CFD Simulation of Triangular Shape and Circular Shape Concentric Triple Tube Heat Exchanger

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Abstract. In the current study, the investigation of heat transfer and fluid flow Characteristics of Pure water when pass through an inner annulus triangular shape and circular shape triple tube heat exchanger (CTTHX). this investigation has been conducted across various Reynolds Number to gain insights into their performance also conducted a computational fluid dynamics (CFD) simulation using the ANSYS-FLUENT software. Result obtained was validated by comparing to empirical correlation data found in the existing literature. The investigation considered various operating variable as Reynolds Number and temperature across the inner, intermediate, and outer tubes. Specifically, the Reynolds Number of 2000 at 305 K, a range of 2000 to 4500 at 340 K, and 2000 at 295 K for the respective tubes. Key findings are that friction factor of triangular shape is increase by 10.5% and for circular shape by 2.69% as compared to correlation in existing literature. And Nusselt number (Nu) for triangular shape increase by 39.19% and for circular shape by 13.30% as compared to correlation in the range of Reynolds Number (Re) from 2000 to 4500. The effectiveness was increased by 16.67% and 7.6% for triangular shape and circular shape respectively as compared to existing literature.

Keywords: CFD, Thermal performance, Concentric, Triple Tube Heat Exchanger.

1. Introduction

Energy is an index to measure the growth of a nation Greater the energy consumption per capita greater is the development. The energy nowadays equivalent to currency Growing populations consumes more energy and energy consumption exerts demands on natural resources making them scarcer. Scarcer resources become harder to extract. If the current population growth rate continues, we'll need 50 percent more energy to sustain humanity by 2050. Energy is big challenge and this challenge can be meet by developing efficient device so we can convert wasted part of energy in useful part of energy. Researchers are still doing hard to come out with highly efficient Heat exchanger (HEX). HEX is a device in which transaction of heat takes place between two or more fluids at the expense of some power needed to initiate the flow in the device. Exchange of energy in this way is utilized in various industrial application and real-life application to meet the today's demand of energy and betterment of life standards of human being on this planet. A conventional double tube heat exchanger (DTHE) exchanging heat between two fluids is not sufficient to enhance heat transfer it need to increase the length having space limitation to come out by this drawback special type of heat exchanger is proposed that is triple concentric tube heat exchanger in this one more concentric tube is inserted in double tube heat exchanger now heat is exchanging between three fluids by inserting one more concentric tube we are increasing the surface areas. Quadir et al. [1] Various studies have reported notable enhancements in heat transfer using nanofluids, higher tube concentrations, and increased Reynolds numbers, improving overall heat exchanger performance. Gomaa et al. [3] Experimental research demonstrated a significant increase in effectiveness (around 53.8%) when using a TTHE compared to a double-tube heat exchanger, validating its superior performance. Gomaa et al. [4] Through their study, researchers effectively enhanced thermal efficiency by implementing semicircular ribs with a 90° inclination angle, resulting in a notable 15.7% improvement in the heat transfer coefficient. Bahiraei et al. [5] Novel computational analysis revealed substantial enhancement in heat exchanger effectiveness by integrating ribs and graphene-based nanofluid. [6] In the exploration of a hybrid nanofluid, the

