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Optimization Techniques for Design a shell and tube heat exchanger from an economic viewpoint

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ABSTRACT: This paper aims to minimize the total annual cost for a shell and tube heat exchanger based on optimization algorithms. The total annual cost is the sum of the initial cost for the construction of the heat exchanger and the cost of power consumption in the shell and tube heat exchanger. The total annual cost is the objective function, which is minimized. This research uses three optimization algorithms including particle swarm optimization, genetic algorithm, and differential evolution, and three optimization variables including shell's inside diameter, tubes' outer diameter, and baffle spacing. Three different studies have been used to compare the results. The results demonstrated that the differential evolution algorithm achieved the most decline in the total annual cost compared to other optimization algorithms. Using differential evolution algorithm, the total annual cost was decreased about 30% in study 1 and about 28.1% in study 2 compared with literature, respectively. The reduction in the total operating cost is about 47.7% for differential evolution algorithm, 45.7% for particle swarm optimization, and 45.3% for genetic algorithm relative to the results reported in the literature for case study 3. Results were compared with at least eight works directly and have been demonstrated in this research.

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1- Introduction

One of the most important instruments in industry is the Heat Exchanger (HE) that used for heat transfer. Heat exchangers have worked without electricity as very useful equipment in industry [1]. There are many methods for the design of Shell and Tube Heat Exchangers (STHEs) such as complex mathematic methods or experimental methods [2]. However, there are some methods that many researchers have used to design shell and tube heat exchangers such as Delaware or Kern methods. Many studies were conducted about the minimization of the total annual cost. The total annual cost is defined as the sum of capital and energy costs in heat exchangers. Capital cost is as initial costs for construction of heat exchanger and energy cost is as operational costs such as current costs. The objective function is optimized and minimized the total annual cost. Segundo et al. [3] demonstrated a minimization of the total annual cost in shell and tube heat exchanger using Tsallis differential evolution algorithm. Asadi et al. [4] demonstrated an optimum total annual cost in the heat exchanger by a cuckoo-search-algorithm. Sadeghzadeh [5] demonstrated an economic design to optimize shell and tube heat exchangers using genetic algorithm and particle swarm optimization algorithm using Delaware method. This method is applied to calculate the heat transfer coefficient and the shell-side pressure drop. Mohanty [6] used the firefly algorithm to optimize the total annual cost in STHE. In many studies, researchers used three optimization variables such as shell internal diameter, outside tube diameter, and baffle spacing as variable variables. Fig. 1 demonstrated a diagram of a shell and tube heat exchanger.

Patel et al. [7] demonstrated an optimum of the total annual cost by particle swarm optimization. Selbas et al. [8] demonstrated an optimum total annual cost of a HE. Caputo et al. [9] used a genetic algorithm for optimizing the total annual cost of a HE. Ortega et al. [10] showed a developed method for optimizing efficiency with a genetic algorithm that used a difference optimization variable, while Hilbert et al. [11] demonstrated an optimization of the total annual cost for STHE using a multi-objective optimization approach. Some researchers used other methods to achieve a minimum total annual cost such as traditional mathematical equations or optimization algorithms [12]. Some researchers used particle swarm optimization and genetic algorithm methods to achieve the optimum total annual cost [13, 14]. Lerou et al. [15] studied a counter flow heat exchanger and minimized entropy generation based on pressure drop and parasitic heat flows. Xie et al. [16] optimized compact a plate-fin heat exchanger by genetic algorithm. The minimum total volume and total annual cost were the objective functions. They showed that pressure drop constraints provide about 30% lower volume or about 15% lower annual cost. Karimi et al.

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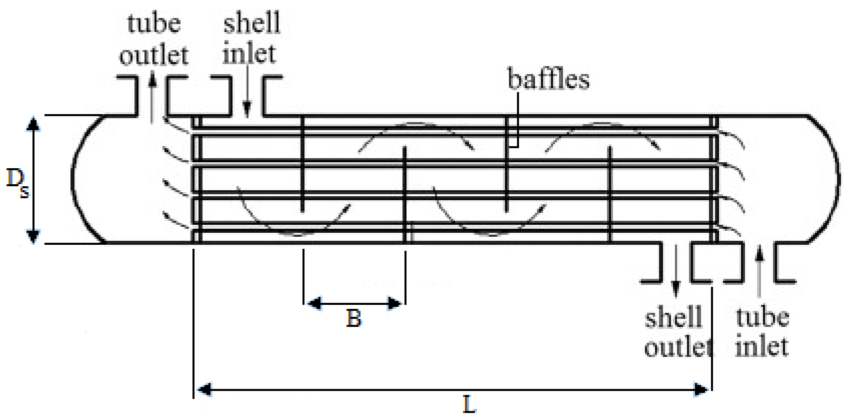

Fig. 1. Diagram of a typical shell and tube heat exchanger

[17, 18] showed optimum results that used some optimization algorithms such as ant colony optimization and shuffled frog leaping algorithm. Also, they achieved an optimum result of the total annual cost in the heat exchanger network [19]. Raja et al. [20] demonstrated an investigation of many-objective optimization of shell and tube heat exchangers such as effectiveness and minimization of total cost, pressure drop and number of entropy generation units of heat exchanger.

