MULTI-OBJECTIVE PARTICLE SWARM OPTIMIZATION OF THE K-TYPE SHELL AND TUBE HEAT EXCHANGER (CASE STUDY)

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ABSTRACT

This paper investigated optimization of two objectives function include the total amount of heat transfer between two mediums and the total cost of shell and tube heat exchanger. The study was carried out for k-type heat exchanger of the cryogenic unit of gas condensates by multiple objective particle swarm optimization. Six decision variables including pipe pitch ratio, pipe diameter, pipe number, pipe length, baffle cut ratio, and baffle distance ratio were taking into account to conduct this simulation-based research. The results of mathematical modeling confirmed the actual results (data collected from the evaporator unit of the Tehran refinery's absorption chiller). The optimization results revealed that the two objective functions of heat transfer rate and the total cost were in contradiction with each other. The results of the sensitivity analysis showed that with change in the pitch ratio from 1.25 to 2, the amount of heat transfer was reduced from 420 to 390 kW about 7.8%. Moreover, these variations caused reduction in cost function from 24,500 to 23,500 $, less than 1%. On the other hand, an increase in pipe length from 3 to 12 meters, the heat transfer rate raised from 365 to 415 kW by 13.7%, while the cost increased from 20,000$ to 24500$ about 22%.

Keywords: *Cryogenic, Heat exchanger, Optimization, Objective*

INTRODUCTION

In recent years, there is growing research on the application of optimization algorithms to solve the problems related to the heat exchanger and power generation units [1-14]. For example, some researchers examined the cost minimization of the t of initial investment based on the surface area of heat as the objective function [15]. While a number of other researchers considered the total cost including the initial investment cost on basis of the surface area of heat transfer plus the current costs including pumping cost as the objective function [16-21].

In other cases, by a number of researchers, the entropy generation is chosen as the objective function [22-24]. Application of GA (genetic algorithm) in heat exchanger optimization has been extensively considered by many researches taking into account of one, two and three objective functions [16, 18, 25-32].

Patel et al. [33] conducted a research on the shell and tube heat exchanger optimization using the particle swarm optimization (PSO). (PSO). In this study, the optimization results were compared with those found by the genetic algorithm, which demonstrate that the PSO algorithm has better predictive performance than the genetic algorithm. Dastmalchi et al. [34] investigated PSO algorithm for finned tubes in double pipe heat exchanger. Their results showed that the optimum height of fin was increased with increasing Reynolds number.

Sahin et al. [35] used the bee colony algorithm with design and optimize the shell and tube heat exchanger (STHE) in order to reduce the overall cost. The results of this study showed that the total cost of the heat exchanger can be reduced from 64480 $ to 50793 $ with utilizing the proposed optimization procedure. Zarea et al. [36] also used bee colony algorithm to optimize a plate fin heat exchanger. He concluded that this algorithm has better performance compared to other optimization algorithms mentioned in the associated paper. paper. Accordingly, in another study [36], they combined the mutation schemes of the Bees and PSO algorithms to optimize a heat exchanger of this type.

Azad and Amidpour [37] conducted the optimization of the STHE based on the structural theory. This theory was inspired by nature and was a new method of optimization in engineering applications. The results of this study showed a 50 percent reduction in total cost.

Rao and Patel [38] used a training optimization algorithm and selecting multiple independent variables to optimize heat transfer rate of STHE and a flat plate heat exchanger. Fetaka et al. [39] used nine independent variables in order to carry out heat exchange process under predefined imposed heat load. In this study, they selected non dominated sorting genetic algorithm (NSGA – 2) and compared their results with a research with one objective function [40]. They concluded that optimization with two objective functions has a better result. Other related studies on the optimization of heat exchanger with this algorithm were reported in literature [41,42].

Rao et al. [43] used the particle swarm optimization algorithm for optimization of heat exchanger with the design objectives of entropy generation, heat exchanger volume and annual cost of the mentioned heat exchanger. In this study, they obtained at least the volume of 0.0106 m^3 heat exchanger, and at least the annual cost of 3018 $ and minimum entropy production unit of 0.053 J/kg K.

