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Original Research Article

Determining the design parameters for manufacturing a shell and tube heat exchanger with minimum cost using The Bees Algorithm

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ABSTRACT

The shell and tube heat exchanger is one of the commonly used heat exchangers. Minimizing the cost required to manufacture these heat exchangers is one of the main objectives for designers and users. This study determined the necessary design parameters for a shell and tube heat exchanger to be manufactured with minimum cost using The Bees Algorithm (BA). These design parameters are the shell side inside diameter, the tube side outside diameter, and the baffle spaces. The system mathematical model is created to find the optimum values of these parameters, the necessary boundary conditions are determined, and an optimization study is carried out. The cost obtained by BA $ 11187.86 compared with GA $ 11190.17 and SPQ $ 18429.4 from the literature. It is observed that The Bees Algorithm (BA) gives successful results in the design of shell and tube heat exchangers.

Keywords: Design optimization; Mathematical Modelling; Heat transfer; Shell and tube heat exchanger; The Bees Algorithm

1. Introduction

Heat exchangers are devices that allow two or more fluids at different temperatures to transfer their heat from one to the other without mixing (contacting). Although the usage areas of heat exchangers are extensive, they are widely used in thermal power plants, nuclear power plants, automotive industry, food industry, pharmaceutical industry, petrochemical industry, building heating, cooling, and air conditioning.

One of the most widely used heat exchangers is shell and tube heat exchangers shown in Fig.1. Shell and tube heat exchangers are among the most widely used heat exchangers, especially in the process industry. This is because they are easy to manufacture and can adapt to different working conditions. Minimizing the cost required to manufacture these heat exchangers is one of the main objectives for designers and users. For the design of heat exchangers, it is necessary to determine the design geometry and the operating parameters of the fluids. In this study, these geometric and working parameters and the system boundary conditions is determined. These boundary conditions are the mass flow rates of the fluids flowing from both sides of the heat exchanger, the inlet and outlet temperatures of the fluid on both sides, the fluid densities, the viscosity values of the fluids, the specific heat capacities of the fluids at constant pressure, the thermal conductivity coefficients of the fluids, the number of tubes, etc. values like. Based on these values, the heat transfer coefficients on both sides are the heat transfer coefficients, and the pressure drop on both sides can be calculated. Using the pressure drop amounts, the pumping

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power of the heat exchanger is calculated and based on this power value, the optimum cost required to manufacture the heat exchanger is calculated. The cost required to manufacture the heat exchanger is a function of the pressure drop on both sides. Therefore, determining the amount of pressure drop has an important place in the optimum design of heat exchangers.

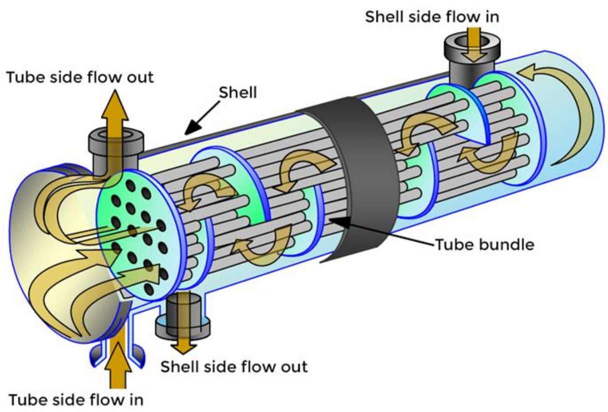

Fig. 1. Shell and tube heat exchanger

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There are many studies in the literature related to the design optimization of shell and tube heat exchangers. It is seen in the studies on the structural analyzes and flow analyzes of the heat exchangers on the ANSYS platform [1, 2]. Besides the ANSYS analysis optimization algorithms widely used in the optimal design of heat exchanger studies. Okbaz et al. compared computational CFD results with the experimental PIV results for the louvered fin and round tube heat exchangers [3]. Kumar et al. used the sequential quadratic programming algorithm and determined the optimum cost amount from the pressure drop amounts of a shell and tube heat exchanger [4]. The design parameters that provide this cost are the shell side inner diameter, tube side outer diameter, and distance between the flow guides. Chowdhury et al. used the Genetic Algorithm to find the optimum cost of shell and tube heat exchanger using the same parameters as Kumar et al. [5]. In this study, it is seen that they found a lower cost value than the cost value found by Kumar et al. and achieved a more successful result using the MATLAB platform. Patel and Rao determined more than three parameters using the Particle Swarm Optimization algorithm [6]. In this study, they carried out simulations for four cases and simulation studies for heat exchangers with different thermal power operating with different fluids. Selbas et al. also determined that genetic algorithm application can be used to determine the minimum cost of shell and tube heat exchangers [7]. Besides conventional algorithms, modern algorithms also used such as Improved Intelligent Tuned Harmony Search algorithm, Teaching-Learning based Optimization Algorithm, Water Cycle algorithm in the solution of complex and highly variable thermal systems [8-11].

