Performance Enhancement of a Shell and Tube Heat Exchanger by Introducing Novel Baffle Design

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A thesis submitted to the National University of Sciences and Technology, Islamabad,

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Mechanical Engineering

Supervisor: Dr. Syed Maaz Hasan

School of Mechanical & Manufacturing Engineering

National University of Sciences & Technology (NUST)

Islamabad, Pakistan

(2024)

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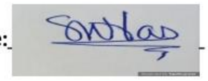
Signature: 

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Copyright Statement

Table of Contents

List of Tables

List of Figures

List of Symbols, Abbreviations and Acronyms

STHE	Shell and Tube Heat Exchanger
B	Baffle Spacing
D_0	Outer Diameter of Tube
D_s	Outer Diameter of Shell
L	Length of the heat exchanger (Shell Part)
N_b	Number of Baffles
N_t	Number of Tubes
T	Inlet Temperature of Fluid Provided to Shell
t	Thickness of Tube

ABSTRACT

This research involves the investigation of the performance of a Shell and Tube Heat Exchanger. The study is focused on examining the existing baffle designs. It also involves the design of changing the baffle to improve thermal performance. The existing model of the thermal performance of the baffle is studied and discussed. Limitations are highlighted and based on those; the changed baffle is proposed.

Meshing of the heat exchanger is performed to observe the theoretical results. After that experiments on the baffle are also performed. Experiments involve observing the results of the temperature variation as well as pressure drops. It was observed that the conventional baffle did not perform as per desire. Main issues were that the copper tubing was initially painted, thus reducing performance. The paint was removed and the results slightly improved. There is also the issue that the heat exchanger is parallel flow which is a lower performing type. We can change the configuration to a counter flow to improve the performance. For future works, it is suggested that the baffle design may be further improved with a pressurized heat exchanger test bench as well as counter flow heat exchanger.

Chapter-1: Introduction

1.1 Heat Exchanger

A heat exchanger is a specialized device designed for the efficient transfer of thermal energy between two different mediums [1]. It is commonly used in heat ventilation and air conditioning. Other applications include oil rigs, thermal plants, power plants, vehicles, and many more. They are usually made using metals which can be bent easily. Therefore, for low pressure applications, the sheets are usually thin.

1.2 Types of Heat Exchangers

There are a huge variety of heat exchanger designs available in the market [1, 2]. A few, which are deemed relevant are discussed as follows:

1.2.1 Shell and Tube Heat Exchanger (STHE)

This type of heat exchanger contains a shell for cold fluid and tubes through which hot fluid usually runs under pressure [3]. STHE is used for transferring heat from the hot to the cold fluid. Applications may vary, but this is the most common type of heat exchanger found throughout the world [4]. The model that we are using is also of this type and is presented in figure 1. The schematic of the heat exchanger is shown in figure 2.

Figure 1: Available Shell and Tube Heat Exchanger Apparatus

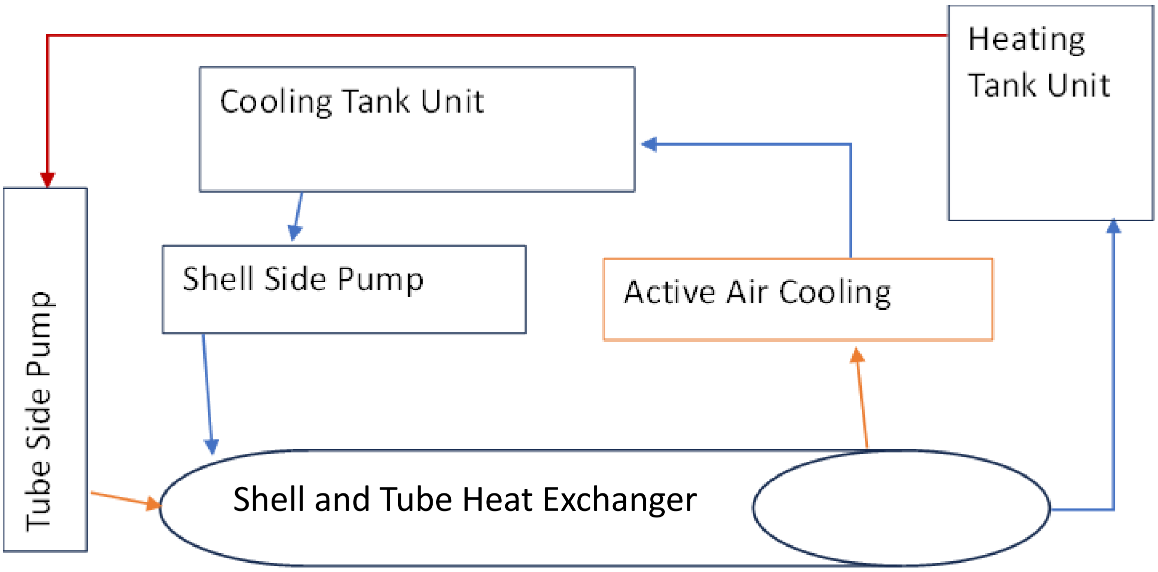

Figure 2: Schematic diagram of the available shell and tube heat exchanger.

1.2.2 Plate Heat Exchangers (PHEs):

Plate instead of tube is the primary separation between the hot and cold fluid [5]. As the plate is usually straight with no curves, these can be of robust and thick materials. These types of heat exchangers usually boast a very high heat transfer rate. The limitation of these is that they are usually are of very small size.

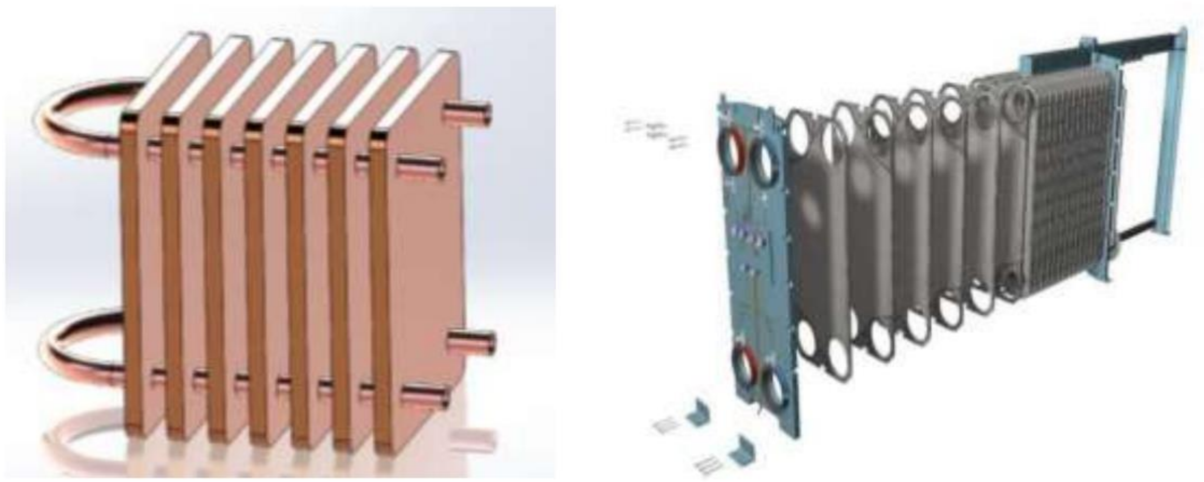

Figure 3: "Model of plate heat exchanger" [5].

As these have very high heat transfer, fluids which are poor in heat transfer often use these for improvement in heat transfer rate. These types are often applied in liquid to gas or gas to gas heat transfer.

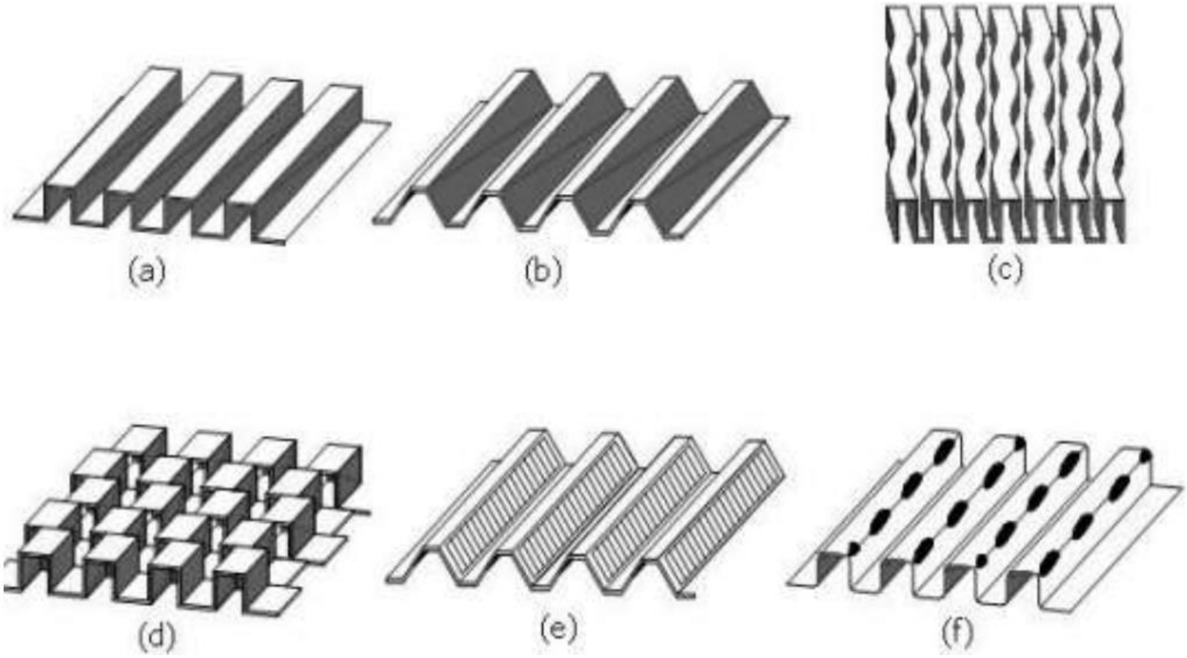

Figure 4: "Types of plate fin surfaces: (a) Plain rectangular (b) Plain trapezoidal (c) Wavy (d) Serrated or offset strip fin (e) Louvered (f) Perforated" [5]

1.2.3 Finned Tube Heat Exchanger:

These are extensions of STHEs. They have elongated fins to improve heat transfer rate. This increases the surface area thus improving the overall heat transfer [6]. Although more efficient, the design cost is relatively high therefore, this was the limitation. The components of STHE are discussed in the following section.

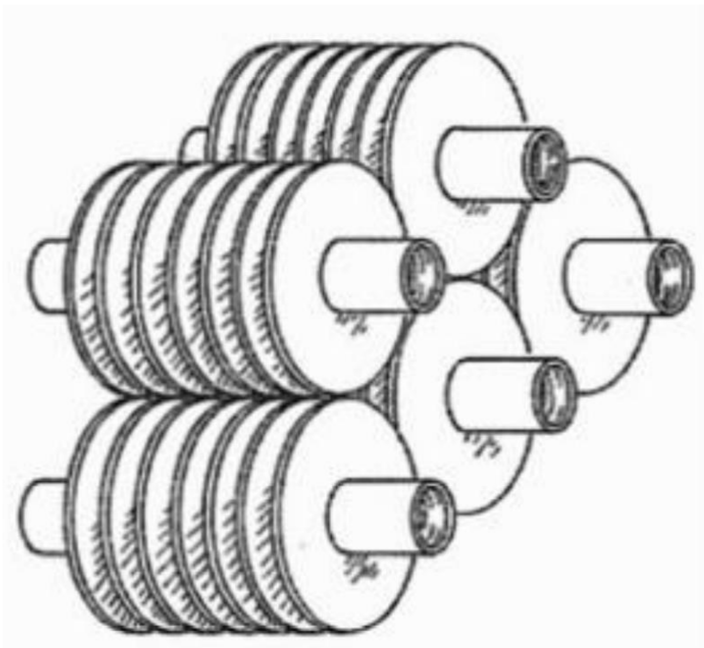

Figure 5: Finned tubes in a heat exchanger [6].

1.3 Components of a STHE

Following are the components of STHE: Shell, Tube Bundle, Tube Sheet, Tube Support Plates, Tube Nuts, Tube End Plugs, Baffles, and Headers. There are a number of methods to enhance the efficiency of SHTEs in literature [7]. The most important one is the use of different baffle designs [8]. Adding baffle plates to the heat exchanger boosts its overall heat transfer rate [9]. They introduce turbulence which helps improve heat transfer [10]. A grid pattern is the more common type of arrangement with different variations. A pressure drop is observed when fluid passes through it [11]. A key consideration that should be kept is that we should consider the effects of fouling [12]. A key issue is that this is found inside tubes.

Figure 6: Fouling inside tubes of heat exchangers. *

* larenbv.com/what-is-fouling-and-scaling-in-heat-exchanger/

The tubes play an important factor which reduces the overall performance if not designed properly [13]. Their design can mean the difference between good and a weak heat exchanger [14]. Improvement in surface area is a significant factor for heat exchanger through tubes [15]. Maximization in area is effective in improvement in heat transfer [16]. The improvement in materials for these tubes in a wide range of applications [17]. Different materials, each possessing unique attributes such as heat and corrosion resistance, thermal conductivity, and heat resistance, are selected based on specific task requirements [18]. Some of the issues that are currently plaguing the STHEs are as follows:

1.4 Problems with Current STHEs

There are some considerable suboptimal heat transfer efficiency issues owing to the considerable thermal resistance of the tube walls [19]. The smaller diameter of these tubes also causes larger than required pressure drops [20]. Another key issue is fouling which requires a regular overhaul or maintenance of the heat exchanger [21]. Maximization in the surface area is another issue that results in lower flow rates [22] along with high maintenance costs [23].