In another study Rao and Saroj [44] proposed a new method of optimization which called elitist-Jaya algorithm. They concluded that this algorithm is better than other optimization algorithms. Also in another study associated with heat exchanger design, literature [45] they optimized a shell and tube heat exchanger with the proposed Jaya algorithm. In this analysis, they considered sedimentation of heat exchanger. They compared the results with other optimization methods such as genetic algorithm (GA), particle swarm optimization (PSO) and civilized swarm optimization (CSO). They concluded that this Jaya optimization has better results.

Segundo et al. [46] proposed an economic optimization of shell and tube heat exchanger by Tsallis differential evolution. They concluded that by using this method, total annual cost of the heat exchanger is reduced in the varying ranges between 27 to 55%.

Etghani and Baboli [47] utilized Taguchi method to carry out an optimization of a helical tube heat exchanger. In this study they considered exergy loss and total heat transfer rate as two optimization objectives and concluded that tube diameter and cold fluid mass flow rate have the most effect on exergy loss.
Several studies were conducted by Raja et al. about the optimization of heat exchanger with heat transfer search algorithm [48-50].

Turgut [51] did an optimization of shell and tube heat exchanger with a combination of backtracking search (BSA) and sine–cosine algorithm (SCA) algorithms. He compared this method of optimization with other optimization methods applicable in mechanical engineering.

In this study, two objective functions of total heat load and total heat exchanger costs are optimized simultaneously. In two objective functions, the answer is curve composed of non- dominated optimal solutions rather than a single optimum point. It should be mentioned the total cost include both investment cost and operational costs which accounts for the influences of the many auxiliary equipment. So far, there has been accomplished few comprehensive studies aiming to investigate two conflicting objective functions as well as sensitivity analysis for individual variables in a k-type of STHE at low temperature fluid. The mathematical model, type of heat exchanger and heat exchanger specification are considered in reference [16, 51-54]. In industry level, optimization of heat exchanger helps to reduction of energy consumption. Also, by multi-objective optimization instead of one optimized point, gives a graph (Pareto front) the user can select the best answer considering technical and economical point of views. For further research, combination of optimization algorithms can be considered.

The innovations of this research are:
- Definition of two objective functions and six variables for k-type STHE
- Optimization of k-type of STHE by MOPSO algorithm
- Sensitivity analysis for the independent decision variables

MATHEMATICAL MODELING

For a typical STHE, The following assumptions are considered in this analysis [51]:

- The evaporative fluid is R134A
- The coolant water is in the direction of the shell.
- R134 is delivered into the tubes in the form of saturated fluid, which is the quality of the coolant (cooler) at the pipe inlet section is 0.0 (x = 0.0).
- The Gungor-Winterson flow rate is used in order to calculate the heat transfer coefficient of the pipe side.
- The flow and temperature of the cold and hot fluid are considered as the input data of the modeling.

Detailed mathematical modeling is based on [51].

The required parameters to compute the total cost Ce, H, η, i , ny are 0.00012 \$/Wh, 7000 h, 0.9, 10% and 20 years, respectively.

The operational conditions of the current heat exchanger with the physical properties of the hot and cool fluid and the deposition resistance on the shell and the tube are presented in the following table. The modeling and the optimization carried out according to these operating conditions [51].

Table 1. The operational conditions for the studied converter.

Description	Unit	Tube side		Shell side
Fluid	(-)	R134a		water
Fluid Stream Type	(-)	Cold stream		Hot stream
Mass flow rate	(kg/s)	1.62		5.35
Inlet temperature T^i	(°C)	7		26
Outlet temperature T^o	(°C)	7		-
Fouling resistance r	(m^{2}K/W)	0.000176		0.000176
Fluid Phase	(-)	Vapor	liquid	liquid
Density ρ	(kg/m^3)	18.32	1271.3	998
Constant pressure specific heat c_p	(kJ/kg K)	929.9	1361.7	4182
Dynamic viscosity (Pa.s)	(Pa.s)	1.01E-5	2.48E-4	9.59E-4
Thermal conductivity	(W/m^{2}K)	0.12	0.088	0.606

PARTICLE SWARM OPTIMIZATION ALGORITHM (PSO)

In this topic, finding the optimum and the best acceptable solution for the given constraints and requirements of the problem is the main goal. For a given problem, maybe there are many different answers which could be obtained after the completed iterations. After that, these results should be compared to find the optimal solution, therefore this function is called the objective function [55].

The choice of this function depends on the nature of the problem and finding the proper objective function is one of the most important steps of optimization. In some occasion several objective functions are needed at the same time, such optimization issues are called multi - objective functions [55].

