lower than that obtained by the steady cooling method by introducing a transient cooling method. The transient cooling method can be briefly explained below;

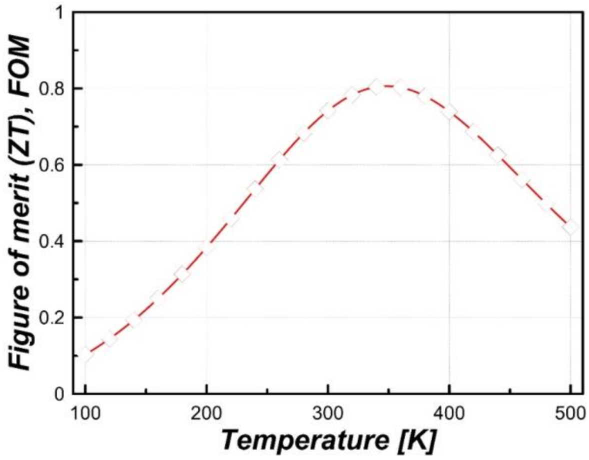


Fig. 2. Figure of merit of bismuth telluride (Bi_2Te_3).

(i) At the initial cooling process, the 1^{st} stage is turned on
(ii) Once the 1^{st} stage temperature is stabilized, the 2^{nd} stage is turned on
(iii) With a designated time interval, the next stages are turned on step by step

In this research paper, four thermoelectric modules are considered and each stage has a different size. Since the refrigeration at the cold-side is always less than the amount of heat rejected at the warm-side, the number of thermocouple installed at the lower stage must be less than that of the neighboring upper stage. The area ratio between the upper and lower stages of thermoelectric modules is fixed to be 4:1. Between each stage, there is a thermal mass. The mass provides thermal inertia by temporarily storing the heat pumped from the lower thermoelectric module, and it also has a 4:1 mass ratio. It is noted that these areas and mass ratios are not optimized values.

2.2. Assumptions and simplifications

Figs. 1(a) and (b) depict schematics of a thermoelectric module and the multistage TEC considered in this study. The assumptions and simplifications for evaluating the transient cooling effect on the multi-stage thermoelectric cooler are as follows;

(i) For all stages, identical thermoelectric material is utilized.
(ii) The transient cooling method is employed for all thermoelectric modules except for the 1^{st} stage.
(iii) During the initial cool-down process of the 1^{st} stage, the temperature of the warm-side is maintained constant to room temperature.
(iv) All the cold parts are thermally insulated. The conductive and radiative heat losses can be negligible. Only the conductive heat ingress through the thermocouples of the modules is considered.
(v) For simplicity, the thermal contact resistance

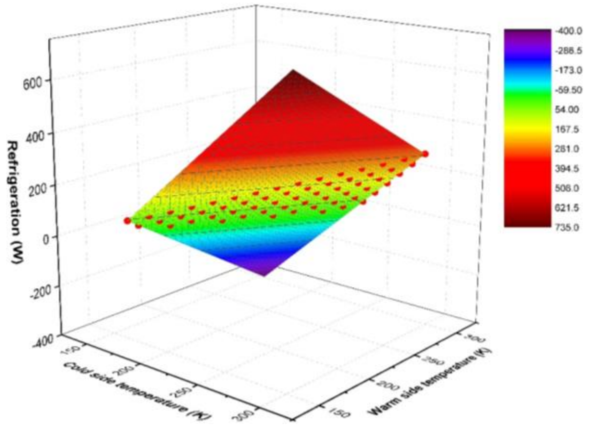


Fig. 3. Curve fitting for refrigeration; negative values are not meaningful.

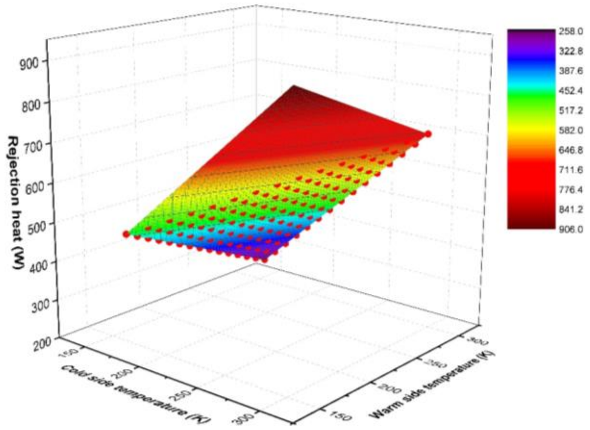


Fig. 4. Curve fitting for rejection heat.

between all interfacial layers is neglected.

(vi) All the thermoelectric modules are excited with an optimized current. The optimized current can be expressed by the following equation [6].

$$I = \frac{\alpha_i A_i T_{c,i}}{\rho_i L_i} \quad (3)$$

Where, I is the optimized current (A), A is the cross-sectional area of the thermocouple (m^2) and L is the length of the thermocouple (m). The subscripts c and i denote the cold-side and the i^{th} stage, respectively.

TABLE 1
SPECIFICATIONS AND OPERATING CONDITIONS OF THE 1ST STAGE.

