Journal of Artificial Intelligence in Electrical Engineering, Vol. 10, No.38 ,September 2021

Optimization of a Thermoelectric Refrigeration System to Enhance Cooling Capacity

Amin Hadidi[1,2]
[1]Department of Mechanical Engineering, Ahar Branch, Islamic Azad University, Ahar, Iran
[2]Iranian Organization for Engineering Order of Building, Province East Azarbaijan, Tabriz, Iran
Email: amin.hadidi@yahoo.com (Corresponding author)

Abstract

Due to the widespread use of refrigeration systems in industries, residential and commercial buildings and the major contribution of these systems in the consumption of electrical energy, extensive research is underway to find new technologies for cooling and refrigeration systems. Considering the high consumption of energy in the compression and absorption refrigeration systems, researchers and engineers are developing new refrigeration methods and systems, including modern thermoelectric refrigeration systems. Due to the low coefficient of performance of thermoelectric based systems, extensive research is needed to optimize, develop and find new design methods for these systems. Therefore, in this research, the optimization of the cooling system based on the thermoelectric system has been conducted. For this purpose, the imperial competitive optimization algorithm (ICA) has been used to optimize the thermoelectric system. The objective function of the optimization is the cooling capacity of the refrigeration system. Various parameters of the thermoelectric refrigeration system, such as the amount of electric current on the cold and hot sides of the refrigeration system, were selected as design and optimization variables. The obtained results of the present study have been compared with the results presented by previous researchers. The outlined results revealed that ICA algorithm has a high capability in the optimal design of thermoelectric refrigeration systems.

Keywords: thermoelectric refrigeration system, cooling capacity, coefficient of performance, imperial competitive optimization algorithm

1. Introduction

Thermoelectric coolers are used in various electronic equipment, such as space equipment, microelectronic systems, telecommunications, military applications and medical equipment. The electronic systems and equipment mentioned above usually have relatively large surfaces and require a low temperature to be able to perform optimally [1, 2]. Therefore, the important advantage of the use of the thermoelectric system in such equipment is to provide an environment with a low and uniform temperature for the proper operation of electronic devices. Usually, thermoelectric refrigeration systems can create a temperature difference of 60 to 70 degrees Kelvin when the hot temperature remains at the ambient temperature. Therefore, the temperature of the cold part of this type of systems can be about 60 to 70 degrees Kelvin lower than the ambient temperature, and this low, uniform and reliable temperature can be very favorable for the operation of electronic and medical equipment [3].

Refrigeration systems based on thermoelectric elements have no moving parts, unlike conventional refrigeration systems that are based on refrigerant condensation. Therefore, they have a very quiet and silent operation; but on the other hand, the coefficient of performance of such refrigeration systems is usually low and as a result, the cost of using such refrigeration systems is high, currently. Therefore, a lot of research is going on to find solutions for more optimal design of such refrigeration systems.

The optimal design of refrigeration systems is a process based on trial and error, therefore it is necessary to use optimization algorithms for their optimal design, like other equipment such as heat exchangers [4-7]. Recently, methods based on timetabling techniques have also been presented to optimize the performance of the thermodynamic system network, including the thermoelectric refrigeration networks [8-13].

The design of refrigeration systems, like many other heating and cooling equipment, includes a large number of geometric and functional variables. These parameters are part of the search space for refrigeration system design parameters; so that the desired cooler can estimate the desired cooling task and satisfy a series of constraints. If the values selected for the design parameters of the refrigeration system are such that the designed system does not estimate the desired performance, the design process will be repeated. If the intended tasks are fulfilled by the designed refrigeration system, the design will not necessarily be optimal. Therefore, the optimal design of refrigeration systems is a process based on trial and error; Hence, there is always a probability that the designed cooler is not the most optimal cooler possible. As a result, researchers seek to optimize thermodynamic systems, including refrigeration systems, using optimization algorithms, and in this regard, interesting and valuable research has been done using mathematical techniques and methods based on artificial intelligence. In this section, some important investigations conducted in this field are reviewed.

