Design and Manufacturing of a Shell and Tube Heat Exchanger

A Final Year Project Report

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Bachelors of Mechanical Engineering

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ABSTRACT

This study examines a novel baffle design for the Shell and Tube Heat Exchangers. The traditional baffle design provides high heat transfer, but there is also too much pressure drop. The research suggests a novel baffle design to solve these restrictions while maintaining the structural integrity of the heat exchanger. Physical testing and simulations were done to compare the new baffle design to the old one. Simulations used computational fluid dynamics (CFD) software, while actual tests measured heat exchanger temperature and pressure drop. Physical studies and calculations indicated that the new baffle design had a slightly lower heat transfer rate and a substantially smaller pressure drop compared to the conventional segmented design. The innovative baffle design may increase Shell and Tube Heat Exchanger performance and provide a valuable research area.

ACKNOWLEDGMENTS

We would like to express our gratitude to everyone who has contributed to the successful completion of this thesis.

First and foremost, we would like to thank our supervisor, Dr Muhammad Sajid, for their invaluable guidance and support throughout the research process. Their expertise and knowledge have been instrumental in helping us to develop our research and to complete this paper.

We would also like to thank all our colleagues and peers for their valuable feedback and suggestions throughout the project.

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Abbreviations

Shell and Tube Heat Exchanger (STHE)

Nomenclature

B	Baffle Spacing
D_o	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

1 Introduction

1.1 Heat Exchanger

A heat exchanger is a device that allows heat energy to be transferred from one medium to another. Heat exchangers are utilized in many different applications, such as air conditioning, refrigeration, and power production. Heat exchangers are utilized in a variety of industrial operations, including chemical and petrochemical processing, as well as the automobile and aerospace sectors. Heat exchangers are usually made of metal, such as aluminum, copper, or stainless steel, and can be air- or water-cooled. Heat exchangers are used to transmit heat from one medium to another while preventing the two mediums from mixing. This is performed by separating a sequence of tubes or plates by a barrier, such as a gasket or a thin sheet of metal. Heat is moved from one medium to another across the barrier, and the heat exchanger is designed to enhance heat transfer efficiency.

1.2 Types of Heat Exchangers

The main types of heat exchangers are listed below:

– **STHEs:**
  A STHE is a type of heat exchanger that is made out of a cylindrical shell with a number of tubes running through it. The walls of the tubes transfer heat from one fluid to another. The fluids can be either liquid or gas, and the STHE can either heat or cool them. The operation of a STHE is based on the notion that heat is transferred from the hotter fluid to the cooler fluid when two fluids of different temperatures come into contact. As the hotter fluid travels through the tubes and the cooler fluid flows through the shell, heat transfer occurs. The surface area of the tubes, the temperature differential between the two fluids, and the flow velocity of the fluids all influence the heat transfer rate.

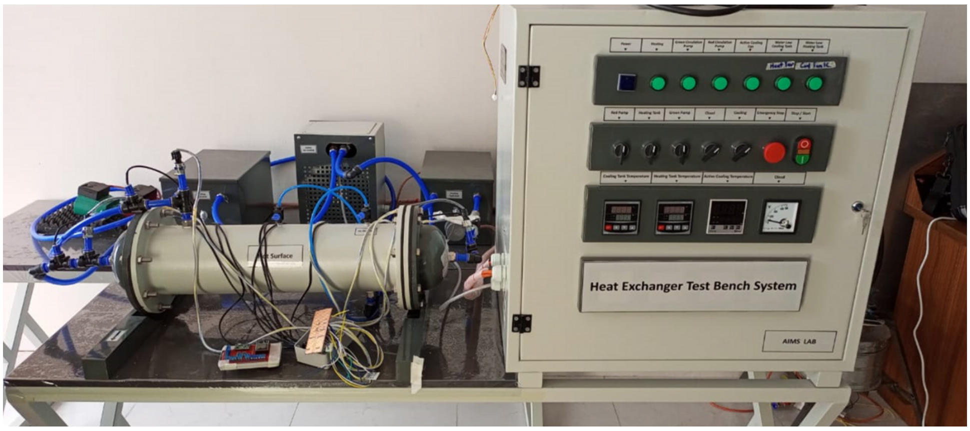

Figure 1: Available Shell and Tube Heat Exchanger Apparatus

– **Plate Heat Exchangers:**
  A plate heat exchanger is a type of heat exchanger that uses metal plates to transfer heat between two fluids. A frame and a series of corrugated plates comprise the plate heat exchanger. Gaskets are attached to the plates, creating path-

ways for the fluids to flow through. The fluids flow in opposing directions, and heat is transferred between them via the plates. The plate heat exchanger is more efficient than normal STHEs because it has a larger surface area for heat transmission. The plate heat exchanger can also handle high-pressure and high-temperature applications.

– **Finned Tube Heat Exchanger:**
  A finned tube heat exchanger is a type of heat exchanger that uses fins to increase the surface area of the tubes, allowing for more efficient heat transmission. Fins are often made of metal and attached to the outside of tubes. Heat is transferred from one fluid to another through the tube walls, and the fins help with this by increasing the surface area of the tubes. The fins help reduce pressure loss across the exchanger, increasing its efficiency. A finned tube heat exchanger works by transferring heat from a hotter fluid to a cooler fluid. Heat is transferred from the hotter fluid to the fins, which then transfer the heat to the cooler fluid.

1.3 Compnents of a STHE

The basic components of a STHE are:

– Shell: This is the outer casing of the heat exchanger. It is usually cylindrical in shape and is made of metal such as stainless steel or carbon steel.

– Tube Bundle: This is the inner part of the heat exchanger and consists of a number of tubes arranged in a specific pattern. The tubes are usually made of stainless steel or other corrosion-resistant materials.

– Tube Sheet: This is a flat plate that is welded to the shell and holds the tubes in place.

– Tube Support Plates: These are plates that are welded to the tube sheet and provide support for the tubes.

– Tube Nuts: These are nuts that are used to secure the tubes to the tube sheet.

– Tube End Plugs: These are plugs that are used to seal the ends of the tubes.

– Baffles: These are plates that are used to direct the flow of the fluids inside the heat exchanger.

– Headers: These are pipes that are used to connect the inlet and outlet of the heat exchanger.

In an heat exchanger, the baffles and tubes are two components that researchers are particularly interested in studying. A heat exchanger is equipped with something called a baffle, which is a device used to boost the fluid velocity and turbulence of the fluid that is moving through the heat exchanger. By expanding the surface area of contact between the two fluids in this way, the rate at which heat is transferred may be made more efficient. In addition, baffles serve to cut down on the pressure drop across the exchanger, which in turn lowers the operating costs of the machine. The process of heat transfer from one fluid to another makes use of heat exchanger tubes. The tubes, which are often fabricated from metals such as copper, stainless steel, or aluminum, are organized in a certain way in order to maximize the surface area that is available for the transfer of heat. These two aspects will be examined in further depth.

