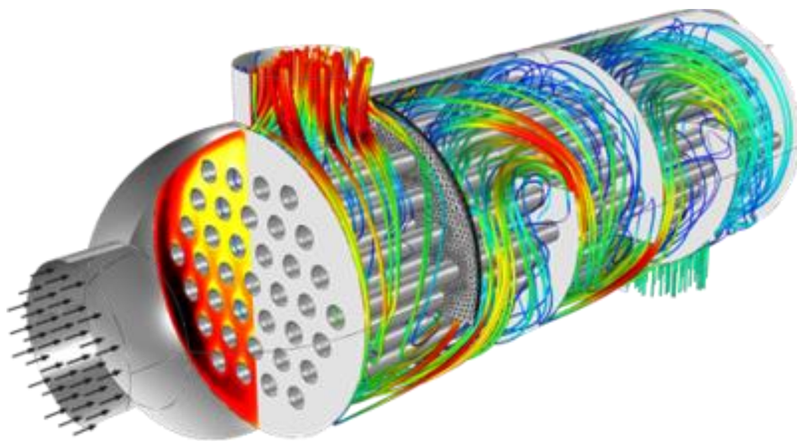
Shell and Tube Heat Exchanger Optimization Design



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ME 43300 Heat Transfer
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Introduction

Heat exchangers are critical components for applications involved with the transfer of thermal energy between two or more fluids without direct contact. Managing heat exchanger's efficiency improves energy efficiency, maintaining temperature control, and enabling processes like heating, cooling, or waste heat recovery. Among the various types of heat exchangers, the shell and tube configuration. This type of heat exchanger consists of a large pressure vessel (the shell) containing tube passes [5]. One fluid flow through the tubes while the other fluid flows around the tubes. The performance of shell and tube heat exchangers can be enhanced through changes to surface area of heat transfer, achieved by adjusting tube length, diameter, or the number of tubes. Various methods of enhancing turbulence within the fluid and ensuring ease of flow in the heat exchanger can improve fluid flow and thus the heat exchange rates. Proper material selection for the shell and tubes also ensures durability and compatibility with the fluids to avoid corrosion and withstanding temperature limits. Shell and tube heat exchangers find use in power generation, as used in condensers and boilers, in the chemical sectors, they support processes such as distillation and chemical reactions and in HVAC systems, they are used for temperature control [6].

I. Problem Statement

A shell-and-tube heat exchanger is to be constructed with 1-in. 12-gage tubes. The cold fluid, flowing in the tubes, is water flowing at the of 18,000 kg/h and is to be heated from 35°C to 65°C. The hot shell fluid is also water flowing at a rate of 12,800 kg/h, entering at 100°C. The tube water flows at an average velocity of 0.3 m/s and the overall heat transfer coefficient are 1,600 W/m-°C. For simplicity assume that the specific heat of each fluid is 4.18 kJ/kg-°C Determine the number of tubes per pass, and the required length of the tubes – examining various tube-pass possibilities but limiting the design to one shell pass.

II. Observations

The shell-and-tube heat exchanger is designed to increase the temperature of the cold water flowing through the tubes from 35°C to a temperature of 65°C. As the heat transfer from the hot water, entering at 100°C, it will experience a temperature drop. The design must account for the potential variations in flow rates due to pressure drops to maintain a consistent flow rate. For optimal operational conditions, turbulent flow is important to minimize fouling and maximize the heat transfer coefficients. It can observe most pressure drop will occur in the shell.

III. Design Constraints

The tubes must be constructed with 1 in 12 gage tubes designed into one shell pass. The cold fluid must be able to heat from 35°C to 65°C while maintaining a flow rate at 18,000 kg/h. The hot fluid must maintain a flow rate of 12,800 kg/h.

IV. Design Concept

The material that will be chosen would be able to tolerate the operational temperature of the fluids in the heat exchanger. A standard pump that will be able to maintain a constant flow rate must be able to provide the necessary power to account for pressure drops during the heat exchange process. Minimizing power is taken into consideration.

V. Problem Definition

Selection of tube number and length will be decided based on the required area due to calculation relating such geometric constraint to the thermodynamic requirements. Pressure drop and feasibility of design will be taken into consideration.