The simplest way to deal with such issues is to form a new objective function as a linear combination of the main objective functions, in which the effect of each function is determined by the weighting factors assigned to it. The second method consider both objective functions individually. In this case, instead of one point, a Pareto front (an optimal solution set) is achieved [55].

Each optimization problem has a number of independent variables called design variables or decision variables. The goal of optimization is to determine the design variables is to minimize or maximize objective function. In the optimization method, all feasible solutions and optimal solutions are defined. Optimization algorithms cover both maximization and minimization problems. Because the maximization problem is capable to be converted to minimization problem (by multiply the objective function in a negative sign) [55].

The PSO model is designed to investigate the sudden movement in the flight of birds, and to analyze the flight patterns by the optimal shape of cloud particles in the space. By careful study, the shift of the particle path from the flight pattern to its neighbors is concerned, each particle taking a pattern from another particle to move in the same way [55].

PSO optimization is one of the group optimization algorithms that operate on the basis of the random generation of the initial population. This algorithm is based on the modeling and simulation of the collective and mass fly behavior (group) of birds or mass movements (group) of fish [55].

Each member in the group is defined by the velocity vector and the position vector in the search space. In each iteration, the new position of the particles is defined due to the velocity vector and the position vector in the search space. At each iteration, the new position of the particles is updated according to the current velocity vector, the best location found by the particle and the best position found by the best particle in the group. This algorithm was initially defined for continuous parameters, but it is also extended to discrete state by considering that we deal with discrete parameters in some applications [55].

The implementation steps of the PSO algorithm are as follows [55]:

1. Random production of elementary particles
2. Choosing the number of elementary particles
3. Evaluation of objective function (based on cost or fitness function) of birds
4. Record of the best position for each particle as well as the best position among the entire particles
5. Convergence test

RESULTS AND DISCUSSION

Before optimizing, it is necessary to measure the validity of the mathematical model. In this regard, the results obtained from the model are compared with the actual results collected from evaporator unit of the Tehran refinery's absorption chiller. For this purpose, input data according to model with realistic HE data are considered and output variables such as heat transfer and pressure drop in the both sides of the STHE are calculated by the model. Finally, the actual results, which are collected from evaporator unit of the Tehran refinery's absorption chiller are compared with the modeling results and the percentage of errors are presented. The following results were obtained by virtue of the mathematical model presented in the preceding sections as well as in terms of the reported operational conditions above. As it can be seen, the error percentage in predicting the pressure drop across the tube and the shell is about 6 % and 8 %, respectively. In addition, deviation between actual and predicted heat transfer between the hot and cold fluid is about 5 %. The numerical results of the model validation are presented in Table 2 [56].

Table 2. Validation of the results of the mathematical modeling of the pipe shell.

Variable	Modeling value	Real value	Error %
(Pa) Tube pressure loss	14788	15700	6%
(Pa) Shell pressure loss	7505	8097	8%
(kW) Heat transferred	318.1	302.8	5%

