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Simulation of the Effect of Using a Finned Tube on the Thermal Efficiency of Shell and Tube Heat Exchangers

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ABSTRACT

Keywords: *Shell and tube heat exchanger, Colburn factor, heat transfer, Fin-tube, Friction factor*

In this paper, flow and heat transfer inside a helicopter shell and tube heat exchanger is simulated in three dimensions. This converter consists of a shell with 90 U-shaped tubes inside. For further heat transfer, the tubes were simulated and compared once without fins and again with fins, which are produced longitudinally and integrally with the tube body. The current flowing in the shell is MIL-PRF 23699 oil and the flowing fluid in the tubes is JP-4 fuel. These two fluids flow in opposite directions and exchange heat with each other. Using Aspen software, the design is done in such a way that the heat exchanger has minimum length and weight to have a better and higher effect on the efficiency of the helicopter. To investigate the effect of tube geometry and oil mass flow on the heat transfer between fuel and oil, simulation has been performed in ANSYS Fluent program. In this simulation, a part of the whole heat exchanger is selected as the geometry and the effect of changing the geometry of the tubes, mass flow of fuel and oil on the heat transfer coefficient, Colburn coefficient, coefficient of friction and their ratio, and outlet temperature changes are investigated. The results of this simulation show that the heat transfer rate between fuel and oil for a heat exchanger with finned tubes is about 11% higher than without a fin. Also, reducing the mass flow of oil entering the shell increases the efficiency of the heat exchanger.

Nomenclature

Re	Reynolds dimensionless number
ρ	Density (kg/m3)
$\vec{V}$	Fluid velocity vector (m/s)
P	Pressure value (pa)
μ	Fluid viscosity (Ns/m2)
μ_T	Turbulence viscosity (Ns/m2)
I	Identity matrix
λ	Thermal conductivity (W/mK)
T	Fluid temperature (oC)
ω	Decomposition rate
Γ	Diffusion coefficient
Q	Heat transfer rate (w)

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h	Heat transfer coefficient (W/m2K)
A	Fluid contact surface (m2)
ΔT_{lm}	Logarithmic mean temperature difference
j	Colburn coefficient
Nu	Nusselt number
Pr	Prandtl number
C_p	Specific heat capacity of the fluid at constant pressure (J/kgK)
u_{in}	Fluid velocity at the inlet (m/s)
f	friction coefficient

Introduction

Heat transfer is used in various industries for cooling or heating fluids or performing chemical and physical processes. In the aviation industry, heat exchangers are used to cool the hot oil, leaving the engine and increase the fuel temperature before entering the engine. Reducing the engine oil temperature increases the life and efficiency of oil and engine. Increasing the fuel temperature also leads to better preheating and combustion in the engine. In shell and tube heat exchangers, oil and fuel pass through different and opposite paths in such a way that they transfer heat to each other through metal walls. In the aviation industry, two parameters of efficiency and weight are very important. In other words, the systems designed for these industries should have the highest efficiency and the lowest possible weight [1,2]. Therefore, the use of finned tubes is very important to increase the efficiency of the heat exchanger and reduce its dimensions. Also, the use of heat exchangers in aircraft is in line with international treaties to protect the environment; because its use reduces fuel consumption, reduces oil change periods and reduces the production of chemical pollutants.

The first experimental studies of shell and tube heat exchangers were conducted in 1998 by Li and Kottke. They investigated the effect of the distance between the baffles and the shell on the amount of pressure drop in a fully developed flow regime for the triangular arrangement of the tubes [3]. In 2001, Nafhon investigated the effect of using torsion fins on the heat transfer rate and pressure drop in heat exchanger tubes. He found that the use of torsion fins increases turbulence inside the tube and increases the rate of heat transfer and pressure drop [4]. Zhang et al. In 2009 simulated a shell-and-tube heat exchanger using the Fluent program. They found that multi-piece torsional baffles with a torsion angle of 40 degrees have the highest efficiency [5]. In 2014, Chen et al. experimentally analyzed heat transfer in a finned tube heat exchanger with H-shaped fins. They provided correlations to estimate the Nusselt number and the pressure drop of the tube bundle. They found that increasing the distance between the fins or increasing the velocity of the flow through the tube bundle reduces the efficiency of the heat exchanger [6]. Hagshenas and Light proposed the idea of using a fuel-oil and air-oil heat exchanger in combination. They stated that to reduce the temperature of the oil, the oil must first pass through an air-oil heat exchanger, then the oil must enter the fuel-oil heat exchanger and transfer heat to the fuel. This prevents fuel evaporation [7]. In 2016, Kim et al. simulated an air-oil heat exchanger for turbofan engines by the Ansys Fluent program. They investigated the effect of changing the size, number and angle of the fins on the amount of heat transfer and pressure drop of the heat exchanger. They found that the pressure drop and heat transfer rate of the pin fins were less than the pressure drop and heat transfer rate of the plate fins; However, due to the fact that the weight of pin fins is less than that of plate fins, the use of pin fins for air-oil heat exchanger in turbofan engines was considered better [8]. In 2018, Wang et al. investigated the effect of using torsional baffles in shell and tube heat exchangers on pressure drop and heat transfer. They found that the highest heat transfer rate and the lowest pressure drop is for the case where the baffle step is 11 rpm [9]. Stearn et al. came up with the idea of using an integrated cooling system for conventional turbofan and gearbox turbofan engines. They stated that this would reduce the weight of the engine and reduce maintenance costs [10]. Turcotte et al. introduced a new fuel-oil heat exchanger in which fuel and oil flow paths are placed parallel to each other. In this heat exchanger, heat transfer is done through the walls between the two channels [11]. In 2019, Wang et al. In China and Yogesh et al. In India simulated the heat transfer between fin-tubes and the flow through them by the Ansys Fluent program. The tubes used in this simulation had an elliptical cross-section. They found that the best turbulence model for this simulation is the k-ω SST model. They also found that increasing the angle of the tubes up to 90 degrees relative to the flow direction increases heat transfer and pressure drop [12,13]. In 2019, El-Said and Al-Sood experimentally investigated the effect of shell and tube heat exchanger baffles shape on pressure drop and heat transfer rate in the exchanger. The pattern of baffles used in their research is CSSB, SSSB, FSB, HSB and SSFR. Finally, they found that the HSB model has the highest heat transfer rate and exergy efficiency is 1.4 times higher than the CSSB model [14]. In 2020, Mohammadi et al. numerically modeled a shell and tube heat exchanger with porous baffles. Using a genetic algorithm, they optimized the porosity of the baffles to achieve the highest heat transfer and the lowest pressure drop [15]. Unger et al. Examined heat transfer in a finned tube heat exchanger. They investigated the effect of fluid velocity passing through tubes and the distance of fins from each other on the amount of pressure drop, heat transfer rate, and Nusselt number. They found that the value of the Nusselt number increased as the angle of the tube handle increased or the flow velocity increased. Also, reducing the distance between the fins increases the Nusselt number [16,17]. Burr et al. Explain how fuel-oil and air-oil heat exchangers work. The heat exchange system presented in this reference includes fuel-oil and air-oil heat exchangers which are connected to each other in series. That is, the hot oil coming out of the gas turbine or gearbox first enters the air-oil converter, then the oil enters the fuel-oil heat exchanger and preheats the fuel entering the gas turbine. They have also proposed the use of two heat exchange systems for separate cooling of the gearbox and the moving components of the gas turbine [18]. In 2020, Keeler and McCabe proposed the idea of using a heat exchanger for fuel imported into aircraft peripherals. Some aircraft have two fuel lanes, one for powering the engine and the other for Setting up ancillary equipment such as the hydraulic system. If frozen fuel or ice components enter these systems, serious damage will be done to this equipment. To prevent this from happening, it is necessary to preheat the fuel entering this equipment [19]. Mastrocola and Pess Came up with the idea of using two heat exchangers to cool the oil. The coolant for the first stage heat exchanger can be fuel, ambient air, or air in the first floors of the compressor; then, for cooling the heat exchanger of the second stage, the fuel tubes taken out of another fuel tank can be used. Using this method to cool the oil greatly reduces the oil temperature [20]. In 2020, Ribarov and Veilleux proposed the idea of using a plate heat exchanger to increase the heat transfer rate between the oil and the coolant. The oil transfers heat from both sides with the air layer and the fuel layer. These heat exchangers can also be used in a two-fluid state, i.e. the oil layer is placed between two layers of fuel or two layers of air. The flow of oil and cooling fluid in the layers is always opposite to each other [21].

