Pareto Optimum Design of Heat Exchangers based on the Imperialist Competitive Algorithm: A Case Study

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Abstract: In this paper, the multi-objective optimum design of shell and tube heat exchangers is investigated. A thermal modelling of an industrial shell and tube heat exchanger is performed using an ϵ-NTU method for estimating the shell side heat transfer coefficient and pressure drop. The efficiency and total cost (includes the capital investment for the equipment and operating cost) are two important parameters in the design of heat exchangers. The fixed parameters and the ranges of the design variables are obtained from a shell and tube recovery heat exchanger in Barez tire production factory located in Kerman city, Iran. The Imperialist Competitive Algorithm (ICA) is used to find the optimal design parameters to achieve the maximum thermal efficiency and minimum consumption cost as the objective functions. The tube inside and outside diameters, tube length and the number of tubes are considered as four design variables. Furthermore, the effects of changing the values of the design variable on the objective functions are independently investigated. At the end, the obtained Pareto front and the related design variables and their corresponding objective functions are presented.

Keywords: Imperialist Competitive Algorithm, Multi-Objective Optimization, Shell, Tube Heat Exchangers

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1 INTRODUCTION

Shell and tube heat exchangers are widely used in many industrial power generation plants as well as chemical, petrochemical, and petroleum industries. There are several effective parameters of design variables for the shell and tube heat exchanger design such as tube diameter, tube arrangement, etc. For an optimum design, in addition to the decision variables, objective functions should be properly determined. Some authors considered the cost of heat transfer surface area or capital investment as an objective function to be minimized [1-2]. While others considered the sum of investment (related to the heat transfer surface area) and operational (fluid head losses) costs as an objective function for optimizing a shell and tube heat exchanger. The optimum design parameters that affect the shell-tube heat exchangers can be regarded as the external and internal diameter, length and number of tubes [3-4].
Several researchers have addressed the shell-tube heat exchanger design and optimization. Multi-objective optimization of total annualized cost and the amount of cooling water required for shell and tube heat exchanger was studied in [5].
In this paper, at first, the thermal modelling of an industrial shell and tube heat exchanger (using the ϵ-NTU method for estimating the shell side heat transfer coefficient and pressure drop) is studied. Then, the exchanger is optimized by maximizing the efficiency as well as minimizing the total cost. The Imperialist Competitive Algorithm (ICA) is applied to provide a set of Pareto optimum solutions. The sensitivity analysis of changing in the optimum values of the efficiency and total cost with changing in the design variables is performed and the results are reported. It should be noted that the fixed parameters and the ranges of the design variables are obtained from a shell and tube recovery heat exchanger in Barez tire production factory located in Kerman city, Iran.

2 THERMAL MODELING

The heat exchanger efficiency for the selected E type TEMA shell and tube heat exchanger is estimated from [6]:

$$\epsilon = \frac{2}{(1+C^{*}) + \coth\left(\frac{NTU}{2}\sqrt{(1+C^{*2})}\right)\sqrt{(1+C^{*2})}} \qquad (1)$$

Where the heat capacity ratio (C*) and the number of transfer units (NTU) are defined as:

$$NTU_{max}=\frac{U_0 A_t}{Cmin} \qquad (2)$$

$$C^{*}=\frac{Cmin}{Cmax}=\frac{\min(Cs,Ct)}{\max(Cs,Ct)}=\frac{\min((m°Cp)s,(m°Cp)t)}{\max((m°Cp)s,(m°Cp)t)} \qquad (3)$$

Where A_t is the total tube outside heat transfer surface area and U_0 is the overall heat transfer coefficient which are computed from:

$$A_t=\pi L d_o N_t \qquad (4)$$

$$U_0=\frac{1}{\frac{1}{hs}+Ro,f+\frac{do\ln(do/di)}{2kt}+Ri,f\frac{do}{di}+\frac{1}{ht}\frac{do}{di}} \qquad (5)$$

