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An imperialist competitive algorithm for optimal design of plate-fin heat exchangers

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ABSTRACT

This paper presents the application of imperialist competitive algorithm (ICA) for optimization of a cross-flow plate fin heat exchanger. Minimization of total weight and total annual cost are considered as objectives. Seven design parameters, namely, heat exchanger length at hot and cold sides, fin height, fin frequency, fin thickness, fin-strip length and number of hot side layers are selected as optimization variables. A case study from literature is presented to show the effectiveness of the proposed algorithm. The numerical results reveal that ICA can find optimum configuration with higher accuracy in less computational time when compared to conventional genetic algorithm (GA).

1. Introduction

Compact heat exchangers (CHEs) are widely used in industrial applications because of their high compactness and relatively good heat transfer efficiency that help saving material and space for a specified heat duty. Between two important types of CHEs namely plate fin heat exchangers (PFHEs) and fin-and-tube type, the former is widely used in different aspects of industry such as automobile, chemical and petrochemical processes, cryogenic and aerospace.

Generally, heat exchanger design is based on trial-and-error process in which geometrical and operational parameters are selected in order of satisfying specified requirements and leading to an optimum solution simultaneously. Since there is always the possibility that the selected design parameters do not ensure the optimum solution, different works have been devoted to propose optimization methods for heat exchangers.

In addition to the traditional optimization methods [1–5] and artificial neural network [6], application of evolutionary algorithms has gained much attention in design of heat exchangers recently. In the early attempts, GA was successfully applied for optimization of shell-and-tube heat exchanger [7,8] as well as obtaining heat transfer correlations for CHEs [9,10].

In case of plate fin heat exchangers, single-objective GAs have been applied for optimizing plate fin heat exchangers [11–16] aiming at minimization of a variety of objectives such as total annual cost, the ratio of number of heat transfer units (*NTU*) to the cold side pressure drop, total volume, total weight and the number of entropy generation units.

Moreover, some works aimed at multi-objective optimization [17–19] using genetic algorithm. A set of conflicting objectives such as "minimum pressure drop and maximum overall heat transfer" or "the maximum effectiveness and the minimum total annual cost" was considered as the objective function. Multi-objective optimization procedure results in Pareto front solutions, i.e. a set of optimal solutions, in which every one of them is a trade-off between objectives and can be selected by the user regarding the application.

Among other evolutionary algorithms, Particle Swarm Optimization (PSO) and GA hybrid with PSO are the only ones which have been applied successfully for the optimization of PFHEs. Peng et al. [20] used a Particle Swarm Optimization (PSO) to optimize a PFHE considering minimization of total annual cost and total weight under given constrained conditions. Comparing their result to the GA, they demonstrated that PSO presents shorter computational time and better results for their case. Also, Rao and Patel [21] employed a PSO to optimize a cross-flow plate fin heat exchanger with the aim of minimizing the entropy generation units, total volume and total annual cost respectively. Their results also demonstrate the better performance of PSO over traditional GA.

Because the social and intellectual evolution of human being takes place significantly faster than their Genetic and physical evolution, some evolutionary algorithms have implemented the cultural aspect of human life to achieve better results. Atashpaz-Gargari and Lucas [22] proposed imperialist competitive

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Nomenclature

A, A_{HT}	heat exchanger surface area (m^2)
A_f	annual coefficient factor
A_{ff}	free flow area (m^2)
C	heat capacity rate (W/K)
C_A	cost per unit area ($\$/m^2$)
C_{in}	initial cost ($/year)
C_{op}	operating cost ($/year)
Cr	$C_{min}/C_{\max}$
C_{in}	initial cost ($)
C_{op}	operating cost ($)
D_h	hydraulic diameter (m)
f	friction factor
$f(x)$	objective function
$g(x)$	constraint function
G	mass flow velocity (kg/m^2 s)
h	convective heat transfer coefficient (W/m^2 K)
H	height of fin (m)
j	Colburn factor
k_{el}	electricity price ($/MWh)
l	lance length of the fin (m)
L	heat exchanger length (m)
m	mass flow rate (kg/s)
n	fin frequency (fins per meter)
n_1	exponent of non-linear increase with area increase
N_a, N_b	number of fin layers for fluid *a* and *b*
N_{col}	number of colonies in ICA
N_{imp}	number of imperialists in ICA
NTU	number of transfer units
P	pressure (N/m^2)
pc	crossover probability
pm	mutation probability
Pr	Prandtl number
Q	rate of heat transfer (W)
r	interest rate
Re	Reynolds number
$R1$	penalty parameter
t	fin thickness (m)
T	temperature $^\circ C$
TAC	total annual cost ($/year)
U	overall heat transfer coefficient
y	depreciation time