2. Material and Methods

2.1. Mathematical modeling of shell and tube heat exchanger

The mathematical model of the shell and tube heat exchanger system is created in two stages. In the first stage, calculations are made using the system's parameters in terms of heat transfer. In the next step, the calculations of the pressure drop amounts on both sides are made. Finally, the pumping power of the heat exchanger is calculated based on the pressure drop amounts and the total cost can be calculated based on the pumping power.

In this study, the fluid on the tube side is crude oil and the fluid on the shell side is gas oil. In this system, the temperature of the crude oil, which is the fluid on the tube side, increases thanks to the hotter fluid gas oil on the shell side, and the gas oil cools by giving its heat to the crude oil. The optimized design parameters in this study are given in Table 1.

Table 1. Design parameters

D_s [m]	Shell inside diameter
d_o [m]	Tube outer diameter
B [m]	Baffle spacing

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The tube side heat transfer coefficient is calculated using equation (1) if the tube side Reynolds number is less than 2300.

$$h_f = \frac{k_t}{d_i}\left(3.657 + \frac{\left(0.0677*Re_t*Pr_t*\left(\frac{d_i}{L}\right)\right)^{1.33^{1/3}}}{1+0.1*Pr_t*(Re_t*\left(\frac{d_i}{L}\right)^{0.3}}\right) \quad (1)$$

The tube side heat transfer coefficient is calculated using equation (2) if the tube side Reynolds number is between 2300 and 10000.

$$h_f = \frac{k_t}{d_i}\frac{\frac{f_t}{8}*(Re_t-1000)*Pr_t}{\left(1+12.7*\left(\frac{f_t}{8}\right)^{0.5}*(Pr_t^{\ 0.667}-1)\right)}*\left(1+\frac{d_i}{L}\right)^{0,67} \quad (2)$$

The tube side heat transfer coefficient is calculated using equation (3) if the tube side Reynolds number is greater than 10000.

$$h_f = 0.027*\frac{k_t}{d_o}*Re_t^{\ 0,8}*Pr_t^{\ 0.667}*\left(\frac{\mu_t}{\mu_{wt}}\right)^{0,14} \quad (3)$$

In these equations, k_t tube side thermal conductivity coefficient, d_i tube inner diameter, Re_t Reynolds number on the tube side, Pr_t Prandtl number on the tube side, L tube length, f_t tube side friction coefficient, μ_t tube side The viscosity value of the fluid on the side of the tube, μ_{wt} refers to the viscosity value on the wall on the tube side, d_o tube outer diameter, and d_i tube inner diameter is taken as 80% of the tube outer diameter.

The coefficient of friction on the tube side f_t also refers to the Darcy coefficient of friction and is calculated using equation (4):

$$f_t = (1.82\log 10^{Re_t} - 1.64)^{-2} \quad (4)$$

The Reynolds number Re_t on the tube side is calculated using equation (5):

$$Re_t = \frac{\rho_t*v_t*d_i}{\mu_t} \quad (5)$$

In the above equation, ρ_t represents the density of the fluid on the tube side, v_t represents the velocity of the fluid on the tube side, and the flow velocity on the tube side is calculated using equation (6):

$$v_t = \frac{m_t}{\left(\frac{\pi}{4}\right)*d_i^{\ 2}*\rho_t}\left(\frac{n}{N_t}\right) \quad (6)$$

In this equation, m_t represents the mass flow rate of the fluid on the side of the tube, n the number of tube passes, N_t the number of tubes. The number of tubes is taken as 60.

The Prandtl number on the tube side is calculated using equation (7):

$$Pr_t = \frac{\mu_t*C}{k_t}d_i = 0.8d_o \quad (7)$$

In this equation, m_t expresses the specific heat capacity of the fluid on the tube side at constant volume.

The heat transfer coefficient on the shell side is calculated using equation (8):

$$h_s = 0,36*\frac{k_t}{d_e}*Re_s^{\ 0,55}*Pr_s^{\ 1/3}*\left(\frac{\mu_s}{\mu_{wts}}\right)^{0,14} \quad (8)$$

In the above equation, k_t expresses the thermal conductivity coefficient of the fluid on the shell side, d_e diameter value on the shell side, Re_s Reynolds number on the shell side, Pr_s Prandtl number on the shell side, μ_s viscosity value of the fluid on the shell side, μ_{wts} expresses the viscosity value on the wall on the shell side.

