

Thermal Design Optimization of Shell-and-Tube Heat Exchanger Liquid to Liquid to Minimize Cost using Combination Bell-Delaware Method and Genetic Algorithm

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ABSTRACT

Shell-and-tube heat exchanger is designed to satisfy certain requirements such as heat transfer capability, allowable pressure drop and limitation of size. Beside such requirements, it is important to consider economical point of view to get the lowest total cost. In this study, computational program and optimization for thermal design shell-and-tube heat exchanger were built for liquid to liquid with no phase change process in four variables design parameters using Bell-Delaware method. The design variables were tube size, tube length, baffle cut to shell inside diameter ratio and central baffle spacing to shell inside diameter ratio. The genetic algorithm was used as optimization method to get lower solution for economical point of view. The results from two study cases show that the genetic algorithm got lower total cost from the original design. The total cost decreased 28.83% in first study case and 52.56% in second study case from the original design.

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I. Introduction

The heat exchanger is an important equipment in the industrial process. One of their types has widely used in industrial energy, petroleum industry and chemical process industry. It is designed based on their characteristics and conditions of fluids, and some design is possible to appear similarly for a particular purpose. In such design, heat transfer capability and pressure drop may similar although they have different dimension and arrangement construction. Because it is possible to get many variants design shell and tube through differences of construction, It is better to have design considering economical point of view. The design should consider total cost from investment and operational cost. The cost of investment is defined as a cost for manufacturing of shell and tube and cost of operation is defined as a cost which is needed along the operational process, and actually, it



is a cost for pumping power. The design with low total cost will have a significant impact to expense for producers and users because it commonly is used for a long time or around ten years. In the other hand, computational processes are developed rapidly, and one of them is global random search methods. The uniqueness of this method can find a global optimum point in all problems of optimization. Genetic algorithm is adapted from natural processes. The genetic algorithm mimics from natural process to transmit heredity characteristics from a parent to an offspring by genes in chromosomes. In addition, the method can be used easier to be implemented for the iterative calculation of optimization because some supporting mathematical software can help to build algorithms. The calculation process combined with the best method and supporting software, can solve the design, which has the cheapest cost. Their components are different depending on type shell and tube particularly. But main components are shell, tubes, front-end head, rear-end head and baffles as shown in Fig. 1.

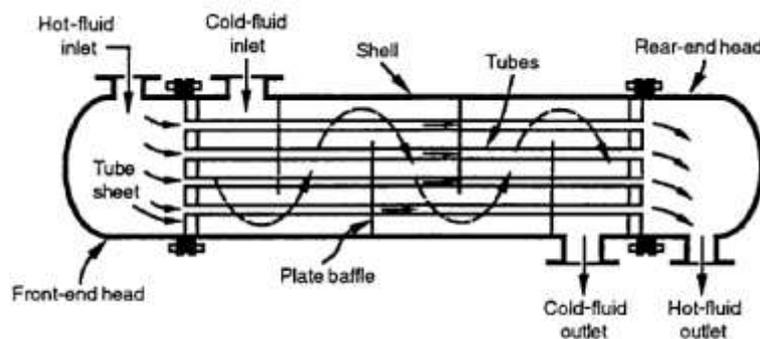


Fig. 1. Main parts of shell-and-tube heat exchanger [1]

There are many standards of shell-and-tube heat exchanger. Tubular Exchanger Manufacture Association (TEMA) standards are widely recognized in many producers and consumers around the world to be used as a standard. TEMA standards are made by engineering principles, researchers and experiences in process design, manufacture and installation to assist designer, engineers and users to work. TEMA standards cover fabrication tolerances and performance information, installation, operation and maintenance, mechanical standards, vibration standards, thermal relations and recommended good practices [1].

Some researchers used algorithms to the optimization of a heat exchanger. Extensive advanced optimization techniques were applied. Trial and error were conducted in various parameter design and operation, and it is very useful to the industry [2]. The study of optimization using particle swarm algorithm in double pipe was employed micro-finned tubes using number of micro-fins from 10 to 60, micro-fin height varying from 0.0 to 0.5 mm and the micro-fin helix angle between 5 and 30° [3]. Grey wolf optimization algorithm reduced total cost using relatively low computing time [4]. Elitist-Jaya algorithm in first case reduced 32.855% and in the second case reduced 5.21% from simulations result compared to original design for continuous parameter optimization [5]. In the current investigation, Multi-Objective optimization of Bees Algorithm Hybrid and Particle Swarm purposed to acquire the maximum effectiveness, and the minimum cost was simultaneously employed. Seven decision parameters were length in hot and cold side, frequency of fin, number of fin layers, thickness of fin, fin height, and fin lance length [6]. Gravitational search algorithm was developed from economic point of view. The algorithm was applied to two cases compared to the original data and other algorithms. The total cost could be reduced by 22.3%

as compared to the original data The Gravitational search algorithm could be successfully applied for design optimization [7].

