# The Optimization of Thermal Performance of an Air Cooler Equipped with Butterfly Inserts by the Use of Imperialist Competitive Algorithm

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The aim of this paper is to apply a novel optimization algorithm based on the imperialist competitive algorithm (ICA) to optimize the thermal performance of an air-cooled heat exchanger equipped with butterfly inserts. Experiments included inserts inclined at angles ranging from 45 to 135°. Also, the Reynolds number varied from 4021 to 16118. After data reduction, the regression equation of thermal performance was obtained as a function of the Reynolds number and the inclined angle. Then the cost function was optimized by the use of ICA. One can be sure that the thermal performance will be optimized due to the optimization of the cost function. Computational results indicate that the proposed optimization-algorithm is quite effective and powerful in optimizing the cost function. According to the results, in order to obtain maximum performance, the inclined angle must be about 95°.  Heat Trans Asian Res; Published online in Wiley Online Library (wileyonlinelibrary.com/journal/htj). DOI 10.1002/htj.20412

**Key words:** air-cooled heat exchanger, thermal performance, butterfly insert, optimization, imperialist competitive algorithm (ICA)

## 1. Introduction

It is commonly known that the heat transfer rate of heat exchangers, especially for single-phase flows can be improved through many enhancement techniques. In general, heat transfer enhancement (HTE) techniques can be divided into two categories: (1) active techniques which need an external power source and (2) passive techniques which do not need an external power source. Some examples of passive HTE methods include: insertion of twisted stripes and tapes [1, 2], insertion of coil wire and helical wire coil [3, 4], and mounting of turbulent decaying swirl flow devices [5, 6]. Despite the high-pressure drop caused by an insert in embedded tubes, the use of tube inserts in heat exchangers has received a lot of attention during the last two decades [2, 7]. The increase in turbulence intensity and swirling flow may be the main reasons for HTE induced by tube inserts. An experimental study was carried out on heat transfer in a round tube equipped with propeller-type swirl generators by Eiamsa-ard et al. [8]. Saha [9] investigated the heat transfer and pressure loss behaviors in rectangular and square ducts with combined internal axial corrugations and twisted-tapes with and without oblique teeth. Promvonge [10] studied the effect of a conical ring tabulator arrangement on the heat transfer rate and friction factor. It was shown that the conical-ring with a diverging conical ring array provided superior thermal performance factor compared to those with the converging conical ring and converging-diverging conical-ring arrays. The effects of the blade angle, pitch ratio, and number of blades on the Nusselt number and pressure loss and enhancement efficiency were also studied. Chang et al. [11, 12] studied the heat transfer enhancement in a tube fitted with serrated twisted tapes and broken twisted tapes. The heat transfer and friction factor characteristics of a circular tube fitted with perforated conical rings was studied by Kongkaitpaiboon et al. [13]. Rahimi et al. [14] studied the heat transfer and friction factor characteristics of a tube equipped with modified twisted tape inserts. It was shown that Nusselt number and thermal performance factor of the jagged insert were higher than those of the three modified twisted tapes (classic, perforated, and notched tube inserts). Recently Shabanian et al. [15] studied the heat transfer enhancement in an air cooler equipped with different tube inserts. They showed that using the different tube inserts (butterfly, jagged, and classic twisted tape inserts) increases the heat transfer from the air cooler. Also, they showed that by using the butterfly insert with an inclined angle of 90°, maximum heat transfer is obtained. Also, their results have revealed that the thermal performance factor decreases with the increase in Reynolds number, due to the more significant role of inserts in increasing the turbulence intensity at lower velocities. The main focus of the present study is based on the experimental data obtained by Shabanian et al. [15] for optimizing thermal performance of an air cooler equipped with butterfly inserts using the imperialist competitive algorithm (ICA). ICA is a new evolutionary algorithm in the evolutionary computation field based on human socio-political evolution. The proposed method for the optimization was developed using MATLAB code. This method has some advantages, such as simplicity, accuracy, and time-saving.