Greek symbols

ε	effectiveness
η	efficiency of the pump or fan
μ	viscosity (kg/(s m))
ρ	density (kg/m^3)
τ	hours of operation
$\phi()$	penalty function
ΔP	Pressure drop (N/m^2)

Subscripts

a, b	fluid a and b
i, j	variable number
max	maximum
min	minimum

algorithm (ICA) which is an evolutionary algorithm based on human's socio-political evolution. This evolutionary optimization algorithm has been successfully utilized in many engineering applications such as control [23], data clustering [24], industrial engineering [25] in recent years and has shown great performance in both convergence rate and achieving global optima. However, to the best knowledge of the authors, ICA has not been well-established in solving thermal engineering problems. Therefore, the primary concern of this study is to check the computational feasibility of the ICA to optimize a PFHE within given restrictions. The optimization aims at minimizing weight and total annual cost respectively. The rest of the paper is organized as follows. Section 2 sheds light on thermal modelling of PFHE. Section 3 presents imperialist competitive algorithm. Objective functions and results are presented in Sections 4 and 5 respectively. Finally, the conclusion is drawn in Section 6.

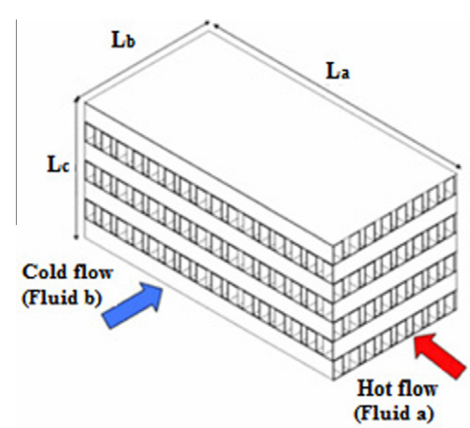

Fig. 1. Schematic representation of cross-flow plate-fin heat exchanger [18].

2. Thermal modelling

A schematic of a typical cross-flow plate fin heat exchanger with offset strip fin can be seen in Figs. 1 and 2. In the analysis, for the sake of simplicity, the variation of physical property of fluids with temperature is neglected and both fluids are considered to be ideal gases. Other assumptions are as follows.

1. Number of fin layers for the cold side (N_b) is assumed to be one more than the hot side (N_a). It is a conventional way in design of heat exchangers in order to reduce heat waste to the ambient.
2. Heat exchanger works under steady state condition.
3. Heat transfer coefficient and the area distribution are assumed to be uniform and constant.
4. The thermal resistance of walls is neglected.

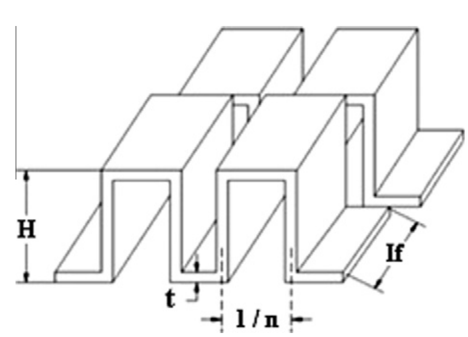

Fig. 2. detailed view of offset-strip fin [18].

5. Fouling is negligibly small for a gas-to-gas heat exchanger. Hence, it is neglected.

In the present work, because the outlet temperature of the fluids is not specified, the $\varepsilon - NTU$ method is employed for rating performance of the heat exchanger in the optimization process. The effectiveness of cross-flow heat exchanger, for both fluids unmixed, is proposed as [26].

$$\varepsilon = 1 - exp\left[\left(\frac{1}{Cr}\right)NTU^{0.22}\{exp[-Cr \cdot NTU^{0.78}] - 1\}\right], \tag{1}$$

where $Cr = C_{min}/C_{\max}$. Neglecting the thermal resistance of the walls and fouling factors, NTU is calculated as follows.

$$\frac{1}{UA} = \frac{1}{(hA)_a} + \frac{1}{(hA)_b}, \tag{2}$$

$$NTU = \frac{UA}{C_{min}}. \tag{3}$$

Heat transfer coefficient is calculated from j Cobourn factor.

$$h = j \cdot G \cdot Cp \cdot Pr^{-\frac{2}{3}} \tag{4}$$

In this formula, $G = \frac{m}{A_{ff}}$, where A_{ff} is free flow cross-sectional area which is calculated considering the geometrical details in Fig. 1.