II. Material and Methods

Procedure to design is conducted through some steps. The step is started with input data mass flow rate and temperature both shell and tube side as well as on inlet and outlet respectively. And then calculations are executed to get overall heat transfer coefficient and pressure drops.

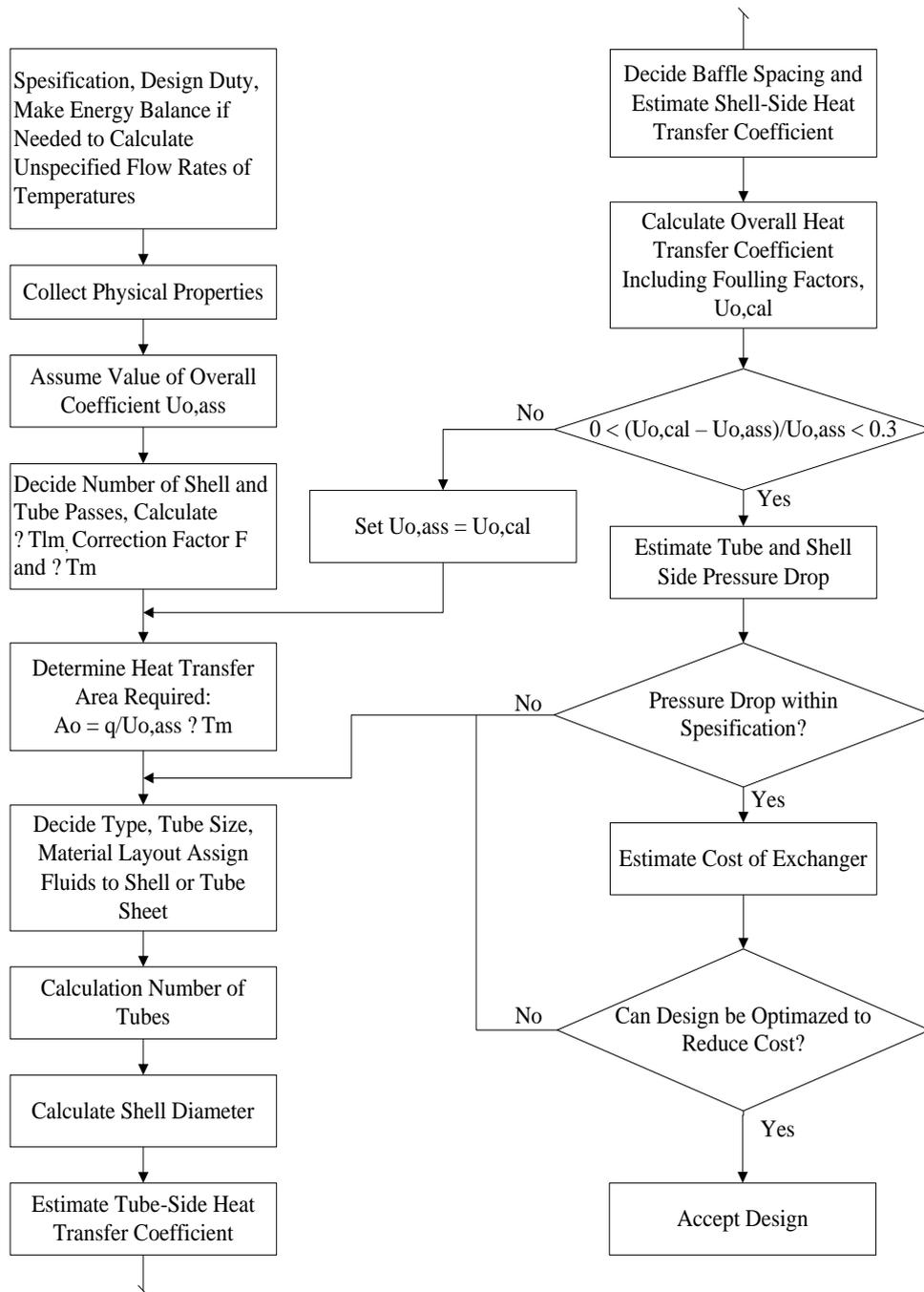


Fig. 2. Design procedure of shell-and-tube heat exchanger [8]

Along calculation processes, assumption and some designer decision are given such as assuming the overall heat transfer coefficient and deciding of some construction type. If the value of overall heat transfer after calculation is less than 30% of the ratio between overall calculated and assumption values of heat transfer while pressure drop does not exceed reasonable limits prescribed, then the design is accepted to be used [8]. Another design may be needed if a designer considers getting a lower cost of heat exchanger.

