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Experimental Evaluation of Performance and Temperature Profile of Shell and Tube Heat Exchangers for Parallel Flow Arrangement

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Abstract:
The thermal evaluation of a Shell and Tube Heat Exchanger (STHE) is essential for maximizing heat transfer efficiency and promoting energy conservation in diverse industrial applications. This paper provides a performance assessment and temperature distributions of Shell and Tube Heat Exchanger (STHE) with parallel flow arrangement and strategies to improve heat transfer efficiency. This paper experimentally examined the performance and Temperature distribution of a shell and tube heat exchanger: heat transfer rates, heat exchanger efficiency, and temperature profiles, are assessed using experimental datasets. The findings revealed that the shell and tube heat exchanger have an efficiency of approximately 94.2%. The inlet temperature of hot temperature is reduced by 31.1°C while the inlet temperature of cold increases by 14,1°C as time increases. The outlet temperature of hot temperature is reduced by 25.2°C while the outlet temperature of cold increases by 21.5°C as time increases. Additionally, the temperature difference decreases which enhances the efficacy of the system and the potential for thermal equilibrium by incorporating an increased heat recovery. The results emphasize the need for appropriate thermal design and maintenance to enhance the efficiency of heat exchangers, conserve energy, and extend the lifespan of equipment in industrial operations.

Keywords: Shell and Tube Heat Exchanger, heat transfer, thermal assessment, efficiency, parallel flow configuration

I INTRODUCTION:

An arrangement in which heat is transferred from one fluid to another is known as a heat exchanger. Heat exchangers are applicable for both heating and chilling applications. To prevent the mingling of fluids, they are separated by solid walls. In certain instances, the fluids may remain in direct contact with one another [1]. Heat exchangers are among the most commonly utilized pieces of equipment in the process industry. Heat exchangers transmit heat between two process streams. A heat exchanger is necessary for any process that involves cooling, heating, condensation, boiling, or evaporation. Process fluids are typically heated or cooled before the process or go through a phase transition. The names of heat exchangers vary depending on their purpose. For example, heat exchangers used to condense are referred to as condensers, whereas heat exchangers used to boil are known as boilers. Heat exchanger performance and efficiency are determined by the amount of heat transferred while employing the least amount of heat transfer area and pressure drop. Calculating the entire heat transfer coefficient provides a more accurate representation of its efficiency. The pressure drop and area required for a given amount of heat transfer provide information on a heat exchanger's capital cost and power requirements [2]

Dumitrescu et al.[3] conducted a Computational Fluid Dynamics) analysis on a gas-liquid heat exchanger that is affixed to a gasification component. Solidworks software is implemented to investigate flow simulation issues with the heat exchanger. To investigate the current research, this software has constructed flow and temperature patterns. The liquid medium receives heat from the flue gases produced by the gasification system. This is subsequently transferred to a secondary heat exchanger, which is employed to heat the water from boilers. The shell and tube-type heat exchanger was analyzed by Aswin et al. [4] using ANSYS. The cylinders are positioned within the shell. Tubes conduct hot water, while the shell conducts frigid water. The fluids' velocity, thermal transfer, and flow are being investigated to analyze the system's streamline. This analysis has taken into account two distinct cases. The heat exchanger with bafflers is one case, while the heat exchanger without bafflers is the other. Undoubtedly, the utilization of baffles in conjunction with heat exchangers results in a more substantial heat transfer.

To enhance the extraction process of olive oil, Perone et al.[5] conducted a CFD analysis on a tubular-type heat exchanger intended for the conditioning of olive purée. The purpose of this analysis is to enhance comprehension of the influence of olive paste's inlet conditions on its thermal and hydrodynamic properties. Solidworks-2016 is employed to conduct the CFD analysis. The present analysis employs the tube-in-tube model of heat exchangers, where the inner tube contains olive paste and the jacket contains hot water. Pressure reduction and heat transfer were determined by adjusting the temperature of the inlet and the mass flow rate.

