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COMPUTATIONAL FLUID DYNAMIC SIMULATION AND EXPERIMENTAL STUDY OF AN OPTIMIZED SHELL AND TUBE HEAT EXCHANGER WITH CONSTANT HEAT TRANSFER COEFFICIENT

Nesrine Gaaliche [1]
Mahmood Alajimi

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ABSTRACT

The heat exchangers are widely used in different industrial applications, such as chemical industry, petroleum, thermal power, and so on. Fluid corrosion and fouling frequently damage shell and tube heat exchangers, resulting in leaks. In order to prevent the fluid losses and increase the efficiency, it is proposed to optimize an old shell and tube heat exchangers (STHE) used in the petroleum field in order to cool down the produced Methanol in petroleum production. Thermal modeling was used to optimize the design of a shell and tube heat exchanger using Computational Fluid Dynamics (CFD). Its heat transfer coefficient, pressure drop, and efficiency were calculated using the log-mean temperature difference (LMTD) method. Computational fluid dynamics (CFD) was performed to study the model of the inlet shell flow field. Our experimental findings show that the performance is around 35.29%. This means that the efficiency has increased by 9.6% of its previous efficiency and the pressure drops of the shell and tube side are 16.422 kPa and 54.262 kPa. The hot and cold fluid outlet temperatures, corrected LMTD and efficiency obtained from CFD simulations were in excellent agreement with experimental results, with an error of 3.6%.

1. INTRODUCTION

These are instructions The aim of this paper is to design a particular heat exchanger which cool down hot methanol with seawater. Heat exchangers are a kind of industrial machinery that exchanges heat between a cold and hot stream. They are applied to heat and cool fluids. Heat exchangers are classified into numerous categories, including air conditioner, shell and tube exchanger, and double-pipe exchanger, and many others. Heat exchangers are used in 80% of power usage systems (Hall, 2012). One of the most widely used fossil fuels is natural gas, as it provides energy for both industrial and household needs. Natural gas, being the world's third-largest energy source, is used for a wide range of applications. It is a popular choice among industries and households alike because it is an environmentally friendly fuel (Hendry, 2020). Singh et al. developed a heat exchanger that was primarily utilized to convert the liquid form of the

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[1] Corresponding author: Nesrine Gaaliche
Email: nessrine.gaaliche1@gmail.com

shell-side fluid to vapor. The liquid enters the cavity through the shell-side entrance, which has an exit for vapor. The tube bundle is made up of several tubes that carry tube-side fluid into a chamber with a longitudinal axis. The developed heat exchanger includes a shell with an inner surface that defines the cavity, a shell includes an inlet for delivering shell-side liquid into the cavity and an exit for releasing shell-side liquid vapor from the cavity. A tube bundle that is placed in a cavity and contains multiple tubes for carrying tube-side fluid with a longitudinal axis. A shroud surrounds the bundle in the circumferential direction and is placed between the bundle and the inner surface of the shroud so that there is a ring between the shroud and the inner surface. An opening at the bottom of the shell that forms the passage between the annular space and the bundle of tubes. The opening at the top of the shell forms a passage between the annular space and the tube bundle (Singh et al., 2009). The study required the development of a specific shell and tube heat exchanger that met particular requirements. The baffles are installed in the shells to help guide the fluid flow on the shell side and generate flow with turbulence. This heat exchanger type has various benefits, including a significant surface area for a lower dimension, ease of maintenance, a suitable mechanical design, and common design techniques (Coulson et al., 1983). Before beginning computations, the parameters and given data for the proposed design must be provided. As a result, the design will be restricted to the company's specifications, as given in Table1 The parameters will be used to develop a suitable design that meet the specified requirements. Kern's approach (Gavin et al., 2008) was followed to develop the heat exchanger in this work. First, the STHE will be modeled using Kern's approach and given parameters to predict the overall area, pressure drop, heat transfer coefficient, and efficiency. The STHE will next be modeled using ANSYS Fluent version 14.0 to determine all of the unknown parameters of methanol and seawater. The simulation of the optimized STHE is carried out after selecting an appropriate mesh, discretization approach, and turbulence model. Different thermal characteristics are determined and compared to the CFD numerical simulation.

