# PRODUCT DESIGN OF SHELL AND TUBE HEAT EXCHANGER SYSTEM FOR EDUCATIONAL TRAINING KIT

Muhammad Izzat Aiman Ahmad Padzil, Nurul Asyiqin Rosli, Nadzirah Mohd Mokhtar

## Abstract

Heat exchanger is the common device applied for heat transfer in thermodynamics, but the current commercial training package is complicated and limits the exploration by students. In this study, a complete shell and tube heat exchanger system was developed for educational purposes. The thermal efficiency of the system was examined by varying the flow rate and temperature. It was observed that the logarithmic mean temperature difference tends to decrease with the increase in inlet hot flow rate. Meanwhile, the effectiveness continues to decline as the inlet hot flow rate increases. The highest overall heat transfer (1.505 $W/m^2.K$) was obtained when the flow rate was set as 10 LPM. It can be concluded that the higher the overall heat transfer coefficient, the lower the effectiveness of the heat exchanger.

**Keywords** Heat Exchanger, Shell and Tube, Educational Kit, Heat Transfer, Thermodynamics.

## Introduction

Heat exchanger is one of the equipment that is practical in industrial and domestic application. This involves the process of energy conversion from small-scale applications to large power stations (Nguyen and Ahn, 2021). Heat exchanger is a device or

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system designed by mankind for the heat transfer process between two fluids at different temperatures. The thermal analysis involves all three known modes of heat transfer by conduction, convection and radiation. The thermal performance of a heat exchanger depends upon many factors. Some of them are feed temperature and pressure, baffle and cutting spacings, number of tubes, tube geometry, and shell diameter (Abd et al., 2018).

Among the heat exchangers, the shell and tube heat exchanger (STHE) offers great durability to meet the requirements and provides the efficient thermal performance (Rao and Raju, 2016). STHE is a type of exchanger built from a bundle of circular tubes and enclosed by a cylindrical shell, with the shell and tube axis parallel to each other. Inside the shell, baffles are installed to hold the tubes together and direct the shell fluid flow to a certain extent (Bashiru et al., 2020). This type of exchanger is considerably flexible in design, since the geometries can be adjusted to meet the design and process requirements. The main advantage of this exchanger is that the configuration results in a large surface area per unit of volume. In addition, this type of set-up provides good mechanical layout and gives good shape for high pressure operation. Typically, the STHE design uses well-established manufacturing techniques and high flexibility of construction materials (Abd and Naji, 2017).

To date, limitations still exist in the teaching of the concept of heat transfer in thermodynamics. Students tend to avoid this course because the course content is too theoretical and difficult to comprehend. The issue also stems from the lack of hands-on sessions to explore the concept of heat transfer. Cartaxo et al. (2014) mentioned that STHE itself requires the knowledge and calculation of complicated heat and fluid flow geometries such as turbulence in the flow, the presence of hydrodynamic and thermal entrance regions, uneven local heat transfer rates and fluid temperatures, secondary flow in the tube bends, vortices in the neighbourhood of the tube-fin junctions, heat conduction along tube walls, natural convection within the tubes, and temperature dependence of fluid properties. Current educational professionals tend to rely on commercial heat exchanger trainer with comprehensive sets of custom computing software.

The learning process becomes easier when we use commercial products as learning tools. However, we did not notice that our action reduced the student's innovative spirit to explore the actual process that happened during the tests. In this project, the main objective is to design a STHE trainer kit that is easy to experience in the laboratory. The system uses the standard design of the conventional STHE system, which was composed of two thermostatic cycles with the addition of a radiator as a coolant for the heat exchanger. The system was evaluated based on Log Mean Temperature Difference (LMTD) and Effectiveness-Number of Transfer Units (ε-NTU). It is hoped that few laboratory modules are able to be developed by this STHE system by varying operating temperatures, pressures, flow rates, fluid types and much more.

## Methodology

### *Design and Fabrication of Shell and Tube Heat Exchanger System*

Figure 1 shows the process and instrument diagram (P&ID) of the STHE system. The system consisted of two water tanks to store the fluids and water used for both heating and cooling medium. Two hydraulic pumps (Pump 1 and Pump 2) were installed to pressure the fluid flow for both the cold (shell side) and the hot (tube side) fluids. An electrical heater was placed inside the hot tank to supply sufficient heat during the experimental works. Three valves (V1, V2 and V3) were set to control the flow at the hot side and another three valves (V4, V5 and V6) were placed on the cold side to control the flow regime. Digital temperature sensors (T1 and T2) were placed to measure the temperature of the water at the hot inlet and outlet, respectively. Temperature sensor, T3, was positioned at the cold inlet to measure the inlet water temperature before entering the system. Meanwhile, T4 was placed at the cold outlet to indicate the temperature after leaving the heat exchanger and T5 was placed after the radiator to show the actual temperature after the water flow passed through the radiator. In this design, the radiator was added to speed up the cooling process after the water exit from the heat exchanger at the cold outlet. The flow rotameters (R1 and R2) were placed to monitor and control the water flow rate inside the pipe.

