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DESIGN AND FABRICATION OF A LABORATORY SCALE SHELL AND TUBE HEAT EXCHANGER

[1]Umar Hassan, [2]Tukur Hassan and [1]Ibrahim Alapatira Qozeem

[1]Department of Mechanical Engineering, Ahmadu Bello University, Zaria Nigeria.
[2] Hassan Usman Katsina Polytechnic, Katsina State Nigeria.

*Corresponding authors' email: uhbindawa8@gmail.com

ABSTRACT
Heat exchangers are critical devices used across various industries to transfer thermal energy between fluids and one of the most important tools in heat transfer and thermodynamics courses. However, Nigerian public institutions often lack access to necessary and well-designed laboratory scale heat exchangers that are easily disassembled to provide students with practical, hands-on experience, limiting their understanding of the key engineering concepts. This paper presents the design, development and fabrication of a laboratory scale shell and tube counter-flow heat exchanger (STHE). Designing the laboratory scale model serves educational and experimental purposes, allowing students and researchers to analyze the thermal behavior, evaluate effectiveness and validate design equations. The design incorporates cost-effective and locally available materials, making it feasible for institution with limited resources. The system was design based on a counter-flow arrangement for maximum temperature gradient and higher heat transfer efficiency, while logarithmic mean temperature difference, LMTD was used to analyze the performance of the heat exchanger. The length for both shell and tubes of the model heat exchanger was 600mm with 8 numbers of tubes with mass flow rates of both hot and cold waters as 0.0194 kg/s and 0.0263 kg/s respectively. The test results showed that the heat transfer rate Q, LMTD and the overall heat transfer coefficient, U for the hot and cold sides of the shell and tube heat exchanger were (1630, 376.2) W, (53.1 for both) oC and (1615.6, 372.9) W/m2 oC respectively. The heat exchanger achieved an effectiveness of 35.97% which is far lower than 75% minimum theoretical predictions. This was due to a smaller surface area of the system and materials used.

Keywords: Shell and Tube, Counter flow, Heat exchanger, Heat transfer

INTRODUCTION
Heat exchangers are widely used in various industries, such as power generation, chemical processing, refrigeration, and HVAC systems, to transfer thermal energy between two or more fluids. There are different types of heat exchanger such as Shell and Tube, Adiabatic Wheel, Plate Fins, Plate and Shell, Spiral Heat Exchangers, etc. Among these basic types of heat exchangers, the shell and tube heat exchanger is the most common and versatile due to its robust construction, high thermal efficiency, and ease of maintenance (Chukwudi and Ogunedo, 2018).
The different forms of heat exchangers may be classified based on the configuration of the direction or path of fluid flow and by their various applications. The majority of the heat exchangers that are grouped based on the configuration of direction of fluid flow are further sub-classified into four (4) major categories: Parallel (concurrent) Flow, Counter (counter-current) Flow, Cross-Flow, and Multi-Pass Cross-(hybrid) Flow (Sachchidanand *et al.,* 2016). The Counter Flow is currently the most efficient, because it can transfer the most heat from the medium due to the fact that the average temperature difference along any unit length is greater and also allows fluids travel roughly perpendicular to one another through the exchanger (Coulson and Richardson, 1999).
STHEs consist of a bundle of tubes enclosed in a shell. One fluid flows through the tubes, while the other fluid flows over the outside of the tubes within the shell. The two fluids are separated by the tube walls, allowing heat to be transferred from the hotter fluid to the colder fluid. The shell and tube design offers; high surface area-to-volume ratio for efficient heat transfer, ability to handle high pressures and temperatures, adaptability to a wide range of applications and operating conditions. Despite these benefits, the design and development of STHEs can be a complex process, involving the consideration of various thermal, hydraulic, and mechanical factors. Proper design is crucial to ensure the heat exchanger meets the required thermal performance while adhering to safety and cost constraints.
Unuerepka *et al*., 2022 designed and fabricated a shell and tube heat exchanger for laboratory experiments. Although they used TEMA and ASME standards in the mechanical design of the system, but the retention mechanism was design using PVC pipes which render the thermal performance of the system deficient. Similarly, Xuejun *et al.,*2020 also designed and evaluated a lab-scale shell and tube heat exchanger. The study investigated the effects of tube shape, flow direction and water flow rates on water and trailer temperature changes. The study was able to achieve a conversion efficiency of 42.3%. However, the study was not tailored toward academic purposes.
While there have been extensive research works on Shell and Tube Heat Exchangers (STHEs), many educational research institutions face challenges in accessing well-designed and fabricated laboratory scale STHE for experimental purposes. Furthermore, existing designs often do not cater to specific educational needs, such as easy disassembly for observation and testing. This gap limits hands-on learning, making it difficult for students and researchers to visualize fluid mechanics and heat transfer processes. Thus, the development of a versatile, easy-to-fabricate STHE for academic purposes is necessary.