heat exchanger's thermal performance is optimized with higher rib height, smaller rib pitch, and greater nanoparticle concentration, while energy efficiency is achieved with smaller rib height, lower rib pitch, and highest nanoparticle concentration. Giovannoni et al. [7] Through numerical analysis, researchers demonstrated that utilizing the triple-tube heat exchanger yields a higher heat transfer rate compared to the double-tube heat exchanger. The results revealed an 18% increase in the percentage of combustion heat transferred in the cold mixture, emphasizing the superior thermal characteristics of the triple-tube configuration. [8] Through numerical analysis, CuO/water nanofluids in a triple concentric-tube heat exchanger exhibited improved thermal performance and effectiveness with higher Reynolds numbers and nanoparticle volume concentrations. [9,10] The triple tube heat exchanger, formed by adding an intermediate tube, outperformed the double concentric-tube design due to increased heat transfer area. Three-fluid heat exchangers enable efficient thermal energy exchange between either identical or distinct fluid streams. Basavapoornima C et al. [9] The work investigates Pr 3+: PPbKANPr glasses for visible lasers and optical amplifiers. Glasses were made using the melt-cast method. FTIR and Raman techniques were used to study vibrational modes. Basava Poornima C et al. [10] The work investigates Pr 3+: PPbKANPr glasses for visible lasers and optical amplifiers. Glasses were made using the melt-cast method. FTIR and Raman techniques were used to study vibrational modes. Yadav S. et al. [11] This paper introduces a micro-TEG system that employs a micro combustion concept. Bhukya MN et al. [12] The research describes a novel PV inverter topology for optimal solar power use. It contains a new MPPT method that uses an artificial neural network to identify shading patterns, a SIMO converter, and a multilayer inverter. The MPPT system's performance is examined under partially shadowed situations. Vijayakumar Y et al. [13] ZnO thin films, doped/co-doped with Al, Fe, were deposited using optimized spray pyrolysis. XRD, TEM, and Raman spectroscopy characterized the films, revealing polycrystalline nature with a Wurtzite structure. Singh B et al. [14] This research provides a detailed analysis of aluminium metal matrix composites (AMMCs), focusing on their current state and future potential. Yue L et al. [15] To solve the issues of volume change and unstable structures in tin and antimony-based anode materials for sodium ion batteries, a thermochemical method is presented. Goud JS et al. [16] The study takes temperature and humidity ratio changes into consideration as driving forces for heat and mass transmission, as well as surface convection, radiation, and internal heat impacts. Reddy PV et al. [17] Tube hydroforming (THF) is widely used in manufacturing complex automobile parts. Internal pressure, axial feeds, material characteristics, and processing conditions are all critical parameters in the process. Design by simulation seeks to find an optimal and cost-effective procedure by modifying these factors to produce defect-free goods. Francis V et al. [18] FFF is a 3D printing process that deposits semi-molten thermoplastic material layer by layer according to a CAD model. FFF is commonly used for rapid tooling and prototyping, and with advancements in printable materials, it is also utilized for direct end-use applications. Misra RK et al. [19] The behavior of fabricated bogie frame structures in railway locomotives varies between un-heat-treated and heat-treated conditions, leading to susceptibility to cracks. Quantifying and analysing this variation are crucial for assessing the samples made of the same material under both conditions. Singh L et al. [20] CFD used to analyse parallel and counterflow shell and tube heat exchanger, studying temperature, velocity, pressure, and length. The cold-water temperature increased along the heat exchanger's length. Verma M et al. [21] Geopolymer concrete (GPC) is a sustainable and environmentally friendly alternative to conventional concrete. It forms a geopolymer bond, unlike regular concrete, which forms a calcium silicate hydrate bond.

2. Material and Methods

2.1 Definition of Heat Exchanger and nanofluids

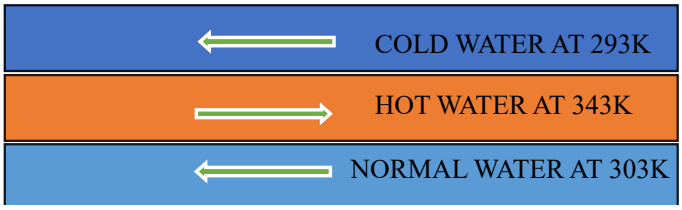

Figure 1 Direction of stream flow (Flow arrangements)

Figure 1 show the direction of stream flow in TTHX along the z-axis normal water is flowing in innermost tube, hot water is flowing in intermediate tube and cold water is flowing in outermost tube [22-25]. This is side front view of symmetric tube. This is counter flow TTHX in which intermediate fluid is moving in opposite direction of the direction of other two fluids. In this tube arrangement of fluid is in NHC (normal hot and cold). The three concentric tubes that make up the model's geometry are an innermost tube with diameters of $d_{i,i}$ and $d_{i,o}$, respectively; an middle tube with diameters of $d_{m,i}$ and $d_{m,o}$; and an outermost tube with diameters of $d_{o,o,}$ and $d_{o,o}$, respectively. The TTHX model configurations are shown in Fig. 1, and the geometry dimensions are provided in Table 1.

