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Modeling of a thermoelectric cooler system, design and optimization of the system's controller

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Abstract. A thermoelectric module was modeled and analyzed in COMSOL Multiphysics using a finite element method (FEM). An optimum coefficient of performance of 0.4 is achieved at an operational current of 2 A, and a maximum heat load of 0.52 W is obtained at zero temperature gradient. The system's dynamic cooling behavior was simulated and the input and output data were exported to the system identification toolbox in MATLAB for the prediction of the mathematical model. The predicted model was validated and a suitable proportional integral (PI) controller was designed for the system. However, the controller needs to be optimized. Optimization techniques namely: Grey Wolf Optimizer (GWO), Particle Swarm Optimization (PSO), Artificial Bee Colony (ABC), and Harris Hawk Optimization (HHO) were tested on the controller. GWO having a settling time of 199 seconds and an overshoot of 5.96% is found to be the best for this model.

Keywords. Modeling; thermoelectric cooler; system identification; proportional integral controller; grey wolf optimizer.

1. Introduction

Thermoelectric coolers (TECs) are solid-state electronic devices that work based on the Peltier effect. A TEC is formed when a direct current or voltage is applied to the input terminals of a thermoelectric module and results in cooling or heating on its surface, reversing the direction of the flow of current will simply change the hot and cold sides [1]. A TEC device as an active cooling system can effectively control and maintain the temperature of an electronic device better than passive cooling systems [2].

Cooling capacity and Coefficient of Performance (COP) are some of the most important parameters used to evaluate the performance of TEC devices [3]. The cooling capacity determines the cooling output of a TEC when given input energy is provided while the COP is the measure of TEC's efficiency and is limited by the Carnot COP [4].

A TEC system is often composed of a TEC module and heat exchangers on both hot and cold sides. Optimization in the design of the TEC system is necessary to achieve a maximum cooling capacity and optimum COP under given operating conditions. Yuanyuan and Jianlin [5] showed that when the finite total thermal conductance is optimally distributed, an optimum COP and a maximum cooling capacity of the TEC system can be obtained. Cheng and Lin [6] established that cooling capacity can be increased through optimization of the TEC legs while at the same time considering its minimum COP. Lin Zhu *et al* [7] demonstrated that the lowest cold side temperature, highest COP, and highest heat flux pumping capability of the TEC can be achieved by choosing an optimal heat transfer area allocation ratio.

A TEC can be modeled, optimized, and analyzed using either steady-state or transient state analysis. At a transient state operation, the TEC performance can be undesirable or at some point in time, the input power to the TEC system may deviate from the desired value. As such, a controller is required to regulate the variations and to ensure that the output temperature is kept at the desired value. The controller should be robust and able to capture temperature, current, and load variations. For a controller design, a mathematical model of a system should be known. However, in complex nonlinear systems, it is not easy to obtain such models. In such situations, the transfer function can be obtained through a system identification which will use experimental input and output data of the system. After obtaining the transfer function, the controller can be designed and

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optimized. A TEC controller is often been incorporated into a TEC system for a thermal management application. It has been shown that a TEC controller can accelerate the cooling process of the TEC three times faster [8]. Song and Qinqin [9] designed a TEC controller using an adaptive NN-PID algorithm for an average linear dynamic model of a TEC.

The aim of this paper is to model a micro TEC system, and design and optimize the system's controller. Here, a micro TEC module with two heat exchangers were modeled. The operational parameters of the TEC system were determined through simulations. Then system identification was used to identify the mathematical model of the system. Finally, the controller of the system was designed and optimized.

2. Method

A TEC module of a desired unicouple as shown in figure 1 can be formed by connecting a number *(N)* of unicouples electrically in series and thermally in parallel. The electrical series connection is to allow the passage of a current from *n*-type (terminal) to *p*–type leg (ground) while the parallel thermal arrangement is to allow the heat transfer from the cold to the hot sides.

Heat absorbed/cooling power and heat released at the two junctions of a TEC are respectively given as:

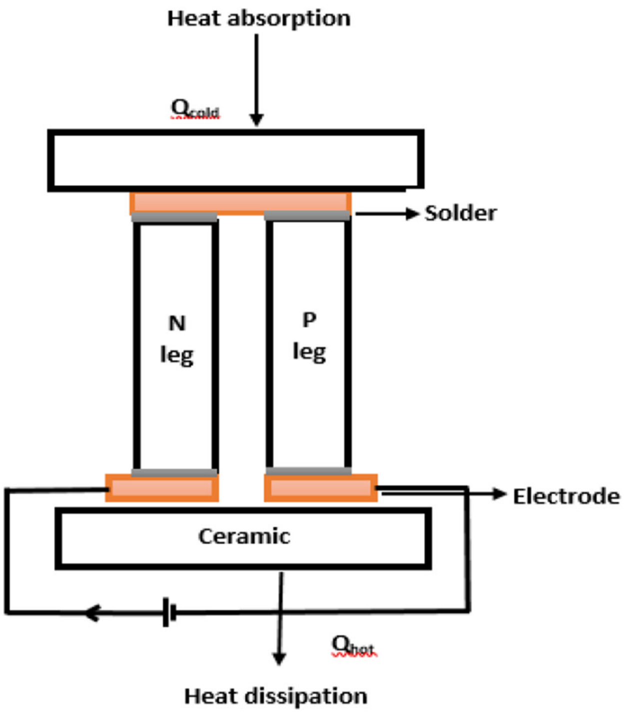

Figure 1. Unicouple thermoelectric cooler.

$$Q_c = (\alpha_p - \alpha_n)IT_c - (T_h - T_c)(k_p + K_n) - \frac{I^2(R_p + R_n)}{2} \tag{1}$$

$$Q_h = (\alpha_p - \alpha_n)IT_h - (T_h - T_c)(K_p + K_n) + \frac{I^2(R_p + R_n)}{2} \tag{2}$$

by subtracting Eq. (1) from Eq. (2), the total electrical energy input is obtained as:

$$P_{ele} = (\alpha_p - \alpha_n)I(T_h - T_c) + I^2(R_p + R_n) \tag{3}$$

where the first term in Eq. (3) is the rate of work to overcome the voltage while the second term is the resistive losses; from Eqs. (1) and (3) COP is given as:

$$COP = \frac{(\alpha_p - \alpha_n)IT_c - (T_h - T_c)(K_p + K_n) - \frac{I^2(R_p+R_n)}{2}}{(\alpha_p - \alpha_n)I(T_h - T_c) + I^2(R_p + R_n)} \tag{4}$$

where α (VK^{-1}) is the Seebeck coefficient, T (K) is the temperature, R *(Ω)* is the internal resistance, K *(WK^{-1})* is the thermal conductance, ρ *(Ω-mm)* is the resistivity, I *(A)* is the input current, the subscripts *h, c, n, p, av* represent hot, cold, *n*-type, *p*-type, and average, respectively.

The micro TEC system is shown in figure 2 and the dimensions are given in table 1. To understand the variation of current with the cooling performance of the TEC system, the system is modeled and simulated in COMSOL Multiphysics. Figure 3 shows the plot of the temperature gradient against the cooling performance of the model. The plot demonstrates that both the temperature gradient and the cooling performance of the TEC increase with an increase in the input current. One thing to note is that the input current cannot be increased continuously. To determine the

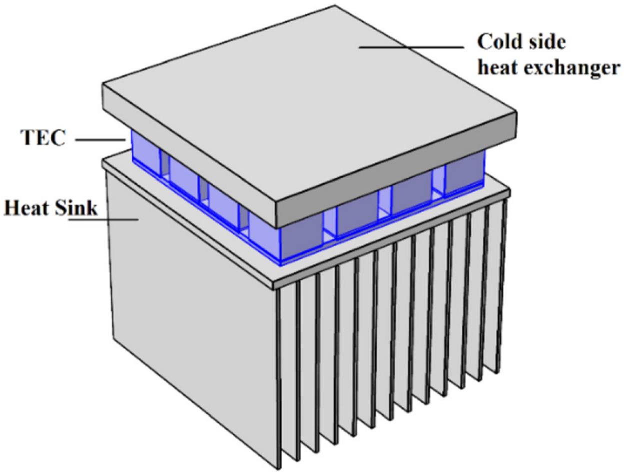

Figure 2. Micro-TEC system.

Table 1. Dimensions of the TEC and heat sink.

Parameter	Dimension
Thermoelement leg	$0.6 \times 0.6 \times 0.5$ mm^3
Electrode	$1.4 \times 0.6 \times 0.05$ mm^3
Ceramics	$3 \times 3 \times 0.07$ mm^3
Heat sink base	$3.5 \times 3.5 \times 0.11$ mm^3
Fin	$0.04 \times 3.5 \times 2.5$ mm^3
Cold side heat exchanger	$3.5 \times 3.5 \times 0.3$ mm^3

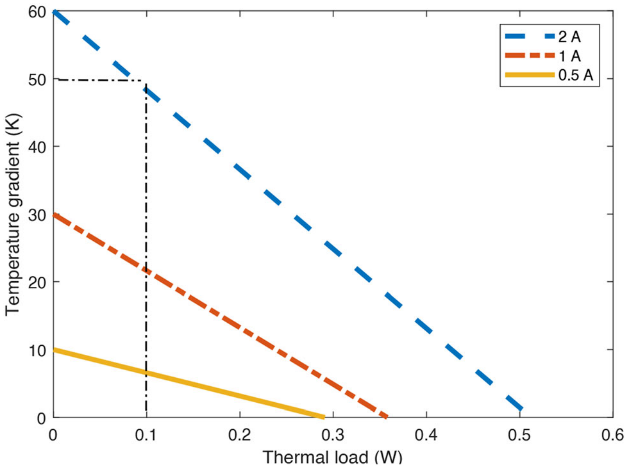

Figure 3. Operational boundaries of the TEC (T_h = 300 K).

optimum current, variation of COP with the input current is needed as shown in figure 4. By varying the input current from 1–4.5 A, an optimum input current of 2 A is determined, that is the point at which the COP has a maximum value of 0.4. These values are determined for a thermal load of 0.1 W at the hot side temperature of 300 K.