The results of the validation on graph are presented in the Figure 1.
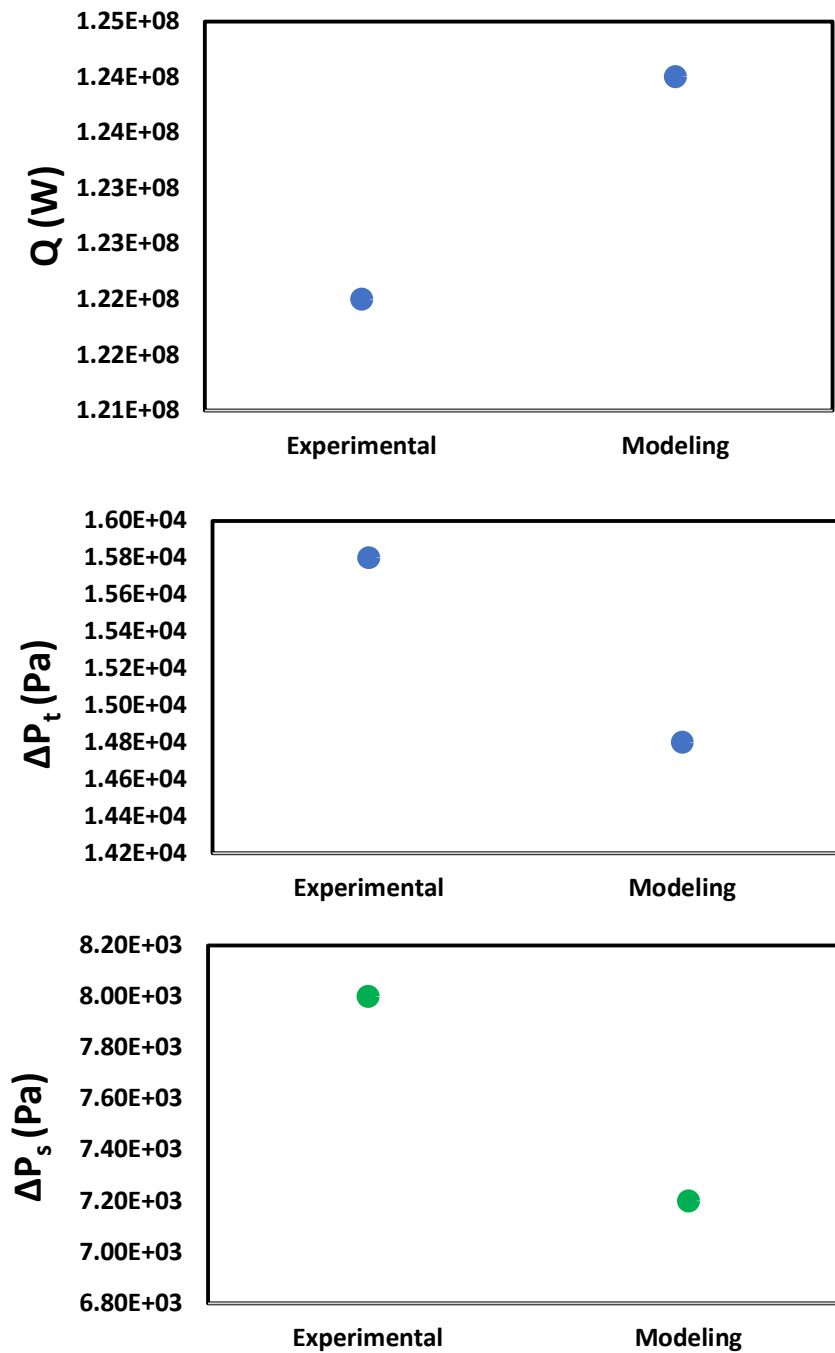
Figure 1. The validation graph of the modeling results of the pipe shell converter.

As it can be seen, the difference between the results of the model and the experimental results for the pressure drop for the shell and tube side as well as the heat transferred is low and insignificant. The actual pressure drop for the tube and shell side is around 15700 and 8097 Pa, while the pressure drop was calculated for the tube and the shell at about 14788 and 7505 Pa. Also, the amount of heat exchanged experimentally was obtained at about 122 MW, while it was calculated to model the value of 124 MW. So three important parameters of model were compared with experimental data acquired from the daily report of factory. They have a good agreement.

In this paper, six independent variables are considered based on the geometrical dimensions of the heat exchanger. These six variables influence the considered two objective functions of the problem, the function of heat transfer rate and the function of cost would change. These dependent variables and independent variables are represented by the following relationships.

$$Q = f\ (d_o, L, N, P_R, Bs, L_c) \tag{1}$$

$$Cost(\&) = g\ (d_o, L, N, P_R, Bs, L_c) \tag{2}$$

In this paper, the design constraint on the fluid pressure drops over the tube and the shell side as well as constraints on the period of change are considered as independent variables. In Tables 3 and 4 the constraints and limitations of the independent variables and pressure drop are presented as below:

Table 3. Constraints and constraints on the independent variables

Variable	Decision variable	Lower bound	Upper bound
d_o	Tube Outer diameter (mm)	10	25
N_t	Number of tube	50	500
L	Tube length (m)	3	12
Pt/d_o	Pitch tube ratio	1.25	2
L_C/D_s	Baffle cut ratio	0.2	0.32
B/D_s	Baffle spacing ratio	0.2	1.4

Table 4. Constraint on pressure drop

Variable	Decision variable	Lower bound	Upper bound
Δp_t	Tube side pressure drop (Bar)	0	1
Δp_s	Shell side pressure drop (Bar)	0	1

Pareto front depicted in Figure 2. shows the best obtained values of the two contradicting objective functions by the proposed MOPSO and non-dominating Pareto – optimal solution. As it can be seen in the following figure, the value of Q (the first objective function: heat transfer rate) is plotted against the C_{total} (the second objective function: heat exchanger cost. Target is maximizing the Q and minimizing the C_{total}. It is clear that increasing the heat transfer rate, increases the cost of heat exchanger and vice versa. It means that if we want a higher heat transfer, the heat exchanger cost is increased.

