Int. J. Advanced Design and Manufacturing Technology, 2023, Vol. 16, No. 1, pp. 89-97

DOI: 10.30495/admt.2022.1949157.1332 ISSN: 2252-0406 https://admt.isfahan.iau.ir

Multi-Objective Optimization of Plate Heat Exchangers by Employing an Imperialist Competitive Algorithm

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Received: 6 January 2022, Revised: 20 April 2022, Accepted: 23 April 2022

Abstract: In this paper, the multi-objective optimum design of plate fin heat exchangers is investigated. To this end, the efficiency and cost as two important factors for the design of heat exchangers are regarded as the objective functions. Fin pitch, fin height, fin offset length, cold stream flow length, no-flow length and hot stream flow length are considered as six design parameters. The ε-NTU method is applied to estimate the heat exchanger pressure drop and its effectiveness. A case study related to a gas furnace in Barez tire group located in the northwest of Kerman, Iran is considered for the constant parameters. The Imperialist Competitive Algorithm (ICA) is used to find the optimal design parameters to achieve the maximum thermal efficiency and minimum consumption cost. The method of the weighting coefficients is applied to change the considered multi-objective optimization problem as a single objective one. Furthermore, the effects of variations of the design parameters on the objective functions are independently investigated, and the related graphs are presented.

Keywords: Consumption Cost, Imperialist Competitive Algorithm, Multi-Objective Optimization, Plate Fin Heat Exchanger, Thermal Efficiency

Biographical notes: Mohammad Javad Mahmoodabadi received his BS and MS degrees in Mechanical Engineering from Shahid Bahonar University of Kerman, Iran in 2005 and 2007, respectively. He received his Ph.D. degree in Mechanical Engineering from the University of Guilan, Rasht, Iran in 2012. During his research, he was a scholar visitor with Robotics and Mechatronics Group, University of Twente, Enchede, Netherlands for 6 months. Now, he is an Associate Professor of Mechanical Engineering at the Sirjan University of Technology, Sirjan, Iran. His research interests include optimization algorithms, nonlinear and robust control, robotics and computational methods. **Soodeh Zarnegar** received her BSc in mechanical engineering from the Sirjan University of Technology, Sirjan, Iran in 2015. Her current research focuses on optimization algorithms, and heat exchangers design.

Research paper

1 INTRODUCTION

Compact heat exchangers are characterized by a large heat transfer surface area per unit volume of the system. A plate fin heat exchanger (PFHE) as a typical compact heat exchanger is widely used in many industries such as cooling process coupled with ortho-para hydrogen conversion [1], superfluid helium cryogenic systems [2], evaporation heat transfer plants [3], cryogenic mechanisms [4], superfluid helium system [5], supercritical carbon dioxide Brayton cycle [6], thermally-induced flow maldistribution mechanisms [7], two-phase flow boiling in offset strip fin channels [8], heat transfer and friction factors correlations for offset strip fin and wavy fin [9], and transient three-dimensional thermo-fluid cryogenic plant [10].

In fact, fins or extended surfaces as the plate elements are implemented to increase the heat transfer area [11]. Moreover, offset strip fins with high compactness, high heat transfer efficiency and high reliability are widely employed in heat exchangers for cooling systems of aircrafts, automobiles etc. [12]. Offset strip fins have higher heat transfer performance than plain fins, whereas, those have higher strength and reliability than louver fins [13]. On the other hands, meta-heuristic algorithms have effectively been exploited for optimum design of complicated nonlinear problems. Moreover, most of real-world problems involve more than one objective function to be optimized simultaneously. In this way, a summation of all objective functions could be regarded to form a single-objective optimization problem. Especially, for a heat exchanger design problem, the system efficiency should be increased, while minimum values of the total cost would be utilized. To name but a few, the following research works clearly illustrate the feasibility of the meta-heuristic algorithms to solve heat exchanger design problems: optimal design of heat exchanger network considering the fouling throughout the operating cycle by Hang et al. in 2022 [14], multi-objective optimum design for double baffle heat exchangers by Abolpour et al. in 2021 [15], optimal shape design and performance investigation of helically coiled tube heat exchangers by Wang et al. in 2021 [16], optimal design of variable-path heat exchangers for energy efficiency improvement of air-source heat pump systems by Sim et al. in 2021 [17], a fast reduced model for a shell-and-tube based latent heat thermal energy storage heat exchangers and its application for cost optimal design by nonlinear programming by Pan et al. in 2021 [18], optimum design of heat exchanging device for efficient heat absorption using high porosity metal foams by Prakash et al. [19], an optimal design for hollow fiber heat exchangers by Bohacek et al. [20], design of optimal heat exchanger networks with fluctuation probability using break-even analysis by Hafizan et al. [21], optimal design parameter selection for performance of alumina nano-material particles and turbulence promotors in heat exchangers by Kumar et al. [22], optimization of propane pre-cooling cycle by optimal Fin design of heat exchangers by Allahyarzadeh-Bidgoli et al. [23].