## Nomenclature

- $A$: heat transfer area, $m^2$
- $Q$: heat transfer rate, W
- $C_p$: specific heat capacity, kJ/kg·K
- $D$: diameter of the smooth tube, m
- $D_h$: hydraulic diameter, m
- $h$: heat transfer coefficient, $W/m^2 \cdot K$
- $K$: thermal conductivity, W/m·K
- $m$: mass flow rate, kg/s
- $Nu$: Nusselt number
- $P$: static pressure, Pa
- $P_{th}$: thermal performance
- Re: Reynolds number
- $T$: temperature, K
- $U$: mean velocity, m/s

## Greek Symbols

- $\nu$: kinematic viscosity, $m^2/s$
- $\theta$: inclined angle

**Subscripts**

*col*: colony
*imp*: imperialist
*pop*: population

## 2. Experimental Apparatus

A schematic view of the experimental rig [15] is shown in Fig. 1(a). The rig consists of two fans and a set of copper tubes. The set of tubes has three sections including a calming section, bent

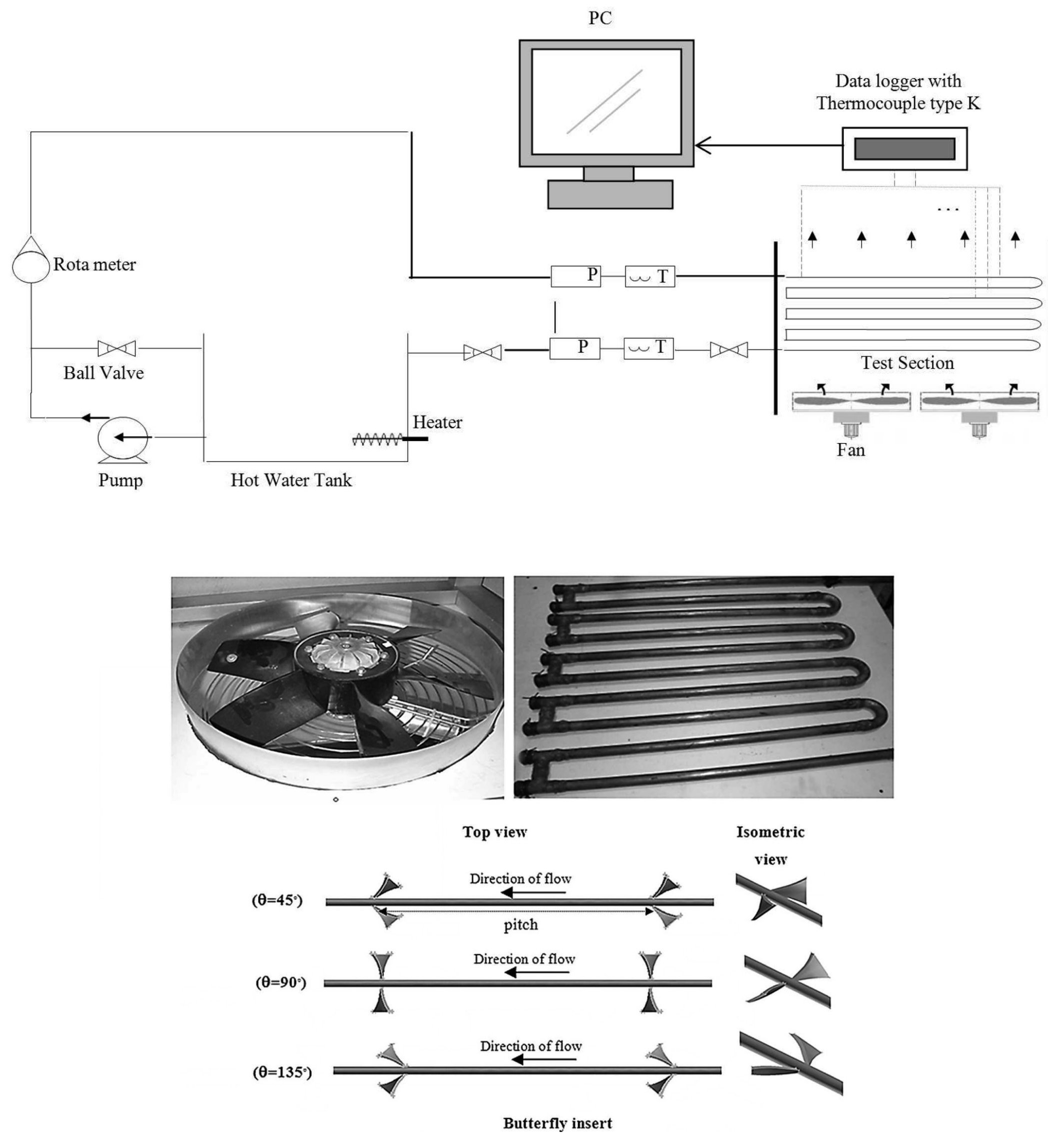


Fig. 1. (a) Schematic diagram of the experimental setup and (b) the components used in the experiment.

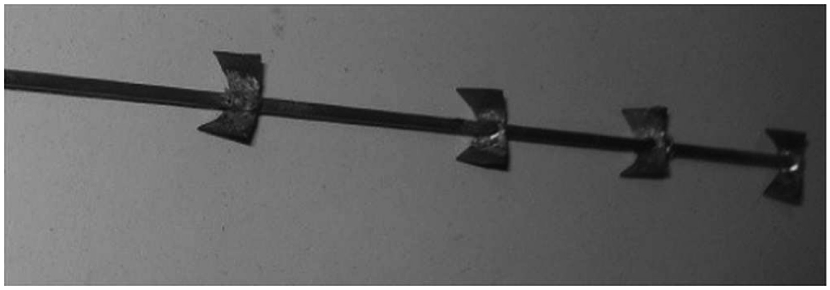

Fig. 2. Schematic of a butterfly insert with the inclined angle of 45°.

tube, and outlet section. The fluid enters the calming section which has a length of 2 m to eliminate the entrance effect. The temperature and pressure are measured at the end of this section at the inlet of the bent tube section. Then, the fluid passes through nine bends in the 6.5 m length of the bent tube and reaches the outlet section. The pressure and the temperature are measured at the outlet section. The 50-W fans with 1400 rpm rotation speed are placed at a 20-cm distance beneath the bent tube and the entire assembly is enclosed in a 60 × 100 × 50 cm cubic channel [15]. Hot water from a 