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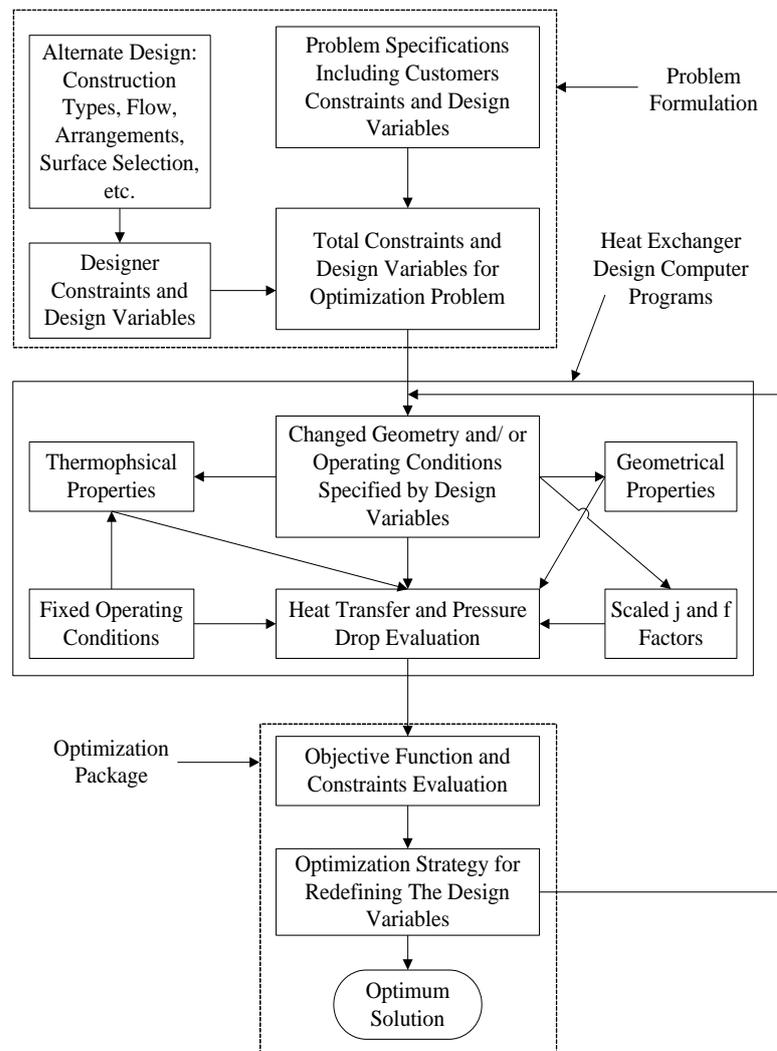


Fig. 3. Methodology for heat exchanger optimization [1]

The program has four variables that are outer tube diameter, tube length, baffle cut to shell inside diameter ratio and baffle spacing to shell inside diameter ratio. Bounds the program for the four variables are described in Table 1. The first bound, Tube outer diameter is taken from BWG standard, which is used correspond to TEMA standard for tube size. The minimum value of outer tube diameter considers cleaning process and vibration of tubes. The cleaning process in the tube can be done with minimum tube size 0.01905 m and vibration also will be reduced using minimum tube size 0.01905 m [9]. The second bound, Range of pipe length depends on space to be expected on size. The third bound, baffle cut to shell inside diameter ratio uses ratio the value ranging from 15% to 45%. It is set to support tubes mechanically against sagging and possible vibration [9]. And the fourth bound, baffle spacing to shell inside diameter ratio uses ratio the value ranging from 20% to 80%. Maximum TEMA standard for baffle spacing is also 80%. It is also used to avoid failure due to tube vibration where it occurs in unsupported tube length more than 80% [9].

Table 1. Bounds of variables

Variable	Minimum Value (m)	Maximum Value (m)
Tube outside diameter (do)	0.01905	0.051
Tube length (L)	1	10
Baffle cut to shell inside diameter ratio	0.15	0.45
Baffle spacing to shell inside diameter ratio	0.2	0.8

The methodology is divided into three main parts which are problem formulation, design and computer program and optimization package, as presented in Fig. 3 Recently, it is possible to get design with minimum cost and satisfied on some constraints by commercial software using optimization methods.

Equations for heat transfer in tube side have many forms. The equation can be selected exactly using a validity statement and Reynolds number. Some correlations heat transfer coefficient in tube side for no phase change process are expressed as follows [10].

$$\text{For } \left(\frac{Re_t Pr_t d_i}{L}\right)^{1/3} (\mu / \mu_w)^{0.14} < 2$$

$$h_i = 3.66K_t / d \quad (1)$$

$$\text{For } \left(\frac{Re_t Pr_t d_i}{L}\right)^{1/3} (\mu / \mu_w)^{0.14} > 2$$

$$\text{For } Re_t < 2100$$

$$h_i = (K_t / d_i) 1.86 \left(\frac{Re_t Pr_t d_i}{L}\right)^{1/3} (\mu / \mu_w)^{0.14} \quad (2)$$

$$\text{For } 2100 < Re_t < 10^4$$

$$h_i = (K_t / d_i) 0.116 (Re_t^{2/3} - 125) Pr_t^{1/3} (1 + d_i / L)^{2/3} (\mu / \mu_w)^{0.14} \quad (3)$$

$$\text{For } Re_t > 10^4$$

$$h_i = (K_t / d_i) 0.027 Re_t^{0.8} Pr_t^{0.4} (\mu / \mu_w)^{0.14} \quad (4)$$

Heat transfer in shell side for no phase change is calculated using Bell-Delaware method. It is more complex, but it is accurate enough. The Bell-Delaware method compares to an ideal tube bank, consider leakage through leakages and bypass flows. So, calculation

of Bell-Delaware method will consider correction factors. Heat transfer in shell side can be found by Eq. 5 [1].

