Journal of Heat and Mass Transfer Research 13 (2026), Serial Number 26, 147 – 157

Journal of Heat and Mass Transfer Research

Journal homepage: https://jhmtr.semnan.ac.ir

Semnan University

ISSN: 2383-3068

Research Article

Design Optimization of a Shell and Tube Heat Exchanger for a Helicopter Considering Objective Functions of Heat Exchanger Weight, Overall Heat Transfer Coefficient, and Manufacturing Cost

Navid Bozorgan *

Department of Mechanical Engineering, Arv.C., Islamic Azad University, Abadan, Iran

ARTICLE INFO

Article history:

Received: 2024-09-19

Revised: 2025-03-13

Accepted: 2025-03-15

Keywords:

Design;

Heat exchanger;

Helicopter;

Heat exchanger weight;

Overall heat transfer coefficient;

Manufacturing cost.

ABSTRACT

In the current study, the optimal design of a shell-and-tube heat exchanger based on the TEMA standard is performed to preheat JP-4 fuel using neopentyl polyol ester (PE-DPE-316) engine oil for the purpose of refurbishing and upgrading the Bell AH-1 Cobra helicopter. The design considers three objective functions: heat exchanger weight, overall heat transfer coefficient, and manufacturing cost. Weight reduction and performance enhancement have consistently been priorities for designers in aerospace systems. For the first time, the reduction of heat exchanger's weight is considered in this research for weight reduction in a helicopter. Design parameters include heat exchanger type (front head, shell, and rear head) comprising five types of floating head shell and tube heat exchangers (AES, AET, BET, AEP, and BEP), four types of U-tube heat exchangers (AEU, BEU, CEU, and CFU), and three types of fixed tube sheet heat exchangers (AEL, BEM, and NEN). Additional parameters are baffle type (single-segment, double-segment, and triple-segment) and baffle cut (20 to 35 percent of shell diameter). The heat exchanger design is performed using ASPEN EDR software and validated through the analysis of shell-side (engine oil) and tube-side (fuel) heat transfer relationships, with coding implemented in MATLAB. A good agreement is seen between the ASPEN EDR software and the MATLAB code. The final heat exchanger design in this study is a BEM type, single-pass with 0.75-inch outer tube diameter and single-segment baffles with a 20% cut. This design achieves a heat exchanger weight of 192.4 kg, an overall heat transfer coefficient of 193.7 $W/m^2 \cdot K$, and a manufacturing cost of $20,398.

1. Introduction

The flight efficiency of any helicopter is directly proportional to its weight; this is the total weight, including the empty weight of the helicopter, plus the weight of the occupants, fuel and cargo. Therefore, the design of a fuel/oil heat exchanger in a helicopter, which is used to preheat fuel and cool the engine oil, must be optimized to have the least possible weight and size while at the same time being as efficient as possible due to the limited space in the engine compartment of a helicopter. The use of a shell-and-tube heat exchanger as a fuel/oil heat exchanger seems to be a wise decision due to its ability to withstand the high working fluid

---

* **Corresponding author.**

E-mail address: n.bozorgan@iau.ac.ir

Cite this article as:

Bozorgan, N., 2026. Design Optimization of a Shell and Tube Heat Exchanger for a Helicopter Considering Objective Functions of Heat Exchanger Weight, Overall Heat Transfer Coefficient, and Manufacturing Cost. *Journal of Heat and Mass Transfer Research*, 13(2), pp. 147-157.

https://doi.org/10.22075/JHMTR.2025.35376.1609

pressure and its design. In the recent past, due to the extensive use of shell-and-tube heat exchangers in various industries and under various conditions of operation, researchers have strived to achieve the best design possible while satisfying specific design goals.

Han et al. [1] carried out a thermo-economic optimization of a shell-and-tube heat exchanger using the sparrow search algorithm, which is a metaheuristic algorithm developed in 2020 by Xue et al. [2]. Their findings suggest that the heat transfer surface area can be cut down by about 15.62% to 49.3% of the initial heat exchanger, while the total costs can be reduced up to 27.93%. Jafari Asl et al. [3] applied the whale optimization algorithm in the reliability-based optimization of a shell and tube heat exchanger. Their results are aligned with the algorithm in regard to the total cost of shell-and-tube heat exchangers. Mawardi et al. [4] analyzed the application of BEM and BJM-type shell and tube heat exchangers in the ocean thermal power plant using Aspen Plus and computational fluid dynamics. In the heat exchanger model employed by the authors, the shell side fluid or hot fluid was seawater at 29°C, and the tube side fluid or cold fluid was ammonia at 8°C. They prove that if a BEM heat exchanger is chosen, the ammonia vapor produced by hot water in the exchanger can turn a turbine and generate 4. 3 kilowatts of electricity. Rao and Majithia [5] have also worked on the optimization of four shell-and-tube heat exchangers where the total cost (fixed cost + operational cost) was used as the cost function. Based on their results, the authors noted that the Rao and SAMP Rao algorithms are well suited for designing shell-and-tube heat exchangers in terms of total cost reduction as compared to other algorithms. Caputo et al. [6] suggested that the majority of the shell-and-tube heat exchanger designers have paid more attention to the proper choice of optimization algorithms than the proper choice of the objective functions in their optimal designs. They pointed out that choosing a thermodynamic objective function only is not sufficient to design cost-effective shell and tube heat exchangers; it requires multi-objective optimization that includes both thermodynamic and economic objective functions. Salimi et al. [7], using ANSYS Fluent software, demonstrated that in a fuel/oil shell-and-tube heat exchanger for a helicopter engine - where the engine oil is cooled and fuel is preheated - the heat transfer rate increases by approximately 11% when finned tubes are used compared to bare tubes.

