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NUMERICAL ANALYSIS OF HYDROTHERMAL CHARACTERISTICS OF MHD TWO PHASE NANOFLUID IN A MICROCHANNEL HEAT EXCHANGER WITH RIBS

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ABSTRACT :

This study aims at delving into what happens to a 2-phase nanofluid hydrothermally as it flows through a microchannel heat exchanger with ribs. The ribs are assumed to be rectangular in nature and the simulation is carried out with the aid ANSYS Fluent, the MHD models and equations employed are all incorporated in the Fluent Setup workspace. The heat exchanger is assumed to be a counter flow type with water (the working fluid) being transported in reverse direction to the two phase nanofluid. The base fluid of the nanofluid is also water while the nanoparticles suspended in it are assumed to be made of iron, iron particles are selected as nanoparticles due to the magneto-hydrodynamic effect being put into consideration. Prior to the simulation, the geometry of the concentric pipe counter flow heat exchanger is drafted on SOLIDWORKs Package with all the dimensions specified.

Keywords: Multi-Phase flow, Nanofluid, Heat Exchanger, Magnetohydrodynamics

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1.0 INTRODUCTION :

Magnetohydrodynamic (MHD) theory was propounded by Hannes Alfren who received a nobel prize for his work. The knowledge of MHD helps our solar system to study and visualize remote astrological areas. The theory can be fully understood by considering a state of matter known as **plasma** which is characterized by the existence of substantial portion of charged particles in electrons/ions. Plasma exists mostly in stars (such as Sun) and some galaxies. Heat exchanger is a widely known industrial technical appliance which transports thermal energy from a hot medium to a cold medium, each medium moving in opposite or the same direction without mixing.

Heat exchanger can also be produced by subjecting an inert gas to a powerful electromagnetic field. In this work however, iron nanoparticles will be suspended in water (base fluid) and the nanofluid will then be subjected to external magnetohydrodynamic effect, the nanofluid flows through a mirochannel heat exchanger of rectangular ribs whose dimensions as specified later. All the arrangements mentioned are assumed to be flowing through a counter flow double pipe heat exchanger, the type of heat exchanger is selected due to its durability, ease of maintenance, ease of manufacture and low cost.

According to Krishnasamy, Sivasankaran and Poobalan (2015), the continuous increase in power density and compactness of electronic chips has invoked the need for more efficient and effective cooling solutions, the stringent operational temperature requirements call for new heat dissipation techniques to address thermal issues.

Brief Theoretical Overview

Definition of Heat Exchanger

Generally, heat exchanger is an equipment in which thermodynamic process of heat energy transfer takes place from one fluid to another fluid without any form of contact between the fluids. The purpose of heat exchanger is to ensure that heat exchange takes place continuously without termination, this is why the fluids must not come in direct contact (heat exchange between the fluids will cease once there is direct contact between the fluids. A very interesting scenario is a pipe conveying natural gas (fluid) which is being carried over water. The gas and the water will continue to exchange heat so far there is no any form of contact. Azza and Hamaira (2023) demonstrated that the hybrid nanofluid exhibits a higher heat transfer rate compared to the conventional fluid, even in the presence of a magnetic field.

There are several forms or classes of heat exchanger depending on the conditions and application required. One of the most popular types of heat exchanger is the **double tube heat exchanger** where one tube is fashioned in another larger tube, one of the fluids is conveyed through the smaller pipe while the other flows through the larger one. Another type of heat exchanger is the **shell and tube heat exchanger**, it is the most versatile and commercially available. It contains a number of tubes placed inside a shell and is thus used when it is required to heat or cool a substantial amount of fluid. A special type of heat exchanger which permits greater surface area of contact between the two fluids is the **plate hest excahnger**. It consists of metal plates between two fluids, it has a higher efficiency though it is more expensive compared to other types of heat exchanger. Based on flow configuration, heat exchangers are also classified as **counter flow, cross flow** and **cocurrent flow.** In counter flow type, the two fluids flow parallel to each other but in opposite direction. In cocurrent flow type, the two heat exchanging fluids flow in the same direction. In crossflow type, the stramlines of the fluids are perpendicular to each other. In the industry however, the above mentioned types of heat exchangers may be incorporated.