Using mathematical optimization, Kraemer et al. [14] designed the optimal thermoelectric generator for power generation using solar energy. These researchers pointed out that thermoelectric systems have not received much attention due to low efficiency and economic limitations. Therefore, in their research, using mathematical optimization, they tried to improve the performance of thermoelectric generators so that they can use this system to produce economical power using solar energy. Su et al. [15] also used the mathematical method to optimize the energy recovery system based on thermoelectric generator, from the combustion exhaust of an internal combustion engine. These researchers stated that most of the energy obtained from combustion in an internal combustion engine is wasted along with the combustion products and is not used. Therefore, in their research, they designed a system to recover this wasted energy and used thermoelectric generators to harness that wasted heat. In order to increase the efficiency and productivity of the proposed system, these researchers used the mathematical optimization method in their research so that the performance of the proposed solution would be economical. Niu et al. [16] also presented a system to recover the wasted heat in internal combustion engines and used mathematical and analytical methods to improve the performance of the system presented in their research. These researchers stated that in order to increase the amount of energy recovered from the combustion products of the internal combustion engine, it is necessary to increase the contact surfaces of the used heat exchanger. As the surface increase, the number of thermoelectric modules also increases; Therefore, the total cost of the designed system also increases. Therefore, the optimal design of this system becomes an optimization problem that determines the characteristics of the optimal system by solving the aforementioned optimization problem. To solve the problem, these researchers used mathematical and analytical optimization methods and did not use methods based on artificial intelligence.

Naturally, the use of intelligent algorithms will lead to better results. As another example of the research done in the field of optimization of thermoelectric based systems, the research of Yazawa et al. [17] could be mentioned. These researchers used mathematical and analytical methods to perform optimization in their research. In their research, the thermoelectric system was used as the topping cycle of the steam turbine cycle. In this way, using a thermoelectric generator to produce additional electricity, in addition to the power produced in the steam turbine coupled to the generator, has been used. They used mathematical optimization to find the optimal point of combined cycle performance and economic optimization of the designed system. In their research, they did not use intelligent optimization methods. Maybe if they used intelligent multi-objective optimization, they would have reached the optimal plan much faster and easier than the analytical method. Rao and Patel [18] used the optimization algorithm based on the improved teaching-learning method (TLBO) to optimize the two-stage thermoelectric refrigeration system. These researchers used TLBO method for multi-objective optimization of thermoelectric cooler. The aim of their research was to maximize the cooling capacity and the performance coefficient of the thermoelectric based cooling system. They compared the performance of TLBO algorithm in the design of optimal thermoelectric refrigeration systems with the results of other intelligence algorithms, including genetic algorithm, particle swarm optimization algorithm (PSO) and artificial bee swarm optimization algorithm (ABC) and showed that the results of the algorithm TLBO optimization is better than the three mentioned methods. This means that the thermoelectric refrigeration system designed using TLBO algorithm has a higher cooling capacity and coefficient of performance compared to the system designed using genetic algorithm, PSO and ABC algorithm methods. Due to the continuous improvement of intelligent and evolutionary optimization algorithms, more studies are needed in the field of proposing new optimization algorithms for the optimal design of thermoelectric systems. Imperialist competitive algorithm (ICA) is one of these methods used in this research to optimize thermoelectric refrigeration systems.

2. Thermoelectric Refrigeration Systems

Practical thermoelectric heat pump and refrigeration systems usually consist of thermoelectric modules that include a number of thermocouples; an example of these modules is shown in Fig. 1.

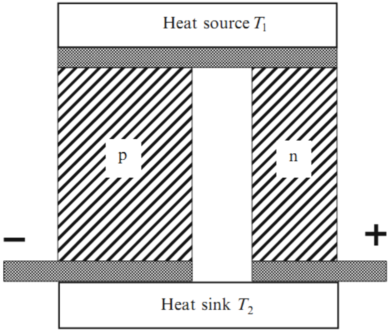

Fig. 1. Simple thermoelectric refrigerator or heat pump [19]

These thermocouples are electrically connected in series and thermally in parallel. An example of thermocouples array is shown in Fig. 2.

This arrangement and configuration makes the thermoelectric refrigeration system able to work with a power source whose current intensity can be adjusted; so that it has a reasonable voltage drop. Therefore, for the analysis of real refrigeration systems based on thermoelectric modules, it is necessary to generalize the relationships derived for single thermocouples to arrays consisting of several thermocouples. In the network of thermocouples of a thermoelectric system, optimization is an important issue so that it can have the desired output. The goal of optimization can be geometric dimensions, total weight, occupied volume, cooling capacity or produced power. In the thermoelectric refrigeration system, the coefficient of performance or the cooling capacity is usually the main goal of optimization.