Selection and design of heat exchanger

In this project, the desired helicopter is introduced and its specifications are presented, then according to the engine specifications and flight conditions of the helicopter, a fuel-oil heat exchanger is designed for it by Aspen Plus and Aspen EDR programs and under TEMA standard. Then, the desired heat exchanger in Catia program is designed in 3D and its drawings are obtained. The heat exchanger is then simulated in the Fluent program and the results are analyzed. In order to investigate the effect of geometry on the rate of heat transfer of the converter, finned tubes are used instead of ordinary tubes, and the simulation is performed again and the simulation results are compared with each other.

First, the aircraft device for which we intend to design the heat exchanger must be identified and the conditions of temperature, pressure and mass flow of oil and fuel must be obtained. In this research, we intend to design a heat exchanger for the Bell AH-1 Cobra helicopter, which is a type of fighter helicopter that the weight and volume of the heat exchanger is important so that it can have good maneuverability. For this purpose, this helicopter is equipped with two PT-6 engines. The motor has three axial compressor stages and one centrifugal compressor stage. This engine also has two axle turbine stages that can produce 1300 kW. According to the information mentioned in the PT-6 engine repair booklet in reference [22], the mass flow rates of fuel and oil, fuel and oil temperature and fuel and oil pressure for this engine are obtained and are presented in Table (1).

Table 1: Fuel and oil conditions for PT-6 engine [22]

Name	Fuel	Oil
Type	JP-4	MIL-PRF 23699
Maximum mass flow (kg/s)	0.13	0.08
Maximum pressure (bar)	12	9
Maximum engine inlet temperature (ºC)	80	65
Maximum engine outlet temperature (ºC)	–	125

Because the temperature is high in the summer, it should be noted that the worst conditions for flying a vehicle in the summer and at high engine speeds. High air temperature reduces air density and increases fuel temperature in the helicopter fuel tank. Reducing the air density reduces the mass flow of air entering the engine and reduces the traction of the engine. On the other hand, increasing the fuel temperature reduces the heat transfer between the oil and the fuel. Another factor is the high engine speed, which increases the temperature of the engine oil and reduces its efficiency. For this purpose, to design a heat exchanger, it is assumed that the helicopter is flying with the highest engine speed and the highest ambient air temperature of about (40 degrees Celsius at an altitude of 3 km above the surface in the summer).

Depending on the heat load, the history of conventional converters in the aerospace industry and the TEMA standard, a shell-tube heat exchanger with a CEU structure should be designed for the helicopter. Because this type of heat exchangers have high heat transfer rate, Ratio of weight to low heat transfer rate and can withstand high pressures.

For design, it is assumed that oil (hot fluid) flows in the heat exchanger shell and its inlet and outlet temperatures are 125 and 65 degrees Celsius, respectively. Also, fuel flows in the heat exchanger tubes and its inlet temperature is considered to be 40 degrees Celsius. The fuel outlet temperature from the heat exchanger must be determined by calculations performed in Aspen Plus and Aspen EDR programs. Also, heat exchanger tubes are made of 304 stainless steel. Also, the dimensions of the heat exchanger are determined by optimizing the mass of the heat exchanger and its heat transfer rate; thus, the length of the heat exchanger tubes is 80 cm, the shell diameter is 12.75 inches, and the diameter of the heat exchanger tube is 0.5 inches. The pattern of tubes is square and with a 90-degree angle. Also, the results of the design by Aspen shows that this heat exchanger has 180 tubes and 6 baffles with a distance of 10 cm from each other and has two current passes. A two-dimensional view of the heat exchanger designed is shown in Figure (1).

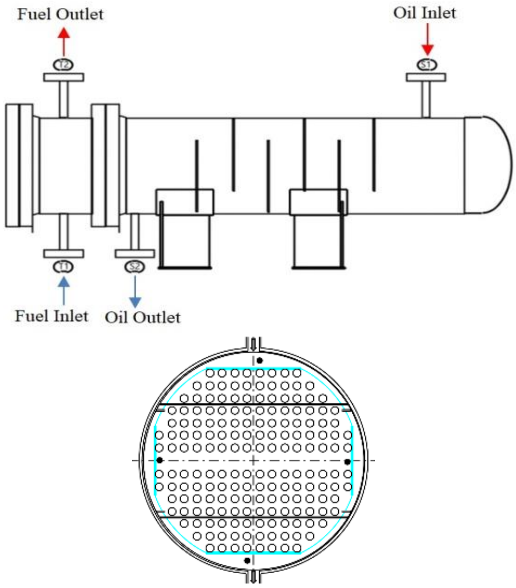

Figure 1: Schematic of a heat exchanger designed by Aspen and its cross-section

The heat exchanger is designed by Aspen EDR; it is then modeled by Aspen Plus. Modeling is one-dimensional. This model calculates the temperature changes of oil and fuel during the heat exchanger. The result of this modeling is presented in Figure (2).

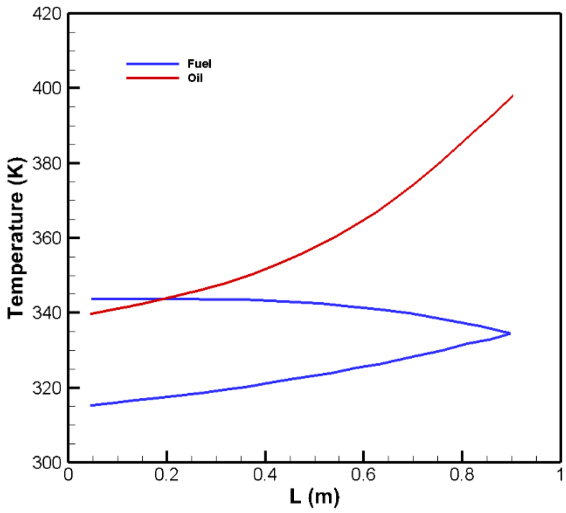

Figure 2: Graph of fuel and oil temperature changes during heat exchanger

In general, in Aspen software, the most optimal mode in terms of dimensions and lower weight can be designed for a suitable heat exchanger and choose whether one or more heat exchangers are in series or parallel to each other in the cycle and prevent pressure drop, and Also reach the desired temperature.

Then, the desired heat exchanger in Catia program is designed in three dimensions. This is done to map the parts and have a three-dimensional understanding of the heat exchanger. Figure 3, is a three-dimensional and cut view of Catia software designed from the heat exchanger.

To start the simulation process, the geometry must first be selected. This geometry can be the whole or half of the heat exchanger or part of it. The important point at this stage is that the geometry chosen should have the simplest possible shape and be a good representative of the flow lines. This increases the accuracy of the solution due to the higher grid resolution at critical points while reducing the computational cost. Due to the symmetry of the heat exchanger to the center plate, and also due to the repetitive flow patterns in the space between the baffles, instead of simulating the entire heat exchanger, only half of the space between two consecutive baffles is simulated here.

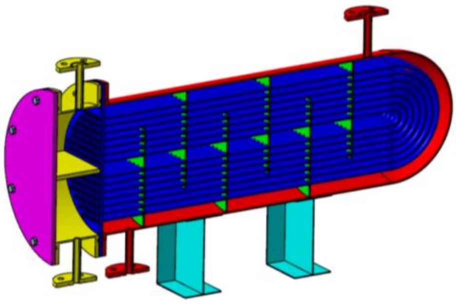

Figure 3: Three-dimensional view of heat exchanger

Governing equations and boundary conditions

Figure 4 shows a schematic of the geometry desired for the simulation. The oil flows in the shell of the heat exchanger and is in contact with the outer surface of the tubes. Fuel also flows inside the tubes. Fuel has two paths; one is path 1 where the current enters the tube bundle and the other is path 2 where the current returns to the output of the converter. The temperature conditions of these two paths are different. It is assumed that the temperature of the fuel and oil at the inlets is uniform. Also, the diameter of the converter tubes is 1.27 cm. the thickness of the tubes is 0.5 mm, the diameter of the shell is 32 cm and the length of the tubes and the shell is 11 cm.