In addition to the above mentioned classifications, heat exchangers are also broadly classified according to their structure as follows:

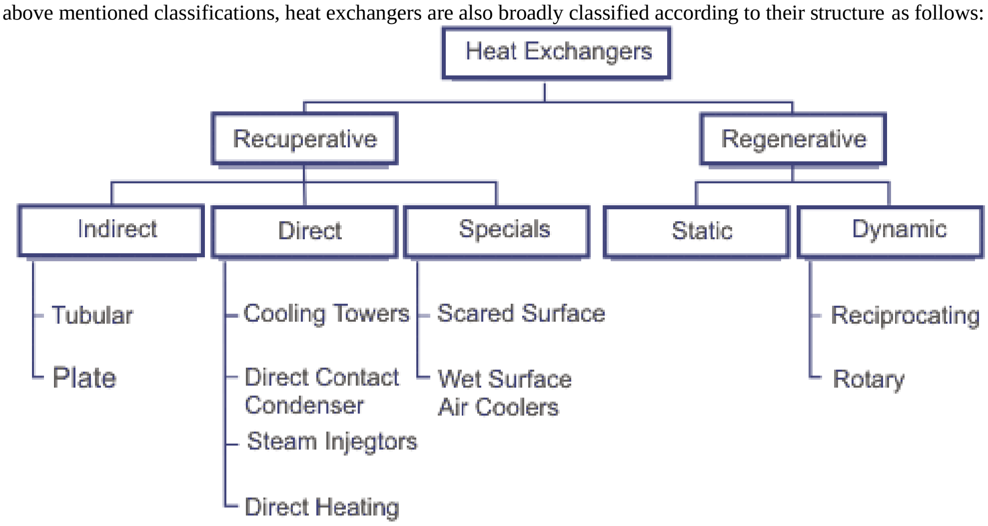


Figure 1.0 Classification of Heat Exchangers by Construction.

1.2. Definition of Nanofluid

A nanofluid is simply described as a fluid made up of particles whose size are of nanometer scale, known as nanoparticles. Nanofluids are primarily composed of some tiny particles (nanoparticles) suspended in a base fluid. Common nanoparticles used are oxides of metals such as aluminum, metallic carbides and carbon nanotubes while the popular base fluids employed are water and oil.

They are now being used in place of normal conventional fluids to enhance fluid and heat flow characteristics in many engineering processes such as mass diffusion, defence, space, cooling of vehicles and industrial equipment, microchips in electronic devices, nuclear chambers, X-ray imaging, cancer therapy, to mention a few. Typical nanoscale substances are depicted in the figure below.

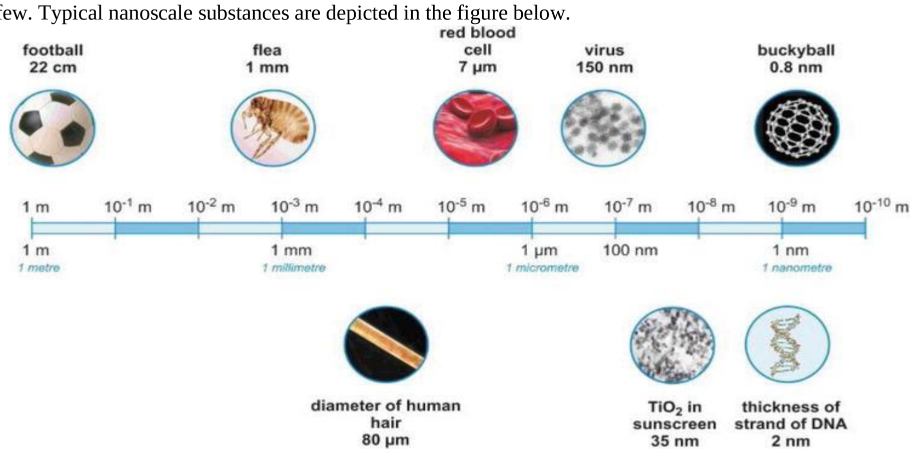


Figure 1.1. Nano-scale substances (intechopen.com)