None of the compiled points in the Pareto frontier are superior to each other. For example, point A is the optimum value for the total heat load (the first objective function), while the total cost (the second objective function) is undesirable value at its maximum. On the other hand, the point of D, heat load is not desirable, but the cost is desirable (at least possible cost).
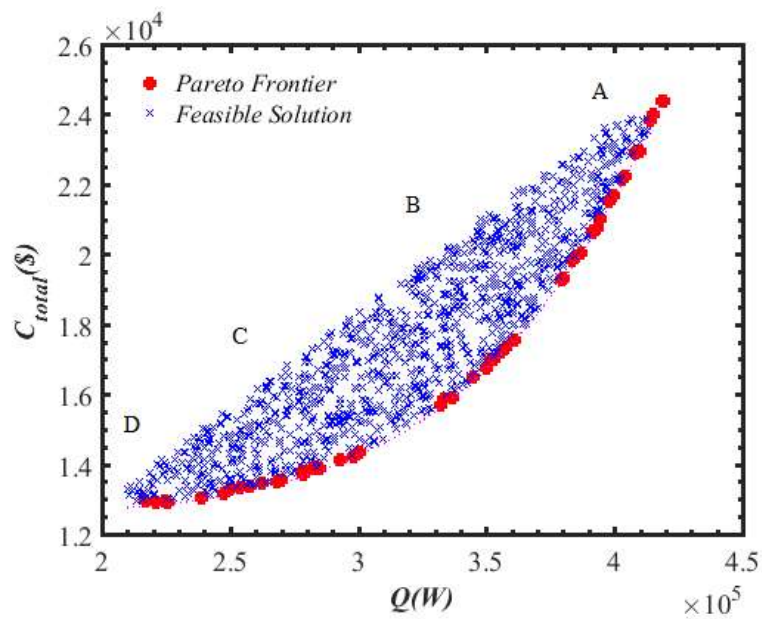
Figure 2. Optimal solutions of the two - objective function for STHE.

Therefore, none of the points A, B, C, D are superior to each other, but among all possible solutions, the best values are achieved along the Pareto frontier. As it can be seen in the figure, the Pareto points provide the lowest possible cost per peak of the heat capacity. Each point in the two dimensional q - cost plane refers to a solution where the calculations are obtained. The numerical results of design variables at two solution points A and D are listed in the following table. The values of the independent variables with values corresponding to the objective functions are presented in this table.

Table 5. Design data for points A and D.

Discription	Variable	Unit	A	B	C	D
Heat transfer	q	kW	420.0	378.7	320	212.1
Total cost	C_{total}	$	24630	18010	14970	12810
Tube diameter	d_o	mm	24.9	24.9	24.9	24.9
Number of Tube	N_t	-	499	391	253	100
Length of Tube	L	m	11.9	9.9	7.1	4
Tube pitch Ratio	P_t	-	1.88	1.91	1.93	2
Baffle cut ratio	Bs	-	0.2	0.20	0.20	0.2
Baffle spacing ratio	L_C/D_S	-	0.21	0.23	0.23	0.24

The influence of sensitivity analysis can be used to determine the effect of each independent variable on the dependent variables. In sensitivity analysis, all variables are assumed to be fixed and only one variable is changed in the allowed range. The results are obtained from the sensitivity analysis as they are shown in Table 6. and Figures 3 to 7.

Table 6. The sensitivity analysis of the independent variables at points A, B, and C, D.

Figure Number	The impact on the cost function	The impact on the q	Independent variable
6	Decrease with average slope decrease	Decrease with low slope	(P_t/d_o) Increasing the tube steps
7	Increase with high slope	Increase with high slope	(L) Increasing the length of the tube
8	Increase with high slope	Increase with high slope	(N_t) Increasing the number of tubes
9	Decrease with high slope	Decrease with low slope	(Bs) Increasing the distance of baffles
10	Decrease with low slope	Decrease with low slope	(l_c/D_s) Increasing the cutting of baffles

In above table, steps of sensitive analysis related variables change on target functions are shown. Each of changes is shown in following figures.