Elangovan et al.[6] conducted a computational fluid dynamics (CFD) analysis of a monolithic type heat exchanger to enhance heat transfer by modifying the material and geometry of the air passage. Oval, hexagonal, and circular are the three primary configurations of air passages. The ceramic materials employed are $CrCO_3$, Al_2O_3, and SiC. ANSYS After modeling the heat exchanger in CATIA, Fluent is employed for analysis purposes. Sharma et al.[7] conducted a comparison of the heat transfer efficacy of two STHXs (Shell & tube heat exchangers) with varying tube arrangements. The staggered grid and inline arrangement were used to arrange the 21 and 24-cylinders. Thermal stratification is perceived to be reduced in a staggered arrangement. The mass flow rate of the shell-side liquid is adjusted from 0.5 kg/s to 0.1 kg/s, while the tube-side liquid's mass flow rate remains constant at 0.25 kg/s. Heat transfer efficiency, effectiveness, and pressure decrease have been examined. The minimum pressure decrease is caused by a mass flow rate of 0.1 kg/s. The study of shell and tube heat exchangers by Cahya and Permatasari [8] involved the comparison of analytical calculations with simulation results using Heat Transfer Research Inc. They concluded by plotting the numerous graphs of the heat transfer coefficient on cold fluid flow, taking into account the number of tubes and the diameter of the shell.

Amirtharaj et al. [9] have investigated the shell and tube heat exchanger with inclined baffles to obtain a lower pressure drop and higher heat transfer efficiency. They conducted a comparison between segmental baffles and inclined baffles using CFD analysis. In comparison to inclined baffles, they determined that segmental baffles facilitate increased heat exchange and decreased pressure drop. Oguz et al. [10] investigated the thermal design of shell and tube heat exchangers using an intelligent tailored harmony algorithm. The design variables were examined about the baffle spacing, shell diameter, and tube diameters. They determined that the intelligent tuned harmony algorithm can be employed to enhance the performance of shell and tube heat exchangers. Simin and Yanzhong [11] have investigated the improvement of heat transmission by installing sealers on the shell side. The opening between the baffle plate and shell was sealed using sealants. They determined that the heat transfer performance has been enhanced and can be employed to enhance the efficiency of heat exchangers. Sangotayo et al[12] presented the design, construction, and testing of an extended surface heat transfer teaching equipment. Experimental studies were conducted on three materials (brass, mild steel, and aluminum) to determine their temperature distribution along the extended surface. Results showed that aluminum has the highest temperature value, followed by brass and mild steel. The equipment's temperature gradient is significant, highlighting its potential as a teaching aid. Therefore, this investigation endeavors to investigate the performance assessment and temperature distributions of Shell and Tube Heat Exchanger (STHE) with parallel flow arrangement.

II METHODOLOGY

Parallel flow has been employed to examine the temperature distribution and efficiency of a shell and tube heat exchanger. The heat exchanger is believed to be adequately insulated, and the fluid on the shell side is considered to possess constant thermal characteristics. Heat dissipation to the surroundings is completely overlooked.

Shell and Tube Heat Exchanger

The fundamental components of a shell-and-tube heat exchanger include the tube box, baffles or fins, end headers, and shell. The baffles support the tubes and direct fluid flow through them, while simultaneously maximizing turbulence within the shell's confined fluid. Various types of baffles may be employed in shell and tube heat exchangers. The type, spacing, and shape of baffles are contingent upon the force required on the shell side. A multitude of versions of these exchangers exists, contingent upon the flow type., as shown in Fig .1

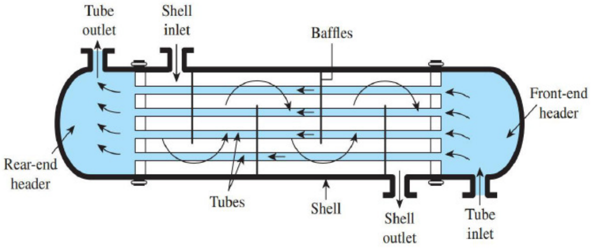

Fig 1: Shell and Tube Heat Exchanger [2]

Parallel Flow: In this scenario, the heated and cooled fluids move in the same direction, as the term suggests. The temperature difference between the hot and cold fluids gradually decreases from one end to the other, as shown in Fig .2.

