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Thermal Design Optimization of No Phase Change Shell-and-Tube Heat Exchanger using Particle Swarm 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 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. Particle swarm algorithm was used as optimization method to get lower solution for economical point of view shell-and-tube heat exchanger. The results from two study cases show that particle swarm algorithm got lower total cost from the original design. The total cost decreased 28.84 % in first study case and 52.57 % in second study case from the original design.

Keywords: *Shell-and-tube heat exchanger; minimizing cost; no phase change, particle swarm algorithm, optimization*

1. INTRODUCTION

Heat exchanger is important equipment in industrial process. One of their types is shell-and-tube heat exchanger which has widely used in industrial energy, petroleum industry and chemical process industry. Shell-and-tube heat exchanger 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, shell-and-tube heat exchangers are 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 operational process, and 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 heat exchanger 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. Particle swarm algorithm is adapted from natural processes. Particle Swarm Algorithm is search algorithm which is built an imitating mechanism of birds' swarm and school of fish moving together. In additional, the method can be used easier to be implemented for 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 shell-and-tube heat exchanger which has the cheapest cost. Components of heat exchanger are different depending on type shell and tube particularly. But main components of shell-and-tube heat exchangers are shell, tubes, front-end head, rear-end head and baffles as mentioned in Figure 1.

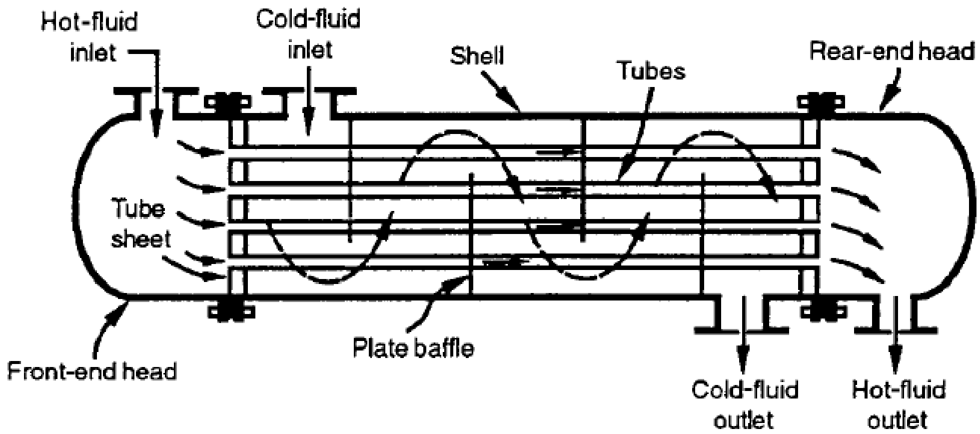

Figure 1. Main parts of shell-and-tube heat exchanger [1]

There are many standards of shell-and-tube heat exchanger. Some standards for shell-and-tube heat exchangers are Tubular Exchanger Manufacture Association (TEMA), Deutsches Institut für Normung (DIN), American Society of Mechanical Engineers (ASME) and other standards from Europe. However, TEMA standards are widely recognized in many producers and consumers shell-and-tube heat exchanger 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 on shell-and-tube heat exchanger. TEMA standards cover fabrication tolerances, general fabrication and performance information, installation, operation and maintenance, mechanical standards, vibration standards, thermal relations and recommended good practices [1].

2. METHODS

Procedure to design shell-and-tube heat exchanger 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. Along calculation processes, assumption and some designer decisions are given such as assuming the value of 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. Another design may be needed if a designer considers getting a lower cost of heat exchanger.