In Figure 4. the effect of the pipe step ratio (Pt / N) is reflected on the heat transfer rate and the total cost of the heat exchanger. Pt is the center distance from the center of the two adjacent tubes in mm. and do is outer diameter of tube in mm. The allowed range of variation of this variable is between 1.25 and 2 in accordance with the Table 4., by changing this variable in this range, as shown in the following figure. As it can be seen, the effect of tube step on the cost is negligible while the effect on the transferred heat is relatively significant. Such that at the design point A by changing the pipe step ratio from 1.25 to 2, the amount of transferred heat reduce from 420 to 390 kW (8.7 % reduction). On the other hand, the total cost is reduced from 24500$ to 23500$ (less than 1 %). In justifying the above mentioned cases, it can be concluded that with increasing of pipe step, the velocity of the flow rate in the shell side decreases, and by reducing the heat transfer coefficient, the total heat transfer is reduced. Also due to the flow rate reduction on the shell side the pressure drops deceases and therefore the operational cost as well as the total cost are reduced.
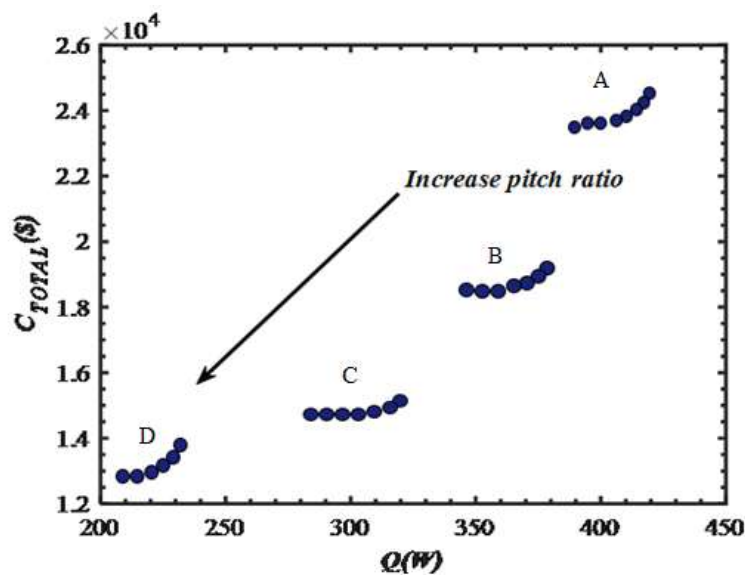

Figure 3. Effect of variable increase on the cost and heat transferred functions

In Figure 4., the cost and heat transfer curve is plotted when the length of the tube varies from 3 to 12 m. As it shows, at point A with increasing the length of the pipe from 3 to 12 m, the heat transfer rate increases from 365 to 415 kW (13.7 % increase), while the total cost increases from 20000$ to 24500$ (22% increase). As it is expected, the effect of the increase of pipe length is significant. Because by the increase of the pipe length and surface of the heat exchanger, increasing the cost of operation and investment. So for selection of best point, we have a choice that how much cost we can pay for increasing the heat transfer.
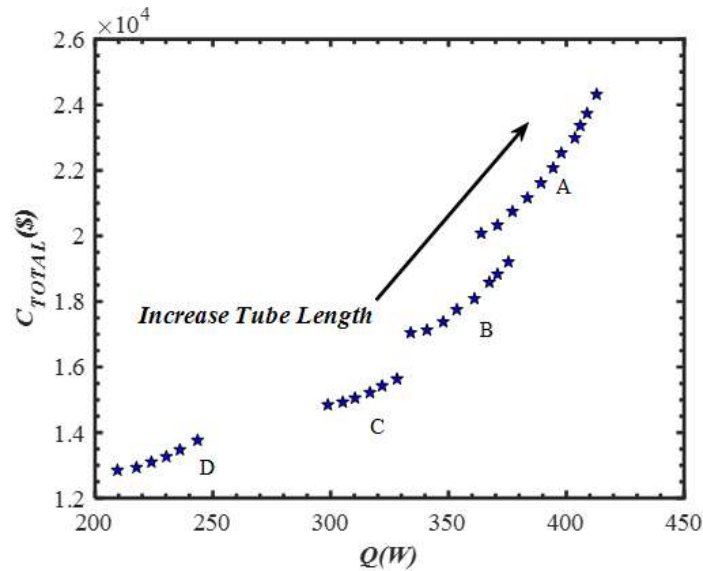

