2011 International Conference on Advancements in Information Technology
With workshop of ICBMG 2011
IPCSIT vol.20 (2011) © (2011) IACSIT Press, Singapore

Entropy Generation Minimization in a Plate Fin Heat Exchanger by a Social-Political Based Evolutionary Algorithm

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Abstract. As a part of the whole system, any thermal devices should be optimized in order of minimizing the amount of wasted energy. This paper investigates the application of Imperialist Competitive Algorithm (ICA) in thermodynamic optimization of a cross-flow plate fin heat exchanger. The method of Bijan is used for the entropy minimization. Seven design parameters are chosen as optimization variables where the constraints are handled using penalty function. To better understand the algorithm, a case study from the literature is presented. The results show that ICA can find better results comparing to traditional genetic algorithms.

Keywords: Optimization, Plate fin heat exchanger, evolutionary algorithms, Imperialist Competitive Algorithm

1. Introduction

PFHE characterises mainly with its relatively high compactness, and are widely used in different aspects of industry from cryogenics to aerospace and automobile industry. Since the thermodynamic optimization of any real system is associated with the second law of thermodynamics, second law based entropy generation minimization (EGM)[1] has been introduced to assess the thermal performance of any real system which is working based on the irreversibilities due to heat and mass transfer or simply fluid flow. The number of entropy generation units(Ns) shows the amount of power that is lost due to the irreversibility. The main sources of irreversibility in a heat exchanger are the finite temperature difference between fluid streams and pressure drops. Considering minimization of number of entropy generation units, the optimization means finding a configuration for the heat exchanger with the minimum amount of lost or unavailable power. Several works have been published on the optimization of heat exchangers considering entropy generation. Ogulata and Doba[1], Vargas and Bejan[2], and Iyengar and Bar-Cohen[3] presented the optimization of flat plate-fin heat exchangers. Since the design of a plate-fin heat exchanger involves searching in a large number of operating and variables the traditional optimization methods cannot perform accurately so in recent years the application of evolutionary algorithms has gained much attention in design of heat exchangers.In case of plate fin heat exchangers,

In case of other evolutionary algorithms, Peng at el.[4] used a Particle Swarm Optimization(PSO) to optimize a PFHE. They considered minimization of total annual cost, total weight under given constrained conditions, respectively. Comparing their result to the traditional Gas, they demonstrated that PSO presents shorter computational time and better results for their case. Also, Rao and Patel [5] employed a PSO to

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optimize a cross-flow plate fin heat exchanger with the aim of minimizing the entropy generation units, total volume and total annual cost respectively.

Since the majority of known evolutionary algorithms are based on the simulation of natural and biological processes, Atashpaz-Gargari and Lucas[6] proposed imperialist competitive algorithm(ICA) which is an evolutionary algorithm based on human's socio-political evolution. in view of the fact that this evolutionary optimization algorithm has shown great performance in both convergence rate and achieving better global optima, ICA has been successfully utilized in many engineering applications such as control[7], data clustering[8], industrial engineering[9] in recent years. However, to the best knowledge of the authors, ICA has not been implemented in thermal engineering problems. Therefore, in the present work an attempt is made to put the entropy generation minimization and Imperialist Competitive Algorithm into the design of a plate fin heat exchanger.

2. Thermal Modelling and Objective Function

In the analysis, for the sake of simplicity, the variation of physical property of fluids with temperature is neglected where both fluids are considered to be ideal gases.

$$Ns = \frac{\dot{S}}{C_{max}} \tag{1}$$

Entropy generation rate for two fluid streams is calculated as:

$$\dot{S} = m_a(\Delta S_a) + m_b(\Delta S_b) \tag{2}$$

Using the methodology of Bejan[10] the above equation gives:

$$\dot{S} = m_a\left[Cp_a \ln\frac{T_{a,2}}{T_{a,1}} - R_a \ln\frac{P_{a,2}}{P_{a,1}}\right] + m_b\left[Cp_b \ln\frac{T_{b,2}}{T_{b,1}} - R_b \ln\frac{P_{b,2}}{P_{b,1}}\right] \tag{3}$$

$T_{a,2}$ and $T_{b,2}$ are outlet temperatures in hot and cold side respectively that calculated knowing the heat exchanger efficiency, ε. The outlet fluids pressures in hot and cold side, $P_{a,2}$ and $P_{a,1}$ are determined as follows.

$$P_{a,2} = P_{a,1} - \Delta P_a \tag{4}$$

$$P_{b,2} = P_{b,1} - \Delta P_b \tag{5}$$

More details of the thermodynamic modelling can be found in the work of Mishra.

In the present work the objective is to find the configuration associated with the minimum number of entropy generation unit. In summaryhe optimization problem at hand is a large-scale, combinatorial problem which deals with both continue and discrete variables. For optimization problem, ICA is used for a constrained minimization. The problem can generally be stated as follows.

$$\text{Minimise } f(X), \quad X = [x_1, .. x_k] \tag{6}$$

Where constraints are stated as

$$g_j(X) \le 0, \; j = 1, \ldots, m \tag{7}$$

and

$$x_{i,min} \le x_i \le x_{i,max,} \quad i = 1, \ldots, k \tag{8}$$

To handle the constrained in the optimization algorithm a penalty function is added to the objective function which converts the unconstrained problem to a constrained one.

$$\text{Minimise } f(x) + \textstyle\sum_{j=1}^{m} \phi(g_j(X)) \tag{9}$$

Subject to

$$x_{i,min} \le x_i \le x_{i,max}, \quad i = 1, \ldots, k \tag{10}$$

Where ϕ is a penalty function defined as,

$$\phi\big(g(X)\big) = R1.\,(g(X)^2 \tag{11}$$

R1 is the penalty parameter which comparing to the $f(x)$ have a relatively large value.