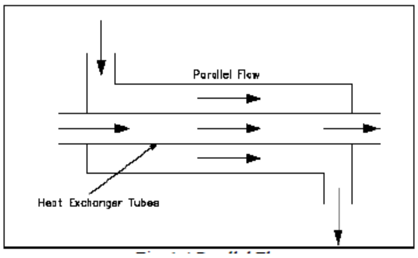

Fig 2: Parallel Flow

Counter Flow: In this arrangement, the heated fluid enters from one end of the exchanger, while the cold fluid enters from the opposite end. This results in a practically constant temperature differential between the heated and cooled fluids. This is a significant factor that makes counter-flow heat exchangers more beneficial than parallel-flow heat exchangers, as shown in Fig .3.

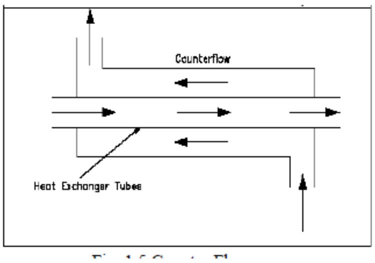

Fig 3: Counter Flow

Design calculations

For the design of shell and tube heat exchangers, the Kern method [13,14] is employed which is most used in heat exchanger design. It offers a simple method for measuring the heat transfer coefficient.

Log mean temperature difference (ΔTm) is calculated as

$$T_m = \frac{(\Delta T_1 - \Delta T_2)}{ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} \qquad (1)$$

where $\Delta T_1 = T_1 – t_2$ and $\Delta T_2 = T_2 – t_1$ (T_1, T_2 = Inlet and outlet tube-side fluid temperature respectively

(°C) and t_1, t_2 = Inlet and outlet shell-side fluid temperature respectively (°C)).

$$Q = U_o \times A \times \Delta T_m \tag{2}$$

Heat transfer rate (Q), where Q = Heat transfer rate (kJ/h), A = Heat transfer area (m^2), ΔT_m = Log mean temperature difference (°C), U_o = Overall heat transfer coefficient ($W/(m^2 K)$.

Experimental Setup:

Experimental procedure for investigating the performance of a shell and tube heat exchanger:

Apparatus:

1. Shell and tube heat exchanger

2. The pump is used for circulating hot/cold fluid)

3. Steam generator is used for the heat source

4. Cooling system: water and fan is used for cooling

5. Temperature measurement instruments K–type thermocouples

8. Data acquisition system – 12 channel temperature recorder data logger is used

Experimental Setup:

The heat exchanger is connected to the pump, heat source, and cooling system, as shown in the image. The required insulation is maintained throughout the system. A 12-channel temperature recorder data logger was installed to monitor the temperature of both hot and cold fluid inlets and outputs. Figures 4 and 5 show the front and back views of the shell and tube exchangers.

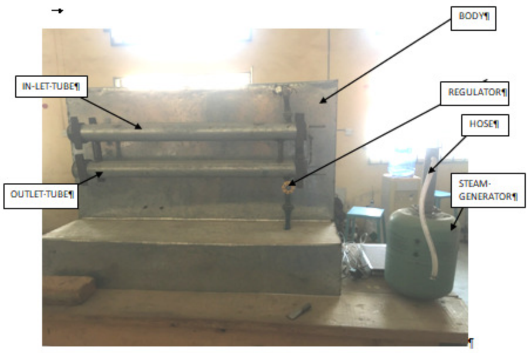

Fig 4: Front View of shell and tube exchanger

Fig 5: Back View of shell and tube exchanger

Experimental Procedure:

Initial Measurements

Ambient temperature was recorded, and the initial temperatures of the hot and cold fluids were measured.

Heat Transfer Measurements

The pump and heat source were activated, progressively increasing the heat input to attain the necessary temperature differentials. The temperature differentials between hot and cold fluids (ΔT) were quantified. The temperature distributions along the length of the heat exchanger were documented.

Performance Evaluation

Heat transfer rates (Q) were computed utilizing Eqns (3 and 4)

$$Q = m*Cp*\Delta T \text{ (for hot fluid)} \qquad (3)$$

$$Q = m*Cp*\Delta T \text{ (for cold fluid)} \qquad (4)$$

The overall heat transfer coefficient (U) was determined using:

$$U = Q / (A * \Delta T) \qquad (5)$$

Effectiveness of shell and tube heat exchanger
The heat exchanger effectiveness is defined as the ratio of actual heat transfer to the maximum possible heat transfer. Evaluate heat exchanger performance using the Effectiveness (ε) equation (6)

$$\varepsilon = Q_{actual} / Q_{max} \qquad (6)$$
$$Q_{actual} = U \times A \times LMTD \qquad (7)$$

III RESULTS AND DISCUSSION

Experimental Results of Shell and Tube Heat Exchanger for Parallel Flow Arrangement

An experiment was undertaken to assess the thermal performance of a shell and tube heat exchanger. The goal was to take temperatures at various places within the heat exchanger at regular intervals of 2 minutes. The experiments were conducted for 15 minutes to determine the effectiveness of the system and 60 minutes for examining the temperature distribution. The following findings were collected during the experiments.