As shown in the figure, substances on the far right of the scale (virus, buckyball, titanium oxide and DNA strand) are of nano-scale. Their size in a billionth (10^{-9}) order. It is worth noting that the thermophysical properties (specific heat, convective heat transfer coefficient, density, viscosity, thermal conductivity) of nanofluids do not match with those of the base fluids. The changes in properties can be attributed to the amalgamation of the nanoparticles with the basefluids, some of these properties are thus obtained by correlations.

Many researchers have been able to solve quite a number of heat transfer problems associated with low conductivity fluids such as water and alcohol by mixing them with nanoparticles to yield nanoparticles which improve their properties. The works of the researchers are discussed in the next chapter.

2.0 LITERATURE REVIEW :

The ancient works on heat exchangers can be traced back to the 17th century when the German scientist Albert Drake was awarded a prize for his prudent work which led to the discovery of what we now know as Plate Heat Exchanger (PHE). However, in Europe and Rome, there exists water baths which produced water at different temperatures (now known as Recuperator), heat exhangers were also being used in the manufacture of pure alcohol. Towards the 18th century, Tubular Heat Exchangers were developed, they were employed in powerplants as condensers and feedwater heaters. Later, the Shell and Tube Heat Exchangers (STHE) were produced and applied mostly in oil factories as condensers, oil heaters for crude oil processing.

Onbasioglu (2004) stated that unlike fins which work as extended heat transfer surfaces, ribs do not work in such manner, they only change the direction of heat flow so as to enhance heat transfer processes. Zhang et al. (2016) studied the effect of rib arrangements on the flow pattern and heat exchanger in an internally ribbed heat exchanger tube. They performed numerical simulation to fathom the impact of rib configuration on pattern of flow and what happens to heat transfer when the heat exchanger is ribbed internally. The used the P-type and V-type ribs and found that indeed, the configuration of the ribs have noticeable effect on flow pattern and heat exchange. In the P-type rib the net mean Nusselt number was found to be 57-90% lesser than that of the V-typed rib while the friction factor was also found to be 86-94% lesser.

Sameer et al. (2023) also worked on the effect of rib configuration on heat transfer enhancement. They employed three ribs each W-shaped in a square duct in their analysis and conducted experiments for low Reynold's number (12, 000 – 20, 000). They analyzed the influence of Reynold's number, pitch ratios, rib shape and rib angle on the mean area heat transfer and friction factor, they observed that the experimental values thus obtained for Nusselt number (Nu) and friction factor (f) in a smooth channel fit will with Dittus-Boelter and Blassius correlations. With an increase in pitch ratio, the Nusselt number was found to increase while the friction factor decreases. They developed a new correlation for Nu and f.

Furthermore, Zhu and Lin (2023) showed that heat transfer efficiency of heat exchanger can be improved by adding an inner ring structure to the heat exchanger. They figured out that the difference in diameter of the inner and outer ring rib has a significant effect on heat dissipation.

Salem et al (2017) carried out an experimental research on the performance of chilled water air conditioning units using a conventional fluid (water) followed by a nanofluid (alumina-water). They applied the known methods of preparing nanofluids to produce Al_2O_3 - water nanofluids with varying mass concentrations ranging from 0.1 - 1%. They investigated the flow rate of the chilled nanofluid as well as the air flowing through the cooling coil and were able to deduce that the chilled fluid in demand for all concentration is obtained at a faster time when the nanofluid is used compared to when pure water is used. They also recorded an increase in the coefficient of performance (COP) of the air conditioner due to minimized power consumption and increased cooling capacity as a result of the use of nanofluid.