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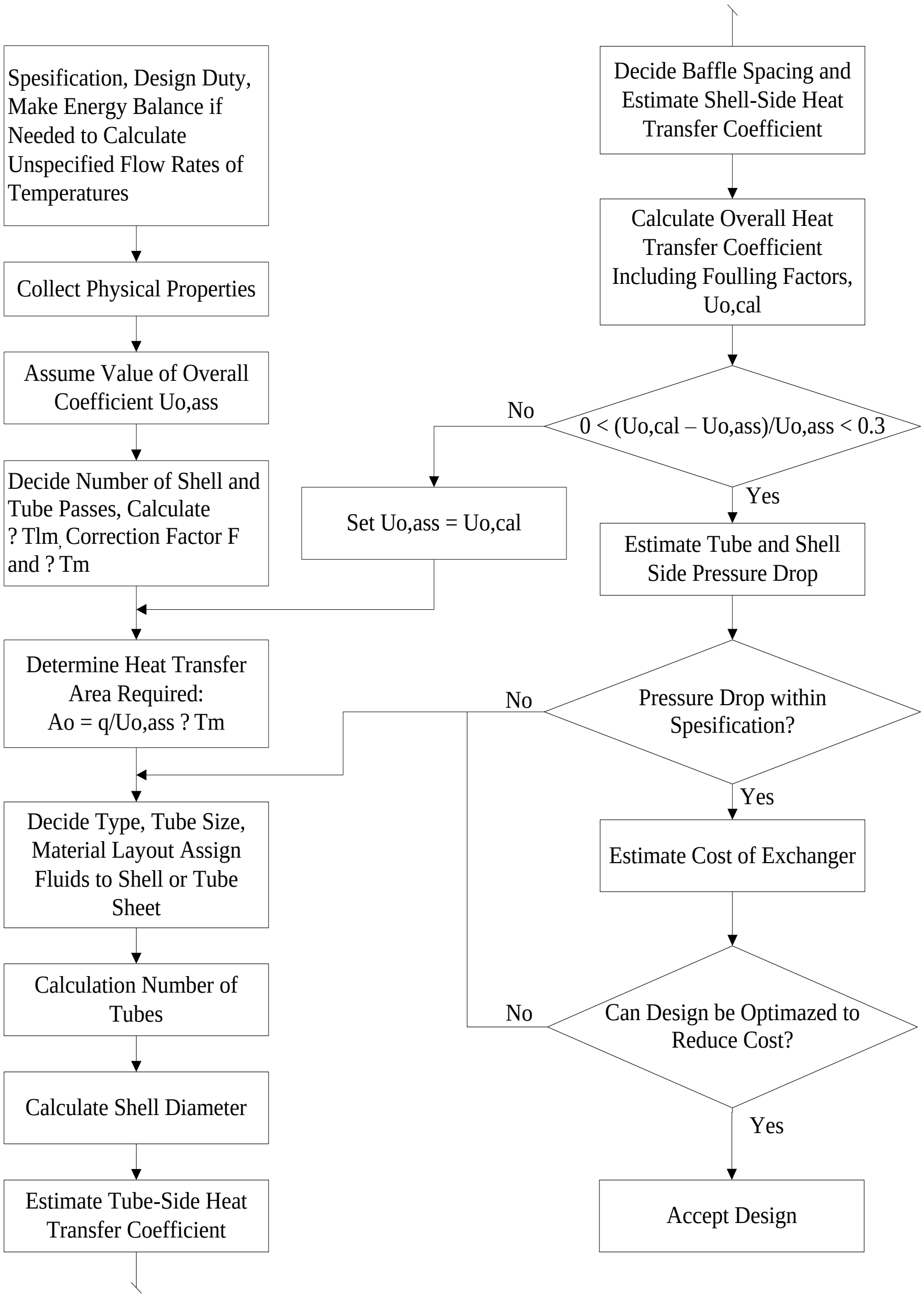


Figure 2. Design procedure of shell-and-tube heat exchanger [2]

The program has four variables that are tube outer 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 tube outer diameter considers cleaning process and vibration of tubes. 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 [3]. The second bound, Range of pipe length depends on space to be expected on size shell-and-tube heat exchanger. 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 [3]. 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 used also to avoid failure due to tube vibration where it occurs in unsupported tube length more than 80 % [3].