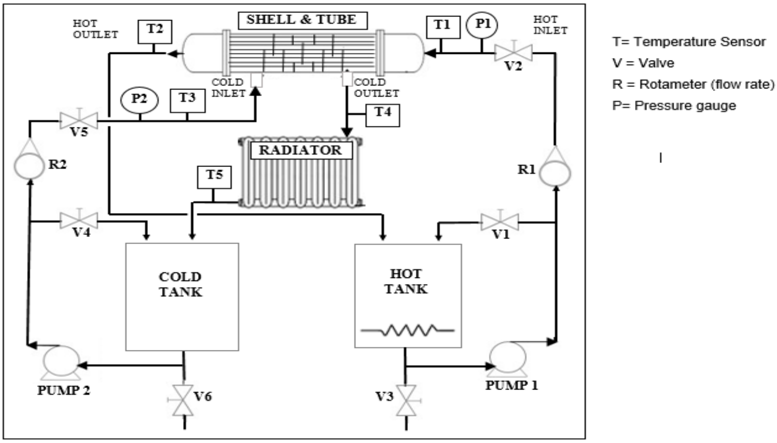


**Figure 1:** Schematic diagram of STHE system.

The 2-dimensional sketch of the heat exchanger design of this project is illustrated in Figure 2. The proposed and selected design of shell and tube heat exchanger was selected based on the best design and materials, and the market price. Due to the limitation of the budget, the design was designed in the simplest way but still followed the right specification dimension and size to ensure the efficiency of the system.

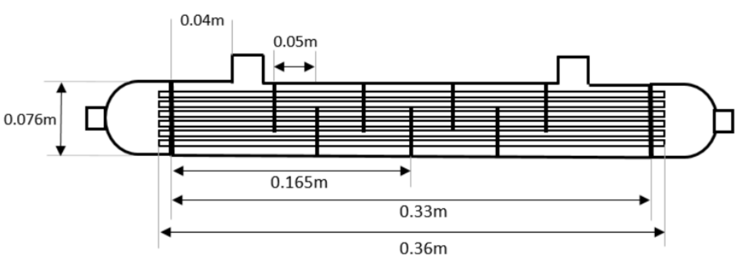


**Figure 2:** Proposed design of STHE.

The fabrication process started with the fabrication of the STHE, which needs to be fabricated parts by parts, starting with the tube bundles, baffles, shell and bonnets, before the parts are combined and fixed into the heat exchanger. After the fabrication of the shell and tube was completed, the saddle and the platform were fabricated based on the weight and estimated size of the whole system. The platform considered the overall system, including the piping and wiring, to make it easy to transport. The pumps, tanks and pipes were then installed on the system according to the design drawing. The piping shall be completely sealed to prevent leaks. Finally, when the entire manufacturing process is completed, electrical fabrication must be done to operate the system. Figure 3 shows the complete prototype of the STHE system.


**Figure 3:** Prototype of the educational STHE system.

***Performance Testing of Shell and Tube Heat Exchanger System***

STHE system analyses were carried out continuously with the hot inlet temperature varied from 40°C to 60°C. The cold inlet flow rate was kept constant at 600 L/h with variation of hot inlet flow rate of 200, 300, 400, 500 and 600 L/h, respectively. The temperatures (T1, T2, T3 and T4) were measured using digital thermometer sensors for every two minutes. The overall heat transfer coefficient and effectiveness of the STHE system were estimated using the LMTD calculation to determine the heat load. The heat transfer rate and ultimately pressure drop were calculated from the initial data on the flow rates and the inlet and outlet temperatures of both shell and tube sides of STHE. The heat load, $Q_{load}$, and heat absorbed, $Q_{abs}$, were calculated by using Equations (1) and (2), where $Q_{load}$ was referred as the heat released by hot fluid and $Q_{abs}$ was referred as the heat successfully absorbed by the cold fluid.

$$Q_{load} = m_h c_{ph}(T_{hi} - T_{ho}) \quad (1)$$

$$Q_{abs} = m_c c_{pc}(T_{co} - T_{ci}) \quad (2)$$

where $m_c$ and $m_h$ are the cold and hot fluid mass flow rates in kg/s, respectively, while $c_{pc}$ and $c_{ph}$ are the specific heats under the constant pressure of cold and hot fluids in kJ/kg. K. After $Q_{load}$ and $Q_{abs}$ were determined, the heat losses, $Q_{loss}$, was calculated by subtracting the latter to the former.