$$A_{ffa} = (H_a - t_a)(1 - n_a t_a)L_b N_a, \tag{5}$$

$$A_{ffb} = (H_b - t_b)(1 - n_b t_b)L_a N_b. \tag{6}$$

Heat transfer area for both sides can be calculated similarly.

$$A_a = L_a L_b N_a[1 + 2n_a(H_a - t_a)], \tag{7}$$

$$A_b = L_a L_b N_a[1 + 2n_b(H_b - t_b)]. \tag{8}$$

Then, total heat transfer area is given by:

$$A_{HT} = A_a + A_b. \tag{9}$$

Heat transfer rate is calculated as follows.

$$Q = \varepsilon C_{min}(T_{a,1} - T_{b,1}). \tag{10}$$

Frictional pressure drop in both sides is given by:

$$\Delta P_a = \frac{2f_a L_a G_a^2}{\rho_a D_{h,a}}, \tag{11}$$

$$\Delta P_b = \frac{2f_b L_b G_b^2}{\rho_b D_{h,b}}. \tag{12}$$

There are many correlations for evaluation of Colbourn factor j and Fanning factor f for offset strip fin. Eqs. (13) and (14) are the correlation presented by Manglik and Bergles [27] which is used in this work.

$$j = 0.6522(Re)^{-0.5403}(\alpha)^{-0.1541}(\delta)^{0.1499}(\gamma)^{-0.0678} \times [1 + 5.269 \times 10^{-5}(Re)^{1.34}(\alpha)^{0.504}(\delta)^{0.456}(\gamma)^{-1.055}]^{0.1}, \tag{13}$$

$$f = 9.6243(Re)^{-0.7422}(\alpha)^{-0.1856}(\delta)^{0.3053}(\gamma)^{-0.2659} \times [1 + 7.669 \times 10^{-8}(Re)^{4.429}(\alpha)^{0.920}(\delta)^{3.767}(\gamma)^{0.236}]^{0.1}, \tag{14}$$

where

$\alpha = \frac{s}{h},\ \delta = \frac{t}{lf},\ \gamma = \frac{t}{s}$ considering $s = (1/n - t)$ and $h = H - t$.

Hydraulic diameter and Reynolds number are defined as below.

$$D_h = \frac{4shl}{2(sl + hl + th) + ts}. \tag{15}$$

The above equations are valid for $120 < Re < 10^4$, $0.134 < \alpha < 0.997$, $0.012 < \delta < 0.048$ and $0.041 < \gamma < 0.121$. These equations correlate j and f factors from experimental data within +20% accuracy in laminar, transition and turbulence flow regimes, therefore, there is no need to describe the flow regime for a specified operating condition and hence very useful in most practical applications.

3. Imperialist competitive algorithm

The proposed algorithm mimics the social–political process of imperialism and imperialistic competition. ICA contains a population of agents or countries. The pseudo-code of the algorithm is as follows.

3.1. Step1: Initial empires creation

Comparable to other evolutionary algorithms, the proposed algorithm starts by an initial population. An array of the problem variables is formed which is called Chromosome in GA and country in this algorithm. In a N_{var}-dimensional optimization problem a country is a $1 * N_{var}$ array which is defined as follows:

$$country = [P_1, P_2, P_3, \ldots, P_{N_{var}}]. \tag{16}$$

A specified number of the most powerful countries, N_{imp}, are chosen as the imperialists and the remaining countries, N_{col}, would be the colonies which are distributed among the imperialists depending on their powers which is calculated using fitness function. The initial empires are demonstrated in Fig. 3 where more powerful empires have greater number of colonies.

3.2. Step 2: Assimilation policy

To increase their powers, imperialists try to develop their colonies through assimilation policy where countries are forced to move towards them. A schematic description of this process is demonstrated in Fig. 4.

The colony is drawn by imperialist in the culture and language axes (analogous to any dimension of problem). After applying this policy, the colony will get closer to the imperialist in the mentioned axes (dimensions). In assimilation, each colony moves with a deviation of θ from the connecting line between the colony and its imperialist by x units to increase the search area, where θ and x are random numbers with uniform distribution and β is a number greater than one and d is the distance between the colony and the imperialist state. $\beta > 1$ causes the colonies to get closer to the imperialist state from both sides.

$$x \sim U(0, \beta * d), \tag{17}$$

$$\theta \sim U(-\gamma, \gamma). \tag{18}$$

3.3. Step 3: Revolution

In each decade (generation) certain numbers of countries go through a sudden change which is called revolution. This process