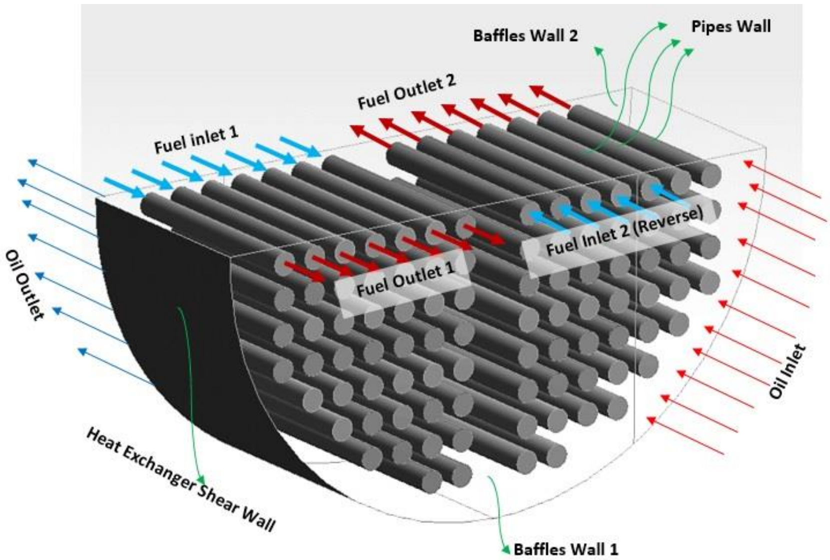

Figure 4: Geometry of heat exchanger with finless tubes and boundary conditions

The geometry used to simulate heat exchangers with finned tubes is similar to the geometry shown in Figure 5; the difference is that there are fins on the tubes along the length of the tube. The number of fins on the tubes is 8. The height of the fins is 2mm and their thickness is 1.5 mm. The cross-sectional shape of the fins used for the tubes is shown in Figure 6.

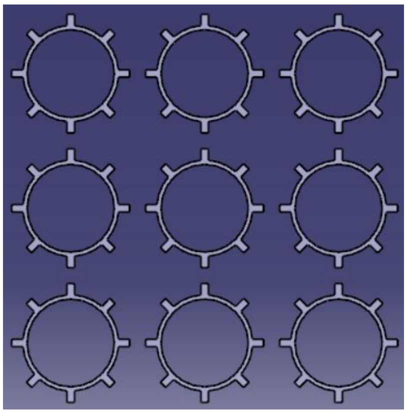

Figure 6: Cross-section of finned tubes

This type of finned tubes has been selected due to the simple and fast manufacturing process (extrusion process) and high resistance to pressure and current impact. Also in these finned tubes, blades and tubes are produced integrated and there is no need to solder the blades to the tube.

For both heat exchangers (original and finned tubes), the temperature of the inlet oil of the shell is 363 Kelvin and the temperature of the inlet fuel to paths 1 and 2 is 322 and 342 Kelvin. Flow conditions at the boundaries of geometry are presented in Table 2.

Table 2: Boundary conditions of fluid flow in shell and tubes

Boundary	Fuel/Oil	Parameter	Value
Inlet	Oil	Mass flow (kg/s)	0.04
		Intensity of turbulence (%)	5
		Hydraulic diameter (m)	0.15
		Temperature (k)	362.78
	Fuel#1	Mass flow (kg/s)	0.065
		Intensity of turbulence (%)	5
		Hydraulic diameter (m)	0.5715
		Temperature (k)	322.4
	Fuel#2	Mass flow (kg/s)	0.065
		Intensity of turbulence (%)	5
		Hydraulic diameter (m)	0.5715
		Temperature (k)	341.7
Outlet	Oil	Pressure gage (Mpa)	0.9
	Fuel#1	Pressure gage (Mpa)	1.3
	Fuel#2	Pressure gage (Mpa)	1.3
Wall		Momentum	No Slip Condition
		Energy	Coupled Heat Transfer

The oil used for the simulation is MIL-PRF 23699. The density of this oil is 947.46 kg/m3, its heat capacity at constant pressure is 1690 J/kg Kelvin, its thermal conductivity is 0.0733 J/K Kelvin and its dynamic viscosity is 0.000737 Pascal. The fuel used is also JP-4; the density of this fuel is 734.57 kg/m3, its specific heat capacity at constant pressure is 1956 joules per kilogram, its thermal conductivity is 0.1313 joule per Kelvin and its dynamic viscosity is 0.600664 Pascal seconds.

Flow Equations

The k-ω SST turbulence model has been used to increase the accuracy of flow simulation near the wall. Also, assuming the stability of solution and incompressibility of fuel and oil, the governing equations for flow are as follows [5,13]:

$$\nabla \cdot (\rho \vec{V}) = 0 \qquad (1)$$

$$\nabla \cdot (\rho \vec{V}\vec{V}) = -\nabla p + \nabla \cdot (\bar{\bar{\tau}}) \qquad (2)$$

$$\bar{\bar{\tau}} = (\mu + \mu_T)\left[\left(\nabla\vec{V} + \nabla\vec{V}^T\right) - \frac{2}{3}\nabla \cdot \vec{V}I\right] \quad (3)$$

Where p is pressure, τ is the stress tensor, μ is the fluid viscosity, μ_T is the turbulence viscosity and I is the identity matrix.

$$u_i \frac{\partial T}{\partial x_i} = \nabla \cdot (\alpha \nabla T) + q \quad \mathbf{w}\ (4)$$

Where α is the thermal diffusivity, T is the fluid temperature and q is the external energy. For turbulence modeling the $k - \omega(SST)$ model was used. It solves the following equations to compute turbulence viscosity.

$$\frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left(\Gamma_k \frac{\partial k}{\partial x_j}\right) + G_k - Y_k \quad (5)$$

$$\frac{\partial}{\partial x_j}(\rho \omega u_j) = \frac{\partial}{\partial x_j}\left(\Gamma_\omega \frac{\partial \omega}{\partial x_j}\right) + G_\omega - Y_\omega + D_\omega \quad (6)$$

Where k is the turbulence kinetic energy, ω is the turbulence destruction frequency, Γ is the diffusion coefficient, G is the production terms, Y is the destruction terms, and D is the cross-diffusion term. All mentioned equations are discretized using second-order upwind.

Displacement heat transfer coefficient

Heat exchangers are divided into two types of direct current and non-direct current. In heat exchangers with the asymmetric flow, the movement of hot and cold fluids are opposite to each other. Therefore, the difference between hot and cold fluid temperature in all parts of the converter are similar. In heat exchangers with the homogeneous flow, the direction of movement of hot and cold fluid flow is the same. In these converters, the temperature difference between the input of the converter and the output of the converter is low. For both types of heat exchangers with the homogeneous flow and heterogeneous flow, the relationship between the inlet and outlet temperatures of hot and cold fluids and the rate of heat transfer in the exchanger is calculated by Equation (7).

$$Q = hA\Delta T_{lm} \quad (7)$$

$$\Delta T_{lm} = \frac{\Delta T_2 - \Delta T_1}{\ln\left(\frac{\Delta T_2}{\Delta T_1}\right)} \quad (8)$$

Where Q is the heat transfer rate in the heat exchanger, h is the displacement heat transfer coefficient, A is the fluid contact surface, and ΔT_{lm} the logarithmic mean temperature difference. The logarithmic mean temperature difference value for heat exchangers with co-current is calculated by Equation (9) and for heterogeneous current by Equation (10).

$$\begin{aligned} \Delta T_1 &= T_{h1} - T_{c1} \\ \Delta T_2 &= T_{h2} - T_{c2} \end{aligned} \quad (9)$$

$$\begin{aligned} \Delta T_1 &= T_{h1} - T_{c2} \\ \Delta T_2 &= T_{h2} - T_{c1} \end{aligned} \quad (10)$$

Also, the value of contact surface A for normal and finned tubes is calculated by Equation (11).

$$A = A_t + \eta_f A_f \quad (11)$$

Where A_t is the surface area of the tube, A_f is the surface area of the fins and η_f the efficiency of the fins. The efficiency of the fin for the current simulation is about 95%. If the tube is without fins, the area of the fin should be considered zero.

