Design and analysis of shell and tube heat exchanger for low temperature applications using CFD

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Abstract. A shell and tube device is deployed for the applications such as oil refinery processes, chemical processes and high pressure technologies. The hot fluid flows to the tubes in the heat exchanger, and the cool fluid moves through the shell section. Hence, heat is transferred from the tube section to the shell section of the heat exchanger. This article is deals with the modelling and analysis of mini shell and tube heat exchanger (MSTHE) for low temperature applications which is less than 250°C. The design of the heat exchanger is made with nine tubes which are of 6 mm diameter and shell of 41 mm diameter. As conventional design does not result in the internal heat transfer, computational fluid dynamics scheme is adopted to design the modified heat exchanger by adopting the conditions such as velocity of tube fluid and pressure drop. The modelling of MSTHE is done by Pro/E whereas CFD analysis is done with ANSYS. The contour obtained from the analysis proves that the MSTHE is applicable for the temperature less than 250°C and have the potential to transfer heat effectively.

1. Introduction
Heat exchanger is a device which is used to transfer heat between fluids at different temperatures. Heat exchanger can be divided into three types based on the flow pattern which includes is cross flow, counter flow and parallel [1]. The system is called parallel flow heat exchanger if both the fluids are in the same direction. In the counter flow heat exchanger, the fluids are in parallel but in opposite directions. Designing the flow in which the fluids pass through the heat exchanger at right angles to each other is referred to as type of cross flow. Heat exchanger is a tool designed for the efficient transfer of heat from one fluid to another [2-4]. It is surrounded by a solid wall to avoid mixing fluids, because they will be contacted directly. These are commonly used in room heating, air conditioning, power and chemical plants, petroleum refineries, petrochemical plants, natural gas processing, and waste water treatment.
An example of a heat exchanger is found in an internal combustion engine where a circulating substance defined as the engine coolant flows through the coils of the radiator, and air flows through the coils, cooling the coolant and heating the air. Through the tube walls, heat is transferred from the exhaust gas through the diesel engine to the fluid, either from the side of the tube to the side of the shell or vice versa [5]. A large heat transfer area should be used to distribute heat effectively, contributing to the need for several tubes [6, 7]. Excess energy can also be used in this manner. It is an energy-efficient way to conserve. To further minimize heat, the hot water from the exchanger is supplied to another heat exchanger [8, 9].

Instead of using the boiler to supply heat, the heat which is recovered from exhaust gas can be used. A liquid and gases pass across the exchanger with different entry temperatures. One moves across the tubes as well as the other passes within the shell just outside of the tube. In order to transfer heat efficiently, a large heat transfer area should be used, leading to the use of many tubes. The flow is counter flow and baffles are used to make the flow in zigzag motion. In this article, three steps are utilized to investigate the MSTHE which includes manual calculation, modeling and analysis.

2. Proposed Methodology
The aim is to build and evaluate a MSTHE which is used to transfer heat for temperature below 250°C. In this process, a liquid and gases pass through the exchanger with varying initial temperatures. The lower temperature fluid flows outside the tube, and the higher temperature flows within the tube but outside the shell. Thermal design procedure of MSTHE is primarily concerned with the following characteristics.

a. Determination of the diameter of the shell.
b. Determination of the total number of tubes.
c. Determination of the overall heat transfer coefficient.
d. Determination of the pressure drop characteristics.

Heat exchange has been assumed that temperature of the high temperature and low temperature fluids remain different while the heat shifting takes place. Thus, the heat transfer is calculated across the barrier and the barrier divides the two heat reservoirs. The temperature of fluids alters as they flow from one end to the other in most heat exchangers. Preparation of tube sheet layout requires the number of tubes, pitch and tube dimension pass partition thickness and number of passes allowances are also taken into consideration. The diameter is obtained by providing required allowance for calculation the number of tube is taken from the tube sheet. The configuration of the tubes inside the MSTHE is a rotated square type. By this arrangement, the tube constitutes the overall area inside the shell with the spacing of the pitch ratio. The baffle spacing can be calculated by 0.2 times the diameters of the shell. The selection of low quality material loads to failure of the vessel. The high quality material loads to the like of price in investments for the design.