1.4 Baffles

The entire efficiency of the heat transfer process may be significantly improved by installing baffles within a heat exchanger, which makes baffles an essential part of this device. The rate of heat transmission can be increased by using baffles, which generate turbulence in the flow of the fluid that they move through. Because turbulence increases the surface area of the fluid that is exposed to the heat source, more heat is able to be transmitted. This is because the surface area rises.
The baffles of a heat exchanger are almost always constructed of metal and are arranged in a certain design inside the device. This pattern is intended to produce a turbulent flow of the fluid, which enhances the rate at which heat is transferred from one location to another. In most cases, the baffles are laid out in a pattern that resembles a staggered grid, with the baffles alternating between orientations that are parallel to the flow of the fluid and orientations that are perpendicular to the flow. A turbulent flow is produced as a result of this staggered pattern, which results in an increased rate of heat transfer.
In a heat exchanger, baffles can also aid to lessen the pressure drop that occurs over time. This is because the baffles produce a bigger surface area for the fluid to pass through, which in turn minimizes the pressure drop that occurs as a result of the fluid moving through the system. This is significant because it contributes to a reduction in the amount of energy that is needed to transport the fluid through the heat exchanger.
In order to decrease the likelihood of the heat exchanger becoming fouled, baffles are another component that may be utilized. The term "fouling" refers to the phenomenon in which particles in the fluid get adhered to the walls of the heat exchanger, hence lowering the effectiveness of the process of heat transfer. A turbulent flow of the fluid is created by the baffles, which helps to keep the particles floating in the fluid and prevents them from clinging to the walls of the heat exchanger. This helps to limit the danger of fouling, which may cause damage to the heat exchanger.
In conclusion, baffles are an essential part of a heat exchanger since their function is to make the process of heat transfer more effective, which makes them a significant component. The turbulent flow of the fluid that is produced by baffles contributes to an increase in the rate of heat transfer and a reduction in the pressure drop. The particles are able to remain suspended in the fluid thanks to the baffles, which further helps to prevent the likelihood of the heat exchanger becoming fouled.

1.5 Tubes

An essential part of a heat exchanger are the tubes that are employed. There are many different uses for heat exchangers, some of which include the cooling systems in vehicles as well as the operations in industrial settings. Heat exchangers typically make use of tubes because these components offer several benefits, including a wide surface area for the transmission of heat, a low overall cost, and the ability to be installed and maintained with ease.
Heat exchangers cannot function without tubes because the tubes facilitate the creation of a wide surface area for the transmission of heat. Heat exchangers function because

heat is transferred from one medium to another. The greater the surface area, the more effectively heat may be transferred from one medium to another. Because they are hollow and enable heat to go freely through them, tubes provide a huge surface area that may be utilized for the transfer of heat. Heat exchangers may be made more effective by having a greater surface area, since this enables a greater quantity of heat to be transported in a shorter period of time.

In comparison to the cost of other components used in heat exchangers, tubes provide a very affordable option. Because of this, they are an alternative that is beneficial in terms of cost for a variety of applications. In addition, tubes are simple to set up and take care of, which makes them a well-liked option for the construction of many different kinds of heat exchangers.

Last but not least, tubes may be purchased in a number of different materials, which enables them to be utilized in a broad variety of contexts. Because of their unique combinations of characteristics, such as resistance to heat and corrosion, heat resistance, and thermal conductivity, different kinds of materials are ideally suited for specific kinds of tasks.

As a conclusion, tubes are a crucial component of heat exchangers because of the huge surface area they provide for the transmission of heat, their low cost, the simplicity with which they can be installed and maintained, and the availability of tubes made from a range of materials. They find employment in a wide number of applications, from the heating and ventilation systems in homes to the manufacturing procedures in factories.

1.6 Problems With Current STHEs

Although Heat Exchangers have been around for quite some time now, they still have some shortcomings. Some of these problems afced by modern STHEs are listed below:

– Low Heat Transfer Efficiency: The current STHEs have a low heat transfer efficiency due to the large thermal resistance of the tube walls.

– High Pressure Drop: The current STHEs have a high pressure drop due to the large number of tubes and the small diameter of the tubes.

– Fouling: The current STHEs are prone to fouling due to the accumulation of deposits on the tube walls.

– Limited Heat Transfer Area: The current STHEs have a limited heat transfer area due to the limited number of tubes and the small diameter of the tubes.

– High Maintenance Costs: The current STHEs require frequent maintenance due to the fouling and the need to periodically clean the tubes.

Heat transfer and pressure drop in a STHE are the most important performance parameters. One wishes to keep the heat transfer rate as high as possible while keeping the pressure drop as low as possible. Heat Transfer and Pressure Drop are affected by several factors, including the type of fluid used, the size and shape of the tubes, the number of tubes, the type of tube material, the tube layout, the type of baffles, the type of end connections, the type of tube sheet, the type of tube support, the type of tube cleaning, the type of insulation, and the type of heat transfer medium.

Having explained the STHE, the main components which are the baffles and tubes, the problems with current heat exchangers are the desired performance parameters, the problem statement is not ready to be stated.

1.7 Problem Statement

The goal of this project is to improve the performance of a STHE by coming up with an improved design of baffles. This includes optimizing the baffle spacing, baffle configurations and the operating parameters such as flow rate, temperature, and pressure. The new design should result in a higher heat transfer rate or the same heat transfer at a lower shell side pressure drop.

2 Literature Review

The main focus of our project is to come up with a new and novel design for the baffle and tube configuration. As such, it was vital to conduct as much literature review as possible to get a comprehensive overview and recapitulation of the given scholarship on the topic of baffle and tube designs in a STHEs. The extensive literature review allows to gain an understanding of existing knowledge, identify gaps in the literature, and determine the direction of future research. The most important literature came across while conducting the review process has been listed down in the table below. This literature contained material that was closely linked and relevant to our approach. Some of the most relevant and insightful research papers that were closely linked to the project are listed below along with their important findings:

- Increasing of baffle spacing results in a decrease of pressure drop [3].
- The results of [4] show that the 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.

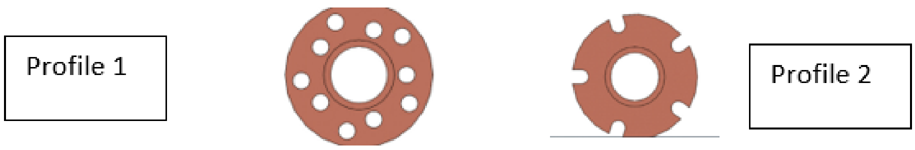

Figure 2: Fin Profiles

- The effectiveness rises as the intake hot water temperature and hot water flow rate rise as concluded by [5].
- 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 is advised in [6]
- CFD simulation results from [7] showed 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 [8].