100-liter reservoir equipped with heater enters the bent tube after passing through the rotameter with a 58 °C temperature. Water volumetric flow rate varies from 100 lit/hr to 400 lit/hr which corresponds to Reynolds numbers from 4021 to 16118. The tube inlet and outlet water pressure and temperature are measured through two pressure transmitters and a copper-constantan thermocouple. Moreover, in order to determine the average Nusselt number, the temperatures at 20 different positions on the outer surface of the tube are measured. All 20 temperature sensing probes are connected to a data logger set [15]. In the experiments, the butterfly insert is placed in the bent tube. Figure 1(b) shows the bent tube, fan, and tube inserts used in the experiment. The tube applied here has a 17-mm diameter and a 1-mm thickness. The butterfly inserts are made of aluminum sheet with a 0.5-mm thickness and consist of a holding rod with a 1.9-mm diameter. In manufacturing these inserts, thin tin plates were used. Later on these plates were cut into a butterfly wing shape or similar to basic triangles having common peaks where the length of each side was equal to 12.5 mm and the total height of triangles being 8.5 mm. Afterwards, the inserts were used at three inclined angles of 45, 90, and 135° placed between the butterfly piece and the holding rod with a 5-cm pitch length and were soldered to it [15]. A representation of a butterfly insert with the inclined angle of 45° is shown in Fig. 2. In the butterfly arrangement, pieces are placed on the rod to increase the flow turbulence intensity in the tube. Also the pieces on the rod are twisted slightly in order to reduce the blocking effect.