3. Designing procedure of MSTHE
In Assume that the inlet temperature of high temperature fluid be 250°C, outlet temperature of hot fluid be 100°C, inlet temperature of low temperature fluid be 30°C, outlet temperature of low temperature fluid be 90°C, tube diameter outlet (dₒ) be 6mm, tube numbers (Nₒ) be 9 and tube length (L) be 500mm. As it is known, the overall heat transfer coefficient for gas and water is 10 – 250 W/m²K. The evaluation of the design of MSTHE has done by the following equations

For counter flow, LMTD is computed using

\[ \Delta T_{m} = \frac{(T_{h1} - T_{c1}) - (T_{h2} - T_{c2})}{ln\left(\frac{T_{h1} - T_{c1}}{T_{h2} - T_{c2}}\right)} \] (1)
But, Heat transfer is given by

\[ Q = AU\Delta T_m \]  \hspace{1cm} (2)

Properties of fluid in Shell side and the tube side can be obtained from the mean temperature of between the inlet and outlet.

The shell diameter is given by

\[ D_s = 0.637 \sqrt{\frac{CL}{CTP} \left[ \frac{A_o (PR)^2 d_o}{L} \right]^{1/2}} \] \hspace{1cm} (3)

Number of tubes can be calculated as

\[ \frac{N_t}{A} = \frac{A}{\pi d_o L} \] \hspace{1cm} (4)

The shell area, length of the baffle and mass velocity is given by

\[ A_s = (P_x - d_o) D_s \] \hspace{1cm} (5)

\[ L_b = \frac{D_s}{5} \] \hspace{1cm} (6)

\[ \frac{G}{A} = m \] \hspace{1cm} (7)

The Reynolds’s and Prandtl number is given by

\[ Re = \frac{G_p D_s}{\mu} \] \hspace{1cm} (8)

\[ Pr = \frac{G_p \mu}{k} \] \hspace{1cm} (9)

The overall heat transfer coefficient is calculated by

\[ \frac{1}{U} = \left[ \frac{1}{h_o} + \frac{1}{h_i} \right] \frac{d_o}{d_i} \] \hspace{1cm} (10)

\[ h_i d_i = 0.332 (Re)^{0.5} (Pr)^{0.333} \] \hspace{1cm} (11)

\[ \frac{h_o d_o}{k} = 0.332 (Re)^{0.5} (Pr)^{0.333} \] \hspace{1cm} (12)

The pressure drop at the tube side and the shell side is given by

\[ \Delta P_t = \frac{4 f G_t^2 L n}{2 \rho d_t} \] \hspace{1cm} (13)

\[ \Delta P_s = \frac{f G_s^2 L d_s}{2 \rho d_s \varphi_s} \] \hspace{1cm} (14)
After finding the pressure drop of the shell and tube side, the pressure of the fluid for higher temperature is compared with the obtained pressure to confirm the safety of the design. Normally, most of the failures relevant in pressure vessel design primarily stress dependent. The need for increasing reliability, reduced cost and improved performance make the designing extremely complex. Reducing cost is proportional to the reducing weight of the MSTHE. Increase reliability with reduced weight can be achieved only on the basis of careful analysis existing stresses should be within the allowable code limits.

4. Result and Discussions
Thermal design is concerned with the computation of total heat transfer, mass flow rate, dimensions of the tubes, tube numbers, and number of passes prevailing in the tube and shell sections. The thermal results are depicted in Table 1.

| Description                      | Unit | Value       |
|----------------------------------|------|-------------|
| Fluids                           |      |             |
| Hot                              | Cold |             |
| Heat                             | Q    | KW          |
| Total heat transfer area         | A    | m²          |
| Mass flow rate                   | mₜ   | Kg/sec      |
| Dimension of tubes               |      |             |
| Outside diameter                 | dₒ   | mm          |
| Length                           | L    | mm          |
| No’ of tubes                     | N_t  |             |
| Inside diameter of shell         | Dᵢ   | mm          |
| No’ of passes                    | N    |             |
| No’ of Baffles                   | N    |             |
| Baffle spacing                   | lₜ   | mm          |
| Shell outside diameter           | Dₒ   | mm          |
| Tube pitch                       | Pₜ   | mm          |
| Pressure drop of shell           | ∆Pₛ | bar         |
| Pressure drop of tube            | ∆Pₜ | bar         |

Finite element analysis of the practical problem requires handling of larger input data. Manual preparation of input data are tedious, time consuming and error proud task particularly for three dimensional stress analysis of solids and the shell. Hence, it will be an added advantage to have software which will aid the preparation of the input data and also in the interpretation of analysis results. Such programs are called pre and post processors to finite element analysis package. A pre processor creates a finite element model and the inputs necessary for a finite element analysis program that accepts the result of the analysis which senates for proper interpretation of the results.