Mohanty [8] optimized two shell-and-tube heat exchangers with thermal capacities of 4.34 and 1.44 megawatts using the firefly algorithm, considering total cost as the objective function. Their results show a 27.4% and 8% reduction in heat transfer surface area and a 29% and 28% reduction in total cost for the 4.34 and 1.44-megawatt heat exchangers, respectively. Mirzaei et al. [9] optimized two parameters - efficiency and cost - in a shell-and-tube heat exchanger using a multi-objective optimization algorithm with two objective functions: cost and efficiency. The goal is maximum efficiency and minimum cost. Through the use of genetic algorithms together with structural theory, they were able to enhance the thermal efficiency by about 28%. Pettinrin et al. [10] worked on heat exchangers of crude oil preheater in a distillation unit which consists of two shell and tube heat exchangers. They used thirteen design parameters with their lower and upper limits and the firefly algorithm to minimize entropy generation. They pointed out that by reducing the entropy generation and the design parameters, the shell volume of the shell and tube heat exchanger can be reduced, thus creating a compact heat exchanger. Bozorgan et al. [11] optimized a shell-and-tube heat exchanger by considering five design parameters: inner and outer tube diameters, the pitch of the tubes, the spacing of the baffles and the length of the tubes. The objective functions were the overall heat transfer coefficient and pressure drop, and they applied the honey bee algorithm. They were able to achieve the enhancement of the overall heat transfer coefficient in the shell-and-tube heat exchanger by about 22.78% with a slight increase in pressure drop of only about 1.8%.

Gürses et al. [12] minimized the set-up and running cost of a shell and tube heat exchanger using the African vulture optimization algorithm (AVOA). Gürses et al. [13] minimized the initial and life cycle cost of a fin plate heat exchanger using the Artificial gorilla troops algorithm (AGTA). They stated that AGTA is suitable for various engineering optimization fields.

Mehta et al. [14] have optimized a fin and tube heat exchanger (FTHE) by considering the overall cost of the FTHE as the objective function (OF) using the novel gradient-based optimization (GBO) algorithm. Their results illustrate the fact that GBO is the robust optimizer when compared to the ES, ALO, SOS, GOA and AF algorithms.

Sait et al. [15] have carried out the economic optimization of a plate-fin heat exchanger using the cheetah algorithm. They have reported that the cheetah optimizer outperforms compared to PVS, SS, GWO, AF, ES, GOA, SOS and ALO algorithms. Gürses et al. [16] have optimized the design of three well-known heat exchangers that used in many heat-recovery systems (shell and tube, tube-fin and plate-fin heat exchangers) by considering the cost factor as the objective function, through the prairie dog optimization algorithm (PDOA).

Patel et al. [17] stated that the SOS, GOA, AF and HTS algorithms performed better than the PVS, SS, ES and ALO algorithms in the cost optimization process of the FTHE. Bozorgan et al. [18] optimized the heat performance of a shell and tube heat exchanger about 12.3% by using the ϒ-Al_2O_3/water nanofluid with a volume concentration of 0.016 as a coolant.

Upon reviewing past research, one can conclude that limited studies have been conducted on optimizing heat exchanger design considering the objective function of exchanger weight, given the need for weight reduction in aerospace system designs. In the present study, the design of a shell-and-tube heat exchanger based on the TEMA standard is performed to preheat JP-4 fuel using neopentyl polyol ester (PE-DPE-316) engine oil for the purpose of refurbishing and upgrading the Bell AH-1 Cobra helicopter. This design considers the objective functions of exchanger weight, overall heat transfer coefficient, and manufacturing cost using ASPEN EDR software.

2. Fuel Heating System

The schematic of the Bell AH-1 Cobra helicopter's fuel system is shown in Figure 1. This system includes a shell-and-tube fuel/engine oil heat exchanger, fuel pump and filter, manual and automatic fuel systems, flow divider valve and drain valve, manifolds, and fuel nozzles. The fuel/engine oil heat exchanger is located at the top right of the gearbox and utilizes engine oil heat to preheat the fuel for improved combustion. This shell-and-tube heat exchanger has installation space limitations. In its design for the present study, the shell diameter range is considered from 6 to 13 inches, and the tube length ranges from 50 to 80 centimeters. Shell JP-4 fuel, with the weight percentages shown in Table 1, flows through the exchanger tubes made of 304 stainless steel, while neopentyl polyol ester oil (PE-DPE-316), with the weight percentages shown in Table 2, flows through the exchanger shell. The values of the thermophysical properties of JP-4 fuel and engine oil are tabulated in Table 3. Additionally, fuel and engine oil conditions are considered according to the PT-6 engine maintenance manual [19] such that the helicopter is flying at an altitude of three kilometers, at maximum engine speed, in an air temperature of 40 degrees Celsius. The mass flow rate of fuel entering the heat exchanger shell is 0.13 kg/s, with a maximum fuel pressure of 12 bar and an inlet temperature to the heat exchanger shell of 40 degrees Celsius. The mass flow rate of engine oil entering the heat exchanger tubes is 0.08 kg/s, with a maximum oil pressure of 9 bar and inlet and outlet oil temperatures to the heat exchanger of 125 and 65 degrees Celsius, respectively. The fouling resistance factor in the heat exchanger is considered to be 0.00035 m^2K/W.