The overall heat transfer coefficient, U (W/m$^2$.k), was determined by dividing the $Q_{load}$ with the product of $\Delta T_{lm}$ with the effective heat transfer area, A (m$^2$). The calculation steps may refer to the following Equations (3).

$$U = \frac{Q_{load}}{A\Delta T_{lm}} \quad (3)$$

$$A = n\pi D_O L \quad (4)$$

where n refers to the number of tubes, $D_0$ is the outlet tube diameter and L is the effective length of the tube. For the LMTD calculation, the formula is presented in Equation (5).

$$\Delta T_{lm} = \frac{(T_{hi}-T_{co})(T_{ho}-T_{ci})}{ln(\frac{T_{hi}-T_{co}}{T_{ho}-T_{ci}})} \quad (5)$$

where $T_{hi}$ and $T_{ho}$ are the tube side inlet and outlet temperatures in kelvin, respectively, and $T_{co}$ and $T_{ci}$ are the shell side inlet and outlet temperatures in kelvin, respectively. The number of transfer unit, NTU of the STHE was then calculated by using Equation (6).

$$NTU = \frac{UA}{C_{min}} = \frac{UA}{(mcp)_{min}} \tag{6}$$

In terms of the STHE thermal performance, the effectiveness was determined using a graph of heat transfer effectiveness as a function of the heat capacity rate ratio for the common types of heat exchangers (Çengel, 1997). It has the following formula:

$$\varepsilon = \frac{1 - exp[-NTU(1 - Cr)]}{1 - Cr[-NTU(1 - Cr)]} \tag{7}$$

where $C_r$ is the ratio of $C_{min}$ and $C_{max}$.

## Results and Discussion

### *Effect of Hot Inlet Temperature and Flow rate on the Log Mean Temperature Difference*

LMTD is a parameter for determining the temperature driving force for heat transfer in flow systems. Figure 4 shows the LMTD trend for two parameters, which are the hot inlet temperature and the flow rate. A decreasing trend was observed when the hot inlet flow increased from 200 L/h to 600 L/h. In contrast, there was an upward trend when the hot inlet temperature went from 40°C to 60°C. However, the effect on LMTD is more significant by the operating temperature compared to the flow rate. This is because temperature plays a major role in transferring heat from the hot side to the cold side. As can be seen from the graph, almost 160-190% LMTD increment was obtained when the hot inlet temperature was changed from 40°C to 60°C. The higher the hot inlet temperature, the greater the LMTD. Meanwhile, a marginal decline of approximately 14-23% was reported when the hot inlet flow was set between 200 L/h to 600 L/h. The flow rate affects the heat transfer inside the system, but the effect is not significant to the fluid temperature.

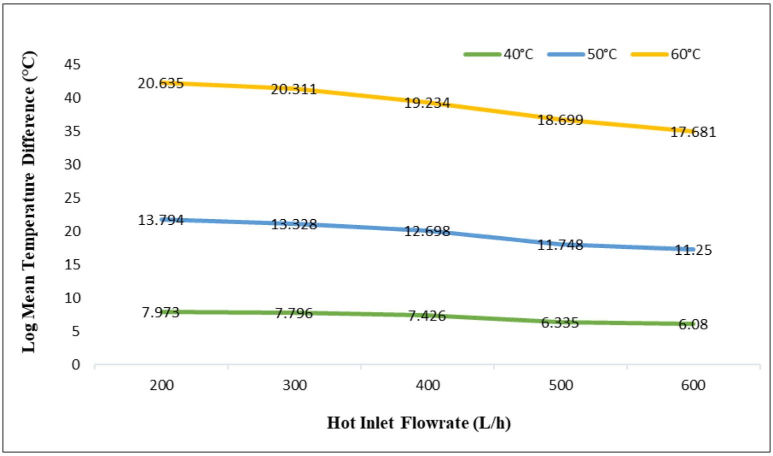


**Figure 4:** Log mean temperature difference vs. hot inlet flow rate with constant cold inlet flow rate at 600 L/h.

***Heat Transfer Analysis of the Shell and Tube Heat Exchanger System***

Figure 5 shows the graph of the overall heat transfer coefficient in relation to hot inlet temperature and flow rate. In general, the higher the overall heat transfer coefficient, the better the heat transfer rate between the two mediums. In this figure, a similar positive trend was observed for the two parameters of operation. A clear upward trend was presented in the graph when the hot inlet flow increased from 200 L/h to 600 L/h. This is because when the flow rate inside the shell is constant, the heat transfer from the tube to shell is fully utilised (Nwokolo et al., 2020). The formation of a higher turbulent flow with an increasing flow may be the reason for the increase in the heat transfer coefficient. However, higher flow rates will result in a shorter contact time between the heat source and the heat sink. A short contact time between the working fluid will lead to inefficient heat transfer between the cold fluid and hot fluid. This is because contact time is important to enhance the heat transfer rate in the STHE. The highest overall heat transfer coefficient recorded by this experiment is 1.505 $W/m^2.K$ when the hot inlet temperature is 60°C with the flow rate of 600 L/h.