The literature of great interest to the project and its findings are discussed below:

- **Novel Three-Zonal Baffle Design:**
  The three-zonal baffle [1] is shaped like a steering wheel with 3 almost elliptical holes towards the edges, having a rotational symmetry of 120°. The middle part includes the holes for tubes to pass through.

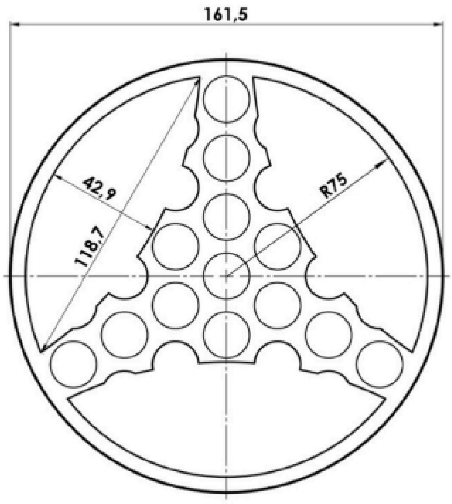

Figure 3: Three-Zonal Baffle [1]

- **Trefoil Baffle:**
  The trefoil baffle [2] has rather eccentric tube holes. 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 4: Trefoil Baffle [2]

- **Comparison of Performance Parameters of the Three-Zonal and Trefoil Baffles:**
  The following graph 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 [1] and [2]. From the graph, it can be seen that the trefoil baffle has considerably high heat transfer but much higher pressure drop. The three-zonal baffle on the other hand has much lower pressure drop but also much lower heat transfer.

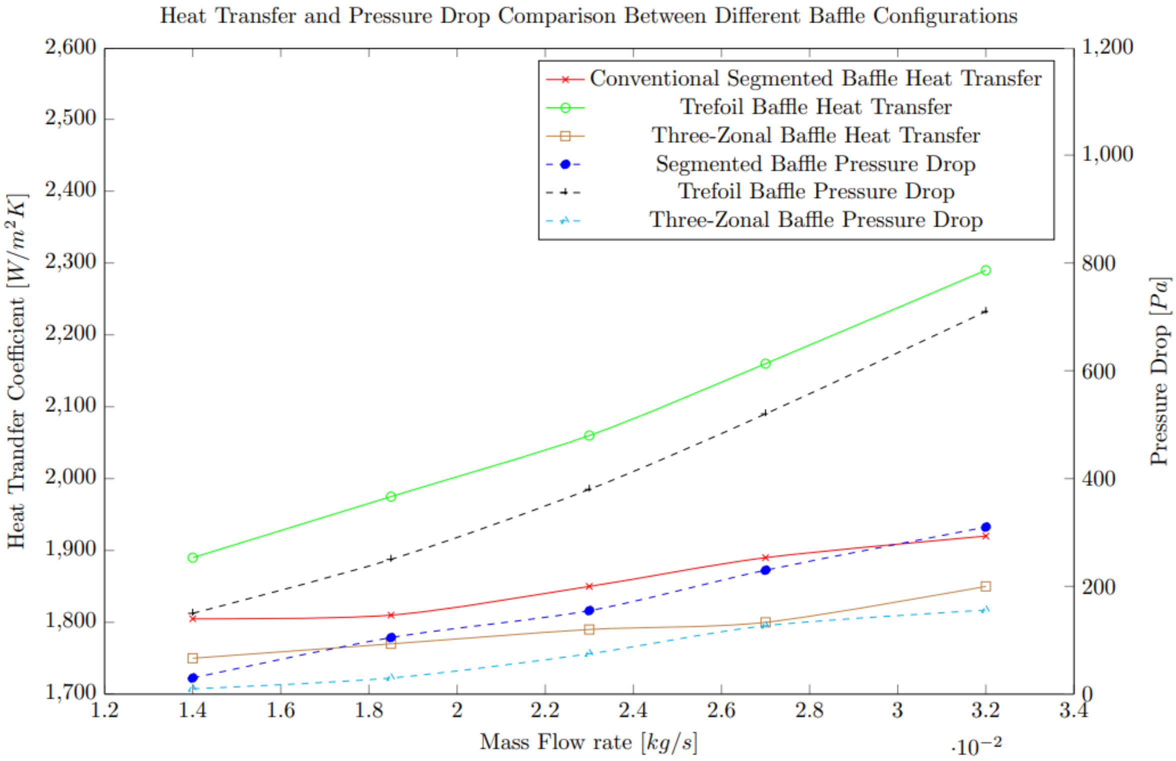

Figure 5: Comparison of Three-Zonal and Trefoil Baffles

3 Design

3.1 The Baffle

The baffle design chosen was a combination of the two baffles looked before in the literature review section. These were the three-zonal and trefoil baffles. A trefoil baffle had a much larger heat transfer coefficient. This was mostly due to the holes in the trefoil baffle. The holes are made so that they aren't perfectly circular but instead reduce the contact of the baffle with the tube. This allows for more contact of the fluid with the tubes and thereby making the heat transfer better. A three-zonal baffle on the other hand has much lower pressure drop. This is due to the three huge open spacing in the baffle which allows for the fluid to pass through without much interruptions. The less baffle area allows for fluid to easily pass through. One of the spacing is also always downwards which also contributes to the lower pressure drop.
By combining the good features of both the baffles, one can get a baffle which may overtake the conventional segmented baffle by having better heat transfer and a lower pressure drop. This is done by designing a new three-zonal trefoil baffle which retains the tube holes of the trefoil baffle to allow for maximum contact of the fluid with the tubes and has three large open spacings with a rotational symmetry of 120° to allow for the uninterrupted flow for a lower pressure drop. The design model is shown below.