The equivalent diameter value on the shell side d_e is calculated using equation (9) if the arrangement of the tubes is square.

$$d_e = 4*\frac{S_t^{\ 2}-(\pi*0.25*d_o^2)}{\pi*d_o} \quad (9)$$

In this equation, S_t represents the length between the centers of the tubes and is taken as 25% more than the outside diameter of the tube.

In this study, the arrangement of the tubes is accepted as a triangular arrangement. The equivalent diameter value on the shell side d_e is calculated using equation (10) if the arrangement of the tubes is triangular.

$$d_e = 4*\frac{0.43*S_t^{\ 2}-(\pi*0.5*d_o^2)}{0.5*\pi*d_o} \quad (10)$$

The cross-sectional area normal to the flow direction is calculated using equation (11).

$$A_s = D_s*B*\left(1-\frac{d_o}{S_t}\right) \quad (11)$$

In the above equation, D_s shell inner diameter, B denotes the distance between the flow guides.

The flow velocity on the shell side is calculated using equation (12):

$$v_s = \frac{m_s}{\rho_s*A_s} \quad (12)$$

In the above equation, m_s refers to the mass flow rate of the fluid at the shell side, and ρ_s refers to the density of the fluid at the shell side.

The Reynolds number on the shell side is calculated using equation (13):

$$Re_s = \frac{m_s*d_e}{\mu_s*A_s}Pr_s \quad (13)$$

The Prandtl number on the shell side is calculated using equation (14):

$$Pr_s = \frac{\mu_s*c_{p_s}}{k_s} \quad (14)$$

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In the above equation, c_{p_s} denotes the specific heat capacity of the shell side fluid at constant volume.

The overall heat transfer coefficient U is calculated using the following equation (15):

$$U = \frac{1}{\left(\frac{1}{h_s}\right) + R_{fs} + \left(\frac{d_o}{d_i}\right) * \left(R_{ft} + \left(\frac{1}{h_t}\right)\right)} \quad (15)$$

In the above equation, R_{fs} and R_{ft} represent the contamination factors on the shell and tube side.

The logarithmic mean temperature is calculated using equation (16):

$$LMTD = \frac{(T_{hi} - T_{co}) - (T_{ho} - T_{ci})}{\ln((T_{hi} - T_{co})/(T_{ho} - T_{ci}))} \quad (16)$$

In the above equation, T_{hi} and T_{ho} outlet are the inlet and outlet temperatures of the shell side fluid; T_{ci} and T_{co} represent the inlet and outlet temperatures of the fluid on the tube side.

The correction factor F used to calculate the heat transfer area is calculated using equation (17):

$$F = \sqrt{\frac{R^2+1}{R-1}} * \frac{\ln((1-P)/(1-P*R))}{\ln((3-P*R-\sqrt{R^2+1})/(3-P*R+\sqrt{R^2+1}))} \quad (17)$$

In the above equation, R stands for the correction coefficient. The coefficient of correction R is calculated using equation (18):

$$R = \frac{T_{hi} - T_{ho}}{T_{co} - T_{ci}} \quad (18)$$

The P value in equation (17) represents efficiency and is calculated using equation (19):

$$P = \frac{(T_{co} - T_{ci})}{(T_{ho} - T_{ci})} \quad (19)$$

The heat exchanger surface area where heat transfer takes place is calculated using equation (20):

$$A = \frac{Q}{U * F * LMTD} \quad (20)$$

In the above equation, $\dot{Q}$ refers to the amount of heat transfer. The amount of heat transfer is calculated using equation (21) and equation (22):

$$\dot{Q} = \dot{m}_h * c_{p_h} * (T_{hi} - T_{ho}) \quad (21)$$

$$\dot{Q} = \dot{m}_c * c_{p_c} * (T_{co} - T_{ci}) \quad (22)$$

Starting from the heat exchanger surface area, the required tube length for heat transfer is calculated using equation (23):

$$L = \frac{A}{\pi * d_o * N_t} \quad (23)$$

The pressure loss on the tube side is equal to the sum of the pressure loss along the tube length and the amount of pressure loss in parts such as elbow, inlet and outlet nozzle. The total pressure loss is calculated using equation (24). $p = 4$ is taken as [6].

$$\Delta p_t = \frac{\rho_t * v_t^2}{2} * \left(\frac{L * f_t}{d_i} + p\right) * n \quad (24)$$