Colburn coefficient and coefficient of friction

In order to compare and evaluate the overall performance of heat exchangers, Colburn and friction coefficients are defined. The Colburn coefficient indicates the rate of heat transfer per unit area. This parameter is defined to calculate the heat transfer performance of the converter and is calculated by Equation (12). The coefficient of friction also indicates the performance of the heat exchanger in terms of hydrodynamic parameters such as pressure drop. This parameter is calculated by Equation (16).

$$j = \frac{Nu}{\mathrm{Re}_H \Pr^{1/3}} \quad (12)$$

$$Nu = \frac{hD}{k} \quad (13)$$

$$\Pr = \frac{C_p \mu}{k} \quad (14)$$

$$\mathrm{Re}_D = \frac{\rho u_{in} D}{\mu} \quad (15)$$

Where j is the Colburn Nu is the Nusselt number, Re is the Reynolds number, Pr is the Prandtl number, h is the convective heat transfer coefficient, D is the diameter of the tubes, k is the fluid thermal conductivity, C_p is the heat capacity of the fluid at constant pressure; ρ is the fluid density and u_{in} is the velocity of the fluid at the inlet.

$$f = \frac{(p_2 - p_1)D}{2\rho u_{in}{}^2 L} \qquad (16)$$

Where f is the coefficient of friction, p2 is the output pressure, p1 is the inlet pressure, and L is the length of the fluid path [13].

The simulation is performed using Ansys Fluent software. As mentioned before, the oil and fuel used in this simulation are MIL-PRF23699 and JP-4, respectively. The properties of these fluids are presented in Table 3.

Table 3: Properties of fuel and oil

Type	MIL-PRF 23699	JP-4
Density (Kg/m^3)	947.46	734.57
Specific heat capacity (J/KgK)	1690.57	1956.12
Thermal conductivity (J/mK)	0.0733	0.1313
Dynamic viscosity (pa.s)	0.000733	0.000664

In order to solved governing equations, the pressure based solver and SIMPLEC algorithm is used.

Grid independence and validation

For better gridding, the cells were selected as tetragonal-prism. These results in boundary layered type mesh in the vicinity of baffle wall and shell to resolve velocity and thermal boundary layers accurately. The width of the first layer on the surface of the tube is 0.1 mm and its growth rate is 1.2. Also, 5 grid layers are specified on the tube wall for each side of oil and fuel. A view of the computational mesh is shown in Figures 7 and 8.

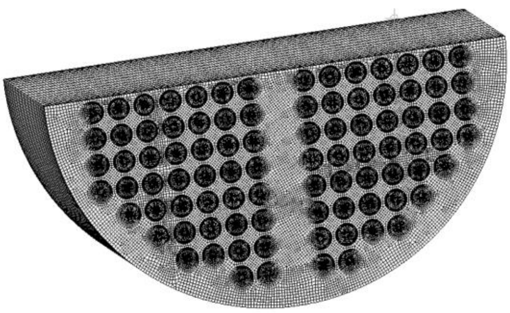

Figure 7: 3D view of the grid used for geometry

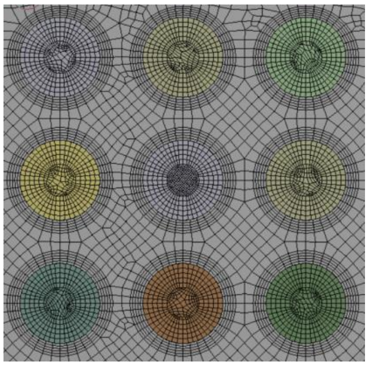

Figure 8: View of the grid around the heat exchanger tubes

In order to check the accuracy of the results as well as the independence of the simulation results from the grid resolution, several simulations with grids with a different number of cells have been performed. Since the best parameter for checking the heat transfer rate in converters is the Colburn coefficient; therefore, the value of the Colburn coefficient for simulation performed with each grid is calculated and compared with each other. The results of this comparison are presented in Figure 9.

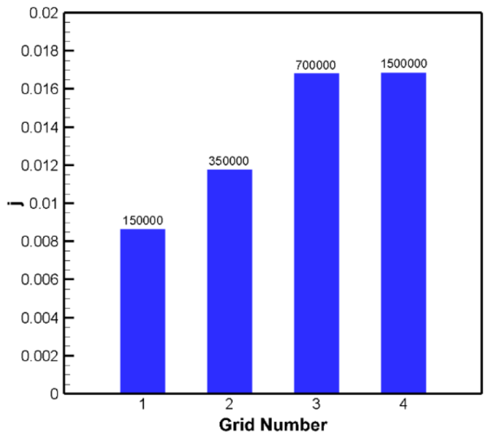

Figure 9: Colburn coefficient variations for different grids

As shown in figure 9, by increasing grid size from 700000 to 1500000, the Colburn number is not changed. . That is, the number of grids 3 is selected for subsequent simulating.

To validate the results of the simulation, the changes of the Colburn and friction coefficient through the distance between the two walls are calculated and compared with the results published by Wang et al [13]. Additionally, since the k-ω SST model is a low Reynolds type turbulent model, the first grid row must be placed in laminar sublayer. Thus, the distance of first grid row from solid wall is adjusted in such a way to satisfy the $Y^+ < 5$ condition.

Figure 10 shows the changes in the Colburn and Figure 11 indicates the friction coefficient relative to the distance between the two walls. It can be seen that the current simulation results and the results in Wang's article are about 2% different. This means that the simulation results are accurate For more accurate validation, paper of of Ambekar et al [23] has also been investigated in which the pressure drop and heat transfer coefficient computed using, the k-ε method. The geometry of their work is illustrated in figure 12 and 13.

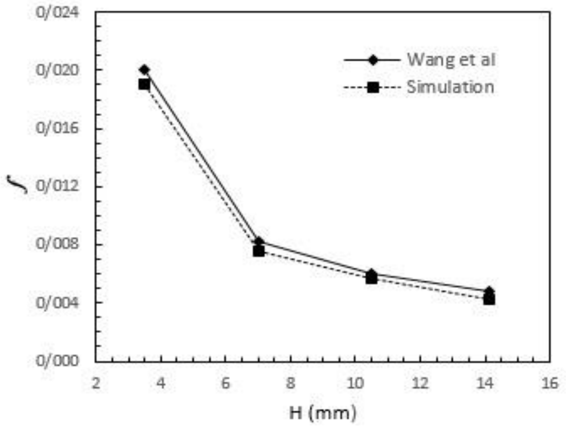

Figure 10: Changes in the Friction coefficient relative to the distance between two walls

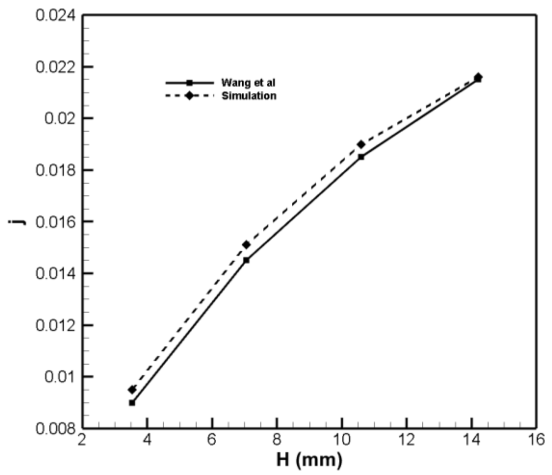

Figure 11: Changes in the Colburn coefficient relative to the distance between two walls

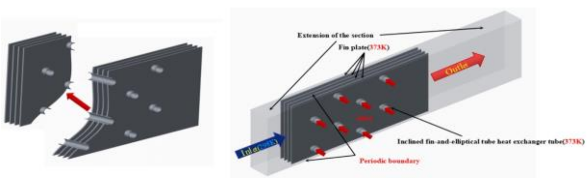

Figure 12: Geometry of Wang et al work [13].