Figure 4. Effect of increasing the variable on cost and heat transfer rate

The analysis outcomes of the number of tubes are approximately similar with the analysis related to the length of the tube, as it is plotted in Figure 5. The cost and transferred heat curve when the number of tubes varies from 50 to 400. As it is shown, increasing the number of tubes increases the heat transfer rate and the cost as well. The increase in the number of tubes increases the surface area of the heat exchanger and increases the cost of purchase and investment. This increase is more considerable for point D that has a lower cost and heat transfer.
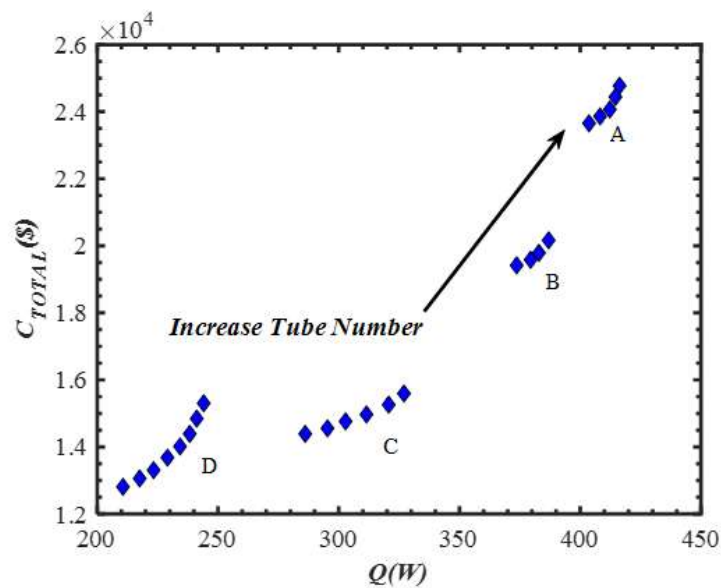

Figure 5. Effect of increasing the variable on cost and heat transfer

In Figure 6. with the increase of baffle space distance, the cost as well as heat transfer rate in the heat exchanger is decreased due to increasing the baffle distance and therefore the flow disturbance is reduced. Moreover, increasing baffle distance causes the decrease in flow disturbance and decreases the pressure drop as well as the operational cost. At the point A, by increasing baffle distance from 20 % to 140 % of the shell diameter, the heat transfer rate is reduced to 6.25 % and the reduction cost is reduced 5.5 %.

Figure 7. shows the effect of baffle cut. As it is shown, this variable has little effect on the cost and heat transfer rate. With increase of the baffle cut due to reduce flow disturbance the pressure drop is reduced lead to the reduction of the total cost. At the point A, by increasing the baffle cut from 20 % to 32% of the shell diameter, heat transfer rate and cost is decreased by 2.5 % and 2 %, respectively.
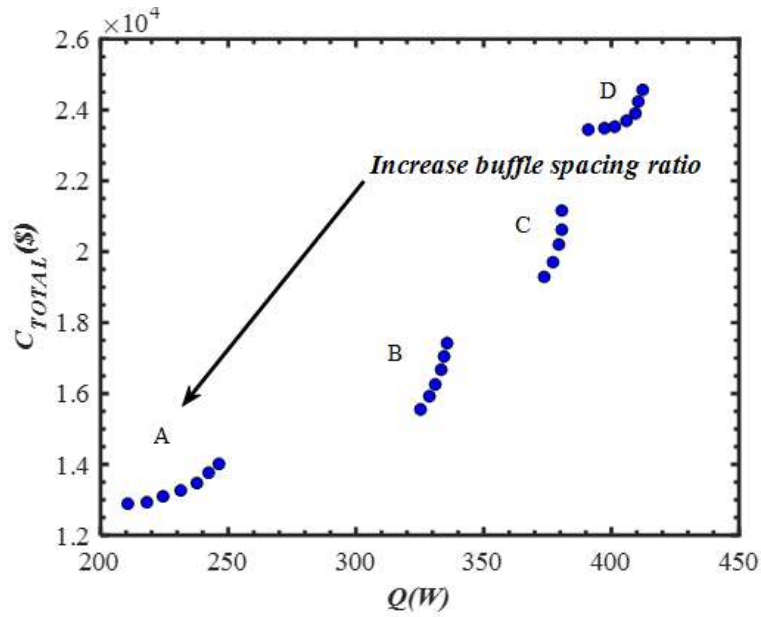