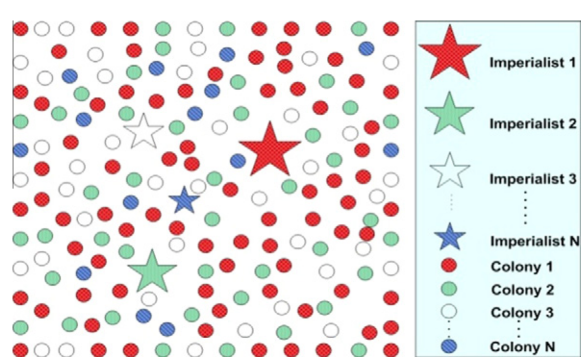

Fig. 3. Generating the initial empires: The more colonies an imperialist possess, the bigger is its relevant ★ mark [22].

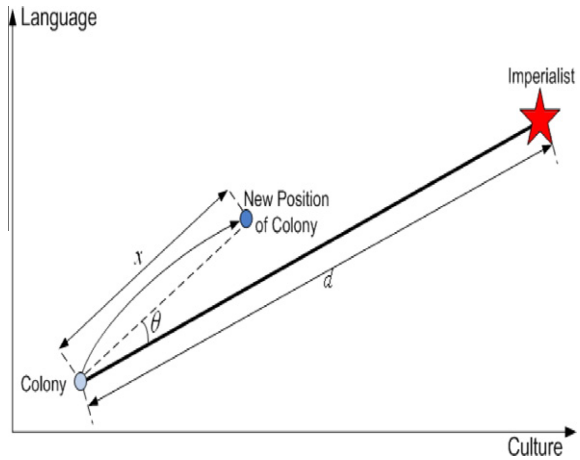

Fig. 4. Movement of colonies toward their relevant imperialist [22].

is similar to mutation process in GA which helps the optimization process escaping local optima traps.

3.4. Step 4: Exchanging the position of imperialist and colony

As the colonies are moving towards the imperialist and revolution happens in some countries, there is a possibility that some of these colonies reach a better position than their respective imperialists. In this case the colony and its relevant imperialist change their positions. The algorithms will be continued using this new country as the imperialist.

3.5. Step 5: Imperialistic competition

The most important process in ICA is imperialistic competition in which all empires try to take over the colonies of other empires. Gradually, weaker empires lose their colonies to the stronger ones. This process is modeled by choosing the weakest colony of the weakest empire and giving it to the appropriate empire which is chosen based on a competition among all empires. Fig. 5. demonstrates a schematic of this process.

In this figure empire 1 is considered as the weakest empire, where one of its colonies is under competition process. The empires 2 to n are competing for taking its possession. In order to begin the competition, firstly, the possession probability calculated considering the total power of the empire which is the sum of imperialist power and an arbitrary percentage of the mean power of its colonies. Having the possession probability of each empire a mechanism similar to Roulette Wheel is used to give the selected colony to one of the empires considering a proportional probability.

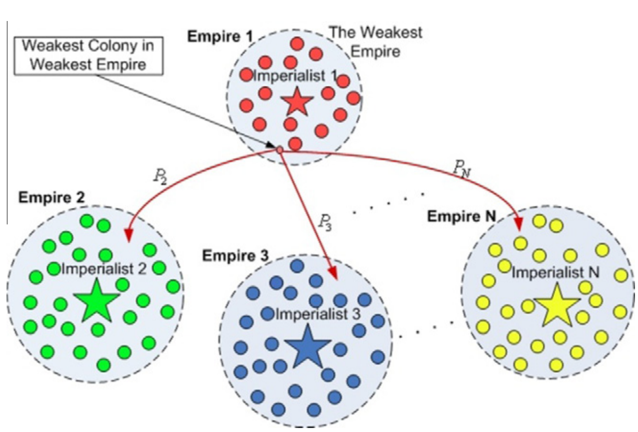

Fig. 5. Imperialistic competition: The more powerful an empire is, the more likely it will possess the weakest colony of the weakest empire [22].

3.6. Step 6: Convergence

Basically the competition can be continued until there would be only one imperialist in the search space, However, different conditions may be selected as termination criteria including reaching a maximum number of iterations or having negligible improvement in objective function. Fig. 6 depicts a schematic view of this algorithm. Whenever the convergence criterion is not satisfied, the algorithm continues.

4. Objective functions and design parameters

In this work, the optimization targets two single-objective functions. The first is the minimum total weight which is mainly associated with the capital cost of the heat exchanger and from economic point of view, minimum total annual cost is considered as the second objective.