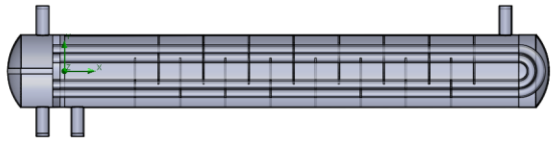

Figure 13: Geometry of Ambekar et al shell and tube heat exchanger [23]

The results of present simulation are compared to those of Ambekar et al [23] in figurs 14 and 15 for heat transfer coefficient and pressure drop respectively. According to these figures, it is observed that the results are very close to the results of Ambekar et al [23].

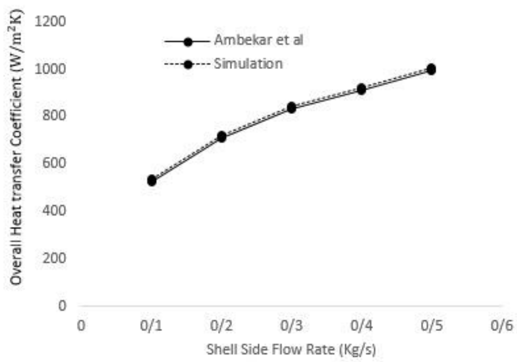

Figure 14: Changes in heat transfer coefficient relative to the flow rate.

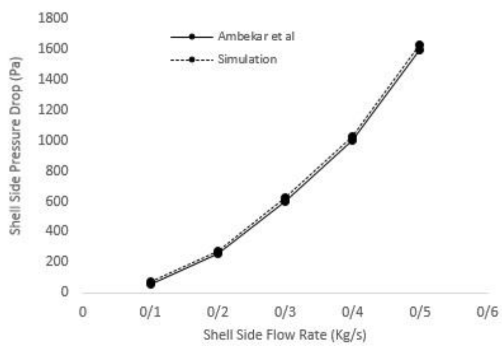

Figure 15: Changes in pressure drop relative to the flow rate.

Results and Discussion

Heat transfer in heat exchanger with finless tubes

The amount of heat transfer surface of this converter is 0.4 square meters. In order to investigate the effects of fuel and oil mass flow rate on heat transfer rate in shell and tube heat exchanger with finless tubes, fuel mass flow rate changes from 0.03 to 0.13 kg/s and oil mass flow rate changes from 0.02 to 0.08 kg/s. After the simulation, the changes of Colburn coefficient, friction coefficient, outlet oil temperature, and heat transfer coefficient with changes in the mass flow rate of fuel and oil are investigated.

The average temperature of the oil entering the space between the baffles is 362 Kelvin and the average temperature of the oil leaving the geometry is 350 Kelvin. This heat transfer increases the fuel temperature of Route 1 from 322 to 326 Kelvin and the fuel temperature of Route 2 from 341 to 344 Kelvin. Also, the amount of energy transferred between the two fluids is 479 watts. Having these characteristics and also knowing the geometric characteristics of the solution area, it is possible to calculate the amount of heat transfer coefficient, Colburn coefficient and coefficient of friction using the equations in section 3. The amount of heat transfer coefficient for this heat exchanger is 50.7143 watts per square meter. Also, the value of Nusselt number is calculated to be 8.8. Finally, the values of Colburn coefficient and friction are 0.0284 and 0.0859, respectively.

Figure 16 shows the oil flow lines in the heat exchanger. As can be seen, the flow lines run parallel through the heat exchanger tubes with minimal disturbance. That is, the oil flow enters in parallel from the top and back, and after passing through the converter tubes, exits from the bottom and front. The fluid also transfers heat to the tubes by flowing through the tubes and interacting with them. Thus, the oil temperature decreases.

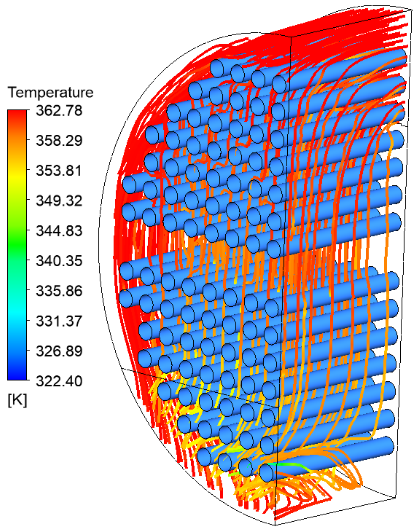

Figure 16: Oil flow lines in the heat exchanger. The color of the flow lines indicates the temperature changes on the flow line.

As shown in Figure 17, as the mass flow rate of oil and fuel increases, the heat transfer coefficient increases; increasing the mass flow of oil and fuel causes low-temperature fuel and high-temperature oil to enter the heat exchanger. This increases the temperature difference between the two fluids; according to Equation (7) for a heat exchanger with a constant surface and heat transfer rate, increasing the temperature difference increases the heat transfer coefficient. On the other hand, increasing the mass flow rate increases the velocity of the fluid passing through the surface; which is also increases the heat transfer coefficient.

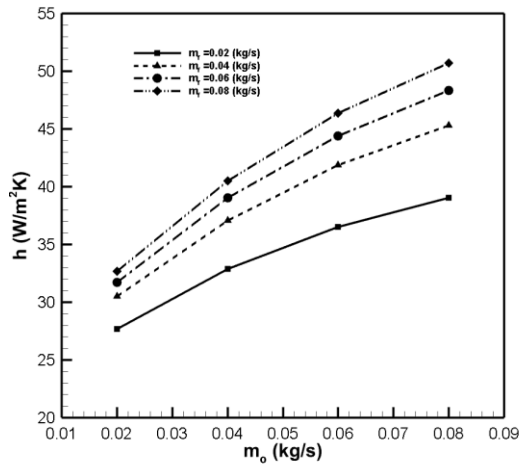

Figure 17: Displacement heat transfer coefficient changes relative to oil mass flow for fin*less* tube heat exchanger.

Figure 18 shows the changes in the Colburn coefficient relative to the mass flow rate of oil and fuel. According to the figure, it can be seen that as the mass flow rate of the oil increases, the value of the Colburn coefficient decreases; however, the intensity of the reduction of the Colburn coefficient is inversely related to the mass flow of oil. Moreover, increasing the mass of the oil increases the flow rate and increases the Reynolds number. The Colburn coefficient represents the competition between the heat transfer rate and the flow rate in the heat exchanger. In this way, it can be seen that the rate of increase in flow rate is more than the rate of increase in heat transfer rate. In other words, oil has great potential for heat transfer, but its high speed prevents it from doing so. On the other hand, increasing the mass flow rate of fuel increases the amount of Colburn coefficient; because increasing the mass flow rate of the fuel causes the fuel to enter the heat exchanger with a lower temperature, and the temperature difference between the hot and cold fluid increases and this leads to an increase in the heat transfer coefficient.

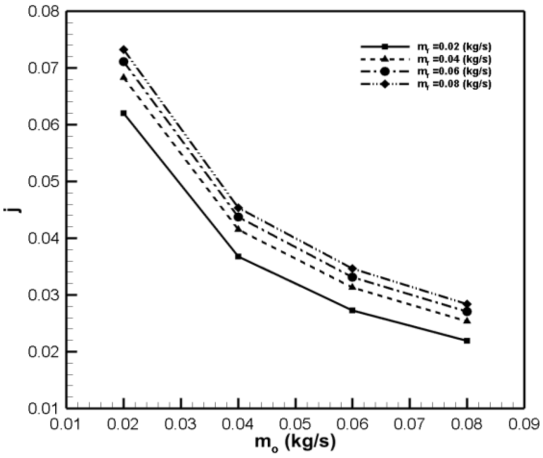

Figure 18: Changes in the Colburn coefficient relative to the mass flow rate of oil

Figure 19 shows the changes in the coefficient of fluid friction relative to the mass flow rate of the oil. It is observed that increasing the mass flow rate of oil leads to a decrease in the coefficient of friction. This coefficient shows the competition between the amount of pressure drop and the velocity of the fluid in the converter. Increasing the mass flow of oil leads to increasing the amount of pressure drop and fluid velocity in the heat exchanger; but for a heat exchanger with finless tubes, the rate of increase in pressure is less than the rate of increase in speed; because in this converter, the current passes easily through the pipes.