In this work, using optimization algorithms including genetic algorithm, particle swarm optimization, and differential evolution, was achieved an optimum total annual cost in a heat exchanger by using some decision variables from geometry properties such as shell inside diameter D_s tubes outer diameter d_o and baffle spacing *B*. The main objective is to achieve minimization of the total annual cost in shell and tube heat exchanger. However, first, all of the influential properties have been optimized and then used to optimize the total annual cost. The design of the heat exchanger is based on the Kern method that is used for calculating pressure drop and heat transfer coefficients. However, some optimization algorithms were used in other works previously but present study could achieve better results compared to others by changing some parameters in algorithms. Validation of these results has been done with several studies. Some researchers changed the lower and upper bounds of the optimization variables that this study compared with others by changing bounds.

2- Mathematical Method

2- 1- Heat transfer

In this section, Kern method for the design of the heat exchanger is presented. First, the tube side heat transfer coefficient h_t is calculated as follows [6]:

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

(if $Re_t < 2300$)

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

(if $2300 < Re_t < 10,000$)

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

(if $Re_t > 10,000$)

where f_t is the Darcy friction factor [3] as achieved by:

$$f_t = \frac{0.079}{Re_t^{0.25}} \tag{4}$$

where Re_t is the tube side Reynolds number demonstrated by [5]:

$$Re_t = \frac{\rho_t v_t d_i}{\mu_t} \tag{5}$$

Table 1. Values of C and n_1 coefficients for $S_t = 1.25 d_o$ [9]

No. of passes	Triangle tube pitch		Square tube pitch	
	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

Flow velocity for the tube side is achieved by [9]:

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

where N_t the number of tubes and n is is the number of tube passes:

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

There are two different tube arrangements including a triangular and square pitch that coefficients of Eq. (7) have been shown in Table 1. Pr_t is the tube side Prandtl number that calculated,

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

Also, $d_i = 0.8 d_o$

shell side heat transfer coefficient h_s is achieved [17]:

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

where, d_e is the shell hydraulic diameter that achieved [21]

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

(For square pitch)

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

(For triangular pitch)

Area of the flow regime is achieved [3]:

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

Flow velocity is achieved for the shell side:

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

Reynolds number for shell side:

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

Prandtl number for shell side:

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

[Eq. (16) showed the overall heat transfer coefficient (U) [6

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

The logarithmic mean temperature difference ($LMTD$) was demonstrated 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) was achieved [5, 17]:

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

where R is the correction coefficient calculated

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

and P is the efficiency:

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

The heat exchanger surface area (A) was computed by [21]

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

and the sensible heat transfer rate was calculated by:

$$Q=m_hC_{ph}\left(T_{hi}-T_{ho}\right)=m_cC_{Pc}\left(T_{co}-T_{ci}\right) \quad (22)$$

The necessary tube length (L) was achieved by [21]:

$$L=\frac{A}{\pi d_oN_t} \quad (23)$$

2- 2- Pressure drop

The type of pressure drop is based on static pressure and moves the fluid in tubes of the heat exchanger. The tube side pressure drop has included pressure drop along the tube length and elbows or in the inlet and outlet nozzle pressure [21].

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

The pressure drop on the tube side is based on the Kern method [17]:

$$P_t=(\frac{\rho_t}{v_t^{\ 2}})/2(\frac{L}{d_if_t}+p)n \quad (25)$$

Constant p is different in different studies, for example in reference [17] $p = 4$ while in reference [21] $p = 2.5$.

The shell side pressure drop is calculated by [21]:

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

where f_s is achieved by [8]:

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

For $Re_s<40,000$, b= 0.72 [17].

Pumping power was obtained by considering pumping efficiency η [17]:

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

3- OPTIMIZATION TECHNIQUES

There are three optimization algorithms in this study including particle swarm optimization, genetic algorithm, and differential evolution. Dong [22] improved a computation method based on particle crowd called Particle Swarm Optimization (PSO). Starting with a random population and searching to achieve an optimum solution by updating productions are evolutionary computation properties. Further details about the applied algorithms can be found in the literature [22-24]. Fig. 2 shows a flowchart of the particle swarm optimization algorithm. A Genetic Algorithm (GA) is a metaheuristic inspired by the process of natural selection that belongs to the larger class of Evolutionary Algorithms (EA). Genetic algorithms are commonly used to generate high-quality solutions to optimization and search problems by relying on biologically inspired operators such as mutation, crossover, and selection. Further details about the applied algorithms can be found in the study of Patel [7]. Fig. 3 demonstrates a flowchart of the genetic algorithm. In evolutionary computation, Differential Evolution (DE) is an optimization method that they are commonly known as metaheuristics. However, metaheuristics such as DE do not guarantee an optimal solution is ever found. Further details about the applied differential evolution algorithm can be found in the study of Mohamed [25]. Fig. 4 demonstrates a flowchart of differential evolution algorithm.