MATERIALS AND METHODS
Materials Used
The key materials used in the fabrication of the laboratory scale shell and tube heat exchanger include; Carbon Steel pipes, Galvanized steel, Carbon steel Fasteners (bolts, nuts, washers), Sealants and gaskets and insulation materials (Kakak *et al.,*2012).

Thermal Properties of the Fluid

The hot water entering the tubes was expected to be around 100°C and the required temperature after cooling be around 60°C while the cold water entering the shell was expected to be around 20°C and the required temperature after gaining heat be around 50°C, so the design had to be suitable for this temperature range. The heat exchanger is expected to effectively transfer heat from hotter side of the heat exchanger to the colder side.

Designed Methodology

Shell with internal diameter of 100mm and small internal diameter tubes with a diameter of 10mm were chosen arbitrarily as they can actively transfer heat from the fluid more effectively compared to larger diameter tubes. This also helps minimize fouling concerns, as the media being cooled does not contain significant precipitation. The tube length was set at 600mm to provide sufficient heat transfer area and residence time for the fluids.

Baffle Design

Segmental semi-circular baffles were chosen, as they are a common and recommended design for shell and tube heat exchangers (Unuereopka *et al.,* 2022). The baffles help create turbulence and direct the fluid flow across the tube bundle to optimize heat transfer.

Fluid Properties

The specific heat capacity of the water-cooling medium was taken as 4.174 kJ/kg·°C (Unuereopka *et al.,* 2022). The mass flow rates were set at 0.0194 kg/s for the hot water and 0.0263 kg/s for the cold water, based on the inlet and outlet temperatures provided.

Minimum Efficiency

A minimum efficiency of 75% was set as the design target for the heat exchanger laboratory scale, to ensure it meets performance requirements.

Design Analysis and Theories

The design of the laboratory scale shell and tube heat exchanger was based on established heat transfer theories and design methodologies, including:

Heat Transfer Coefficient Calculation

The overall heat transfer coefficient (U) for the heat exchanger was calculated from Kakac *et al.* (2012), Theodore *et al.* (2011) and Rajput, (2006) as shown in equation 2.

$$Q = U \times A \times LMTD \quad (1)$$

Where:

Q is the rate of heat transfer

A is the heat transfer area (based on the tube dimensions)

LMTD is the log mean temperature difference

Log Mean Temperature Difference (LMTD)

The LMTD method was used to calculate the driving temperature difference for heat transfer, taking into account the counter-flow arrangement of the fluids. The LMTD is given by Kakac *et al.,* (2012) and Rajput, (2006) in equation 2.

$$LMTD = [(Thi - Tco) - (Tho - Tci)] / ln[(Thi - Tco) / (Tho - Tci)] \quad (2)$$

Where:

Thi is the hot water inlet temperature

Tho is the hot water outlet temperature

Tci is the cold water inlet temperature

Tco is the cold water outlet temperature

Heat Transfer Rate Calculation

The rate of heat transfer (Q) was calculated from Theodore *et al.* (2011) and Kaita *et al*. (2024) as shown in equation 3:

$$Q = mCp(Thi - Tho) \quad (3)$$

Where:

i. m = mass flow rate (kg/s)
ii. Cp = specific heat capacity (J/kg·°C)
iii. Thi = inlet temperature of the hot fluid (°C)
iv. Tho = outlet temperature of the hot fluid (°C)

Table 1: Design Calculations

Initial Data	Calculations	Results
C_p = 4.174 KJ/kg°C m_h = 0.0194 kg/s m_c = 0.0263 kg/s T_{hi} = 100°C T_{ci} = 20°C Ƞ = 75%	Temperature of hot water leaving the heat exchanger $\eta = \frac{McCp(Thi - Tho)}{MhCp(Thi - Tci)}$ 0.75 = 0.0263 x 4.174 x (100-T_{ho}) / 0.0194 x 4.174 x (100-20)	T_{ho} = 56°C
C_p = 4.174 KJ/kg°C m_h = 0.0194 kg/s m_c = 0.0263 kg/s T_{hi} = 100°C T_{ci} = 20°C	Temperature of cold water leaving the heat exchanger; $Q_h = m_hC_p(T_{hi}-T_{ho})$ Q_h = heat transfer rate of the hot water Q_h = 0.0194 x 4.174(100-56) Rate of heat loss = Rate of heat gain $Q_c = m_cC_p(T_{co}-T_{ci})$ 3587.2 = 0.0263 x 4.174 x (T_{co}-20)	Q_h = 3587.2W T_{co} = 53°C
T_{hi} = 100°C T_{ho} = 56°C T_{ci} = 20°C T_{co}= 53°C	Logarithmic Mean Temperature Difference, LMTD(ΔT); $\Delta T = \frac{(Tin - Tout)}{\ln(\frac{Tin}{Tout})}$ = (T_{hi}-T_{ci})-(T_{ho}-T_{co}) / ln ((T_{hi}-T_{ci}) / (T_{ho}-T_{co}) = (80 – 3) / ln (80/3)	ΔT = 22.8°C