Figure 7: Disassembly for Heat Exchanger Maintenance. *

* https://idrojet.com/heat-exchanger-maintenance/

Based on these and a number of others, the problem statement is as follows:

1.5 Problem Statement

The objective of this research is to improve the current efficiency of the heat exchanger. The heat exchanger is of STHE type as this is the most used in the world and is relatively cheaper to fabricate. The outcome expected is an improved heat transfer rate with a reduction in pressure drop.

Chapter-2: Literature Review

This chapter is focused on discussing the current research on the heat exchanger. The main focus is the heat exchanger baffles used inside the STHE. Figure below shows the fin baffle profile. It should be noted that an increment in baffle spacing leads to a decrease of pressure drop [24]. Research [25] shows that profile 1 is more efficient than profile 2 and the base model because it features a high heat transfer rate along with minimal pressure drop.

Figure 8: Fin Profiles

The effectiveness of the heat exchanger rises as the intake hot water temperature and hot water flow rate rises [26]. For best performance, a circular segmental baffle cut of 25% of the inner shell diameter is recommended, and a parabolic baffle cut of 30% of the inner shell diameter [27]. Figure 9 shows some of the more conventional baffle designs.

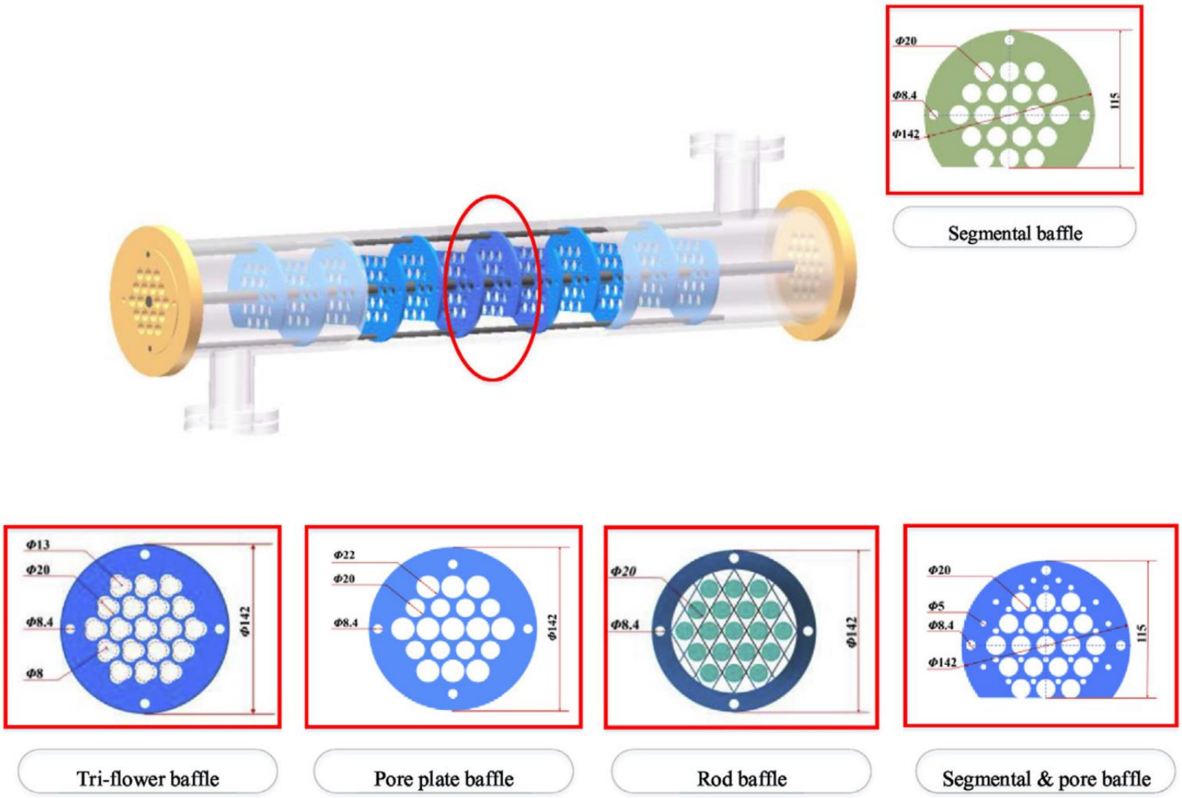

Figure 9: Geometric models of different types of baffles in a shell and tube heat exchanger [28]

CFD simulation results [29] show that copper tubes have a better heat transfer than brass tubes when transferring the heat from biogas to water. Triangular ribbed tubes have a better heat transfer coefficient (30% better) as tested with disk and combined segmented disk baffles and much closer, though lesser, than SB-STHE. Overall performance increase was seen by triangular and circular ribbed tubes in [30]. Returning to the baffle design, baffles play a significant role in determining the net effectiveness of a heat exchanger.
The baffle designs considered in this project are discussed below:

2.1 Three-Zonal Baffle Design:

The three-zonal baffle [31] is shaped like a steering wheel with 3 almost elliptical holes towards the edges, having a rotational symmetry of 120^0 as shown in figure 10. The middle part includes the holes for tubes to pass through.

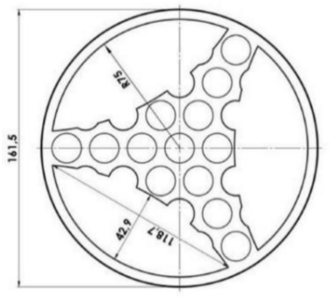

Figure 10: Three-Zonal Baffle [1]

2.2 Trefoil Baffle:

The trefoil baffle [32] has rather eccentric tube holes (figure 11). The tubes holes aren’t circular instead have reduced area of contact with the tubes. When the tubes go through the hole, there are three vacant areas around the tube to allow for the fluid to go through them.

Figure 11: Trefoil Baffle [2]

2.3 Comparison of Performance Parameters of the Three-Zonal and Trefoil Baffles:

The following graph (figure 12) shows the heat transfer and pressure drop for the three-zonal and trefoil baffles and its comparison with the conventional segmented baffle. The data is from [31] and [32].

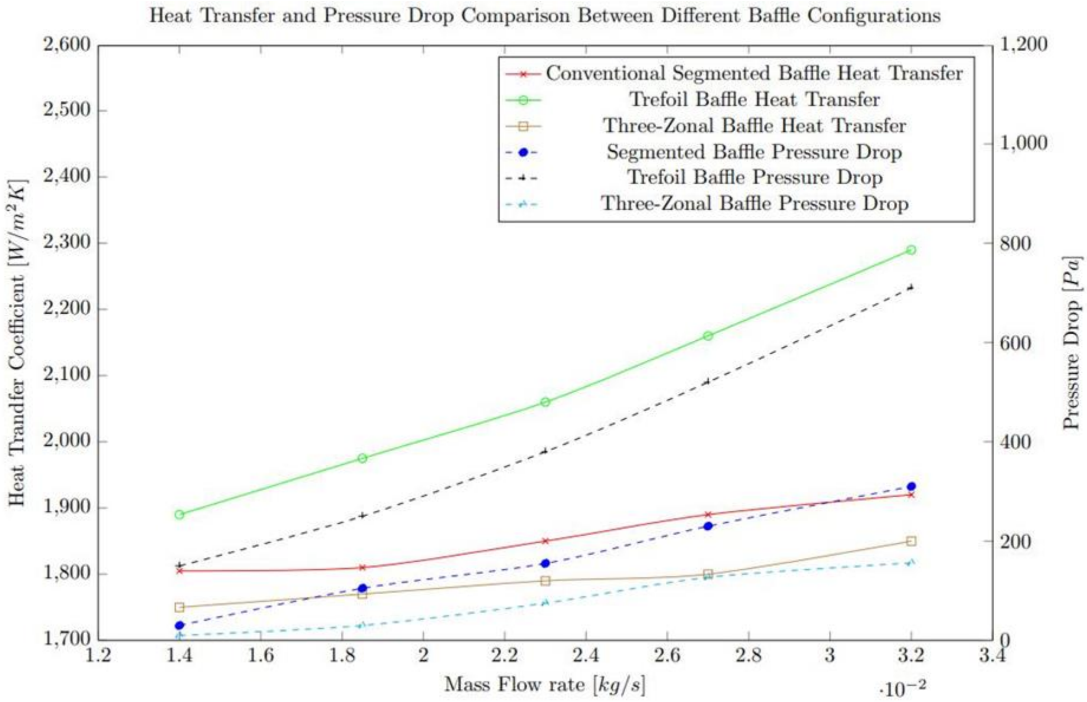

Figure 12: Comparison of Three-Zonal and Trefoil Baffles

From the graph, it can be seen that the trefoil baffle has considerably high heat transfer, but much higher pressure drops. The three-zonal baffle on the other hand has a much lower pressure drop but also much lower heat transfer.

Chapter-3: Design Methodology

3.1 The Baffle

The selected baffle design is a synthesis of two previously examined baffles from the literature review section: the three-zonal and trefoil baffles. The trefoil baffle exhibits a significantly higher heat transfer coefficient, primarily attributed to the distinctive holes in its design. This intentional design promotes increased fluid contact with the tubes, enhancing heat transfer efficiency.

On the contrary, the three-zonal baffle is chosen for its notably lower pressure drop. By amalgamating the favorable attributes of both baffles, it is possible to create a baffle that surpasses the conventional segmented baffle in terms of improved heat transfer and reduced pressure drop. This is achieved through the development of a novel three-zonal trefoil baffle. This innovative design retains the tube holes from the trefoil baffle, facilitating maximum fluid contact with the tubes. Additionally, it incorporates three large open spacings with a rotational symmetry of 120 degrees to ensure uninterrupted fluid flow, resulting in a lower pressure drop. The design model is depicted below (figure 13).

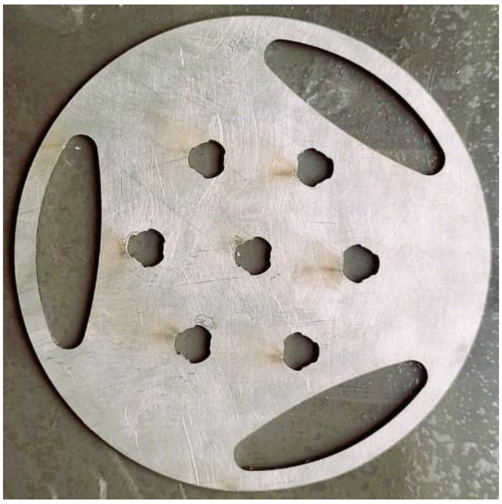

Figure 13: Three-Zonal Trefoil Baffle proposed design.

3.2 Dimensions of the New Baffle

The dimensions of the newly proposed baffle design were subject to certain limitations, as the diameter had to align with the inner diameter of the existing shell in the available Shell and Tube Heat Exchanger (STHE) setup. Likewise, the hole size was constrained to correspond to the predetermined tube diameters already in use. While the dimensions of the trefoil holes were adjustable, as were the sizes of the three outer large holes. The ultimate baffle design, along with its specific dimensions, is presented below:

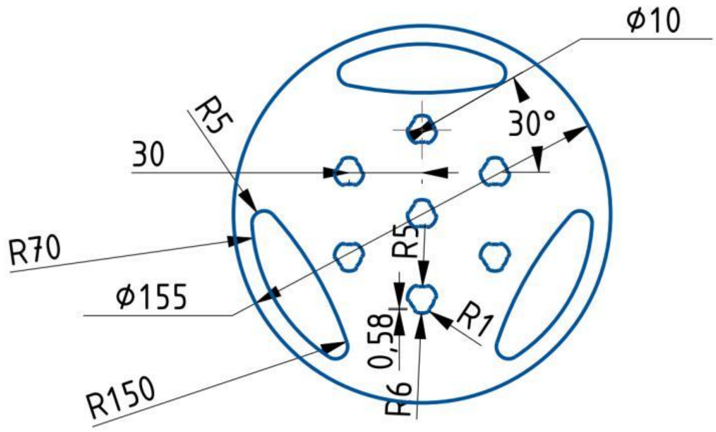

Figure 14: *Three-Zonal Trefoil Baffle Dimensions*

3.3 Cross section of tubes

Copper tubes with a circular cross-section were selected due to their ready availability. Although tubes with fins or alternative cross-sections offer enhanced efficiency by providing increased surface area, their manufacturing complexity and unavailability in the market led to the preference for copper tubes with a circular cross-section.

3.4 Number of tubes

For the testing of the baffle design, a set of 7 tubes was chosen. This number was selected because it represents the minimum quantity of tubes that allows for experimentation with various tube arrangements. The decision to keep the number at 7 is motivated by the desire to streamline the analysis process and avoid unnecessary complexity. Increasing the number of tubes would not only complicate the analysis but also escalate material costs and the volume of simulations to be conducted. Additionally, the selection of 7 tubes aligns with numerous research papers on baffle design, facilitating easier comparisons and reducing the overall number of simulations needed.

3.5 Arrangement of tubes

Several tube arrangements are available for selection, including:

- Rectangular
- Rotated rectangular.
- 30° rotated triangular.
- 60° rotated triangular.

The chosen arrangement for our design is the 30° rotated triangular configuration due to its optimal heat transfer characteristics. The horizontal tube pitch was set at 30 mm to facilitate straightforward comparisons with existing research papers and experimental data.

Table 1*:Various Parameters of the Shell and Tube Head Exchangers*

Parameters	Values
B	72 mm
D_0	10 mm
D_s	156 mm
L	612 mm
N_b	6
N_t	7
T	25^o
Tube bundle geometry and pitch	30^o Rotated Triangular, 30 mm
t	1 mm

3.6 Number and spacing of baffles.

In accordance with findings from [33], the recommended baffle spacing falls within the range of 0.3 to 0.6 times the internal diameter of the shell. Based on these insights, the decision was made to use 6 baffles for the simulations. For the simulation runs, the baffle spacing was fixed at 72 mm. It is noteworthy that the ultimate determination of the optimal spacing will be ascertained through practical experimentation.