## 3. Data Reduction

In order to express the experimental results in a more efficient way, the measured data are reduced using the following procedure [15].

The heat transfer rate resulted from the hot fluid in the tubes is expressed as

$$Q = mC_p(T_o - T_i)$$

On the other hand, the heat transfer rate to the air surrounded the tube is approximated by

$$Q = hA(\overline{T}_w - T_b)$$

where

$$T_b = (T_o + T_i)/2 \quad \text{and} \quad \overline{T}_w = (\sum T_w)/20$$

$T_w$ is the local wall temperature and is measured at the outer wall surface of the tubes. Also, $T_o$ and $T_i$ are the outlet and inlet temperatures of the fluid, respectively, and $T_b$ is the average temperature of the outlet and inlet temperatures. The relations used in calculation of the average heat transfer coefficient and the average Nusselt number are as follows [15]:

$$h = mC_p(T_o - T_i)/A(\overline{T}_w - T_b)$$

$$Nu = hD_h/K$$

In addition, the Reynolds number is obtained according to the following equation:

$$\mathrm{Re} = UD_h/v$$

In the present work, the uncertainties of experimental measurements are determined based on ANSI/ASME [16]. The maximum uncertainties for *Nu* and Re are estimated at 7% and 5.2%, respectively.

## 4. Imperialist Competitive Algorithm

The optimization problem can be easily described as finding an argument *x* whose relevant cost *f*(*x*) is optimum, and has been extensively used in many different situations such as industrial planning, resource allocation, scheduling, pattern recognition, and so on. Different methods have been proposed to solve the optimization problem. Evolutionary algorithms, such as genetic algorithm [17, 18], particle swarm optimization [19, 20], taboo search [21–23], ant colony optimization [24–26], bees algorithm [27–29], and simulated annealing [30, 31] are a set of algorithms that are introduced and suggested in the past decades for solving optimization problems in different science and engineering fields. The Imperialist Competitive Algorithm (ICA) is an algorithm have been introduced for the first time in 2007 by Atashpaz-Gargari and Lucas [32] and used for optimizing inspired by imperialistic competition which has considerable relevance to several engineering applications [33–39]. Like other evolutionary algorithms, the proposed algorithm starts with an initial population. Population individuals called country are of two types: colonies and imperialists that all together form some empires. Imperialistic competition among these empires forms the basis of the proposed evolutionary algorithm. During this competition, weak empires collapse and powerful ones take possession of their colonies. Imperialistic competition hopefully converges to a state in which there exists only one empire and its colonies are in the same position and have the same cost as the imperialist [32]. Using this algorithm, one can find the optimum condition of most functions. In this connection, the proposed model based on regression analysis is then embedded into the ICA to optimize the objective function. The goal of optimization algorithms is to find an optimal solution in terms of the variables of the problem (optimization variables). We form an array of variable values to be optimized. In genetic algorithm terminology, this array is called a "chromosome," but here the term "country" is used for this array. In an $N_{\mathrm{var}}$-dimensional optimization problem, a country is a $1 \times N_{\mathrm{var}}$ array. This array is defined by:

$$country = [p_1, p_2, p_3, ..., p_{N_{\mathrm{var}}}] \quad (1)$$

The variable values in the country are represented as floating point numbers. The cost of a country is found by evaluating the cost function $f$ at the variables $(p_1, p_2, p_3, \ldots, p_{N_{\mathrm{var}}})$ [32]. Then

$$cost = f(country) = f(p_1, p_2, p_3, ..., p_{N_{\mathrm{var}}}) \quad (2)$$

The flowchart of the ICA algorithm is shown in Fig. 3. To start the optimization algorithm we generate the initial population of size $N_{pop}$. We select $N_{imp}$ of the most powerful countries to form the empires. The remaining $N_{col}$ of the population will be the colonies, each of which belongs to an empire. Then we have two types of countries: imperialist and colony. To form the initial empires, we divide the colonies among imperialists based on their power. That is, the initial number of colonies of an empire should be directly proportionate to its power. To divide the colonies among imperialists proportionally, we define the normalized cost of an imperialist by $C_n = c_n - \max\{c_i\}$, where $c_n$ is the

