International Journal of Applied Operational Research
Vol. 9, No. 2, pp. 41-48, Spring 2019

Journal homepage: ijorlu.liau.ac.ir

Coefficient of performance optimization of a single stage thermoelectric cooler

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Received: 12 January 2018 **;** **Accepted:** 19 June 2018

Abstract In thermoelectric coolers (TECs) applied external voltage potential is generated to a temperature difference based on the Peltier effect. Main and basic structure of TECs is in the form of single stage device. Due to the low efficiency, especially low coefficient of performance (COP) of thermoelectric coolers, optimal design of geometrical parameters of such devices is vital. For this purpose, usually optimization algorithms are used. Therefore, in this research, chemical reaction optimization algorithm (CRO) is used in order to optimal design of structure of single stage thermoelectric cooler. CRO algorithm is a novel optimization scheme inspired form chemical reaction mechanisms. The results of the research are compared with previous data obtained using other optimization algorithm. Comparison of the results shows that application of CRO algorithm results in enhancement of COP of the system. Therefore, CRO algorithm proposed in this research could be used for better design of single stage TECs to achieve higher efficiency and coefficient of performance of the system.

Keyword: Cooling Capacity, COP, Thermoelectric Cooler, Optimization

1 Introduction

Thermoelectric coolers (TECs) are solid state cooling devices that use the Peltier effect. These types of coolers are used to convert electrical energy into a temperature gradient [1]. Schematic of a single stage TEC is shown in Fig. 1. TECs use no refrigerant and have no dynamic parts which make these devices highly reliable and require low maintenance [2]; therefore, recently, thermoelectric devices are taken into consideration in a practical power generation, refrigeration and energy recovery applications [3]. However, thermoelectric devices have some disadvantages; so that, they are typically more expensive and have low efficiency [4]. An improvement on the performance of TECs can be achieved by means of developing new materials, optimizing design and fabrication, improvement of the heat exchange efficiency and employment of multi-stages system [5].

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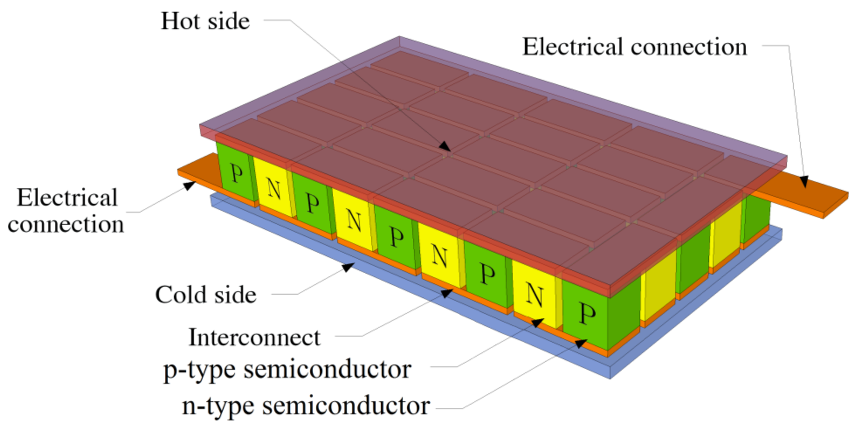

Fig. 1 Schematic of a single stage TEC

Limitations of single stage thermoelectric coolers cause the need for optimal design of these devices with current technology and available materials. In this regard, optimal design of TECs is to define a set of design parameters. Therefore, researchers try to optimize operation of these devices. Some of these studies have been surveyed in following.

Huang et al. [6] optimized a thermoelectric cooler using a mathematical approach based on the simplified conjugate-gradient in order to achieve maximum cooling capacity of the system. Design parameters in this research were three geometrical parameters of coolers including the pair number of semiconductor, length of thermoelectric legs and the base area of semiconductor. Cheng and Shih [7] used the genetic algorithm for optimization of two-stage thermo-electric coolers. The goal of optimization in their research was maximizing of cooling capacity and coefficient of performance of the system, individually. The results of these studies showed that the application of genetic algorithm as an intelligent base approach to the optimal design of considered thermoelectric cooler leads to better performance in comparison to traditional design methods and other non-evolutionary algorithms.