$$h_o = h_{id} J_c J_l J_b J_s J_r \quad (5)$$

Total pressure drop is the summation of pressure drop from tube and shell side. Pressure drop in tube side commonly due to frictions and indentations along tubes. Pressure drop for all tubes can be obtained by Eq. 6 [11].

$$\Delta P_t = v_t^2 / 2 \left(\frac{4f_t L}{d_i} + 2.5 \right) n_p \rho_t \quad (6)$$

Pressure drop in shell side is calculated using Bell-Delaware method which is evaluated from cross-flow tip baffle to tip baffle. Pressure drop in shell side is commonly due to dividers from baffle and frictions along flow in shell side. Pressure drop in shell side is the sum of pressure drop from the central section, window area and inlet-outlet area considering some correction factors. Pressure drop in shell side can be determined by Eq. 7 [1].

$$\Delta P_s = [(N_b - 1)\Delta P_{b,id}R_b + N_b\Delta P_{w,id}]R_l + 2\Delta P_{b,id} \left(1 + \frac{N_{r,cw}}{N_{r,cc}} \right) R_b R_s \quad (7)$$

The estimated cost of a heat exchanger is got from the summation of investment and operational cost. The total cost can be expressed by Eq. 8 [12].

$$C_{tot} = C_{inv} + C_{op} \quad (8)$$

The investment cost is used as the initial cost to make a shell-and-tube heat exchanger. It can be especially determined for shell material and tube material by Eq. 9, Eq. 10, Eq. 11, Eq. 12 or Eq. 13 [13].

For material (Shell: Carbon Steel and Tube: Carbon Steel)

$$C_{in} = 6411 + 329.7A^{0.80} \quad (9)$$

For material (Shell: Carbon Steel and Tube: Stainless Steel)

$$C_{in} = 7731 + 372A^{0.85} \quad (10)$$

For material (Shell: Stainless Steel and Tube: Stainless Steel)

$$C_{in} = 8000 + 259.2A^{0.91} \quad (11)$$

For material (Shell: Carbon Steel and Tube: Titanium)

$$C_{in} = 12821.9 + 562A^{0.92} \quad (12)$$

For material (Shell: Titanium and Tube: Titanium)

$$C_{in} = 16027 + 640A^{0.93} \quad (13)$$

The operational cost has been used for an operational process for a lifetime of a heat exchanger. Actually, operational cost is used for pumping power due to pressure drop in shell and tube side. Operational cost is calculated considering inflation rate and efficiency of the pump. Operational cost due to inflation rate effects for the lifetime can be determined by Eq. 14 [14].

$$C_{op} = \sum_{k=1}^{n_y} \frac{C_o}{(1+\lambda)^k} \quad (14)$$

Operational cost for annual current cost is calculated considering operation hours. It can be determined by Eq. 15 [14].

$$C_o = P K_{el} \tau \quad (15)$$

Where pumping power considering efficiency of pump can be calculated using Eq. 16 [14].

$$P = \left(\frac{\dot{m}_t \Delta P_t}{\rho_t} + \frac{\dot{m}_s \Delta P_s}{\rho_s} \right) \frac{1}{\eta} \quad (16)$$

Process of genetic algorithm is started with defined initial parameters. The process continues until maximum number of iteration and satisfy the criteria. A flow process for genetic algorithm is illustrated by flow chart in Fig. 4.

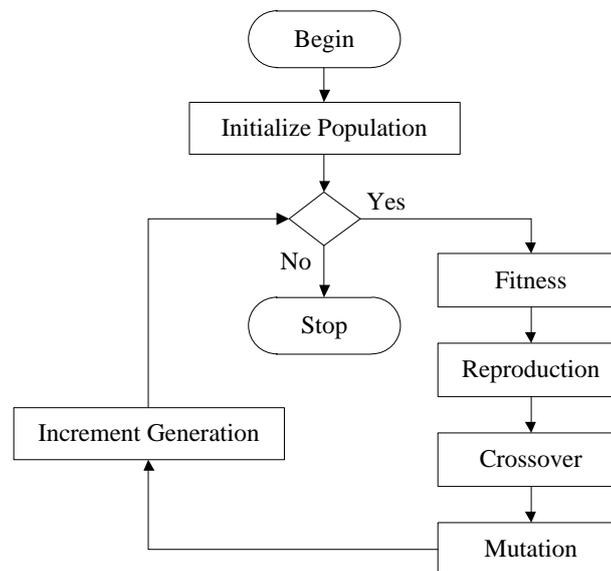


Fig. 4. Principle process of genetic algorithm [15]

Genetic Algorithm is a search algorithm which is built an imitating mechanism of natural selection principles of Darwin for the survival of the fitness. Genetic Algorithm mimics natural process to transmit heredity characteristics from a parent to an offspring by genes in chromosomes. The process will continue from a parent to offspring to get the best individual. The best individual represents an optimal solution [15]. Flow process for Genetic Algorithm is illustrated by flow chart in Fig. 4.