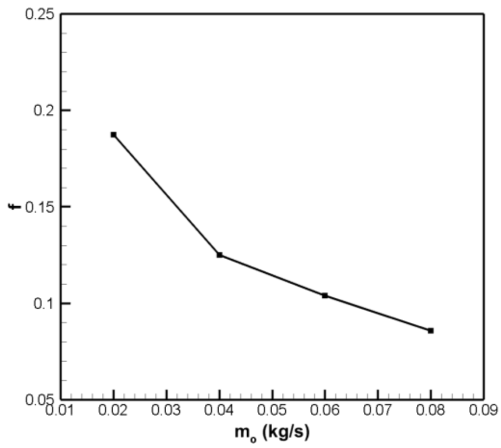

Figure 19: Changes in the coefficient of fluid friction relative to the mass flow rate of oil for finless tube heat exchanger.

Figure 20 shows the diagram of the changes in the j/f parameter relative to the mass flow rate of oil and fuel. An increase in this ratio means a higher rate of heat transfer in the heat exchanger compared to the mass flow rate entering it. As shown in Figure 17, increasing the mass flow rate of the oil leads to a decrease in heat exchanger efficiency. But increasing the mass flow rate of fuel increases the performance of the heat exchanger; Because the increase in mass flow of oil does not lead to its passage through the tubes, but causes part of the oil to pass through the space between the shell wall and the tubes, this oil does not conduct any heat transfer with the converter tubes. Also, the fuel that passes through the tubes has to transfer heat under any circumstances. This leads to an increase in the tendency of the fuel and a decrease in the tendency of the oil to transfer heat. Of course, this point must be kept in mind. The mass flow rate of fuel is always higher than the mass flow rate of oil.

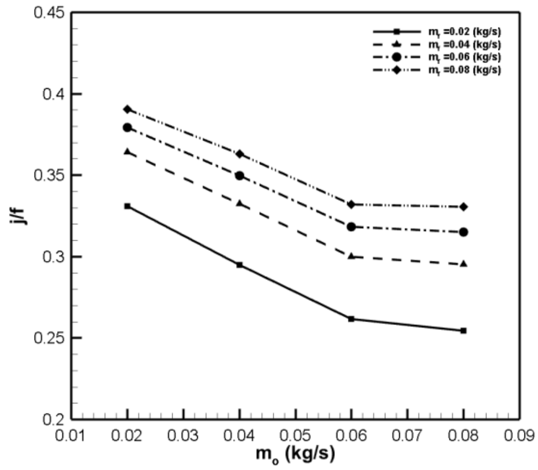

Figure 20: the diagram of changes in the j/f parameter relative to the mass flow rate of oil for finless tube heat exchanger.

Figure 21 shows the oil temperature change in the converter outlet relative to changes in the oil mass flow rate. It can be seen that increasing oil mass flow rate leads to an increase in output temperature; Because with increasing the mass flow of oil, its speed also increases and the oil has less opportunity to contact the surface of the rods and heat transfer. Also, increasing the mass flow of oil causes the oil to pass near the wall of the converter shell and no heat transfer occurs. Increasing the mass flow rate of the fuel reduces the temperature of the oil at the outlet. This increases the temperature difference between the oil and the fuel and thus increases the heat transfer rate. Increasing the heat transfer rate from oil to fuel reduces the oil temperature.

Figure 22 shows the three-dimensional contour of the fuel and oil temperature. It is observed that the oil temperature after entering the heat exchanger (from the top and back) interacts with the fuel tubes of route 2 and transfers heat with them. The amount of energy transferred in the area of the tube line of route 2 is 183 watts. The slightly cooled oil then strikes the handle of the fuel tubes in Route 1. Since the difference in oil and fuel temperature for this category of tubes is greater than the category of tubes in route 2; therefore, the energy exchange rate between oil and fuel for this category of tubes is about 296 watts.

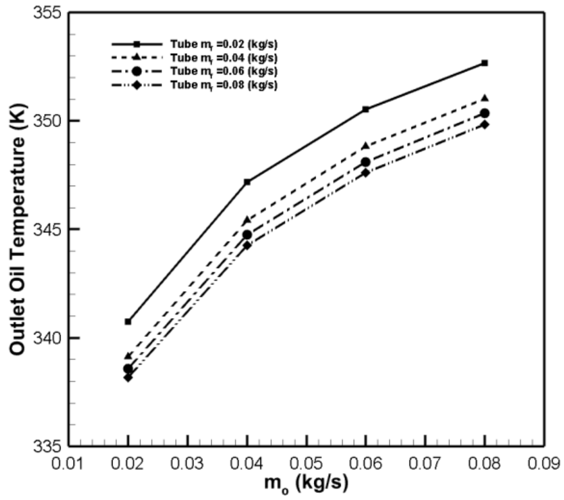

Figure 21: Changes in oil outlet temperature relative to oil mass flow rate for finless tube heat exchanger.

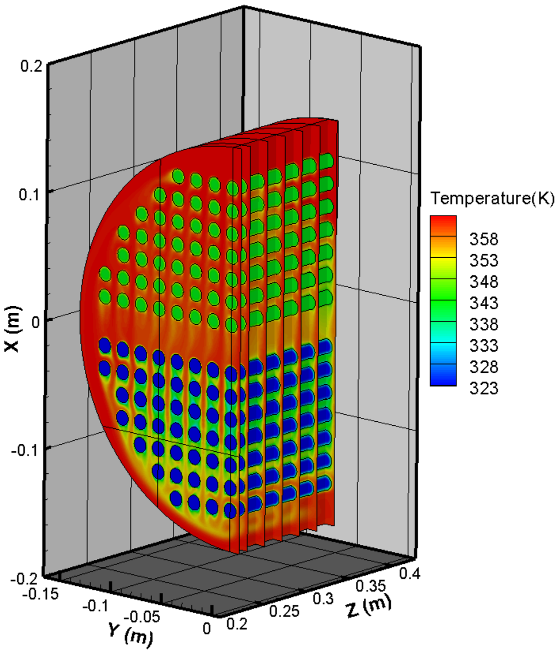

Figure 22: Temperature change contour for oil flow rate of 0.08 and fuel flow rate of 0.13 kg / s in finless tube heat exchanger.

Heat transfer in a heat exchanger with finned tubes

One of the ways to increase the rate of heat transfer in exchangers is the use of finned tubes. This method increases the level of fluid contact with the wall and increases the rate of heat transfer. For this purpose, this method has been used to increase the rate of heat transfer in the heat exchanger of the shell and the tube.

The average temperature of the oil entering the space between the baffles is 362 Kelvin and the average temperature of the oil leaving the geometry is 346 Kelvin. This heat transfer increases the fuel temperature of Route 1 from 322 to 327 Kelvin and the fuel temperature of Route 2 from 341 to 345 Kelvin. Also, the amount of energy transferred between the two fluids is 523 watts and the heat transfer surface is 0.62 square meters. Having these characteristics and also knowing the geometric characteristics of the solution domain, it is possible to calculate the amount of heat transfer coefficient, Colburn coefficient and coefficient of friction using the equations in section 3. The amount of heat transfer coefficient for this heat exchanger is 38.56 watts per square meter. The value of the Nusselt number is 6.7. Finally, the values of Colburn coefficient and friction are 0.0216 and 0.2695, respectively.

Figure 23 shows the oil flow lines in the heat exchanger. As can be seen, the flow lines run parallel through the heat exchanger tubes with minimal disturbance. But in this exchanger, the oil stream tends to pass close to the wall of the heat exchanger shell, which increases the flow rate in this area. However, the temperature of the fluid passing through the finned tubes decreases, and when these two currents merge at the outlet, the average temperature at the outlet becomes lower than at the finless state.

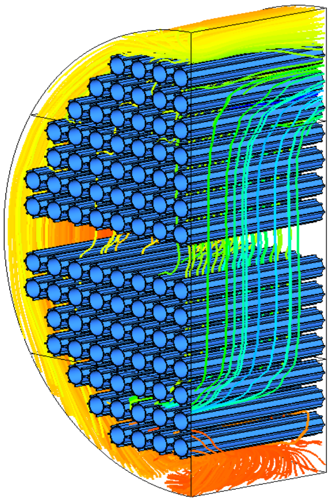

Figure 24: Flow lines in shell-tube heat exchanger with finned tubes; The color of the flow lines indicates the temperature changes.

