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Comparative Design of Offset Strip Plate Fin Heat Exchanger for Maximum Heat Transfer Co-Efficient Using Particle Swarm Optimization Algorithm With Different Design Co-Relation.

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ABSTRACT *Heat exchangers are devices that facilitate heat transfer between two fluids at different temperatures. Heat transfer co-efficient maximization is one of the important objective for thermal design of heat exchanger. This study explores the use of particle swam optimization (PSO) for thermodynamic design optimization of cross flow plate-fin heat exchanger. Maximization of heat transfer co-efficient is considered as an objective function for specific heat duty requirement of late-fin heat exchanger. Seven design variables such as heat exchanger length, fin frequency, number of fin layer, lance length of fin, fin height and fin thickness are considered for optimization. Design correlation proposed by Maiti-sarangi, Joshi-Webb and Manglik-Bergles are considered for the design optimization. An application example is also presented to demonstrate the effectiveness and accuracy of the proposed method.*

KEYWORDS : Cross flow plate-fin heat exchangers; correlation of heat transfer; Particle swarm optimization; offset strip fin; Colburn factor; friction factor; maximum heat tranfer

INTRODUCTION

Heat exchangers are used to transfer thermal energy between two or more medium. There are wide range of heat exchangers which used in different industrial application, one of the important among them are Compact Heat Exchangers, which include plate-fin types and tube-fin type heat exchangers. Cross flow plate-fin heat exchangers are widely used in gas-gas applications such as cryogenics and microturbine; in addition it is also used in automobile, chemical process plants, naval and aeronautical applications. Plate-fin heat exchangers has high thermal effectiveness, because fins are employed on both sides to interrupt boundary layer growth, large heat transfer surface area per unit volume and has high thermal conductivity due to thin thickness of plate. This leads to reduce space, weight, energy requirement and cost. However this superior thermal performance of the compact heat exchanger is at the expense of higher frictional losses (i.e. pressure drop). Therefore, the optimum design of compact heat exchanger always required the optimal trade-off between the increased heat transfer rate and the power consumption due to higher pressure drop within the given set of constrain. The analysis based on the second law of thermodynamics is one of the effective tools, which would allow the evaluation of the heat transfer enhancement methods by consideration of both trade-off factors.

In addition to using traditional mathematical methods [1, 2], simulated annealing [3] and artificial neural network [4] many researchers have successfully employed evolutionary and swarm intelligence based computation in design optimization of PFHE. Mishra et al. [5] and Mishra and Das [6] used GA for optimal design of plate-fin heat exchangers. The authors had considered minimization of total annual cost and total thermo-economic cost. Najafi et al. [7] carried out multi-objective optimization of PFHE considering total heat transfer rate and total annual cost of the heat exchanger simultaneously using multi-objective GA. Xie et al. [8] used GA for optimal design of PFHE. The authors had considered minimization of total annual cost as an objective function and pressure drop as a constraint. In the present work for calculating entropy generation unit, three different correlation of heat transfer and pressure drop are considered and listed below.

$$j = 0.53(\mathrm{Re})^{-0.5}\left(\frac{l}{d_k}\right)^{-0.15}\left(\frac{s}{H-t}\right)^{-0.14} \quad [1]$$

(Joshi and webb correlation)

$$j = 0.36(\mathrm{Re})^{-0.51}\left(\frac{H-t}{s}\right)^{0.275}\left(\frac{l}{s}\right)^{-0.27}\left(\frac{t}{s}\right)^{-0.065} \quad [2]$$

(Maitte and Sarnagi correlation)

$$j = 0.483(\mathrm{Re})^{-0.536}\left(\frac{l}{d_k}\right)^{-0.162}\left(\frac{s}{H-t}\right)^{-0.184} \quad [3]$$

(Manglik and Bergles correlation)
(If $\mathrm{Re} \leq 1500$)

$$j = 0.21(\mathrm{Re})^{-0.4}\left(\frac{l}{d_k}\right)^{-0.24}\left(\frac{t}{d_k}\right)^{-0.02} \quad [4]$$

(Joshi and webb correlation)

$$j = 0.18(\mathrm{Re})^{-0.42}\left(\frac{H-t}{s}\right)^{0.288}\left(\frac{l}{s}\right)^{-0.184}\left(\frac{t}{s}\right)^{-0.05} \quad [5]$$

(Maitte and Sarnagi correlation)

$$j = 0.242(\mathrm{Re})^{-0.368}\left(\frac{l}{d_h}\right)^{-0.322}\left(\frac{t}{d_h}\right)^{0.05} \quad [6]$$