The temperature distribution of the heat exchanger throughout 15 minutes. The experiment entailed measuring temperatures at four different points within the heat exchanger. T_1 denotes the hot fluid's inlet temperature, T_2 the hot fluid's outlet temperature, T_3 the cold fluid's inlet temperature, and T_4 the cold fluid's outlet temperature.

Temperatures were recorded at the start of the experiment, at 2 minutes: $T_1 = 91.3°C$, $T_2 = 60.2°C$, $T_3 = 31.1°C$, and $T_4 = 38.76°C$. As the experiment went on, the temperatures varied slightly, showing heat transfer between the hot and cold fluids in the exchanger. It is important to highlight that these experimental results are specific to the settings and equipment used in this particular experiment. Variations in experimental parameters or heat exchanger designs may result in distinct temperature profiles. Nonetheless, the collected data provide a platform for additional investigation and evaluation of the heat exchanger's performance. The data acquired during this experiment are used to estimate heat transfer efficiency and analyze the heat exchanger's temperature profile under operational settings.

Calculation of the Head Load:

The selected temperature design parameters are as follows: 91.3^{o}C for steam T_1 (hot fluid), 60.2^{o}C for water T_3, 31.1^{o}C for steam T_2, and 38.76^{o}C for water T_4.

The log mean temperature difference (LMDT) is

$$LMDT = \frac{\Delta T1 - \Delta T2}{Ln \frac{\Delta T_1}{\Delta T_2}}$$

Where; $Th_1 = 91.3 + 273 = 364.3K$,

$Th_2 = 60.2 + 273 = 333.2K$,

$Tc_1 = 31.1 + 273 = 304.1K$,

$Tc_2 = 38.76 + 273 = 311.76K$.

$$LMDT = \frac{(Th1 - Tc2) - (Th2 - Tc1)}{Ln \frac{(Th_1 - Tc_2)}{(Th_2 - Tc_1)}} \qquad (8)$$

$$LMDT = \frac{(364.3 - 311.76) - (333.2 - 304.1)}{Ln \frac{(364.3 - 311.76)}{(333.2 - 304.1)}}$$

$$= \frac{23.44}{0.59} = 39.7K$$

Using equation (8), calculate the log mean temperature difference whether the fluid flows concurrently or in parallel.

$$LMDT = \frac{(Th1 - Tc1) - (Th2 - Tc2)}{Ln \frac{(Th_1 - Tc_1)}{(Th_2 - Tc_2)}} \qquad (9)$$

$$\text{LMDT} = \frac{(364.3-304.1)-(333.2-311.76)}{Ln\frac{(364.3-304.1)}{(333.2-311.76)}}$$

$$\text{LMDT} = \frac{38.76}{1.034} = 37.54\text{K}$$

The heat or energy balance

$$Q = M_c C_{P\,c} \qquad (10)$$

Heat lost by hot fluid equals heat acquired by cold fluid, calculated using the hot fluid's temperature difference.

$$Q = M_h C_p(Th_1-Th_2) \qquad (11)$$

Where M_h is the Mass flow rate of hot fluid, C_p is the Specific heat capacity of hot fluid

M_h= 4.666 x 10^{-4}kgS^{-1} C_p= 4187J/kg K, h

= 364.3K – 333.2K = 31.1K

Q = (4.666 × 10^{-4}kgS^{-1}) × (4187J/kgK) × (31.1K)