In this paper after thermal modeling of a PFHE, this equipment is optimized as maximizing the effectiveness as well as minimizing the total annual cost. The imperialist competitive algorithm is applied to provide a set of Pareto multiple optimum solutions. The sensitivity analysis for variations of the design parameters on the effectiveness and total annual cost is performed and the results are reported.

The structure of the paper is organized as follows. Section 2 represents the mathematical modelling of the thermal behavior of the plate heat exchangers. The objective functions, design variables and constraints are illustrated in Section 3. The considered case study is described in Section 4. The imperialist competitive algorithm and multi-objective optimization method are described in Section 5. Results and analysis are illustrated in Section 6. Finally, Section 7 concludes the paper.

2 THERMAL MODELING

In this paper, the $\varepsilon - \mathrm{NTU}$ scheme is employed for modelling the dynamics of the heat exchanger. The effectiveness of a cross-flow heat exchanger having unmixed fluids is computed by the following Equation [24]:

$$\varepsilon = 1 - \exp[-(1 + C^*)\mathrm{NTU}] \times [I_0(2\mathrm{NTU}\sqrt{C^*}) + \sqrt{C^*} I_1(2\mathrm{NTU}\sqrt{C^*} - \frac{1-C^*}{C^*}\sum_{n=2}^{\infty} C^{*\frac{n}{2}} I_n(2\mathrm{NTU}\sqrt{C^*})] \quad (1)$$

Where, I is the modified Bessel function. The Number of Transfer Units (NTU) and heat capacity ratio C^* are calculated by the following relations [11]:

$$\mathrm{NTU} = \frac{UA_{tot}}{C_{min}} \quad (2)$$

$$C^* = C_{min}/C_{max} \quad (3)$$

Where, U denotes the overall heat transfer coefficient, and A_{tot} states the total heat transfer surface area that can be calculated by the fallowing Equations:

$$U = \frac{1}{\frac{1}{h_c \eta_{s,c}} + \frac{1}{\frac{A_{tot,h}}{A_{tot,c}}}(h_h \eta_{s,h})} \quad (4)$$

$$A_{tot} = (\beta V_p)_c + (\beta V_p)_h \quad (5)$$

Where, h represents the convection heat transfer coefficient. Moreover, β shows the heat transfer surface area per unit volume and can be found by the following relations [25]:

$$\beta = \frac{A_{cell}}{V_{cell}} = \frac{2(b-t_f)x+2(c-t_f)x+2(b-t_f)t_f+ct_f}{bcx} \quad (6)$$

Where, b, t_f, x and c denote the height, thickness, pitch and length of the fin, respectively. Further, $V_{p,h}$ and $V_{p,c}$ respectively illustrate the volume between plates for hot and cold stream sides of the heat exchanger:

$$V_{p,c} = L_c L_h b_c (N_p + 1) \quad (7)$$

$$V_{p,h} = L_c L_h b_h N_P \quad (8)$$

IF $N_p$is regarded as the number of the passages for the hot side, while N_p+ 1 passages are considered for the cold side, then:

$$N_p = \frac{L_n - b_c + 2t_w}{b_h + b_c + 2t_w} \quad (9)$$

Where, t_w demonstrates the plate thickness. Moreover, L_c, L_h and $L_n$mention the cold stream flow length, hot stream flow length and no-flow length, respectively. Besides, $\eta_s$in "Eq. (4)" as overall surface efficiency could be calculated as follows [11]:

$$\eta_s = 1 - \frac{A_f}{A_{cell}}(1-\eta_f) \quad (10)$$

Where, A_f defines the fin heat transfer area (for a single fin without base area) formulated as follows [25]:

$$A_f = 2(b - t_f)x + 2(b - 2t_f)t_f + ct_f \quad (11)$$

$$\eta_f = \tanh(ml)/(ml) \quad (12)$$

Where,

$$m = \sqrt{\frac{2h}{k_f t_f}} \quad (13)$$

and:

$$l = \frac{b}{2} \quad (14)$$

Where, k_f shows the heat conductivity of the material. The above Equations are valid for $120 < Re < 10^4$. For ratios, the fallowing relations are defined.