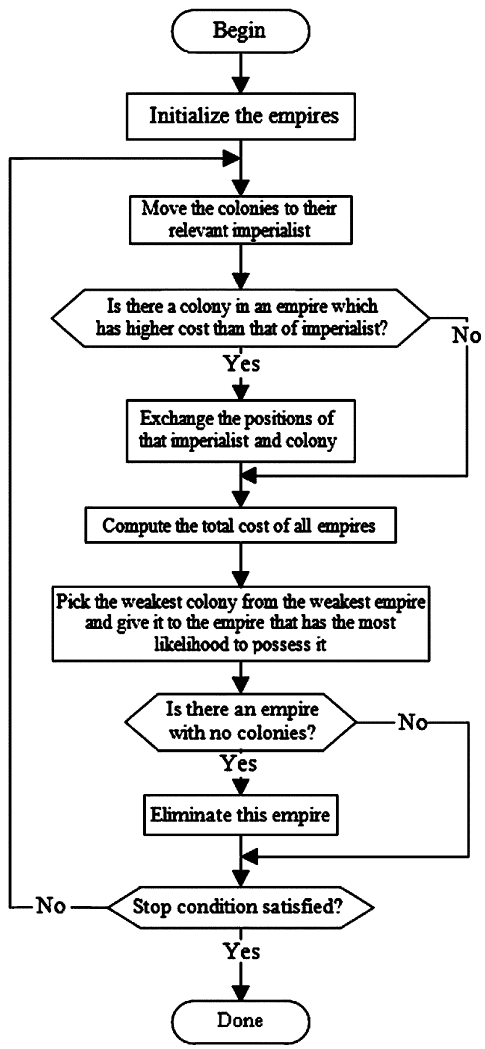


Fig. 3. Procedure of the proposed algorithm [32].

cost of $n$-th imperialist and $C_n$ is its normalized cost. Having the normalized cost of all imperialists, the normalized power of each imperialist is defined by [32]

$$p_n = \left| \frac{C_n}{\sum_{i=1}^{N_{imp}} C_i} \right| \tag{3}$$

From another point of view, the normalized power of an imperialist is the portion of colonies that should be possessed by that imperialist. Then the initial number of colonies of an empire will be

$$N.C._n = round\{p_n . N_{col}\} \tag{4}$$

where $N.C._n$, is the initial number of colonies of the $n$-th empire and $N_{col}$ is the number of all colonies. To divide the colonies, for each imperialist we randomly choose $N.C._n$ of the colonies and give them to it. These colonies along with the imperialist will form the $n$-th empire. As shown in this figure, bigger (powerful) empires have more colonies while smaller (weaker) ones have less [32]. As mentioned, imperialist countries start to improve their colonies. We have modeled this fact by moving all the colonies toward the imperialist. This movement is shown in Fig. 4, where the colony moves toward the imperialist by $x$ units. The new position of the colony is shown in a darker color. The direction of the movement is the vector from colony toward imperialist. In this figure $x$ is a random variable with uniform or any proper profile [32]. Then for $x$ we have

$$x \sim U(0, \beta \times d) \tag{5}$$

where $\beta$ is a number greater than 1 and $d$ is the distance between colony and imperialist. When $\beta > 1$, it causes the colonies to get closer to the imperialist state from both sides.