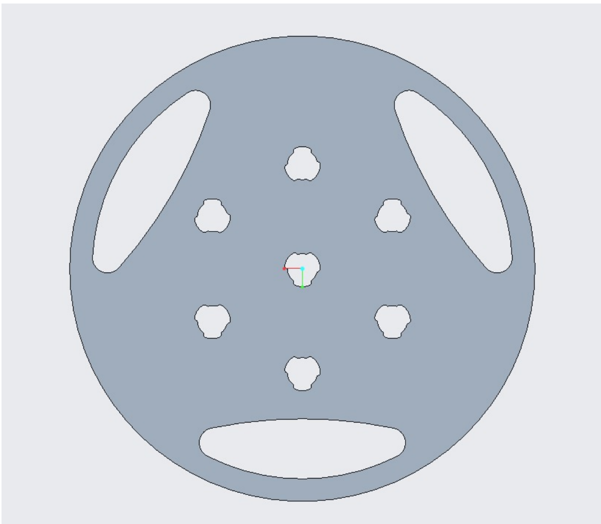

Figure 6: Three-Zonal Trefoil Baffle Proposed Design

3.2 Dimensions of the New Baffle

The dimensions of the new baffle design were rather restricted as the diameter was constrained to match the inner diameter of the shell of the already available STHE setup. The hole size was constrained to match the already available tube diameters. The trefoil hole dimensions were changeable along with the size of the three outer big holes. The finalized baffle design with its dimensions is shown below:

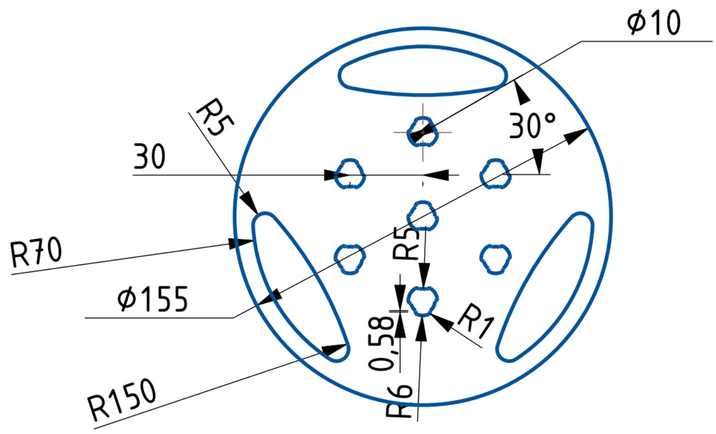

Figure 7: Three-Zonal Trefroil Baffle Dimensions

3.3 Cross section of tubes

Copper tubes with circular cross section were chosen because of their availability. Tubes with fins or a different cross section are much more efficient because of their increased surface area but they are difficult to manufacture and are not available in market.

3.4 Number of tubes

The number of tubes selected for the testing of baffle design is 7. The reason for selecting 7 is because it is the minimal number of tubes with which all the different tube arrangements can be tried. Increasing the number of tubes will complicate the analysis and will also increase the material cost and simulations to be performed. Furthermore, there are a lot of research paper on baffle design in which the same number has been selected so the comparison becomes easy and the number of simulation required will also decrease.

3.5 Arrangement of tubes

There are a number of tube arrangement from which one can select. The arrangements include:

– rectangular

– rotated rectangular

– 30° rotated triangular

– 60° rotated triangular

The arrangement chosen for our design was the 30° rotated triangular as it results in the maximum amount of heat transfer. the horizontal tube pitch was kept 30 mm to enable easy comparison with the research papers and experimental data.

D_s	156 mm
D_o	10 mm
t	1 mm
Tube bundle geometry and pitch	30° Rotated Triangular, 30 mm
N_t	7
L	612 mm
T	25°
B	72 mm
N_b	6

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

3.6 Number and spacing of baffles

According to [9] the optimal baffle spacing lies somewhere between 0.3 to 0.6 times the internal diameter of shell. Using these results the number of baffle were selected to be 6. For simulations the baffle spacing was set to 72 mm The optimal spacing will be determined during practical experimentation.

3.7 Material of tubes

Copper tubes were selected for the analysis as they are available in market in different sizes and they also have good heat transfer capabilities. Furthermore, most of the research paper involving STHE with fluid on both sides had copper tubes.
The complete tube bundle design with the six baffles and the seven tubes passing through is shown below:

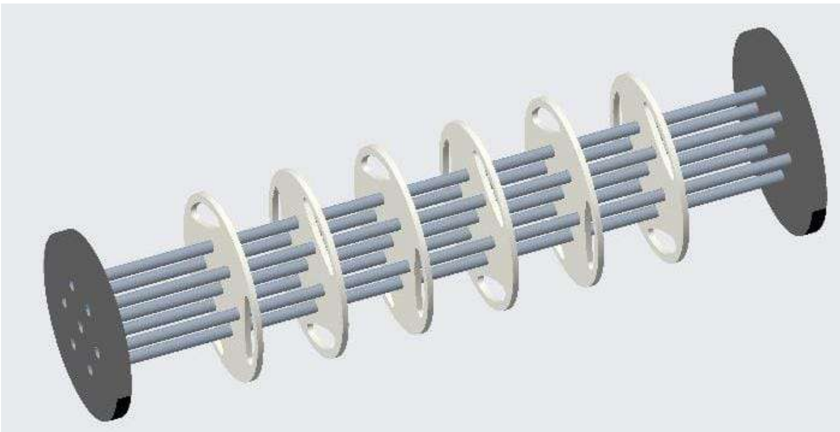

Figure 8: Tube Bundle Design

4 Methodology

4.1 Simulation

For simulation a SimScale (a cloud based simulation platform) was used because of low computing power at our disposal. To select a design, simulation for only the shell side fluid was done and the tubes were given a constant temperature. When the design was finalized then both the shell side and tube side analysis was done.

4.1.1 Boundary conditions

The desired mass flow rate and temperature values are assigned to the inlet nozzle of the heat exchanger. The shell inlet temperature is set to 45°. The tube inlet temperature is set to 55°. Zero gauge pressure is assigned to the outlet nozzle, in order to obtain the relative pressure drop between inlet and outlet. The inlet velocity profile is assumed to be uniform. No slip condition is assigned to all surfaces. The zero heat flux boundary condition is assigned to the shell outer wall, assuming the shell is perfectly insulated outside. The flow rate in the tube side was kept constant in all the simulation @ 0.4167 kg/s because this is the flow rate that the pump available on the test bench can provide. The shell side flow rate was changed from 0.25 kg/s to 0.75 kg/s with the increment of 0.25 kg/s. The same boundary conditions were applied to simple segmented baffle with a 25% cut.
The CFD Methodology is summarized in the flow chart below:

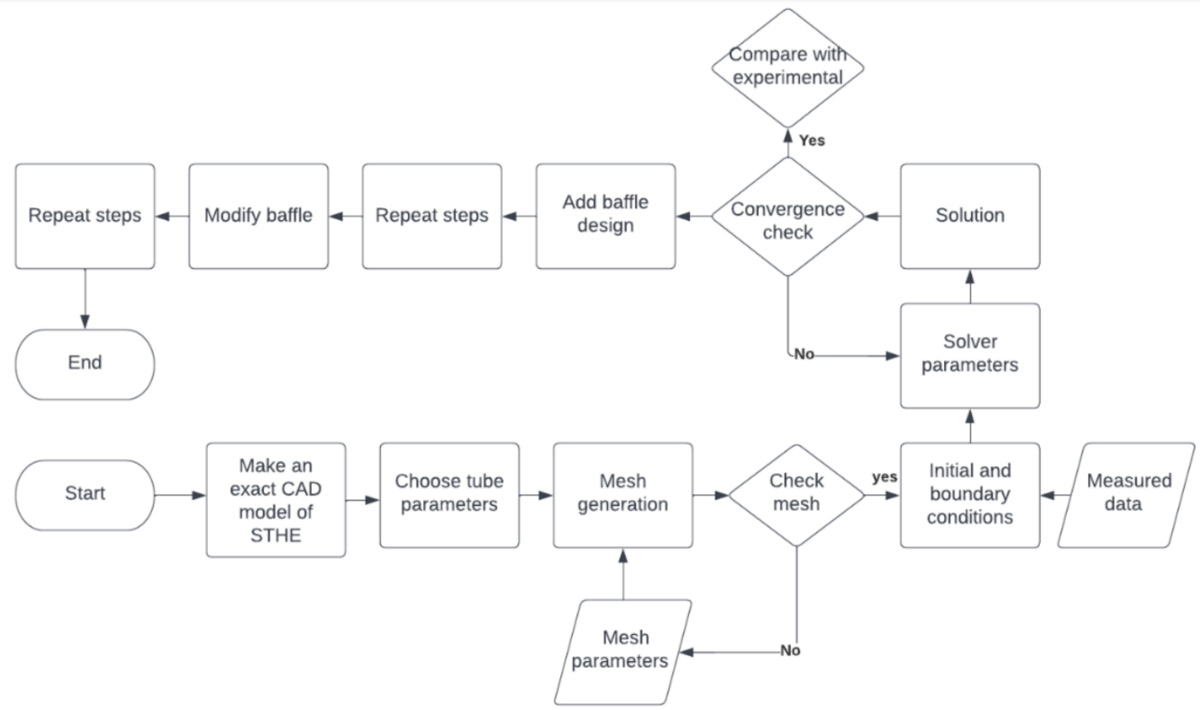

Figure 9: CFD Methodology

4.1.2 Mesh

Because of the complexity of the geometry standard meshing algorithm was used with some refinement parameters and inflation is added to the boundaries to better predict the flow near walls. The mesh with approximately a little more than 9.5 million elements and 2.5 million nodes was formed.
A general view of the overall mesh formed is shown below. The mesh between two

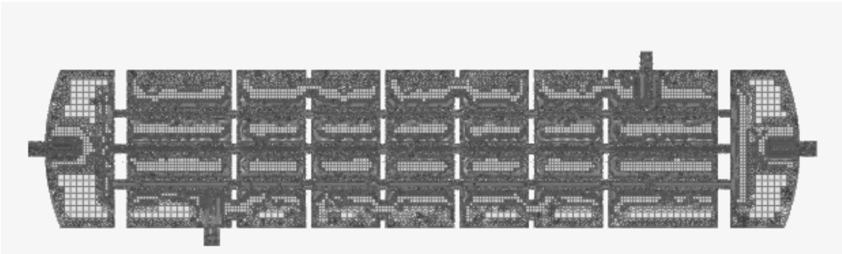

Figure 10: Overall Mesh

baffles is shown. The left baffle is attached dowanwards while the right side baffle is attached upwards.

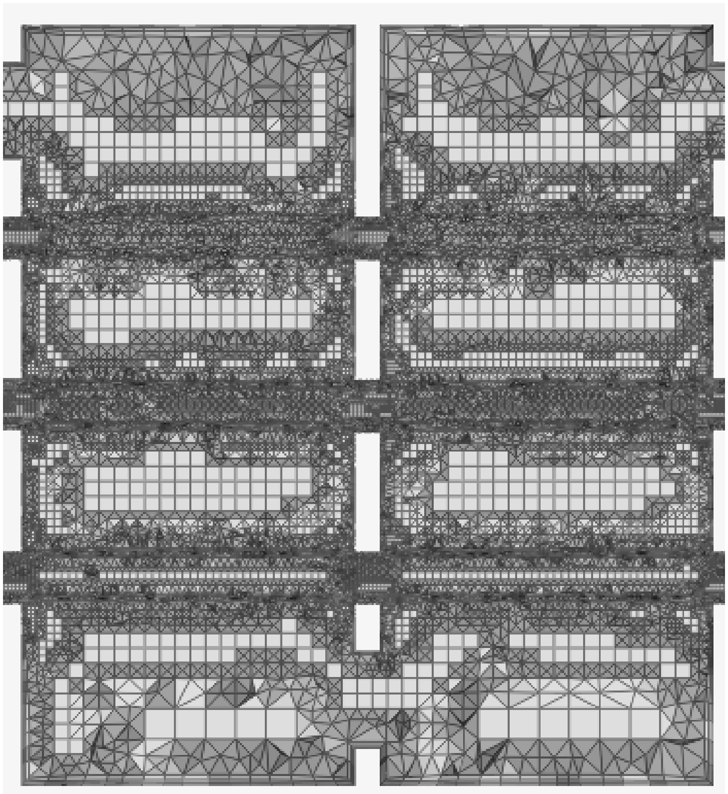

Figure 11: Mesh Between two baffles

The mesh below shows the cuts inside the three-zonal trefoil baffle. The mesh at the

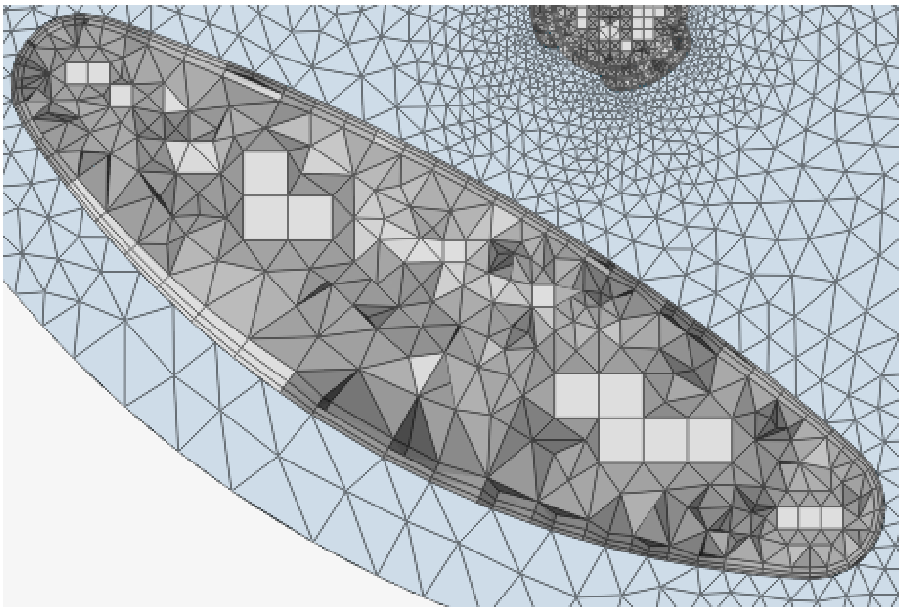

Figure 12: Mesh of the cuts in the baffle

inlet and outlet of the shell side fluid is shown.