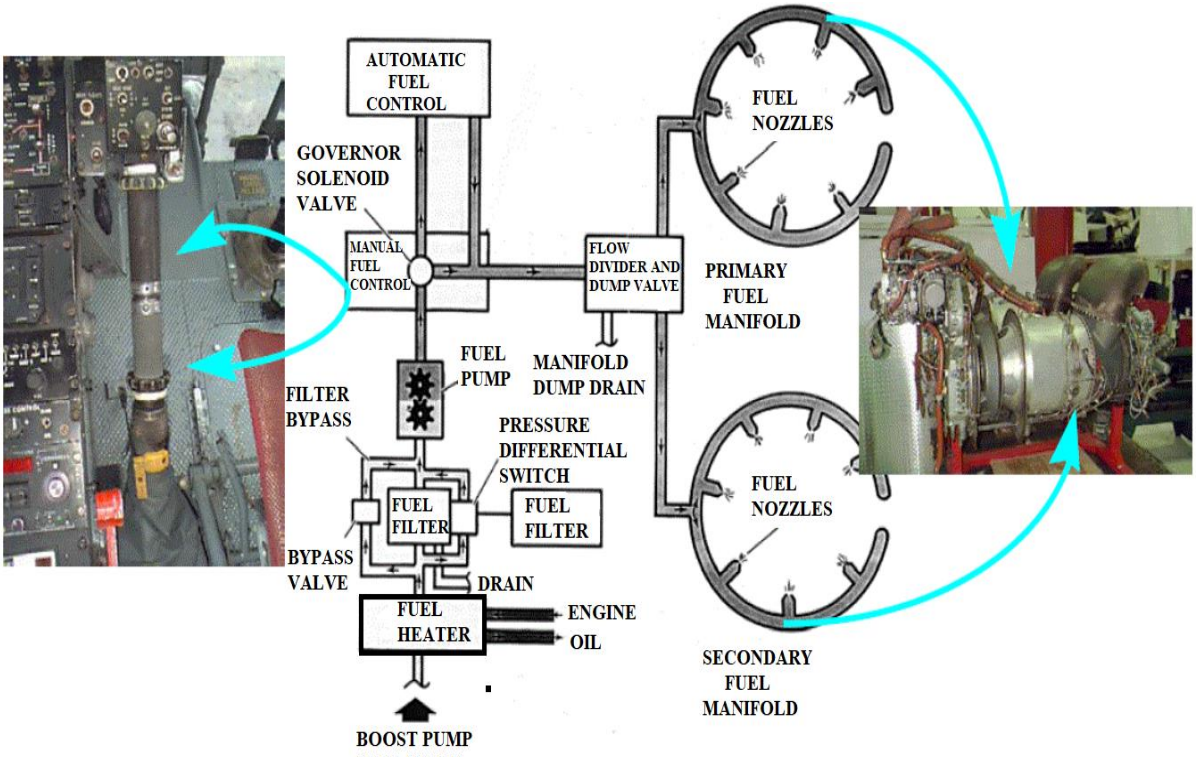


Fig. 1. Schematic of the fuel system

Table 1. Weight percentages of JP-4 fuel components [20]

Component	Weight Percentage
Heptane	4.73
Octane	7.48
Nonane	7.24
Decane	11.25
Indane	0.42
Undecane	16.62
Dodecane	11.49
Tridecane	6.07
Tetradecane	3.19
Pentadecane	0.96
3-Methylhexane	3.05
2-Methylheptane	3.08
3-Methylheptane	1.64
2,5-Dimethylpentane	0.18
2,4-Dimethylpentane	0.63
Cyclohexane	1.52
Methylcyclohexane	5.68
Methylbenzene (Toluene)	3.77
m-Xylene	2.6
p-Xylene	1.7
o-Xylene	2
1,3,5-Trimethylbenzene	1.52
1,2,4-Trimethylbenzene	2
1,2,3-Trimethylbenzene	0.3

Table 2. Weight percentages of neopentyl polyol ester (PE-DPE-316) engine oil components [21]

Component	Weight Percentage
Itaconic acid	20
Glutaric acid	46
Suberic acid	2
Azelaic acid	31
Sebacic acid	1

Table 3. Thermophysical properties of JP-4 fuel and engine oil

Characteristic	Specific heat (J/kgK)	Density (kg/m^3)	Thermal conductivity (W/mK)	Dynamic viscosity (kg/ms)
Engine Oil	2179.86	1129.35	0.1618	0.001861
Fuel	2182.77	739.23	0.1248	0.000621

3. Heat Transfer Analysis

In the present study, the validation of shell and tube heat exchanger designed by ASPEN EDR is achieved from the analysis of heat transfer relations for the shell fluid (engine oil) and the tube fluid (fuel) following a sequence of coding the problem into MATLAB software and comparing the result obtained from overall heat transfer coefficient formula. Thus, the overall heat transfer coefficient is determined by evaluating shell and tube fluid heat transfer coefficients. It is assumed that the flow is incompressible, steady-state, and turbulent. Also, the effect of body force is neglected.

3.1. Coefficient of Heat Transfer of the Fluid on the Shell Side

The heat transfer coefficient of the shell-side fluid (engine oil) is calculated according to the relationship proposed by Kern [22] for fluid flowing in a shell with single-cut baffles as follows:

$$h_h = \frac{0.36 k_h}{D_e} \mathrm{Re}_h^{0.55} \mathrm{Pr}_h^{\frac{1}{3}} \tag{1}$$

In equation (1), the equivalent shell diameter (De) is defined as:

$$D_e = \frac{4\left(P_t^2 - \frac{\pi d_o^2}{4}\right)}{\pi d_o} \tag{2}$$

The symbols used in the above equation are do for the outer diameter of the tube and Pt for the tube pitch. In equation (1), the dimensionless Reynolds and Prandtl numbers for the shell-side fluid are defined as:

$$\mathrm{Re}_h = \left(\frac{\dot{m}_h}{A_s}\right)\left(\frac{D_e}{\mu_h}\right) \tag{3}$$

$$\mathrm{Pr}_h = \frac{c_{p,h}\mu_h}{k_h} \tag{4}$$

In equation (3), $\dot{m}_h$ is the mass flow rate of the shell-side fluid and As is the cross-sectional area of flow, which is obtained by the following equation:

$$A_s = (D_s - N_{TC} d_o) B \tag{5}$$

$$N_{TC} = \frac{D_s}{P_t} \tag{6}$$

According to the equation (5), Ds and B represent the inner diameter of the shell cylinder and the baffle spacing, respectively. The inner diameter of the shell cylinder is calculated as follows [23]:

$$D_s = \left(\frac{N_t (CL)(PR)^2 d_o^2}{0.785(CTP)} \right)^{0.5} \tag{7}$$

The tube pitch ratio (PR) is equal to:

$$PR = \frac{P_t}{d_o} \tag{8}$$

Let us note that in the equation (7) CTP and CL are constants. The CTP in case of a single-pass heat exchanger is typically kept at 0.93. C_L in triangular tube arrangement is 0.87 [23]. The number of tubes (N_t) is obtained with the mass flow rate of the tube-side fluid according to the following equation:

$$N_t = \frac{4\dot{m}_c}{\rho_c \pi d_i^2 u_m} \tag{9}$$

3.2. Coefficient of Heat Transfer for the Tube Side Fluid

The heat transfer coefficient of the tube-side fluid (JP-4 fuel) is obtained by defining the Petukhov Nusselt number (for Reynolds numbers greater than 10000) according to the following equation [24]:

$$Nu_c = \frac{(f_c/2)\,\mathrm{Re}_c\,\mathrm{Pr}_c}{1.07 + 12.7(f_c/2)^{1/2}(\mathrm{Pr}_c^{1/2} - 1)} \tag{10}$$