2. KERN DESIGN METHODOLOGY

The following steps are to be followed as mentioned by Kern's method in order to design the heat exchanger in an optimal manner (Gavin et al., 2008). Several assumptions will be made while calculating the energy balance of the two fluids, including no energy losses and potential, kinetic energy transformations are neglected and steady-state conditions (Serth et al., 2007).

$$q_{cold} = q_{hot} \qquad \text{(Energy Balance Equation)} \qquad (1)$$

$$\dot{m}_{hot} c_{Phot} \left(T_{hotin} - T_{hotout}\right) = \dot{m}_{cold} c_{Pcold} \left(T_{coldin} - T_{coldout}\right) \qquad (2)$$

Where, $\dot{m}_{cold}$ = 8.056 Kg/s and $\dot{m}_{hot}$= 0.652 Kg/s.
The following equation can be sued to calculate the heat transfer:

$$q = \dot{m}_{hot} c_{Phot} \left(T_{hotin} - T_{hotout}\right) \qquad (3)$$

Using values from (**Error! Reference source not found.**), the heat transfer can be calculated, as shown below:

$$q = 8.056 \times \frac{2.095+2.354}{2}(130-50).$$
$$q = 1435.646\ kW$$

Table 1. Given specifications by the company for the design

Seawater	Temperature in (°C)	50
	Temperature out (°C)	130
	Density, ρ (Kg/m^3)	680
	Dynamic Viscosity, μ (Pa.s)	1.44x10^{-5}
	Specific heat, Cp $\frac{KJ}{Kg\,.C}$	2.225
	Thermal conductivity, k ($\frac{w}{m\,.K}$)	0.0456
Methanol	Temperature in (°C)	175
	Temperature out (°C)	144.37
	Density, ρ,(Kg/m^3)	922.6
	Dynamic Viscosity, μ (Pa.s)	1.026x10^{-4}
	Specific heat, Cp $\frac{KJ}{Kg\,.C}$	3.232
	Thermal conductivity, k, ($\frac{w}{m\,.K}$)	0.0456
Fouling Resistance in both sides=11630w/m^{2}K		
Outside tube Diameter=19.05mm		
Inner tube Diameter=17mm		

3. STHE DESIGN

To begin the computations, one shell pass and two tube passes is considered to get LMTD. Ken's Method will be implemented to determine the area of STHE. The temperature difference in heat exchangers is determined using the LMTD Ken's approach. It is defined as the differential between hot and cold working fluids. To optimize the LMTD, the methanol and seawater are utilized in counter-flow. As shown in Table 1, the temperatures, Densities, Dynamic Viscosities, Specific heats, Thermal conductivities for both shell and tube sides are provided as specifications by the company for the optimal design.

For the accurate prediction of LMTD in STHE design, all the physical and geometric parameters specified by Table1, have been implemented into the equation (4).
For the total heat transfer area calculation, the equation (5) is selected. The following equations are used to determine LMTD:

For counter current:

$$LMTD = \frac{(T_{hot,inlet} - T_{cold,outlet}) - (T_{hot,outlet} - T_{cold,inlet})}{ln\frac{(T_{hot,inlet} - T_{cold,outlet})}{(T_{hot,outlet} - T_{cold,inlet})}} \quad (4)$$

3.1 Value of heat transfer coefficient

LMTD and heat transfer coefficient must be calculated in order to compute the heat exchanger area. Therefore, it is recommended to begin with the assumption of the heat transfer coefficient specified by the company, which is 333.24W/m^2.K.

3.2 Calculation of total heat transfer area

The heat transfer area is determined by the LMTD and the assumed heat transfer coefficient. The below formula can be determined to determine the overall area:

$$A = \frac{q}{U \times LMTD} \quad (5)$$

Therefore,

$$A = \frac{1435.646 \times 10^3}{333.246 \times 59.798}$$
$$A = 71.943\ m^2$$

3.3 Determination of tube number:

To begin, a tube with common dimensions is selected having an outside diameter of 19.05 mm (Kuppan, 2000). Carbon steel was chosen for the tubes because of its good heat conductivity and is commonly applied in methane-containing applications. Furthermore, it has a strong mechanical strength and high resistance to corrosion. In addition, the tube has a length of 2.7 m, which is suitable for the design to minimize the cost and shell diameter. Since longer tubes provide more heat transfer and pressure drop (Bisoniya, 2015). Thermal conductivity is $K_{\text{carbon steel}} = 45\ W/m.K$ (Tritt, 2020).