The total amount of pressure loss on the shell side is calculated using equation (25):

$$\Delta p_s = f_s \left(\frac{\rho_s * v_s^2}{2}\right) \left(\frac{L}{B}\right) \left(\frac{D_s}{d_e}\right) \quad (25)$$

In the above equation, f_s denotes the friction coefficient on the shell side. f_s is calculated using equation (26). b_o= 0.72 is taken [6].

$$f_s = 2 * b_o * (Re_s)^{-0,15} \quad (26)$$

The pumping power of the heat exchanger is calculated using the following equation (27). η denotes pumping efficiency and is taken as 0.70.

$$P = \frac{1}{\eta} \left(\frac{m_t * \Delta p_t}{\rho_t} + \frac{m_s * \Delta p_s}{\rho_s}\right) \quad (27)$$

Total cost is defined as the objective function in the MATLAB program. The total cost includes the sum of the capital and the annual operating costs associated with the pumping power to overcome friction losses.

The principal cost is a function of the heat exchanger's surface area and is calculated using equation (28). a_1 =8000, a_2=259.2 and a_3=0.93 [8]. The annual operating cost is calculated using equation (29). C_e = 0.12 $/kWh [1]. This value is the energy cost per kilowatt-hour. It is taken as H = 7000 hours [1]. This value is also the annual working hours. The total cost is calculated using equation (30):

$$C_i = a_1 + a_{2A} * A^{a_3} \quad (28)$$

$$C_{od} = P * C_e * H \quad (29)$$

$$C_{tot} = C_i + C_{od} \quad (30)$$

The model parameters and values used in obtaining the mathematical model of the shell and tube heat exchanger are given in Table 2.

Table 2. Model parameters

	Shell Side	**Tube Side**
Fluid	**Kerosene**	**Crude Oil**
Mass Flow	5.52	18.8
T_i **[C°]**	199	37.8
T_o **[C°]**	93.3	76.7
ρ **[kg/m^3]**	850	995
C_p **[Kj/Kg-K]**	2.47	2.05
μ **[Pa-s]**	0.0004	0.00358
k **[W/m-K]**	0.13	0.13

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2.2. The Bees algorithm

The Bees Algorithm, first proposed by D.T. Pham et al. in 2006, has taken an intuitive view by likening The Bees Algorithm searching behavior for resources such as nectar and water to learning, remembering, and sharing information using swarm intelligence [12]. Kalyoncu laid the foundations of studies in the field with their studies that determine different controller parameters with The Bees Algorithm [13, 14]. In addition, Eser et al. to obtain maximum comfort in a quarter vehicle model used The Bees Algorithm to determine the suspension system parameters [15]. Zarea et al. carried out their studies on two shell-and-tube heat exchangers [16]. The first is a 4.34 MW heat exchanger with methanol and brackish water. The second one has a power of 0.415 MW and works with distilled water and untreated water. As a result of this study, they reduced the total cost by 54% compared to the study of Kern in 1950 [17]. They also found that The Bees Algorithm is fast in solving the design problem, can generate many alternative solutions, gives the designer more flexibility than other traditional methods, and quickly optimizes many thermal systems. Bozorgan et al. carried out an optimization study to maximize the total heat transfer coefficient and minimize the pressure loss by using The Bees Algorithm in a shell and tube heat exchanger [18]. For this, they determined five design parameters. These parameters are tube inner diameter, tube outer diameter, distance between tube centers, distance between flow directors and tube length. As a result of this study, which they carried out using The Bees Algorithm, they observed an increase of 22.78% in the total heat transfer coefficient with a low increase of 1.8% in the total pressure loss. They also observed an increase of 1% in the heat transfer coefficient and a 25% decrease in the pressure loss.

There are many parameters in the working principle of The Bees Algorithm. These:

Number of scout bees (*n*), number of the most suitable regions selected from n visited points (*m*), number of elite regions within m selected regions (*e*), number of bees sent to the best *e* region (*nep*), bees sent to the remaining (*m-e*) region number (*nsp*), region size (*ngh*), number of stopping criteria/iteration (*itr*).

The Bees Algorithm flow chart is shown in Fig. 2. As seen in the figure, this cycle continues until the optimization's stopping criterion (*itr*) is met. The Bees Algorithm parameters used in this study are shown in Table 3.