In the above equation, the friction coefficient, Reynolds number, and Prandtl number for the tube-side fluid are respectively equal to [24]:

$$f_c = (1.58 \ln \mathrm{Re}_c - 3.28)^{-2} \tag{11}$$

$$\mathrm{Re}_c = \frac{\rho_c u_m d_i}{\mu_c} \tag{12}$$

$$\mathrm{Pr}_c = \frac{c_{p,c}\mu_c}{k_c} \tag{13}$$

The tube-side fluid heat transfer coefficient is obtained by calculating the Nusselt number according to the following equation:

$$h_c = \frac{Nu_c k_c}{d_i} \tag{14}$$

3.1. Total Convection U-Value

By calculating the heat transfer coefficients of the tube and shell fluids, the overall heat transfer coefficient can be obtained according to the following equation [25]:

$$U = \left(\frac{1}{h_h} + \frac{1}{h_c} \times \frac{d_o}{d_i} + \frac{r_o \ln(r_o / r_i)}{k} \right) \tag{15}$$

4. Design Optimization of Shell-and-Tube Heat Exchanger

In the present study, multiple factors such as heat exchanger weight (considering the flight efficiency of each helicopter relative to its weight), appropriate thermal performance, available installation space constraints, and manufacturing costs are taken into account in designing the optimal shell-and-tube heat exchanger under investigation. To this end, the type of exchanger (front head, shell, and rear head), baffle type (single-segment, double-segment, and triple-segment), and baffle cut percentage are considered as design parameters in achieving a suitable shell-and-tube heat exchanger for the helicopter fuel heating system. The difference in the weight of 12 different types of shell and tube heat exchangers discussed in this paper can be mostly due to the weight of the front head, rear head and the number of tubes and baffles.

4.1. Optimum Selection of Shell-and-Tube Heat Exchanger Type

Based on the standards of the Tubular Exchanger Manufacturers Association (TEMA), which provides a well-known table for combining various types of heads and shells, the type of shell-and-tube heat exchanger under study is determined. Accordingly, five types of floating head shell-and-tube heat exchangers (AES, AET, BET, AEP, and BEP), four types of U-tube shell-and-tube heat exchangers (AEU, BEU, CEU, and CFU), and three types of fixed tube sheet shell-and-tube heat exchangers (AEL, BEM, and NEN) are examined and evaluated to select the most suitable type of shell-and-tube heat exchanger for the helicopter fuel heating system under study. This evaluation considers the objective functions of weight, thermal performance, and manufacturing cost of the heat exchanger. The wide variety in types of shell-and-tube heat exchangers in terms of operation, tube arrangement within the shell, exchanger size and dimensions, and other standards used in the manufacturing and design process have resulted in significant price differences among these exchangers. The results of the shell-and-tube heat exchanger type selection process in the present study, performed using ASPEN EDR software, are shown in Figure 2. Weight variations stem from header design, tube bundle configuration, shell thickness, and baffles, while costs are driven by design complexity, materials, and maintenance features.

4.1.1. Shell and Tube Heat Exchangers with One Floating Head in Classes S, T, and P

In heat exchangers with one floating head at the front, the tube sheet with a larger diameter is welded to the shell, but the tube sheet at the rear header, which has a smaller diameter than the shell, is not welded to it. However, it is only permitted to slide or float. The use of a floating head design accommodates the thermal expansion of the heat exchanger. In the present work, five basic types of shell and tube heat exchangers with one floating head, namely AES, BET, AET, BEP, and AEP, have been analyzed to determine the most appropriate type of shell and tube heat exchanger for the helicopter fuel heating system. The results are presented in Figure 2.

(a). Class S Floating Head Heat Exchanger (AES):

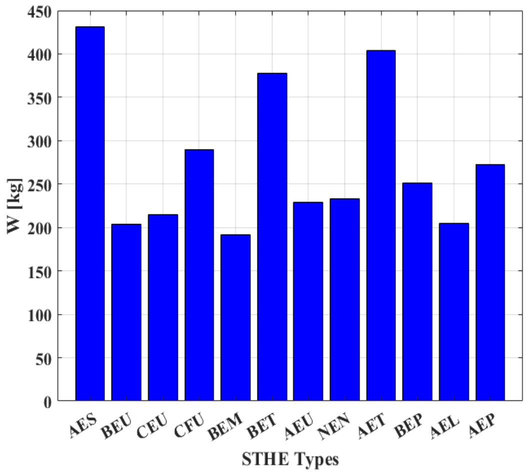
Figure 2 (a) shows that the weight of the AES-type heat exchanger is the highest among all the shell and tube heat exchangers considered in this research and is equal to 431. 3 kg. Hence, due to its high weight and construction cost ($33,290), in addition to the fact that the tube bundle cannot be removed from the exchanger and the components have to be disassembled to take out the bundle from the shell, this type of exchanger is not chosen for the helicopter fuel heating system in the present work. Among the most significant factors influencing the weight and cost of AES heat exchangers are the use of corrosion-resistant alloys, the employment of thick shells and tubes, precision manufacturing and assembly processes for components, and the requirement for a greater number of tubes to achieve optimal thermal efficiency.