$$\alpha = \frac{c}{b} \qquad \delta = \frac{t_f}{x} \qquad \gamma = \frac{t_f}{c} \quad (15)$$

The specifications of the considered system are according to a PFHE of a gas furnace in Barez tire factory located in the northwest of Kerman city, Iran

3 OBJECTIVE FUNCTIONS, DESIGN VARIABLES AND CONSTRAINTS

In this study, the efficiency and total annual cost of the PFHE system are considered as two objective functions. The total annual cost includes the investment cost (annualized cost of the heat transfer surface area) and the operating cost of the compressor to flow the fluid as calculated by the following Equations [26]:

$$C_{total} = aC_{inv} + C_{ope} \quad (16)$$

$$C_{inv} = C_A A_{tot}^n \quad (17)$$

$$C_{ope} = \left(k_{el}\tau\frac{\Delta p V_t}{\eta}\right)_c + \left(k_{el}\tau\frac{\Delta p V_t}{\eta}\right)_h \quad (18)$$

Where, C_A and k_{el} present the heat exchanger investment cost per unit surface area and the electricity unit cost, respectively. Moreover, n is a constant, and τ denotes the operation hours of the exchanger per year. Further, Δp, V_t and η represent the pressure drop, volume flow rate and compressor efficiency, respectively. Finally, a denotes the annual cost coefficient defined as follows [11]:

$$a = \frac{r}{1-(1+r)^{-y}} \quad (19)$$

Where, r and y demonstrate the interest rate and depreciation time, respectively. In this study, fin pitch (c), fin height (b), fin offset length (x), cold stream flow length (L_c), no-flow length (L_n) and hot stream flow length (L_c) are regarded as the design variables. The following constraints are imposed to insure that parameters α, δ and γ are selected from the acceptable ranges $0.134 < \alpha < 0.997$, $0.012 < \delta < 0.048$ and $0.041 < \gamma < 0.121$ with respect to the physical configurations related the case study.

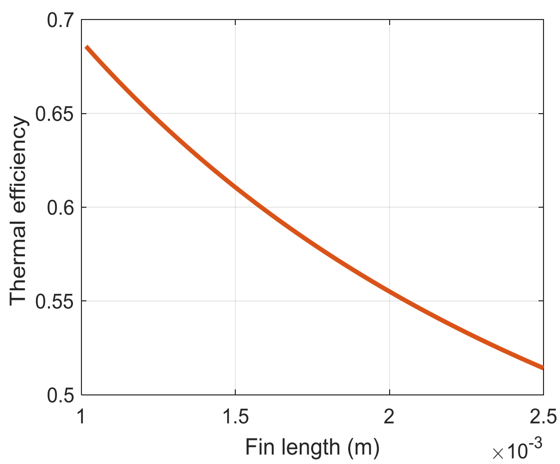
4 CASE STUDY

The design parameters of a plate fin heat exchanger would be optimized for a case related to a gas furnace in Barez tire factory located in Kerman, Iran. The temperature of the furnace is about 500 K at first and around 1500 K at end. The hot gases go out from the middle stage with 1.45 kg/s flow rate of the mass and temperature 700 K. The environmental air moves with 1.35 kg/s flow rate of the mass and 300 K temperature.

The PFHE is made from Aluminum having thermal conductivity k_w= 239 W/m K. Numerical values of other operating conditions are given in “Table 1”. The thermophysical properties of air such as Prandtl number, viscosity and specific heat are regarded as temperature dependent. The effects of the design parameters on the efficiency and normal total cost (objective functions) are plotted in “Figs. 1 to 6”.