Figure 25 shows the graph of changes in the displacement heat transfer coefficient relative to the mass flow rate of the oil. It is observed that increasing the mass flow rate of oil and fuel increases the heat transfer coefficient. The value of heat transfer coefficient for finned tubes is less than the corresponding value for non-finned tubes; because in the finned state, the flow velocity near the surface of the tube decreases, and since the heat transfer coefficient is directly related to the velocity, the value of this coefficient also decreases.

As shown in Figure 26, increasing the mass flow rate of oil and fuel increases the Colburn coefficient. Given that the Colburn coefficient shows the competition between flow velocity and heat transfer; it can be seen that for finned tubes, the heat transfer rate grows faster than the flow velocity. In other words, as the oil flow rate increases, so does the heat transfer rate. This condition occurs due to the increase in the contact area of the fluid with the tube wall.

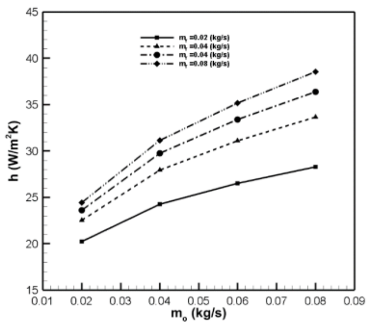

Figure 25: Changes in heat transfer coefficient relative to oil mass flow for heat exchanger with finned tubes

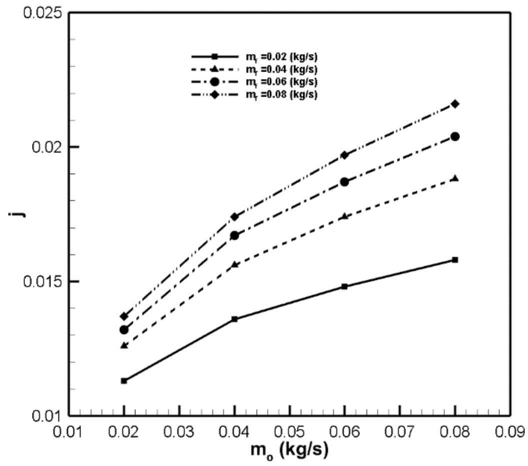

Figure 26: Changes in the Colburn coefficient relative to the oil mass flow rate for finned tube heat exchanger.

Figure 27 shows the diagram of changes in the coefficient of fluid friction for different mass flow of oil. It is observed that increasing the mass flow rate of oil increases the coefficient of friction. Since this coefficient represents the change in oil pressure drop with respect to the inlet dynamic pressure, it can be concluded that the amount of increase in pressure is greater than the amount of increase in velocity. Because the presence of fins reduces the cross-section of the flow and increases the resistance to oil flow and ultimately increases the pressure drop.

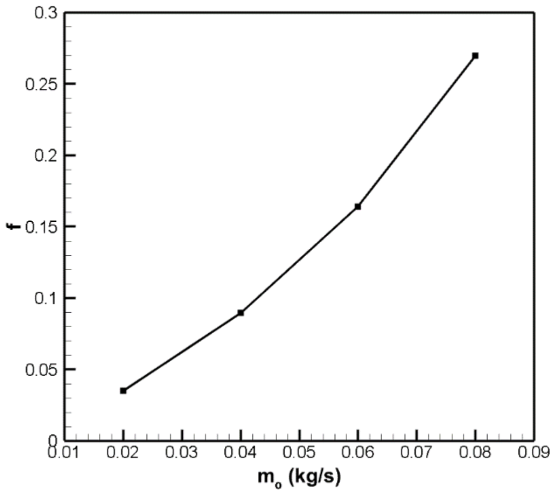

Figure 27: Changes in the coefficient of fluid friction relative to the mass flow of oil for a heat exchanger with a finned tube

As shown in Figure 28, the j/f ratio decreases as the oil mass flow rate increases. This also happens for the finless mode; but for the finned state, the sensitivity of the j/f parameter to the mass flow rate of the oil is higher. This occurs due to drastic changes in the coefficient of friction and pressure drop relative to changes in the oil mass flow rate for finned tubes.

Figure 29 shows the oil temperature at the heat exchanger outlet with finned tubes. As shown in this figure, the temperature of the oil increases with increasing mass flow; because increasing the temperature of the oil increases its speed between the rods and reduces the possibility of heat transfer. Also, increasing the mass flow rate of the fuel reduces the oil temperature; this is because cold fuel enters the tubes and increases the temperature difference between the fuel and the oil, and ultimately increases the heat transfer rate and decreases the oil temperature.

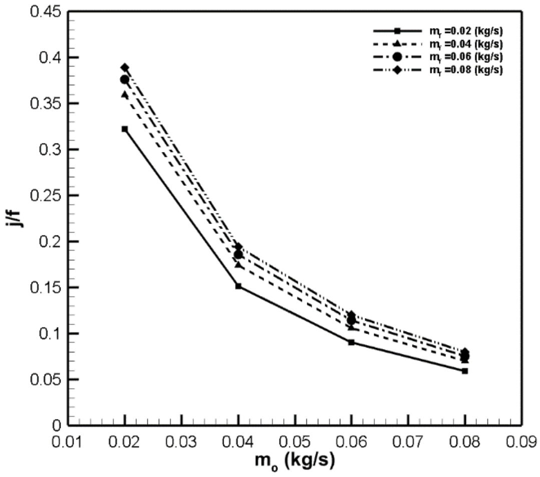

Figure 28: Changes in the coefficient of j/f relative to the mass flow rate of oil for a heat exchanger with a finned tube

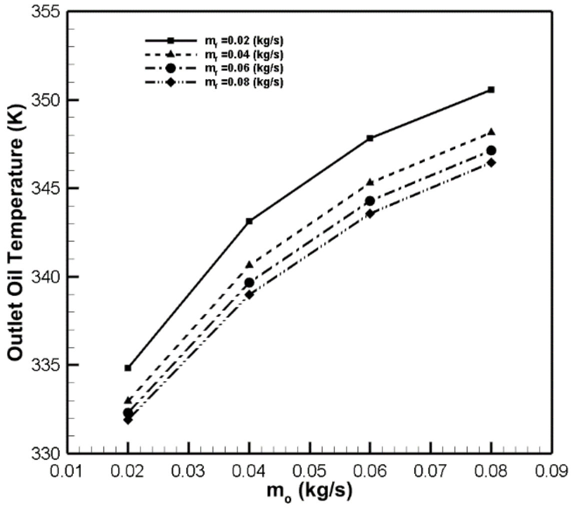

Figure 29: Changes in oil temperature at the outlet relative to the mass flow of oil for a finned tube heat exchanger

The contour of the temperature changes in the middle plate between the baffles is shown in Figure 30. As can be seen, the oil transfers heat to the fuel after hitting the surface of the tubes where the fuel is flowing, and the oil temperature decreases. Due to the presence of fins on the tubes, the level of heat transfer between the fuel and the oil increases and reduces the temperature of the oil passing through the tubes as much as possible.

Due to the presence of fins on the outer wall of the tubes, more heat is transferred to the inner surface of the tube. The internal contact surface of the tubes in contact with the fuel has not changed from that of the bladeless state; therefore, the temperature of the fuel near the inner wall of the finned tube is higher than that without the vane. This increase in temperature may cause partial evaporation of fuel in these areas; But due to the lack of fuel to reach the evaporation point and also the high pressure of fluid in these tubes, no fuel evaporates. Also, the oil velocity is very low near the surface of the tubes and between the fins. This increases the residence time of the oil near the surface of the tube and increases the amount of heat transfer between the oil and the fuel.