(Manglik and Bergles correlation)
(If Re > 1500)
Where, ja and jb are Colburn factor for hot side and cold side respectively for calculating heat transfer co-efficient

$$f = 8.12(\mathrm{Re})^{-0.74}\left(\frac{l}{d_h}\right)^{-0.41}\left(\frac{s}{H-t}\right)^{-0.02} \quad [7]$$

(Joshi and webb correlation)

$$f = 4.67(\mathrm{Re})^{-0.70}\left(\frac{H-t}{s}\right)^{0.196}\left(\frac{l}{s}\right)^{-0.181}\left(\frac{t}{s}\right)^{-0.104} \quad [8]$$

(Maitte and Samagi correlation) [8]

$$f = 7.661(\mathrm{Re})^{-0.712}\left(\frac{l}{d_h}\right)^{-0.41}\left(\frac{s}{H-t}\right)^{-0.092} \quad [9]$$

(Manglik and Bergles correlation)
(If Re ≤ 1500)

$$f = 1.12(\mathrm{Re})^{-0.36}\left(\frac{l}{d_h}\right)^{-0.65}\left(\frac{t}{d_h}\right)^{-0.17} \quad [10]$$

(Joshi and webb correlation)

$$f = 0.32(\mathrm{Re})^{-0.286}\left(\frac{H-t}{s}\right)^{0.221}\left(\frac{l}{s}\right)^{-0.185}\left(\frac{t}{s}\right)^{-0.023} \quad [11]$$

(Maitte and Samagi correlation)

$$f = 7.661(\mathrm{Re})^{-0.712}\left(\frac{l}{d_h}\right)^{-0.41}\left(\frac{s}{H-t}\right)^{-0.092} \quad [12]$$

(Manglik and Bergles correlation)
(If Re > 1500)
Where, fa and fb are fanning friction factor required for calculating pressure drop

PARTICLE SWARM OPTIMIZATION (PSO) ALGORITHM

Particle swarm optimization (PSO) is an evolutionary computation technique developed by Kennedy and Eberhart [29]. It exhibits common evolutionary computation attributes including initialization with a population of random solutions and searching for optima by updating generations. Potential solutions, called 'birds' or 'particles', are then "flown" through the problem space by following the current optimum particles. The particle swarm concept was originated as a simulation of a simplified social system. The original intent was to graphically simulate the graceful but unpredictable choreography of a bird flock. Each particle keeps track of its coordinates in the problem space, which are associated with the best solution (fitness) it has achieved so far. This value is called 'pBest'. Another "best" value that is tracked by the global version of the particle swarm optimization is the overall best value and its location obtained so far by any particle in the population. This location is called 'gBest'. The updates of the particles are accomplished as per the following equations.

$$V_{i+1} = wV_i + c_1 r_1\left(pBest_i - X_i\right) + c_2 r_2\left(gBest_i - X_i\right) [13]$$

$$X_{i+1} = X_i + V_{i+1} \quad [14]$$

Equation (1) calculates a new velocity (Vi+1) for each particle (potential solution) based on its previous velocity, the best location it has achieved ('pBest') so far, and the global best location ('gBest'), the population has achieved. Equation (14) updates individual particle's position (Xi) in solution hyperspace. The two random numbers 'r1' and 'r2' in equation (13) are independently generated in the range [0, 1].

The acceleration constants 'cl' and 'c2' in equation (13) represent the weighting of the stochastic acceleration terms that pull each particle towards 'pBest' and 'gBest' positions.

APPLICATION EXAMPLE

A case study is considered to demonstrate the effectiveness of different design correlation using PSO for the thermodynamic design optimization of plate-fin heat exchanger (As shown in Figure 1). A gas-to-air cross flow plate-fin heat exchanger having heat duty of 10 kW having air and nitrogen as a fluid on both the side of heat exchanger needs to be design and optimized for minimum entropy generation. The original design specifications, shown in Table-1 were supplied as an input. The plate fin surfaces having same specifications are assumed on both sides of heat exchanger. So, the objective is to find out the heat exchanger dimensions, number of fin layer and other fin parameters giving the required heat duty for maximum heat transfer co-efficient.