III. Results and Discussions

A. First Case Study

The first case study is a kerosene liquid in shell side and crude oil in tube side. Both shell and tube are made of stainless steel. Energy cost for shell and tube is set as 0.12 €/kWh and interest rate is set as 10% per year. Working hour is set as 7,000 hours/year and the lifetime is set as 10 years with the efficiency of pump 0.7 [11].

Data of fluids and physical properties are known for both stream sides. The data of each stream are mass flow rate, temperature inlet and outlet, density, viscosity, thermal

conductivity, specific heat and fouling resistance. The data of each stream is detailed in Table 2.

Table 2. First case study: data of fluids and physical properties [11]

	\dot{m} (kg/s)	T_h (°C)	T_c (°C)	ρ (kg/m ³)	$\mu \times 10^5$ (Pa.s)	$k \times 10^2$ (W/mK)	C_p (J/kg)	$R_f \times 10^4$ (m ² K/W)
Shell Side: Kerosene	5.52	199.0	93.3	850	40	13	2,470	61
Tube Side: Crude Oil	18.80	37.8	76.7	995	358	13	2,050	61

The original design from the first case study uses pattern of square tube arrangement, one shell pass, four tube passes, tube pitch equal to 1.25 of outer tube diameter and baffle spacing equal to 0.24 of inner diameter shell [11]. Optimization of the first case study was carried out by genetic algorithm. Comparison of the result optimization to original data is presented in Table 3.

Table 3. Design comparison of the first case study to original data

Parameters	Original Data	Genetic Algorithm
Tube Layout (°)	Square	30
N (Shell)	1	1
N _p (Passes)	4	2
N _t (Tubes)	158	202
d _o (m)	0.025	0.01905
d _i (m)	0.020	0.01619
D _s (m)	0.539	0.400
P _t (m)	0.031	0.02381
L _{bc} (m)	0.127	0.133
L _c (m)	-	0.063
L (m)	5.983	5.293
A (m ²)	74.21	64.18
ΔT_{lm} (K)	84.55	84.55
F	0.89	0.89
v _t (m/s)	1.523	0.906
v _s (m/s)	0.483	0.615
G _t (kg/m ² s)	1,515.4	901.2
G _s (kg/m ² s)	410.6	522.6
Pr _t	5.6	5.6
Pr _s	7.6	7.6
Re _t	8,468	40,762
Re _s	25,344	24,890
Q (W)	1,441,156	1,441,156
h _i (W/m ² K)	1,086	2,112.9
h _o (W/m ² K)	978.9	745.1
U (W/m ² K)	268.1	309.9
ΔP_t (Pa)	53,195	7,900
ΔP_s (Pa)	25,344	16,550
P (W)	1,671	367
C _{in} (€)	21,054	19,438
C _{op} (€)	8,920	1,894
C _{tot} (€)	29,974	21,332

Optimization process using genetic algorithm has been successfully minimizing total cost on the first case study. Algorithm methods have been decreasing the total cost of the shell-and-tube heat exchanger 28.83% using Genetic Algorithm from the total cost of original data, as mentioned in Table 7. Total cost decreases on the first case study due to decreasing total investment and operation cost. In this case, total operational cost decreases 78.77% using Genetic algorithm. Total investment cost decreases 7.68% using Genetic algorithm from total operational cost and total investment cost of original data.