Said et al (2019) conducted a research on a nanofluid-based composite parabolic trough solar collector under laminar flow conditions. In their research, they observed that the thermal conductivity increased significantly when the TiO_2 particle is mixed with the base fluid. There is also a noticeable increase in energy as well as exergy-efficiency.

Figure 1.7. Image of Aluminium nanoparticles used (intechopen.com)

One of the earliest research on MHD heat exchanger in two phase flow was performed by Malashety et al (1992). In their work, the channel is assumed to be horizontal and the fluids in the two phase are assumed to be immiscible, incompressible and electrically conducting with different viscosities. The transport characteristics of the two fluids were made constant and the temperature at boundary of the pipe also maintained constant.

A two-phase approach to flow within a channel was performed by Mehdi et al (2020), they employed V-shaped ribs and made a copper-water nanofluid to flow through the channel with attack angles varied between 45° and 60°. The found that the 45° rib, due to its lower entropy generation, has a higher superiority than the 60° rib. They also recorded that the total entropy generation and the total exergy destruction reduces with a rise in volume fraction of the nanofluid.

Dongonhi et al (2016) further carried out a research to investigate magnetohydrodynamics properties of nanofluid flow and stretching or shrinking of convergent/divergent channel putting thermal radiation into consideration. A similarity transformation procedures was utilized by these researchers to convert the radial momentum-energy equation into nonlinear ordinary differential equations with appropriate boundary conditions, they then employed the Duan-Rach approach to solve the nonlinear differential equations generated, the method reduce the stress of applying numerical methods to obtain undetermined coefficients, a modification of Adomian Decomposition Method, which involves direct application of the inverse operators at the boundary conditions. They selected a viscous incompressible water based nanofluid between, made to flow from a heat source between two stretchable walls.

Recently, Goswami et al (2022) also published a journal on MHD two phase fluid flow and heat transfer problem in a horizontal channel in the presence of a uniform magnetic field, they considered a fully developed flow of the fluids with constant transport properties. The fluids were also assumed to be at different viscosities and thermal conductivities. However, unlike the work of Malashety et al, the lower phase fluid is assumed to be a poor electrical conductor. They obtained analytical solutions for the velocities, induced magnetic field and temperature distributions for different heights and viscosity ratios of the two fluids.

In this work, the presence of magnetic field effect on the electrically conducting nanofluid which flows through the heat exchanger imparts a body force on the nanofluid, the equations peculiar to the hydrothermal characteristics of the MHD two phase are solved numerically using Finite Element Method by use of ANSYS Fluent Software package. The temperature distribution, velocity distribution and magnetic field profiles will be shown in the next section, all parameters and properties used will be clearly stated.

3.0 METHODOLOGY :

In this chapter, various mathematical expressions and models for determining thermophysical properties of the nanofluid in terms of those of the nanoparticle and the base fluid will be stated, the governing equations as well as the parameters employed in the numerical analysis of the nanofluid heat exchanger will be stated as well.

DENSITY OF THE NANOFLUID

The mathematical expression shown in equ.3.0 below is used in determining the density of a nanofluid:

$$\rho_{nf} = (1-\phi)\rho_f + \phi\rho_{np} \quad (3.00)$$

Where:

ρ_{nf} = density of the nanofluid (mixture of the nanoparticle and base fluid)

ρ_f = density of the base fluid

ρ_{np} = density of the nanoparticle and

ϕ = volume fraction of the nanoparticle.

SPECIFIC HEAT OF THE NANOFLUID

The equation below describes how the specific heat of the nanofluid can be obtained at constant pressure:

$$c_{p,\ nf} = (1-\phi)c_{p,\ f} + \phi\, c_{p,\ np} \quad (3.01)$$

Where:

$c_{p,\ nf}$ = specific heat capacity of the nanofluid

$c_{p,\ f}$ = specific heat capacity of the base fluid

$c_{p,\ np}$ = specific heat capacity of the nanoparticle

THERMAL CONDUCTIVITY OF NANOFLUID

There are several models in literature for obtaining the thermal conductivity of a nanofluid. The major ones will be stated in the subsequent equations.