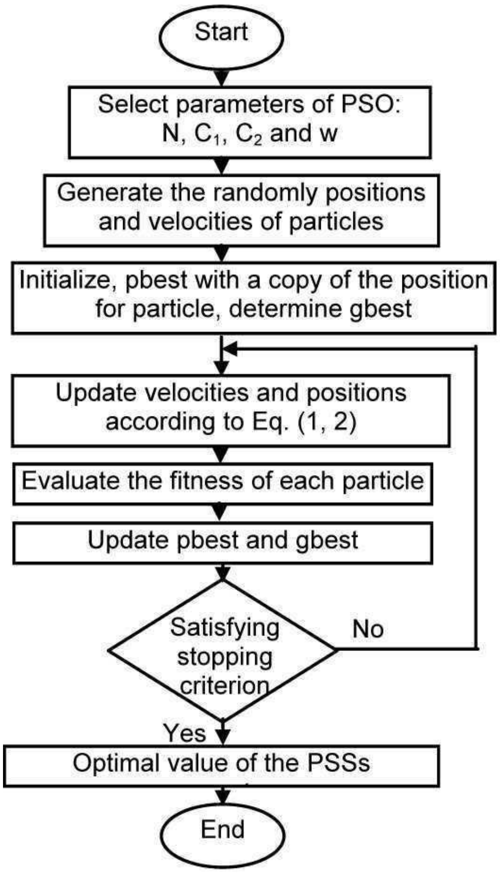

Fig. 2. Flowchart of particle swarm optimization

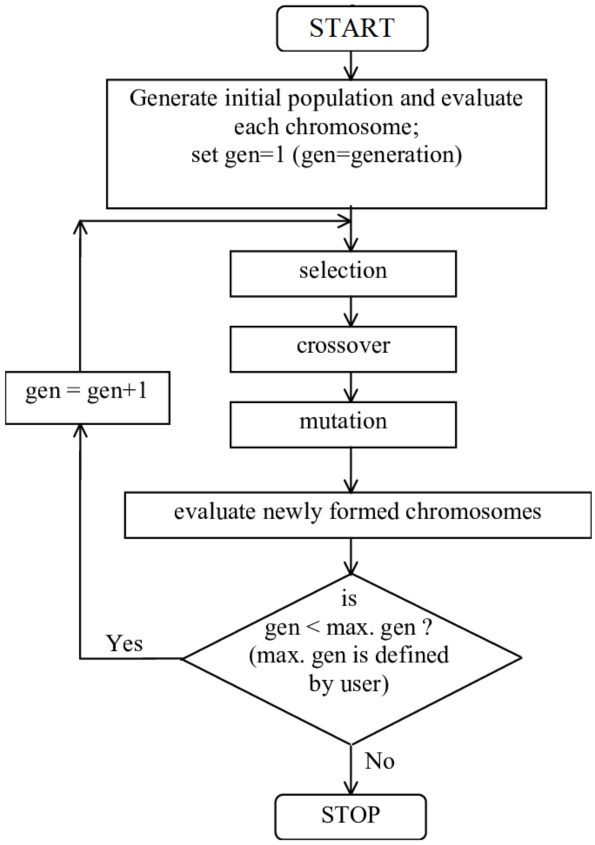

Fig. 3.flowchart of Genetic algorithm

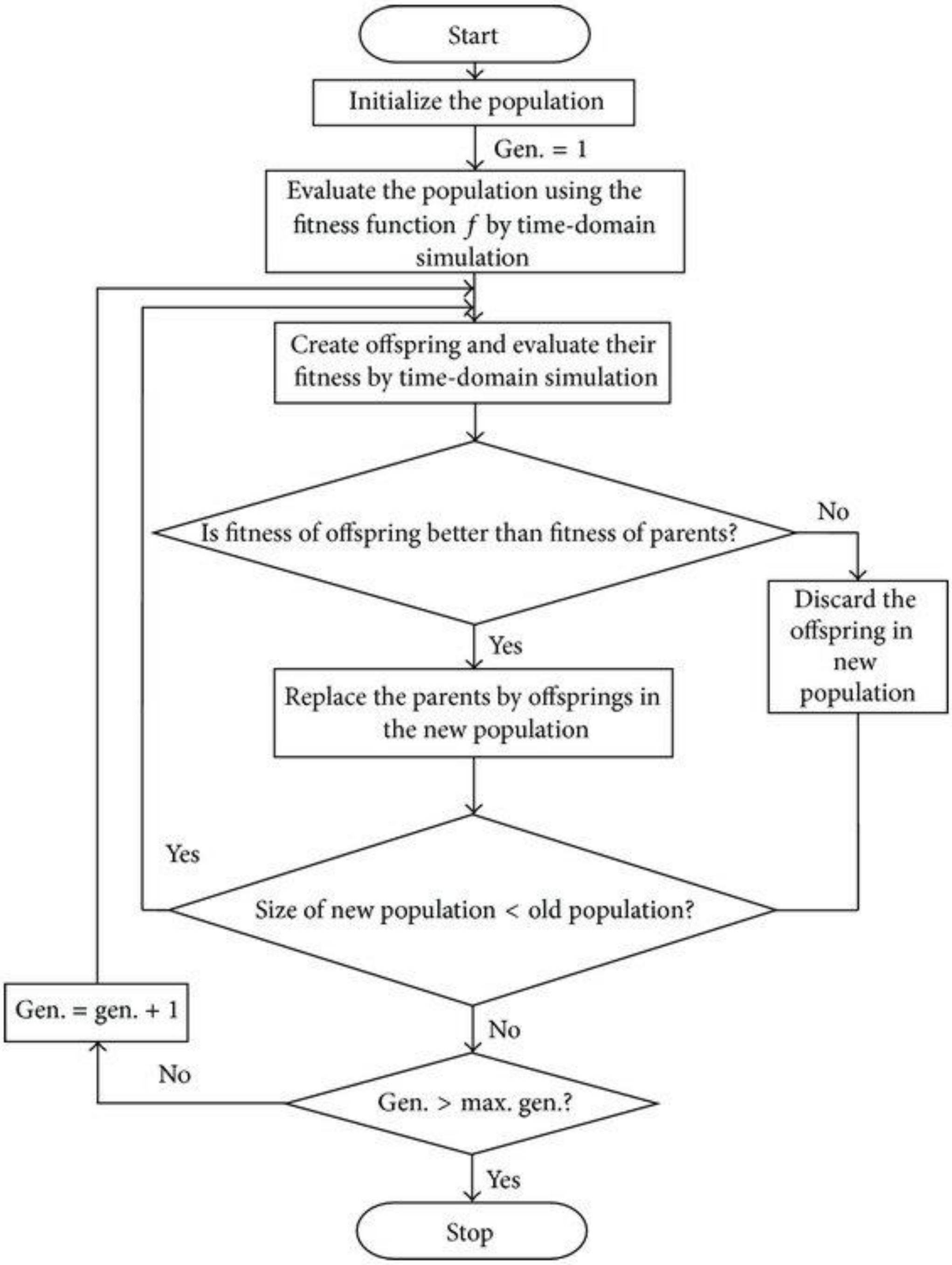

Fig. 4. Flowchart of differential evolution algorithm

4- Objective Function

The total annual cost C_{tot} is achieved by Caputo et al [9].

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

The capital investment cost C_i and the total discounted operating cost C_{od} are considered asfollows [9]

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

where a_1 is the installation factor, a_2 is the material factor, and a_3 is the exponent. These coefficients depend on the type of materials of the heat exchanger. There are three types of exchangers: cheap, expensive, and mixed. The cheap type of heat exchangers contains typical materials such as carbon steel while the expensive types contain anti-corrosion materials such as titanium and the mixed types contain both anti-corrosion and typical materials such as carbon steel and titanium. It assumed that cheap type has been used in shell and tube sides. Therefore, these coefficients are a_1 = 8000, a_2 = 259.2, and a_3=0.93 [26] .The total operating cost is computed based on the following equation [9]:

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

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

where C_e is the energy cost and C_o is the annual operating cost

As mentioned, there are three design variables including, shell inside diameter (D_s), baffle spacing (*B*), and tube outer diameter (d_o) that have used to minimize the objective function. Physical properties of the fluid in the shell and tube sides of the heat exchanger are shown in Table 2. Lower and higher bounds for optimization decision variables are given in Table 3 [9]. Also, discounted operating costs are calculated with ny =10 yr, annual discount rate *i* = 10%, energy cost C_e =0.12 V/kW h, and work hours annual *H*= 7000 yr/h [7].