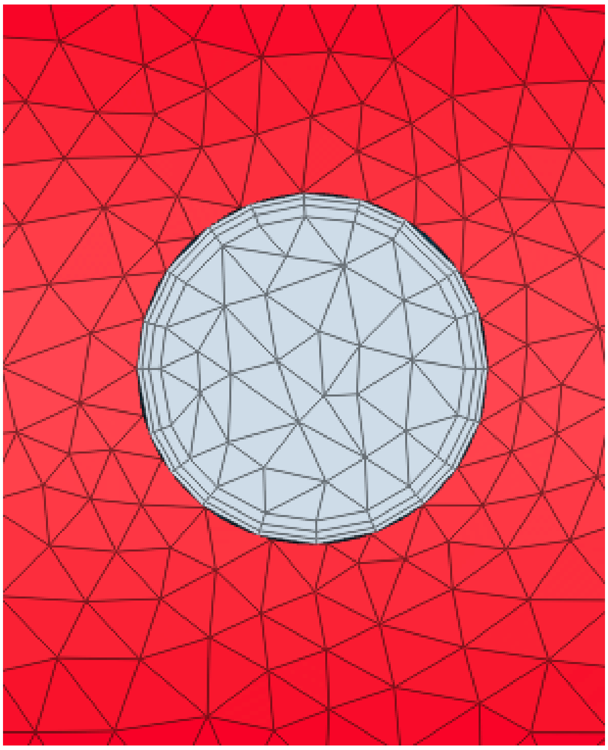

Figure 13: Mesh at the inlets and outlets of the shell side fluid

The mesh formed between the tubes is shown. Areas around and near the tube have finer meshes compared to the dormant mid area which has coarse mesh. The mesh

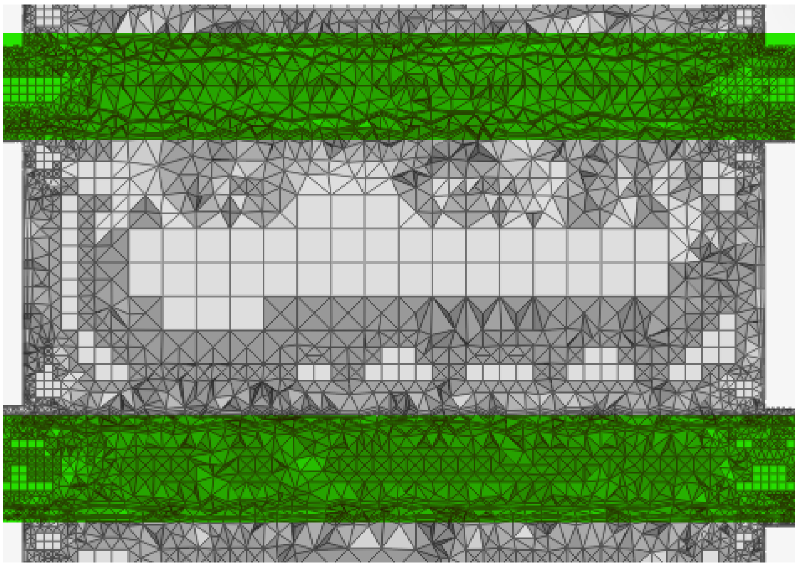

Figure 14: Mesh between the tubes

formed around the tubes is shown. Once again a finer mesh is observed around the tube area since this is a area of great interest hence the need for a finer mesh to get accurate result.

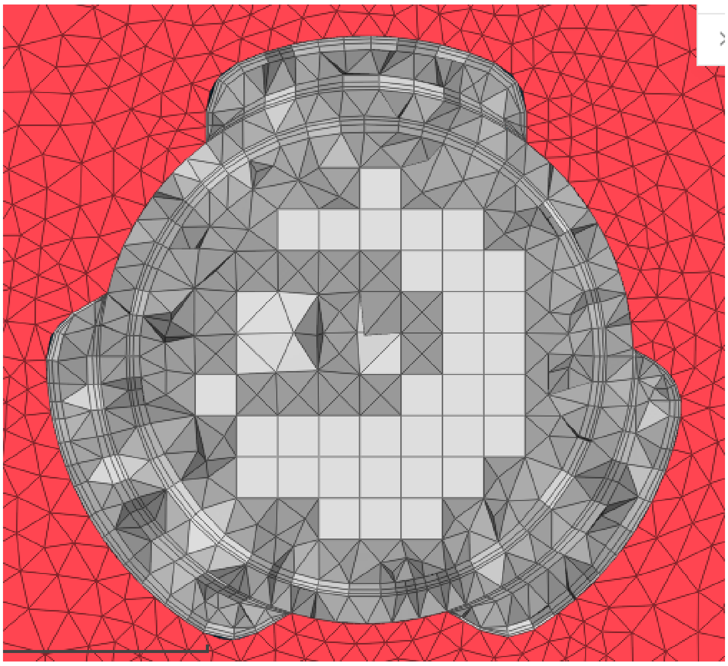

Figure 15: Mesh around the tubes

4.1.3 Simulation Results

The temperature distributions are shown below. This shows the temperature of the fluid at different stages of the flow. It is seen that the fluid generally gets hotter as it moves through the shell as expected. A much higher temperature is observed in regions closed to the tubes.