	1st stage
Warm-side temperature	300 K
Cold-side temperature	237 K (no-load temperature)
Number of thermocouple	1,156
FOM	0.62
Electrical resistivity	$9.46*10^{-6}$ μΩ-m
Thermal conductivity	1.83 W m^{-1} K^{-1}
Seebeck coefficient	$1.99*10^{-4}$ mV K^{-1}
Rejection heat	516 W
Refrigeration	0 W

2.3. Thermocouple material properties

In this research paper, bismuth telluride (Bi_2Te_3) is utilized as a thermocouple material [6]. The thermoelectrical properties are as follows;

Seebeck coefficient

$$\alpha_P = -\alpha_N = \left(22224 + 930T - T^2\right) \times 10^{-9} \quad (4)$$

Electrical resistivity

$$\rho_P = \rho_N = \left(5112 + 163T + 0.6T^2\right) \times 10^{-10} \quad (5)$$

Thermal conductivity

$$k_P = k_N = \left(62605 - 278T + 0.4T^2\right) \times 10^{-4} \quad (6)$$

Where, the subscripts P and N denote P and N-type semiconductor fillets, respectively. Fig. 2 shows the calculated FOM derived from the above properties.

2.4. Equations for evaluating the performance of the thermoelectric module [7]

Refrigeration at the cold-side

$$Q_{ref,i} = \left[I_i \alpha_i T_{c,i} - \frac{1}{2} I_i^2 \frac{\rho_i L_i}{A_i} - \frac{k_i A_i}{L_i}\left(T_{w,i} - T_{c,i}\right) \right] N_i \quad (7)$$

Rejection heat at the warm-side

$$Q_{rej,i} = \left[I_i \alpha_i T_{w,i} + \frac{1}{2} I_i^2 \frac{\rho_i L_i}{A_i} - \frac{k_i A_i}{L_i}\left(T_{w,i} - T_{c,i}\right) \right] N_i \quad (8)$$

Where, Q_{ref} is the refrigeration (W), Q_{rej} is the rejection heat (W), N is the number of thermocouple and the subscript w denotes the warm-side. Figs. 3 and 4 show the curve fitting for the refrigeration and rejection heat for the 1st stage's thermoelectric module. The refrigeration and rejection heat are linearly proportional to the number of thermocouple.

3. RESULTS AND DISCUSSION

3.1. Steady operation of the 1st stage

The warm-side temperature of the 1st stage is maintained constant to be 300 K. The specifications and operating conditions are tabulated in Table 1.

As the current supplied to the 1st stage thermoelectric module, 516 W-heat is dumped from the warm-side (at 300 K) to the atmosphere when its temperature is stabilized. When the cold-side temperature is to be 236 K, the amount of heat that can be absorbed is 0 W, which can be considered to have reached the no-load temperature. The time taken for the 1st stage to reach the no-load temperature from room temperature was conservatively calculated to be 1,000 seconds, and it can be shortened in actual operating conditions.

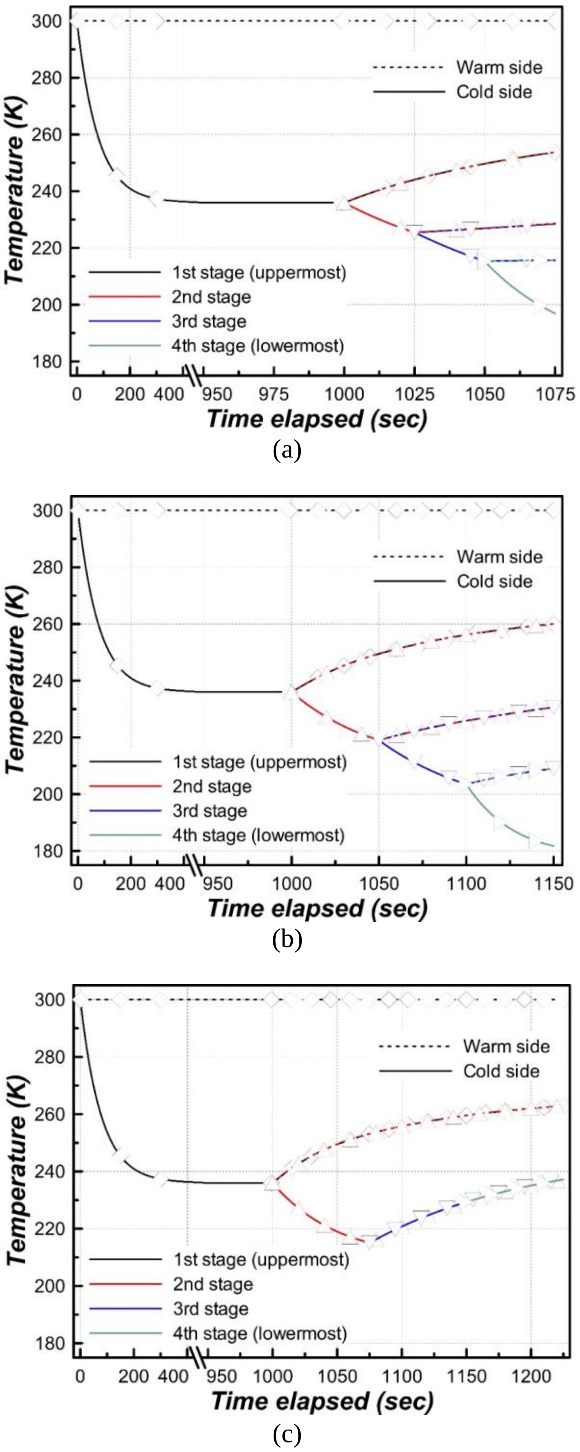


Fig. 5. Temperature variation during transient operations; holding duration for (a) 25 seconds, (b) 50 seconds and (c) 75 seconds.