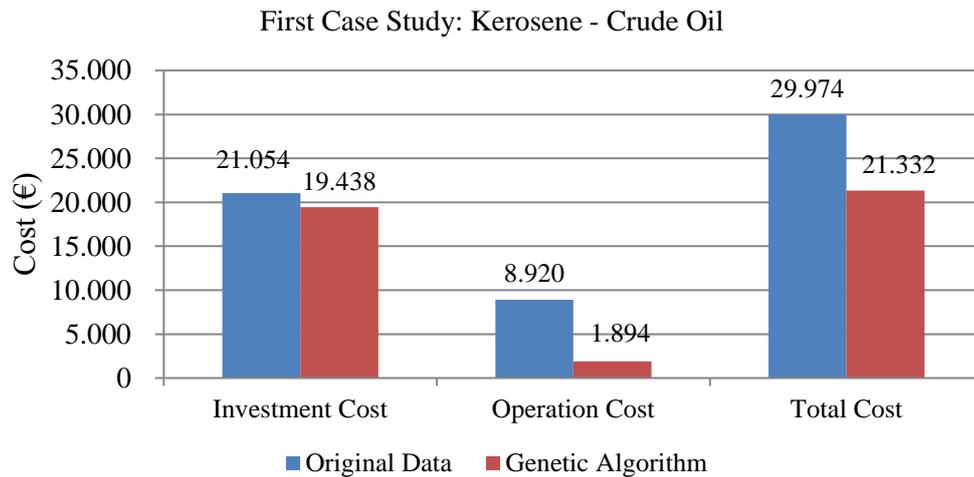


Fig. 5. Cost comparison of first case study

Value of overall, tube side and shell side heat transfer coefficient tends higher than original data. Results of overall heat transfer coefficient increases 15.60% using Genetic algorithm from overall heat transfer of the original data. For heat transfer in tube side, the results increase 94.56% using Genetic algorithm from original data. For heat transfer in shell side, the results increase 23.88% using Genetic algorithm from the original data. Overall heat transfer increases compared to original data because heat transfer area is smaller than the original data. It affects increasing value of heat transfer coefficient in shell and tube side, as presented in Fig. 6.

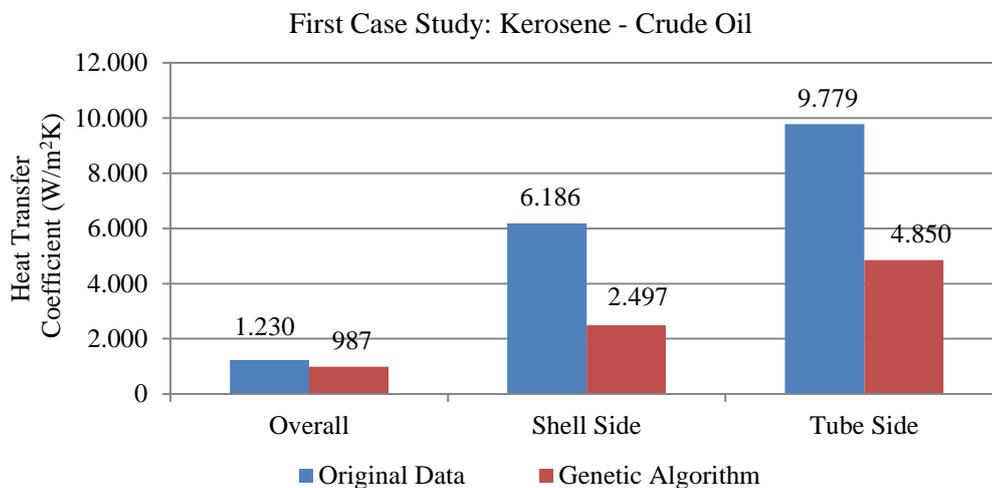


Fig. 6. Heat transfer coefficient comparison of first case study

Pressure drop tends to decrease in the tube side. Pressure drop in tube side decreases 85.15% using Genetic algorithm from the original data. Pressure drops in shell side increases 28.87% using Particle Swarm algorithm from original data. As appears in Fig. 7, It happens because velocity both in tube and shell side is decreased.

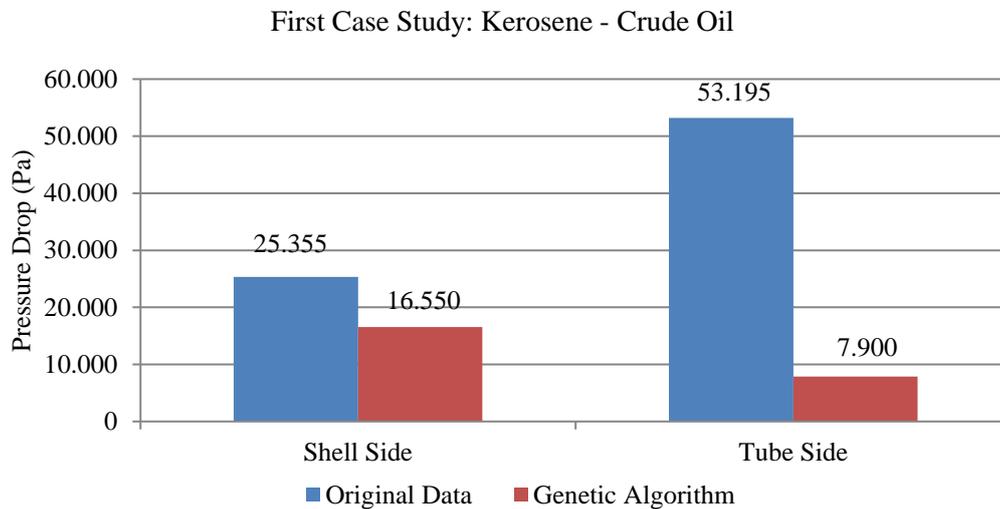


Fig. 7. Pressure drop comparison of first case study

B. Second Case Study

The second case study is a distilled water in shell side and raw water in tube side. Both shell and tube are made of stainless steel. Energy cost for shell and tube is set as 0.12 €/kWh and interest rate is set as 10% per year. Working hour is set as 7,000 hours/year and the lifetime is set as 10 years with the efficiency of pump 0.7 [11].