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

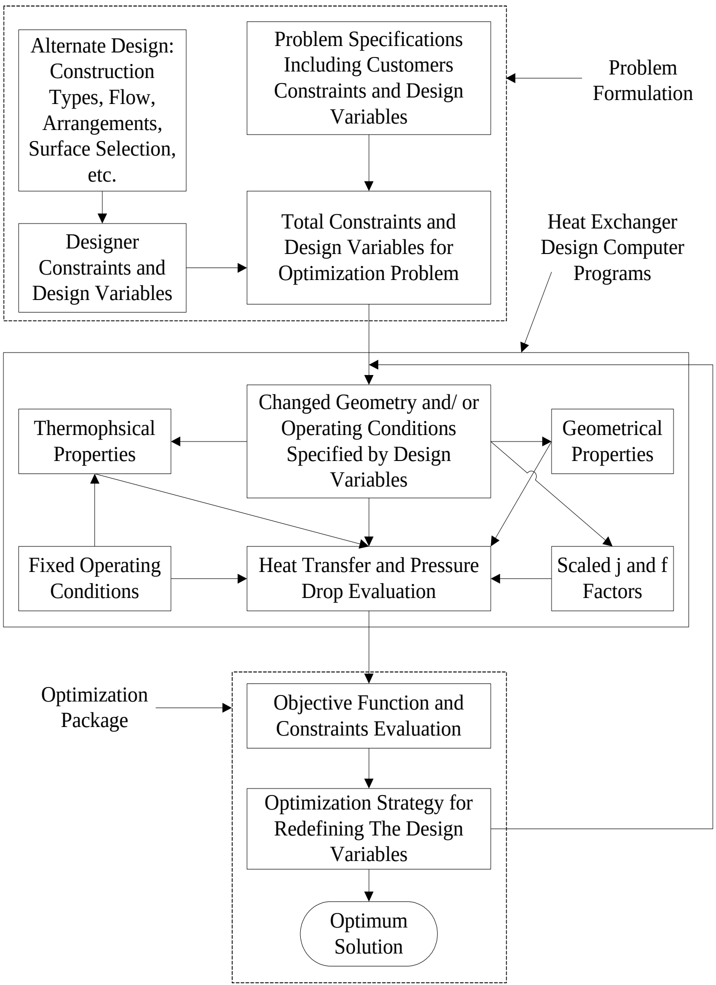


Figure 3. Methodology for heat exchanger optimization [1]

The methodology of shell-and tube heat exchanger optimization is divided into three main parts which are problem formulation, heat exchanger design and computer program and optimization package as presented in Figure 3. Recently, it is possible to get design heat exchanger 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 [4].

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

$$h_i = 3.66K_t / d \tag{1}$$

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

For $Re_t < 2100$

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

For $2100 < Re_t < 10^4$

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

For $Re_t > 10^4$

$$h_i = (Kt / di)\ 0.027\ Re_t^{0.8}\ Pr_t^{0.4}\ (\mu / \mu_w)^{0.14} \tag{4}$$

Heat transfer in shell side for no phase change is calculated using Bell-Delaware method. Calculation of Bell-Delaware method is more complex but it is accurate enough. Bell-Delaware method compares to 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].

$$h_o = h_{id}\ J_c\ J_l\ J_b\ J_s\ J_r \tag{5}$$

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 [5].

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

And 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].

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

The estimation cost of a heat exchanger is got from the summation of investment and operational cost. Total cost can be expressed by Eq. 8 [6].

$$C_{tot} = C_{inv} + C_{op} \tag{8}$$

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 [7].

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

$$C_{in} = 6411 + 329.7A^{0.80} \tag{9}$$

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

$$C_{in} = 7731 + 372A^{0.85} \tag{10}$$

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

$$C_{in} = 8000 + 259.2A^{0.91} \tag{11}$$

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

$$C_{in} = 12821.9 + 562A^{0.92} \tag{12}$$

For material (Shell: Titanium and Tube: Titanium)

$$C_{in} = 16027 + 640A^{0.93} \tag{13}$$

And the operational cost has been used for an operational process for a lifetime of a shell-and-tube 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 [8].

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

Operational cost for annual current cost is calculated considering operation hours. It can be determined by Eq. 15 [8].

$$C_o = P\, K_{el}\, \tau \tag{15}$$

Where pumping power considering efficiency of pump can be calculated using Eq. 16 [8].

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

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

Particle Swarm Algorithm is search algorithm which is built an imitating mechanism of birds' swarm and school of fish moving together. A few individuals explore to search the best position for objective function. The best position of individual in a group called global best position. The individual best position is obtained from updating initial position and velocity [9]. A flow process for Particle Swarm algorithm is illustrated by flow chart in Figure 4. After one cycle completed, the process will be repeated until a few iterations. Step by step particle swarm algorithm can be expressed in Table 4.

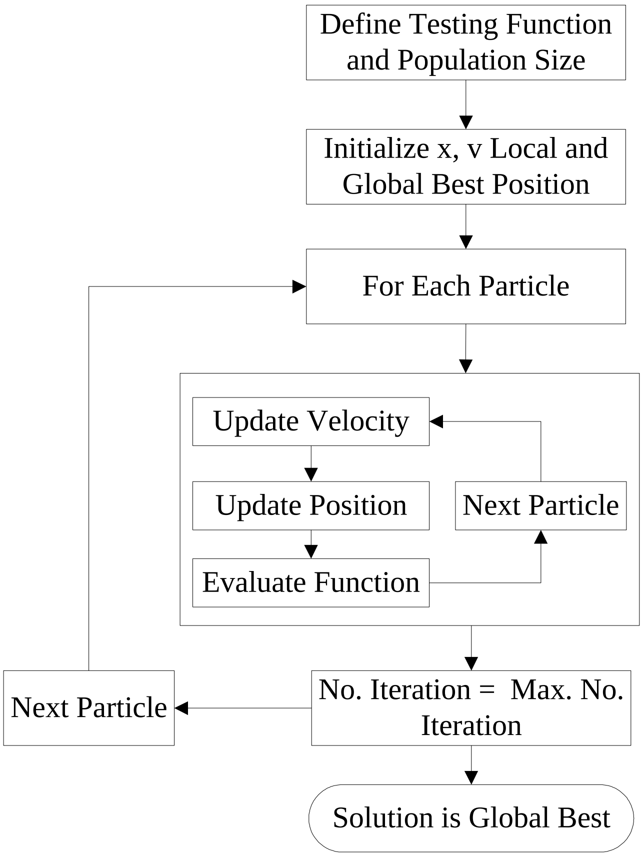


Figure 4. Principle Process of Particle Swarm Algorithm [4]