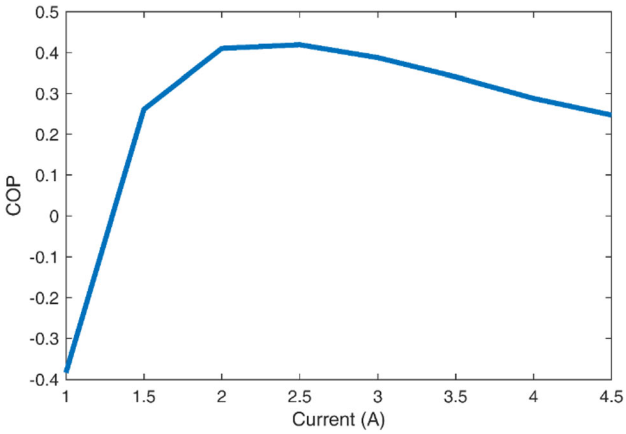

Figure 4. Plot of coefficient of performance against input current (T_h = 300 K, Q_L = 0.1 W).

Table 2. Proportional and integral coefficients of the controllers.

	Kp	Ki
GWOPI	−0.15243	0.0018321
HHOPI	−0.16092	0.0018311
ABCPI	−0.1044	0.0042
PI	−0.08	0.0045
PSOPI	−0.0781	0.003

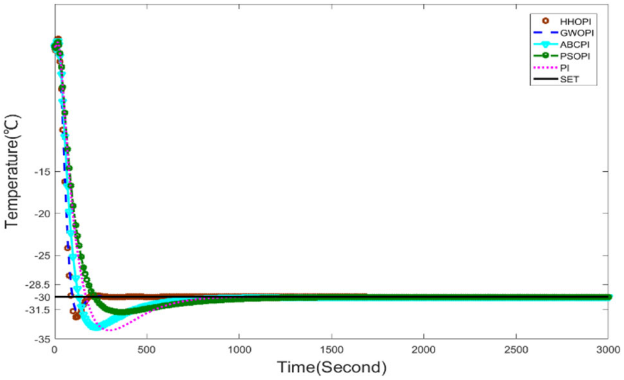

Figure 5. Response of the controllers (T_h = 300 K).

In this study, a PI controller is designed and optimized via Particle Swarm Optimization (PSO) [10], Grey Wolf Optimizer (GWO) [11], Harris Hawk Optimization (HHO) [12], and Artificial Bee Colony (ABC) [13].

3. Results

A TEC controller works with a sensor attached to the cold side heat exchanger. The desired temperature set-point is established for the TEC controller, and the sensor reads the temperature and sends it as feedback via a control loop. The controller then adjusts its output (dc current) proportional to the error between the set-point and the temperature. Here, the mathematical model obtained from the system identification was exported to Simulink in MATLAB, and a PI controller was designed using the Ziegler–Nichols tuning method. The controller has an overshoot of 13.2% and a settling time of 988.6 seconds. The performance of the controller is not desirable, therefore, four optimization techniques namely PSO, GWO, HHO, and ABC were employed to obtain better performance. Table 2 shows the gain values of the PI controllers obtained from the optimizations and figure 5 shows the response of the cold side temperature controller. A closer view of figure 5 is shown in figure 6. The GWOPI has the best performance as the set temperature of −30°C is achieved within a settling time of

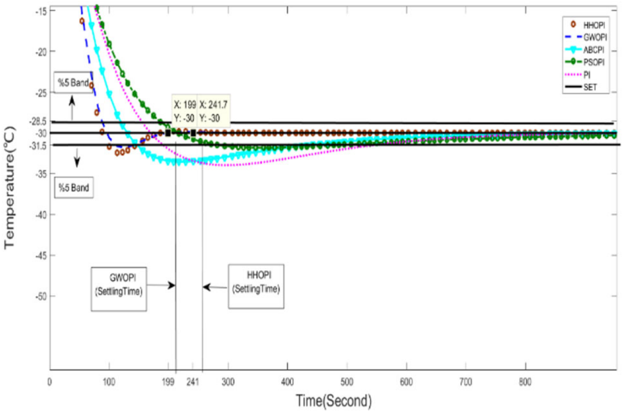

Figure 6. Close view of figure 5 (T_h = 300 K).

