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Optimization of the Total Annual Cost in a Shell and Tube Heat Exchanger by Ant-Colony Optimization Technique

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Abstract: This paper examines the total annual cost from economic view heat exchangers based on ant colony optimization algorithm and compared the using optimization algorithm in the design of economic optimization of shell and tube heat exchangers. A shell and tube heat exchanger optimization design approach is expanded based on the total annual cost measured that divided to area of surface and power consumption. The optimization and minimization of the total annual cost is considered as the objective function. There are three parameters as decision variables in optimization algorithm such as tube outer diameter, shell diameter and central baffle spacing. Two cases studies considered to demonstrate the accuracy of algorithms Results have been compared with the findings of previous studies. The total annual cost is reduced about 10% and 40% for case 1 and 2 using ant colony optimization algorithm, respectively.

Keywords: Ant colony optimization, Shell and tube heat exchanger, cost analysis, kern method.

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1. Introduction

The Shell and tube heat exchangers (STHEs) are significant components in many industries such as in energy conversion systems. There are two fluid streams including hot and cold streams. Among the various types of heat exchangers, the shell and tube type is the most vastly used heat exchangers, which contribute approximately more than 65% of the exchangers in process industries [1]. The design of shell and tube heat exchangers, including thermodynamic analysis, cost estimation and optimization, represents a complex process containing an integrated whole of design rules and empirical knowledge of various fields [2]. A typical shell and tube heat exchanger are shown in Fig. 1.The design of STHEs involves a large number of geometric and operating variables as part of the search for an exchanger geometry. There are so many resrerch that has been carried out with objective functions aimed on reducing the total annual cost (T.A.C) and heat transfer area. Hall [3] optimized a heat

Exchanger network for minimizing the total annual costs in local levels, however there are better situations for these types of exchangers at a global level. The total annual cost of heat exchangers are calculated based on the sum of contain running costs and capital costs. Some researchers have used various optimization techniques to consider various objective functions to optimize the heat exchanger designs. Patel and Rao [4] optimized the shell and tube heat exchangers using three design parameters such as inside and outside tube diameter and spacing of baffles for two types of tube arrangements Triangle and Square tube pitch using a particle swarm optimization algorithm.

Selbas et al. [5] optimized a shell and tube heat exchanger from economical view using a genetic algorithm. However, objective function was heat transfer area. They showed that the total cost increases when as the heat transfer area increases. Caputo et al. [6] used genetic algorithm for optimizing a heat exchanger based on the total cost as an objective function.

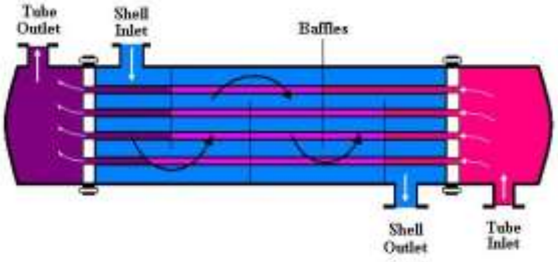

Fig.1 Diagram of a typical shell and tube heat exchanger.

Jose et al. [7] developed the heat exchanger efficiency for several practical cases through optimizing a shell and tube heat exchanger using a genetic algorithm, while Hilbert et al. [8] used a multi-objective optimization approach to maximize heat transfer and minimize total annual cost. Several other researchers also used strategies based on Genetic and traditional mathematical optimization algorithms [9] for various objective functions like minimum entropy generation [10,11] and minimum cost of shell and tube heat exchangers [12,13] to optimize total annual cost. Sadeghzadeh [14] demonstrated design of techno-economically optimum shell and- tube heat exchangers using of genetic and particle swarm algorithms. Total annual cost is the objective function and use Delaware method to calculate the heat transfer coefficient and the shell-side pressure drop.