Table 2. Step by Step Particle Swarm Algorithm [9]

Step 1: Initialize i_{max}, w, φ_1, φ_2, n (population size), $x_{i,min}$ and $x_{i,max}$
Step 2: Initialize the starting position and velocities of the variables as
$x_{i,k} = x_{i,min} + (x_{i,max} - x_{i,min})u_i \quad k = 1 \ldots n$
$v_{i,k} = 0$
Step 3: Compute $p_{i,k} = f(x_{i,k}) \quad k = 1 \ldots n$
Step 4: Compute $pbest_{i,k} = p_{i,k}$ and $gbest_i$ = minimum ($pbest_{i,k}$)
The location of $pbest_k$ and $gbest$ is given by p_{xik} and g_{ix}
Step 5: Update velocity
$v_{i+1,k} = w_1 v_{i,k} + \varphi_1(p_{xik} - x_{i,k})u_i + \varphi_2(g_{ix} - x_{i,k})u_i$
Step 6: Update position $x_{i+1,k} = x_{i,k} + v_{i+1,k}$
Step 7: Update fitness $p_{i+1,k} = f(x_{i+1,k})$
Step 8: If $p_{i+1,k} < pbest_{i,k}$
then $pbest_{i+1,k} = p_{i+1,k}$
Step 9: Update $gbest_{i+1}$ = minimum ($pbest_{i+1,k}$)
Step 10: If $i < i_{max}$ then increment i and go to step 5, else stop

3. Result and Discussion

3.1 First Case Study

The first case study is a shell-and-tube heat exchanger with 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 of the shell-and-tube heat exchanger is set as 7,000 hours/year and the lifetime of the shell-and-tube heat exchanger is set as 10 years with the efficiency of pump 0.7 [5].

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 3. First case study: data of fluids and physical properties [5]

	ṁ (kg/s)	**Th (°C)**	**Tc (°C)**	**ρ (kg/m³)**	**μ x 10⁵ (Pa.s)**	**k x 10² (W/mK)**	**Cp (J/kg)**	**Rf x 10⁴ (m²K/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

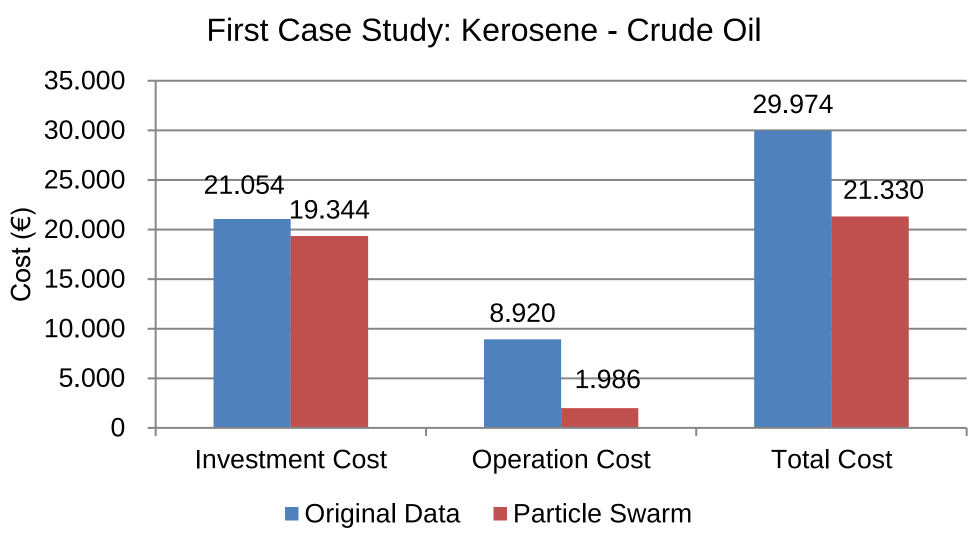
The original design from the first case study uses pattern of square tube arrangement, one shell pass, four tube passes, tube pitch equal to 1.25 of outer tube diameter and baffle spacing equal to 0.24 of inner diameter shell [5]. Optimization of first case study was carried out by particle swarm algorithm. Comparison of the result optimization to original data is presented in Table 3.