Where L, N_t, d_i, d_o, $R_{i,f}$, $R_{o,f}$, K_t are the tube length, the number of tubes, the inside and outside diameters of the tube, tube and shell side fouling resistances and thermal conductivity of tube wall respectively. Also, the tube side heat transfer coefficient (h_t) was estimated from [6]:

$$h_t=(k_t/d_i)0.024Re_t^{0.8}Pr_t^{0.4} \qquad (6)$$

Where k_t and Pr_t are tube side fluid thermalconductivity and Prandtl number, Also Re_t is Reynolds number of tube flow which is defined as:

$$Re_t=\frac{m_t d_i}{\mu_t A_{o,t}} \qquad (7)$$

Where m_t is the mass flow rate and $A_{o,t}$ is the tube side flow cross section area per pass estimated as:

$$A_{o,t}=0.25\pi d_i^2 N_t/np \qquad (8)$$

And n_p is the number of tube passes.
The shell diameter is estimated from [7]:

$$D_s = 0.637P_t\sqrt{\pi N_t CL/CTP} \qquad (9)$$

Where P_t is tube pitch and CL is tube layout constant that has a unit value for 45° and 90° tube arrangement and 0.87 for 30° and 60° tube arrangements. Also, CTP is the tube count constant which is 0.93, 0.9, 0.85 for single pass, two passes and three passes of tubes, respectively [8].
The shell side heat transfer coefficient is calculated as follows:

$$h_s = h_{id}J_cJ_JJ_bJ_sJ_r \qquad (10)$$

Where h_{id} is the j factor for a category ideal Celeron and J_c, J_J, J_b, J_s and J_r are the correction factors for baffle configuration (cut and spacing), baffle leakage, bundle and pass partition by pass streams, bigger baffle spacing at the shell inlet and outlet sections, and the adverse temperature gradient in the laminar flow, respectively [9].

3 OBJECTIVE FUNCTIONS, DESING VARIABLE AND CONSTRAINTS

In this study, the efficiency and total cost are considered as two objective functions. The total cost includes the investment cost of heat transfer surface area (C_{in}) as well as the operating cost for the pumping power (C_{op}).

$$C_{total} = C_{in} + C_{op} \tag{11}$$

The investment cost for both shell and tube (stainless steel) is [10]:

$$C_{in} = 8500 + 409A_t^{0.85} \tag{12}$$

Where A_t is the total tube outside heat transfer surface area.
The total operating cost related to pumping power to overcome friction losses of both hot and cold streams is computed from [11]:

$$C_{op} = \sum_{k=1}^{ny} \frac{C_o}{(1+i)^k} \tag{13}$$

$$C_o = P\, K_{el} \tau \tag{14}$$

$$P = \frac{1}{\eta}\left(\frac{m_t}{\rho_t}\Delta P_t + \frac{m_s}{\rho_s}\Delta P_s\right) \tag{15}$$

Where ny is the equipment life time in year, i is the annual discount rate K_{el}, τ and η are the price of the electrical energy, the hours of the operation per year and the pump efficiency, respectively.

4 CASE STUDY

The characteristics of the considered system are in agreement with those of an oil cooler shell and tube heat recovery heat exchanger in Barez tire production factory located in Kerman, Iran. The objectives are the maximization of the efficiency and minimization of the total cost. The oil (hot stream, C_p=2113 j/kg k) mass flow rate is 2.65 kg/s with 53.7°C inlet temperature which enters the shell side. The fresh water (cold stream, C_p=4120j/kg k) with a 5.25 kg/s mass flow rate at 38.3°C which enters the tube side. The other operating conditions are listed in “Table 1”. The heat exchanger constant parameters have been measured in the factory and are listed in “Table 2”. The effectiveness of the design variables on the efficiency and total cost is shown in “Fig. 1 to Fig. 10”. In this study, the equipment life period is ny =10 yr, the rate of the annual discount is i=10%, the price of the electricity is K_{el}=0.12 $/kWh and the hours of operation and the pump efficiency are considered as τ=7100 h/yr and η=0.6, respectively.

Table 1 The operating conditions of the shell and tube heat exchanger (input data for the model).

Thermo physical and process data	Shell side (hot stream) (oil)	Tube side (cold stream) (water)
Density (kg/m^3)	856	995
Specific heat (j/kg K)	2113	4120
Viscosity	0.0651	0.00068
Thermal conductivity (W/m K)	0.12	0.638
Fouling factor (m^{2}W/K)	0.00015	0.0000798

Table 2 The heat exchanger parameters measured in Barez tire factory

Row	Variables	Measured value
1	Tube inside diameter (m)	0.012
2	P_t/do	2.86
3	Tube length (m)	0.6
4	Tube number	28
5	Tube outside diameter (m)	0.014
6	h_t (W/m^2 k)	6726/45
7	h_s (W/m^2 k)	587.78