Mohanty [17] studied a shell and tube heat exchanger optimization design approach and developed with respect to the total annual cost by application of Firefly algorithm. Karimi et al. [18] minimized the total annual cost in the mixed material heat exchanger. They used kern method to consider pressure drop and heat transfer coefficient in shell and tube side. However, they used three optimization techniques such as Genetic-particle swarm optimization (GA-PSO) and shuffled frog-leaping algorithm (SFLA) to minimize the total annual cost. In another research, Karimi et al. [19] studied a mixed materials heat exchangers networks. They used two methods for minimizing the total annual cost such as total and partial decomposition. In these methods, networks divided to two separated subsystems including corrosive and anti-corrosive flows and investigated separately. The total annual cost is decreased using the partial decomposition more than another method.

In the present work, ant colony optimization is applied to investigate reducing the total annual cost. The objective functions are to: 1. Optimize the influential parameters of STHEs, 2. Represent the effectiveness of ACO in the design optimization of STHEs from economic point of view . The kern method is used to determine heat transfer coefficients and the shell-side pressure drops. The optimization and minimization of the total annual cost is as objective function. The effect of ant colony optimization has been studied on the total annual cost. However, two cases studies have been considered for validation of results.

2. Mathematical Models

2.1. Heat transfer

According to flow regime, the tube side heat transfer coefficient (h_t) is computed from correlation as [17]:

$$h_t = \frac{k_t}{d_i}\left[3.657 + \frac{0.0667\left(Re_t Pr_t\left(\frac{d_i}{L}\right)\right)^{1.33}}{1 + 0.1 Pr_t\left\{Re_t\left(\frac{d_i}{L}\right)\right\}^{0.3}}\right] \quad (1)$$

(if $Re_t < 2300$ [7])

$$h_t = \frac{k_t}{d_i}\left[\frac{(f_t/8)(Re_t - 1000)Pr_t}{1 + 12.7(f_t/8)^{\frac{1}{2}}\left(Pr_t^{\frac{2}{3}} - 1\right)}\left(1 + \frac{d_i}{L}\right)^{0.67} \right. \quad (2)$$

(if $2300 < Re_t < 10{,}000$ [6])

$$h_t = 0.027\frac{k_t}{d_i}{Re_t}^{0.8}{Pr_t}^{\frac{1}{3}}\left(\frac{\mu_t}{\mu_{tw}}\right)^{0.14} \quad (3)$$

(if $Re_t > 10{,}000$ [6])

Where, f_t is the Darcy friction factor [15] given as:

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

Ret is the tube side Reynolds number and given by

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

Flow velocity for tube side is found by

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

N_t is the number of tubes and n is the number of tube passes which can be found approximately from the following equation [16, 17]

$$N_t = C\left(\frac{D_s}{d_o}\right)^{n_1} \quad (7)$$

C and n_1 are coefficients that are taking values according to flow arrangement and number of passes. These coefficients are shown in Table 1 for different flow arrangements.

Pr_t is the tube side *Prandtl* number and given by,

$$Pr_t = \frac{\mu_t C_{pt}}{k_t} \quad (8)$$

Also, di = 0.8do

Kern's formulation for segmental baffle shell-and-tube exchanger is used for computing shell side heat transfer coefficient h_s [17, 18]

$$h_s = 0.36\frac{k_t}{d_e}{Re_s}^{0.55}{Pr_s}^{\frac{1}{3}}\left(\frac{\mu_t}{\mu_{wts}}\right)^{0.14} \quad (9)$$

Where, de is the shell hydraulic diameter and computed as [6],

Table 1 Values of C and $\boldsymbol{n_1}$ coefficient [6].

No. of passes	**Triangle tube pitch $\boldsymbol{S_t = 1.25d_o}$**		**Square tube pitch $\boldsymbol{S_t = 1.25d_o}$**	
	C	n_1	C	n_1
1	0.319	2.142	0.215	2.207
2	0.249	2.207	0.156	2.291
4	0.175	2.285	0.158	2.263
6	0.0743	2.499	0.0402	2.617
8	0.0365	2.675	0.0331	2.643

$$d_e = \frac{4\left(S_t^2 - \frac{\pi}{4}d_o^2\right)}{\pi d_o} \quad (10)$$

(For square pitch)

$$d_e = 4\left(\frac{0.43S_t^2 - 0.5\frac{\pi}{4}d_o^2}{0.5\pi d_o}\right) \quad (11)$$