(b). Class T floating head heat exchangers (AET and BET):

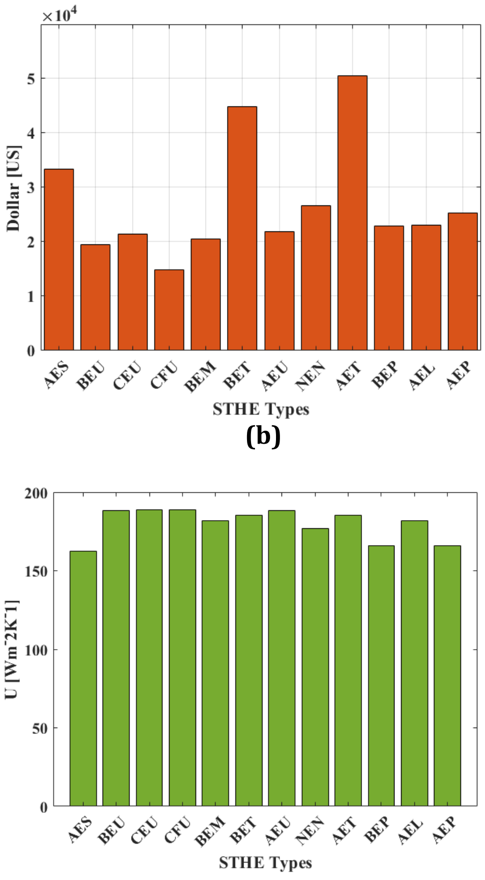
Figure 2 (b) shows that the AET and BET have the highest construction cost among all the shell and tube heat exchanger types, with $50,313 and $44,679, respectively. However, as is seen in Figure 2 (c), AET and BET heat exchangers have suitable thermal performance because of the large cross-sectional area of the shell-side inlet nozzle and proper heat distribution across the tube bundle. Also, the tube bundle can be removed from these exchangers for inspection and or cleaning quite easily because of the direct bolting of the floating head to the floating tube sheet. These two types of exchangers are not suitable for the helicopter fuel heating system because of their weight (404 and 377. 5 kg) and construction costs. Key factors contributing to the high weight of AET and BET shell-and-tube heat exchangers include thick-walled shells, baffles, and tubes; steel components such as bonnets; and the triangular tube arrangement, which enhances tube density and necessitates a larger number of tubes. Among the most significant factors driving the elevated manufacturing costs of these exchangers are: the need for precise engineering and complex calculations to withstand thermal and mechanical stresses; the use of double tube sheets; high-cost raw materials like Inconel or titanium; and the heavy machining required for parts like the tube sheet.

(c). Class P floating head heat exchangers (AEP and BEP):

The Class P shell and tube heat exchangers studied in this research are of two common and widely used types: AEP and BEP, which are the two most used acronyms associated with the two types of power plants. As seen in the results illustrated in Figure 2 (A and B), both heat exchangers have smaller weight and construction costs compared to the analyzed Class S and T heat exchangers. The weights of the exchanger and construction cost for AEP and BEP models are 273 and 251. 6 kg, $25,126 and $22,734, respectively. However, AEP, BEP shell, and tube heat exchangers are lighter and cheaper than the studied Class S and T heat exchangers and their suitable sealing systems. Since AEP and BEP exchangers have lower thermal efficiency than other shell and tube heat exchangers, as shown in Figure 2 (c), applying these exchangers in this study is not suitable. The lower thermal performance of AEP and BEP shell-and-tube heat exchangers is attributed to their packing design and the increased clearance between the floating head and the shell, which generates significant bypass streams. These streams bypass the tubes without participating in heat transfer.



(a)



(b)

(c)

Fig. 2. Results for (a) weight; (b) construction cost; (c) overall heat transfer coefficient in various types of shell and tube heat exchangers

4.1.2. Class U Shell and Tube Heat Exchangers

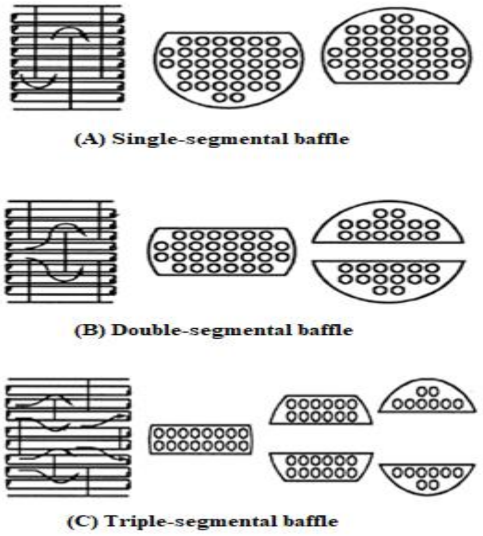
The Class U shell and tube heat exchangers studied in this research are of four common types: These are AEU, BEU, CEU and CFU. As shown in Figure 2 (A and B), the weight and the construction costs of the Class U heat exchangers examined in this study are low since the use of U-shaped tubes in the exchangers requires one tube sheet. Nevertheless, the U-shaped tubes are connected to the tube sheet and shell on one side only; thus, one tube sheet is sufficient. This arrangement allows the tubes to expand when hot and does not impact the rest of the exchanger in any way. This saves on the construction cost since only one tube sheet is needed to make the heat exchanger. The results in Figure 2 (b) show that the construction cost of the CFU-type heat exchanger is the least among all the types of heat exchangers discussed in this paper at $14,715. However, this type of heat exchanger, despite its relatively low construction cost and thermal efficiency being quite satisfactory, cannot be recommended for use in the helicopter fuel system due to its fairly high weight of approximately 290.1 kg. As illustrated in Figure 2 C, the thermal performance of Class U heat exchangers is fairly good because the U-shaped tubes provide good contact between the fluids in the tubes and the fluids in the shell. According to the results, it is possible to state that the weight of the BEU-type heat exchanger is 203.9 kg less than other Class U exchangers. Considering the low weight of the heat exchanger, the reasonable construction cost and the appropriate thermal performance, it is advisable to use the BEU-type shell and tube heat exchanger in the helicopter fuel heating system.