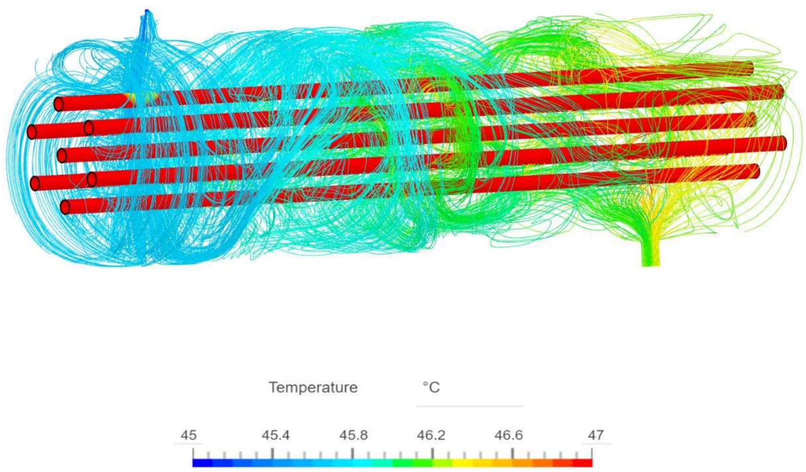

Figure 16: General Temperature Distribution

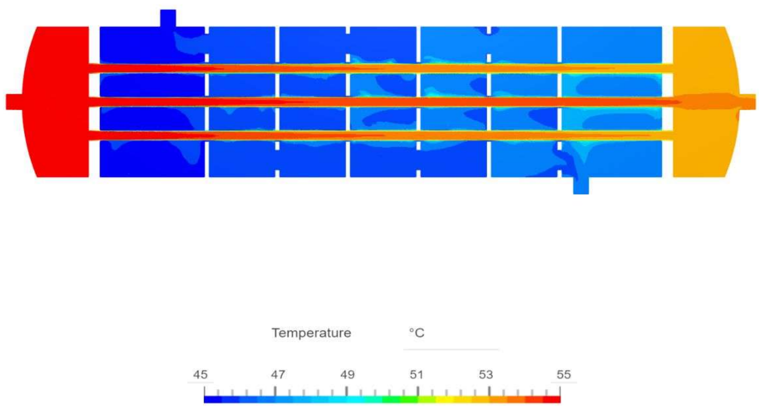

Figure 17: Temperature Distribution on Shell Side

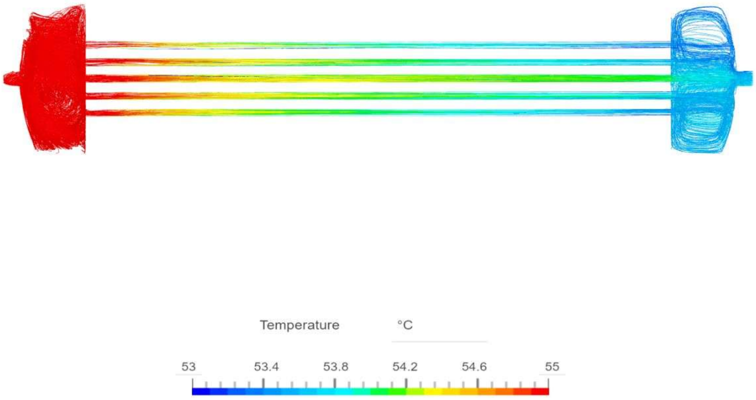

Figure 18: Temperature Distribution on Tube Side

The residual plot is shown below. It is a graphical representation of the difference between the observed values of a variable and the values predicted by a model. It is used to assess the accuracy of the model and to identify any patterns in the residuals that may indicate a need for further investigation.

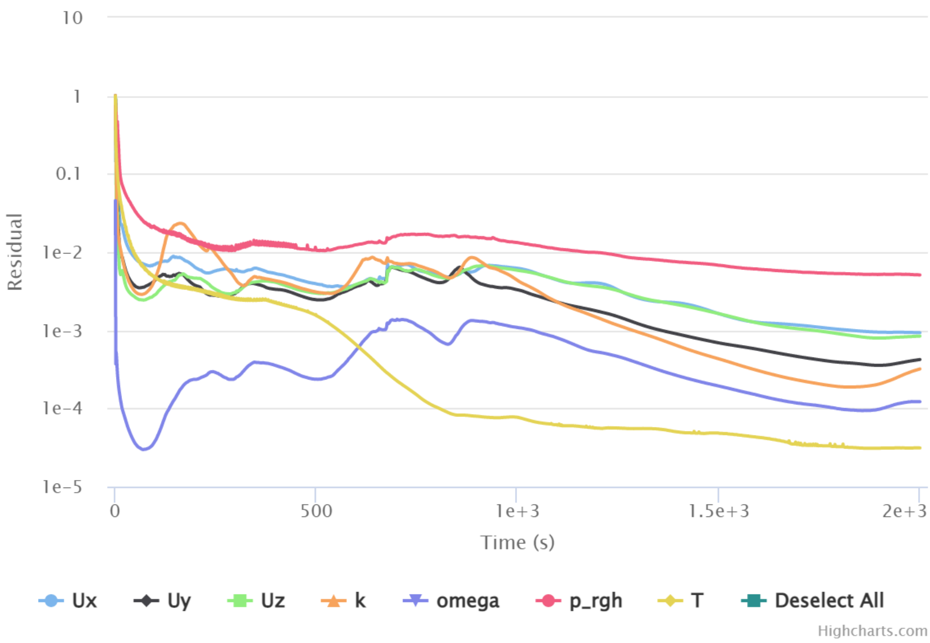

Figure 19: Residual plot

4.1.4 Turbulence Model

Because the flow in this investigation is turbulent, turbulence effects must be accounted for utilizing turbulence modeling. In CFD simulations, the choice of turbulence model is crucial. There is, however, no general criterion for choosing a turbulence model. The turbulence model employed in one research might not work in another. It is recommended to experiment with various turbulence models. For our simulation the SST k–ω turbulence model is used.