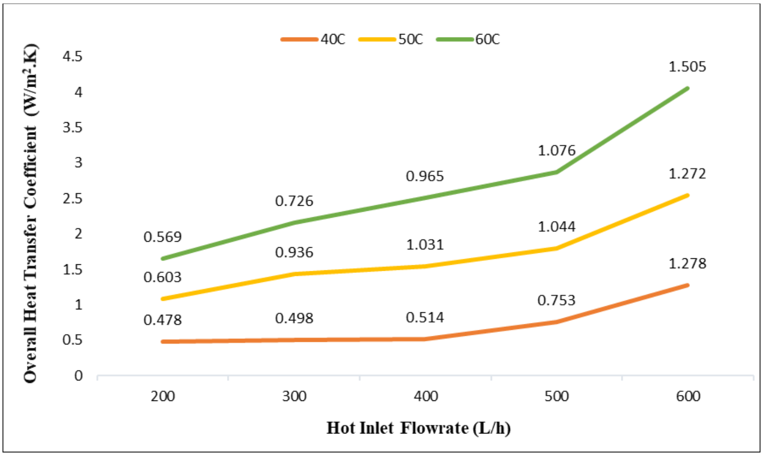


**Figure 5:** Overall heat transfer coefficient vs. hot inlet flow rate with constant cold inlet flow rate at 600 L/h.

Figure 6 shows the graph of STHE effectiveness with respect to the hot inlet temperature and flow rate. Typically, STHE efficiency is defined as the ratio of actual heat transfer to the maximum possible heat transfer. It is impossible to have the ε-NTU greater than 1. According to the graph, the effectiveness continues to decrease as the mass flow of hot water increases. For a hot inlet flow between 200 L/h and 600 L/h, the efficiency decreases by 0.34 to 0.12. Efficiency depends on the level of hot input flow. The peak STHE was determined to be 0.34 when the water flow rate at 60°C was 200 L/h. Although temperature is a dominant effect for STHE, the ε-NTU at 40°C is much higher when operating at 200 L/h than hot water (60°C) flows at 600 L/h. Further work is required to identify the optimum operating conditions of the STHE system.

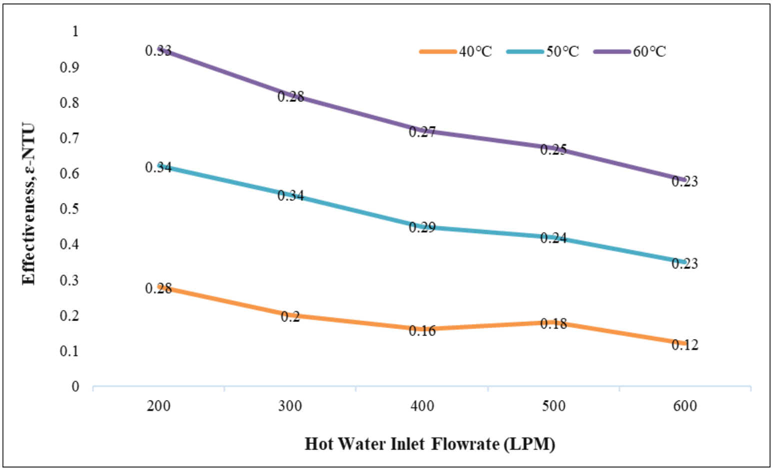


**Figure 6:** Effectiveness vs. hot water inlet flow rate with constant cold water inlet flow rate at 600 L/h.

## Conclusion

The STHE system has been successfully manufactured in this work, which is portable and can easily be disassembled along with ease of maintenance. The current prototype can be used for educational purposes, but it is not yet marketable. Additional considerations must be taken into account prior to commercialisation, such as economic analysis, system accuracy and sensitivity, service, etc. This design of the heat exchanger focuses on the purpose of the educational toolkit, and its dimensions were not suitable for industrial use. The results of the analysis indicated that the highest total heat transfer was recorded at 1.505 $W/m^2$. K. The conclusion that can be drawn is the higher the overall heat transfer coefficient, the less efficient the heat exchanger is. It can be highlighted that temperature gives a dominant effect to the LMTD over flow rate.

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