Table 4. Design comparison of first case study to original data

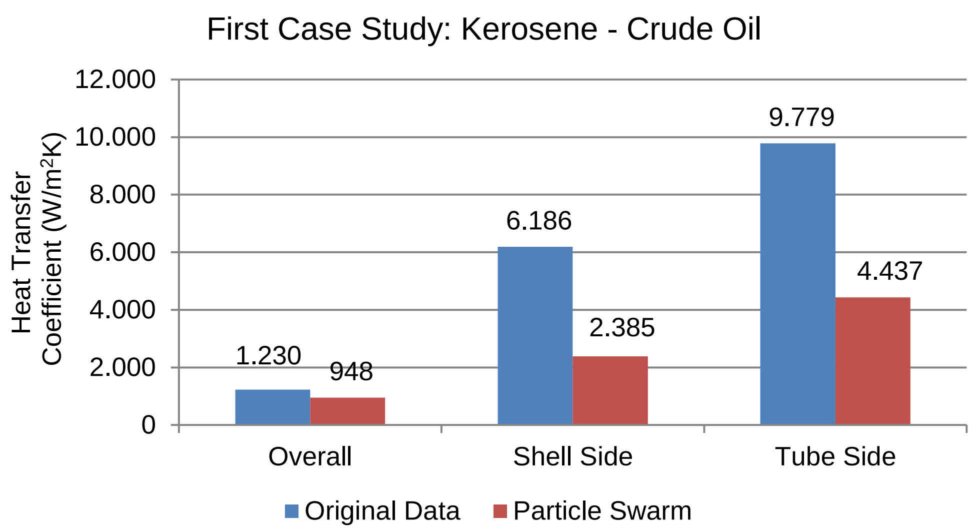
Parameters	**Original Data**	**Particle Swarm**
Tube Layout (°)	Square	30
N (Shell)	1	1
Np (Passes)	4	2
Nt (Tubes)	158	200
do (m)	0.025	0.01905
di (m)	0.020	0.01619
Ds (m)	0.539	0.399
Pt (m)	0.031	0.02381
Lbc (m)	0.127	0.129
Lc (m)	-	0.063
L (m)	5.983	5.300
A (m²)	74.21	63.60
ΔTlm (K)	84.55	84.55
F	0.89	0.89
v_t (m/s)	1.523	0.915
v_s (m/s)	0.483	0.639
Gt (kg/m²s)	1,515.4	910.5
Gs (kg/m²s)	410.6	543.2
Pr_t	5.6	5.6
Pr_s	7.6	7.6
Re_t	8,468	41,184
Re_s	25,344	25,870
Q (W)	1,441,156	1,441,156
hi (W/m²K)	1,086	2,130.4
ho (W/m²K)	978.9	759.1
U (W/m²K)	268.1	312.8
ΔP_t (Pa)	53,195	8,057
ΔP_s (Pa)	25,344	18,026
P (W)	1,671	385

Parameters	Original Data	Particle Swarm
C_{in} (€)	21,054	19,344
C_{op} (€)	8,920	1,986
C_{tot} (€)	29,974	21,330

Optimization process using particle swarm algorithm has been successfully minimizing total cost of shell-and-tube heat exchanger on the first case study. Algorithm methods have been decreasing total cost of the shell-and-tube heat exchanger 28.84 % using Particle Swarm Algorithm from the total cost of original data, as mentioned in Table 7. Total cost decreases on first case study due to decreasing total investment and operation cost. In this case, total operational cost decreases 77.74 % using Particle Swarm Algorithm. Total investment cost decreases 8.12 % using Particle Swarm algorithm from total operational cost and total investment cost of original data.



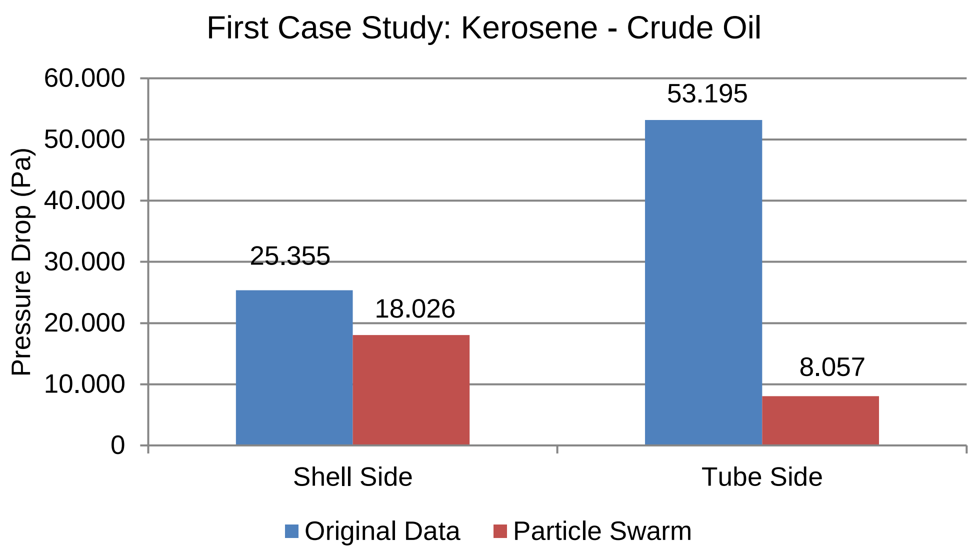
Graphic 1. Cost comparison of first case study