4.1.3. Fixed Tube Sheet Shell and Tube Heat Exchangers in Classes L, M, and N

Fixed tube sheet heat exchangers are a kind of shell and tube heat exchanger. These have straight, one-pass tubes that are fixed on a stationary tube sheet. The shell is made by welding this tube sheet to it. These types of heat exchangers can be divided into three classes: L, M and N (according to TEMA standards). In this study, we examine three popular kinds from group (AEL, BEM and NEN) for their use in heating systems for the helicopter fueling process. As per the results illustrated in Figure 2, it is observed that the BEM type's weight of around 191.8 kg is less than that of AEL & NEN types along with various other studied shell tube heat exchangers mentioned in this research work. The reduced weight of the BEM-type shell-and-tube heat exchanger stems from the removal of intricate components, including the floating head, supplementary sealing plates, and expansion joints. So considering these findings, if we take into account its lightness - low massiveness-, reasonable price for construction -not too expensive when compared with some models-, as well as suitable thermal performance, then the application might be considered a wise recommendation, especially where there exists necessity related to helicopter fuel heating system.

4.1.4. Optimum Selection between BEU and BEM Shell and Tube Heat Exchangers

As discussed, after examining 12 different types of shell and tube heat exchangers according to the TEMA standard, considering the objective functions of exchanger weight, construction cost, and overall heat transfer coefficient, it is observed that two types of heat exchangers, BEU and BEM, are suitable for application in helicopter fuel heating systems. These two types are among the most common shell and tube heat exchangers in many industries, each with its specific advantages and disadvantages. Both types are identical except for the tube shape and rear head. The type B front head for both exchangers allows access to the tube sheet for cleaning after disconnection from the piping system. Taking into account the fact that lower weight is critical to the efficiency of helicopter flight and since the designed BEM type heat exchanger weighs about 12. 1 kg less than the BEU type, however, the construction cost is about $1,082 more, and the overall heat transfer coefficient is about 6. 6 W/m^{2}K, the BEM type shell and tube heat exchanger with straight one-pass tubes are selected for the helicopter fuel heating system. Also, since flight safety is critical in helicopters, it is recommended to use heat exchangers with straight tubes rather than U-shaped tubes since the tube wall resistance in the bent portion tends to degrade over time and can fail. However, it should be mentioned that in the BEM-type heat exchanger, because the straight tubes are mounted on the tube sheet, an expansion joint should be provided in the middle of the shell to compensate for the thermal expansion.


(A) Single-segmental baffle

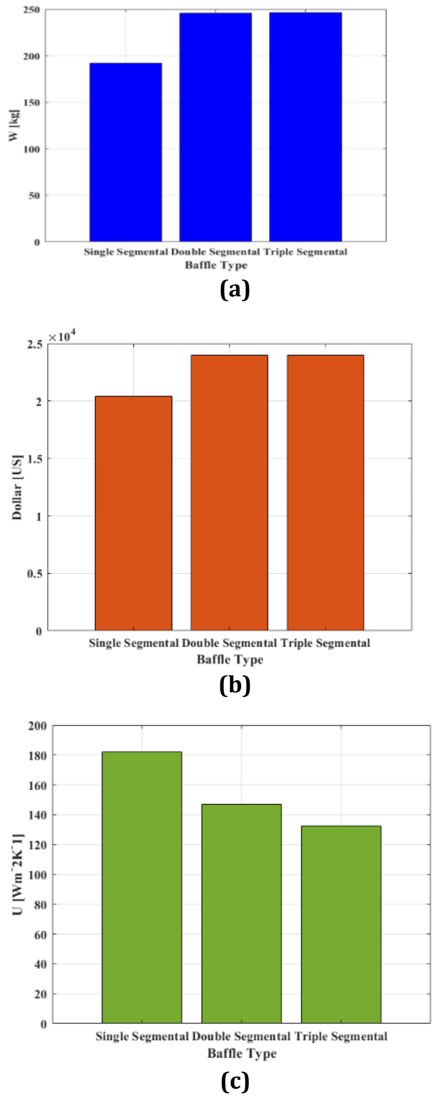
(B) Double-segmental baffle

(C) Triple-segmental baffle

Fig. 3. Various types of segmental baffles

4.2. Selection of the Optimal Baffle Type in BEM Shell and Tube Heat Exchanger

Baffles serve as physical supports for the tube bundle in shell and tube heat exchangers. Baffle design should minimize the shell-side fluid bypass (flow without heat exchange with the tubes) and maximize contact between the shell-side fluid and the outer surface of the tubes. The most common type of baffles is segmental baffles. This study investigated the application of single-segmental, double-segmental, and triple-segmental baffles, as shown in Figure 3, in the design of shell and tube heat exchangers. These baffles are made of carbon steel due to its resistance to thermal stress and corrosion. In segmental baffles, the shell-side fluid flow between the tube bundles is turbulated by removing a segment or section of the circle, ultimately enhancing heat transfer in the heat exchanger by creating turbulence. According to the results obtained from heat exchanger design using ASPEN EDR software, it is observed that the shell's outer diameter increases from 219.08 mm to 273.05 mm when changing the baffle type from single-segmental to double or triple-segmental. The increase in shell diameter leads to a decrease in flow velocity and, consequently, a reduction in heat transfer. Despite decreasing heat transfer in the heat exchanger with baffle-type change, the reduction in flow momentum is sometimes necessary to prevent exchanger vibration and tube deformation or bending. However, given that the heat exchanger design with single-segmental baffles using ASPEN EDR software does not exhibit vibration, single-segmental baffles are selected. The results in Figure 4 demonstrate that selecting single-segmental baffles, compared to double and triple-segmental baffles, results in lower weight and construction cost of the designed heat exchanger and a higher overall heat transfer coefficient.