(For triangular pitch)

Cross section area normal to flow direction is determined by [5]:

$$A_s = D_s B\left(1 - \frac{d_o}{S_t}\right) \quad (12)$$

Flow velocity for the shell side can obtain from [5],

$$v_s = \frac{m_s}{\rho_s A_s} \quad (13)$$

Reynolds number for shell side follows

$$Re_s = \frac{m_s d_e}{A_s \mu_s} \quad (14)$$

Prandtl number for shell side follows,

$$Pr_s = \frac{\mu_s C_{ps}}{k_s} \quad (15)$$

The overall heat transfer coefficient (U) depends on both the tube side and shell side heat transfer coefficients and fouling resistances are given by [5],

$$U = \frac{1}{\frac{1}{h_s} + R_{fs} + \left(\frac{d_o}{d_i}\right)\left(R_{ft} + \left(\frac{1}{h_t}\right)\right)} \quad (16)$$

Considering the cross flow between adjacent baffle, the logarithmic mean temperature difference (LMTD) is determined by,

$$\Delta T_{LM} = \frac{(T_{hi} - T_{co}) - (T_{ho} - T_{ci})}{Ln\left[\frac{T_{hi} - T_{co}}{T_{ho} - T_{ci}}\right]} \quad (17)$$

The correction factor F for the flow configuration involved is found as a function of dimensionless temperature ratio for most flow configuration of interest [18].

$$F = \sqrt{R^2 + 1}\frac{Ln\ \frac{1 - P}{1 - PR}}{(R - 1)Ln\left(\frac{2 - P(R + 1 - \sqrt{R^2 + 1})}{2 - P(R + 1 + \sqrt{R^2 + 1})}\right)} \quad (18)$$

Where R is the correction coefficient given by:

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

P is the efficiency given by,

$$P = \frac{T_{co} - T_{ci}}{T_{hi} - T_{ci}} \quad (20)$$

Considering overall heat transfer coefficient, the heat exchanger surface area (A) is computed by:

$$A = \frac{Q}{UF\Delta T_{LM}} \quad (21)$$

For sensible heat transfer, the heat transfer rate is given by:

$$Q = m_h C_{ph}(T_{hi} - T_{ho}) = m_c C_{Pc}(T_{co} - T_{ci}) \qquad (22)$$

Based on total heat exchanger surface area (A), the necessary tube length (L) is:

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

2.2. Pressure Drop

The pressure drop in shell and tube heat exchanger is the static pressure which expended to drive the fluid through the exchanger. In all heat exchangers, there are physical properties and economical dependency between heat transfer and pressure drop. For a constant heat capacity in the heat exchanger, increasing the flow velocity will cause an up rise of heat transfer coefficient. However increasing flow velocity makes the more pressure drop in heat exchanger, which results in additional running cost. For this reason when designing a heat exchanger pressure drop must be considered with heat transfer and best solution for the system must be found. Tube side pressure drop includes distributed pressure drop along the tube length and concentrated pressure losses in elbows and in the inlet and outlet nozzle. [18]

$$\Delta P_t = \Delta P_{tube\ lenght} + \Delta P_{tube\ blew} \qquad (24)$$

As defined by Kern's relations [18], the pressure drop on tube side is [18]

$$\Delta P_t = \frac{\rho_t {v_t}^2}{2}\left(\frac{L}{d_i} f_t + p\right) n \qquad (25)$$

Different authors consider different values of constant p. Kern [20] assumed p = 4, while Sin not et al. [21] assumed p = 2.5. The shell side pressure drop is

$$\Delta P_s = f_s \left(\frac{\rho_s {v_s}^2}{2}\right)\left(\frac{L}{B}\right)\left(\frac{D_s}{d_e}\right) \qquad (26)$$

Where

$$f_s = 1.44 {Re_s}^{-0.5} \qquad (27)$$

For Res < 40,000 , b= 0.72 [6]