To search different points around the imperialist we added a random amount of deviation to the direction of movement. Figure 5 shows the new direction. In this figure, $\theta$ is a random number with uniform or any proper profile. Then

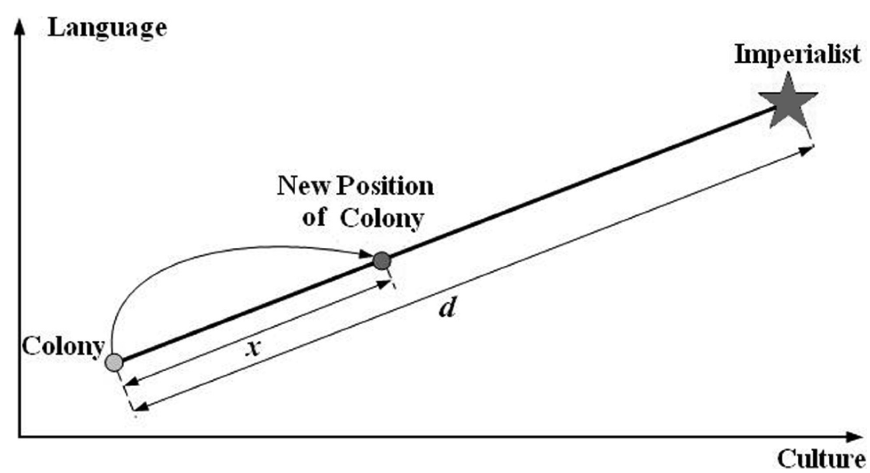


Fig. 4. Moving colonies toward their relevant imperialists [32].

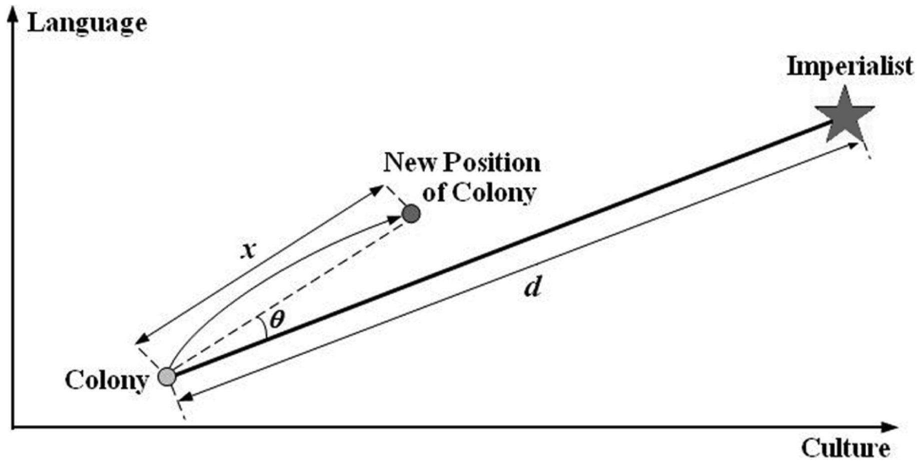


Fig. 5. Moving colonies toward their relevant imperialist in a randomly deviated direction [32].

$$\theta \sim U(-\gamma, \gamma) \tag{6}$$

where $\gamma$ is a parameter that adjusts the deviation from the original direction. Nevertheless, the values of $\beta$ and $\gamma$ are arbitrary. In most of our implementation, a value of about 2 for $\beta$ and about $\pi/4$ (Rad) for $\gamma$ has resulted in good convergence of countries to the global minimum.

### 5. ICA Optimization Results and Discussion

In order to use ICA, the optimization (input) and output variables with their levels must be determined. As can be seen in Table 1, we use seven levels of Reynolds number (Re) ranging from 4021 to 16118, with three-inclined insert angles ($\theta$) from 45° to 135° as optimization variables, and the thermal performance of the air cooler ($P_{th}$) as output variable. Then the experiments were carried out based on a general full factorial design. After data reduction, the values of the average Nusselt number and friction factor for 21 different tests were determined. Then the thermal performance was calculated from the following parameter [40]:

$$P_{th} = (Nu / Nu_0)/(f / f_0)^{(1/3)} \tag{7}$$

where $Nu_0$ and $f_0$ are the Nusselt number and friction factor for the plain tube. The above parameter is called the thermal performance factor which means the comparison is made based on constant pumping power. The values of thermal performance are shown in Table 2. Then, a correlation for the