Knowing the provisional area, it can be used along with data from (Table1) to calculate the number of tubes, using the following formula:

$$N_t = \frac{A}{\pi \times d_0 \times L} \quad (6)$$

Therefore,

$$N_t = \frac{71.943}{\pi \times (19.05 \times 10^{-3}) \times 2700 \times 10^{-3}}$$
$$N_t = 445.225\ Tubes$$
$$N_t = 445\ Tubes$$

The next formula is used to determine the number of tubes per pass:

$$Nttp = \frac{Number\ of\ Tubes}{Number\ of\ Passes} \quad (7)$$

Since the Natural Gas Preheater is a 1 shell 2 tube heat exchanger, using values from Table1 the following is determined:

$$Nttp = \frac{445}{2}$$
$$Nttp = 222\ tubes$$

3.4 Bundle and shell diameter

The bundle diameter is calculated by the next formula:

$$D_b = d_o(\frac{N_t}{K_1})^{1/n_1} \quad (8)$$

Where, $K_1 = 0.156, and\ n1 = 2.291\ \ for\ the\ square\ pitched\ arrangement$ and the heat exchanger has two passes.

Therefore,

$$D_b = 19.05(\frac{445}{0.156})^{1/2.291}$$
$$D_b = 613.865\ mm$$

The shell clearance for a fixed and U-tube heat exchanger is obtained from Fig. 1 by taking the bundle diameter into account, therefore the shell clearance is around 14 mm (Gavin P. Towler et al., 2008). The shell diameter (Ds) is calculated using these two variables.

$$D_s = D_b + clearance \quad (9)$$

Therefore,

$$D_s = 613.865 + 14 D_s = 627.865\ mm$$

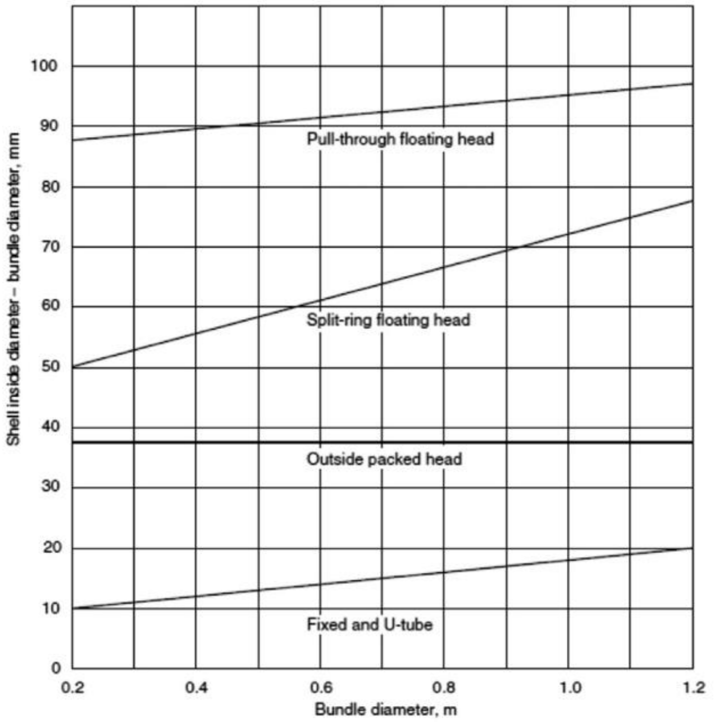

Figure 1. Bundle diameter and shell diameter (Gavin et al., 2008)

3.5 Baffle Spacing

The last step to designing the heat exchanger is to calculate the baffle spacing, that is done using the following formula:

$$B_s = 0.4D_s \qquad (10)$$

Therefore,

$$B_s = 0.4 \times 627.875$$
$$B_s = 251.146\ mm$$

3.6 Pressure drop in tube and shell sides

The pressure drop in shell side can be estimated by using the following equation:

$$\Delta P_s = \frac{2\, f\, M_s{}^2\, D_b\, (N_B+1)}{\rho\, d_e\, (\frac{\mu}{\mu_s})^{0.14}} \qquad (11)$$