1. Maxwell Model.

$$k_{nf} = k_f\left[\frac{k_p+2k_f+2\phi(k_p-k_f)}{k_p+2k_f-\phi(k_p-k_f)}\right] \quad (3.02)$$

Where:

k_{nf} = thermal conductivity of the nanofluid
k_f = thermal conductivity of the base fluid
k_p = thermal conductivity of the nanoparticle

2. Hamilton-Crosser Model. This model further improves Maxwell's model by including a factor 'n' which compensates for the shape of the nanofluid. The model is represented below.

$$k_{nf} = k_f\left[\frac{k_p+(n-1)k_f+\phi(n-1)(k_f-k_p)}{k_p+(n-1)k_f-\phi(k_f-k_p)}\right] \quad (3.03)$$

Where n is the shape factor of the nanofluid.

3. Voi and Choi Model. This model is an extension of Maxwell and Hamilton-Crosser models as it further accounts for interfacial layers around the nanoparticles, which has a considerable effect on the value of k.

$$k_{nf} = k_f\left[\frac{k_p+2k_f+2\beta\phi(k_p-k_f)}{k_p+2k_f-\beta\phi(k_p-k_f)}\right] \quad (3.04)$$

Where β is represents the empirical shape factor of the nanofluid.

4. Pak and Cho Model. This model is obtained from experimental data endemic to spherical nanofluids. It is also an empirical model but it differs from Voi and Choi model in that it considers the temperature of the nanofluid as shown below.

$$k_{nf} = k_f(1 + 7.47\phi + 0.01T) \quad (3.05)$$

Where T denotes the temperature in degree Celsius

5. Modified Maxwell-Garnett Model. This model further compensates for the interaction between nanoparticles and the surrounding fluids.

$$k_{nf} = k_f \left[1 + \frac{3\phi(k_p - k_f)}{k_p + 2k_f - \phi(k_p - k_f)}\right] \quad (3.06)$$

DYNAMIC VISCOSITY OF THE NANOFLUID

There are diverse models for estimating the dynamic viscosity of nanofluids. Few of such models are mentioned below.

1. Einstein's Viscosity Model. It applies to dilute suspensions having low volume fraction (i.e. $\phi < 0.02$).

$$\mu_{nf} = \mu_f(1 + 2.5\phi) \quad (3.07)$$

Where:

μ_{nf} = dynamic viscosity of the nanofluid.
μ_f = dynamic viscosity of the base fluid.

2. Batchelor's Model. This model is applied for slightly higher concentrations, it further accounts for the interaction between particles.

$$\mu_{nf} = \mu_f(1 + 2.5\phi + 6.2\phi^2) \quad (3.08)$$

3. Brinkman Model. This applies to nanofluid whose nanoparticles have moderate concentration.

$$\mu_{nf} = \mu_f(1 - \phi)^{-2.5} \quad (3.09)$$

4. Pak and Cho Model. This is applied to water based nanofluids with Al_2O_3 and TiO_2 nanoparticles.

$$\mu_{nf} = \mu_f(1 + 39.1\phi + 533.9\phi^2) \quad (3.10)$$

5. Maga et al Model. This is an improvement over the Pak and Cho Model. It also applies to water based nanofluids but there is a further extension in the choice of nanoparticles. The nanoparticles which obey this model are Al_2O_3, CuO and SiO_2.

$$\mu_{nf} = \mu_f(1 + 7.3\phi + 123\phi^2)$$

GEOMETRY

The heat exchanger is modelled using SOLIDWORKs, the material of the is heat exchanger is assumed to be aluminium. Three geometries were drafted: circular (baseline), rectangular, and triangular ribs and each geometry consists of 8 sided ribs.