Table 1. Optimization Variables in Thermal Performance and Their Levels

| | Notation | Coding | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Optimization Variables | | -3 | -2 | -1 | 0 | +1 | +2 | +3 |
| Reynolds number | Re | 4021 | 6037 | 8053 | 10076 | 12085 | 14101 | 16118 |
| Inclined angle | θ | - | - | 45° | 90° | 135° | - | - |

Table 2. Design Matrix

| No | Reynolds number, Re | Inclined angle, θ | Average Nusselt number, Nu | Friction factor, f | Thermal performance, $P_{th}$= $(Nu/Nu_0)/(f/f_0)^{(1/3)}$ |
|---|---|---|---|---|---|
| 1 | -3 | -1 | 94.280 | 1.077 | 1.4010 |
| 2 | -2 | -1 | 125.714 | 0.731 | 1.3510 |
| 3 | -1 | -1 | 152.857 | 0.527 | 1.3411 |
| 4 | 0 | -1 | 177.142 | 0.431 | 1.3210 |
| 5 | 1 | -1 | 200.000 | 0.368 | 1.3111 |
| 6 | 2 | -1 | 224.285 | 0.340 | 1.3010 |
| 7 | 3 | -1 | 244.286 | 0.311 | 1.2809 |
| 8 | -3 | 0 | 114.44 | 1.264 | 1.6192 |
| 9 | -2 | 0 | 156.020 | 0.867 | 1.5590 |
| 10 | -1 | 0 | 186.660 | 0.640 | 1.5356 |
| 11 | 0 | 0 | 218.050 | 0.521 | 1.5289 |
| 12 | 1 | 0 | 245.000 | 0.436 | 1.5222 |
| 13 | 2 | 0 | 271.100 | 0.368 | 1.5189 |
| 14 | 3 | 0 | 295.000 | 0.334 | 1.4980 |
| 15 | -3 | 1 | 94.2840 | 0.878 | 1.4635 |
| 16 | -2 | 1 | 125.011 | 0.561 | 1.4380 |
| 17 | -1 | 1 | 147.140 | 0.385 | 1.4420 |
| 18 | 0 | 1 | 169.721 | 0.306 | 1.4280 |
| 19 | 1 | 1 | 191.421 | 0.266 | 1.4150 |
| 20 | 2 | 1 | 214.281 | 0.232 | 1.4050 |
| 21 | 3 | 1 | 232.861 | 0.221 | 1.3750 |

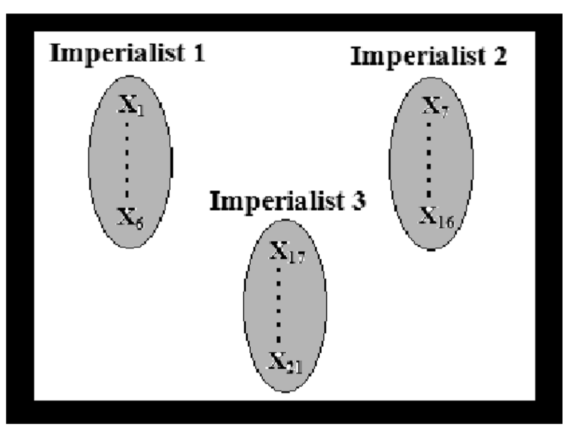


Fig. 6. The physical interpretation of ICA in terms of heat transfer parameters.