Pumping power obtained with to consider pumping efficiency (η)

$$P = \frac{1}{\eta}\left(\frac{m_t}{\rho_t}\Delta P_t + \frac{m_s}{\rho_s}\Delta P_s\right) \qquad (28)$$

3. Ant Colony Optimization Algorithm

Ant colony optimization (ACO) [22] is one of the optimization methods that has specifically been used in recent studies. The Inspirational source of ACO algorithms are real ant colonies. More specifically, ACO is inspired by the ants' foraging manner. Based on this behavior, the ants can indirectly communicate together using their chemical pheromone. This increase the ant's success in finding their nest and food resources using the shortest ways. This specification of real ant colonies have been used in ACO algorithms for example, for solving discrete optimization problems.

Therefore, ACO algorithms may belong to different classes of approximate algorithms. Seen from the artificial intelligence (AI) aspect, ACO algorithms are one of the most successful threads of swarm intelligence [23].

The design of intelligent multi-agent system is the aim of swarm intelligence by taking inspiration from the collective behavior of social insects such as ants, bees and other animal societies such as flocks of birds or fish schools. instances of "swarm intelligent" algorithms other than ACO are those for clustering and data mining inspired by ants' cemetery building manner [25], those for dynamic task dedicated inspired by the behavior of wasp colonies [24], and particle swarm optimization. Seen from the operations research (OR) perspective, ACO belong to the type of metaheuristics. The term metaheuristic, first introduced in [28], has been achieved from the composition of two Greek words. Heuristic has been extracted from the heuriskein means "to find", and the meta means "beyond, in an upper level". Before this term was adopted widely, metaheuristics were often called modern heuristics. Also ACO, other algorithms have often been regarded as metaheuristics such as evolutionary computation, iterated local search, simulated annealing, and tabu search.

Marco Dorigo introduced the first ACO algorithms [25]. The development of these algorithms has been developed by the observation of ant colonies. Ants are social insects. They live in colonies and their manner is managed by the aim of colony survival rather than being focused on the survival of others ants. When searching for food, ants initially search around of their nest in a random manner. With this moving, ants leave a chemical pheromone trail on the earth and others can smell pheromone. When choosing their paths, they desire to choose, most probably, ways marked by strong pheromone concentrations.

An ant investigates the quantity and the quality of the food and carries some of it back to the nest for finding food sources. During the return to nest, the quantity of pheromone may depend on the quantity and quality of the food. The pheromone trails that an ant leaves on the ground will guide other ants to the food source.

It has been shown in [26] that the indirect communication between the ants via pheromone trails enables them to find shortest ways between their nest and food sources. The ACO metaheuristic, as know it today, was first studied by Dorigo and colleagues [29]. The definition of the ACO metaheuristic covers most existing ACO types for discrete optimization problems. Fig. (2) showed flowchart of ant colony optimization.