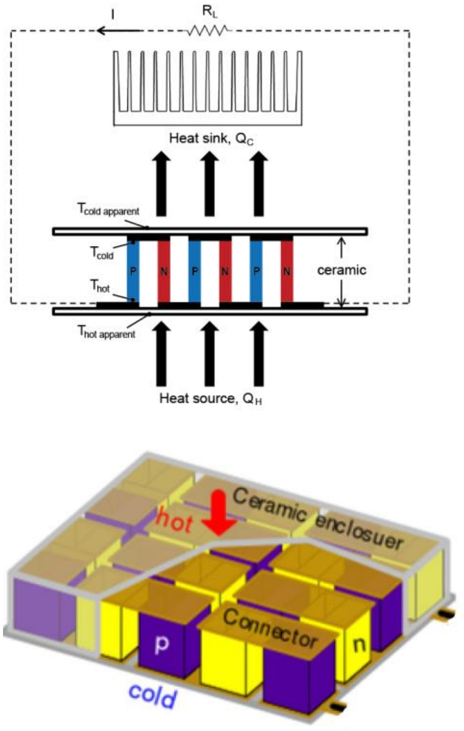

Fig. 2. Thermocouples array in a thermoelectric device [20]

3. Governing Equations

In the current research, two-stage thermoelectric refrigeration system has been studied. In this system, two thermoelectric coolers are electrically connected in series as shown in Fig. 3.

Cooling capacity of the considered refrigeration system is calculated as:

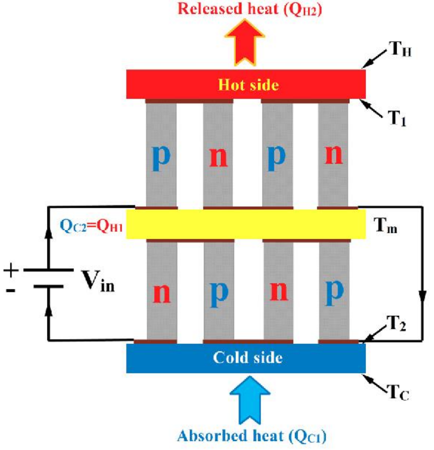

Fig. 3. Two-stage electrically series thermoelectric refrigeration system

$$Q_{c,c} = \frac{N_t}{r+1} \times \left[\alpha_c I_c T_{c,c} - \frac{1}{2} I_c^2 R_c - K_c \left(T_{c,h} - T_{c,c} \right) \right] \quad (1)$$

In the above mentioned equation, N_t and r are the total pair number of thermocouples of the considered refrigeration system and ratio of pair number of thermocouples between the hot and cold stages, respectively. N_t is a constant parameter for a given thermoelectric system and r is a design parameter in this research. Also, I_c and I_h are input electrical currents applied to cold and hot stages of the thermoelectric refrigeration system, respectively. These parameters also are considered as design variables in this research. The cold side temperature of the refrigeration system is represented by $T_{c,c}$ and hot side temperature of the system is denoted by $T_{h,h}$; while, temperatures of the hot side of the cold stage and cold side of hot stage are represented by $T_{c,h}$ and $T_{h,c}$, respectively.

The thermoelectric properties of the constituent materials of each of the two stages of the discussed thermoelectric refrigeration system are described as follows.

$$\alpha_i = \left| \alpha_{i,p} \left(T_{i,ave} \right) - \alpha_{i,n} \left(T_{i,ave} \right) \right| \quad (2)$$

$$R_i = \frac{\rho_{i,p} \left(T_{i,ave} \right) + \rho_{i,n} \left(T_{i,ave} \right)}{G} \quad (3)$$

$$K_i = \left[k_{i,p} \left(T_{i,ave} \right) + k_{i,n} \left(T_{i,ave} \right) \right] G \quad (4)$$

Cooling capacity of the thermoelectric refrigeration system is selected as objective function in this research. Also, design parameters of the optimization process of the considered thermoelectric refrigeration system are: input electrical current to the cold stage of the refrigeration system, I_c, input electrical current to the hot stage of the refrigeration system, I_h and the ratio of thermocouples of hot stage to the thermocouples of the cold stage of the refrigeration system, r.