Table 1 Thermophysical and process data of the considered PFHE (input data for modeling)

Symbol	Operating conditions	measured value
$\dot{m}_{fc}$	Flow rate of hot fluid (kg/s)	1.45
$\dot{m}_{fh}$	Flow rate of cold fluid (kg/s)	1.35
T_h	Hot gas temperature (K)	700
T_c	Cold gas temperature (K)	300
C_A	Price per unit area ($/m2)	90
P_c	Cold pressure (kPa)	150
P_h	I tot pressure (kPa)	200
k_{el}	Electrical energy pṅce ($ MWh_1)	20
η	Efficiency of the compressor	0.6
τ	Operation hours per year (h/year)	5000



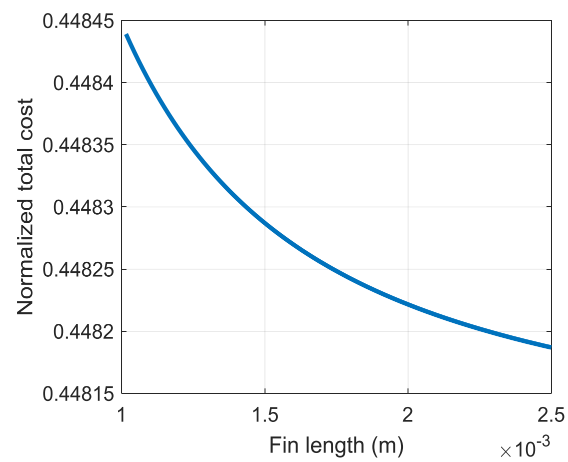


Fig. 1 Effects of the fin length (c) on the thermal efficiency (ϵ) and normalized total cost (C^N_{total}).

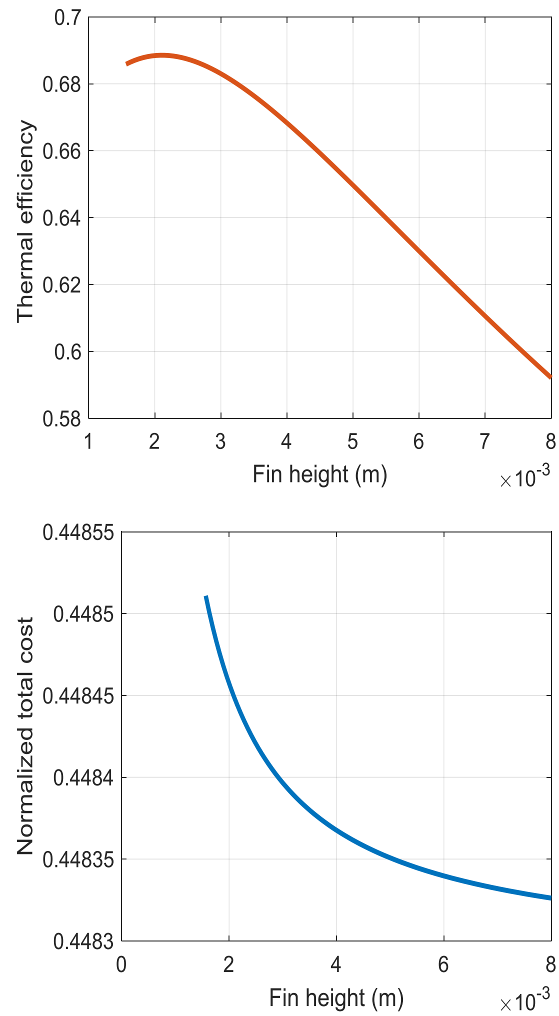


Fig. 2 Effect of the fin height (b) on the thermal efficiency (ϵ) and normalized total cost (C^N_{total}).