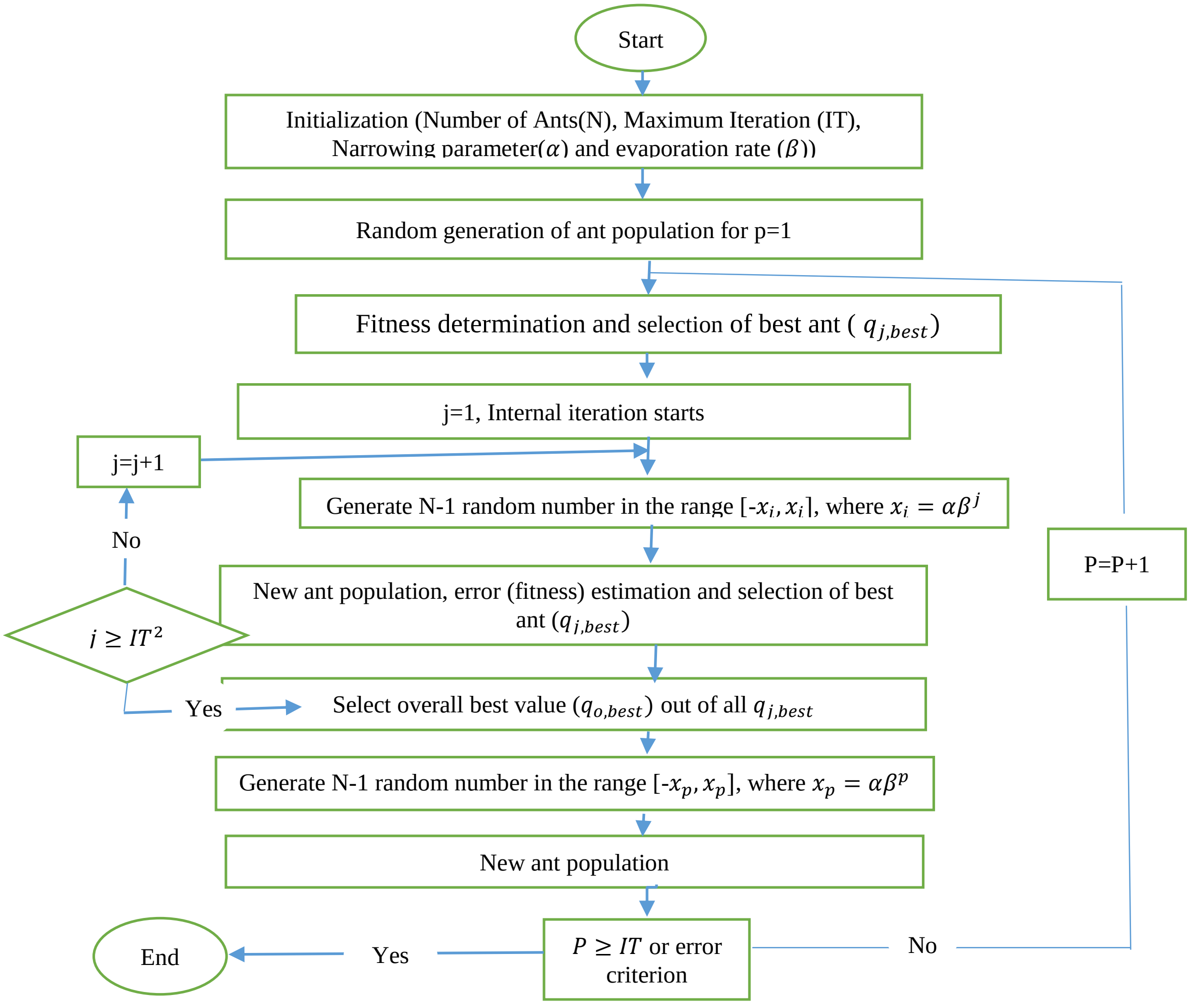

Fig. 2 Flow chart of the ACO.

Table 2. Process input data and physical properties for two case studies [6].

	$m\left(\frac{kg}{s}\right)$	$T_i(^oC)$	$T_o(^oC)$	$\rho(\frac{kg}{m^3})$	$C_P(\frac{J}{kg})$	$\mu(Pa\ s)$	$k\left(\frac{W}{mk}\right)$	$R_f(\frac{m^2k}{W})$
Case 1 **Shell side: methanol** **Tube side: sea water**	27.8 68.9	95 25	40 40	750 995	2840 4200	0.00034 0.0008	0.19 0.59	0.00033 0.0002
Case 2 **Shell side: distilled water** **Tube side: raw water**	22.07 35.31	33.9 23.9	29.4 26.7	995 999	4180 4180	0.00008 0.000092	0.62 0.62	0.00017 0.00017

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4. Objective Function

In this work, the total annual cost (C_{tot}) has been defined as the objective function. The total annual cost is calculated taking into account the capital investment cost (Ci), energy cost (Ce), annual operating cost (Co) and the total discounted operating cost (Cod) as considered by Caputo et al. [6].

$$C_{tot} = C_i + C_{od} \tag{29}$$

The capital investment is computed as a function of heat exchanger surface area according to Tall et al. [27].