The friction factor f is estimated to be 0.037. The dynamic viscosity of low pressured steam at the surface temperature of the shell of 36.2℃ is $6.8\text{x}10^{-4}$Pa.s. The mass velocity is 159.874 kg/m^2.s.

$$\Delta P_s = 16.422KPa$$

4. MODELLING DETAILS

The CFD simulation was carried out on a STHE for realistic modeling of heat transfer. For the heat exchanger design, several geometric and mechanical characteristics were considered. Table 1 contains data on design parameters. The first liquid is water, and the second one is methane, the STHE made from carbon steel. Both inlet temperature and flow rate are defined as the boundary conditions for this developed STE. Table 1 shows the detailed geometrical characteristics. The standard gravity and no-slip condition are also considered in this FE model. The tubes and shells are modeled as solid, with input temperatures of 36.2°C. The next step of the pre-processing is to perform the meshing. After developing the computational domain, the STHE is discretized into tetrahedral elements by means of Ansys. The convergence was accomplished using medium mesh size. Thus, the proposed tetrahedral mesh is selected.

5. RESULTS AND DISCUSSION

5.1 Optimized STHE design validation of the Kern's LMTD method

All calculations and simulations will be done in order to design the STHE in an optimal manner. For the accurate prediction of pressure drops and the heat transfer coefficient calculation in STHE design, Kern's LMTD method is selected. Kern's LMTD model for designing the STHE is a reliable method and is validated against many heat exchangers (Gavin et al., 2008). The optimized STHE designed by LMTD (Gavin et al., 2008) and its previous counterpart, having similar heat transfer characteristics and listed in Table 1, are compared with respect to its effectiveness and geometry (number of tubes per pass, tube pitch, Bundel diameter and overall size). Table 2 shows the difference in properties between the previous and optimized heat exchangers. The overall size of the heat exchanger is reduced compared to the old STHE as per industrial requirements (GPIC) due to limited space. Since the number of tubes per pass and the bundle diameter are decreased from 328 to 222and 840mm to 613.865mm, respectively. This consequently led to a decrease in the provisional area of the heat exchanger from 98.8 m^2 to 71.943m^2. The number of baffles was also reduced, which will lower overall costs and lighter weight. Because the boiler was designed to be vertical, there was some wastewater soaking at the bottom of the boiler, which increase the corrosion at the bottom causing leaks. This study demonstrates that the horizontal steam boiler much more efficient than the vertical boiler. Since, they suffer from more stress as the flues are not completely covered with water. The pressure drop on the heat exchanger's shell and tubes rises as the corrected LMTD increases. After improving the heat exchanger, efficiency improve from 25.63% to 35.29%. As a result, it is clear that this improved design offers the appropriate pressure drop. Improving STHE design utilizing the LMTD approach has been demonstrated to have a considerable effect on its efficiency across both thermal and pressure drop analyses.

Table 2. Comparison between previous and optimised STHE

Property	Optimized Heat Exchanger	Old Heat Exchanger
Heat Transfer (kW)	1435.6	
Heat Transfer Coefficient ($W/m^2.K$)	333.246	
Number of Tubes per Pass	222	328
Tube Pitch (mm)	23.813	24.5
Bundle Diameter (mm)	613.865	840
Corrected LMTD (°C)	59.798	43.5
Shell – Side Pressure Drop (kPa)	16.422	1.27
Tube – Side Pressure Drop (kPa)	54.262	50
Provisional Area (m^2)	71.943	98.8
Efficiency (%)	35.29	25.63

5.2 CFD Simulation of the STHE

to be validated. The computed heat exchange rate between methanol and seawater being 1383.9 W, the heat transfer results show that the CFD model has only a difference with analytical results by 3.6%. As shown in figure 2, Methanol enters the shell hot and exits cold, its temperature has decreased from 167°C to 142°C because show that the temperature of the fluid is lower on the outside of the shell.