VI. Problem Solution

The material will be selected to best meet the operational temperature, lower cost and be able to hold up to possible corrosion over time. The pump will be decided based on the power requirements to maintain flow rate. To determine number of tubes and length, the heat transfer equation is applied to find the required heat transfer area in which different lengths and number of tubes will be explored

VII. Plan Execution

a. Assumptions: Assuming constant density, velocity and an unchanging overall heat transfer coefficient.

b. Analysis:

The calculations for the optimal number of tubes and length of tubes requires first calculating the required area to achieve the design constraints. First, heat transfer and Log mean temperature difference is found.

$$Q = \dot{m} C_p \Delta T \text{ (Equation 1)}$$

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_2}{\Delta T_1}\right)} \text{ (Equation 2)}$$

Area can then be related to the geometric configurations and the thermodynamics parameters, where N represents the number of tubes, U represent the velocity

$$A = \frac{Q}{U * \Delta T_{lm}} \text{ (Equation 3)}$$

$$A = \pi D L N \text{ (Equation 4)}$$

The calculation for the required area is then found from given information.

$$Q = 5 \frac{kg}{s} * 4180 \frac{J}{kg} (65°\text{C} - 35°\text{C})$$

$$Q = 627\ kW$$

$$T_{out,hot} = T_{in,hot} - \frac{Q}{\dot{m}_{hot} * C_{p,hot}}$$

$$T_{out,hot} = 57.81°C$$

$$\Delta T_1 = 35°C \qquad \Delta T_2 = 22.81°C$$

Plugging in the temperature differences into equation 2 yields:

$$\Delta T_{lm} = 28.47°C$$

With the LMTD, Q and given U, the area is then found by plugging in the values int equation 3.

$$A = 13.763\ m^2$$

To determine combination of length and number of tube necessary, different values are iterated to determine the closest area output needed. Considerations to take must also include limiting the number of tubes to the typical 50-200 tubes to reduce the cost of the design as well as limiting the length to reduce the pressure drops (Figure 1).

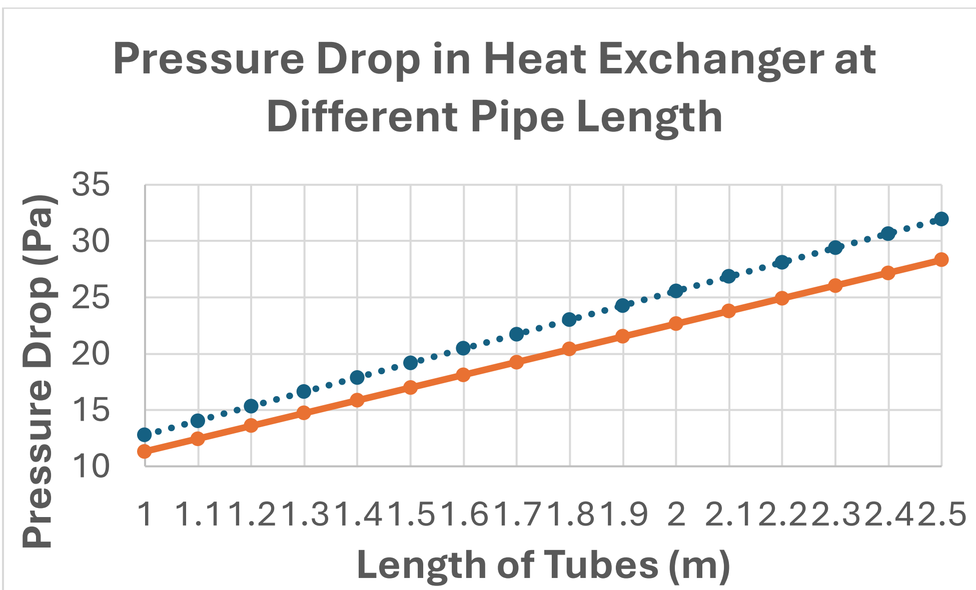

Figure 1: Pressure drop experienced by the heat exchanger due to change in tube length. The dashed blue line represents in tube pressure drop and orange solid line represents out of tube pressure drops.

Pressure drops were found by using the Darcy-Weisbach equation on both inside and around the tube and using mean temperature to determine the fluid properties.

$$\Delta P = f\frac{\rho U^2 L}{2D}$$

VIII. Final Design

At various number of tube and length iterations, the final design results closest to required area and considering pressure drop, yielding an area of 13.96 m^2:

$$L = 1.7\ m\ \ N = 100$$

A preliminary design is made of the possible configuration of the Shell and tube heat exchanger:

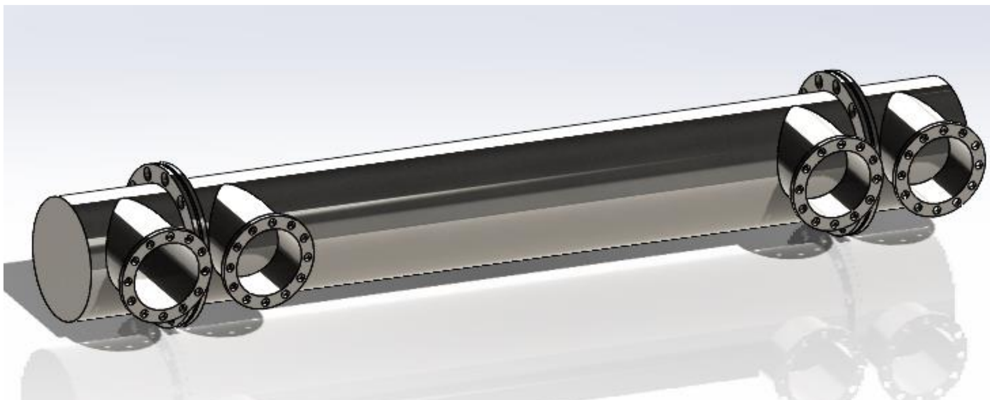

Figure 2: Shell and tube Heat exchanger final design. 2 inlet and outlet are shown for the cold and hot fluid. Tube has a length of 1.7 m.

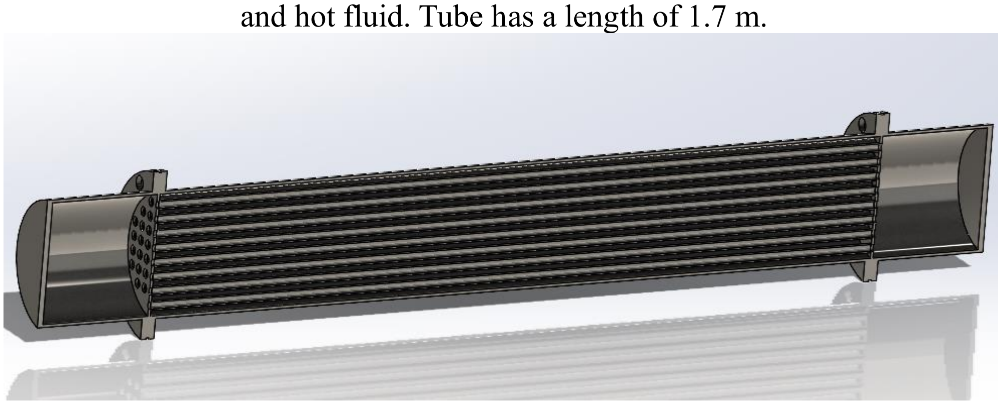

Figure 3: Sectional view of the shell and tube heat exchanger design with a total of 50 tubes.

Material Selection

The material selected for this design will solely be based on the metallurgical feasibility and cost as the overall heat transfer coefficient is taken to be constant. The material to be used is stainless steel 304 for its ability to uphold over time (corrosion resistance) and relatively reasonable pricing. Other alternative materials considered were various carbon steels or copper but were eliminated due to lower corrosion resistance [2].

Pump Selection

The pump selection must be enough to account the design constraint (flow rate of the cold and hot fluids). Given the heat exchanger does not require high precision and therefore efficiency is more at play, a centrifugal pump would be most ideal. The pump selected with these constraints:

Grundfos CR series centrifugal Pump [3].

IX. Testing

By utilizing the pump, the heat exchanger will be run to determine the heat output of the cold liquid. To test whether the pump is meeting design constraint, a temperature, pressure and flow meter must be implemented to make sure proper values are being reached. The temperature sensor will be placed at the outlet. Pressure drop must be within the range specified by the design.

References

[1] Brogan, R. J. (n.d.). *Shell and tube heat exchangers*. THERMOPEDIA. https://www.thermopedia.com/content/1121/

[2] Which materials are the best fit for your heat exchanger ... (n.d.). https://www.upmet.com/sites/default/files/whitepapers/heat-exchanger-materials.pdf

[3] Grundfos. (n.d.). https://product-selection.grundfos.com/us/products/cr-cre-cri-crie-crn-crne-crt-crte?tab=products

[4] Heat Transfer Essentials by Latif M. Jiji, Quadratic Press, 3rd Ed.

[5] Fundamental of Heat and Mass Transfer, by Incropera, DeWitt, Bergman & Lavine, John Wiley & Sons. Heat Transfer by J. P. Holman, McGraw Hill.

[6] Design. (2024). *Applications of Shell & Tube Heat Exchangers*. BEPeterson. https://www.bepeterson.com/types-and-applications-of-shell-tube-heat-exchangers

[7] *Shell-and-tube heat exchanger*. COMSOL. (n.d.). https://www.comsol.com/model/shell-and-tube-heat-exchanger-12685