Table 3. The Selected Optimal Parameters of Proposed ICA Model

| | |
|---|---|
| Number of total countries | 130 |
| Number of initial imperialist countries | 9 |
| Number of epochs (decades) | 2 |
| Revolution rate | 0.4 |
| Assimilation coefficient | 2 |
| Assimilation angle | 0.5 |
| Cost function | $-P_{th}$ |

thermal performance in terms of Reynolds number and inclined angle in the coded form was developed as given below:

$$P_{th}=1.53 - 0.0156\ \mathrm{Re} + 0.0472\ \theta - 0.163\ \theta^2 + 0.00153\ \mathrm{Re}^2 + 0.00225\mathrm{Re}\times\theta \tag{8}$$

The adjusted R-squared of the above correlation is 98.3%. In regard to the effect of different parameters on the thermal performance, we could emphasize that according to Eq. (8) the most important parameters are inclined angle and Reynolds number, respectively. After that, the regression equation was embedded into the ICA to be optimized. Simplicity, accuracy, and time-saving are some of advantages of the ICA algorithm. However, if the adjusted R-squared of the regression equation is low enough then the results obtained by ICA would not be compared with the experimental results. In the ICA terminology, country is basically a vector of input parameters as below:

$$X_i = \begin{bmatrix} \mathrm{Re}_i \\ \theta_i \end{bmatrix} \tag{9}$$

Population is defined as the collection of countries competing internally in order to minimize their costs to become an imperialist. It also indicates the optimum level of those input parameters which gives maximum thermal performance. After the competition between the countries is completed then the second stage is started. The second stage is the external competition between imperialists. In this stage, that particular Imperialist having the least cost is taken as the winner as shown in Fig. 6, which is equivalent to the maximum thermal performance obtained in this study. The main parameters used in the ICA model are shown in Table 3. The results of optimization are shown in Table 4. Figure 7 shows the minimum and mean cost of all imperialists. As it can be understood from these results, the maximum value (thermal performance) of the objective function ($P_{th}$) occurs

Table 4. Results of Optimization

| | | Re | θ | $P_{th}$ |
|---|---|---|---|---|
| Maximum thermal performance | Coded value | -3.0000 | 0.1245 | 1.59<br>31 |
| | Decoded value | 4021 | 95.6025 | |

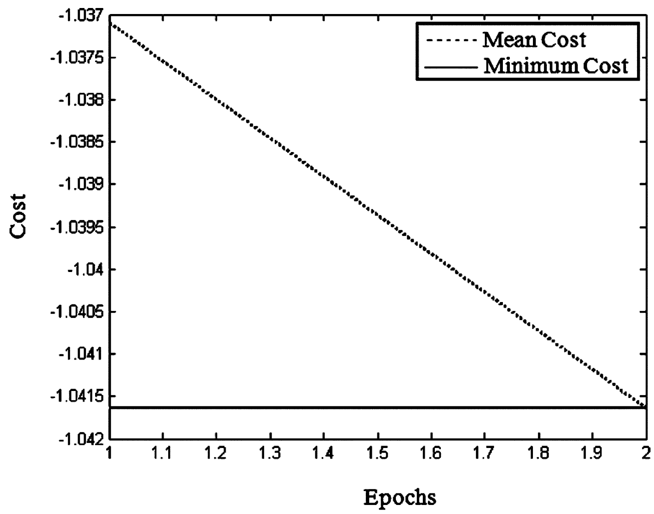


Fig. 7. Mean and minimum cost of all imperialists versus epochs for maximum thermal performance.

at the inclined angle of 95 and Reynolds number of 4021. These results reveal the thermal performance factor decreases with the increase in Reynolds number. This indicates that the role of inserts in increasing the turbulence intensity is more significant at lower velocities than at higher velocities. Also, a higher thermal performance factor can be obtained at the inclined angle of 95°.

## 6. Conclusions

In this paper, experiments were carried out based on general full factorial design of experiments for generating data. A correlation was developed to gain relationship between two optimization parameters, namely Reynolds number and the inclined angle of the inserts and an output variable, the thermal performance of the air cooler. Then the correlation was embedded into the ICA to be optimized. According to the optimization results, the maximum value (thermal performance) of the correlation ($P_{th}$) occurs at the inclined angle of 95°.

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