Graphic 2. Heat transfer coefficient comparison of first case study

Value of overall, tube side and shell side heat transfer coefficient tend higher than original data. Results of overall heat transfer coefficient increases 16.66 % using Particle Swarm algorithm from overall heat transfer of the original data. For heat transfer in tube side, the results increase 96.17 % using Partical Swarm algorithm from original data. For heat transfer in shell side, the results increase 22.45 % using Particle Swarm 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 Graphic 2.

Pressure drop tends to decrease in the tube side. Pressure drop in tube side decreases 84.85 % using Particle Swarm algorithm from the original data. Pressure drops in shell side decreases 28.87 % using Particle Swarm algorithm from original data. As appears in Graphic 3, It happens because velocity both in tube and shell side is decrease.



Graphic 3. Pressure drop comparison of first case study

3.2 Second Case Study

The second case study is a shell-and-tube heat exchanger with 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 of the shell-and-tube heat exchanger is set as 7,000 hours/year and the lifetime of the shell-and-tube heat exchanger is set as 10 years with the efficiency of pump 0.7 [5].

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 5. Second case study: data of fluids and physical properties [5]

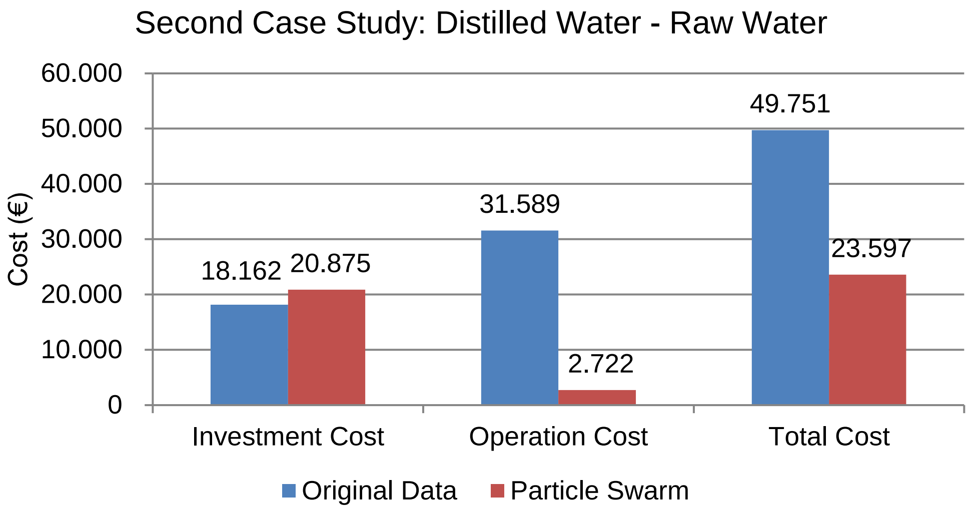
	$\dot{m}$ (kg/s)	Th (°C)	Tc (°C)	ρ (kg/m³)	μ x 10⁵ (Pa.s)	k x 10² (W/mK)	Cp (J/kg)	Rf x 10⁴ (m²K/W)
Shell Side: Distilled Water	22.07	33.9	29.4	995	80	62	4,180	17
Tube Side: Raw Water	35.31	23.9	26.7	999	92	62	4,180	17

Optimization of second case study was carried out by genetic algorithm. Comparison of the result optimization to original data is presented in Table 5.