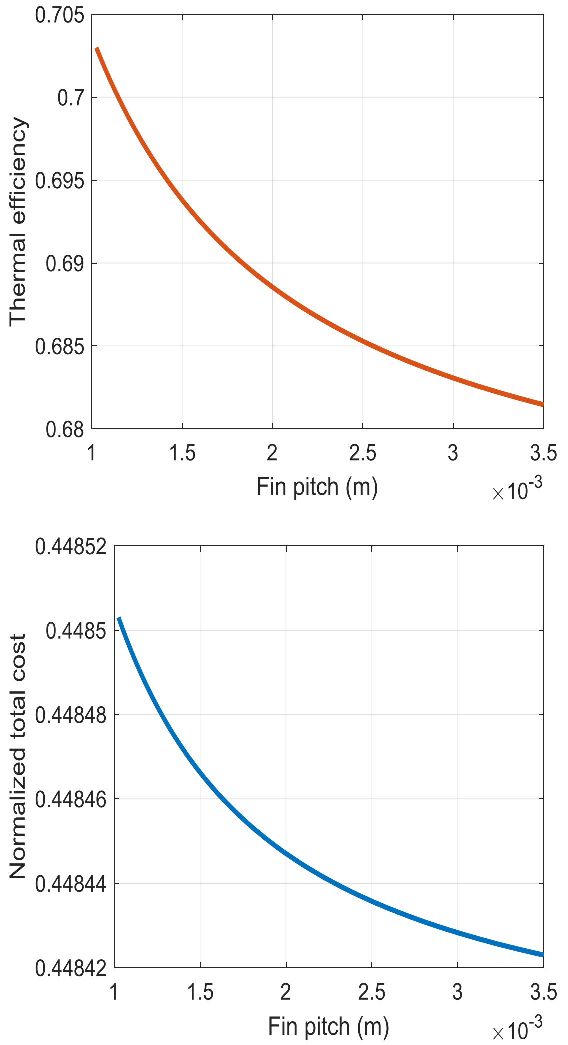
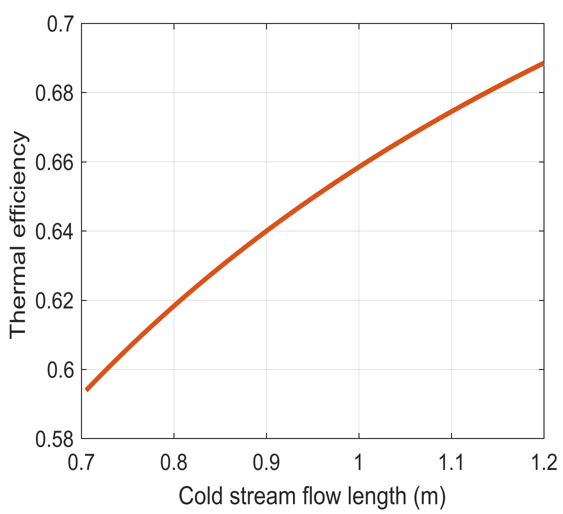


Fig. 3 Effect of the fin pitch (x) on the thermal efficiency ($\boldsymbol{\epsilon}$) and normalized total cost ($\mathbf{C}_{\mathbf{total}}^{N}$).



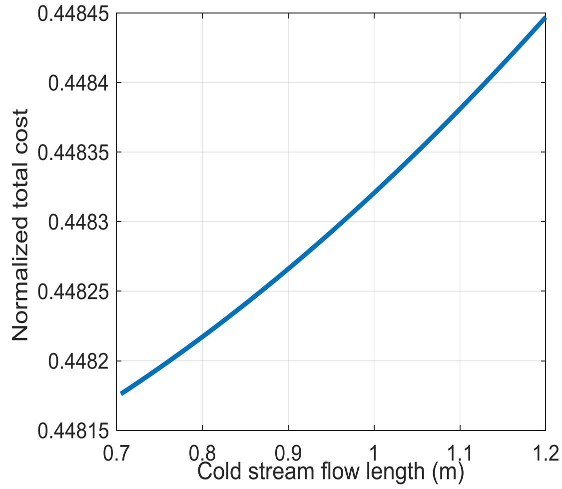


Fig. 4 Effect of the cold stream flow length ($\mathbf{L_c}$) on the thermal efficiency ($\boldsymbol{\epsilon}$).