$$C_i = a_1 + a_2 A^{a_3} \tag{30}$$

Where a_1 is Installation factor, a_2 is Material factor and a_3 is exponent. heat exchangers has been made by stainless steel for both shell-and-tubes sides. Therefore, a_1 = 8000, a_2 = 259.2 and a_3 =0.93 [27]. The total discounted operating cost related to pumping power for overcome friction losses is computed from the following equation

$$C_o = PC_eH \tag{31}$$

$$C_{od} = \sum_{x=1}^{ny} \frac{C_o}{(1+i)^x} \tag{32}$$

Based on all above calculations, the total cost is calculated from equation (29). With computing new value of exchanger area (A), exchanger length (L), the total annual cost (Ctot) and a corresponding exchanger architecture meeting the specifications. Values of the design variables (do, Ds and B) was changed the in an attempt to minimize the objective function. Specifications and input data of the fluid in the shell and tube sides' heat exchanger are listed in Table 2. Low and high bounds for optimization decision variables for a given objective are given in Table 3 [18]. In all of the cases, all the values of discounted operating costs are calculated with ny =10 yr, annual discount rate (i) = 10%, energy cost (Ce) =0.12 V/kW h and an annual amount of work hours H= 7000 yr/h [18].

5. Case Studies

The effectiveness of the present approach using ACO is assessed by analyzing two case studies. these cases studies were taken from literature [21].In the ACO approach following upper and lower bounds for the optimization variables are imposed: rang of shell inside diameter (Ds) between 0.1 m and 1.5 m; rang of tubes outer diameter (do) between 0.015 m and 0.051 m; rang of baffle spacing (B) from 0.05 m to 0.5 m.

Case 1: 4.34(MW) duty, methanol-brackish water exchanger [21]. The input data and physical properties shown in Table 2, are supplied as inputs to the described ACO algorithm for cases. The resulting optimal exchanger architectures obtained by ant colony compared with the results obtained by literature [21]. Table 4 shows the optimization results for case study 1 comparing results for the [21]. It shows remarkable changes in all of the significations of shell and tube heat exchanger, also shows that the total operating cost decreases by about 10% relative to [21].

The ACO achieves better results than methods employing the Kern method [20]. The shell-side pressure drop in the heat exchanger is reduced compared to literature [21] for Kern method. This decreasing in pressure drop leads to a decrease in the investment cost in case 1. Considering the decrease in heat transfer area is about 60% with comparing Ref. [21]. The tube- and shell-sides pressure drops are lower for ACO, yielding an operational cost decrease of 24.5%. However, the total annual cost reduced almost 8% compared with Sinnot et al. [21]. It is clearly understood that the present method using (Ant Colony Optimization algorithm) provides the optimal design of a heat exchanger from an economic point of view for attaining a specified heat duty.

Table 3. Bounds for design parameters [18]

Parameters	Lower value	Upper value
Tubes outside diameters(m)	0.01	0.051
Shell diameters(m)	0.1	1.5
Central baffle spacing(m)	0.05	0.5

Table 4. Optimal heat exchanger geometry using ant colony optimization method for case 1.

	Literature[21]	This work(ACO)
$\boldsymbol{L(m)}$	4.83	1.0088
$\boldsymbol{d_o(m)}$	0.02	0.1759
$\boldsymbol{B(m)}$	0.356	0.1694
$\boldsymbol{D_s(m)}$	0.894	0.1680
$\boldsymbol{St(m)}$	0.025	0.01875
$\boldsymbol{Nt(m)}$	918	1103
$\boldsymbol{v_t(m/s)}$	0.75	0.18962
$\boldsymbol{Re_t}$	14,925	2830.5708
$\boldsymbol{Pr_t}$	5.7	5.7
$\boldsymbol{h_t(W/m^2k)}$	3812	1288.6
$\boldsymbol{f_t}$	0.028	0.009
$\boldsymbol{\Delta P_t(Pa)}$	6251	2825
$\boldsymbol{d_e(m)}$	0.014	0.0106
$\boldsymbol{v_s(m/s)}$	0.58	0.247
$\boldsymbol{Re_s}$	18381	5821
$\boldsymbol{Pr_s}$	5.1	5.1
$\boldsymbol{h_s(W/m^2k)}$	1573	645.09
$\boldsymbol{f_s}$	0.33	0.154
$\boldsymbol{\Delta P_s(Pa)}$	35789	34791.8
$\boldsymbol{U(W/m^2k)}$	615	322.5
$\boldsymbol{A(m^2)}$	278.6	111.9
$\boldsymbol{C_i}$	51507	49562
$\boldsymbol{C_o}$	2111	1592
$\boldsymbol{C_{od}}$	12973	9822
$\boldsymbol{C_{tot}}$	64480	59384