3.7 Material of tubes

The choice of copper tubes for analysis was driven by their widespread availability in various sizes and their commendable heat transfer capabilities. Additionally, a significant number of research papers focusing on Shell and Tube Heat Exchangers (STHE) with fluid on both sides have utilized copper tubes.

Below is the depiction of the entire tube bundle design, featuring six baffles and seven tubes passing through:

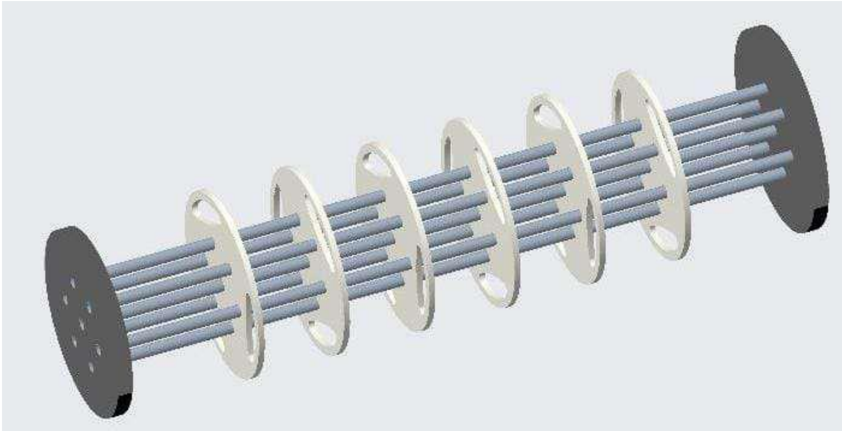

Figure 15: Tube Bundle Design3.8 Simulation.

The design selection process involved initially conducting simulations solely for the shell-side fluid, with the tubes assigned a constant temperature. Once the design was finalized, comprehensive analyses were performed for both the shell side and tube side configurations.

3.8.1 Boundary conditions

The following boundary conditions are applied to study.”

***Table 2**: Boundary Conditions*

Boundary Name	**Conditions**
Inlet Temperature (Shell Side)	45°C
Inlet Temperature (Tube Side)	55°C
Inlet Velocity Profile	Uniform
Slip Condition (All Surface)	Zero
Shell-Side mass flow rate (variable)	0.25kg/s, 0.5kg/s, 0.75kg/s
Shell Outer Wall	Zero-heat flux
Tube-Side mass flow rate	0.4167 kg/s

The same boundary conditions are applied to the simple a “25% cut segmented baffle”. The summarized CFD methodology is presented in the flow chart presented as follows:

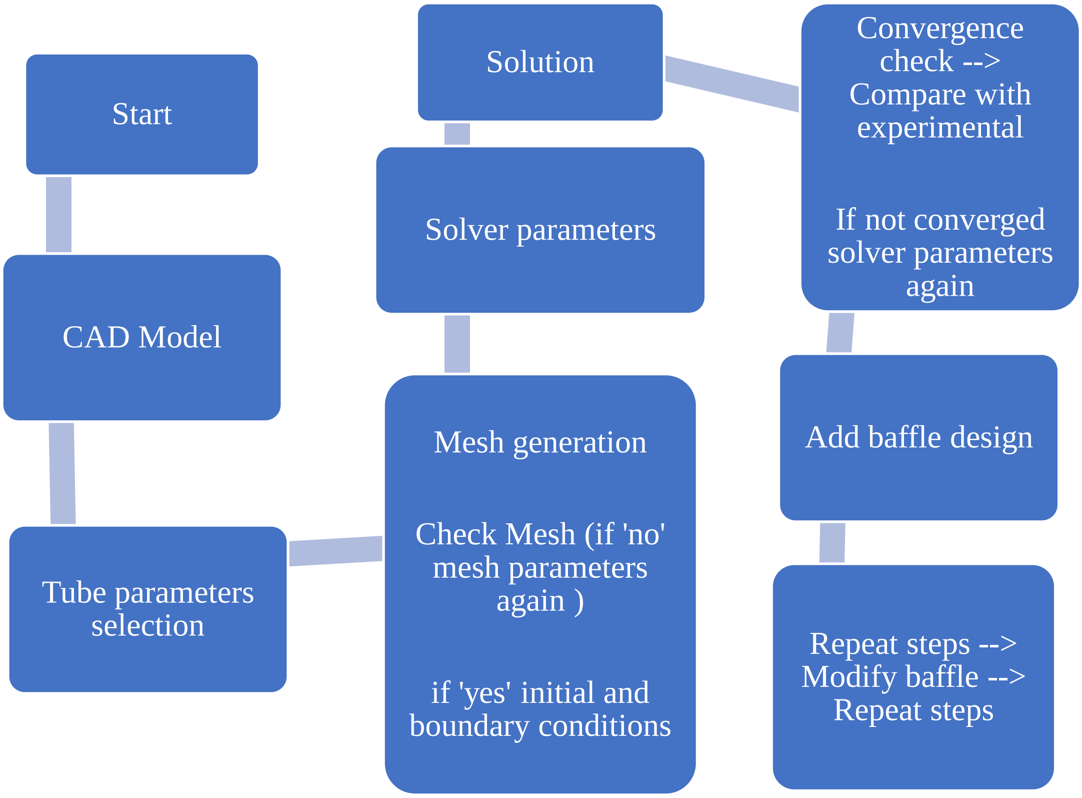

Figure 16: CFD Methodology

3.8.2 Mesh

Due to the intricacy of the geometric configuration, a conventional meshing algorithm was employed, incorporating specific refinement parameters. Additionally, inflation was applied to the boundaries to enhance the accuracy of flow predictions in close proximity to walls. The resulting mesh comprised slightly over 9.5 million elements and approximately 2.5 million nodes.

The following figures present a comprehensive depiction of the overall mesh that was generated. The mesh between the two baffles is given as below.

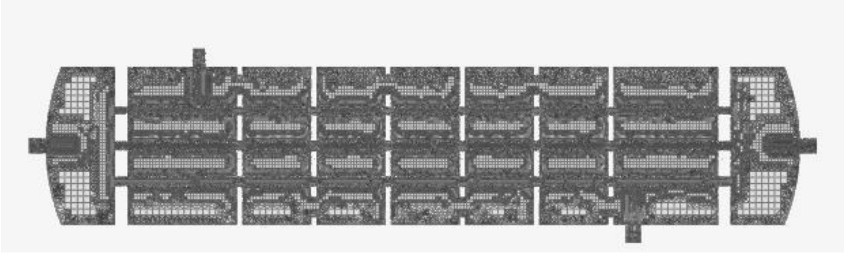

Figure 17: Overall Mesh of the heat exchanger.

The right-side baffle is attached upwards while the left baffle is attached downwards.

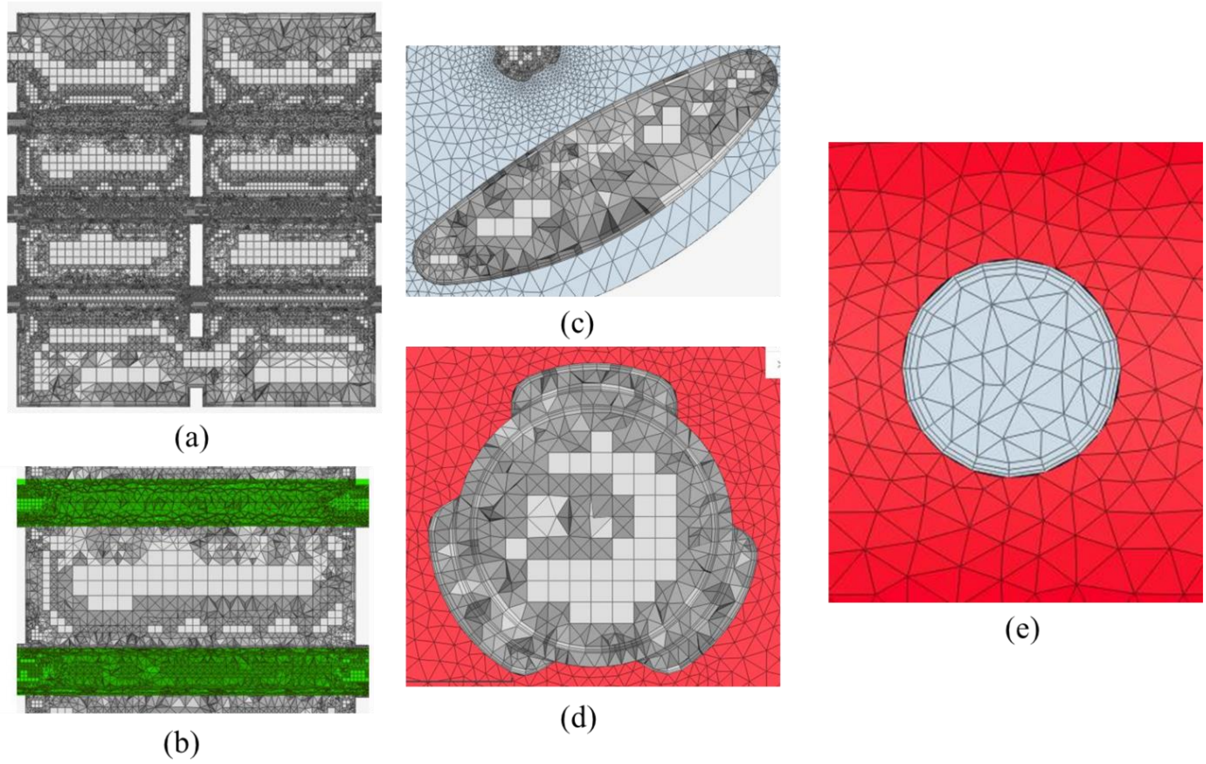

Figure 18: (a) mesh between 2 baffles. (b) mesh between the tubes. (c) mesh of the cuts in the baffle (d) mesh around the tubes. (e) mesh at the inlets and outlets of the shell side fluid.

This below given mesh depicts the cuts in the three-zonal trefoil baffle. The mesh at the outlet and inlet of the shell-side fluid is given below. The displayed mesh captures the configuration between the tubes, showcasing finer mesh resolution in the regions surrounding and near the tubes, in contrast to the relatively coarser mesh in the inactive mid-region. The illustrated mesh pertains to the formation around the tubes. Once more, a more refined mesh is evident in the vicinity of the tube area, emphasizing its significance and the necessity for enhanced precision in obtaining accurate results.

3.8.3 Simulation Results

Below are the temperature distributions, indicating the fluid temperature at various stages of the flow. These were developed by my colleagues at the lab. The trend reveals that the fluid tends to increase in temperature as it progresses through the shell, in line with expectations. Significantly higher temperatures are notable in areas proximate to the tubes.

The residual plot, depicted below, serves as a visual representation of the variance between the observed values of a variable and the values predicted by a model. This graphical tool is employed to evaluate the accuracy of the model and to identify any discernible patterns in the residuals that might suggest a necessity for additional investigation.

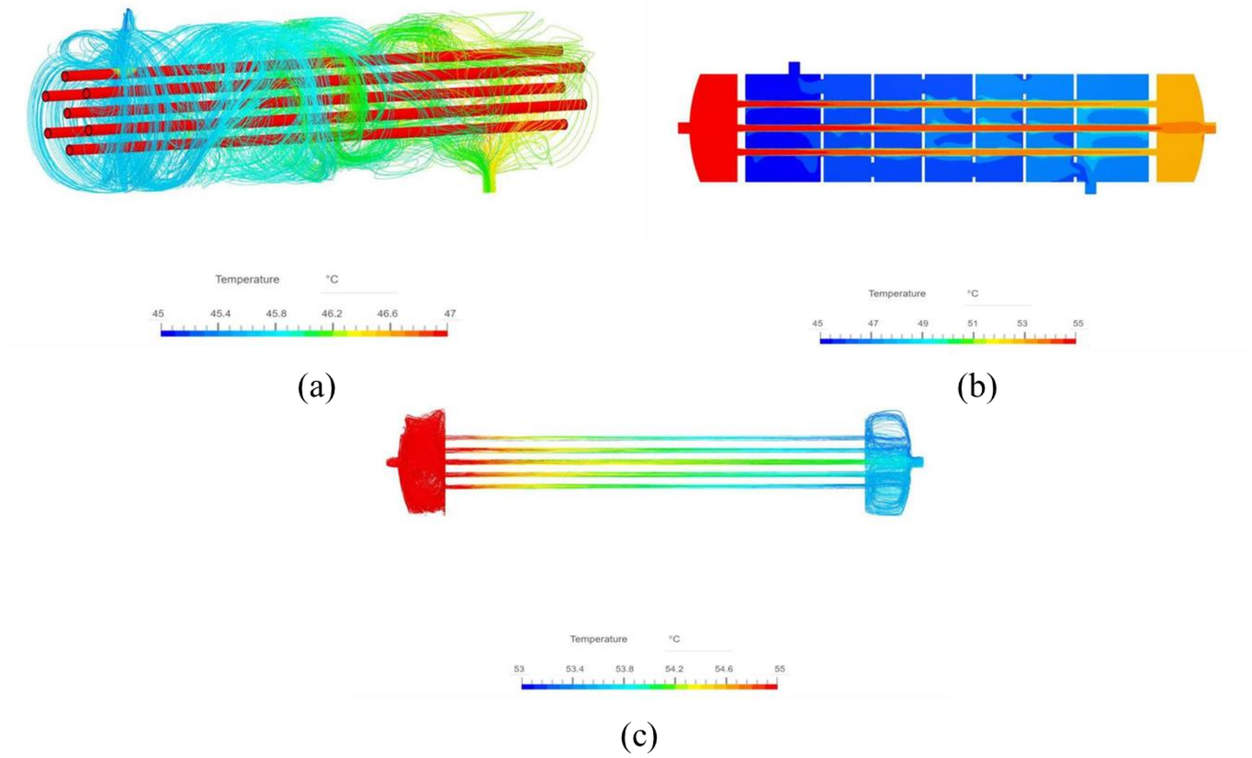

Figure 19: (a) General temperature distribution. (b)Temperature gradient of the shell.