2.2 Design Modular Geometry of triangular triple tube heat exchanger

Table 1 Dimension of geometry.

Inner tube inner diameter(di,i)	22mm
Inner tube outer diameter(di,o)	30mm
Middle tube inner side (Sm,i)	34mm
Middle tube outer side (Sm,o)	47mm
Outer tube inner diameter(do,i)	70mm
Outer tube inner diameter(do,o)	78mm
Length of heat exchanger(L)	500mm

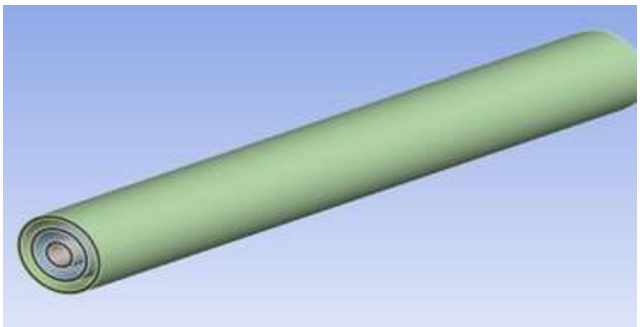

Figure 2 3D Design Modular Geometry.

2.3 Data calculation methodology

The computed variables and parameters are used to analyse the friction factor and Nu number in the TTHX when nanofluids are used [26-28]. These variables provide detailed insights into the data results.

It is possible to compute the heat transfer rate of hot, cold fluid, and normal fluids as follows:

$$\dot{Q}_h = \dot{m}_h \cdot c_h (T_{\text{ho}} - T_{\text{hi}}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$\dot{Q}_c = \dot{m}_c \cdot c_c (T_{c_o} - T_{c_i}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$$\dot{Q}_n = \dot{m}_n \cdot c_n (T_{n_o} - T_{n_i}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

The following formula can be taken to express the heat quantities for the TTHX's cold, normal, and hot fluid sides:

$$\dot{Q}_h = \dot{Q}_c + \dot{Q}_n \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

The following formula is used to evaluate the average heat transfer rate between the three fluids ($\dot{Q}_{avg}$):

$$\dot{Q}_{avg} = (\dot{Q}_h + \dot{Q}_c + \dot{Q}_n)/2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

The Nu and f correlation by V. Gnielinski.

$$Nu = \frac{\left(\frac{f}{8}\right)(Re - 1000)\Pr}{1 + 12.7\sqrt{\frac{f}{8}}\left(\Pr^{\frac{2}{3}} - 1\right)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

$$\text{Where } f = (1.82 \log Re - 1.64)^{-2} \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

The effectiveness of the TTHX (∈) is evaluated by Sekulic and Kmecko as:

$$\in = \frac{\dot{Q}_{avg}}{\dot{Q}_{max}} = \frac{\dot{Q}_{avg}}{mc_{min}\left(T_{h_i} - T_{c_i}\right)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

2.4 Numerical CFD modelling

In the pursuit of unveiling the enigmatic heat transfer and fluid flow characteristics of the remarkable TTHX (Triple Tube Heat Exchanger), the governing equations find solace through the meticulous application of FVM. The study employed a FVM with a (RNZ)k-ε turbulence model for simulating turbulent flows, accounted for conjugate heat transfer, used a pressure-velocity coupling method with the SIMPLE algorithm, applied a standard pressure discretization scheme, and utilized second-order upwind schemes to solve momentum and energy equations [29-31]. This comprehensive numerical approach allowed for investigation of the fluid flow characteristics and heat transfer within the TTHX, taking into consideration the complex interplay between heat transfer and fluid flow.

2.5 Grid Generation

Mesh generation is the process of dividing the computational domain into a number of distinct regions known as control volumes [32-34]. These control volumes serve as the focus of seeking the solution within the domain. In this works we have generated a structured mesh. It is a grid or network of geometrically regular and interconnected cells or elements that cover a physical domain. Each cell in a structured mesh is typically of the same shape (e.g., quadrilaterals in 2D or hexahedra in 3D), and the arrangement of cells follows a well-defined pattern or structure.

