Optimal Design of Plate-fin Heat Exchangers by Particle Swarm Optimization

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ABSTRACT

This study explores the application of Particle Swarm Optimization (PSO) for optimization of a cross-flow plate fin heat exchanger. Minimization total annual cost is the target of optimization. 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 the literature proves the effectiveness of the proposed algorithm in case of achieving more accurate results.

Keywords: Plate fin heat exchanger, Particle Swarm Optimization, Genetic Algorithm, Optimization

1. INTRODUCTION

Plate-fin heat exchangers (PFHEs) are widely used in industrial applications from cryogenics to aerospace and automobile industry.

A trial-and-error process is the common design method for PFHEs. The complicated design task consists of selecting geometrical and operational parameters so that specific requirements are achieved while leading to an optimum solution at the same time.

The common objectives in heat exchanger design are associated with minimizing capital cost and original cost. Practically, a higher velocity yields to higher heat transfer coefficient which consequently leads to smaller heat transfer area and lower capital cost. It should be noticed that, however, higher velocity results in higher pressure drop and power consumption, too. Therefore, before the optimal design is performing, the objective function should be considered based on the requirements. In most cases a compromise between the capital cost and power cost should be achieved by the design parameters. GA's, as stochastic global search algorithms, have been widely implemented in design and optimization of compact heat exchangers[1-12] since they have been proved to be very effective tools in finding near optimal solutions without having information of the derivatives. Particle Swarm Optimization(PSO), a new evolutionary based technique, has been recently introduced by Kennedy and Eberhart[13]. Similar to GAs, PSO starts with an initial population of the possible solutions. Each solution is called a 'Chromosome' in GA and a 'Particle' in PSO where on the contrary to the former new solutions are not created from the parents within the evolution process. In PSO, any individual just tries to evolve its social behavior and move towards destination.

In this work, it is desired to see the applicability of this algorithm in design of PFHE.

2. 2- THERMAL MODELING

In the present work, since the outlet temperature of the fluids is not specified the $\varepsilon - \mathrm{NTU}$ method is used for rating performance of the heat exchanger in the optimization process. The rating is done similar to [4], the only difference is that for the calculation of Colborn factor j and Fanning factor f for offset strip fin correlation presented by Manglik and Bergles [14] which are used. 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.

A schematic of a typical cross-flow plate fin heat exchanger with offset strip fin can be seen in Fig. 1. 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.

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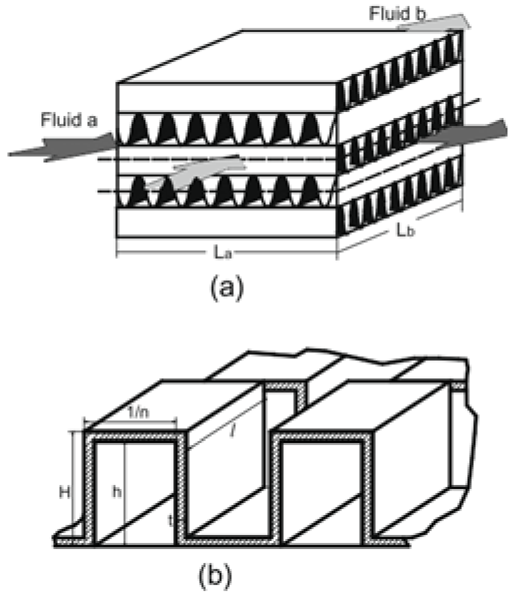

Fig. 1. (a) Schematic representation of cross-flow plate-fin heat exchanger, and (b) detailed view of offset-strip fin.

3. GA AND PSO

GA's are based on the Darwinian idea of the survival of the fittest. A solution is called a 'chromosome' and consists of different genes any of them represent a variable of the possible solution. A population consists of an arbitrary number of chromosomes randomly created within the search space. The merit of each member is evaluated using a desired objective function. To mimic the survival of the fittest concept, best individuals, based on their merits, are selected to create the next generation of chromosomes. Usually a large number of generations are needed to arrive at a near-optimum solution. Basically GAs consist three main operators namely, selection, crossover and mutation. More details on GA and its application in heat transfer problems can be seen in[15].

In PSO the process begins with generation of a random population of possible solutions, each of them called a 'Particle'. Throughout the process, each particle, i , having the current position of Xi in the search space, flies with the velocity of Vi towards the solution while keep track of its best position, Pi , in all previous cycles. Moreover, the position of the best particle (a particle with the best fitness) in the current cycle is represented by Pg. The velocity of each particle in each cycle is calculated as follow.

$$New\ V_i = \omega \times current\ V_i + c_1 \times rand(\,) \times (P_i - X_i) + c_2 \times Rand(\,) \times (P_g - X_i) \tag{1}$$

Subject to: $\mathrm{V_{max}} \geq \mathrm{V_i} \geq -\mathrm{V_{max}}$

And the new position becomes:

$$New\ position\ X_i = current\ position\ X_i + New\ V_i \tag{2}$$

In the above formula, c_1 and c_2 are two positive numbers associated with cognition and social collaboration of a particle respectively (usually $c_1=c_2=2$) where rand() and Rand() are uniformly distributed random functions in the range of [0,1]. ω is an inertia weight for controlling the effect of the previous velocity on the current one. This operator balances the role of the local search and the global search. V_{max} and $-V_{max}$ are upper and lower bonds of the velocity.

4. OBJECTIVE FUNCTION

In this work, the optimization is targeting total annual cost. 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[5],[2] and[16].