Finite element method is primarily used for stress analysis of components which are complex in nature; these may not be predicated using conventional methods with reasonable accuracy. By using
the CFD package, the analysis of thermal distribution, pressure drop, and velocity distribution in each point and also the change in temperature, pressure, velocity can be studied easily. It also results the promising outcome about the failure which occur in a particular region. It is an effective tool to model any complex design and easy to import the design to ANSYS software through IGS file. From Fig.1, it is noticed that the inlet and outlet are provided in the shell of the MSTHE to supply the low temperature fluid. In addition, it is observed that the equally spaced baffle, a ring like structure is also provided in the MSTHE.

![Figure 1. Modeling of MSTHE.](image)

The cut section view of the MSTHE is depicted in Fig.2. The diagram assures that the modeling is done as per the calculations and values in the Table.1 for the MSTHE. The hot water passages inside the shell of nine numbers are implemented in a triangular layout to occupy more number of tubes. The inlet and outlet of the cold water passage is placed in the top and bottom of the MSTHE. The six numbers of baffles provided to make a zigzag motion and to increase the flow area of the cold water through the tubes of the MSTHE.

![Figure 2. Cut section view of MSTHE.](image)

The solid model of the tube is created in proE and exported in ANSYS; the finite element model generally refers to the creation of nodes and element for the analysis of MSTHE. The goal of fluent
meshing is to use meshing tools efficiently that simplifies the process of mesh creation. The meshing of MSTHE is shown in Fig.3, in which the Global size control value of 2 is taken to execute a fine mesh. The default values are assigned for minimum thickness across the tube. The element 142 type fluids are selected for meshing type to support the fluid flow in 3Dspace. The mesh is done in the overall volume and the obtained mesh size is 1,095,246 for the triangular size.

![Figure 3. Meshing of MSTHE.](image)

The modeling of MSTHE is done for the conditions of constant inlet pressure. In this MSTHE the shell side fluid was water and the tube side is hot air of 250°C. The Fig.4 shows the temperature of the MSTH in which the input parameters are given in above table.1. Since the calculation of Reynolds number obtained is laminar flow, so the same input boundary condition is used for the analysis of the MSTHE. The temperature distribution in the internal portion of the MSTHE shows maximum of 251.46°C and minimum of 42.88°C. It can be identified that the maximum temperature obtained at the tube sections and the minimum temperature obtained at the internal shell side of the MSTHE. It can be noticed that the temperature of the baffle is also maximum because the hot tube is attached in the baffle. Besides, the intermediate temperature of 182.63°C obtained between the fastened baffle and shell of the MSTHE. However, the temperature difference obtained is 52.33 °C, but the preceding analyst achieved 43.5 °C and 47.99 °C Musilim et al [10] and Safarian et al [11] respectively for their CFD analysis.

The temperature of bundle of tubes used in MSTHE is shown in Fig.5. The low temperature fluid passes through the shell but outside the tubes of the MSTHE. Thus, from Fig.5 it is noticed that the temperature outside the tubes is less because the water flows around it. The flow is counter and hence the inlet temperature of the tubes in MSTHE is higher than the outer temperature. The intermediate temperature obtained for the tubes is 132.28°C of the MSTHE.
Fig. 4 shows the temperature of the inner portion of the tubes of MSTHE, hence they give the temperature difference of the tube external and internal surface. It can be noticed from the figure that the inlet temperature of the tube increases and then considerably reduces the temperature when it passes the outlet of MSTHE. It is also observed that the temperature of the outside surface of the tube decreased and the internal temperature increases. The intermediate portion of tube shows the transition
of temperature occurred throughout in the MSTHE. The minimum and maximum temperature obtained internally for the tube is 54.02°C and 250°C respectively.

Figure 6. Temperature inside the tube of the MSTHE.

5. Conclusion
The MSTHE is designed with one shell along with one tube pass and it meets the required conditions based on velocity of tube fluid, and pressure drop. To investigate the internal flow and to find the heat transfer effect, the computational fluid dynamics scheme is adopted to design the MSTHE. The result identifies that it is also possible to design the heat exchanger for required range based on the calculation steps for the optimum usage. The study suggests that the number of tubes, diameter of the shell, and the parameters of the baffle space gives the proper design for the heat exchanger. The usage of more number of tubes increases the dimensions of the exchanger. The investigation identifies that the internal flow of the shell as well as the tube in the heat exchanger can be predicted by the CFD tool with their heat transition areas. Furthermore, the designed MSTHE is utilized for the application such as heat reduction in exhaust of internal combustion engine, waste heat recovery, pressure drop, detonation due to high temperature, etc.

6. References
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