Case 2: 0.46 (MW) duty, distilled water-raw water exchanger. Table 5 illustrated the optimized values for case 2. As seen, the total annual cost was decreased by about 40% compared with [21]. However, these changes are remarkable for each specification of shell and tube heat exchanger. Fig.3\s (3) and (4) show the result of the total annual cost for literature [21] compared with cases 1 and 2. The total annual cost is reduced about 8% and 40% using ACO algorithm for cases 1 and 2, respectively. Fig. 5 shows the convergence of the objective function, which is obtained ant colony optimization for case study 1. As seen, after number of almost eighty iteration, there isn't remarkable changes in final answer.

6. Conclusion

In the present work, the ant colony optimization (ACO) is applied to obtain an optimal design for a shell and tube heat exchanger. The heat exchanger is an integral component of all thermal systems.

The present study has demonstrated successful application of ant colony technique for the optimal design of a shell and tube heat exchanger from the economic view point. In the optimization, the total annual cost (objective function) of the heat exchanger is minimized.

Table 5 Optimal heat exchanger geometry using Ant colony optimization method for case 2.

	Literature[21]	**This work(ACO)**
$L(m)$	4.88	3.7
$d_o(m)$	0.013	0.015
$B(m)$	0.305	0.294
$D_s(m)$	0.387	0.1
$St(m)$	0.023	0.018
$Nt(m)$	160	110.05
$v_t(m/s)$	1.76	0.967
Re_t	36,400	12608.68
Pr_t	6.2	6.2
$h_t(W/m^2k)$	6558	1578.7
f_t	0.023	0.0072
$\Delta P_t(Pa)$	62,812	45,919.8
$d_e(m)$	0.013	0.0106
$v_s(m/s)$	0.94	0.147
Re_s	16,200	12,608.67
Pr_s	5.4	5.4
$h_s(W/m^2k)$	5735	5108.3
f_s	0.337	0.128
$\Delta P_s(Pa)$	67,684	57,575
$U(W/m^2k)$	1471	319.29
$A(m^2)$	46.6	35.53
C_i	16,549	14,999.89
C_o	4466	1528
C_{od}	27,440	11204.35
C_{tot}	43,989	26204.24

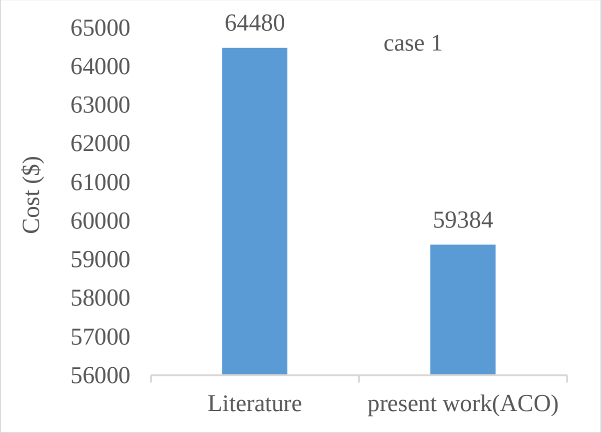

Fig. 3 Total annual cost in literature [21] and ACO algorithm for case 1.