Figure 2 displays the simulation results

there is a heat transfer through convection from the outer walls of the tubes to the exchanger. The seawater enters cold and goes out hot in the tubes, its temperature has increased from 50°C to 90°C because there is a heat transfer by conduction between the external and internal wall of the tubes. The temperature contours

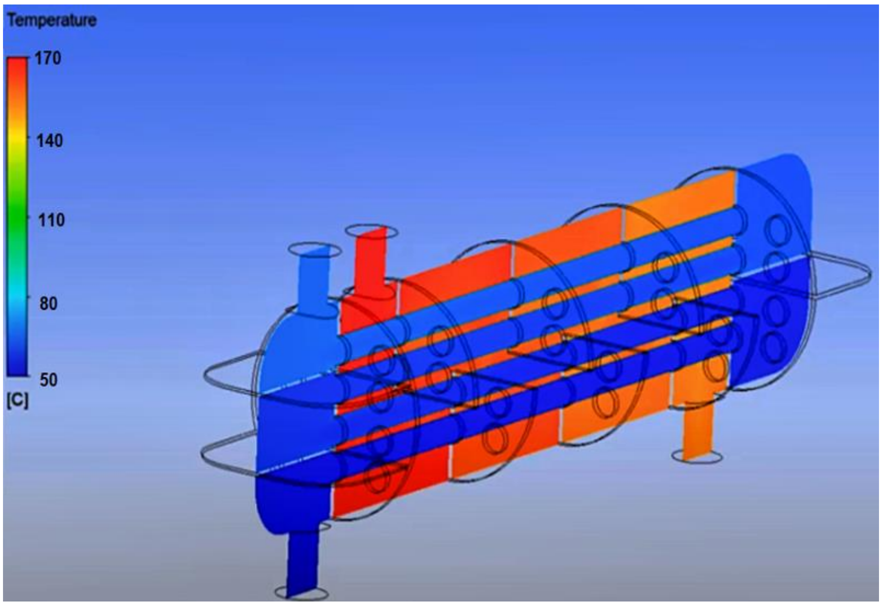

Figure 2. Temperature distribution in both fluids

6. CONCLUSION

The heat transfer and flow properties of a STHE are investigated in this paper using CFD method and the LMTD approach. The proposed heat exchanger is efficient, since it can cool down methanol from 175 °C to 144.38 °C by using seawater at 50 °C. Moreover, fluid flow rates can be produced with a suitable pressure drop. Kern's approach is provided, and it helps to predict accurate values of heat transfer coefficient, pressure drop, and efficiency. The basic idea is to use the Kern's design method to improve the efficiency of STHE. It depicts that pressure decreases with temperature. Since vertical boiler designs have much higher corrosion and leakages, that can lower the effective life of the device, the horizontal heat exchangers are more useful because the pressure is dispersed over a wider surface area. After improving the heat exchanger, efficiency rose from 25.29% to 35.29%. As a result, it is clear that this optimized design offers the appropriate pressure drop. Improving STHE design using the LMTD approach has been demonstrated to have a considerable effect on its efficiency across both thermal and pressure drop analyses. Furthermore, a computational model is employed to compute and compare the STE's performance. The temperature and pressure contours show that the temperature and pressure are lower towards the shell's outside edge. The hot and cold fluid outlet temperatures, pressure drop, and efficiency computed accord well with the experimental measurements. To summarize, the shell and tube heat exchanger is a viable option for this.

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Nomenclature:

A	Overall heat transfer area (m^2)	D_s	Shell diameter (mm)
d_0	Tube outer diameter (mm)	L_b	Baffle spacing (mm)
P_t	Tube pitch(m)	M_s	Mass velocity (kg/m^2s)
L	Pipe length (m)	ΔP	Pressure drop (Pa)
Nt	Number of tubes	F	Friction factor
D_b	Bundle diameter (mm)	d_e	Equivalent diameter (m)
		L_b	Baffle spacing (mm)

Nesrine Gaaliche
School of Engineering, Bahrain
Polytechnic, PO Box 33349, Isa Town,
Kingdom of Bahrain,
nessrine.gaaliche1@gmail.com
ORCID: 0000-0002-6659-8637

Mahmood Alajimi
School of Engineering, Bahrain
Polytechnic, PO Box 33349, Isa Town,
Kingdom of Bahrain,
Mahmod.Alajmi@gmail.com