= 60.758 JS^{-1}

:. The heat load = 60.758 JS^{-1}

Radius of inner tube = 1.55 cm = 1.55 10^{-2} m

Radius of outer tube = 8.6 cm = 8.6 × 10^{-2} m

Length of tube = 70 cm = 70 × 10^{-2} m

Area $A = \pi Dl \qquad (12)$

$$R = \frac{D}{2} \qquad (13)$$

R = 1.55 × 10^2 m

L = 70 cm = 70 × 10^{-2} m

Radius of outer tube = 8.6 cm = 8.6 × 10m

R = $\frac{D}{2}$. D = 8.6 × 10^2× 2 = 0.172m

A = πDl, A = 3.142 × 0.031 × 0.7,

A = 0.07 m^2

The overall heat coefficient (U)

$$U = \frac{Q}{ALMDT} \qquad (14)$$

$$U = \frac{60.758}{0.07 \times 12.5},\ U = 65.437\text{W/m}^2\ \text{k}$$

Effectiveness of the Shell and Tube Heat Exchanger

The effectiveness (ε) of the shell and tube heat exchanger is calculated using the equation (15).

$$\varepsilon = Q_{actual} / Q_{max} \qquad (15)$$

Given that, Q_{max} = 60.758JS^{-1},

Q_{actual} is determined using eqn (7).

$$Q\_{actual} = U \times A \times LMTD$$

Substituting the given values:

Q_{actual} = 65.437 × 0.07 × 12.5 = 57.257 JS^{-1}

The effectiveness is obtained using eqn (7),

$$\varepsilon = Q_{actual} / Q_{max}$$

ε = 57.257 / 60.758 = 0.942 = 0.942 × 100%

= 94.2%

The shell and tube heat exchanger has an efficiency of approximately 0.942, or 94.2%. The efficiency of the shell and tube heat exchanger is 94.2%, which is considered outstanding. This indicates that the heat transfer area is effectively utilized and that there is high heat recovery with minimal energy losses.

The Temperature Distribution of the Heat Exchanger with Varying Time

The graphical representation of the experimental results for the temperature distribution of the shell and tube heat exchanger is shown in Figure 6 - 9. This graph visually represents the temperature values recorded at each time interval. The x-axis represents time in minutes, while the y-axis represents temperature in degrees Celsius. Each line represents the temperature value at a specific point within the heat exchanger. The points on the lines indicate the recorded temperatures at each time interval.

Figure 6 displays the inlet temperature of cold, (Tci), and hot, (Thi) water against time, for 15 mins. It shows that the inlet temperature of hot temperature is reducing while the inlet temperature of cold, (Tci) increases as time increases, implying hot fluid loses heat and cold fluid is gaining heat, there is exchange of heat.

Figure 7 displays the outlet temperature of cold, (Tco), and hot, (Tho) water against time, for 15 mins. It shows that the outlet temperature of hot temperature is reducing while the outlet temperature of cold, (Tci) increases as time increases.

The temperature distribution of the heat exchanger throughout one hour is seen in Figures 8 through 11. Figure 8 illustrates the inlet and outlet temperatures of hot fluids, demonstrating that both temperatures decrease over time, indicating a heat transfer to the cool fluid. Figure 9 illustrates the intake and output temperatures of the cold fluid for 1 hour. The temperature distribution of the inlet and output fluids rises with rising temperature, indicating that the cold fluid absorbs heat from the hot fluid.

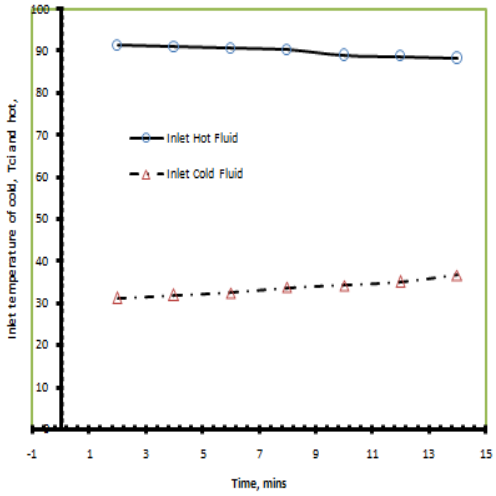

Fig 6: The plot of Inlet temperature of cold, (Tci) and hot, (Thi) water against time, for 15 mins