(a)

(b)

(c)

Fig. 4. Results for (a) weight; (b) Construction cost; (c) Overall heat transfer coefficient of shell and tube heat exchanger with different segmental baffle types

4.3. Determination of the Optimal Baffle Cut Percentage in BEM Shell and Tube Heat Exchanger

The baffle cut is the portion of the shell in which the shell-side fluid flows parallel to the tubes. This cut helps support the tubes and allows flow control to establish a better flow rate in the tube bundle. In this study, the baffle cut direction in the shell and tube heat exchanger design using ASPEN EDR software was considered horizontal with cut values between 20% and 35% of the shell diameter. This is the standard range in industries. From the results, it can be concluded that the construction cost of the designed heat exchanger with various baffle cut percentages is estimated to be $20,398. Also, the overall heat transfer coefficient was reduced by approximately 6.54 percent (as shown in Figure 5) when the baffle cut was raised from 20% to 35% because the shell-side fluid velocity was low. However, the heat exchanger weight was reduced slightly by approximately 0.6 kg (from 192.4 to 191.8 kg). Thus, the baffle cut percentage of the studied shell and tube heat exchanger design is assumed to be 20% of the shell diameter.

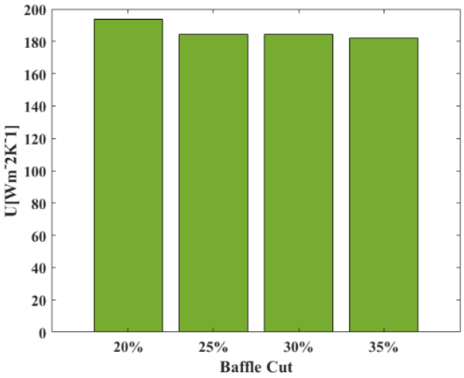


Fig. 5. Overall heat transfer coefficient of shell and tube heat exchanger at various baffle cut percentages

4.4. Geometric Specifications of the Designed Shell and Tube Heat Exchanger

Tables 4 provides the information about the geometric specifications and operating conditions of the optimal design of shell-and-tube heat exchanger. The tubes in this heat exchanger are one-pass with a triangular arrangement pattern at a 30-degree angle and 23.81 mm pitch, 0.75-inch outer diameter, 1.65 mm thickness, and 800 mm length, made of 304 stainless steel, totaling 51 tubes. In this heat exchanger, the baffles are single-segmental with a horizontal cut of 20%, made of carbon steel, and there are 8 baffles placed 80 mm apart. The shell is made of carbon steel with outer and inner diameters of 219.08 mm and 205 mm, respectively.

Table 4. Geometric specifications and operating conditions of the shell-and-tube heat exchanger

Description	**Value**
Internal tube diameter	15.75 mm
External tube diameter	19.05 mm
Tube length	800 mm
Tube pitch	23.81 mm
Baffle spacing	80 mm
Number of tubes	51
Number of baffles	8
Baffle type	Single-segmental
Baffle cut percentage	20%
Engine oil mass flow rate (shell-side fluid)	0.08 kg/s
Engine oil inlet temperature	125 °C
Fuel inlet temperature (tube-side fluid)	40 °C

5. Validation of Heat Exchanger Design Using ASPEN EDR Software

To ensure that the shell-and-tube heat exchanger design obtained from the ASPEN EDR software is correct, the overall heat transfer coefficient of the heat exchanger was determined by using the geometric and operational specifications shown in Table 4 and the weight percentages of JP-4 fuel and engine oil components shown in Tables 1 and 2, respectively. All the above was done with the help of ASPEN EDR software for different mass flow rates of fuel. These were then compared with the results from a MATLAB code developed from the shell and tube heat transfer analysis equations in section 3. The values of the thermophysical properties of JP-4 fuel and engine oil presented in Table 3 were used in the MATLAB code. This heat exchanger has single-pass tubes that are triangular in shape. A good agreement is seen between the ASPEN EDR software and the MATLAB code. According to Table 5, the minimum and maximum differences with the results are about 0. 15% and 3%, at fuel mass flow rates of 0. 12 and 0. 15 kg/s, respectively. Due to the small variation in the overall heat transfer coefficient, the accuracy of the design done by ASPEN EDR software can be guaranteed.

Table 5. Comparison of overall heat transfer coefficient results from ASPEN EDR and MATLAB cod

Fuel mass flow rate (Kg/s)	Overall heat transfer coefficient (ASPEN EDR) (W/m^{2}K)	Overall heat transfer coefficient (MATLAB code) (W/m^{2}K)	Percentage difference in results
0.12	182.4	182.126	0.15
0.13	181.8	179.4	1.32
0.14	181.2	177.7	1.93
0.15	180.7	175.2	3

6. Conclusions

In this work, an optimal shell and tube heat exchanger for fuel/engine oil of the Bell AH-1 Cobra helicopter was designed using ASPEN EDR software with the objective functions of exchanger weight, overall heat transfer coefficient and construction cost. According to the TEMA standards, five types of shell and tube heat exchangers with one floating head (AES, AET, BET, AEP, and BEP), four types of U-tube heat exchangers (AEU, BEU, CEU, and CFU) and three types of fixed tube sheet heat exchangers (AEL, BEM, and NEN) were considered for the selection of the most The analysis of the data obtained proved that the application of BEU and BEM type heat exchangers is more effective in the helicopter fuel heating system compared to other types. Taking into account the fact that lower weight is crucial for the helicopter flight, it is worth mentioning that the designed BEM type heat exchanger weighs approximately 12.1 kg less than the BEU type, and the safety issues arising from the possibility of failure of U-shaped tubes with time due to the lower tube wall resistance in the bent part, the BEM type shell and tube heat exchanger was adopted for the helicopter fuel heating in this study despite the higher construction cost of about $1,082 and lower overall heat transfer coefficient of about 6.6 W/m^{2}K lower than the BEU type. After that, the use of single-segmental, double-segmental, and triple-segmental baffles in shell and tube heat exchanger design was studied. It was found that the option of single-segmental baffles was lighter and cheaper to construct than the double and triple-segmental baffles and that the overall heat transfer coefficient of the designed heat exchanger was higher. In the last design step in ASPEN EDR software, a horizontal baffle cut direction was chosen with a percentage ranging from 20 to 35% of the shell diameter, as it is standard in industries. The analysis of the results indicated that a baffle cut of 20% of the shell diameter is optimal for the studied shell and tube heat exchanger design, given the reduction of the overall heat transfer coefficient of approximately 6.54% when the baffle cut was raised from 20% to 35%. Last but not least, the designed heat exchanger's weight, overall heat transfer coefficient, and construction cost were 192.4 kg, 193.7 W/m^{2}K, and $20,398, respectively.