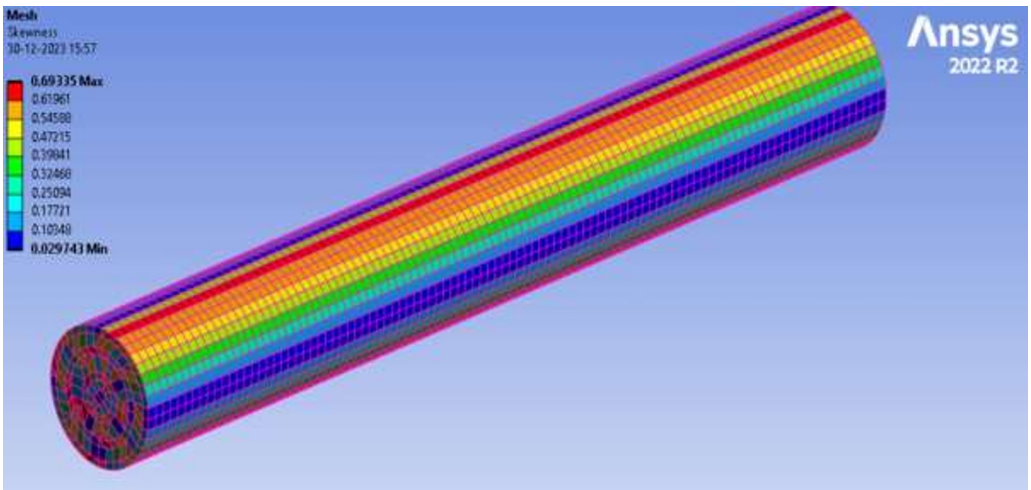

Figure 3 Three-Dimensional Model of Meshing.

Table 2 Mesh Description

Mesh matrix	
No. of elements	50852
Skewness maximum	0.69
Elemental quality	0.89

A 3D view of meshing is shown in figure 3 and mesh description is available in table 2 in which number of elements, maximum skewness and Elemental quality are tabled.

3. Result and Discussion

The heat transfer rate was optimized, ensuring effective exchange between the hot and cold fluids. The pressure drop was within acceptable limits, indicating smooth flow. Additionally, the temperature distribution analysis helped identify areas for potential improvement and achieving a more uniform heat distribution [35-37]. These findings contribute to enhancing the heat exchanger's design and industrial applications.

3.1) Validation and Verification of Data for TTHX

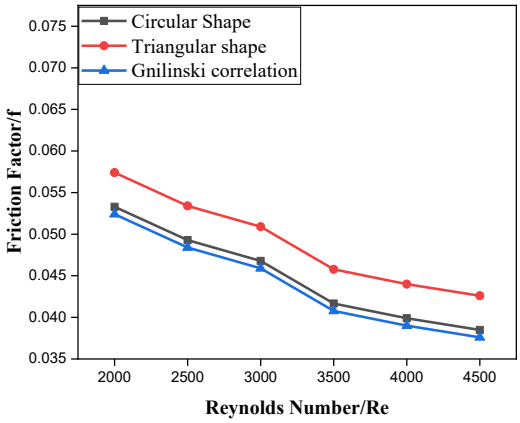

Figure 4 Friction Factor vs Reynolds Number

As the Re Number increases, the f decreases. This is because the Re number represents the ratio of inertial forces to viscous forces in a fluid flow. At higher Reynolds numbers, inertial forces dominate over viscous forces, resulting in a smoother flow with lower friction. Essentially, the fluid particles are better able to overcome resistance and move more freely through the system, causing a reduction in friction. This phenomenon can be attributed to the fluid's increased ability to maintain momentum and exhibit more streamlined behaviour. At a Reynolds Number (Re) of 2500 a 2.69% and 10.5% deviation occur for circular shape and triangular shape respectively from the correlation in existing literature.