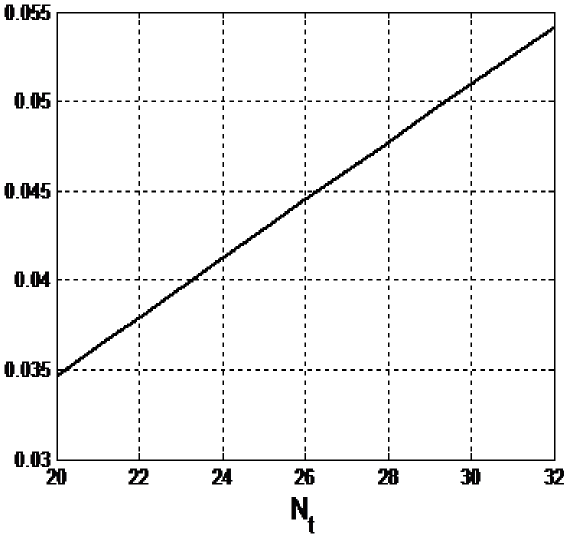

Fig. 1 The effect of the number of tubes (N_t) on the thermal efficiency ($\in$).

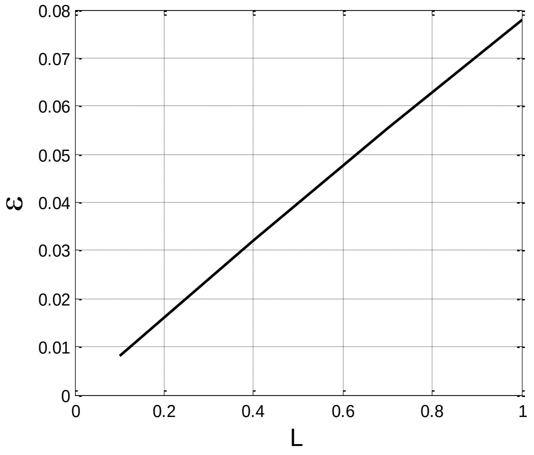

Fig. 2 The effect of the tube length (L) on the thermal efficiency (∈).

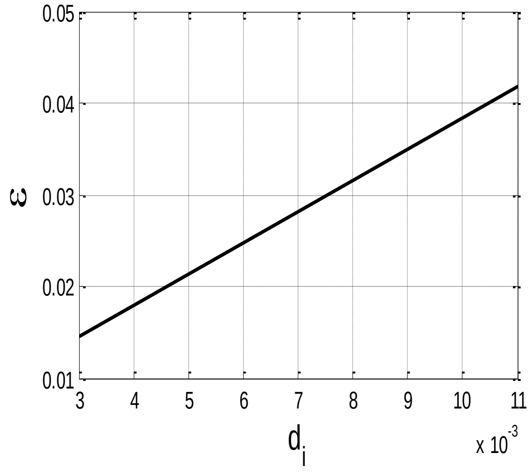

Fig. 3 The effect of the tube inside diameter (d_i) on the thermal efficiency (∈).

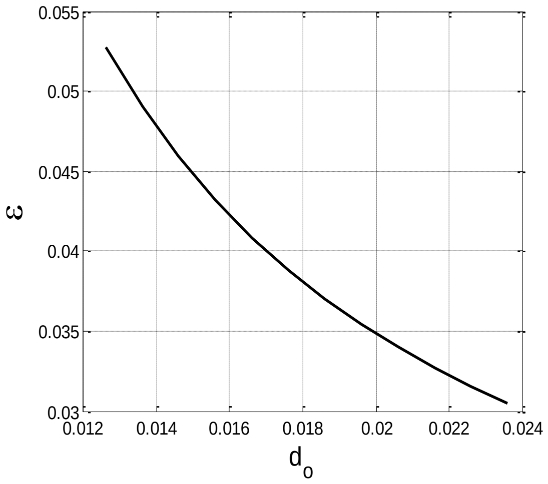

Fig. 4 The effect of changing the tube outside diameter (d_o) on the thermal efficiency (∈).