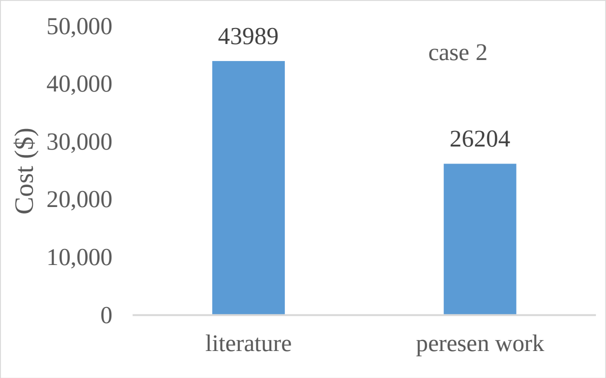

Fig.4 Total annual cost in literature [21] and ACO algorithm for case 2.

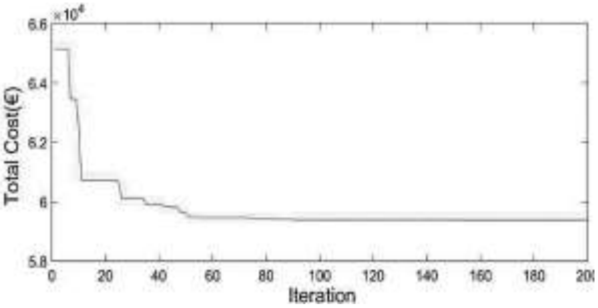

Fig.5 Convergence of ACO for case study 1.

Three parameters are considered as decision variables: tube outer diameter, shell diameter and central baffle spacing. The proposed methodology is applied to two case studies and the results are compared with the original design. The result showed that the heat transfer area was decreased about 60% and the tube- and shell-sides pressure drops are lower using ACO, yielding an operational cost decrease of 24.5%. The total annual cost reduced almost 8% for case study 1. The total annual cost was decreased by about 40% in case study 2 compared with other result. Hence this method can be adopted as a suitable and reliable method for design of a shell and tube heat exchangers in industrial applications.

7. Nomenclature

a1	numerical constant (€)
a2	numerical constant (€/m2)
a3	numerical constant
as	shell side pass area (m2)
A	heat exchanger surface area (m2)
B	baffles spacing (m)
C	numerical constant
Ce	energy cost (€/kW h)
Ci	capital investment (€)
Cl	clearance (m)
Co	annual operating cost (€/yr)
Cod	total discounted operating cost (€)
Cp	specific heat (J/kg K)
Ctot	total annual cost (€)
de	equivalent shell diameter (m)
di	tube inside diameter (m)
do	tube outside diameter (m)
Ds	shell inside diameter (m)
F	temperature difference correction factor
fs	shell side friction coefficient
ft	tube side friction coefficient
H	annual operating time (h/yr)
hs	shell side convective coefficient (W/m2 K)
ht	tube side convective coefficient (W/m2 K)
i	Annual discount rate (%)
k	thermal conductivity (W/m K)
L	tubes length (m)
LMTD	logarithmic mean temperature difference (K)
ms	shell side mass flow rate (kg/s)
mt	tube side mass flow rate (kg/s)
n	number of tube passes
n1	numerical constant
ny	equipment life (yr)
Nt	number of tubes
P	pumping power (W)
Prs	shell side Prandtl number
Prt	tube side Prandtl number
Q	heat duty (W)
Res	shell side Reynolds number
Ret	tube side Reynolds number
Rfs	shell side fouling resistance (m2 K/W)
Rft	tube side fouling resistance (m2 K/W)
St	tube pitch (m)
Tci	cold fluid inlet temperature (K)
Tco	cold fluid outlet temperature (K)
Thi	hot fluid inlet temperature (K)
Tho	hot fluid outlet temperature (K)
U	overall heat transfer coefficient (W/m2 K)
vs	shell side fluid velocity (m/s)
vt	tube side fluid velocity (m/s)
Dh	heat transfer difference (W/m2 K)
DP	pressure drop (Pa)
DPtube elbow	elbow pressure drop
DPtube length	length pressure drop (Pa)
Greek letters	
μ	dynamic viscosity (Pa s)
ρ	density (kg/m3)
η	overall pumping efficiency Subscripts
c	cold stream
e	equivalent
h	hot stream
i	inlet
o	outlet
s	shell side
t	tube side
wt	wall

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