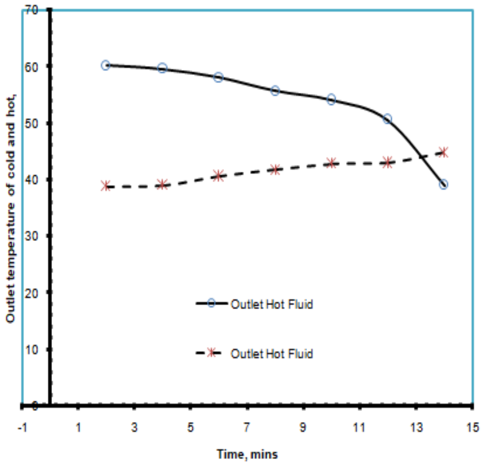

Figure 7 The plot of Outlet temperature of cold, (Tco) and hot, (Tho) water against time, for 15 mins

Figure 10 displays the inlet temperature of cold, (Tci), and hot, (Thi) water against time, for 45 mins. It shows that the inlet temperature of hot temperature is reducing while the inlet temperature of cold, (Tci) increases as time increases, It implies that as time increases: hot fluid temperature decreases due to heat transfer, and Cold fluid temperature increases due to absorbed heat and temperature difference (Thi - Tci) decreases.

Figure 11 displays the outlet temperature of cold, (Tco), and hot, (Tho) water against time, for 45 mins. It shows that the outlet temperature of hot temperature (Tho) is reducing while the outlet temperature of cold, (Tco) increases as time increases, The hot fluid temperature decreases as time progresses due to heat transfer, while the cool fluid temperature increases as a result of absorbed heat. Additionally, the temperature difference (Tho - Tco) decreases. Enhances the efficacy of the system and the potential for thermal equilibrium by incorporating an increased heat recovery.

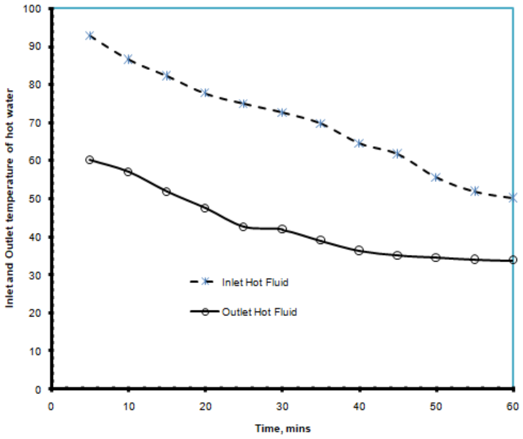

Figure 8 The plot of Inlet and Outlet temperature of hot water against time, for 60 mins

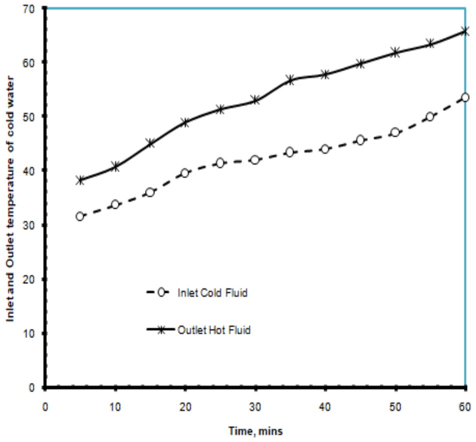

Figure 9: The plot of Inlet and Outlet temperature of cold water against time, for 60 mins

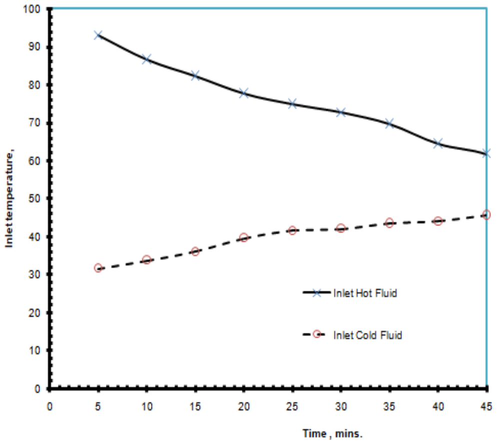

Figure 10 The plot of Inlet temperature Distribution of cold, (Tci) and hot, (Thi) water against time for 45 minutes