(c) Temperature gradient of the tube

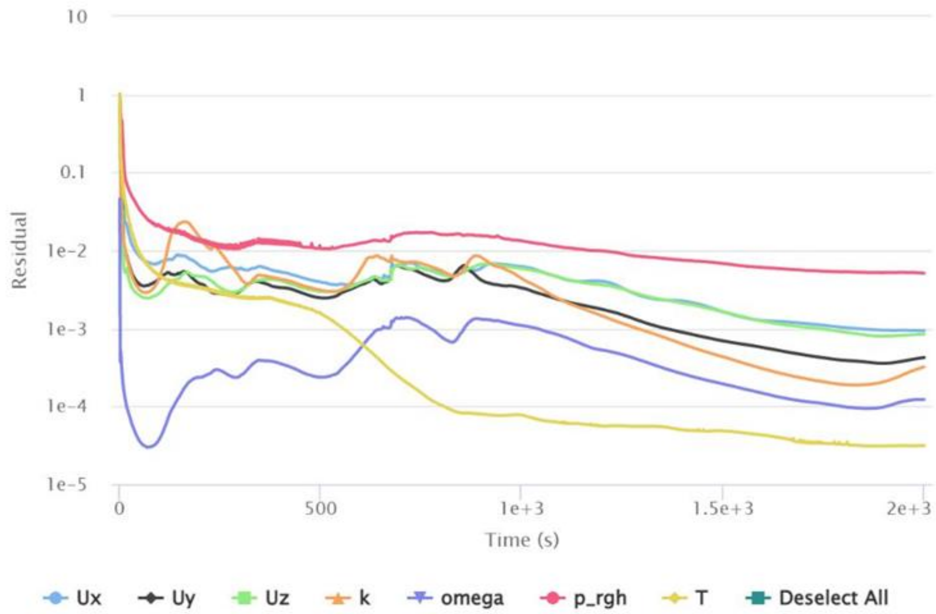

Figure 20: Residual Plots

Chapter-4: Experimentation

4.1 Available Heat Exchanger

Available heat exchanger at the disposal is given in the below figure. It is shell and tube heat exchanger having parallel flow streams. The novel three zonal trefoil baffle is installed in it. Many experiments are done on it varying the desired temperatures on the shell and tube sides.

Figure 21: Available Shell and Tube Heat Exchanger

The image shows the available Heat Exchanger Test Bench System used for experimental purposes to study heat transfer and pressure drop in heat exchangers. Here's a detailed explanation of the components of this heat exchanger:

4.1.1 Left Side (Heat Exchanger Setup):

1. **Heat Exchanger Unit (Labeled "Hot Surface")**:
   - This cylindrical component is the actual heat exchanger where the heat transfer process occurs. It contains the shell and tube arrangement through which the hot and cold fluids flow.
2. **Piping and Connections**:
   - Various pipes and connections are visible, likely for the inlet and outlet of hot and cold fluids. These pipes allow the fluids to enter and exit the heat exchanger.
3. **Control Valves and Sensors**:
   - The setup includes control valves to regulate the flow rates of the fluids and sensors to measure temperature and pressure at different points in the system.

4.2 Overall Function:

The Heat Exchanger Test Bench System is used to conduct experiments to understand heat transfer principles and pressure drop characteristics in heat exchangers. The control panel allows users to monitor and adjust various parameters, ensuring the system operates correctly and safely.

4.3 Programming Code:

With the help of the programming code, data is collected and formulated in excel sheets for further processing. All the sensors output is accumulated in an Arduino unit. These values of flow rates, temperatures and pressures are then fetched by the computer through programming. The interface of the programming side is shown in the image below.

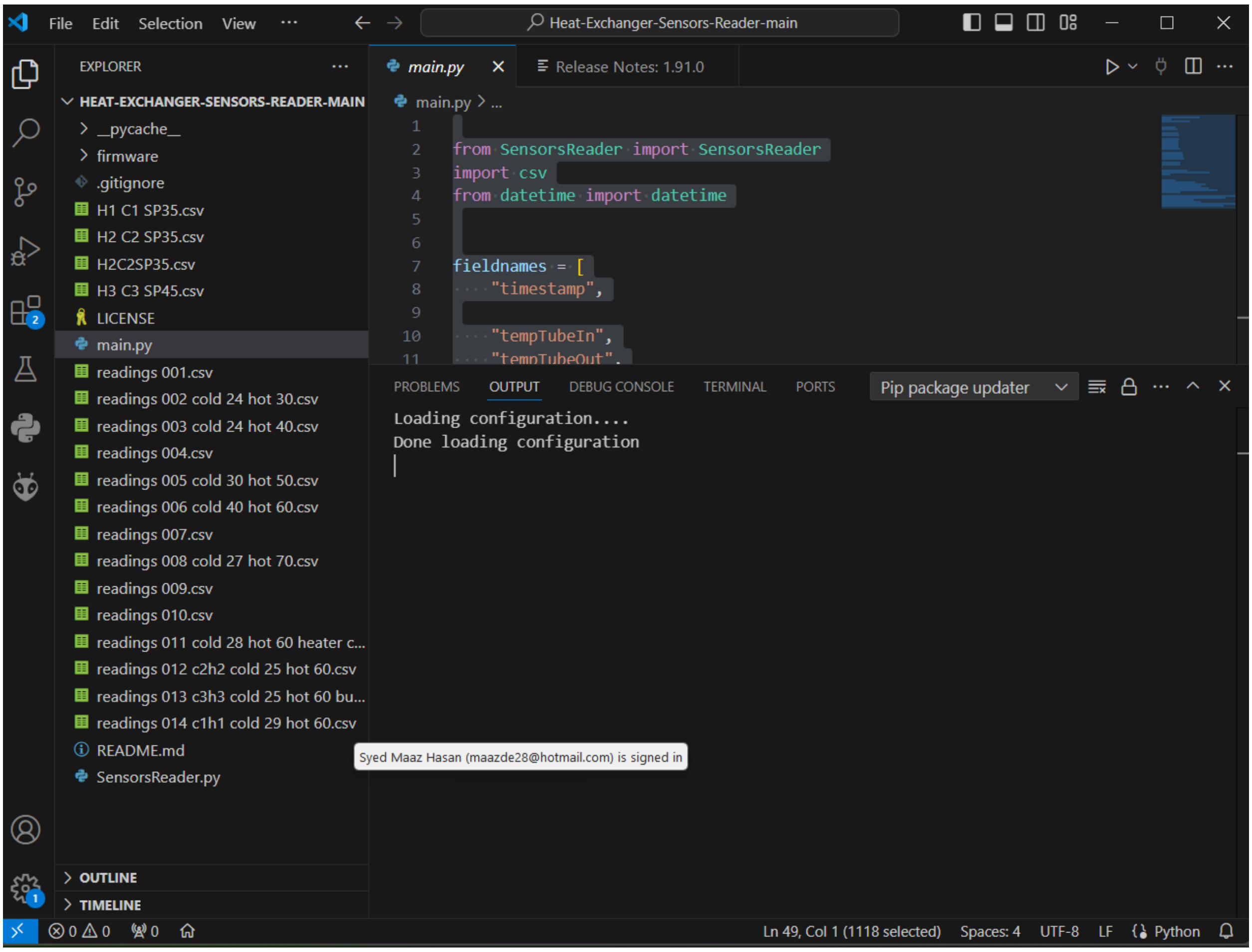

Figure 22: Interface of the Programming Code

```
from SensorsReader import SensorsReader
import csv
from datetime import datetime


fieldnames = [
    "timestamp",
```

```
    "tempTubeIn",
    "tempTubeOut",

    "tempShellIn",
    "tempShell1",
    "tempShell2",
    "tempShell3",
    "tempShell4",
    "tempShellOut",

    "pressureTubeIn",
    "pressureTubeOut",
    "pressureShellIn",
    "pressureShellOut",

    "flowRateTube",
    "flowRateShell"
]

if __name__ == '__main__':
    sensorsReader = SensorsReader('/dev/ttyACM0')
    i = 0


    while (1):
        if (sensorsReader.read()):
            sensorsReader.convertRawReading()
            sensorsReader.LabelReading()
            sensorsReader.printLabeledReadings()
            print(f"----------------{i}----------------")
            i = i+1

            with open('readings.csv', 'a', encoding='UTF8', newline='') as f:
                writer = csv.DictWriter(f, fieldnames=fieldnames)
                if f.tell() == 0:
                    writer.writeheader()
                sensorsReader.LabelledReadings["timestamp"] = datetime.now()
                writer.writerow(sensorsReader.LabelledReadings)
```

4.4 Experimentation

To perform the experiments and monitor heat transfer rate, experiments are done by varying the temperature parameters of Cold side water and Hot side water.

Cold side water temperature is set to 25°C and Hot side water temperature is set to 60°C. Data of 810 points or intervals is received from the sensors through the code and stored in Microsoft Excel sheet.

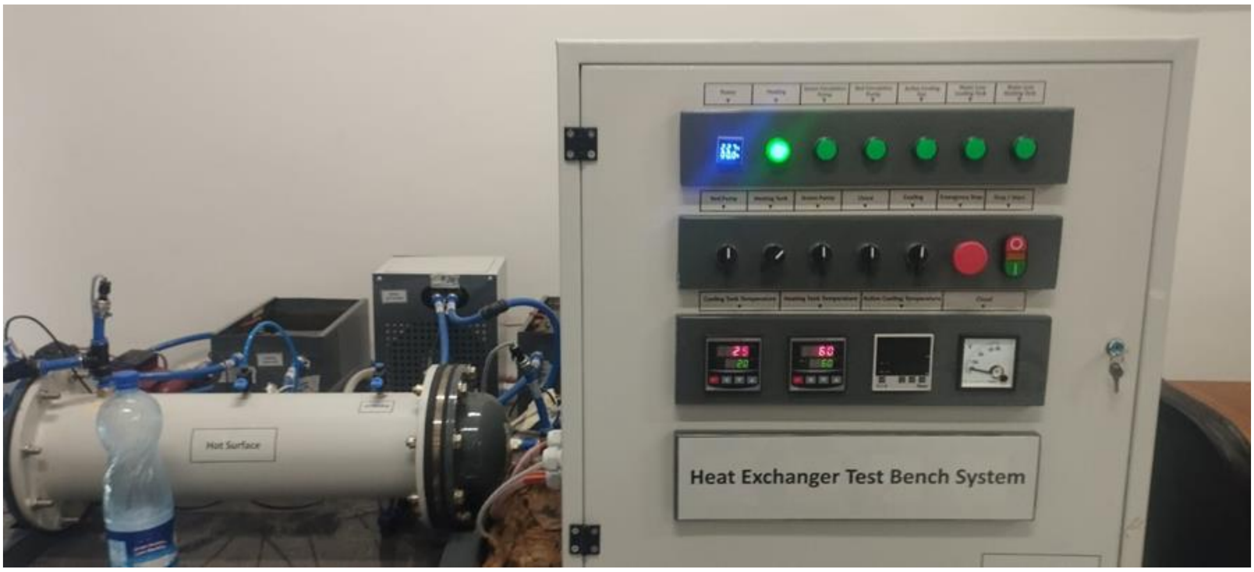

Figure 23: Cold water at 25°C, Hot water at 60°C.

The results of heat transfer and pressure drop are presented as follows. At the start mass flow rate is zero hence no heat transfer took place. As the flow rate becomes stable, heat transfer begins. At the stable change in temperature (ΔT), heat transfer is calculated.

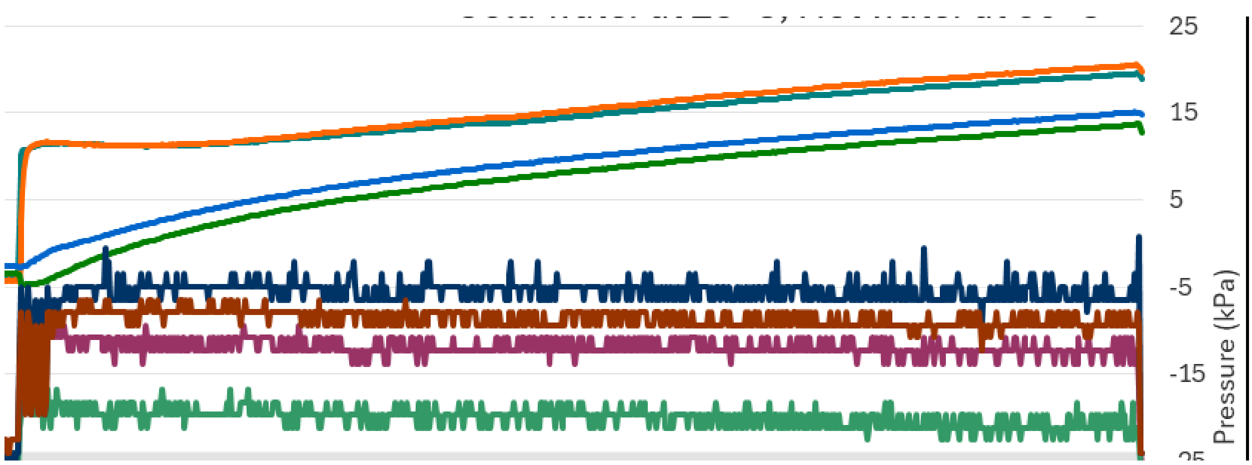

Figure 24: Graphical representation of Temperature and Pressure Cold water at 25°C, Hot water at 60°C.