For the cost calculation, total annual cost is considered as the sum of investment cost and operating cost. Investment cost is the annualized cost of the heat transfer area while operating cost associates with the electricity cost for the compressors. The same approach for cost estimation was considered by [12,18,21].

$$C_{in} = A_f \cdot C_A \cdot A_{HT}^{n_1}, \tag{19}$$

$$C_{op} = \left[k_{el}\tau\frac{\Delta P \cdot m}{\eta \cdot \rho},\right]_a + \left[k_{el}\tau\frac{\Delta P \cdot m}{\eta \cdot \rho}\right]_b, \tag{20}$$

$$TAC = C_{in} + C_{op}. \tag{21}$$

C_A and n_1 are cost per unit surface area and the exponent of non-linear increase with area increase respectively. k_{el}, τ and η are the electricity price, hours of operation and compressor efficiency respectively. Here A_f is the annual coefficient factor that can be defined as follows.

$$A_f = \frac{r}{1-(1+r)^{-y}}. \tag{22}$$

where r and y represent interest rate and depreciation time respectively. The parameters needed for cost evaluation in this work are presented in Table 1.

In summary, the optimization problem at hand is a large-scale, combinatorial problem which deals with both continuous and discrete variables.

5. Constraint handling

In the present optimization problem, ICA is used for a constrained minimization. The problem can generally b described as follows.

$$\text{Minimise } f(x),\ x = [x_1, \ldots, x_k]. \tag{23}$$

where constraints are stated as

$$g_j(x) \leqslant 0, \quad j = 1, \ldots, m. \tag{24}$$

And

$$x_{i,min} \leqslant x_i \leqslant x_{i,max}, \quad i = 1, \ldots, k. \tag{25}$$

To handle the constraints in the optimization algorithm, penalty function scheme is employed which converts the unconstrained problem to a constrained one by adding an additional value corresponding to the level of constraint violation to the original objective value.

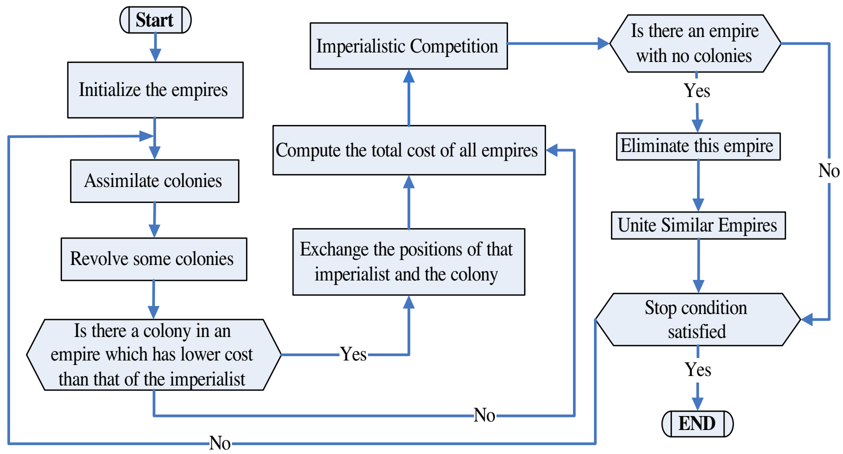

Fig. 6. Flowchart of the imperialist competitive algorithm [22].

Table 1
Cost coefficients of heat exchanger.

Economic parameters	
Cost per unit area, $C_A(\$/\mathrm{m}^2)$	90
Hours of operation, τ (hour)	5000
Electricity price, k_{et}($/MWh)	20
Compressor efficiency, η	60%
Exponent of non-linear increase with area increase, n_1	0.6
Depreciation time, y (year)	10
Inflation rate, r	0.1

Table 2
Operating parameters selected for the case study.

Parameters	Hot side (a)	Cold side (b)
Mass flow rate, m (kg/s)	1.66	2
Inlet temperature, T (°C)	900	200
Specific heat, Cp (J/kg K)	1122	1073
Density, ρ (kg/m^3)	0.6296	0.9638
Dynamic viscosity, μ (kg/s m)	401E−7	336E−7
Prandtl number, Pr	0.731	0.694
Maximum pressure drop, ΔP N/m^2)	9.50	8.00

Table 3
Variation range of design parameters.