Table 3. Settling time and overshoot values of the different controllers.

	Settling time (second)	Overshoot (%)
GWOPI	199	5.96
HHOPI	241.7	8.06
ABCPI	798.7	11.7
PI	988.6	13.2
PSOPI	1341	6.06

199 s in a 5% band limit and an overshoot of 5.96%. This is likely due to its robust leader approach algorithm which is not there in the other optimizations. Table 3 shows the settling time and the overshoot values for the five different controllers.

4. Conclusions

Thermoelectric cooler as an active cooling system is increasingly being used in thermal management applications such as in defense, space-mission, refrigeration, aerospace, biomedical, computer, and electronic industries. TEC system is often composed of a TEC module and heat exchangers. A TEC controller is usually incorporated into a TEC system in order to speed up the response and to main the temperature of the cold side of the system at the desired value. Herein, modeling of a TEC system, design, and optimization of the system's controller was conducted. The TEC system was simulated in a COMSOL Multi-physics environment and its performance was evaluated. System identification in MATLAB was carried out to obtain a mathematical model, which was used to design a PI controller using Ziegler–Nichols tuning method. The response of the initial controller is not desirable. Thus, four optimization techniques: PSO, GWO, HHO, and ABC were used to tune the PI controller.

The simulation results for this model showed that at an operational current of 2 A, a maximum temperature gradient of 60 K at zero heat load and a maximum heat load of 0.52 W at a zero temperature gradient were achieved with an optimum COP of 0.4. The GWO-PI controller having a settling time of 199 seconds and an overshoot of 5.96% has the best performance.

List of symbols

α	Seebeck coefficient
T_c	Cold side temperature
T_h	Hot side temperature
R	TEC internal resistance
K	Thermal conductivity
ρ	Resistivity
I	*TEC i*nput current
COP	Coefficient of performance
Q_c	Heat absorbed on the cold side
Q_h	Heat released on the hot side
Q_L	Heat load
P_{ele}	Input electrical energy
ΔT	Temperature gradient

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References

[1] Riffat S B and Ma X 2003 Thermoelectrics: a review of present and potential applications. *Appl. Therm. Eng.* 23: 913–935

[2] Chein R and Huang G 2004 Thermoelectric cooler application in electronic cooling. *Appl. Therm. Eng.* 24: 2207–2217

[3] Wang X-D, Huang Y-X, Cheng C-H, Ta-Wei Lin D and Kang C-H 2012 A three-dimensional numerical modeling of thermoelectric device with consideration of coupling of temperature field and electric potential field. *Energy* 47: 488–497

[4] Phelan P E, Chiriac V A and Lee T-YT 2002 Current and future miniature refrigeration cooling technologies for high power microelectronics. *IEEE Trans. Comp. Packag. Technol.* 25: 356–365

[5] Zhou Y and Yu J 2012 Design optimization of thermoelectric cooling systems for applications in electronic devices. *Int. J. Refrig.* 35: 1139–1144

[6] Cheng Y-H and Lin W-K 2005 Geometric optimization of thermoelectric coolers in a confined volume using genetic algorithms. *Appl. Therm. Eng.* 25: 2983–2997

[7] Zhu L, Tan H and Yu J 2013 Analysis on optimal heat exchanger size of thermoelectric cooler for electronic cooling applications. *Energy Convers. Manag.* 76: 685–690

[8] Sundayani, Sinulingga D F, Prasetyawati F M, Palebangan F M, Suhendi A, Ajiwiguna T A, Handayani I P and Fathonah I W 2017 PID temperature controlling of thermoelectric based cool box. In: *Proceedings of the International Conference on Control, Electronics, Renewable Energy and Communications (ICCREC)*, Yogyakarta: IEEE, pp. 236–240

[9] Shaojing S and Qinqin 2010 Temperature control of thermoelectric cooler based on adaptive NN-PID. In: *Proceedings of the International Conference on Electrical and Control Engineering*, pp. 2245–2248

[10] Selvi V and Umarani Dr R 2010 Comparative analysis of ant colony and particle swarm optimization techniques. *Int. J. Comput. Appl.* 5: 1–6

[11] Mirjalili S, Mirjalili S M and Lewis A 2013 Grey wolf optimizer. *Adv. Eng. Softw.* 69: 46–61

[12] Heidari A A, Mirjalili S, Faris H, Aljarah I, Mafarja M and Chen H 2019 Harris hawks optimization: algorithm and applications. *Future Gener. Comput. Syst.* 97: 849–872

[13] Sharma S and Bhambu P 2016 Artificial bee colony algorithm: a survey. *Int. J. Comput. Appl.* 149: 11–19