The graph displays the temperature and pressure variations at different points inside the heat exchanger system over time. The components and trends observed in the graph are as follows:

Temperature Trends:

1. **tempTubeIn (Green Line):**
   - Represents the temperature of the fluid entering the tube side of the heat exchanger.
   - Starts around 25°C and gradually increases, reaching approximately 40°C.
2. **tempTubeOut (Orange Line):**
   - Indicates the temperature of the fluid exiting the tube side.
   - Starts around 20°C and rises steadily, reaching about 45°C.
3. **tempShellIn (Blue Line):**
   - Shows the temperature of the fluid entering the shell side.
   - Begins around 25°C and follows a slight upward trend, stabilizing around 35°C.
4. **tempShellOut (Light Blue Line):**
   - Represents the temperature of the fluid exiting the shell side.
   - Starts around 35°C and increases to approximately 45°C.

Pressure Trends:

1. **pressureTubeIn (Purple Line):**
   - Represents the pressure of the fluid entering the tube side.
   - Remains fairly constant around 15 kPa with minor fluctuations.
2. **pressureTubeOut (Brown Line):**
   - Indicates the pressure of the fluid exiting the tube side.
   - Exhibits a more variable pattern but generally stays around 0 kPa.
3. **pressureShellIn (Light Green Line):**
   - Shows the pressure of the fluid entering the shell side.
   - Fluctuates around -15 kPa.
4. **pressureShellOut (Dark Brown Line):**
   - Represents the pressure of the fluid exiting the shell side.
   - Maintains a relatively constant value near -5 kPa.

Key Observations:

- **Temperature Increase:**
  - The temperature of both tube and shell side fluids increases over time, indicating heat transfer from the hot fluid (in the tube side) to the cold fluid (in the shell side).

- **Pressure Stability:**
    - The pressure values are relatively stable with minor fluctuations. The tube side inlet pressure is higher compared to the shell side, which is due to the design and flow rates in the system.
- **Flow Rates and Performance:**
    - The temperatures and pressures provide insight into the performance of the heat exchanger, with consistent temperature rises and stable and lower pressure drops indicating effective heat transfer without lowering the pressure much.

Figure 25: Cold water at 40°C , Hot water at 60°C

The heat transfer and pressure drop results are presented below. Initially, with a zero-mass flow rate, no heat transfer occurs. As the flow rate stabilizes, heat transfer begins. Once the temperature change (ΔT) stabilizes, the heat transfer is calculated.

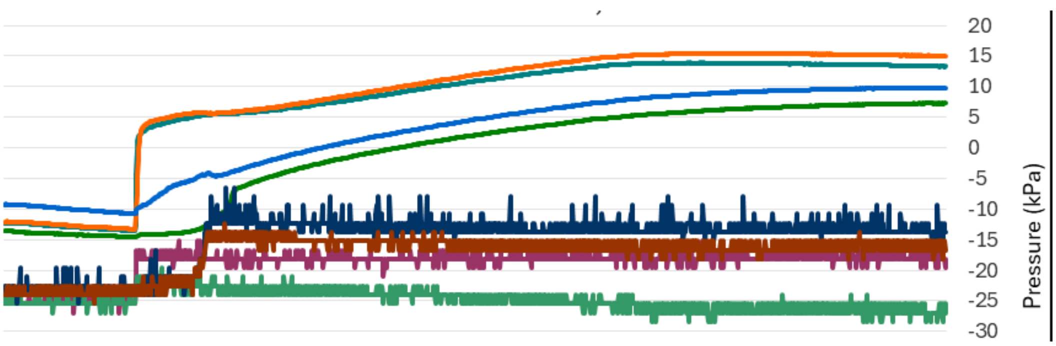

Figure 26: Graphical representation of Temperature and Pressure Cold water at 40°C, Hot water at 60°C.

The graph illustrates the variations in temperature and pressure at different points within the heat exchanger system over time.

The observed components and trends are as follows:

Temperature Trends:

1. **tempTubeIn (Green Line):**
   - Represents the temperature of the fluid entering the tube side of the heat exchanger.
   - Starts around 30°C and gradually increases to approximately 35°C.
2. **tempTubeOut (Orange Line):**
   - Indicates the temperature of the fluid exiting the tube side.
   - Begins around 45°C and steadily risen to about 55°C.
3. **tempShellIn (Blue Line):**
   - Shows the temperature of the fluid entering the shell side.
   - Starts at 40°C, showing a slight upward trend, stabilizing around 45°C.
4. **tempShellOut (Light Blue Line):**
   - Represents the temperature of the fluid exiting the shell side.
   - Starts at 50°C and increases to approximately 55°C.

Pressure Trends:

1. **pressureTubeIn (Purple Line):**
   - Represents the pressure of the fluid entering the tube side.
   - Remains fairly constant around 10 kPa with minor fluctuations.
2. **pressureTubeOut (Brown Line):**
   - Indicates the pressure of the fluid exiting the tube side.
   - Exhibits a more variable pattern, generally staying around 0 kPa.
3. **pressureShellIn (Light Green Line):**
   - Shows the pressure of the fluid entering the shell side.
   - Fluctuates around -15 kPa.
4. **pressureShellOut (Dark Brown Line):**
   - Represents the pressure of the fluid exiting the shell side.
   - Maintains a relatively constant value near -20 kPa.

Key Observations:

- **Temperature Increase:**
  - The temperatures of both the tube and shell side fluids increase over time, indicating heat transfer from the hot fluid (tube side) to the cold fluid (shell).

- **Pressure Stability:**
    - The pressure values remain relatively stable with minor fluctuations. The inlet pressure on the tube side is higher compared to the shell side, due to the design and flow rates of the system.
- **Flow Rates and Performance:**
    - The temperatures and pressures provide insight into the performance of the heat exchanger. Consistent temperature rises and stable, lower pressure drops indicate effective heat transfer without significant pressure reduction.

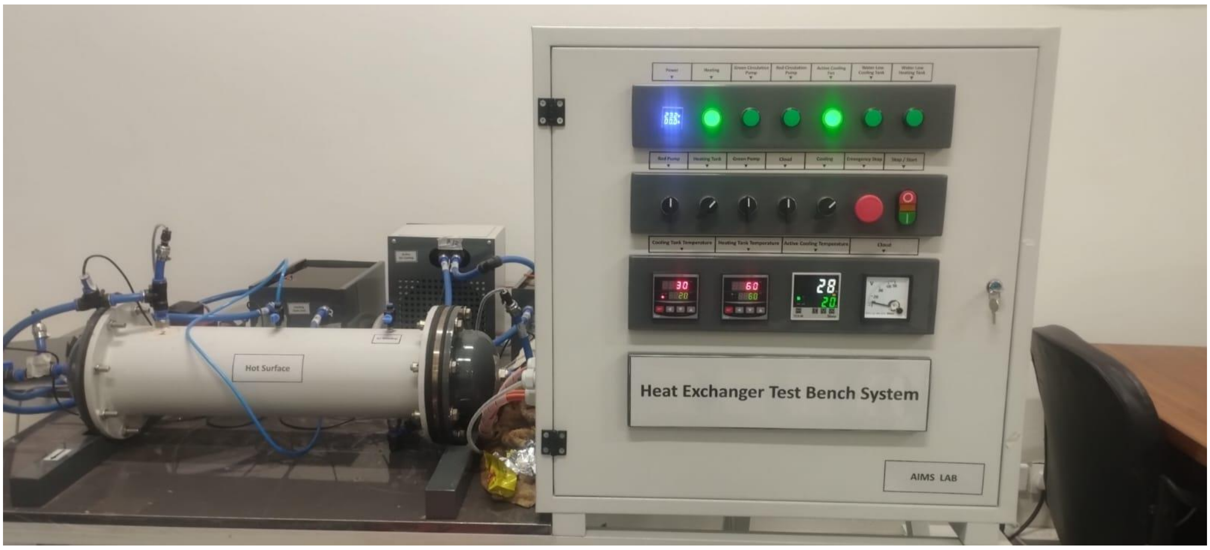

Figure 27: Cold water at 29°C, Hot water at 60°C.

The heat transfer and pressure drop results are presented below. Initially, with a zero-mass flow rate, no heat transfer occurs. As the flow rate stabilizes, heat transfer begins. Once the temperature change (ΔT) stabilizes, the heat transfer is calculated.

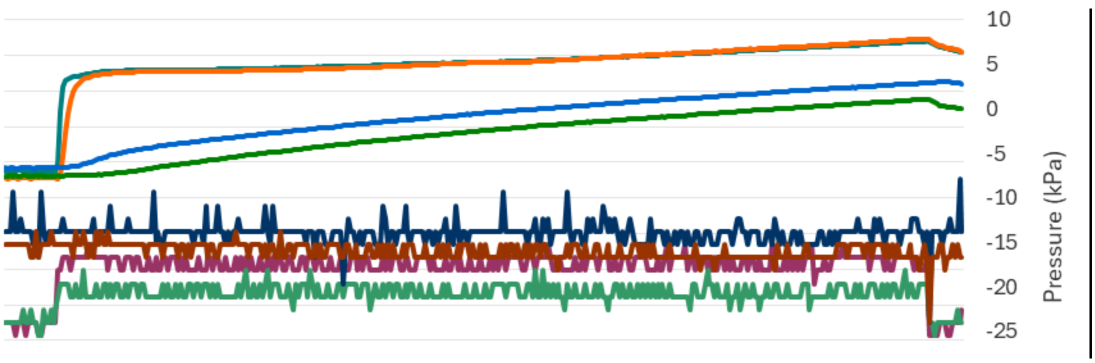

Figure 28: Graphical representation of Temperature and Pressure Cold water at 29°C, Hot water at 60°C.

The graph illustrates the variations in temperature and pressure at different points within the heat exchanger system over time. The observed components and trends are as follows:

Temperature Trends:

5. **tempTubeIn (Green Line):**
   - Represents the temperature of the fluid entering the tube side of the heat exchanger.
   - Starts around 28°C and gradually increases to approximately 38°C.
6. **tempTubeOut (Orange Line):**
   - Indicates the temperature of the fluid exiting the tube side.
   - Begins around 41°C and steadily risen to about 47°C.
7. **tempShellIn (Blue Line):**
   - Shows the temperature of the fluid entering the shell side.
   - Starts at 30°C, showing a slight upward trend, stabilizing around 40°C.
8. **tempShellOut (Light Blue Line):**
   - Represents the temperature of the fluid exiting the shell side.
   - Starts at 50°C and increases to approximately 55°C.

Pressure Trends:

5. **pressureTubeIn (Purple Line):**
   - Represents the pressure of the fluid entering the tube side.
   - Remains fairly constant around 10 kPa with minor fluctuations.
6. **pressureTubeOut (Brown Line):**
   - Indicates the pressure of the fluid exiting the tube side.
   - Exhibits a more variable pattern, generally staying around 0 kPa.
7. **pressureShellIn (Light Green Line):**
   - Shows the pressure of the fluid entering the shell side.
   - Fluctuates around -15 kPa.
8. **pressureShellOut (Dark Brown Line):**
   - Represents the pressure of the fluid exiting the shell side.
   - Maintains a relatively constant value near -20 kPa.

Key Observations:

- **Temperature Increase:**
  - The temperatures of both the tube and shell side fluids increase over time, indicating heat transfer from the hot fluid (tube side) to the cold fluid (shell side).

- **Pressure Stability:**
    - The pressure values remain relatively stable with minor fluctuations. The inlet pressure on the tube side is higher compared to the shell side, due to the design and flow rates of the system.
- **Flow Rates and Performance:**
    - The temperatures and pressures provide insight into the performance of the heat exchanger. Consistent temperature rises and stable, lower pressure drops indicate effective heat transfer without significant pressure reduction.

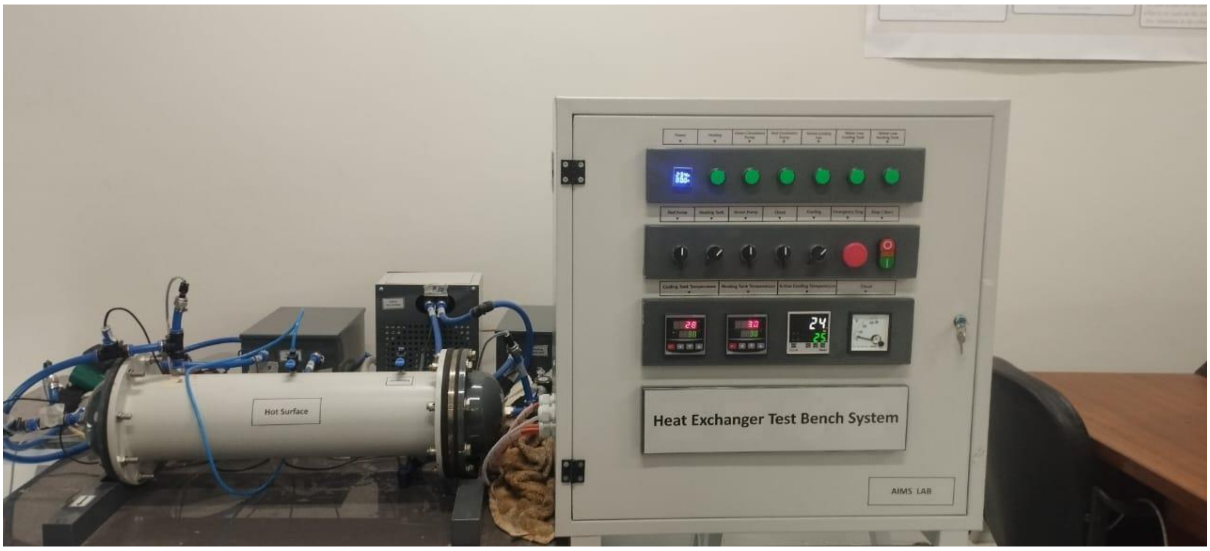

Figure 29: Cold water at 24°C, Hot water at 30°C.

The results for heat transfer and pressure drop are outlined below. At the outset, with a mass flow rate of zero, no heat transfer occurs. As the flow rate becomes stable, heat transfer commences. Once the temperature change (ΔT) reaches a steady state, the heat transfer is calculated.