Table 6. Design comparison of second case study to original data

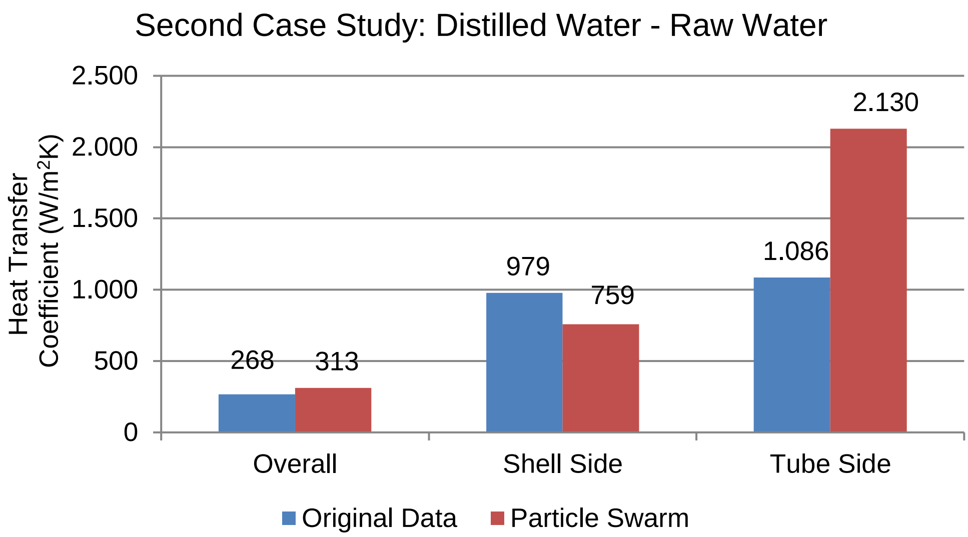
Parameters	Original Data	Particle Swarm
Tube Layout (°)	Triangular	30
N (Shell)	1	1
Np (Passes)	2	2
Nt (Tubes)	160	432
do (m)	0.019	0.01905
di (m)	0.0152	0.01619
Ds (m)	0.387	0.564
Pt (m)	0.023	0.02381
Lbc (m)	0.305	0.341
Lc (m)	5.904	2.822
L (m)	-	0.086
A (m^2)	56.35	73.09
ΔTlm (K)	6.31	6.31
F	0.94	0.94
v_t (m/s)	2.436	0.793
v_s (m/s)	1.022	0.578
Gt (kg/m^2s)	2,433.6	792.5
Gs (kg/m^2s)	1,016.9	575.7
Pr_t	6.2	6.2
Pr_s	5.4	5.4
Re_t	40,207	13,948
Re_s	17,155	13,709
Q (W)	415,137	415,137
hi (W/m^2K)	9,799	4,437.0
ho (W/m^2K)	6,186	2,385.1
U (W/m^2K)	1,230	948.4
ΔP_t (Pa)	65,657	4,708
ΔP_s (Pa)	88,520	9,141
P (W)	6,120	527
C_{in} (€)	18,162	20,875
C_{op} (€)	31,589	2,722
C_{tot} (€)	49,751	23,597

Optimization process using particle swarm has been successfully minimizing total cost of shell-and-tube heat exchanger on the first case study. Algorithm methods have been decreasing total cost of the shell-and-tube heat exchanger 52.57 % using particle swarm algorithm from the total cost of original data, as mentioned in Table 9. Total cost decreases on first case study due to decreasing total investment and operation cost. In this case, total operational cost decreases 91.38 % using particle swarm algorithm. Total investment cost increases 14.94 % using particle swarm algorithm from total operational cost and total investment cost of original data.



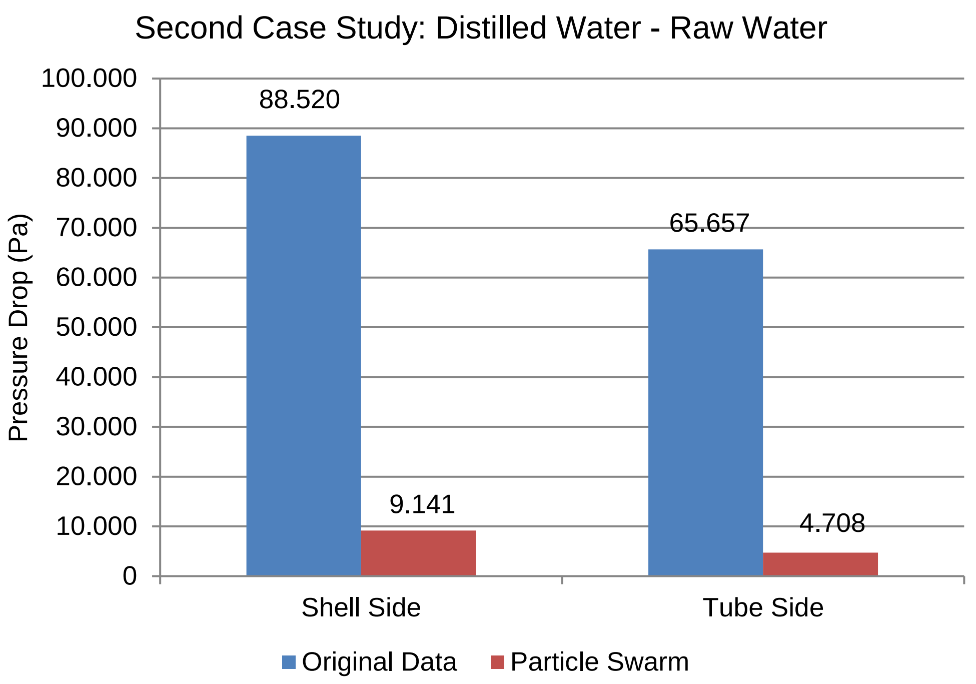
Graphic 4. Cost comparison of second case study