4. Optimization Algorithm

In this article, the imperialist competitive optimization algorithm (ICA) has been used to the optimal design of the thermoelectric refrigeration system. ICA is a powerful heuristic evolutionary algorithm. Similar to other evolutionary algorithms, this algorithm starts with an initial population. Each individual of the population is called a country. Some of the best countries (in optimization terminology, countries with the least cost) are selected to be the imperialist states and the rest form the colonies of these imperialists. All the colonies of initial countries are divided among the mentioned imperialists based on their power. The power of each country, the counterpart of fitness value in the GA, is inversely proportional to its cost. The imperialist states together with their colonies form some empires. After forming initial empires, the colonies in each of them start moving toward their relevant imperialist country. The total power of an empire depends on both the power of the imperialist country and the power of its colonies [6].

5. Results and Discussion

The performance of the proposed optimization algorithm in this research for optimization of considered two-stage thermoelectric refrigeration system examined by solving a case study and the obtained results was compared with available results of previous researchers.

In the considered test case, The temperature of the cold side of the colder stage of the two-stage thermoelectric refrigeration system is equal to 240 degrees Kelvin, and the temperature of the hot side of the hotter stage is equal to 300 degrees Kelvin. The ratio of the cross-sectional area to the length of the thermocouples is equal to 1.8×10^{-3} and the total number of pairs of two-stage thermocouples is equal to 50. The contact resistance of thermoelectric elements is equal to 2×10^{-6}. The obtained results are presented in Table 1.

Table 1. Characteristics of the optimized two-stage thermoelectric refrigeration system with the objective function of the maximum cooling power using different algorithms

parameter	Base design [21]	GA [22]	ICA (this research)
I_c (A)	7.45	7.425	8.2
I_h (A)	7.45	7.425	8.2
r	3.17	2.846	2.87
$Q_{c,c}$ (W)	3.08	3.211	3.58

The performance of the imperialist competitive optimization algorithm in the optimal design of the thermoelectric refrigeration system with the considered specifications is compared with the performance of the genetic algorithm and also the basic design using the traditional design method in Table 1. This comparison shows that the imperialist competitive algorithm has a better performance compared to the traditional design method which is based on trial and error technics. So that the cooling capacity of the refrigeration system designed by the imperialist competitive optimization algorithm has increased by 16.2% compared to the traditional design.

Comparison of the performance of the considered algorithms also is shown in Fig. 4. Considering the results presented in Fig. 4, it is concluded that the optimization of the designed thermoelectric refrigeration system using ICA algorithm has led to the improvement of the overall cooling capacity of the refrigeration system ($Q_{c,c}$) compared to the genetic optimization method; so that the cooling capacity of the optimized refrigeration system using the ICA is about 11.5% higher than its corresponding value using the genetic optimization algorithm (GA).

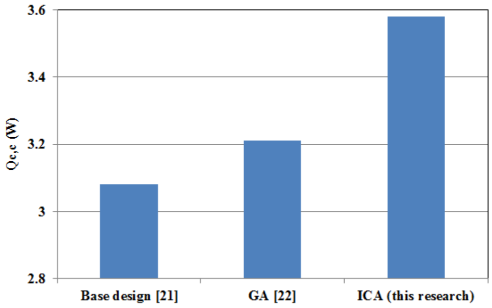

Fig. 4. Comparison of the cooling capacity of the two-stage thermoelectric refrigeration system designed with different methods

6. Conclusion

In this research, the imperialist competitive algorithm (ICA) was used for the optimal design of a two-stage electrically series thermoelectric refrigeration system. The obtained results showed that the thermoelectric refrigeration system optimized by the imperialist competitive algorithm has a greater cooling capacity compared to the basic design of this system by using traditional methods and the system optimized by the genetic optimization algorithm. An increase of about 16.7% in the cooling capacity of the refrigeration system designed using the imperialist competitive algorithm in the present study compared to the basic design and an increase of about 11.5% compared to the results of the genetic algorithm are among the most important achievements of this research.

Acknowledgments

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 titled as ‘‘Geometrical optimization of the thermoelectric refrigeration system to be used in the building”.

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