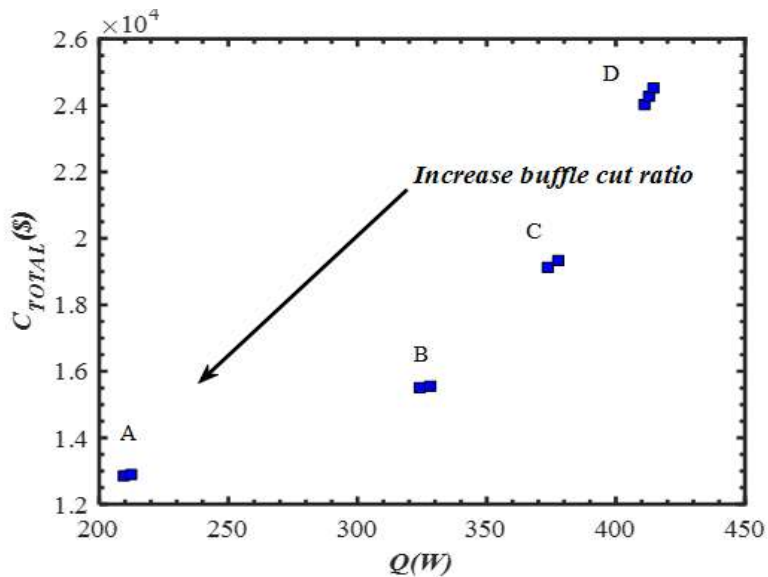**Figure 6**. Effect of variable increase on cost and heat transfer

Figure 7. Effect of variable increase on cost and heat transfer

CONCLUSION

In this paper, the two objective optimization of the shell and tube heat exchanger were carried out by considering six decision variables (pipe pitch, tube diameter, tube length, baffle ratio and baffle distance) with the assistance of the PSO algorithm. Optimization of heat exchanger with this algorithm give a view to user to select the best answer considering heat transfer and heat exchanger costs.

The modeling and optimization results were as follows:

- Modeling results of mathematical approaches were well matched to the actual results (data collected from the evaporator unit of the Tehran refinery's absorption chiller). The error rate in the pipeline pressure drops and the shell, was calculated at about 6 % and 8 % respectively, and the error rate in the prediction of heat transfer between the hot and cold fluid at about 5 %.
- The ratio of tube step to tube diameter had a slight effect on the cost while its effect on heat transfer rate was relatively significant (the allowable range of this variable was between 1.25 and 2).
- The analysis of the number of tubes, approximately similar with the length of the tube. When the number of tubes varied from 50 to 400, increased the heat transfer rate and the cost as well. The increase in the number of tubes increased the surface area of the heat exchanger and increased the cost of purchase and investment.
- By the increase of baffle space distance, the cost as well as heat transfer rate in the heat exchanger were decreased due to increasing the baffle distance and therefore the flow disturbance was reduced. Moreover, increasing baffle distance caused the decrease in flow disturbance and decreases the pressure drop as well as the operational cost.
- The effect of baffle cut had little effect on the cost and heat transfer rate. With increase of the baffle cut due to reduce flow disturbance the pressure drop was reduced lead to the reduction of the total cost.
- By increase the pitch ratio from 1.25 to 2, the heat transfer was reduced from 420 to 390 kW about 7.8%.
- Increasing the pipe length from 3 to 12 m, the heat transfer rate raised from 365 to 415 kW by 13.7%, while the cost increased from 20,000$ to 24500$ about 22%.

NOMENCLATURE

B Baffle spacing (m)

d_o Tube outside diameter (m)

L Tube length (m)

N Number of rows

Pr Reduced pressure (pa/psat)

Q Heat load (W)

Greek Symbols

μ Dynamic viscosity (Pa s)

ρ Density (kg/m^3)

η Pumping efficiency

Subtitle

b Bulk

f Fluid

i Inlet

o	Outlet
l	Liquid
g	Gas
s	Shell
t	Tube
w	Wall

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