Initial Data	Calculations	Results
D_i = 10mm = 0.01m D_i = Diameter of inner tube L_t = 600mm = 0.6m L_t = Length of tube	Area of the inner tube, A_i ; $A_i = \pi D_i L_t$ A_i = 3.142 x 0.01 x 0.6	A_i = 0.0189m^2
Q_h = 3587.2W A_i = 0.0189m^2 ΔT = 22.8°C	Coefficient of heat transfer at the Inner tube, U_i ; $Q = UA\Delta T$ $U = Q / (A\Delta T)$ U_i = 3587.2 / (0.0189 x 22.8)	U_i = 8324.9 W/m^2°C
t = 2mm D_i = 10mm L_o = 600mm	Area of the outer tube, A_o ; $A_o = \pi D_o L_t$ $D_o = D_i + t$ = 10 + 2 = 12mm A_o = 3.142 x 0.012 x 0.6	A_o = 0.0226m^2
Q_h = 3587.2W A_o = 0.0226m^2 ΔT = 22.8°C	Coefficient of heat transfer at the outer tube, U_o ; $Q = UA\Delta T$ $U = Q / (A\Delta T)$ U_i = 3587.2 / (0.0226 x 22.8)	U_o = 6961.7 W/m^2°C
U_i = 8324.9 W/m^2°C U_o =6961.7 W/m^2°C	Total coefficient of heat transfer in the heat exchanger, U (W/m^2°C) ; $U = U_i + U_o$ U = 8324.9 + 6961.7	U = 15286.6 W/m^2°C
L_t = 600mm	Spacing of Baffle (B_s); $B_s = L_t / 5$ Baffle spacing should be minimum of one fifth of the length of the tube B_s = 600 / 5	B_s =120mm
D_o = 12mm	Shell Diameter: Tp = Tube pitch (mm) Tp = 1.25 x D_o Tp = 1.25 x 12 = 15mm D_{si} = (Tp x n) + Clearance for the baffles D_{si} = shell inner diameter n = number of tubes = 8 (adopted) Clearance for baffles = 10mm (assumed) D_{si} = (15 x 8) + 10 = 130mm Assuming thickness of about 2mm; 130 + 2 = 132mm	D_{si} = 130mm D_{si} = 100mm (adopted)

Fabrication Process

The construction and assembly process of the model shell and tube heat exchanger was carried out focusing precision and adherence to the calculated design specifications. The model scale has a shell length of 600mm and a diameter of 100mm, with tubes measuring 600mm in length and 10mm in diameter. The fabrication processes are as follows:

i. Tools such as meter rule, compass, scriber and punch were used to accurately mark out dimensions on the selected materials and it was ensured that all markings were clearly done to facilitate accurate cutting and shaping.
ii. The marked materials were cut out to shape using saws and shears. The parts taken through the cutting process includes the shell, tubes, tube sheets, and baffles.
iii. Holes were drilled in tube sheets and flanges as required for proper assembly and fluid connections.
iv. Electric welding was employed to join the cut pieces together securely to ensure structural integrity and preventing leaks.
v. The various components including the shell, tubes, and baffles, were carefully positioned to ensure correct alignment before gas welding. Oxy-acetylene gas welding was then selected due to its versatility and control over heat input and tack welds were first applied at several points along the joints. The tube sheets were then welded to the ends of the shell. The end caps which cover the shell at both ends were then welded to ensure a leak proof seal. The flanges were also welded at the necessary junctions to facilitate future disassembly and ease maintenance of the heat exchanger.