In summary the optimization problem at hand is a large-scale, combinatorial problem which deals with both continuous and discrete variables. In the present optimization problem, PSO is used for a constrained minimization. The problem can generally be stated as follows.

$$Minimise\ f(x) \quad , \mathrm{X} = [\mathrm{x}_1, .. \mathrm{x}_\mathrm{k}] \tag{3}$$

Where constraints are stated as

$$g_j(X) \leq 0,\ j = 1, \dots, m \tag{4}$$

and

$$x_{i,min} \leq x_i \leq x_{i,max,} \quad i = 1, \dots, k \tag{5}$$

To handle the constraints in the optimization algorithm, a static penalty function approach is applied. A penalty value is added to the objective function which converts the unconstrained problem to a constrained one.

$$Minimise\ f(x) + \sum_{j=1}^{m} \phi(g_j(X)) \tag{6}$$

Subject to

$$x_{i,min} \leq x_i \leq x_{i,max,} \quad i = 1, \dots, k \tag{7}$$

Where ϕ is a penalty function defined as,

$$\phi\big(g(X)\big) = R1.(g(X)^2 \tag{8}$$

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

5. A CASE STUDY

To clarify the application of the mentioned optimization algorithm, a case study taken from the work of shah[17] 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 weight and minimum total annual cost separately. Maximum flow length and no-flow length of the exchanger is 1m and 1.5m respectively. Gas and air inlet temperatures are 900°C and 200 °C where 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 at hot and cold side. The offset strip fin surface is used on the gas and air sides.

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 except the number of hot side layers are continuous. Thickness of the plate, t_p is considered to be constant at 0.5mm and is not to be optimized. The variation ranges of the design 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 layers(N_a)	1	200

6. RESULTS AND DISCUSSION

The optimization target is the minimum total annual cost of the PFHE. Fig. 2 depicts the variation of the objective function during the iteration process. A sharp decrease in the objective function can be noticed in the first 10 generations. The variation of the objective function becomes minute when the iteration reaches 50. The minimum total annual cost is found to be 944$ after 200 generations. In Table 3 the results of optimization is presented for the object of minimum total annual cost. 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. Also, In Table 2 the results are compared with those obtained by GA using the same population and number of iterations. It reveals that PSO can converge to better results in less computational time.

Table 2 Comparison of results from PSO and GA methods

Parameters	PSO	GA
Total annual cost($)	944	1009
CPU time(s)	3.75	4.31

Table 3. Comparison of the preliminary design and PSO results for minimum TAC

		Preliminary design	PSO
Optimal design variables	hot flow length(La)(m)	0.3	0.71
	cold flow length(Lb)(m)	0.3	0.92
	fin height(H)(mm)	2.49	10.00
	fin thickness(t)(mm)	0.102	0.150
	fin frequency(n)(m^{-1})	782	263
	fin offset length(lfa)(mm)	3.18	8.8
	number of hot side layers(N_a)	167	71
Constrained Conditions	ΔP_a at hot side(kPa)	9.34	0.31
	ΔP_b at clod side(kPa)	6.90	0.39
	no-flow length,L_C(m)	1.00	1.5
Objective	total annual cost()($)	6780.7	944.0

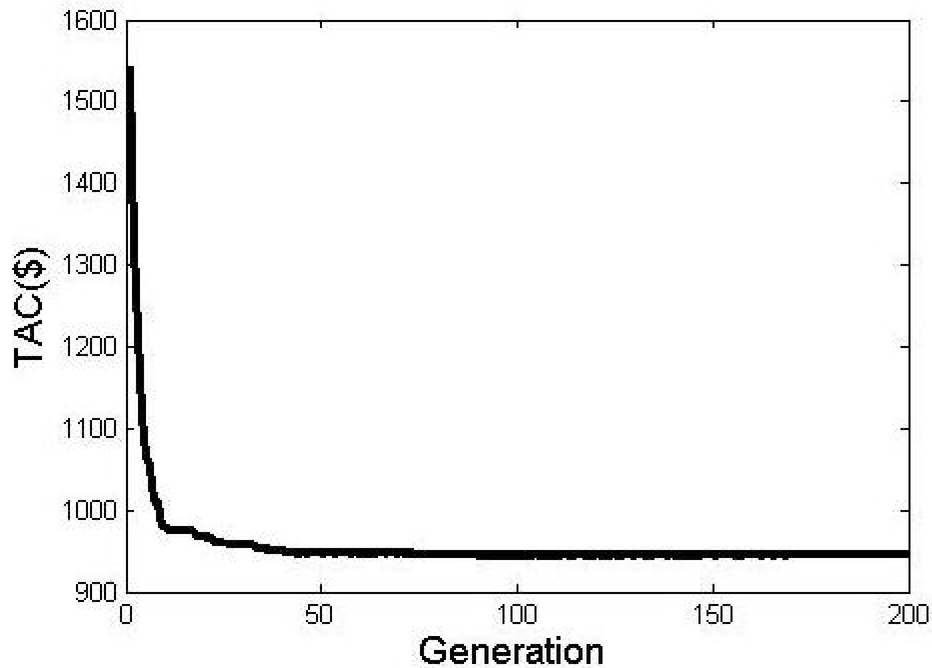

Fig2. Iteration process of the PSO algorithm

7. CONCLUSIONS

This study presents thet application of Particle Swarm Optimization for optimization of a PFHE. Minimum total annual cost is considered as single objective function. 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 the result attained from PSO have shown improvement respect to the preliminary design.

2- PSO comparing to the traditional GA shows considerable improvements in finding the optimum designs in less computational time under the same population size and iterations.

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