However, due to the continuous advances in optimization algorithms, further studies on the application of newly proposed schemes in the design of thermoelectric devices are needed. Khanh et al. [1] used Simulated Annealing optimization algorithm for geometric optimization of single stage thermoelectric coolers. They showed the applicability of the utilized optimization algorithm in maximizing of cooling capacity of the cooler. Chen and Lin [7] used genetic and simulated annealing algorithms for optimal design of thermoelectric coolers with a large number of thermoelectric modules. They concluded that application of artificial-intelligence based algorithms result in better design of such systems. Also, they showed that the performance of the thermoelectric system optimized by a genetic algorithm is close to the performance of the system designed using the simulated annealing algorithm. However, the advantage of the simulated annealing algorithm is that it converges faster compared with genetic algorithm. Cheng and Lin [8] used a genetic algorithm for geometric optimization of thermoelectric coolers in a confined volume in another research. They investigated the effects of different geometrical parameters of the cooler on the objective functions including a coefficient of performance and cooling capacity of the system. Arora et al. [9] investigated thermodynamic performance of multistage thermoelectric coolers by using a multi-objective optimization analysis. They examined the efficiency of multi-objective genetic algorithm in handling of complex objective. The main focus of their research was investigation of performance of different decision making methods in their considered optimization algorithm. Wu et al. [10, 11] considered the effects of thermal resistances between the TEC and the number of the TEC legs on the performance of a TEC system. Several studies have been

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conducted on optimization of the segmented TECs, and they have proposed algorithms that have optimized the internal structure of systems to maximize COP [12, 13]. According to the importance of the maximizing of COP of the thermoelectric coolers, in this research an approach is proposed based on implementation of chemical reaction optimization (CRO) algorithm. Methodology and results of this implementation are presented in the following.

2 Mathematical modeling

The main objective function of this study is COP of the thermoelectric cooler defined as [8]:

$$\mathrm{COP} = \frac{Q_c}{Q_h - Q_c} \tag{1}$$

where Q_c is the cooling capacity of the system and Q_h is rejected heat from the thermoelectric cooler.

Cooling capacity and rejected heat from the cooling system is defined respectively, as [3]:

$$Q_c = N\left[\alpha \cdot I \cdot T_c - \frac{1}{2} I^2 \left(\rho_r \frac{L}{A} + \frac{2r_c}{A}\right) - \frac{k \cdot A\left(T_h - T_c\right)}{L}\right] \tag{2}$$

$$Q_h = N\left[\alpha \cdot I \cdot T_h + \frac{1}{2} I^2 \left(\rho_r \frac{L}{A} + \frac{2r_c}{A}\right) - \frac{k \cdot A\left(T_h - T_c\right)}{L}\right] \tag{3}$$

Seebeck coefficient (α) could be calculated as [3]:

$$\alpha = \left(-263.38 + 2.78 T_{ave} - 0.00406 \times T_{ave}^2\right) \times 10^{-6} \tag{4}$$

Also, electrical resistivity and thermal conductivity could be correlated, respectively, as [2]:

$$\rho = \left(22.39 - 0.13 T_{ave} + 0.00030625 \times T_{ave}^2\right) \times 10^{-6} \tag{5}$$

$$k = 3.95 - 0.14 T_{ave} + 0.00001875 \times T_{ave}^2 \tag{6}$$

In the mentioned equations, T_{ave} is average temperature of the cooler, which is the mean value of cold (T_c) and hot side (T_h) temperatures of the system.

Design variables of this study are geometrical parameters of the system, including the cross-sectional area of the TEC leg (A), length of the TEC leg (L) and number of the TEC legs (N). First two parameters are real variables, whereas the last is an integer variable. Range of variation of these parameters is considered to be [2]:

$$\begin{cases} 0.03\,\mathrm{mm} < L < 1\,\mathrm{mm} \\ 0.09\,\mathrm{mm}^2 < A < 100\,\mathrm{mm}^2 \\ 1 < N < 1000 \end{cases} \tag{7}$$

Structural constraint of the optimization problem in this research is in the form of an inequality constraint defined as:

$$A \cdot N < 100\,\mathrm{mm}^2 \tag{8}$$

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In the next section, optimization algorithm used to solving the governing equations is introduced.