TABLE-1
PROCESS INPUT AND PHYSICAL PROPERTIES FOR APPLICATION EXAMPLE

Parameters	Fluid a	Fluid b
Inlet temperature, T1 (K)	513	277
Inlet pressure, P1 (Pa)	1.00E+05	3.00E+05
Specific heat, Cp (J/kg K)	1017.7	1011.8
Density, ρ (kg/m3)	0.8196	0.9385
Dynamic viscosity, μ (N s/m2)	241	218.2
Prandtl number, Pr	0.6878	0.6954
Mass flow rate, m (kg/s)	0.1-0.8	0.1-0.8
Heat exchanger length (La)	0.1 - 1 m	0.1 - 1 m
Heat exchanger length (Lb)	0.1 - 1 m	0.1 - 1 m
Fin height (H)	0.002 - 0.01 m	0.002 - 0.01 m
Fin frequency (n)	100 - 1000 fins/m	100 -1000 fins/m
Fin thickness (t)	0.1 - 0.2 mm	0.1 - 0.2 mm
Lance length of fin (l)	0.001 - 0.01 m	0.001 - 0.01 m
Number of fin layer	10	10
Heat duty of the exchanger, Q (kW)	1	1

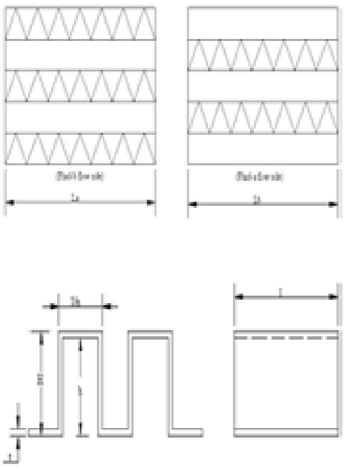

Figure 1: Front view and side view of plate-fin heat exchanger and offset-strip fin.

RESULT AND DISCUSSION

The maximum heat transfer co-efficient obtained using the proposed algorithm for different correlation is given in Table 2.

Compression between Maiti-sarangi co-relation with Joshi-Webb co-relation

A brief investigation is carried out to compare the Design parameters of Maiti-sarangi co-relation with Joshi-Webb co-relation. The results are demonstrated in Table 2. For the Maiti-sarangi co-relation, length of heat exchanger for fluid a and b are 0.459m and 0.276m while in Joshi-Webb co-relation length of heat exchanger for fluid a and b are 0.412 m and 0.203m. Number of fin layers for fluid a and b are same for both co-relation and the values are 3 and 4. convective heat transfer coefficient for fluid a and fluid b are 2.1276 W/m^{2}K and 3.1359 W/m^{2}K in Maiti-sarangi co-relation but in Joshi-Webb co-relation these values are 1.2545W/m^{2}K and 2.0427W/m^{2}K and its decreased. height and thickness of fin are 0.098 and0.00197 calculated by Joshi-Webb co-relation which are decreased for height and increased for thickness of fin in Maiti-sarangi co-relation and the values of these parameters are 0.0996 and 0.00221. The lance length of the heat exchanger for Maiti-sarangi and Joshi-Webb co-relation is 0.119 m and 0.131 m. the value of fin frequency of heat exchanger calculated by Maiti-sarangi co-relation is 73.21 less than Joshi-Webb co-relation by 70.72. The pressure drops is 0.3419 n/m^2 for the a fluid and for the b fluid is 0.0378 n/m^2 in Maiti-sarangi co-relation but in Joshi-Webb co-relation, the pressure drops are 0.4577 n/m^2 and 0.0323 n/m^2 which is increased for fluid a and decreased for fluid b. Effectiveness of heat exchanger is 0.8306 in Maiti-sarangi co-relation and 0.7969 in Joshi-Webb co-relation which shows decrement in that parameter. The desired value of minimum entropy generation unit of the heat exchanger obtained using the correlations developed by maiti and sarangi is 0.1671 which is decreased to 0.1514 in Joshi-Webb co-relation.