Table 2. Process input data and physical properties for three case studies [9]

	$\dot{m}(\frac{kg}{s})$	$T_i\,^\circ C$	$T_O\,^\circ C$	$\rho(\frac{kg}{m^3})$	$C_p(\frac{J}{kg})$	$\mu(Pa\cdot s)$	$k(\frac{W}{m\cdot K})$	$R_f(\frac{m^2K}{W})$	$\mu_w(Pa\cdot s)$
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	0.00038 0.00052
Case 2: Shell side: kerosene Tube side: crude oil	5.52 18.80	199 37.8	93.30 76.70	850 995	2.47 2.05	0.0004 0.00358	0.13 0.13	0.00061 0.00061	0.00036 0.00213
Case 3 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	

Table 3. Bounds for design parameters [7]

Parameters	Lower value	Upper value
Tubes outside diameters (m)	0.015	0.051
Shell diameters (m)	0.1	1.5
Central baffle spacing (m)	0.05	0.5

5- Case Study

The influence of the optimization algorithms in reducing the total annual cost was studied by analyzing three case studies where these case studies were used from the literature [21].

- Case study 1: 4.34 MW heat duty was considered for methanol-brackish water in the heat exchanger [21] . The resulting optimal geometry of heat exchanger was calculated based on three optimization algorithms that were compared with the results reported by the previous study. Table 4 demonstrates the optimum results of geometry properties of heat exchanger for case study 1 compared with the results reported in the literature [21]. The application of the differential evolution algorithm is better than the other two algorithms. Using the differential evolution algorithm decreased the total operating cost by about 3% compared to PSO and 27.4% compared to the GA algorithm.