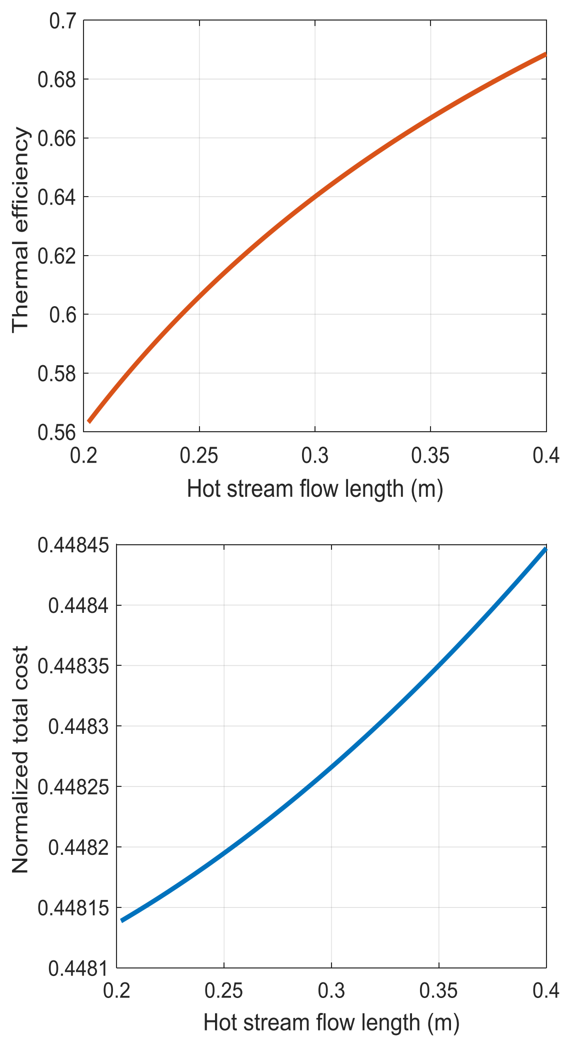


Fig. 5 Effect of the hot stream flow length ($\mathbf{L_h}$) on the thermal efficiency ($\boldsymbol{\epsilon}$).

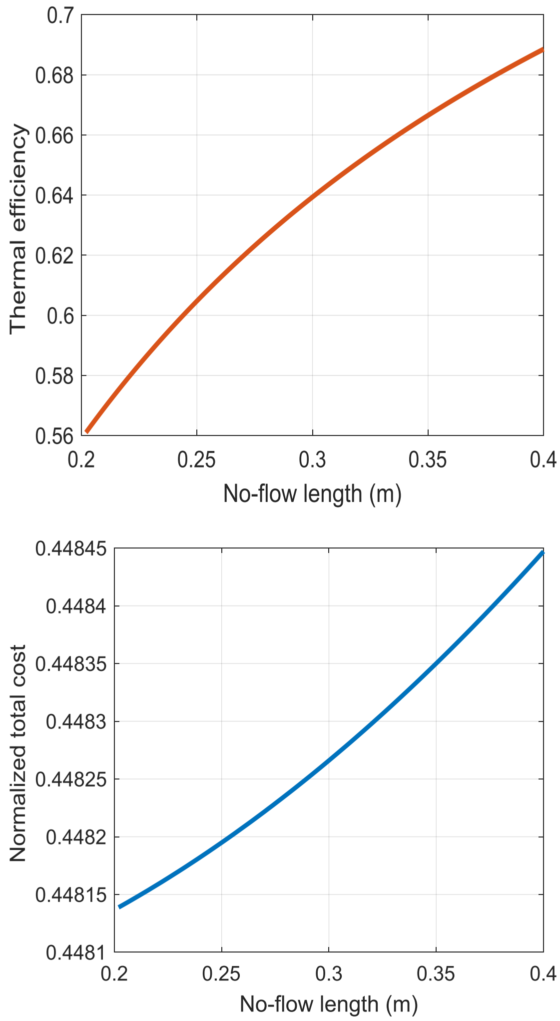


Fig. 6 Effect of the No-flow length (L_n) on the thermal efficiency (ϵ).

5 IMPERIALIST COMPETITIVE ALGORITHMS

The Imperialist Competitive Algorithm (ICA) [27-28], as a successful meta-heuristic algorithm has been widely utilized to solve different types of optimization problems in various areas of engineering and sciences such as environmental constrained energy management of microgrids [29], energy and operational management of virtual power plants [30], environmental emissions for walnut production [31], combined heat and power economic dispatch problems [32]. Like other optimization algorithms, the ICA does not need the gradient of the objective function in its operation process. The block diagram of the ICA as a mathematical model and a computer simulation of human social evolution is depicted in "Fig. 7". This algorithm starts from a set of candidate random solutions, called initial countries, in the feasible search space of the optimization problem. The cost function of the optimization problem determines the power of each country, and the best countries (the countries having the least cost function) are regarded as the imperialists that control other countries (called colonies) [27].