Comparision between Maiti-sarangi and Manglik-Bergles co-relation

For the Maiti-sarangi co-relation, length of heat exchanger for fluid a and b are 0.459m and 0.276m while in Manglik-Bergles co-relation length of heat exchanger for fluid a and b are 0.419m and 0.211m. Number of fin layers for fluid a and b are same for both co-relation and the values are 3 and 4. Convective heat transfer coefficient for fluid a and fluid b are 2.1276 W/m^{2}K and 3.1359 W/m^{2}K in Maiti-sarangi co-relation but in Manglik-Bergles co-relation these values are 1.3493 W/m^{2}K and 2.11732 W/m^{2}K and its decreased. height and thickness of fin are 0.104 and 0.00199 calculated by Manglik-Bergles co-relation which are decreased for height and increased for thickness of fin in Maiti-sarangi and the values of these parameters are 0.0996 and 0.00211. The lance length of the heat exchanger for Maiti-sarangi and Manglik-Bergles co-relation is 0.119 m and 0.11 m. the value of fin frequency of heat exchanger calculated by Maiti-sarangi co-relation is 73.21 less than Manglik-Bergles co-relation by 77.36. The pressure drops is 0.3419 n/m^2 for the a fluid and for the b fluid is 0.0378 n/m^2 in Maiti-sarangi co-relation but in Manglik-Bergles co-relation, the pressure drops are 0.3811 n/m^2 and 0.0282 n/m^2 which is increased for fluid a and decreased for fluid b. Effectiveness of heat exchanger is 0.8306 in Maiti-sarangi co-relation and 0.7924 in Manglik-Bergles co-relation which shows decrement in that parameter. The desired value of minimum entropy generation unit of the heat exchanger obtained using the correlations developed by maiti and sarangi is 0.1671 which is decreased to 0.1533 in Manglik-Bergles co-relation.

Comparison between Manglik-Bergles co-relation and Joshi-Webb co-relation

For the Manglik-Bergles co-relation, length of heat exchanger for fluid a and b are 0.419 m and 0.211 m while in Joshi-Webb co-relation length of heat exchanger for fluid a and b are 0.412m and 0.211m. Number of fin layers for fluid a and b are same for both co-relation and the values are 3 and 4. Convective heat transfer coefficient for fluid a and fluid b are 1.3493 W/m^{2}K and 2.11732 W/m^{2}K in Manglik-Bergles co-relation but in Joshi-Webb co-relation these values are 1.2545 W/m^{2}K and 2.0427 W/m^{2}K and its decreased. Height and thickness of fin are 0.098 and 0.00197 calculated by Joshi-Webb co-relation which is increased for height and thickness of fin in Manglik-Bergles co-relation and the values of these parameters are 0.104 and 0.00199. The lance length of the heat exchanger for Manglik-Bergles and Joshi-Webb co-relation is 0.11 m and 0.131 m. the value of fin frequency of heat exchanger calculated by Manglik-Bergles co-relation is 77.36 less than Joshi-Webb co-relation by 70.72. The pressure drops is 0.3811 n/m^2 for the a fluid and for the b fluid is 0.0282 n/m^2 in Manglik-Bergles co-relation but in Joshi-Webb co-relation, the pressure drops are 0.4577 n/m^2 and 0.0323 n/m^2 which is decreased for fluid a and b. Effectiveness of heat exchanger is 0.7924 in Manglik-Bergles co-relation and 0.7969 in Joshi-Webb co-relation which shows increment in that parameter. The desired value of minimum entropy generation unit of the heat exchanger obtained using the correlations developed by Manglik-Bergles co-relation is 0.1533 which is decreased to 0.1514 in Joshi-Webb co-relation.

TABLE-2
COMPARATIVE RESULTS OF DIFFERENT CORRELATION FOR MAXIMUM HEAT TRANSFER CO-EFFICIENT DESIGN

Sr. No	Design Parameter	Maiti-sarangi co-relation	Joshi-Webb co-relation	Manglik-Bergles co-relation
1	L_a (m)	0.459	0.412	0.419
2	L_b (m)	0.276	0.203	0.211
3	H (m)	0.0996	0.098	0.104
4	n(fins/m)	73.21	77.36	70.72
5	t (m)	0.00221	0.00197	0.00199
6	l (m)	0.119	0.131	0.11
7	N_a	3	3	3
8	N_g	4	4	4
9	h_a (W/m^{2}K)	2.1276	1.2545	1.3493
10	h_b (W/m^{2}K)	3.1359	2.0427	2.11732
11	ΔP_a (N/m^2)	0.3419	0.4577	0.3811
12	ΔP_b (N/m^2)	0.0378	0.0323	0.0282
13	ε	0.8306	0.7969	0.7924
14	N_s	0.1671	0.1514	0.1533

CONCLUSION

The determination of heat transfer co-efficient is one of the important thing for the design optimization of heat exchangers. This study demonstrates successful application of PSO for the thermodynamic design optimization of cross flow plate-fin heat exchanger based on different correlation for finding out heat transfer co-efficient and pressure drop. The effectiveness of the different co-relation and PSO algorithm was demonstrated using an application example. It is observed from the result that Maiti-sarangi co-relation result in maximum heat transfer co-efficient on fluid a side followed by Manglik-Bergles co-relation and Joshi-Webb co-relation. Similarly, Maiti-sarangi co-relation result in maximum heat transfer on fluid b side followed by Manglik-Bergles co-relation and Joshi-Webb co-relation.

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