3.2) *Nusselt number for* TTHX

When the Re number increases, the Nu number also tends to increase. The Nusselt number is a nondimensional parameter that relates the convection heat transfer rate to the conduction heat transfer rate in a fluid flow. As the Re number increases, the flow becomes more turbulent and chaotic. This turbulence promotes better mixing and increase the convective heat transfer. fluid flows in a manner that creates eddies and swirls, increasing the contact between the fluid and the solid surface. This increased contact area allows for more efficient heat transfer. Furthermore, the higher Reynolds number leads to the formation of a thinner boundary layer, which is the region of flow closest to the solid surface where velocity changes occur. A thinner boundary layer implies reduced thermal resistance and improved heat transfer. Nusselt number (Nu) for triangular shape increase by 39.19% and for circular shape by 13.30% as compared to correlation in the range of Reynolds Number (Re) from 2000 to 4500. Overall, the increased turbulence, improved mixing, larger contact area, and thinner boundary layer that accompany higher Reynolds numbers result in greater convective heat transfer. Consequently, the Nu number improve as the Re number increases.

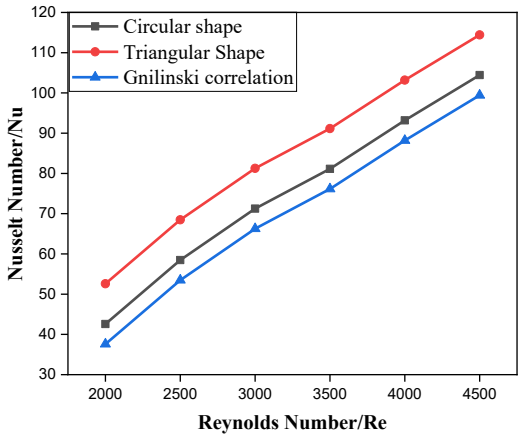

Figure 5 Nusselt Number vs Reynolds Number

3.3) Effectiveness of TTHX

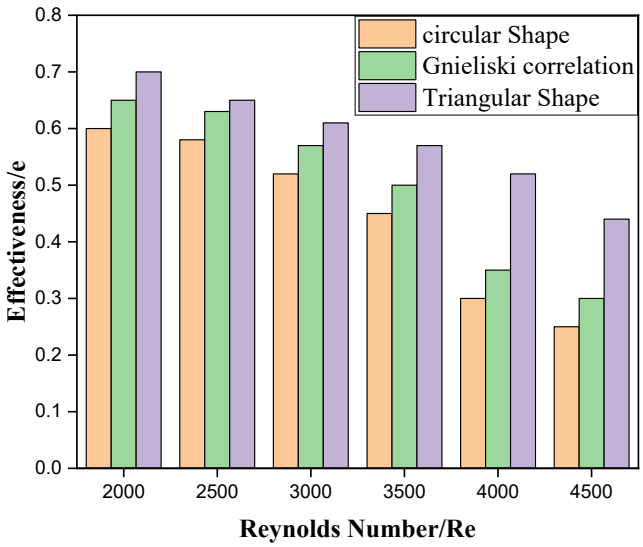

Figure 6 Effectiveness vs Reynolds Number

The effectiveness of a heat exchanger tends to reduce with an improvement in Re number. The effectiveness of a heat exchanger refers to its ability to transfer heat efficiently between two fluids. At higher Re numbers, the flow inside the heat exchanger becomes more turbulent and chaotic. Turbulence enhances convective heat transfer but also increases pressure drop and fluid mixing. turbulence results in a reducing the temperature difference between the two fluids, reducing the overall effectiveness of heat transfer. the turbulent flow causes a higher rate of heat transfer near the surface of the heat exchanger, but it also leads to increased resistance to flow and reduced thermal gradients. Consequently, the temperature driving force for heat transfer diminishes, resulting in less efficient heat exchange between the fluids. Additionally, the increased turbulence can lead to flow maldistribution, where the fluid distribution becomes uneven across the heat exchanger's surface, further impacting heat transfer effectiveness. The effectiveness was increased by 16.67% and 7.6% for triangular shape

and circular shape respectively as compared to existing literature. Overall, the rise in Reynolds number leads to increased turbulence, reduced temperature gradients, flow maldistribution, and greater pressure drop, all contributing to a decrease in the effectiveness of the heat exchanger.