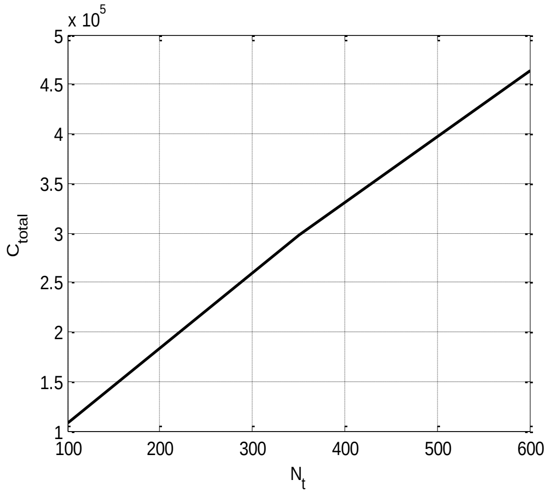

Fig. 5 The effect of changing the tube number (N_t) on total cost (C_{total}).

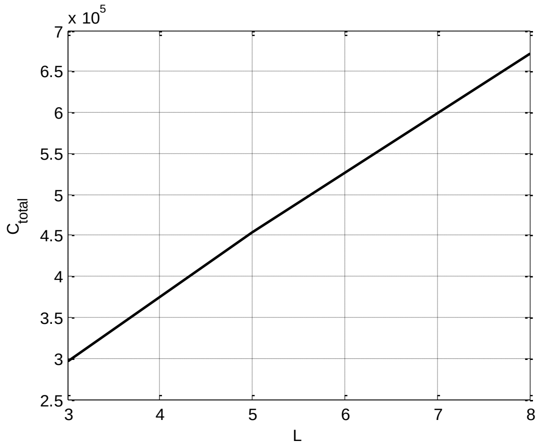

Fig. 6 The effect of the tube length (L) on the total cost (C_{total}).

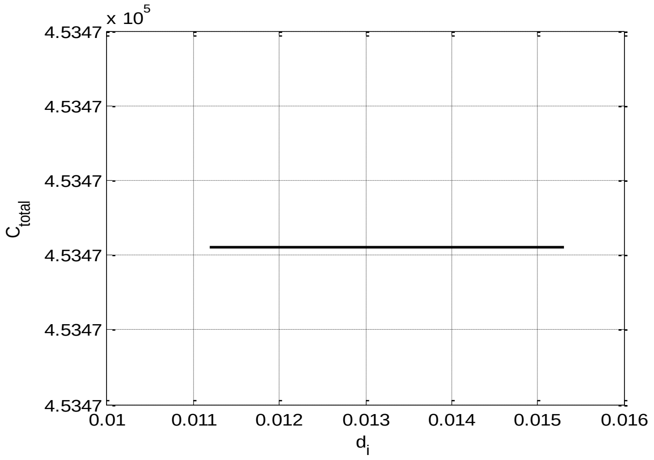

Fig. 7 The effect of the tube inside diameter (d_i) on the total cost (C_{total}).

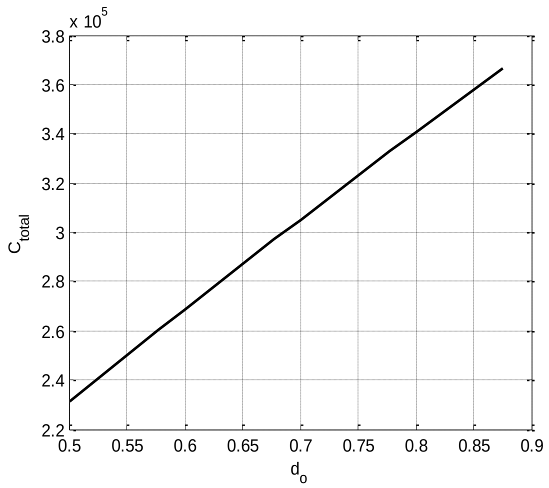

Fig. 8 The effect of the tube outside diameter (d_o) on the total cost (C_{total}).

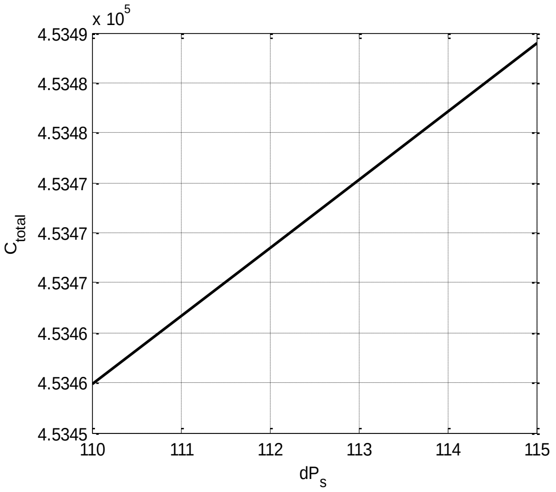

Fig. 9 The effect of the shell side pressure (ΔP_s) on the total cost (C_{total}).

