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Research Paper

Optimization of electrically separated two-stage thermoelectric refrigeration systems using chemical reaction optimization algorithm

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HIGHLIGHTS

- A new approach is proposed for optimization of thermoelectric refrigeration system.
- The first application of a CRO algorithm for optimization of thermoelectric cooler.
- COP of the thermoelectric refrigeration system enhanced using CRO algorithm.
- Cooling capacity of the thermoelectric cooler increased using CRO algorithm.

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ABSTRACT

A robust method is proposed for optimal design of electrically separated two-stage thermoelectric refrigeration systems based on chemical reaction optimization algorithm (CRO). In order to investigate the performance of the proposed method, a full computer code was developed and different test cases were solved by it to show the accuracy and efficiency of the method. Cooling capacity and coefficient of performance of the refrigeration system are considered as objective functions of the optimization process. The effects of the joint thermal resistance at the interface of the two stages on objective functions in all of the case studies also were studied and sensitivity analysis of COP and cooling capacity of the system to this parameter is conducted. The obtained results were compared to those obtained by literature approaches. The outlined results showed improvement of the objective functions using the CRO method in comparison to the results of the genetic algorithm previously used for optimization of the considered refrigeration system. The obtained results of the paper showed that the CRO algorithm can be successfully employed for optimal design of electrically separated two-stage thermoelectric refrigeration system.

1. Introduction

Recently thermoelectric devices are taken into consideration in practical power generation, refrigeration and energy recovery applications [1,2]. This is because of noticeable features and advantages of these devices, including simplicity, lack of moving parts, ability to heat and cool with the same module, solid-state operation, environmentally friendly operation [3,4]. However, thermoelectric devices have some disadvantages; so that, they are typically more expensive and have low efficiency [5]. Therefore, researchers try different methods to optimize operation of these devices. Some of these studies have been surveyed in following.

Jang and Tsai [6] optimized a thermoelectric generator for use in a waste heat recovery system. They conducted a numerical simulation of thermoelectric generator using finite difference method to perform optimization of the system. The objective function of their research was the output power density of the generator which should be maximized. Optimization variables in their research were module spacing and spreader thickness of the generator. They determined optimum values of these variables to maximization of the objective function. Yazawa et al. [7] optimized thermoelectric system used as a topping cycle of combined steam turbine cycles for the energy economy. They used numerical and analytical approach to determine the optimal value of the temperature of the interface connecting thermoelectric generator to the steam turbine. Their objective was minimization of generating energy costs. Huang et al. [8] conducted a geometric optimization of thermoelectric coolers. 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. An objective function of their study was cooling capacity of the cooler which should be maximized. They used a

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Nomenclature

a	constant factor (m^2)
A	cross-sectional area of thermocouples (m^2)
COP	coefficient of performance
I	electrical current (A)
G	structural parameter of thermocouples (m)
K	thermal conductance of thermocouples (W/K)
KE	kinetic energy (J)
k	conductive heat transfer coefficient (W/m K)
L	length of thermocouples (m)
m	random number
N_t	total pair number of thermocouples
PE	potential energy (J)
q	random number
Q	rate of heat transfer (W)
r	ratio of pair number of thermocouples of the hot stage to the cold stage
rad	equivalent radius (m)
R	electrical resistance of thermocouples (Ω)
RS_{cont}	contact thermal resistance (K/W)
RS_j	joint thermal resistance at the interface (m^2 W/K)
RS_{sprd}	spreading thermal resistance (K/W)
RS_t	total thermal resistance (K/W)
s	random number
$S_{h,s}$	thickness of the substrate of the hot stage (m)
T	temperature (K)

Greek symbols

α	Seebeck coefficient (V/K)
ε	dimensionless parameter
λ	dimensionless parameter
π	Pi number
ρ	electrical resistivity (Ω m)
τ	dimensionless parameter
ϕ	dimensionless parameter
ψ	dimensionless parameter
ω	molecule/CRO solutions

Subscripts

ave	average
c	cold stage
c,c	cold side of cold stage
c,h	hot side of the cold stage
h	hot stage
h,c	cold side of the hot stage
h,h	hot side of the hot stage
n	n-type thermoelectric material
p	p-type thermoelectric material

mathematical approach which was simplified conjugate-gradient method for determination of optimum value of the objective function. Optimization of thermoelectric heat pumps was conducted by David et al. [9]. Objective function in their analytical research was the maximum coefficient of performance of the heat pump. They optimized heat exchanger, mini-channel and heat sinks used in the considered heat pump. Design variables of this research were geometric parameters of heat sink, mini-channel and heat exchanger as well as hydrodynamic and heat transfer characteristics of cold and hot flows of the heat pump.

Other researchers also investigated numerical or analytical optimization of thermoelectric devices which majority of them was focused on performance optimization or heat exchanger optimization of thermoelectric generators used in heat recovery of exhaust [10–15].

In the above studies, the analytical, mathematical and numerical based analysis were conducted for optimization of thermoelectric devices either cooler or generator applications. The design of thermodynamic equipment such as thermoelectric coolers represents a complex process involving an integrated whole of design rules, calculating methods and empirical knowledge of various fields [16,17]. The design procedure is a trial-and-error process. In this regard, there is always the possibility that the designed results are not the optimum. Hence, designers and researchers try to optimize these devices by using of optimization algorithms based on metaheuristic and artificial intelligence based techniques [18,19]. Some studies which have used optimization algorithms in optimal design of thermo-electric devices are surveyed in the following.

Chen and Lin [20] used artificial-intelligence techniques for optimization of multiple-module thermoelectric coolers. They used and examined performance of two optimization algorithms including genetic and simulated annealing algorithms for optimal design of single stage multiple module thermoelectric coolers with a large number of thermoelectric modules. They concluded that application of artificial-intelligence based algorithms have led to the better results. Also, they showed that the performance of the thermoelectric system optimized by genetic algorithm is close to the performance of the system designed using simulated annealing algorithm. However, the advantage of the simulated annealing algorithm is that it converges faster compared with genetic algorithm. Therefore, there is a need to develop new and power full optimization approaches to optimal design and improvement of performance of the thermoelectric refrigeration systems. Arora et al. [21] used thermodynamic modeling and multi-objective optimization analysis of thermoelectric systems with different configuration of stages. They considered a two-stage thermoelectric generator and examined the efficiency of multi-objective genetic algorithm in handling of complex objective functions of two-stage thermoelectric generator including dual and triple objectives. The main focus of their research was investigation of performance of different decision making methods in their considered optimization algorithm. They considered different objective functions including maximum power output, maximum thermal efficiency and minimum entropy generation. Applicability of NSGA-II optimization algorithm in handling of different combination of these objective functions in multi-objective optimization problem in that research was investigated. Cheng and Lin [22] used a genetic algorithm to geometric optimization of thermoelectric coolers in a confined volume. These researchers considered coefficient of performance and cooling capacity of the thermoelectric coolers as objective function of the optimization process. They declared that these parameters are most important index of operation of such cooler systems. Therefore, they investigated the effects of different geometrical parameters of the cooler on the objective functions. In other research, Cheng and Shih [23] used the genetic algorithm for optimization of two-stage thermo-electric coolers in order to maximizing of cooling capacity and also coefficient of performance of the system.

The results of these studies showed that the application of genetic algorithm to optimal design of considered thermoelectric cooler leads to better performance in comparison to traditional