The graph illustrates the variations in temperature and pressure at different points within the heat exchanger system over time. The observed components and trends are as follows:

Temperature Trends:

1. **tempTubeIn (Green Line):**
    - Represents the temperature of the fluid entering the tube side of the heat exchanger.
    - Starts around 23°C and gradually increases to approximately 30°C.

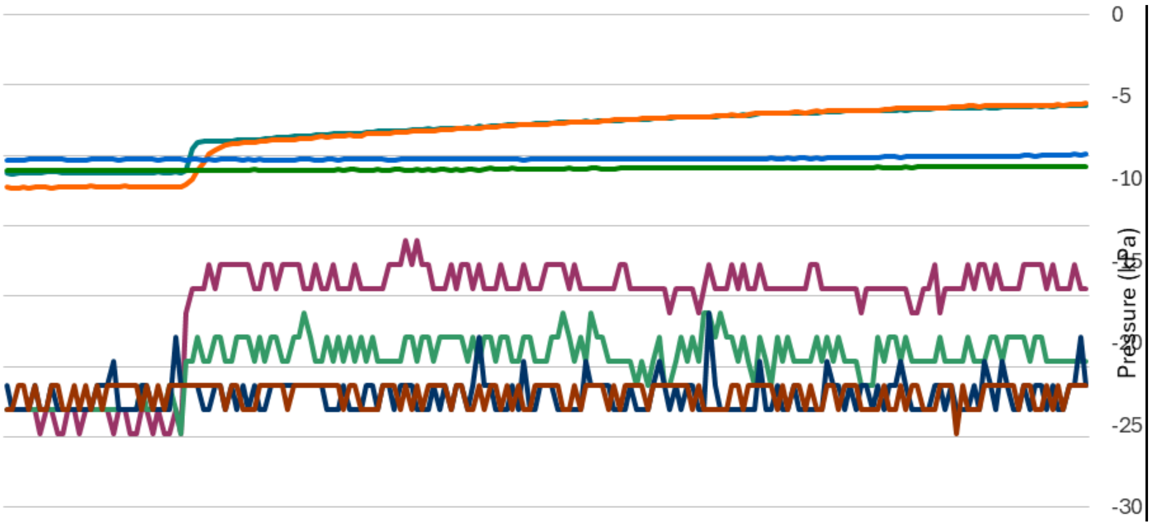

Figure 30: Graphical representation of Temperature and Pressure Cold water at 24°C, Hot water at 30°C.

2. **tempTubeOut (Orange Line):**
    - Indicates the temperature of the fluid exiting the tube side.
    - Begins around 22°C and steadily risen to about 28°C.
3. **tempShellIn (Blue Line):**
    - Shows the temperature of the fluid entering the shell side.
    - Starts at 24°C, showing a slight upward trend, stabilizing around 25°C.
4. **tempShellOut (Light Blue Line):**
    - Represents the temperature of the fluid exiting the shell side.
    - Starts at 27°C and increases to approximately 29°C.

Pressure Trends:

9. **pressureTubeIn (Purple Line):**
    - Represents the pressure of the fluid entering the tube side.
    - Remains fairly constant around -15 kPa with minor fluctuations.
10. **pressureTubeOut (Brown Line):**
    - Indicates the pressure of the fluid exiting the tube side.
    - Exhibits a more variable pattern, generally staying around -23 kPa.
11. **pressureShellIn (Light Green Line):**
    - Shows the pressure of the fluid entering the shell side.
    - Fluctuates around -20 kPa.
12. **pressureShellOut (Dark Brown Line):**
    - Represents the pressure of the fluid exiting the shell side.
    - Maintains a relatively constant value near -24 kPa.

Key Observations:

- **Temperature Increase:**
    - The temperatures of both the tube and shell side fluids increase over time, indicating heat transfer from the hot fluid (tube side) to the cold fluid (shell).
- **Pressure Stability:**
    - The pressure values remain relatively stable with minor fluctuations. The inlet pressure on the tube side is higher compared to the shell side, due to the design and flow rates of the system.
- **Flow Rates and Performance:**

    The temperatures and pressures provide insight into the performance of the heat exchanger. Consistent temperature rises and stable, lower pressure drops indicate effective heat transfer without significant pressure reduction.

Figure 31: Cold Water at 27°C, Hot water at 70°C.

The results for heat transfer and pressure drop are outlined below. At the outset, with a mass flow rate of zero, no heat transfer occurs. As the flow rate becomes stable, heat transfer commences. Once the temperature change (ΔT) reaches a steady state, the heat transfer is calculated.

The graph illustrates the variations in temperature and pressure at different points within the heat exchanger system over time. The observed components and trends are as follows:

Temperature Trends:

1. **tempTubeIn (Green Line):**
    - Represents the temperature of the fluid entering the tube side of the heat exchanger.
    - Starts around 25°C and gradually increases to approximately 47°C.

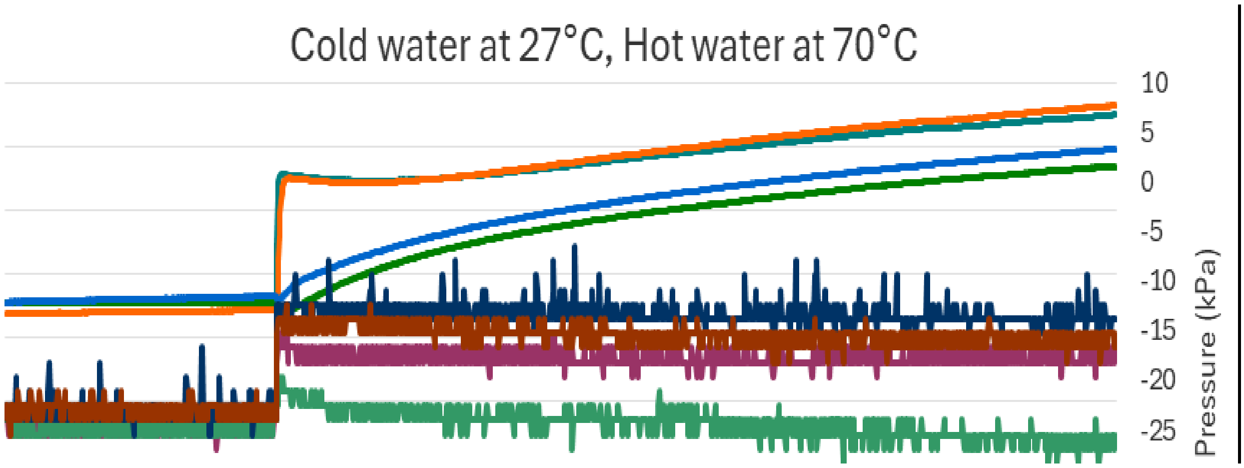

Figure 32: Graphical representation of Temperature and Pressure Cold water at 27°C, Hot water at 70°C.

2. **tempTubeOut (Orange Line):**
   - Indicates the temperature of the fluid exiting the tube side.
   - Begins around 25°C and steadily risen to about 55°C.
3. **tempShellIn (Blue Line):**
   - Shows the temperature of the fluid entering the shell side.
   - Starts at 27°C, showing a slight upward trend, stabilizing around 50°C.
4. **tempShellOut (Light Blue Line):**
   - Represents the temperature of the fluid exiting the shell side.
   - Starts at 45°C and increases to approximately 55°C.

Pressure Trends:

13. **pressureTubeIn (Purple Line):**
    - Represents the pressure of the fluid entering the tube side.
    - Remains fairly constant around -17 kPa with minor fluctuations.
14. **pressureTubeOut (Brown Line):**
    - Indicates the pressure of the fluid exiting the tube side.
    - Exhibits a more variable pattern, generally staying around -15 kPa.
15. **pressureShellIn (Light Green Line):**
    - Shows the pressure of the fluid entering the shell side.
    - Fluctuates around -25 kPa.
16. **pressureShellOut (Dark Brown Line):**
    - Represents the pressure of the fluid exiting the shell side.
    - Maintains a relatively constant value near -13 kPa.

Key Observations:

- **Temperature Increase:**
  - The temperatures of both the tube and shell side fluids increase over time, indicating heat transfer from the hot fluid (tube side) to the cold fluid (shell side).
- **Pressure Stability:**
  - The pressure values remain relatively stable with minor fluctuations. The inlet pressure on the tube side is higher compared to the shell side, due to the design and flow rates of the system.
- **Flow Rates and Performance:**

The temperatures and pressures provide insight into the performance of the heat exchanger. Consistent temperature rises and stable, lower pressure drops indicate effective heat transfer without significant pressure reduction.

4.4 EFFECTIVENESS OF A HEAT EXCHANGER

The effectiveness of a heat exchanger is a crucial performance metric that quantifies the actual heat transfer achieved relative to the maximum possible heat transfer in the system [34]. This is important for heat transfer enhancement [35]. The formula for effectiveness (ε) in a counterflow heat exchanger is presented as follows:

$$\varepsilon = \frac{Actual\ heat\ transfer\ rate}{Maximum\ possible\ heat\ transfer\ rate}$$

$$\varepsilon = \frac{T_{hi} - T_{ci}}{T_{hi} - T_{co}}$$

where:

- T_{hi} is the inlet temperature of the hot fluid,
- T_{ci} is the inlet temperature of the cold fluid, and
- T_{co} is the outlet temperature of the cold fluid.

Effectiveness values range from 0 to 1, with 1 indicating perfect heat transfer and 0 indicating no heat transfer.

Chapter-5: Results and Discussion

The graph below shows the pressure drop and heat transfer results for both the baffle designs:

5.1 Comparison of Heat Transfer between two baffle designs (Simulation)

The trend of simulation results is comparatively the same with each other at all flow rates.

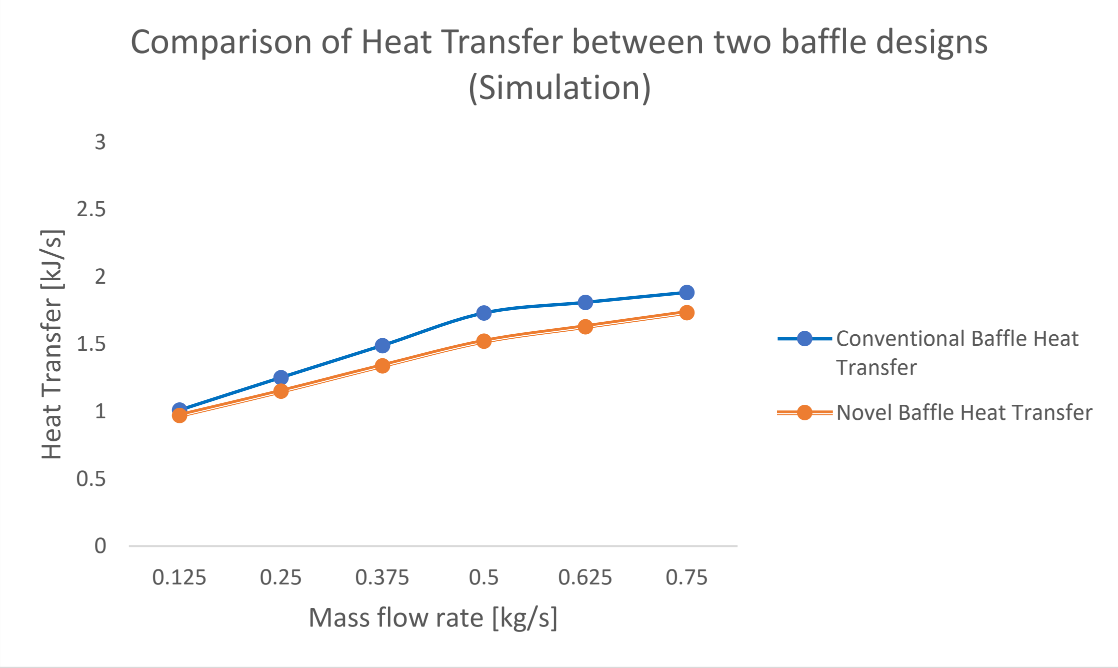

Figure 33: Comparison of Heat Transfer between two baffle designs (Simulation)

5.2 Comparison of Pressure Drop between two baffle designs (Simulation)

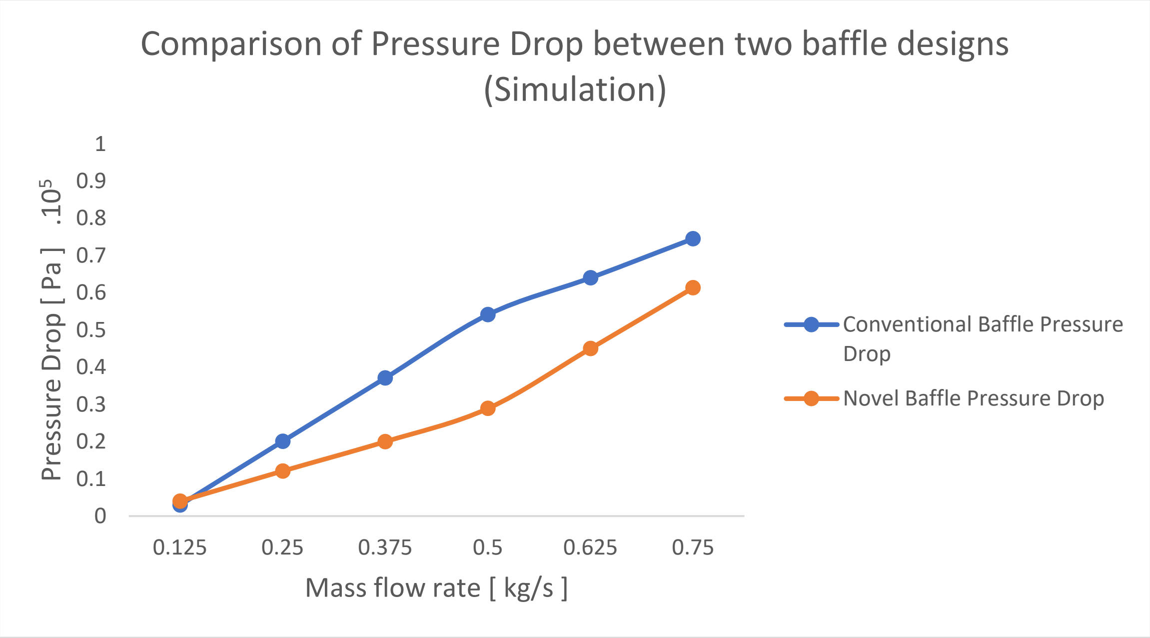

Figure 34: Comparison of Pressure Drop between two baffle designs (Simulation)

5.3 Comparison of Heat Transfer between two baffle designs (Experiment)

The relationship between heat transfer and flow rate in a fluid system can vary depending on the specific conditions and configurations. However, there are some general trends associated with increased flow rates and enhanced heat transfer:

Increased Convective Heat Transfer: In forced convection heat transfer, higher flow rates generally lead to increased convective heat transfer. As the fluid flows more rapidly over a heated surface, it reduces the thermal boundary layer thickness and enhances the convective heat transfer coefficient.