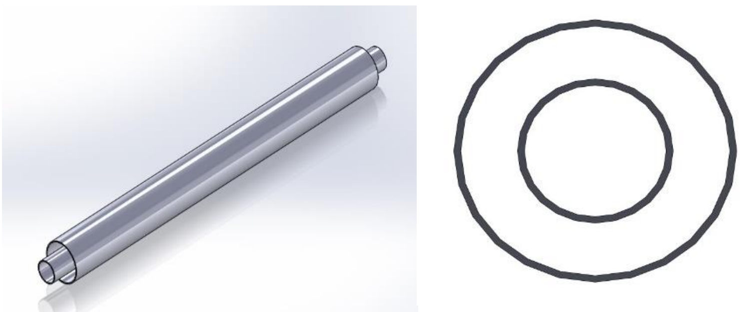


Figure 3.01: Circular Geometry(Baseline)

Figure 3.02: Rectangular Geometry

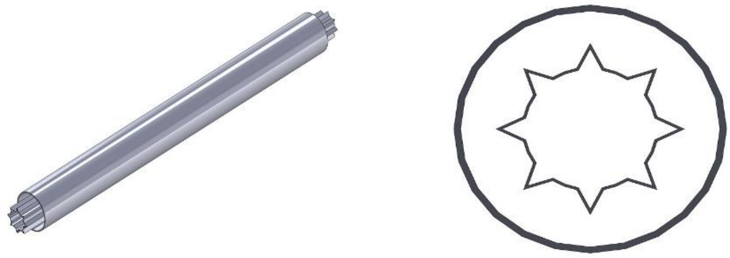


Figure 3.03: Triangular Geometry

PARAMETERS

Geometry

1. Outer diameter = 20mm.
2. Inner diameter = 10mm,
3. Length of tube = 200mm,
4. Thickness = 0.5mm

Nano-fluid

Nanofluid is composed of Iron nanoparticles with water as base fluid

Thermophysical Properties of the Nanofluid

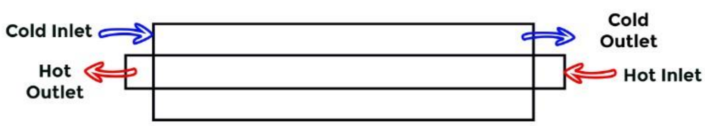
The thermophysical properties are calculated using the properties of the nanoparticles and the base fluid. One of the models mentioned earlier in this chapter is employed in obtaining the properties. The properties are thus listed below

- Thermal conductivity of nanofluid equals 0.692W/m^{2}K
- Specific heat of nanofluid at constant pressure equals 3084.65J/KgK
- Density of the nanofluid equals 1340.85kg/m^3.
- Viscosity of nanofluid equals 0.001125 Ns/m^2
- Volume fraction of nanoparticles in the nanofluid is taken as 5%
- The nanofluid is assumed spherical with diameter of 1nm.

Heat Exchanger properties

All conditions are applicable for each geometry. Water is taken as the hot fluid while the nanofluid is taken as the cold fluid. The conditions at entry and exit of the heat exchanger are highlighted below.

- Cold inlet mass flow rate is 0.081kg/s and temperature equals 309.15K.
- Hot inlet mass flow rate is 0.19kg/s, at temperature of 373.15K
- Wall condition: The wall is assumed to be an adiabatic wall.



3.04. Schemetic Diagram of heat exchanger.

Simulation Methodology

The simulation is perform in three different ways which are water - water, water - nano fluid and water - nano fluid (including MHD).

Note: Water is taken as the hot fluid. This conditions is applicable to all the three geometry. The purpose is to know the effect of each ribs (triangular and rectangular) on the heat exchanger and to compare the contours of each geometry. The circular rib is use as the baseline in which there is no effect of ribs on the fluid flow.

4.0 RESULTS :

Circular Ribs

The contours show the distribution of the hot and cold fluid in the heat exchanger. At the water - nano fluid contours, it is shown that there is thin layer of hot temperature distribution due to convective heat transfer between the wall of hot fluid and cold fluid. Also, at the MHD effect contour is shown that at the region of the hot inlet there is wide area of convective heat transfer to the cold region, this shows the effect of MHD in the fluid flow.