Data of fluids and physical properties are known from both stream sides. The data of each stream are mass flow rate, temperature inlet and outlet, density, viscosity, thermal conductivity, specific heat and fouling resistance. The data of each stream is detailed in Table 4.

Table 4. Second case study: data of fluids and physical properties [11]

	\dot{m} (kg/s)	T_h (°C)	T_c (°C)	ρ (kg/m ³)	$\mu \times 10^5$ (Pa.s)	$k \times 10^2$ (W/mK)	C_p (J/kg)	$R_f \times 10^4$ (m ² K/W)
Shell Side:								
Distilled Water	22.07	33.9	29.4	995	80	62	4,180	17
Tube Side:								
Raw Water	35.31	23.9	26.7	999	92	62	4,180	17

Optimization of the second case study was carried out by genetic algorithm. Comparison of the result optimization to original data is presented in Table 5. Optimization process using genetic algorithm has been successfully minimizing total cost on the first case study. Algorithm methods have been decreasing total cost of 52.56% using Genetic Algorithm from the total cost of original data, as mentioned in Table 9. Total cost decreases on the first case study due to decreasing total investment and operation cost. In this case,

total operational cost decreases 89.91% using Genetic algorithm. Total investment cost increases 12.39% using Genetic algorithm from total operational cost and total investment cost of original data.

Table 5. Design comparison of the second case study to original data

Parameters	Original Data	Genetic Algorithm
Tube Layout (°)	Triangular	30
N (Shell)	1	1
Np (Passes)	2	2
Nt (Tubes)	160	388
do (m)	0.019	0.01905
di (m)	0.0152	0.01619
Ds (m)	0.387	0.536
Pt (m)	0.023	0.02381
Lbc (m)	0.305	0.346
Lc (m)	5.904	3.030
L (m)	-	0.156
A (m ²)	56.35	70.22
ΔT_{lm} (K)	6.31	6.31
F	0.94	0.94
v_t (m/s)	2.436	0.887
v_s (m/s)	1.022	0.601
Gt (kg/m ² s)	2,433.6	885.7
Gs (kg/m ² s)	1,016.9	597.7
Pr _t	6.2	6.2
Pr _s	5.4	5.4
Re _t	40,207	15,588
Re _s	17,155	14,233
Q (W)	415,137	415,137
hi (W/m ² K)	9,799	4,849.7
ho (W/m ² K)	6,186	2,497.2
U (W/m ² K)	1,230	987.1
ΔP_t (Pa)	65,657	6,052
ΔP_s (Pa)	88,520	9,849
P (W)	6,120	618
C _{in} (€)	18,162	20,413
C _{op} (€)	31,589	3,188
C _{tot} (€)	49,751	23,601

Value of overall, tube side and shell side heat transfer coefficient tends lower than original data. Results of overall heat transfer coefficient decreases 19.75% using Genetic algorithm from overall heat transfer of the original data. For heat transfer in tube side, the results decrease 50.51% using Genetic algorithm from original data. For heat transfer in shell side, the results decrease 50.51% using Genetic algorithm from the original data. Overall heat transfer decreases compared to original data because heat transfer area is smaller than the original data. It affects increasing value of heat transfer coefficient in shell and tube side, as presented in Fig. 9.