Plate I: Front View of the Assembled Components

Testing Procedure

i. The fabricated heat exchanger was correctly installed with proper supports and connections. Inlet and outlet valves for the hot and cold fluids were connected to the hot and cold fluid supplies.
ii. The flow was initiated by turning on the pumps to start the hot and cold-water streams while the flow rates were adjusted to achieve the desired flow rates for both the hot and cold fluids.
iii. The system was allowed to run for about 10 minutes to reach a stable operational temperature and flow condition.
iv. Inlet and outlet temperatures for both the hot and cold fluid streams were recorded as Th_{in}, Th_{out}, TC_{in}, TC_{out} .
v. All the stream temperatures and flow rates were monitored to ensure they remain close to the desired settings and all the collected data were recorded
vi. Pumps were switched off after completing the experiment.

RESULTS AND DISCUSSION

The Test was Carried out to get a Satisfying and Accurate Measurement and the Results are as Follows:

Table 2: Test Result

Parameter	Hot Fluid	Cold Fluid
Inlet Temp (°C)	100	28
Outlet Temp (°C)	70	34
Mass Flow Rate (kg/s)	0.013	0.015
Specific Heat Capacity (kJ/kg°C)	4.18	4.18

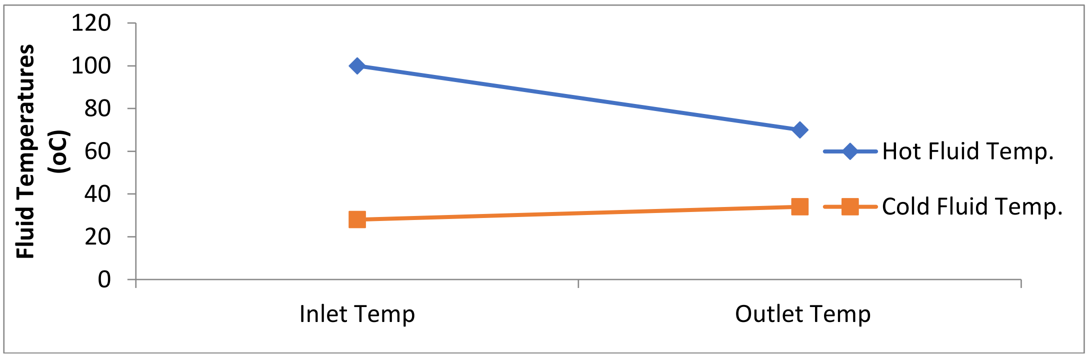

Figure 1: Plot of Inlet and Outlet Temp. For Hot & Cold Fluids

Figure 1 shows the inlet and outlet temperatures for both hot and cold fluids. From the graph, the two outlets temperatures from the hotter and the colder sides indicated the heat lost from the hotter side (30 ^{o}C) is much higher than the heat gain at the colder side (6 ^{o}C) . This was due to improper insulation of the heat exchanger leading to heat losses, less thermal conductivity of the materials used or slight inaccuracies in temperature measurement.

Table 3: Calculated Heat Transfer Parameters

Parameter	Hot Fluid (Tube Side)	Cold Fluid (Shell Side)
Heat Transfer Rate, Q(W)	1630	376.2
Log Mean Temperature Difference (°C)	53.1	53.1
Overall Heat Transfer Coefficient U (W/m² °C)	1615.6	372.9

The computed heat transfer rates for both hot and cold fluid as depicted from Table 3 show that the hot fluid was significantly much higher than the cold fluid and the the system has an approximate thermal efficiency of 35.97%, meaning that only 35.97% of the available heat was transferred to the cold water, which is quite low compared to 70-90% under good condition. The obtained thermal efficiency was also lower than that obtained by Xuejun *et al.,* 2020 (42.3%). The lower thermal efficiency was attributed to a significant heat loss to the surrounding and thermal conductivity of the materials used. The thermal conductivity of the material used in this study (galvanized carbon steel, 42 W/m^2 ^{o}C) is much lower than that of the material used by Xuejun *et al.,* 2020 (copper, 401 W/m^2 ^{o}C). However, it can be observed that the heat exchanger worked moderately by exchanging heat between the two fluids at a considerable and moderate heat transfer rate which satisfies the aim of the study.

CONCLUSION

The design, fabrication and testing of a laboratory scale shell and tube counter flow heat exchanger was successfully carried out based on thermal and mechanical considerations. The length and the internal diameter of the designed heat exchanger shell were 600mm and 100mm respectively with 8 numbers of tubes of 10mm internal diameter each. Fabrication process was carried out from the calculated designed values. The system achieved the heat transfer rate, Q (1630, 376.2) W, logarithmic mean temperature difference, LMTD (53.1 for both) ^{o}C and the overall heat transfer coefficient, U (1615.6, 372.9) W/m^2 ^{o}C for the hot and cold sides of the shell and tube heat exchanger respectively. While 35.97 was achieved as the overall thermal efficiency of the heat exchanger.

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