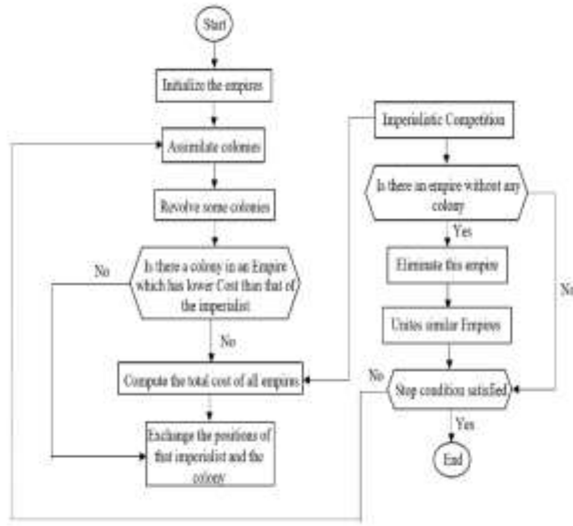


Fig. 7 Flowchart of the imperialist competitive algorithm.

Two main operators of the imperialist competitive algorithm are assimilation and revolution. The assimilation operator makes classification for the colonies in the space of socio-political characteristics. The revolution operator makes sudden random variations in the position of the selected countries in the search space. During the assimilation and revolution operations, a colony might reach a better position and has the chance to control the entire empire and replace the current imperialist of the empire [28]. Besides, in this algorithm, all the empires try to win this game and take the colonies of other empires.

Finally, in competition step, any empire has the chance to control the colonies of the weakest empire based on its power [27]. The algorithm continues via the mentioned steps (assimilation, revolution, competition) until the pre-defined stop criterion is satisfied.

In this paper, the method of the weighting coefficients is applied to solve the considered multi-objective optimization problem via the introduced single objective ICA [33]. In other words, the two objective functions are combined with each other by using weighting coefficients and to make a single cost function. The weighting coefficient of an objective function is related to its importance and the more important objective function has a greater weighting coefficient. Hence, this multi-objective optimization problem is converted into a single objective problem as follows:

$$F(x)= \sum_{i=1}^{k} w_i F_i\,(x) \quad (20)$$

$$\sum_{i=1}^{k} w_i = 1 \tag{21}$$

Where, k is the number of objective functions, w_i denotes the i-th weighting coefficient, $F_i(x)$ demonstrates the i-th objective function, and $F(x)$ represents the total objective function. In fact, $F_1(x)$ represents the thermal efficiency, whereas $F_2(x)$ signifies the normal value of the total cost. By changing the weighting coefficients, total objective function $F(x)$ would be varied and a new point in the Pareto front would be obtained.

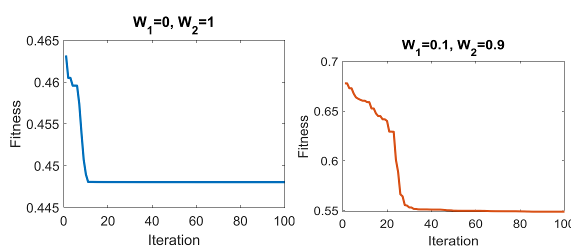
6 MULTI-OBJECTIVE OPTIMIZATION OF THE PLATE FIN HEAT EXCHANGER

In this section, the proposed multi-objective imperialist competitive algorithm is utilized to optimize the PFHE system modeled in the Sections 2 to 4. The numerical values of the objective function, weighting summation of the efficiency and total cost, obtained via the optimization process are depicted in "Table 2" for different values of the weighting coefficients.

Table 2 Objective functions for different values of the weighting coefficients achieved by the ICA

w_1	w_2	F
0	1	0.44803
0.1	0.9	0.54884
0.2	0.8	0.64922
0.3	0.7	0.74961
0.4	0.6	0.8500
0.5	0.5	0.95039
0.6	0.4	1.0508
0.7	0.3	1.1512
0.8	0.2	1.2516
0.9	0.1	1.3519
1	0	1.4523

The evolutionary trajectories for the optimum design of the PFHE and for various values of the weighting coefficients found by applying the imperialist competitive algorithm are illustrated in "Fig. 8".