3 Implementation of the CRO algorithm for optimization of the single stage TEC

Applications of metaheuristic and intelligence-based optimization algorithms have received a great deal of attention thanks to their effectiveness in solving of different and complex problems [14-16]. The chemical reaction optimization algorithm is one of recently introduced optimization algorithms. This optimization technique is capable for use in different fields [17]. In this research this algorithm is used for geometric optimization of single stage thermoelectric cooler to achieve the maximum coefficient of performance of the system. This algorithm is developed based on the phenomena occur in chemical reactions. The chemical reaction is a process in which one or more molecules named as reactants are converted to one or more different molecules named as products. In a chemical reaction, the process is progressing in such a way that the total energy of the products reaches to a minimum level of energy. This minimum energy level corresponds to the stable conditions of the molecules. This phenomenon is analogous to general solutions of optimization problems [4]. In a chemical reaction optimization algorithm, Molecular Structures are corresponding to solutions of optimization problem which are geometric parameters of considered thermoelectric cooler (A, L, N). Also, potential energy is allocated to the value of the objective function, namely COP in this research. Finally, kinetic energy is corresponding to a Measuring tolerance of having worse solutions [17]. In the following, results of application of the CRO algorithm in optimal design of TEC are presented.

4 Results and discussions

In this section, the performance of the implemented CRO algorithm in the optimal determination of geometrical parameters of a single stage TEC is presented. Cold and hot side temperatures of the considered cooler in this research were both fixed to 323K. Obtained results of the optimum determination of geometrical characteristics of considered thermoelectric cooler using the proposed method in this research based on CRO algorithm are presented in Table 1. In order to perform validation of the results, obtained data using a chemical reaction optimization algorithm (CRO) are compared with similar results of the novel hybrid genetic algorithm and simulated annealing (NHGASA) [1].

Table 1 Comparison of the optimal dimensions of single stage thermoelectric cooler obtained using different optimization algorithms

	NHGASA [1]	CRO (present work)
I= 0.1 (A)		
N	300	294
A (mm^2)	0.3326	0.3401
L (mm)	0.3	0.32
Q_c (W)	1.94	1.90
COP	9.06	9.18
I= 0.5 (A)		

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	NHGASA [1]	CRO (present work)
N	404	396
A (mm^2)	0.2473	0.2525
L (mm)	0.3001	0.29
Q_c (W)	8.93	8.87
COP	0.92	0.96
I=1 (A)		
N	202	199
A (mm^2)	0.4931	0.5025
L (mm)	0.3	0.29
Q_c (W)	8.94	8.89
COP	0.92	0.95

Results show that application of CRO algorithm results in a better COP and consequently better performance of the system; in other words, the COP of the single stage thermoelectric cooler optimized using the CRO algorithm is higher than the cooler designed using the novel hybrid genetic algorithm and simulated annealing (NHGASA). It is seen that for input electrical current equal to 0.1 A, COP of the cooler is about 9.18 whereas it was 0.906 in original design [1]. Therefore, COP of the system is increased more than 1% thanks to increment of cross-sectional area of the TECs legs.

For input electrical current equal to 0.5A COP of the cooler is increased from 0.92 using NHGASA to 0.96 by the application of CRO algorithm. Therefore, in this case also the implementation of the chemical reaction optimization algorithm leads to enhancement of system's COP.

In the last case study for input electrical current value of 1 A, COP of the thermoelectric cooler is upgraded to 0.95 using CRO method compared with 0.92 corresponding to the base design.

Comparison of the COP of considered single stage thermoelectric cooler optimized using CRO algorithm (present investigation) and NHGASA algorithm [1] for input electrical current of 0.5 A is shown in Figure 2. It is seen that the application of CRO technique resulted in increasing the COP of the system about 4.35%, which is a considerable enhancement of performance of such low power cooling systems.

Effects of different values of input electrical current of the considered cooler on its COP and cooling capacity are shown in figures 3 and 4, respectively.

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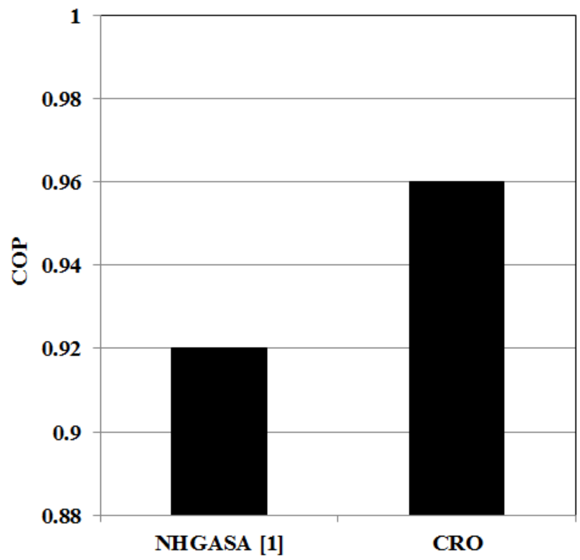

Fig. 2 Comparison of COP single stage thermoelectric cooler obtained using different algorithms

Considering Figure 3, it is clear that an increase in the input electrical current of the cooler, leads to reduction of COP of the system. While, according to the results presented in Table 1 and shown in Figure 4, cooling capacity of the system increases by the increment of the input electrical current. This means that the optimum value of cooling capacity and COP of the single stage TEC could not be achieved, simultaneously.