5 Results and Discussion

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

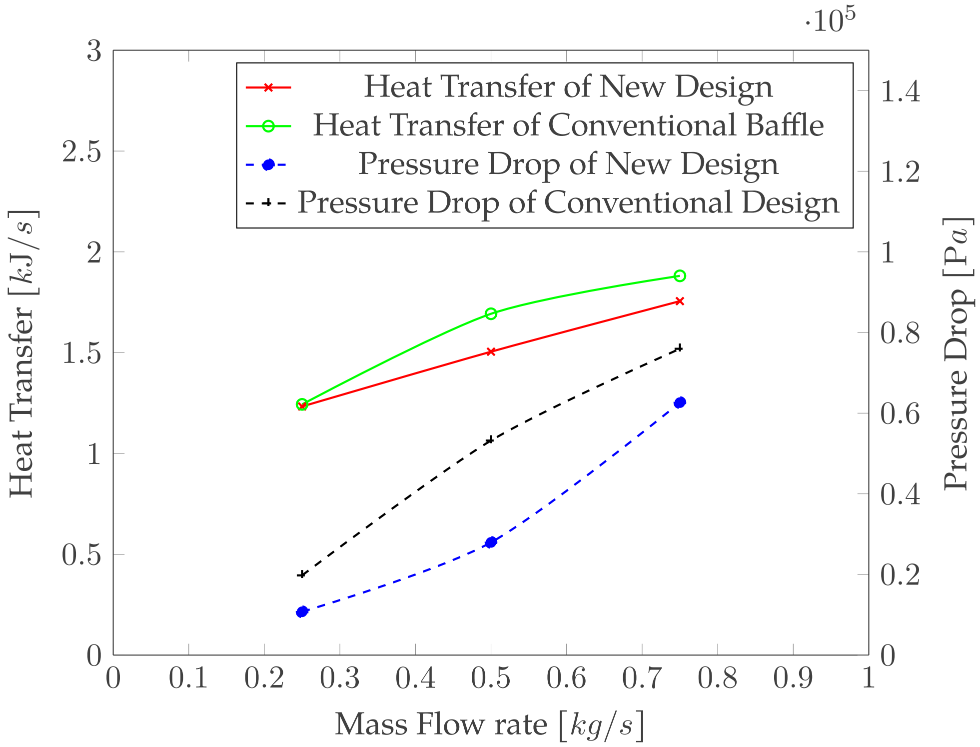

Figure 20: Comparison between two baffle designs based on Simulations

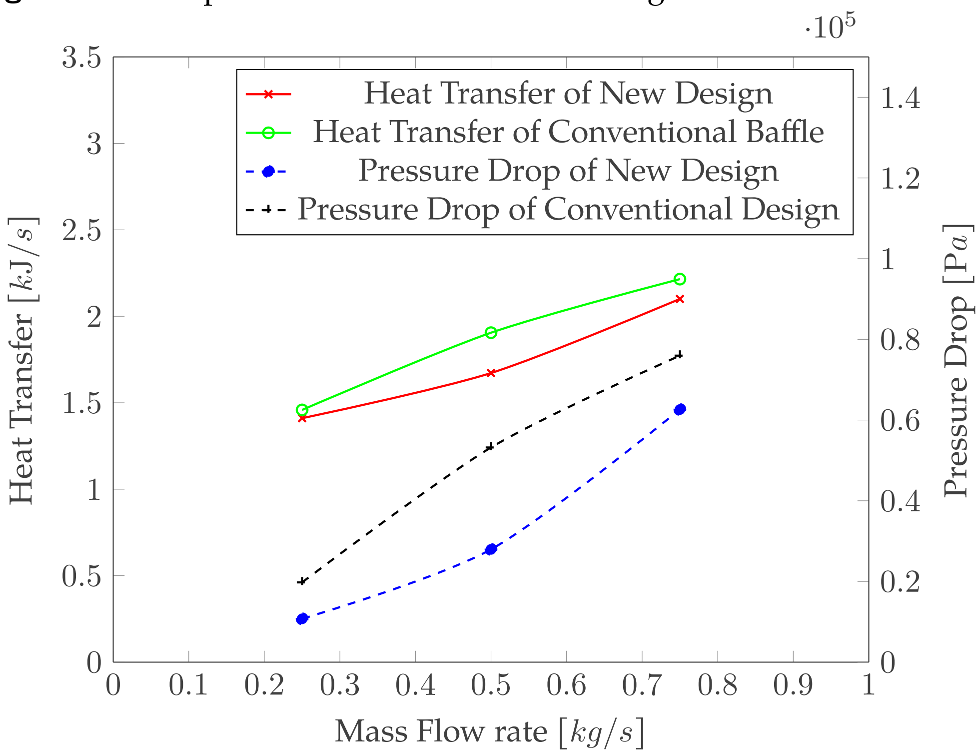

Figure 21: Comparison between two baffle designs based on Experimentation

The results of the experiments are that the three-zonal trefoil baffle outperforms the conventional baffle when it comes to a lower pressure drop. As for heat transfer, the new design seems to have a slightly lower heat transfer. Note though that the difference is almost negligible. Recall that the desired outcome is a higher heart transfer and a lower pressure drop, which means that overall a higher heat transfer per pressure drop is required. Comparing the heat transfer per pressure drop of the conventional and new baffle will clearly demonstrate the difference between the better of the two. The graph below shows the heat transfer per pressure drop for both the new and conventional designs:

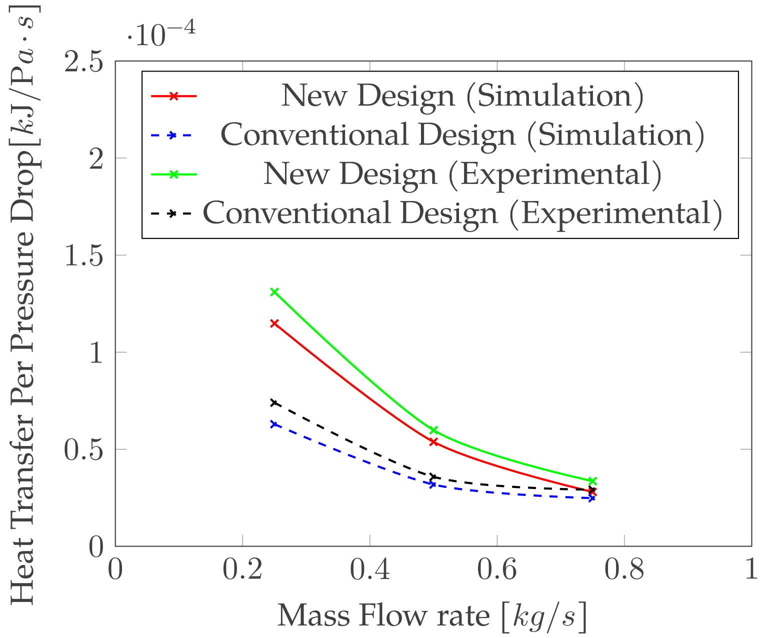

Figure 22: Heat Transfer By Pressure Drop

From the graphs, it is evident that the new design has a higher heat transfer per pressure drop compared to the conventional baffle. However, this is only valid for lower mass flow rate. As the flow rate increases to $0.75\,\mathrm{kg/s}$, the heat transfer per pressure drop of both the baffles seems to be equal. Therefore, it can be concluded that the new baffle design is a good alternative to the conventional one when one stays to a lower mass flow rate.

The new three-zonal baffle is an overall good alternative to the much used conventional segmented baffle. Helical baffles, which are generally regarded as better than segmented baffles are difficult to manufacture due to the curved surfaces. The three-zonal trefoil baffle has a simple design which is relatively much easier to manufacture.

6 Conclusion and Recommendations

It is concluded that the new proposed three-zonal trefoil baffle is a effective replacement for the conventional segmented baffle. The heat transfer per pressure drop of the new design is better than the segmented baffle while the pressure drop is much lower. The new design outperforms the conventional baffle for lower flow rates. At higher flow rates, both baffles perform the same. The new design also has the potential to reduce the cost of manufacturing and installation. The results of this study demonstrate that the new baffle design is a viable option for STHEs and should be further investigated for potential applications.
It is advised that innovative tube designs be examined, and then built so that they may be tested. This will allow for future research. The capabilities of the manufacturing processes available restricted the amount of testing that could be done with this project. If more advanced manufacturing processes had been readily available, it is possible that research into new tube designs would have also taken place, with the goal of further enhancing and improving the required characteristics.

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