Table 4. Optimal heat exchanger geometry using optimizations method for case 1

	Sinnot et al. [21]	DE	PSO	GA
L (m)	4.83	2.78	2.6871	3.9089
d_o (m)	0.02	0.015001	0.015063	0.015
B (m)	0.356	0.49543	0.49967	0.49989
D_s (m)	0.894	0.74888	0.81143	0.74105
N_t (m)	918	1438.8	1238	1365.5
$v_t\,(\frac{\text{m}}{\text{s}})$	0.75	0.83912	0.83349	0.893
Re_t	14,925	12978	27909	13386
Pr_t	5.7	5.69	5.69	5.69
$h_t\,(\text{W/m}^2\text{K})$	3812	4561.6	3740.8	4639.7
f_t	0.028	0.007	0.0212	0.0073
ΔP_t (Pa)	6251	4316.1	4730	5191.3
d_e (m)	0.014	0.0108	0.0141	0.0106
v_s (m/s)	0.58	0.49	0.498	0.499
Re_s	18381	11671	15489	11716
Pr_s	5.1	5.1	5.1	5.1
$h_s\,(\text{W/m}^2\text{K})$	1573	4994.3	9075.7	1648.9
f_s	0.33	0.35294	0.313	0.353
ΔP_s (Pa)	35789	12620	21355	18033
$U\,(\text{W/m}^2\text{K})$	615	947.58	900.98	686.71
$A\,(\text{m}^2)$	278.6	183.17	198.78	252.58
C_i	51507	40168	44116	50737
C_O	2111	802.75	2561.5	1085.2
C_{od}	12973	4896	2340	6685
C_{tot}	64480	45064	46456	57422.51

- Case study 2: 1.44MW duty was considered for kerosene crude oil exchanger in the heat exchanger. Table 5 shows the optimum results for case study 2 and compared to literature [21]. The reduction of the total operating cost was about 28.13% for the DE algorithm, 24.4% for PSO, and 20.8% for the genetic algorithm relative to the results reported in the literature [21].The results showed that differential evolution algorithm has achieved a better solution compared to the other two algorithms. The differential evolution algorithm has decreased the total operating cost by about 5.067% compared to the PSO and 10.15% compared to the GA algorithm.

- Case study 3: 0.46 MW heat duty was considered for distilled water - raw water in the heat exchanger. Table 6 shows the optimum results for case study 3 and these results compared with the results of literature [21]. The reduction of the total operating cost was about 47.7% for the DE algorithm, 45.7% for PSO, and 45.3% for the genetic algorithm relative to the results reported in the literature [21]. Differential evolution algorithm is a better solution than the other two algorithms in case study 3 too. Using the Differential Evolution algorithm was decreased the total operating cost by about 3.22% compared with PSO and 4.034% compared with the GA algorithm.

Table 5. Optimal heat exchanger geometry using optimizations method for case 2

	Sinnot et al. [21]	DE	PSO	GA
$L\,(\mathrm{m})$	4.88	3.6029	5.1896	3.291
$d_o\,(\mathrm{m})$	0.025	0.015	0.015005	0.0150
$B\,(\mathrm{m})$	0.127	0.22757	0.22243	0.2102
$D_s\,(\mathrm{m})$	0.539	0.37436	0.37395	0.4168
$N_t\,(\mathrm{m})$	158	302	30	382
$v_t\,(\frac{\mathrm{m}}{\mathrm{s}})$	1.44	1.1115	0.94561	0.87
Re_t	8227	3877	10818	2930.4
Pr_t	55.2	55.2	55.2	55.2
$h_t\,(\mathrm{W/m^2K})$	619	1518.6	1151.5	1013.7
f_t	0.033	0.0101	0.0317	0.046
$\Delta P_t\,(\mathrm{Pa})$	49,245	8683.6	16683	12615
$d_e\,(\mathrm{m})$	0.025	0.010719	0.032749	0.0107
$v_s\,(\mathrm{m/s})$	0.47	0.38215	0.37071	0.372
Re_s	25281	8670.9	16485	8443
Pr_s	7.5	7.5	7.5	7.5
$h_s\,(\mathrm{W/m^2K})$	920	1377.2	1090.2	1359
f_s	0.315	0.36913	0.31941	0.37
$\Delta P_s\,(\mathrm{Pa})$	24909	12929	14905	13200
$U\,(\mathrm{W/m^2K})$	317	373.32	290.56	324.71
$A\,(\mathrm{m^2})$	61.5	50.999	63.858	59.14
C_i	19007	17848	19850	19275
C_O	1304	256.01	429.91	338.63
C_{od}	8012	1574.5	2724.2	2109.8
C_{tot}	27020	19419	20403	21391.8