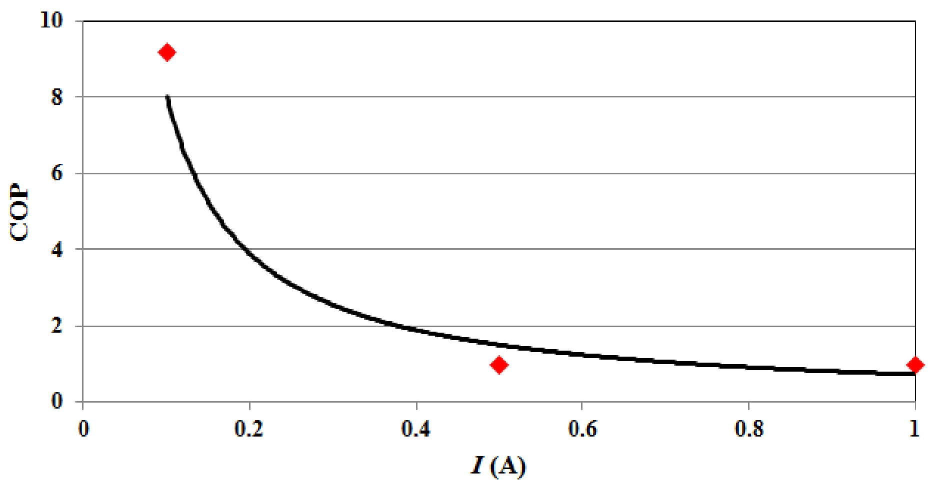

Fig. 3 Effect of different values of input electrical current on COP of considered single stage TEC

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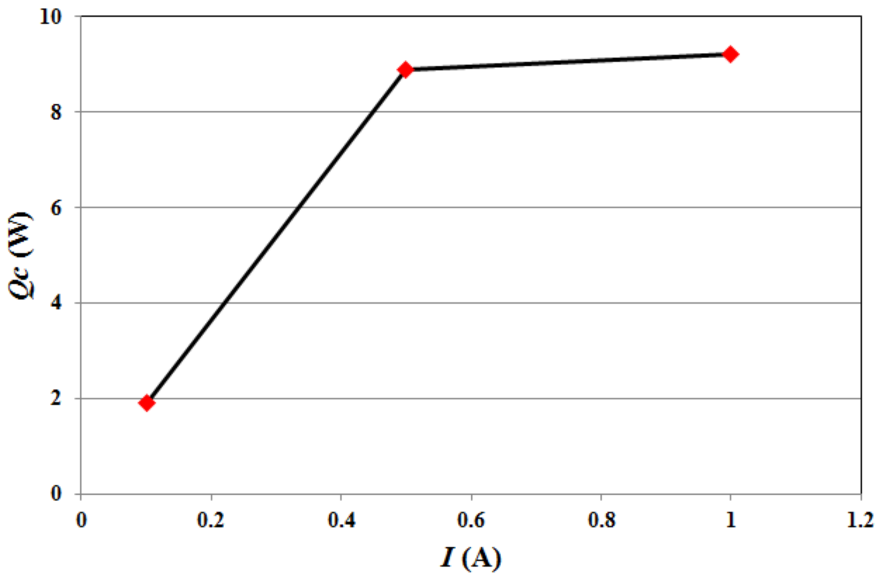

Fig. 4 Effect of input electrical current on cooling capacity of single stage TEC

5 Conclusions

In this research, chemical reaction optimization algorithm is implemented for optimal design of single stage thermoelectric cooling system. To perform this optimization, geometrical parameters are considered as design variables. Therefore, the optimization task in this research was structural dimensions of the TEC. Using proposed scheme, geometrical variables of the cooler were determined and obtained results were compared with available results of the base design which have been determined using the novel hybrid genetic algorithm and simulated annealing (NHGASA). In all cases, results show improvement of COP of the considered cooler using CRO method; so that, up to 4.35% of enhancement is achieved in COP of the system. Consequently, CRO algorithm could be successfully used for geometric optimization of single stage thermoelectric coolers.

Acknowledgment

The author would like to appreciate Iranian Organization for Engineering Order of Building, Province East Azarbaijan, Tabriz, Iran for the financial support of this research, which is based on a research project contract.

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