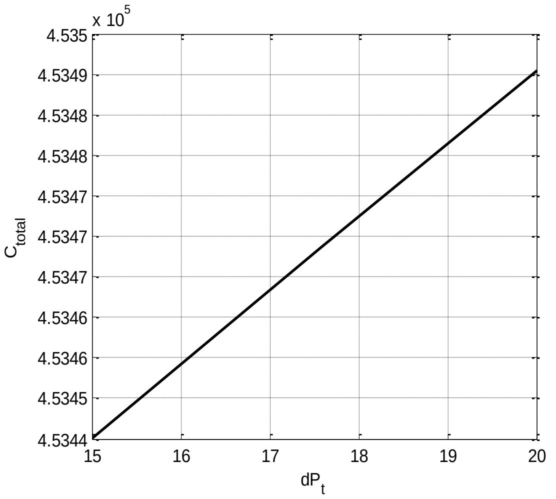

Fig. 10 The effect of the tube side pressure (ΔP_t) on the total cost (C_{total}).

5 THE IMPERIALIST COMPETITIVE ALGORITHM

The Imperialist Competitive Algorithm (ICA) is a computational method that is used to solve different types of optimization problems [12-13]. Like most of the methods in the area of evolutionary computation, the ICA does not need the gradient of the function in its optimization process. From a specific point of view, ICA can be regarded as the social counterpart of genetic algorithms (GAs) [14-15]. ICA is the mathematical model and computer simulation of human social evolution, while GAs are based on the biological evolution of species. Figure 11 shows the flowchart of the ICA. This algorithm starts by generating a set of candidate random solutions in the search space of the optimization problem. The generated random points are called the initial countries. Countries in this algorithm are the counterpart of chromosomes in GAs and particles in Particle Swarm Optimization (PSO) [16-17].

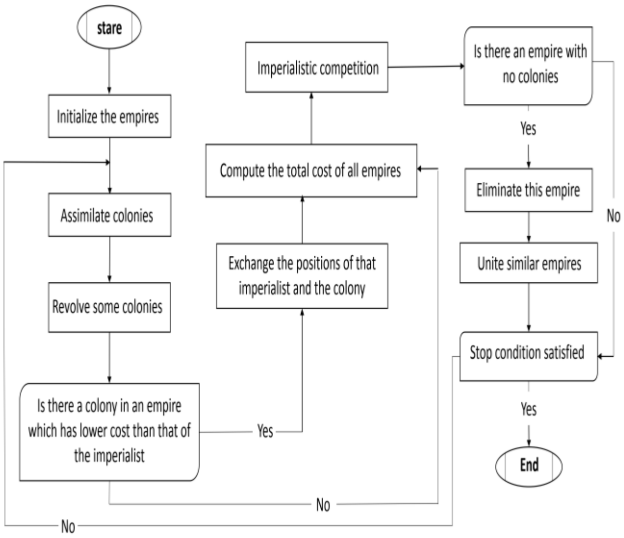

Fig. 11 The flowchart of the ICA.

The cost function of the optimization problem determines the power of each country. Based on their power, some of the best initial countries (the countries with the least cost function value), become Imperialists, which control other countries (called colonies) and form the initial Empires. Two main operators of this algorithm are assimilation and revolution. Assimilation makes the colonies of each empire get closer to the imperialist state in the space of socio-political characteristics. Revolution brings sudden random changes in the position of some of the countries in the search space. During assimilation and revolution, a colony might reach a better position and has the chance to control the entire empire and replace the current imperialist state of the empire. Imperialistic Competition is another part of this algorithm. All the empires try to win this game and take possession of colonies of other empires. In each step of the algorithm, based on their power, all the empires have the chance to control one or more of the colonies of the weakest empire. The algorithm continues with the mentioned steps (Assimilation, Revolution, Competition) until a stop condition is satisfied. The ICA is used to solve different optimization problems in various areas of engineering and science, such as: designing a controller for industrial systems designing [18], intelligent recommender systems [19], fuzzy controller design [20], solving optimization problems in communication systems [21-23], solving scheduling and production management problems [24-30], training and analysis of artificial neural networks [31], design and thermodynamic optimization of plate-fin heat exchangers [32], feature selection [33] and so on [34-37].