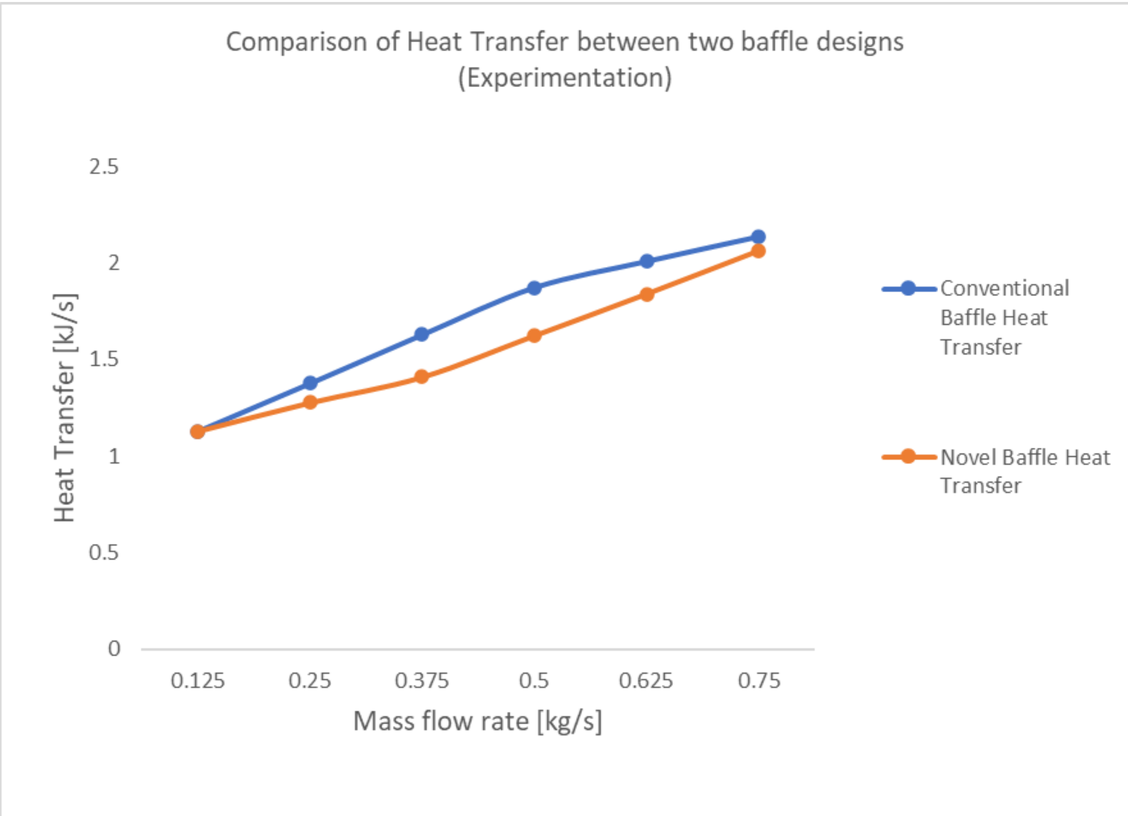

Figure 35: Comparison of Heat Transfer between two baffle designs (Experimentation)

5.4 Comparison of Pressure Drop between two baffle designs (Experiment)

Frictional Losses:

Higher flow rates lead to increased frictional losses within the system. As the fluid moves through pipes or channels, it encounters resistance from the surfaces, causing friction. This frictional resistance results in a pressure drop along the flow path. With higher flow rates, the magnitude of frictional losses becomes more pronounced, contributing to an overall increase in pressure drop.

Turbulent Flow:

At higher flow rates, fluid flow is more likely to transition from laminar to turbulent. Turbulent flow is associated with increased mixing and higher frictional losses, further contributing to a higher pressure drop.

Accelerated Fluid Momentum:

An increase in flow rate results in a greater amount of fluid momentum. When there are changes in the direction of flow, such as in bends or fittings, this increased momentum can lead to additional pressure losses.

Density Changes:

In certain cases, such as compressible fluids, an increase in flow rate might be accompanied by changes in fluid density. As density decreases (e.g., in gases under compression), the pressure drop may increase.

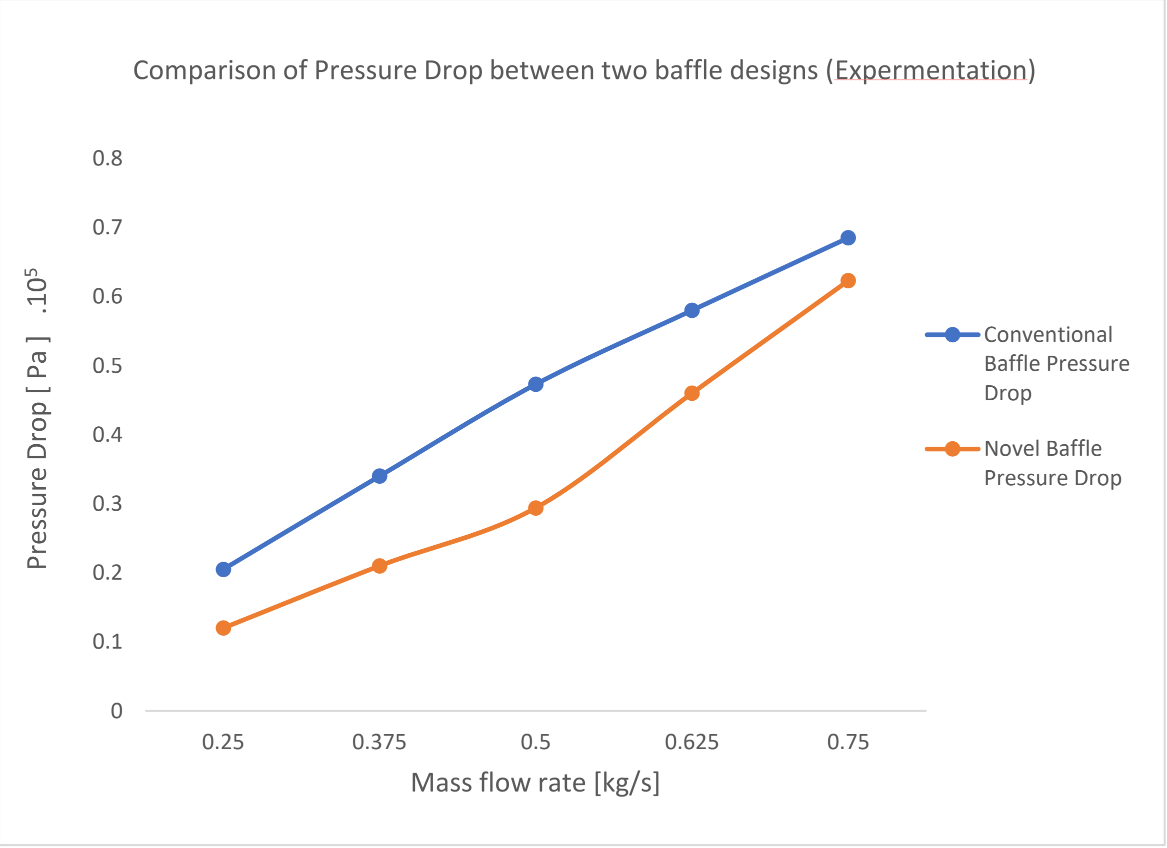

Figure 36: Comparison of Pressure Drop between two baffle designs (Experimentation)

5.5 Heat Transfer by Pressure Drop

At higher flow rates of fluid in shell and tube heat exchangers, the heat transfer by pressure drop for different designs tends to converge or become similar due to several fluid dynamics and thermodynamic factors. Here are some reasons that contribute to this phenomenon:

Turbulent Flow Dominance:

At higher flow rates, the fluid flow within the heat exchanger is more likely to transition from laminar to turbulent. Turbulent flow enhances heat transfer through increased fluid mixing and a thinner thermal boundary layer. In turbulent flow, the convective heat transfer coefficient becomes less dependent on the specific geometry of the heat exchanger, leading to similar heat transfer characteristics across different designs.

Diminished Thermal Boundary Layer:

Higher flow rates result in a reduced thermal boundary layer. The thermal boundary layer is the region near the surface where the temperature of the fluid changes from the bulk temperature to the surface temperature. As flow rates increase, the thermal boundary layer becomes thinner, leading to more effective heat transfer and making the impact of specific heat exchanger design less pronounced.

Similar Reynolds Numbers:

At higher flow rates, different heat exchanger designs may operate at similar Reynolds numbers. The Reynolds number is a dimensionless parameter that characterizes the flow regime (i.e., laminar or turbulent) and is crucial in determining heat transfer characteristics. When Reynolds numbers are comparable, the heat transfer behavior tends to be more uniform among different designs.

Reduced Residence Time:

Higher flow rates typically result in shorter residence times for the fluid within the heat exchanger. While this may reduce the time available for heat transfer, it also prevents the fluid from becoming thermally saturated. The impact of residence time on heat transfer becomes less significant at higher flow rates, contributing to similar heat transfer by pressure drop trends.

Balanced Effects:

At elevated flow rates, the interplay between convective heat transfer, pressure drop, and other fluid dynamics tends to reach a balance. Any advantages or disadvantages associated with a specific heat exchanger design may be offset by the overall increased efficiency of heat transfer in the turbulent flow regime.

The experimental findings indicate that the three-zonal trefoil baffle surpasses the performance of the traditional baffle in terms of achieving a reduced pressure drop. However, concerning heat transfer, the innovative design exhibits a slightly lower heat transfer rate. It is crucial to note that the observed difference is nearly negligible. It is essential to reiterate that the sought-after outcome is an elevated heat transfer coupled with a diminished pressure drop, emphasizing the need for an overall superior heat transfer per pressure drop. A comprehensive comparison between the heat transfer per pressure drop of the conventional and new baffles will clearly illustrate the superiority of one over the other. The accompanying graph illustrates the heat transfer per pressure drop for both the new and conventional designs.

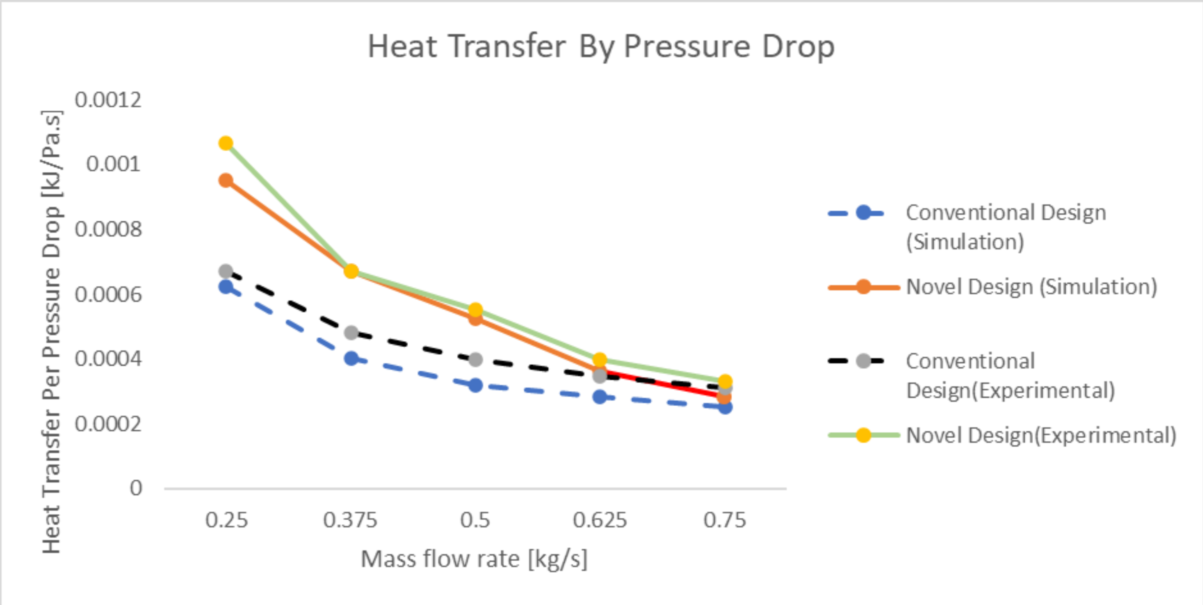

Figure 37: Heat Transfer by Pressure Drop

The graph illustrates the relationship between heat transfer per pressure drop [kJ/Pa·s] and mass flow rate [kg/s] for both conventional and novel heat exchanger designs, evaluated through both simulation and experimental methods. The following observations are made:

General Trends:

- **Heat Transfer Per Pressure Drop**: This metric indicates the efficiency of the heat exchanger in transferring heat relative to the pressure drop. A higher value suggests better performance.
- **Mass Flow Rate**: As the mass flow rate increases, the heat transfer per pressure drop generally decreases for both designs and methods.