Table 6. Optimal heat exchanger geometry using optimizations method for case 3

	Sinnot et al. [21]	DE	PSO	GA
$L\,(\mathrm{m})$	4.88	2.27	6.1809	2.55
$d_o\,(\mathrm{m})$	0.013	0.015	0.015014	0.015
$B\,(\mathrm{m})$	0.305	0.49	0.49848	0.5
$D_s\,(\mathrm{m})$	0.387	0.55607	0.56466	0.5095
$N_t\,(\mathrm{m})$	160	688	198.91	598
$v_t\,(\frac{\mathrm{m}}{\mathrm{s}})$	1.76	0.86586	1.0606	1.0579
Re_t	36,400	12987	13832	13706
Pr_t	6.2	6.2	6.2	6.2
$h_t\,(\mathrm{W/m^2K})$	6558	4418.6	3743.8	4459
f_t	0.023	0.0074	0.02308	0.0073
$\Delta P_t\,(\mathrm{Pa})$	62,812	5170	7986.1	6069
$d_e\,(\mathrm{m})$	0.013	0.0107	0.032717	0.0107
$v_s\,(\mathrm{m/s})$	0.94	0.44	1.5811	0.4235
Re_s	16,200	5632.4	33494	5754
Pr_s	5.4	5.4	5.4	5.4
$h_s\,(\mathrm{W/m^2K})$	5735	4726.4	3490.9	4801
f_s	0.337	0.393	0.32	0.39
$\Delta P_s\,(\mathrm{Pa})$	67,684	7914.8	14473	7849
$U\,(\mathrm{W/m^2K})$	1471	1137.5	1146.3	1081
$A\,(\mathrm{m^2})$	46.6	67.6	74.4	71.44
C_i	16,549	20784	21279	21339
C_O	4466	380.22	3181.3	377.25
C_{od}	27,440	2320	2569	2697
C_{tot}	43,989	23104	23848	24036

Table 7 shows the results of geometry properties of the heat exchanger in this research compared with previous works for case study 1. As already mentioned, the total annual cost had decreased about 30% using the DE algorithm compared with Sinnot et al. [21] and about 1.6%, 20.6%, 12.24%, 22.21%, and 18.12% compared with FFA, ICA, BBO, GA and PSO methods, respectively. As seen, the total annual cost is less than the result of Patel et al. [7] with the PSO algorithm in this study for case study 1. Heat exchanger area is decreased due to some reason such as decreasing of tube length and increasing of the overall heat transfer coefficient in case studies 1,2 and 3. Fig. 2 showed a direct comparison between these methods for heat exchanger area with previous works. As observed, for DE algorithm, there are a reduction of about 24.9% for tubes outside diameter and 16.2% for shell diameter, and an increasing about 39.16% for central baffle spacing. For the PSO algorithm, there is a reduction of about 24.6% for tubes outside diameter and 9.23% for shell diameter and an increasing about 40.3% for central baffle spacing. For the genetic algorithm, there is a reduction of about 25% for tubes outside diameter and 17.1% for shell diameter, and an increasing about 40.41% for central baffle spacing compared with Sinnot et al. [21] in case study 1. As seen, the heat exchanger area is decreased because of decreasing tube length and increasing the overall heat transfer coefficient.

As already mentioned, the total annual cost was reduced by

Table 7. Optimal properties of the heat exchanger for case study 1

Parameter	Sinnot et al. [21]	DE (present work)	PSO (present work)	GA (present work)	FFA [6]	ICA [27]	BBO [28]	GA [7]	PSO [7]
$L\,(\mathrm{m})$	4.83	2.78	2.6871	3.9089	2.416	3.107	2.040	3.379	3.115
$d_o\,(\mathrm{m})$	0.02	0.015001	0.015063	0.015	0.0157	0.0105	0.015	0.016	0.015
$B\,(\mathrm{m})$	0.356	0.49543	0.49967	0.49989	0.1054	0.0924	0.500	0.5	0.424
$D_s\,(\mathrm{m})$	0.894	0.74888	0.81143	0.74105	0.7276	0.3293	0.74	0.83	0.81
$N_t\,(\mathrm{m})$	918	1438	1238	1366	1692	1752	3587	1567	1658
$v_t\,(\frac{\mathrm{m}}{\mathrm{s}})$	0.75	0.83912	0.83349	0.893	0.656	0.699	0.77	0.69	0.67
Re_t	14,925	12978	27909	13386	10286	10429	7643	10,936	10,503
Pr_t	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7
$h_t\,(\mathrm{W/m^2K})$	3812	4561.6	3740.8	4639.7	6228	3864	4314	3762	3721
f_t	0.028	0.007	0.0212	0.0073	0.031	0.031	0.034	0.031	0.0311
$\Delta P_t\,(\mathrm{Pa})$	6251	4316.1	4730	5191.3	4246	5122	6156	4298	4171
$d_e\,(\mathrm{m})$	0.014	0.0108	0.0141	0.0106	0.0105	0.011	0.007	0.011	0.0107
$v_s\,(\mathrm{m/s})$	0.58	0.49	0.498	0.499	0.54	0.42	0.46	0.44	0.53
Re_s	18381	11671	15489	11716	12625	9917	7254	11,075	12,678
Pr_s	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1
$h_s\,(\mathrm{W/m^2K})$	1573	4994.3	9075.7	1648.9	1991	1740	2197	1740	1950.8
f_s	0.33	0.35294	0.313	0.353	0.349	0.362	0.379	0.357	0.349
$\Delta P_s\,(\mathrm{Pa})$	35789	12620	21355	18033	18788	12367	13799	13,267	20,551
$U\,(\mathrm{W/m^2K})$	615	947.58	900.98	686.71	876.4	677	755	660	713.9
$A\,(\mathrm{m^2})$	278.6	183.17	198.78	252.58	202.3	256.6	229.95	262.8	243.2
C_i	51507	40168	44116	50737	39336	48370	44536	49,259	46,453
C_O	2111	802.75	2561.5	1085.2	1040	975	984	947	1038.7
C_{od}	12973	4896	2340	6685	6446	5995	6046	5818	6778.2
C_{tot}	64480	45064	46456	57422	45782	54366	50582	55,077	53,231