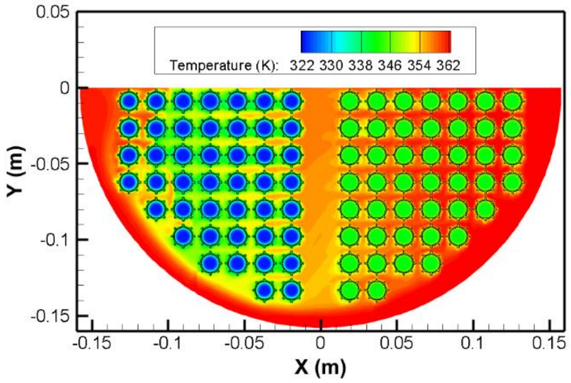

Figure 30: Contour of temperature changes in heat exchanger with finned tubes

Figure 31 shows the three-dimensional contours of the fuel and oil temperature. It is observed the presence of longitudinal vanes on the tubes increases the contact area between hot oil and tubes incrases heat transfer with the fluid. Thus, the temperature of the oil passing through the blades reaches 340 K, and after merging this oil with the oil passing through the side of the shell wall, its average temperature reaches 346 K. Meanwhile, the passage temperature of the oil through the bladeless converter tubes is 347 K, and its temperature reaches 350 K, after merging with the oil passing through the side of the shell wall.

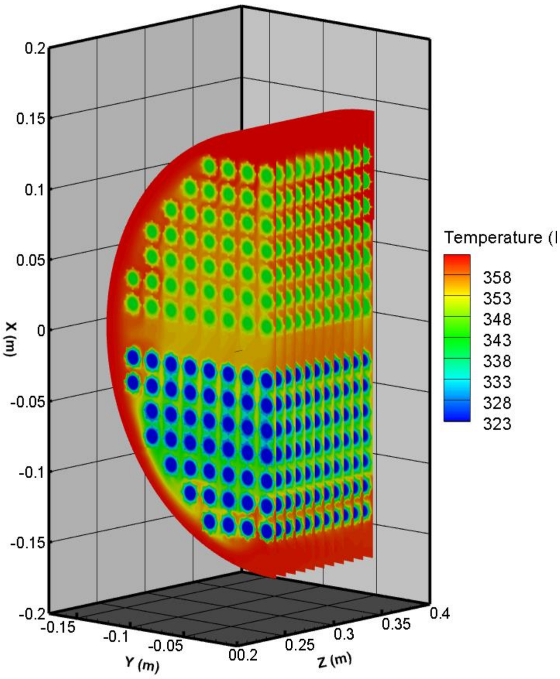

Figure 31: Contour of temperature changes in heat exchanger with finned tubes

Conclusion

In this paper, a shell and tube heat exchanger is simulated, which is selected and designed in such a way that in terms of dimensions and weight is the least possible to include more efficiency and lower manufacturing costs. This heat exchanger is used to transfer heat between fuel and oil in helicopters. In order to investigate the effect of tube geometry on heat transfer rate, simulations were performed for heat exchangers with finless tubes and again for a finned mode. Also, the effects of changing the mass flow rate of fuel and oil on the converter pressure drop and its heat transfer rate have been investigated. Using the results of these simulations, heat exchangers with different capacities can be designed. The most important results of this study are:

- In the finless state, the amount of heat transfer surface is 5.6 square meters with a heat transfer rate of 6600 watts. In Finned case, the heat transfer surface area increases to 8.68 square meters and the heat transfer rate increases to 7400 watts. Thus, the heat transfer rate in the heat exchanger with finned tubes is 11% higher than in the finless mode. Also, the lower the mass flow of oil, the higher the efficiency of the converter.

-In all cases examined here, there is no fuel evaporation in the fuel tubes, because the fuel temperature in these tubes is lower than its evaporation temperature at atmospheric pressure; On the other hand, the fuel pressure in these tubes is high; these two factors are so important that they prevent the fuel from evaporating.

- Colburn coefficient increases with increasing fuel flow. Also, increasing the mass flow rate of oil increases the Colburn coefficient for heat exchangers with finned tubes and decreases the Colburn coefficient for heat exchangers with finless tubes.

- Increasing the mass flow of oil increases its temperature in the outlet, also increasing the fuel flow and the use of finned tubes reduces the temperature of the output oil.

- Increasing the mass flow of oil and fuel increases the heat transfer coefficient. Also, the amount of heat transfer coefficient for finned tubes is less than finless tubes.

- The use of finned tubes increases the pressure drop of the heat exchanger compared to the state without fins. Also, in the heat exchanger with finned tubes, the oil stream tends to pass through the side of the shell wall.

- Increasing the mass flow of oil increases the coefficient of fluid friction in the heat exchanger with finned tubes and also reduces the coefficient of fluid friction in the heat exchanger with finless tubes.

References

[1] Rago, G., Concentric fuel/oil filters and heat exchanger package. 2001, Google Patents.

[2] Burr, D.N., et al., Fuel and oil heat management system for a gas turbine engine. 1988, Google Patents.

[3] Li, H. and V. Kottke, Effect of the leakage on pressure drop and local heat transfer in shell-and-tube heat exchangers for staggered tube arrangement. International Journal of Heat and Mass Transfer, 1998. 41(2): p. 425-433.

[4] Naphon, P., Thermal performance and pressure drop of the helical-coil heat exchangers with and without helically crimped fins. International Communications in Heat and Mass Transfer, 2007. 34(3): p. 321-330.

[5] Jian-Fei Zhang, Y.-L.H., Wen-Quan Tao, 3D numerical simulation on shell-and-tube heat exchangers with middle-overlapped helical baffles and continuous baffles – Part II: Simulation results of periodic model and comparison between continuous and noncontinuous helical baffles. International Journal of Heat and Mass Transfer, 2009.

[6] Chen, H., et al., Experimental investigation of heat transfer and pressure drop characteristics of H-type finned tube banks. Energies, 2014. 7 :p. 7094-7104.

[7] Hagshenas, B. and S.H. Light, Combination fuel-oil and air-oil heat exchanger. 2015, Google Patents.

[8] Kim, M., M.Y. Ha, and J.K. Min, A numerical study on various pin–fin shaped surface air–oil heat exchangers for

an aero gas-turbine engine. International Journal of Heat and Mass Transfer, 2016. 93: p. 637-652.

[9] Wang, X., et al., Numerical analysis and optimization study on shell-side performances of a shell and tube heat exchanger with staggered baffles. International Journal of Heat and Mass Transfer, 2018. 124: p. 247-259.

[10] Stearns, E.K., J.A. Glahn, and D.J. McKaveney, Gas turbine engine with geared turbofan and oil thermal management system with unique heat exchanger structure. 2018, Google Patents.

[11] Turcotte, H., K. Ng, and J. Dubreuil, Heat exchanger for gas turbine engines. 2018, Google Patents.

[12] Yogesh, S.S., et al., Heat transfer and pressure drop characteristics of inclined elliptical fin tube heat exchanger of varying ellipticity ratio using CFD code. International Journal of Heat and Mass Transfer, 2018. 119: p. 26-39.

[13] Wang, P., et al., An investigation of influence factor including different tube bundles on inclined elliptical fin-tube heat exchanger. International Journal of Heat and Mass Transfer, 2019. 142: p. 118448.

[14] El-Said, E.M. and M. Abou Al-Sood, Shell and tube heat exchanger with new segmental baffles configurations: a comparative experimental investigation. Applied Thermal Engineering, 2019. 150: p. 803-810.

[15] Mohammadi, M.H., et al., Thermal optimization of shell and tube heat exchanger using porous baffles. Applied Thermal Engineering, 2020. 170: p. 115005.

[16] Unger, S., et al., An experimental investigation on the air-side heat transfer and flow resistance of finned short oval tubes at different tube tilt angles. International Journal of Thermal Sciences, 2019. 140: p. 225-237.

[17] Unger, S., et al., Thermal and flow performance of tilted oval tubes with novel fin designs. International Journal of Heat and Mass Transfer, 2020. 153: p. 119621.

[18] Burr, D.N., et al., *Fuel and oil heat management system for a gas turbine engine*. 1988, Google Patents.

[19] Keeler, B.J. and P.S. McCabe, *Engine fuel-oil heat exchange system*. 2020, Google Patents.

[20] Mastrocola, N.E. and M. Pess, Super-cooled heat exchanger of an air cycle machine. 2020, Google Patents.

[21] Ribarov, L.A. and L.J. Veilleux Jr ,Multiple flow heat exchanger. 2020, Google Patents.

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

[23] Ambekar, A.S., et al., CFD simulation study of shell and tube heat exchangers with different baffle segment configurations. Applied Thermal Engineering, 2016. 108: p .999-1007.