Value of overall, tube side and shell side heat transfer coefficient tend to lower than original data. Results of overall heat transfer coefficient decreases 22.90 % using particle swarm algorithm from overall heat transfer of the original data. For heat transfer in tube side, the results decrease 54.72 % using particle swarm algorithm from original data. For heat transfer in shell side, the results decrease 61.44 % using particle swarm 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 Graphic 4.



Graphic 5. Heat transfer coefficient comparison of second case study

Pressure drop tends to decrease in the tube side. Pressure drop in tube side decreases 92.83 % using particle swarm algorithm from the original data. Pressure drops in shell side decreases 88.87 % using Genetic algorithm. As appears in Graphic 5, It happens because velocity both in tube and shell side is decrease.



Graphic 6. Pressure drop comparison of second case study

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4. CONCLUSION

Based on the research that has been done, some conclusions can be drawn as follows. Collecting suitable equations for the computational process have been done, calculation process does not need any table, chart or graph to define parameters to design of shell-and-tube heat exchangers. All calculation process were done by using the formula for wide range cases. It could be design shell-and-tube heat exchangers tube layout 30º, 45º, and 90º. The estimate cost is provided for shell-and-tube heat exchanger made of carbon steel, stainless steel, titanium and the combination of their materials. 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. Setting parameters for particle swarm algorithm have been found to get a minimum total cost of shell-and-tube heat exchangers. in particle swarm algorithm, minimum cost can be got using particles 250, first tuning factor 2, second turning factor 2, and 100 maximum iterations. The program has been applied for solving three thermal design shell-and-tube heat exchangers. The first case is a shell-and-tube heat exchanger with kerosene and crude oil fluids, the results show that program can reduce 28.84 % using particle swarm algorithm of the total cost from the original data. The second case is a shell-and-tube heat exchanger with distilled water and raw water, in which the result shows that program can reduce 52.57 % using particle swarm algorithm of the total cost from the original data.

REFERENCES

1. Shah, R. K. and Sekulic, D. P. Fundamentals of Heat Exchanger Design. New Jersey: John Wiley & Sons, Inc. 2003.
2. Sinnot, R. K. Chemical Engineering Design. Oxford: Elsevier Butterwoth-Heinneman. 2005.
3. Hewitt, G. F., Shires G. L., and Bott, T. R. Process Heat Transfer. New York: Begell House, Inc. 2000.
4. Sadeghzaden, H., Ehyaei M. A., Rosen, M. A. Techno-Economic Optimization of a Shell and Tube Heat Exchanger by Genetic and Particle Swarm Algorithm. Energy Conversion and Management, vol. 93, pp. 84-91, 2015. https://doi.org/10.1016/j.enconman.2015.01.007
5. Yang, J., Oh, S., Liu, W. Optimization of Shell-and-Tube Heat Exchangers using A General Design Approach Motivated by Constructal Theory. International Journal of Heat and Mass Transfer, vol. 77, pp. 1144-1154, 2014. https://doi.org/10.1016/j.ijheatmasstransfer.2014.06.046
6. Caputo, A. C., Pelagagge, P. M., Salini, P. Heat Exchanger Design Based on Economic Optimization. Applied Thermal Engineering, vol. 28, pp. 1151-1159, 2008. https://doi.org/10.1016/j.applthermaleng.2007.08.010
7. Taal, M., et al. Cost Estimation and Energy Price Forecasts for Economic Evaluation of Retrofit Projects. Applied Thermal Engineering, vol. 23, pp. 1819-1835, 2013. https://doi.org/ 10.1016/S1359-4311(03)00136-4
8. Sanaye, S., Hajabdollahi, H. Multi-Objective Optimization of Shell and Tube Heat Exchangers. Applied Thermal Engineering, vol. 30, pp. 1937-1945, 2010. https://doi.org/10.1016/j.applthermaleng.2010.04.018
9. Arora, R. K. Optimization Algorithms and Applications. Florida: CRC Press Taylor & Francis Group. 2015.