about 28.1% using the DE algorithm compared with Sinnot et al. [21] and about 0.072%, 4.15%, 2.01%, 4.55%, and 2.6% compared to FFA, ICA, BBO, GA and PSO methods, respectively.

Sadeghzadeh et al. [5] obtained the optimum of the total annual cost with changing lower and upper bounds of optimization decision variables that are shown in Table 8 [5]. They decreased lower bound for tube outside diameter from 0.015 to 0.01. Fig. 5 shows the optimum of the total annual cost optimization methods in this study compared with Sadeghzadeh [5] using new values of the tube outside diameter. The total annual cost reduced about 7% and 4.8% using the DE algorithm compared with GA and PSO methods in reference [5], respectively. However, the total annual cost reduced about 1.89% using the PSO algorithm compared with the PSO algorithm in reference [5] for case study 1.

Segundo et al. [3] obtained the total annual cost with changing lower and upper bounds for optimization decision variables that are shown in Table 9 [3]. They changed most of the values in lower and upper bounds of decision variables. Fig. 5 showed total annual cost optimization methods compared with Segundo et al. [3] . Fig. 6 shows the optimum total annual cost compared with Segundo et al. [3] for case study 1. The total annual cost reduced about 7.628% and 7.624% using the DE algorithm compared with DE and TDE methods in reference [3], respectively.

Table 8. Bounds for design parameters [5]

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

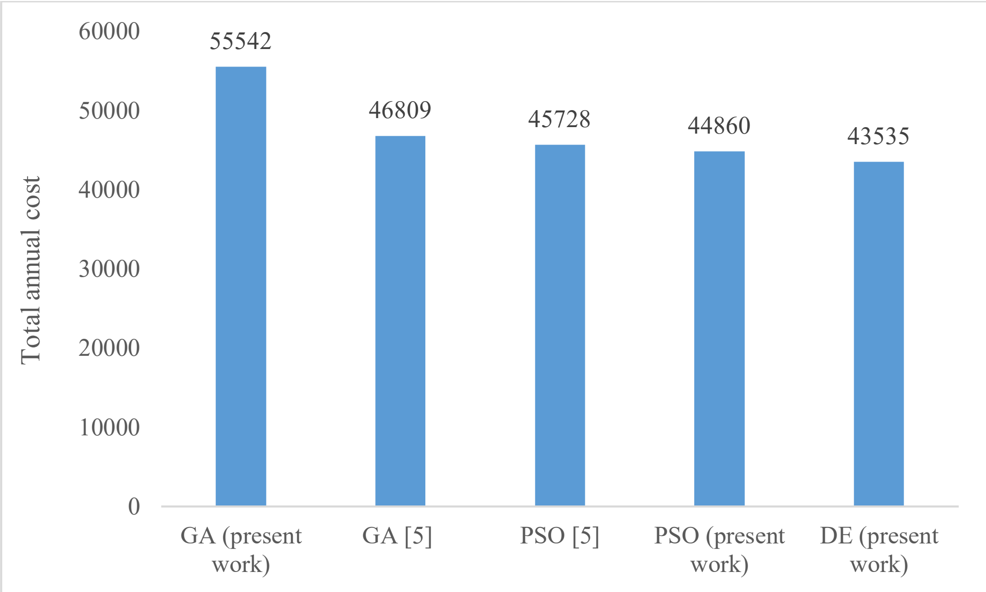

Fig. 5. showed a direct comparison between these methods for heat exchanger area with previous works.

Table 9. Bounds for design parameters [3]

Parameters	Lower value	Upper value
Tubes outside diameter (m)	0.008	0.051
Shell diameter (m)	0.2	1.0
Central baffle spacing (m)	0.2	0.45

6- Conclusions

In the present study, particle swarm optimization, genetic algorithm ,and differential evolution were applied to achieve an optimum total annual cost for a shell and tube heat exchanger. The present study demonstrated successful applications of optimization techniques to gain optimum design of a shell and tube heat exchanger from the economic view. For the optimization, the total annual cost (objective function) of the heat exchanger was optimized and minimized. In this work, results were studied in three different cases and compared with previous studies. The most important results have been followed:

- The total annual cost had decreased about 30% using the DE algorithm compared with literature for case study 1
- The total annual cost reduced about 1.6%, 20.6%, 12.24%, 22.21%, and 18.12% compared to FFA, ICA, BBO, GA, and PSO methods for case study 1, respectively.
- The total annual cost reduced about 28.1% using the DE algorithm compared with literature for case study 2.
- The total annual cost reduced about 0.072%, 4.15%, 2.01%, 4.55%, and 2.6% compared with FFA, ICA, BBO, GA, and PSO methods for case study 2, respectively.
- The reduction in the total operating cost is about 47.7% for the DE algorithm, 45.7% for PSO, and 45.3% for genetic algorithm relative to the results reported in the literature for case study 3.