Parameter	Minimum	Maximum
Hot flow length (L_a)(m)	0.1	1
Cold flow length (L_b)(m)	0.1	1
Fin height (H) (mm)	2	10
Fin thickness (t) (mm)	0.1	0.2
Fin frequency (n) (m^{-1})	100	1000
Fin offset length (lf)(mm)	1	10
Number of hot side layers (N_a)	1	200

$$Minimise\ f(x) + \sum_{j=1}^{m} \phi(g_j(x)) \tag{26}$$

Subject to Eq. (23).

ϕ is a predefined function. The most common penalty function, which has been widely employed in PFHE design is describes as.

$$\phi(g_j(x)) = R \cdot \upsilon_j(x)^2 \tag{27}$$

where R is a penalty parameter which has a relatively large value comparing to $f(x)$. The difficulty of using this scheme is how to decide the proper amount of R for controlling the severity of the penalty associated with the constraint violation. Excessively large amount of penalties eliminate the infeasible solutions quickly, but decrease search efficiency, also, insufficient penalties usually result in infeasible final solutions. The amount of R should be set by a trial-and-error process. This process should be repeated for any objective since it is problem-dependant.

6. A case study

To clarify the application of the mentioned optimization algorithm, a case study taken from the work of Shah and Sekulić [28] is considered. The same problem was investigated in [22]. A gas-to-air single pass cross-flow heat exchanger having heat duty of 1069.8 kW is needed to be designed for the minimum weight and minimum total annual cost separately. Maximum flow length and no-flow length of the exchanger is 1 m and 1.5 m respectively. Gas and air inlet temperatures are 900 °C and 200 °C where gas and air mass flow rates are 1.66 kg/s and 2.00 kg/s respectively. Pressure drops are set to be limited to 9.50 kPa and 8.00 kPa at hot and cold side. The offset strip fin surface is used on the gas and air sides. The heat exchanger material is Aluminum with density of 2700 kg/m^3. Table 2 presents the Operating conditions used in thermal modelling of PFHE.

In this study, a total number of seven parameters namely, hot flow length (L_a), cold flow length (L_b), number of hot side layers (N_a), fin frequency (n), fin thickness (t), fin height (H) and fin strip length (lf) are considered as optimization variables. All variables with the exception of the number of hot side layers are continuous. Thickness of the plate, t_p is considered to be constant at 0.5 mm and is not to be optimized. The variation ranges of the design variables are shown in Table 3.

Additional inequality constraints are set to guarantee that the no-flow length, pressures drop and α, δ, γ at both sides maintain in their prescribed ranges. Moreover, another constraint is implemented to ensure that a minimum required heat transfer is achieved.

7. Results and discussion

7.1. Minimum weight of PFHE (case study A).

For the prescribed heat duty and allowable pressure drop, the optimization problem is finding the design variables that minimize the weight of the PFHE. ICA algorithm is used to optimize the heat exchanger subject to the mentioned constraints. ICA parameters are selected based on Atashpaz-Gargari and Lucas [22] recommendations. β, γ and revolution rate values are set to 2, $\pi/4$ and 0.1 respectively. Also, the ratio of initial imperialists to the initial countries is set to 1/10. To choose the proper number of countries for the optimization, the algorithm is executed for different number of initial countries and the respected results for the minimum total weight can be seen in Fig. 7. Due to the stochastic nature of the algorithm, each execution of the algorithm results in a different result, therefore in the entire study the best solution out of 10 executions is presented as the optimization result. The variation of the objective function is very high for the number of countries less than 50. Increasing the number of countries up to 100 slightly improves the results. Although more increase in the number of initial countries yields in decrease in the objective function, the changes is not considerable. Therefore, the number of countries for this study is set to 100 for the rest of the paper.

Fig. 8 demonstrates the iteration process of ICA method. A significant decrease in the target function is seen in the beginning of the evolution process (first 10 decades). After certain decades (more than 110) the changes in the fitness function become relatively minute. Finally the optimum weight of the PFHE after 200 decades is found to be 26.69 kg. Table 4 shows the PFHE preliminary design and the configuration found by ICA that yields to minimum weight. A significant decrease (58%) in the PFHE weight can be noticed comparing to the 64.63 kg preliminary design. It can be observed that in the minimum weight design the fin frequency is increased from 782 to 1000 and reached its maximum limit while the fin strip length is decreased from 3.18 mm to 2.1 mm. The pressure drop on both sides, as predicted, is close to their maximum allowable amount, thus the operating cost of the PFHE is increased by 4.2%.