Detailed Analysis:

1. **Conventional Design (Simulation - Blue Dotted Line)**:
   - The performance starts around 0.00045 kJ/Pa·s at a 0.25 kg/s flow rate.
   - There is a consistent decline in performance as the mass flow rate increases, reaching about 0.0002 kJ/Pa·s at 0.75 kg/s.
2. **Novel Design (Simulation - Orange Line)**:
   - Begins with a higher efficiency at about 0.001 kJ/Pa·s at 0.25 kg/s.
   - Efficiency drops more steeply with increasing mass flow rate, aligning closely with the conventional design at higher flow rates.
3. **Conventional Design (Experimental - Black Dotted Line)**:
   - Starts with a similar efficiency as the simulation but slightly higher.
   - The decline in performance follows a similar trend to the simulated conventional design, though the values are slightly higher across all mass flow rates.
4. **Novel Design (Experimental - Yellow Line)**:
   - Shows the highest initial efficiency at around 0.0012 kJ/Pa·s for a 0.25 kg/s flow rate.
   - The decline is steeper initially, but the efficiency remains higher than all other methods and designs up to around 0.625 kg/s.
   - At 0.75 kg/s, the performance aligns closely with both the experimental and simulated conventional designs.

Key Observations:

- **Initial Performance**: The novel design outperforms the conventional design in terms of heat transfer per pressure drop, especially at lower mass flow rates. This is evident in both simulation and experimental results.
- **Performance Convergence**: As the mass flow rate increases, the performance of both designs converges, suggesting that the advantages of the novel design are more pronounced at lower flow rates.
- **Simulation vs. Experimental**: Experimental results show slightly higher efficiency compared to simulations for both designs, indicating real-world conditions may offer slight improvements over theoretical predictions.

The novel design of the heat exchanger demonstrates superior performance in terms of heat transfer per pressure drop at lower mass flow rates, making it more efficient in transferring heat with less pressure loss. Both simulation and experimental data validate this trend, suggesting that the novel design's benefits are most significant at lower flow rates.

The graphical representation indicates that the innovative design exhibits a higher heat transfer per pressure drop in comparison to the conventional baffle, particularly evident at lower mass flow rates. However, as the flow rate escalates to 0.75 kg/s, both baffles demonstrate an equivalent heat transfer per pressure drop. Consequently, it can be inferred that the new baffle design serves as a commendable alternative to the conventional one, particularly at lower mass flow rates.

The three-zonal trefoil baffle emerges as a promising substitute for the commonly employed conventional segmented baffle. Helical baffles, although generally considered superior to segmented baffles, pose challenges in manufacturing due to their curved surfaces. In contrast, the three-zonal trefoil baffle features a straightforward design, rendering it comparatively easier to manufacture.

5.6 Determination of effectiveness of this shell and tube heat exchanger by using Tap Water and Distilled Water

The given results are based on the data over two weeks. For the long-term health of Heat Exchanger this period of observation is kept very small. As the tap water would have caused contamination, rusting, scaling, and coagulation for using tap water over a long period of time.

Table 3: Effectiveness and Difference of Heat Transfer against two fluids

Flow Rate [kg/s]	**Difference of Heat Transfer**	**Effectiveness [ε]**
0.25	0.0021	0.9978
0.5	0.0025	0.9975
0.75	0.0024	0.9975

However, based on this two-week data, annual projection is predicted that results in a 5.6% decrease in heat transfer every year if tap water is used instead of distilled water.

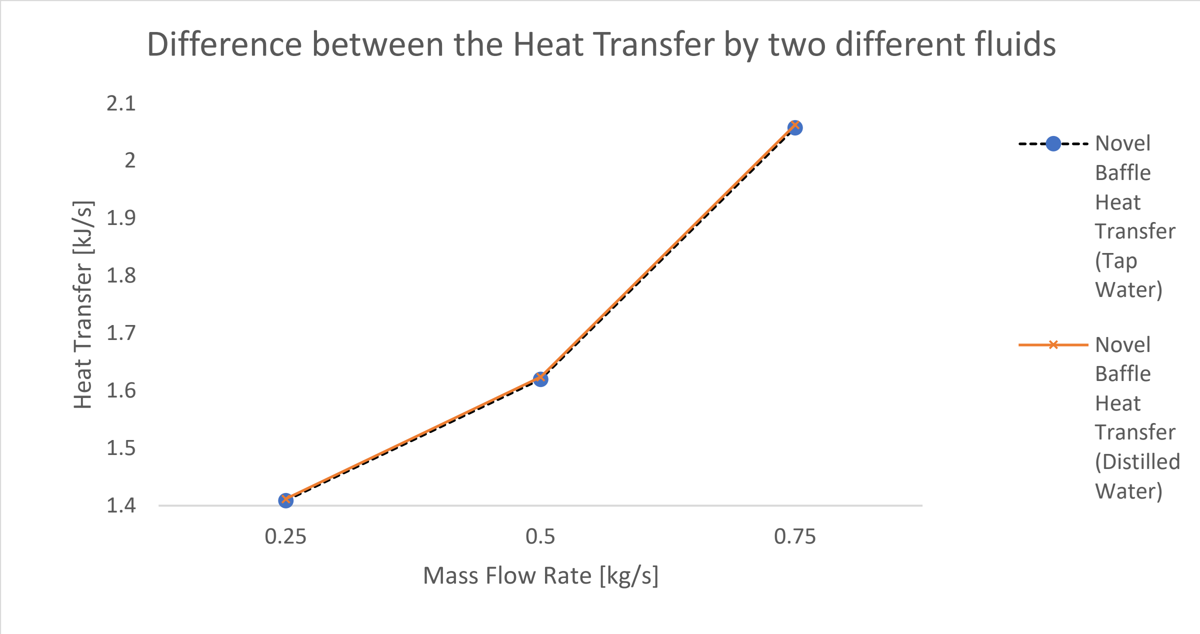

Figure 38: Difference between the Heat Transfer by two different fluids.

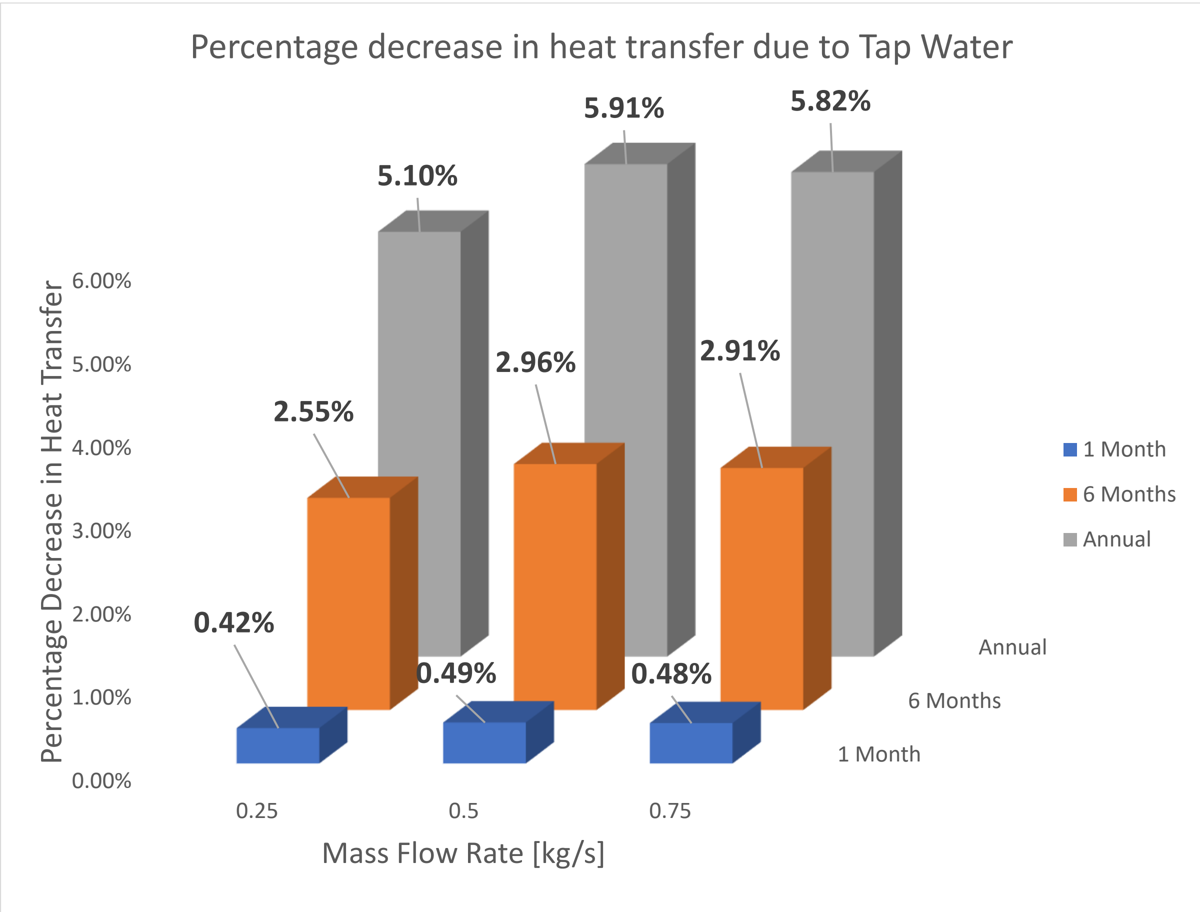

Figure 39: Percentage decrease in heat transfer due to Tap Water

The graph illustrates the percentage decrease in heat transfer effectiveness of a shell and tube heat exchanger when tap water is used, compared to a baseline (distilled water) over different periods (1 month, 6 months, and annually) and at various mass flow rates (0.25 kg/s, 0.5 kg/s, and 0.75 kg/s).

5.7 Analysis:

1. **Effect of Time on Heat Transfer Decrease**:
   - **1 Month (Blue Bars)**:
     - For all mass flow rates, the decrease in heat transfer is minimal after 1 month.
     - The percentage decrease ranges from 0.42% to 0.49%.
   - **6 Months (Orange Bars)**:
     - The decrease in heat transfer becomes more significant over 6 months.
     - The percentage decrease ranges from 2.55% to 2.96%.
   - **Annual (Grey Bars)**:
     - The annual decrease in heat transfer is the most pronounced.
     - The percentage decrease ranges from 5.10% to 5.91%.
2. **Effect of Mass Flow Rate on Heat Transfer Decrease**:
   - **0.25 kg/s**:
     - The percentage decrease is relatively higher at lower mass flow rates.
     - Annual decrease: 5.10%, 6 months: 2.55%, 1 month: 0.42%.
   - **0.5 kg/s**:
     - The percentage decrease is slightly lower compared to 0.25 kg/s.
     - Annual decrease: 5.91%, 6 months: 2.96%, 1 month: 0.49%.
   - **0.75 kg/s**:
     - The percentage decrease is similar to 0.5 kg/s but slightly less in the long term.
     - Annual decrease: 5.82%, 6 months: 2.91%, 1 month: 0.48%.

Interpretation:

- **Initial Period (1 Month)**:
  - The minimal decrease in heat transfer effectiveness after 1 month indicates that using tap water has a negligible impact in the short term.
- **Medium Term (6 Months)**:
  - The noticeable increase in the percentage decrease over 6 months suggests that deposits or scaling from tap water start to impact the heat exchanger.

- **Long Term (Annual)**:
    - The significant percentage decrease over a year shows that prolonged use of tap water can considerably reduce the heat exchanger's effectiveness due to scaling and fouling.
- **Mass Flow Rate Influence**:
    - Lower mass flow rates (0.25 kg/s) show a higher percentage decrease in heat transfer over time compared to higher flow rates (0.5 kg/s and 0.75 kg/s). This suggests that higher flow rates might mitigate some of the fouling effects by reducing the residence time of water in the heat exchanger tubes, thus limiting scale formation.

When tap water is used in the tubes of a shell and tube heat exchanger, its effectiveness decreases over time due to scaling and fouling. The impact is more pronounced over longer periods and at lower mass flow rates. In contrast, distilled water would likely result in a lower decrease in heat transfer effectiveness, maintaining better performance due to the absence of minerals and impurities that cause scaling. This highlights the importance of using clean water and possibly implementing regular maintenance or water treatment measures to ensure optimal performance of the heat exchanger.

However, based on this two-week data, annual projection is predicted that it results in 5.6% decrease in heat transfer every year if tap water is used instead of distilled water. The duration of data collection is kept small for the overall health of heat exchanger. As the prolonged period could have caused scaling, coagulation, rusting and choke points etc.

Chapter-6: Conclusion and Recommendations

6.1 Conclusion

In this thesis, a new type of heat exchanger with a new baffle design was investigated. The heat exchanger was of shell and tube type with parallel flow. The baffle used in this study had three openings on the shell side and seven on the tube side. The performance of the heat exchanger was tested with cold and hot waters at different temperatures. It was also originally found that the performance of the heat exchanger was not up to the mark. Initially it was observed that during fabrication, the tubes were painted, and this caused low thermal performance. After removing the said paint from the copper tubes, the performance improved. The heat exchanger, however, still did not perform better than the models existing in literature. It is recommended as future works to change the configuration to counter flow and pressurize the fluid to get better results. It is also observed that the heat exchanger has lower values than hot working fluid. This is also an area that should be improved in the future if significant research output is required from this heat exchanger.

6.2 Future Research & Potential Applications

This study shows the 3-zonal tre-foil baffle is a viable alternative to the conventional segmented baffle. Further research should explore its full potential, like long-term durability, material optimization, customization for specific apps, & integration with advanced heat exchanger designs. By advancing the tre-foil baffle, it could become a standard in high-performance heat exchangers, driving energy savings & operational efficiency.

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