Funding Statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

Authors Contribution Statement

Navid Bozorgan: Writing – original draft, Investigation, Conceptualization, Validation, Resources.

References

[1] Han, S., Li, X., Liu, Z., Zhang, B., He, C., Chen, Q., 2023. Thermal-economic optimization design of shell and tube heat exchanger using an improved sparrow search algorithm. *Thermal Science and Engineering Progress*, 45, 102085.

[2] Xue, J., Shen, B., 2020. A novel swarm intelligence optimization approach: sparrow search algorithm. *Syst. Sci. Control. Eng.*, 8, pp. 22-34.

[3] Jafari-Asl, J., Montaño, O.D.L., Mirjalili, S., Faes, M.G.R., 2024. A meta-heuristic approach for reliability-based design optimization of shell-and-tube heat exchangers. *Appl. Therm. Eng.*, 248, 123161.

[4] Mawardi, M., Wirjosentono, B., Ambarita, H., Koto, J., 2022. Development of tin copper alloys in shell and tube evaporator heat exchanger systems in ocean thermal energy converse power plant. *Eastern-European Journal of Enterprise Technologies*, 5, pp. 37-52.

[5] Rao, R.V., Majethia, M., 2022. Design optimization of shell-and-tube heat exchanger using Rao algorithms and their variants. *Thermal Science and Engineering Progress*, 36, 101520.

[6] Caputo, A.C., Federici, A., Pelagagge, P.M., Salini P., 2022. On the selection of design methodology for shell-and-tube heat exchangers optimization problems. *Thermal Science and Engineering Progress*, 34, 101384.

[7] Salimi, M.R., Rostami, M., Farajolahi, A.H., Ghanbari, M., 2022. Simulation of the effect of using a finned tube on the thermal efficiency of a Helicopter shell and tube heat exchanger. *Journal of Aerospace Science and Technology,* 15, pp. 83-98.

[8] Mohanty, D.K., 2016. Application of firefly algorithm for design optimization of a shell and tube heat exchanger from economic point of view. *International Journal of Thermal Sciences*, 102, pp. 228-238.

[9] Mirzaei, M., Hajabdollahi, H., Fadakar, H., 2017. Multi-objective optimization of shell-and-tube heat exchanger by constructal theory. *Applied Thermal Engineering*, 125, pp. 9-19.

[10] Petinrin, M.O., Bello-Ochende, T., Dare, A.A., Oyewola, M.O., 2018. Entropy Generation Minimisation of Shell-and-Tube Heat Exchanger in Crude Oil Preheat Train using Firefly Algorithm. *Applied Thermal Engineering*, 145, pp. 264-276.

[11] Bozorgan, N., Ghafouri, A., Assareh, E., Ardebili-Seyed, M.S., 2022. Design and thermal-hydraulic optimization of a shell and tube heat exchanger using bees algorithm. *Thermal Science*, 26, pp. 693-703.

[12] Gürses, D., Mehta, P., Sait, S.M., Yildiz, A.R., 2022. African vultures optimization algorithm for optimization of shell and tube heat exchangers. *Materials Testing*, 64(8), pp. 1234–1241.

[13] Gürses, D., Mehta, P., Patel, V., Sait, S.M., Yildiz, A.R., 2022. Artificial gorilla troops algorithm for the optimization of a fine plate heat exchanger. Materials Testing, 64(9), pp. 1325–1331.

[14] Mehta, P., Yildiz, B.S., Sait, S.M., Yildiz, A.R., 2022. Gradient-based optimizer for economic optimization of engineering problems. *Materials Testing*, 64(5), pp. 690–696.

[15] Sait, S.M., Mehta, P., Gürses, D., Yildiz, A.R., 2023. Cheetah optimization algorithm for optimum design of heat exchangers. *Materials Testing*, 65(8), pp. 1230–1236.

[16] Gürses, D., Mehta, P., Sait, S.M., Kumar, S., Yildiz, A.R., 2023. A multi-strategy boosted prairie dog optimization algorithm for global optimization of heat exchangers. *Materials Testing*, 65(9), pp. 1396–1404.

[17] Patel, V., Raja, B., Savsani, V., Yildiz, A.R., 2021. Qualitative and Quantitative Performance Comparison of Recent Optimization Algorithms for Economic Optimization of the Heat Exchangers. *Archives of Computational Methods in Engineering*, 28, pp. 2881–2896.

[18] Bozorgan, N., Shafahi, M., 2017. Analysis of Gasketed-plate Heat Exchanger Performance Using Nanofluid*. Journal of Heat and Mass Transfer Research, 4(1), pp. 65-72.*

[19] Canada, P.a.W., 2007. PT6A-41 series engines Certificate Data Sheet, EASA.

[20] Faroon, O., Mandell, D., Navarro, H., 1995. Toxicological Profile for Jet fuels JP-4 and JP-7. *U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES Public Health Service Agency for Toxic Substances and Disease Registry*.

[21] Cottington, R.L., Ravner, H., 1954. Neopentyl Polyol Esters for Jet Engine Lubricants-Effect of Tricresyl Phosphate on Thermal Stability and Corrosivity. *Naval Research Laboratory Washington*, D.C.

[22] Kern, D., 1954. Process Heat Transfer. *New York: McGraw-Hill*.

[23] Kakac, S., Liu, H., 2002. Heat Exchangers Selection, Rating, and Thermal Design. *Boca Raton London New York Washington, D. C*.

[24] Petokhov, B.S., 1970. Heat Transfer and Friction in Turbulent Pipe Flow with Variable Physical Properties. *Academic Press, New York*.

[25] Cao, E., 2010. Heat transfer in process engineering. *New York: McGraw-Hill*.