Table 3. The Bees Algorithm parameters

itr	*n*	*m*	*e*	*nep*	*nsp*	*ngh*
50	30	5	2	2	4	0.1

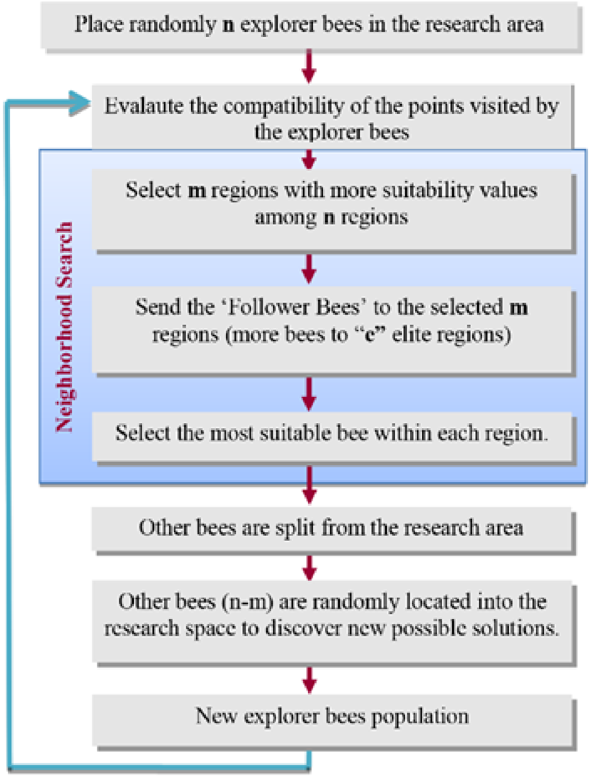

Fig. 2. Flowchart of The Bees Algorithm

3. Results and Discussion

In this study, the mathematical model calculations of the shell and tube heat exchanger and the determination of the design parameters with The Bees Algorithm is made on the Matlab platform. In the optimization study, the total pressure loss amount and the total cost is selected as the objective function and their minimization is taken as a basis. In order to keep the cost at a minimum, the parameters to be determined by optimization of the inner diameter of the shell, the outer diameter of the tube and the baffle spaces and the minimum and maximum values of these parameters is determined by examining the studies in the literature. The minimum and maximum values of the optimization parameters are given in Table 4.

Table 4. Optimization range of design parameters

	D_s	d_o	B
Min	0.2	0.015	0.2
Max	2	0.051	0.5

Kumar et al. In optimizing the shell and tube heat exchanger, the design parameters are determined with the SQP algorithm by using the *fmincon* command on the MATLAB platform. In addition, Chowdhury et al. used Genetic Algorithm. The design parameters and cost results determined by The Bees Algorithm are compared with the studies of Kumar and Chowdhury and are given in Table 5.

Table 5. Compared results

	BA	GA	SPQ
D_s [m]	0.4812	0.4830	1.0545
d_o [m]	0.0510	0.0510	0.0459
B [m]	0,5000	0.5000	0.5000
Cost [$]	11187.86	11190.17	18429.4

In the optimization study using The Bees Algorithm, it is seen that the result is reached quickly. The cost convergence graph is given in Fig. 3.

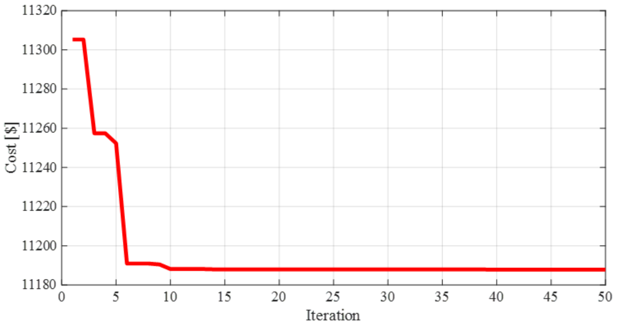

Fig. 3. The cost convergence

4. Conclusion

This study determined the required design parameters for a shell and tube heat exchanger to be manufactured with minimum cost using The Bees Algorithm. Three main geometric parameters are determined to minimize the cost. It is aimed to minimize the total cost as a function of the total pressure loss and the total pressure loss by giving these parameters at specific intervals. As a result of a specific iteration, the necessary optimum parameter values is obtained and the minimum cost value is reached. The results obtained with The Bees Algorithm is compared with the studies in the literature.

It is observed that The Bees Algorithm gives successful results in determining the design parameters of the shell and tube heat exchangers. Therefore, it can be used in optimization studies on different thermal systems using different configurations and objective functions. In addition, it can yield successful results in experimental and simulation studies.

Authorship contribution statement for Contributor Roles Taxonomy

Yusuf Ziya Akman: Writing - original draft, Investigation, Conceptualization. Abdullah Çakan: Visualization, Investigation, Writing – review & editing. Ahmet Ali Sertkaya: Investigation, Supervision. Mete Kalyoncu: Methodology, Software, Supervision.

Conflict of interest

The author(s) declares that he has no conflict of interest.

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