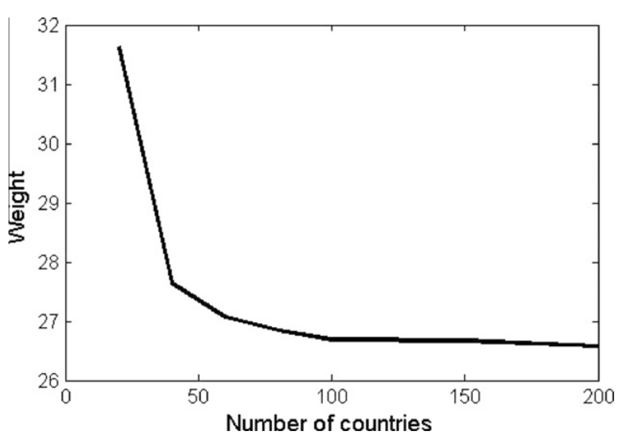

Fig. 7. Effect of variation of the number of countries on the minimum weight.

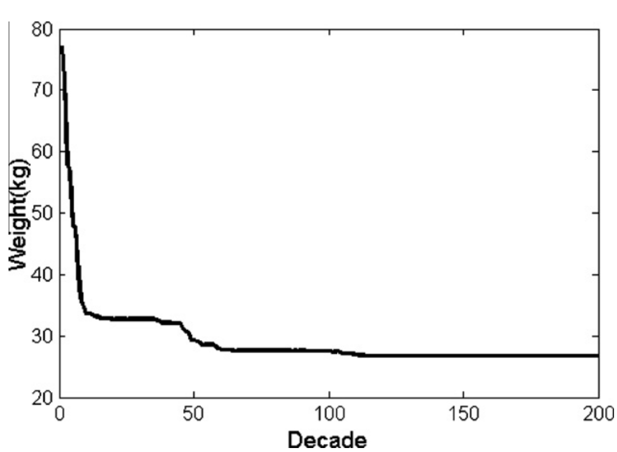

Fig. 8. Convergence of the objective of minimum weight.

Table 4
Comparison of the preliminary design and ICA results for minimum weight.

	Variables	Preliminary design	Optimal design
Design variables	Side a length (L_a) (m)	0.3	0.21
	Side b length (L_b)(m)	0.3	0.23
	Fin height (H) (mm)	2.49	6.8
	Fin thickness (t) (mm)	0.102	0.1
	Fin frequency (n) (m^{-1})	782	1000
	Lance length (lfa) (mm)	3.18	2.1
	Number of hot side layers (Na)	167	80
	ΔP_a at hot side (kPa)	9.34	9.15
	ΔP_b at cold side (kPa)	6.90	7.96
	No-flow length, L_c (m)	1	1.178
Objective	Total weight	64.63	26.69

7.2. Minimum total annual cost of PFHE (Case study B)

For the case study B, the optimization goal is minimum total annual cost of the PFHE. Fig. 9 depicts the variation of the objective function during the iteration process where a similar manner to the case study A is observed. A sharp decrease in the objective function can be noticed in the first 10 decades. The variation of the objective function becomes small when the iteration reaches less than 50 decades. The minimum total annual cost is found to be 942$ after 200 decades. In Table 5 the results of optimization is presented for the object of minimum total annual cost. Also to better understand the effect of investment cost and operating cost on the total annual cost, the result of minimization of these two objectives are presented too. It is observed that the operating cost is the dominant parameter in the total annual cost, because of the price of electricity, therefore the configuration found by ICA for the minimum total annual cost and minimum operating cost are almost the same. In an opposite manner to the objective of minimum weight, fin frequency is decreased while fin strip length is increased to its maximum limit.

Pressure drop is set as low as possible to reduce the price of electricity for compressors needed for the PFHE. Table 5 demonstrates the results of the optimization process.

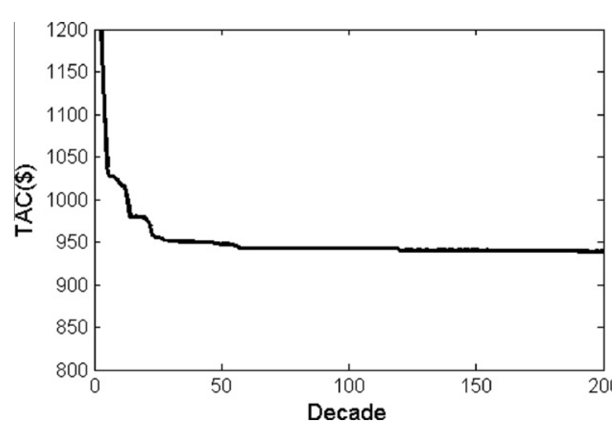

Fig. 9. Convergence of the objective of total annual cost.