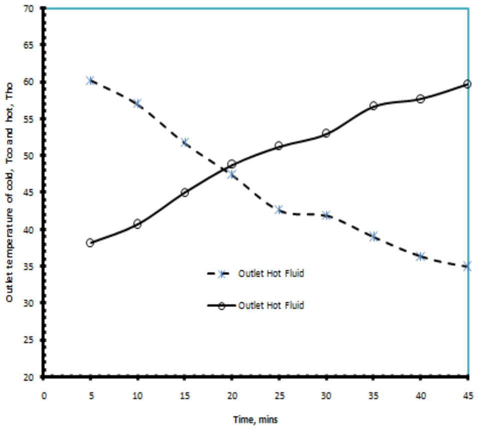

Figure 11 The plot of outlet temperature Distribution of cold, (Tco) and hot, (Tho) water against time, for 45 minutes

The temperature profile for 45 minutes is depicted in Figure 12. The initial temperature of Cold Fluid is 31.5°C, and it increases by 14.1°C (31.5-45.6°C) with a temperature gradient of 0.35°C/min. The initial temperature of hot water is 92.8°C, and it decreases by 31.1°C (92.8 - 61.7°C) with a temperature gradient of -0.78°C/min. It has been noted that the temperature of cold fluids increases steadily over time, while the temperature of heated fluids decreases steadily over time. Additionally, the temperature difference between cold and hot fluids decreases over time. Also, the temperature trend for parallel movements is illustrated in Figures 6, 10, and 12. Parallel flow necessitates the transfer of heat through radiation, as the inlet temperature of heated water is 92.8°C, and the inlet cold water temperature is 31.5°C. Certainly, the quantity of heat transfer decreases as a logarithmic function as it passes through the heat exchanger. As a result, the arrangement of heat flow is crucial in the transmission of heat through radiation in compact heat. This argument is substantiated by Asadi and Khoshkhoo[15].

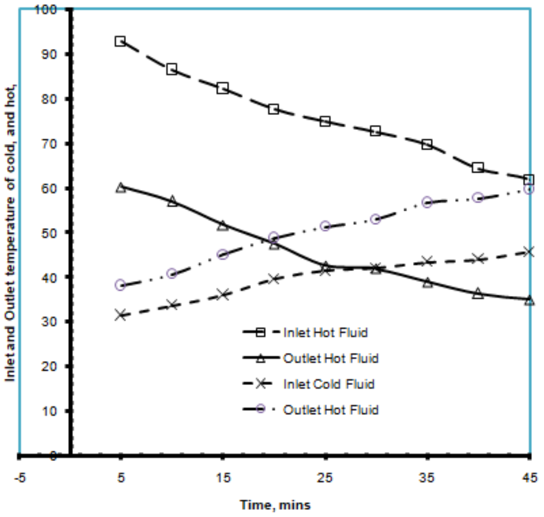

Figure 12: The plot of temperature distribution against the time of the heat exchanger for both cold and hot fluid for 45 minutes

IV CONCLUSIONS

The thermal evaluation of Shell and Tube Heat Exchangers (STHEs) is crucial for optimizing performance, improving energy efficiency, and ensuring long-term dependability in industrial applications. This study experimentally analyzed the performance and temperature distribution of a shell and tube heat exchanger, evaluating heat transfer rates, heat exchanger efficiency, and temperature profiles using experimental datasets. The intake temperature of the hot fluid decreases while the inlet temperature of the cold fluid increases over time. The exit temperature of the hot stream decreases while the outlet temperature of the cold stream increases over time. Furthermore, the reduction in temperature differential improves system efficiency and the likelihood of thermal equilibrium through enhanced heat recovery. The evaluation of the design and tube arrangement's impact on heat exchanger efficiency underscored the requirement for suitable design and maintenance techniques. The optimal performance of STHEs across several industrial sectors depends on the ongoing refinement of design and thermal evaluation, leading to improved process outputs, sustainability, and energy efficiency.

Notations

l:	Length of model (mm)
ΔT_m:	Log-mean temperature difference (°C)
c_p:	Specific heat of fluid (J/kg °C)
A:	Heat transfer area (m^2)
T_1:	Inlet tube side fluid temperature (°C)
T_2:	Outlet tube side fluid temperature (°C)
t_1:	Inlet shell side fluid temperature (°C)
t_2:	Outlet shell side fluid temperature (°C)
U:	Overall heat transfer coefficient (W/m^2 °C)
Q:	Heat transfer rate (kW)
D:	Diameter of shell (mm)
d:	Diameter of tubes (mm)

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