3.2. Transient operation of other stages

For the thermoelectric modules installed at the other stages except for the 1st stage, the transient cooling method was introduced by supplying the current step by step. The heat rejected and absorbed at both sides of the thermoelectric module installed at each stage varies simultaneously as the timing of the supplied current changes. It was confirmed how the temperature changes by varying the timing of the current supplied to each stage.

Fig. 5(a) shows the temperature profile of both sides of each stage as the current is supplied to the 2nd stage thermoelectric module, and then the current is sequentially supplied to the remaining stages at intervals of 25 seconds. Figs. 5(b) and (c) represent the cases of supplying the current at intervals of 50 seconds and 75 seconds, respectively. By comparing the results of Figs. 5(a), (b) and (c), it can be found that the temperatures that can be ultimately reached at the cold-side of the 4th stage are 197 K, 182 K and 237 K, respectively. In the case of Fig. 5(a), the no-load temperature did not reach that of Fig. 5(b) because the current was supplied to the next stage thermoelectric modules without sufficiently drawing out the cooling effect of the thermoelectric module of the previous stage. On the other hand, in the case of Fig. 5(c), the warm-side temperature is greatly increased due to the excessive holding time of the current.

From these results, it can be inferred that the timing or total amount of current suppled to the thermoelectric module installed in each stage is the key parameter affecting the no-load temperature. Consequently, the cooling effect can be maximized by properly controlling the timing of the current fed to the thermoelectric module installed in each stage.

4. CONCLUSION AND FUTURE WORKS

Thus far, the theoretical study on a multistage thermoelectric cooler (TEC) has been conducted in conjunction with an innovative transient cooling technique. The major findings are as follows;

(i) Proposal of a transient cooling concept by introducing a certain thermal mass
(ii) Demonstration that the transient cooling works theoretically
(iii) Amount of the current supplied to each thermoelectric module is the main parameter affecting the no-load temperature of the multistage TEC

This research has taken a step in the demonstration of the concept. It is important to emphasize that the example in the research limits our interpretation. Of course, it is possible that utilizing this multistage TEC for other promising applications may produce entirely different results. At this point, it is important to select a proper thermoelectric material with respect to the temperature range of each stage. Amount of the current specified in (iii) above can also be expressed as a form of the heat at both sides of thermoelectric module. Once the heat amounts are quantified, the required thermal mass is also determined. Optimization would be possible by analyzing the exergy for each stage to maximize it.

ACKNOWLEDGEMENT

This work was supported by the R&D program of Korea Evaluation Institute of Industrial Technology (KEIT), granted financial resource from the Ministry of Trade, Industry & Energy, and partially by the Basic Research Fund of the Korea Institute of Machinery and Materials (KIMM).

REFERENCES

[1] M. S. Dresselhaus, et al., "New directions for low-dimensional thermoelectric materials," *Adv. Mater.*, vol. 19, no. 8, pp. 1043-1053, 2007, doi: 10.1002/adma.200600527.

[2] D. Rowe, "CRC handbook of thermoelectrics," 2018.

[3] R. J. Cava, "Structural chemistry and the local charge picture of copper oxide superconductors," *Science.*, vol. 247, no. 4943, pp. 656-662, 1990, doi: 10.1126/science.247.4943.656.

[4] H. Xi, L. Luo, and G. Fraisse, "Development and applications of solar-based thermoelectric technologies," *Renewable and Sustainable Energy Reviews*, vol. 11, no. 5. Pergamon, pp. 923-936, Jun. 01, 2007, doi: 10.1016/j.rser.2005.06.008.

[5] D. R. Brown, J. A. Dirks, N. Fernandez, and T. E. Stout, "The Prospects of Alternatives to Vapor Compression Technology for Space Cooling and Food Refrigeration Applications," Richland, WA (United States), Mar. 2010. doi: 10.2172/979500.

[6] X. C. Xuan, "Optimum staging of multistage exo-reversible refrigeration systems," *Cryogenics*, vol. 43, no. 2, pp. 117-124, 2003, doi: 10.1016/S0011-2275(03)00049-3.

[7] X. C. Xuan, K. C. Ng, C. Yap, and H. T. Chua, "The maximum temperature difference and polar characteristic of two-stage thermoelectric coolers," *Cryogenics*, vol. 42, no. 5, pp. 273-278, 2002, doi: 10.1016/S0011-2275(02)00035-8.