Table 5
ICA results for objective of minimum total annual cost.

	Variables	C_{op}	C_{in}	TAC
Design variables	Side a length (L_a) (m)	0.22	1	0.83
	Side b length (L_b)(m)	0.23	1	1
	Fin height (H) (mm)	6.8	10	9.7
	Fin thickness (t) (mm)	0.10	0.19	0.2
	Fin frequency (n) (m^{-1})	997.0	204.2	228.2
	Lance length (lfa) (mm)	2.1	10	10
	Number of hot side layers (Na)	78	71	73
	ΔP_a at hot side (kPa)	9.50	0.29	0.28
	ΔP_b at clod side (kPa)	8.00	0.21	0.31
	No-flow length, L_c (m)	1.15	1.5	1.5
Objective	investment cost	247.9	199.2	228.8
	Operation cost	6941.4	755.6	713.2
	Total annual cost	7189.3	954.8	942

7.3. Constraint handling

The effect of penalty parameter, R, on the optimization results, for case study A has been investigated in Table 6. The penalty parameter for any objective function is set through a trial-and-error process (see Table 6).

In Table 6, any constraint violation or infeasible solution is marked with $*$. It can be observed that selecting light penalties could result in infeasible solutions which violate constrain. However, selecting excessive penalties, 30 in this case could degrade the search diversity and hence results in poor solutions. The results presented in the table are the minimum amount achieved in 10 executions of the algorithm. However, it should be noted that, because the optimization algorithm is naturally random-based, even with a harsh penalty, it is possible to achieve an optimum or near-optimum solution after numerous executions. It means that the succession rate (the number of times optimum solution is achieved in 100 executions) is decreased with an excessive penalty factor. In case study B, the proper amount of penalty function parameter, R, is found to be 100.

7.4. A Comparison between ICA and GA

A brief investigation is carried out to compare the design efficiency of the proposed algorithm with traditional GA. The results are demonstrated in Table 7. To be fair in the comparison, a series of experiments has been conducted to find the best set of GA parameters for the PFHE problem. It is found that, crossover probability and mutation rate of 0.5 and 0.005 respectively, similar to the work of [13], lead to the best performance of GA. Population size and number of generations are set to 100 and 200 respectively, similar to ICA configurations. Both ICA and GA algorithms are programmed in MATLAB® and run on an Intel® Core™ i5 CPU. The mentioned CPU time is the average of 10 executions of the computer code.

It can be seen that in both case studies ICA provides better results both in case of accuracy and computational time. For the case study A with the weight as the objective function, GA yields to 35.79 kg which is 34% higher than the results of ICA. In case study B with the total annual cost as the objective function, GA result is 7.1% higher than ICA 942$ result.

Table 6
The effect of penalty function parameter on the results.

Penalty parameter (R)	1	10	20	25	30
ΔP_a	881*	9.49	555*	9.24	8.94
ΔP_b	347*	252.88*	7.44	7.99	7.97
L_c	0.10	0.3067	0.1989	1.055	0.71
Q	1069	1069	1069	1069	1069
Objective (weight)	11.18*	19.52*	19.70*	26.69	32.34

Table 7
Comparison of results from ICA and GA methods.

	Parameters	ICA	GA
Case study A	Weight (kg)	26.69	35.79
	CPU time (s)	3.29	4.60
Case study B	Total annual cost ($)	942	1009
	CPU time (s)	3.55	4.31

8. Conclusions

This study presents the application of a socia-political based evolutionary algorithm, imperialist competitive algorithm, for optimization of a PFHE. Minimum total weight and minimum total annual cost are considered as two single objective functions. The $\varepsilon - NTU$ method is used for the PFHE thermal calculations. A case study from the literature is selected for examination of the performance and accuracy of this new method. The main findings of this study are as follows.

1- The study shows that in both case studies the result obtained by ICA have shown improvement respect to the preliminary design considering the respected objective functions.
2- ICA algorithm comparing to the traditional GA shows considerable improvements in finding the optimum designs in less computational time under the same population size and iterations.

The design procedure for the PFHEs presented in this study using ICA can be applied for the other types of heat exchanger such as fin-and-tube heat exchangers, shell-and-tube heat exchangers and recuperators as well. Moreover, other types of fins such as plain, perforated, wavy and louvered fins can be applied on both cold and hot sides of the heat exchanger rather than the serrated fins which is applied on the both side in the present work. Therefore, ICA can be applied in design of different types of heat exchangers to search for the optimum designs based in the desired objectives.

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