3.4) Temperature Contour for TTHX

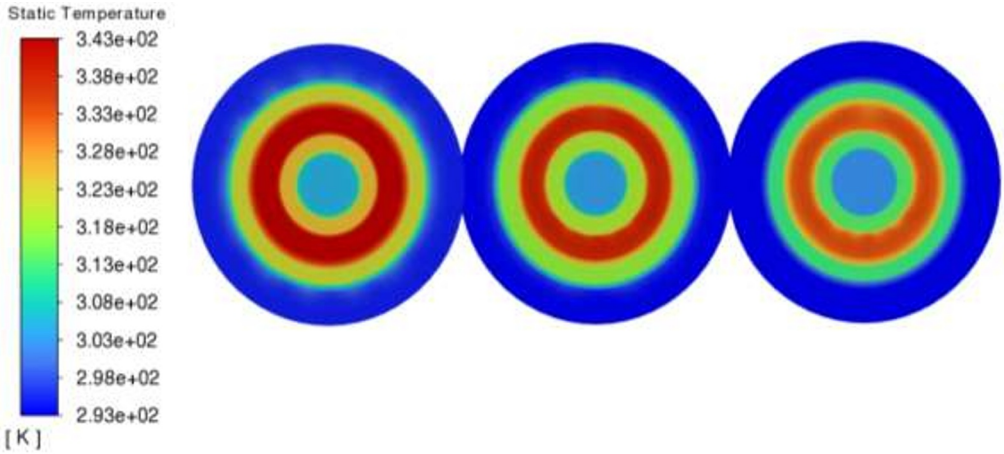

Figure 7 static Temperature Contour for intermediate circular tube in XY plane at Z=0m, Z=0.25m and Z=0.50m.

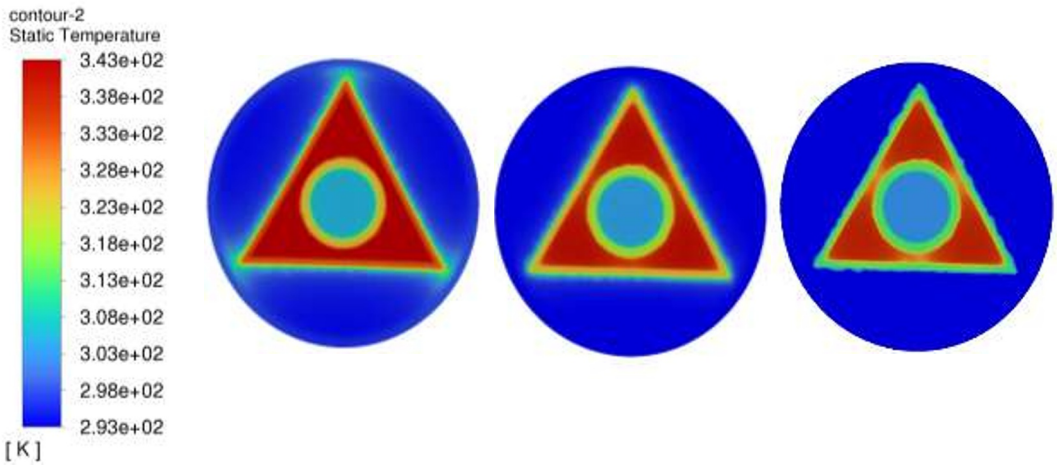

Figure 8 static Temperature Contour for intermediate Triangular shape tube in XY plane at Z=0m, Z=0.25m and Z=0.50m