3. Imperialist Competitive Algorithm

In this algorithm each individual of the population is called a country. There are two types of countries, namely Imperialist and Colony. Depending on its power, each Imperialist colonized some of the countries. The main processes of this algorithm are assimilation and competition.

After formation of the initial empires, the imperialistic competition between them starts. Any empire which cannot increase its power in the competition or at least preserve its colonies would be eliminated eventually. To increase their powers, Imperialists have to try to develop their colonies.

Following some decades, the power difference between the Imperialists and their colonies will be less and convergence would occur. Basically the imperialist competition can be continued until there would be only one empire in the search space. In this situation the colonies are similar to the imperialist regarding their powers. In any optimization problem the goal is to find an optimal solution in terms of the problem variables. The colony is drawn by imperialist in the culture and language axes. After applying this policy the colony will get closer to the imperialist in the mentioned axes. In assimilation, each colony moves on the line that connects the colony and its imperialist by x units, 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.

4. A Case Study

To clarify the application of mentioned optimization algorithm, a case study taken from the work of shah[11] is considered. 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 number of entropy generation units. Maximum dimension of the exchanger is 1*1*1m. Gas and air inlet temperatures are 900 and 200 c, respectively and gas and air mass flow rates are 1.66kg/s and 2.00 kg/s respectively. Pressure drops are set to be limited to 9.50kPa and 8.00kPa. The gas and air inlet pressures are 160kPa and 200kPa absolute. The offset strip fin surface is used on the gas and air sides. The plate thickness is set at 0.5mm and is not an optimization variable.

In this study, a total number of 7 parameters namely, hot flow length(La), cold flow length(Lb),number of hot side layers(Na),fin frequency(n), fin thickness(t),fin height(H) and fin strip length(lf) are considered as optimization variables. All variables except number of hot side layers are continuous. Thickness of the plate, tp is considered to be constant at 0.5mm and is not to be optimized. The variation ranges of the variables are shown in Table 1.

Table 1. Variation range of design parameters

Parameter	Minimum	Maximum
hot flow length(La)(m)	0.1	1
cold flow length(Lb)(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	1	200

layers(N_a)

5. Results and Discussion

For the prescribed heat duty and allowable pressure drop, the optimization problem is finding the design variables that minimize the weight of the PFHE. The ICA algorithm is used to optimize the heat exchanger subject to the mentioned constraints.ICA parameters are selected based on Atashpaz-Gargari and Lucas[6] recommendations. β, γ and revolution rate values are set to 2, $\pi/4$ and 0.1 respectively. The ratio of initial imperialists to the initial countries is set to 1/10. After testing different number of initial countries, it is found that 100 countries can serve the best in this problem. The iteration process can is demonstrated in Fig.1.

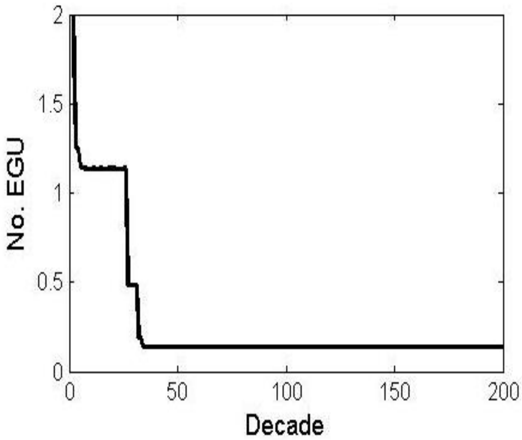

Fig. 1: The iteration process for the objective function

Finally the minimum number of EGU of the PFHE is found to be 0.1374 after 200 decades. A considerable decrease (12.8%) in the number of EGU of PFHE can be noticed comparing to the 0.1576 preliminary design. Fin frequency is decreased from 782 to 240 while the fin strip length is increased from 3.18 to 9.6. The pressure drop on both sides is as low as possible to decrease the amount of irreversibility as much as possible. Flow length on hot and cold side are increased to 1m and 0.88m from their preliminary 0.3m design respectively while no-flow length is decreased from 1m to 0.87m.

A brief investigation is carried out to compare the design efficiency of the proposed algorithm with traditional GA. The results are demonstrated in table 5. For the GA optimization the crossover probability and mutation rate are set to 0.9 and 0.005 respectively similar to the work of Sanaye et al.[15] while the population size and number of generations are set to 100 and 200 respectively. The GA yields to 0.1416 which is higher than the results of ICA.

6. Conclusions

The main findings of this study are as follows.

- The findings demonstrate that the result attained from the ICA is better than the preliminary design considering the respected objective function.

- The ICA algorithm comparing to the traditional GA shows improvements in the optimum designs under the same population size and iterations.

The design procedure for the PFHEs presented in this study by using the ICA can be applied for the other types of heat exchanger such as fin-and-tube heat exchangers, sell-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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