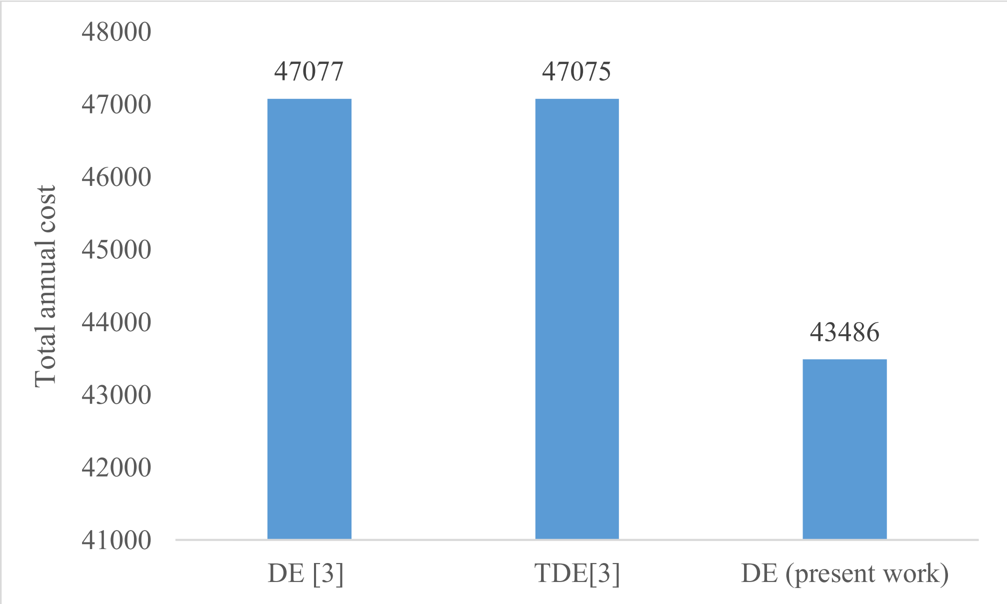

Fig. 6 showed total annual cost optimization methods compared with Segundo et al. [3] .

The effects of the applied techniques were examined to achieve the most economical design for a shell and tube heat exchanger with the same heat duty in three case studies.

Nomenclature

a_1	numerical constant (€)
a_2	numerical constant (€/m^2)
a_3	numerical constant
As	shell side pass area (m^2)
A	heat exchanger surface area (m^2)
B	baffles spacing (m)
C	numerical constant
Ce	energy cost (€/kW h)
C_i	capital investment (€)
Cl	clearance (m)
C_O	annual operating cost (€/yr)
C_{od}	total discounted operating cost (€)
C_p	specific heat (J/kg K)
C_{tot}	total annual cost (€)
d_e	equivalent shell diameter (m)
d_i	tube inside diameter (m)
d_o	tube outside diameter (m)
Ds	shell inside diameter (m)
F	temperature difference correction factor
f_s	shell side friction coefficient
f_t	tube side friction coefficient
H	annual operating time (h/yr)
h_s	shell side convective coefficient (W/m^2
h_t	tube side convective coefficient (W/m^2
I	Annual discount rate (%)
K	thermal conductivity (W/m K)
L	tubes length (m)
LMTD	logarithmic mean temperature differenc
m_s	shell side mass flow rate (kg/s)
m_t	tube side mass flow rate (kg/s)
n	number of tube passes
n_1	numerical constant
ny	equipment life (yr)
N_t	number of tubes
P	pumping power (W)
Pr_s	shell side Prandtl number
Pr_t	tube side Prandtl number
Q	heat duty (W)
Re_s	shell side Reynolds number
Re_t	tube side Reynolds number
R_{fs}	shell side fouling resistance (m^2 K/W)
R_{ft}	tube side fouling resistance (m^2 K/W)
St	tube pitch (m)
T_{ci}	cold fluid inlet temperature (K)
T_{co}	cold fluid outlet temperature (K)
T_{hi}	hot fluid inlet temperature (K)
T_{ho}	hot fluid outlet temperature (K)

U	overall heat transfer coefficient (W/m^2 K)
v_s	shell side fluid velocity (m/s)
v_t	tube side fluid velocity (m/s)
D_h	heat transfer difference (W/m^2 K)
D_P	pressure drop (Pa)
$D_{Ptube\ elbow}$	elbow pressure drop(Pa)
$D_{Ptube\ length}$	length pressure drop (Pa)
Greek letters	
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
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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