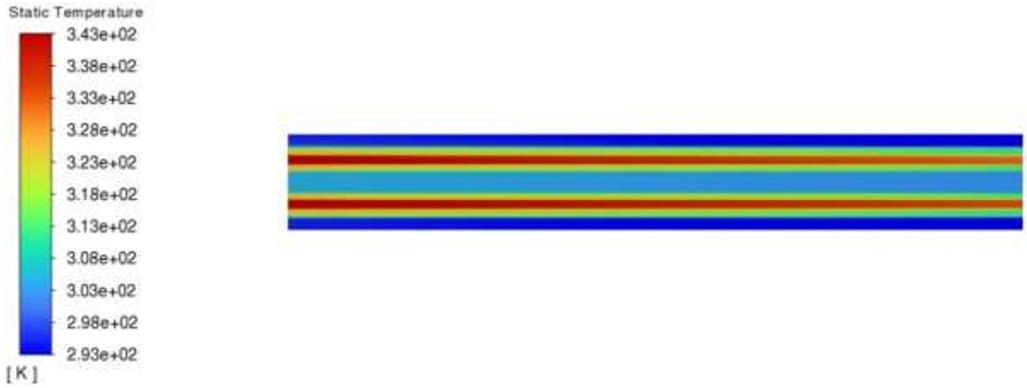

Figure 9 static Temperature Contour for intermediate circular shape tube in YZ plane at X=0m.

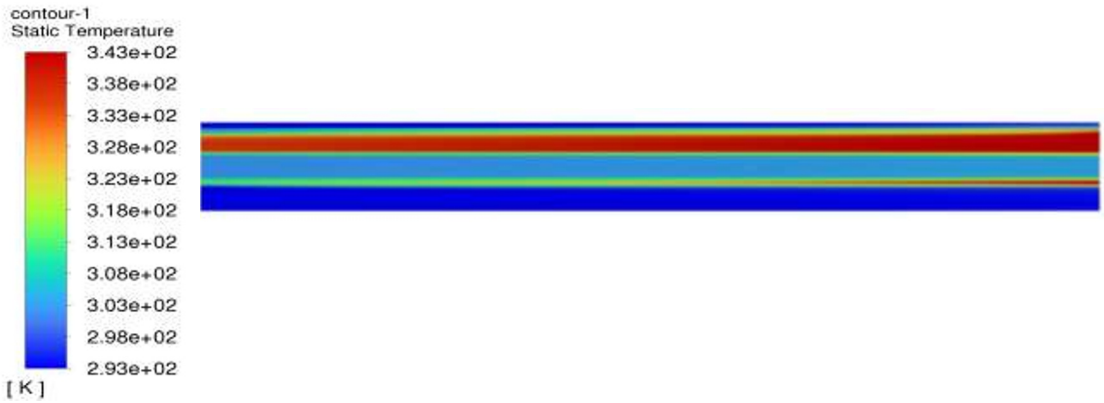

Figure 10 static Temperature Contour for intermediate Triangular shape tube in YZ plane at X=0m

Figure 7-10 has shown about the temperature contour of TTHX. In a heat exchanger, the temperature distribution refers to how the temperature varies across the heat exchanger's surfaces and the fluids flowing through it. As the fluids flow through the exchanger, heat is transferred between them. This results in a gradual change in temperature along the flow path. The temperature distribution depends on the heat exchanger design, flow rates of the fluids, Nu, and the thermal properties of the fluids. Achieving a uniform temperature distribution is desirable to ensure efficient heat transfer and to prevent thermal gradients that could lead to thermal stress or inefficiencies in the system. As the Reynolds number increases in a heat exchanger, the temperature change becomes less significant. Higher Reynolds numbers correspond to increased fluid turbulence, which enhances heat transfer but also reduce hot and cold fluids temperature gap. This decrease in temperature change can limit the overall effectiveness of heat exchange in the system.

4. Conclusion

The hot and cold-water flow in a triple tube heat exchanger facilitates effective heat transfer between the two fluids. The arrangement of the triple tube design allows for enhanced thermal efficiency. The hot water flows through the inner tube, transferring its heat to the surrounding cold water flowing in the annular space between the inner and outer tubes. This configuration maximizes the surface area for heat exchange and promotes efficient energy transfer. The counter-current flow configuration improves heat transfer even more by maintaining a temperature gradient down the length of the exchanger. Overall, the triple tube heat exchanger design promotes efficient heat exchange between the hot and cold-water streams**.** The specific conclusions are listed below:

- Friction factor of triangular shape is increase by 10.5% and for circular shape by 2.69% as compared to correlation in existing literature.
- Nusselt number (Nu) for triangular shape increase by 39.19% and for circular shape by 13.30% as compared to correlation in the range of Reynolds Number (Re) from 2000 to 4500.

- The effectiveness was increased by 16.67% and 7.6% for triangular shape and circular shape respectively as compared to existing literature.

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