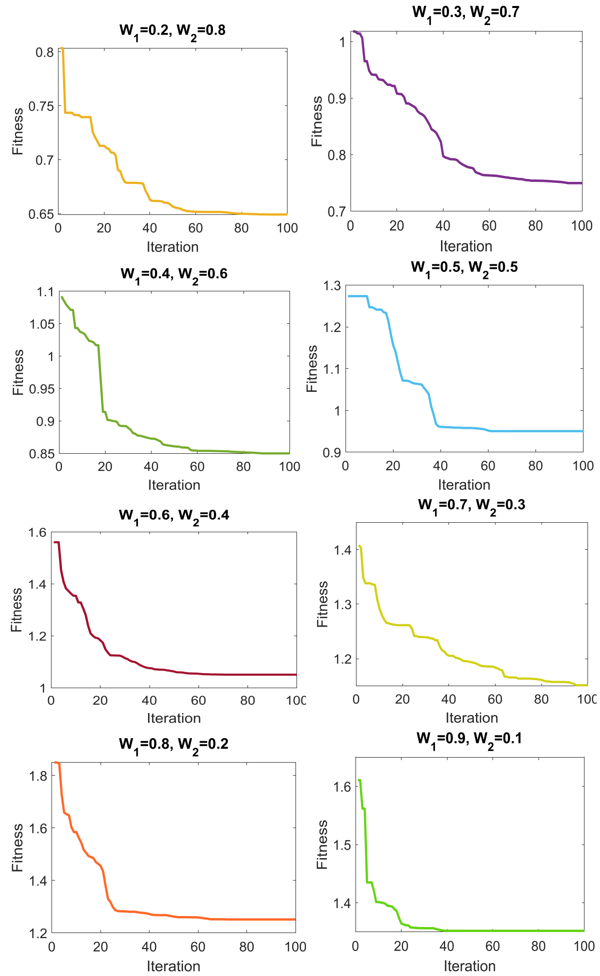


Fig. 8 Evolutionary trajectories for PFHE design for various values of the weighting coefficients found by applying the imperialist competitive algorithm

Moreover, the related Pareto front is illustrated in "Fig. 9", and the found optimum design variables (optimum point B) are represented in "Table 3".

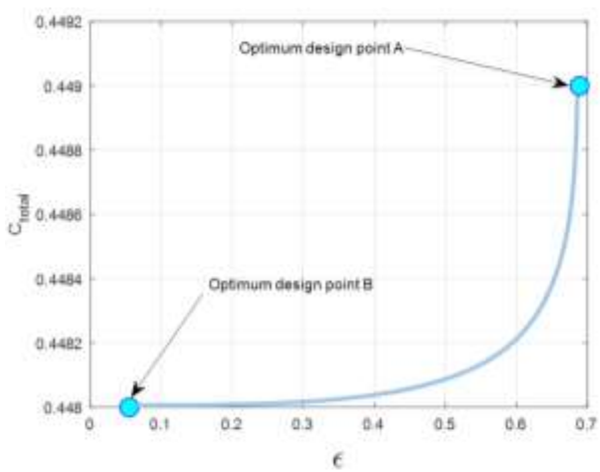


Fig. 9 Optimum Pareto front for design of the PFHE by using the empiricist competitive algorithm.

Table 3 Design parameters (decision variables) related to the optimum solution found by the ICA

Variables	Optimum value
Pitch of the fin (mm)	1.00
Height of the fin (mm)	2.116
Length of the fin (mm)	1.85
Length of the hot gas flow (m)	0.4
Length of the cold gas flow (m)	1.2
No-flow length (m)	0.4

In “Fig. 9”, points A and B stand for the best efficiency and the total cost, respectively. It is clear from this chart that all optimum points could be selected by the designer to represent optimum plate heat exchangers. In fact, choosing a better value for any objective function in the Pareto front would cause a worst value for another one. In other words, the found design variables related to the non-dominated solutions are the best possible design points. This figure illustrates that if any other vector of the design variables is selected, the related point to the objective functions would be located in the top/left side of “Fig. 9”. Such important design facts could not be reached without applying a multi-objective optimization process.

7 CONCLUSIONS

Appendix or nomenclature, if needed, appears before the acknowledgements. This research has investigated the Pareto optimal design of the plate heat exchangers by using the imperialist competitive algorithm. The $\varepsilon - NTU$ method has been applied for mathematically modelling the considered plate heat exchanger. The constant parameters of the model have been selected from a case study existing in Barez tire group, Kerman, Iran. The nonlinear effects of the design parameters on the efficiency and total cost have been investigated. The weighting coefficient method has been implemented to transfer the multi-objective optimization problem to a single objective one. The numerical values of the obtained results have been reported, and the related Pareto front has been displayed to provide several different choices as the non-dominated solutions for designers.

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