6 THE MULTI-OBJECTIVE OPTIMIZATION APPROACH

In this paper, the method of weighting coefficients is used to solve the multi-objective optimization problems [38]. In other words, the two objective functions are combined using weighting coefficients with each other and make a final function. The value of the weighting coefficient of the objective function depends on its importance. In fact, the more important objective function has a greater weighting coefficient. Hence, this multi-objective optimization problem is converted into a single objective problem. F(x) is the total objective function as follows:

$$\mathrm{F(x)} = \sum_{\mathrm{i}=1}^{\mathrm{k}} \mathrm{w_i F_i\,(x)} \tag{16}$$

$$\sum_{\mathrm{i}=1}^{\mathrm{k}} \mathrm{w_i} = 1 \tag{17}$$

k is the number of objective functions, $\mathrm{w_i}$ is the i-th weighting coefficient, and $\mathrm{F_i(x)}$ is the i-th objective function. The values of the weighting coefficients determine the importance of the objective functions and make a new total objective function. Therefore, via the weighting coefficients changing, the total objective function (F(x)) would be changed and a new point of the Pareto front [39-40] would be obtained.

7 SIMULATION AND RESULTS

The proposed multi-objective imperialist competitive algorithm is used for Pareto multi-objective optimization of the shell and tube heat exchanger existed in the Barez tire company. The objective functions have to be maximized and minimized, respectively. The design variables are tube inside diameter, tube outside diameter, tube length and the number of tube. A population size of 100 was chosen with 10 empires and 100 maximum iterations. Figure 12 depicts the obtained non-dominated optimum design points as a Pareto front of the objective function. In this figure, points A and B stand for the best efficiency and total cost, respectively. It is clear from this figure that all the optimum design points in a Pareto front are non-dominated and could be chosen by a designer as the optimum shell and tube heat exchanger.

It is also clear that choosing a better value of any objective function in a Pareto front would cause a worse value for another objective. The values of objective functions related to the Pareto optimum points are illustrated in "Table 3".

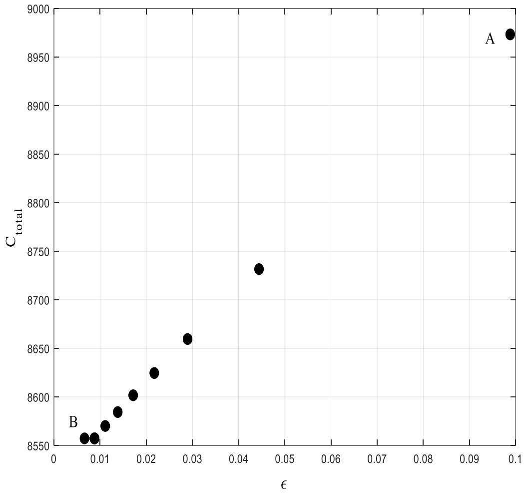

Fig. 12 The Pareto front of the optimum points.

Table 3 The value of weighting coefficients, total objective functions, efficiency and total cost of the optimum points shown in "Fig. 12"

	$\mathrm{w_1}$	$\mathrm{w_2}$	Total objective function	$\in$	$\mathrm{C_{total}}$
1	0	1	8557.2618	0.0066279	8557.3
2	0.1	0.9	7712.9232	0.0087815	8557.3
3	0.2	0.8	6868.5847	0.0087815	8557.3
4	0.3	0.7	6024.2461	0.0087815	8557.3
5	0.4	0.6	5178.0168	0.011117	8570.1
6	0.5	0.5	4328.3894	0.013817	8584.4
7	0.6	0.4	3475.6279	0.017166	8601.7
8	0.7	0.3	2619.5815	0.021733	8624.6
9	0.8	0.2	1759.5508	0.028949	8659.6
10	0.9	0.1	893.4214	0.044423	8731.6
11	1	0	101.1900	0.098824	8973.3

8 CONCLUSIONS

The thermal modeling and optimum design of shell and tube heat exchangers were presented in this paper. A multi- objective imperialist competitive algorithm was applied to obtain the maximum efficiency and maximum total cost. The effects of the design variables on the objective functions were analyzed. The results of the optimum design as the Pareto optimum solution were presented.

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