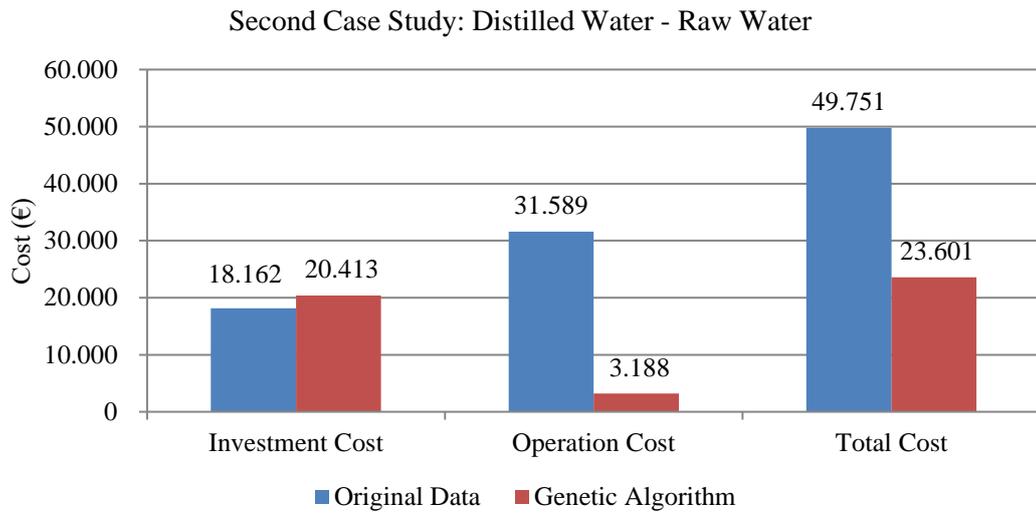


Fig. 8. Cost comparison of second case study

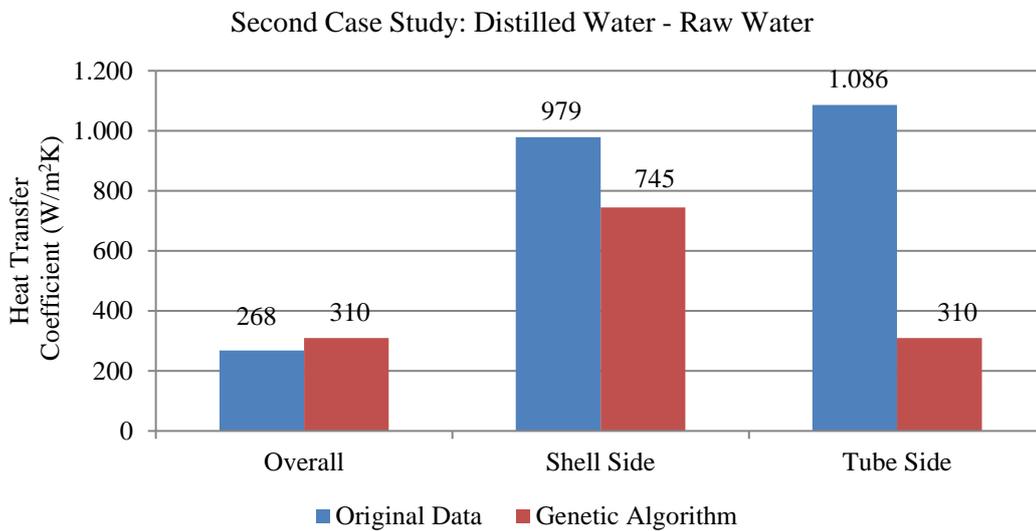


Fig. 9. Heat transfer coefficient comparison of second case study

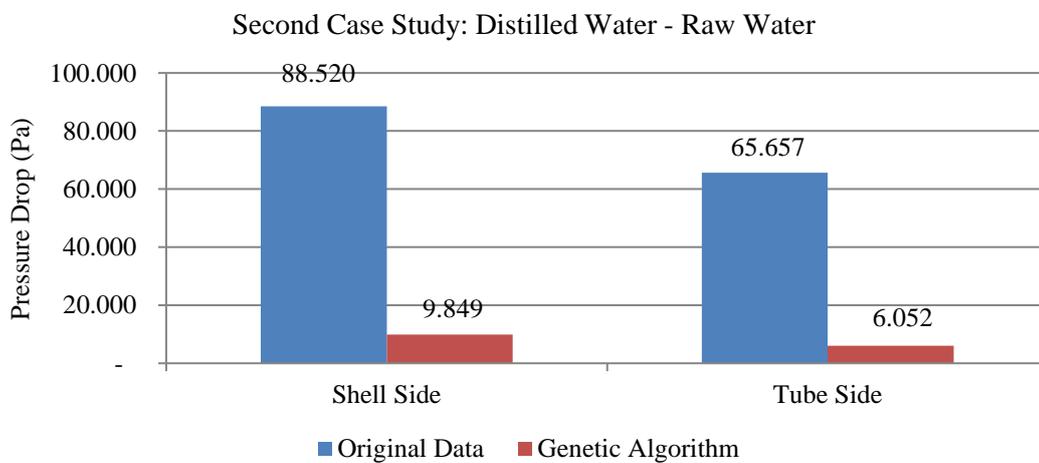


Fig. 10. Pressure drop comparison of second case study

Pressure drop tends to decrease in the tube side. Pressure drop in tube side decreases 90.78% using Genetic algorithm from the original data. Pressure drops in shell side decrease 89.67% using Genetic algorithm. As appears in Fig. 10, It happens because velocity both in tube and shell side is decrease.

IV. Conclusion

The program of calculation could be design shell-and-tube heat exchangers tube layout 30° , 45° and 90° . Building codes of efficient algorithm for computational calculation and correspond to TEMA standards has been done, sequences algorithm in computational process were work properly and define TEMA standards into algorithm such as BWG tube standard, minimum value of 1.25 tube pitch to outer tube diameter ratio and maximum value 80% baffle spacing to shell inside diameter ratio. The estimate cost is provided for made of carbon steel, stainless steel, titanium and the combination of their materials. The program has been applied for solving two thermal design shell-and-tube heat exchangers. The first case is a kerosene and crude oil fluids, the results show that program can reduce 28.83% for Genetic algorithm of the total cost from the original data. The second case is a distilled water and raw water, in which the result shows that program can reduce 52.56% for Genetic algorithm of the total cost from the original data.

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