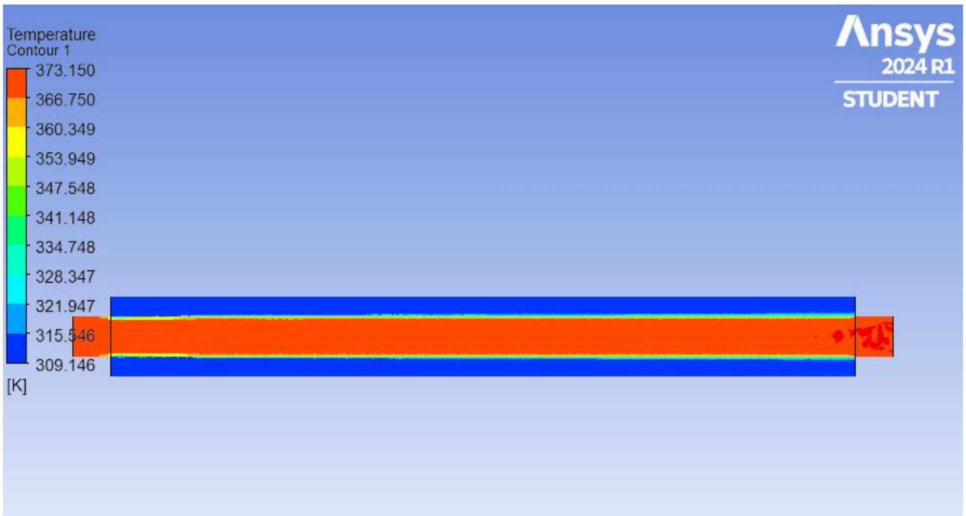


Fig 4.00. Water- nanofluid contour

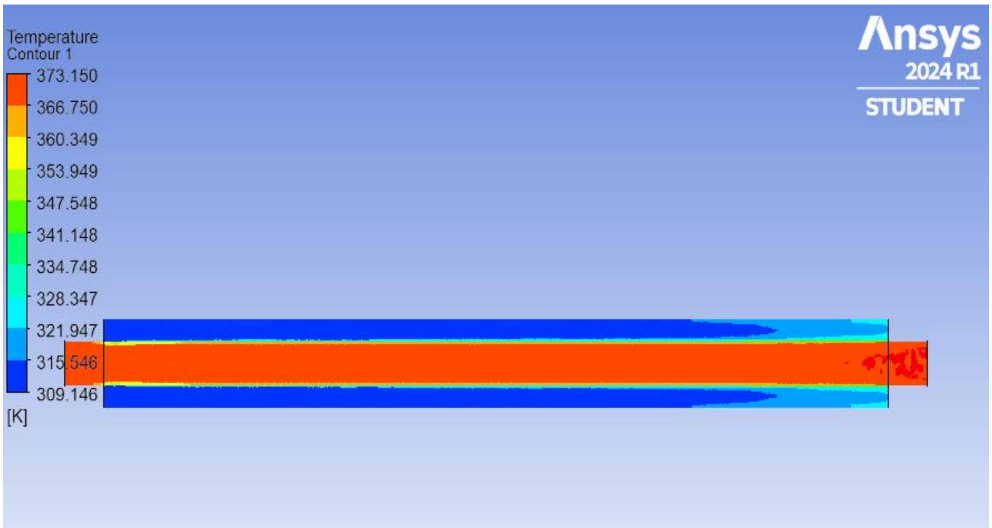


Fig. 4.01 MHD effect contour

Rectangular ribs

The contours show the distribution of the hot and cold fluid in the heat exchanger. At the water - nano fluid contours, it is shown that there is wide layer of hot temperature distribution due to convective heat transfer between the wall of hot fluid and cold fluid comparing the contours with the baseline contour show the effect of rectangular rib in heat exchanger. Also, at the MHD effect contour is shown that at the region of the hot outlet there is indication of convective heat transfer to the cold region leading to the cooling of hot fluid at the outlet. This shows the effect of MHD in the fluid flow since the nano particles configuration is random in the flow.

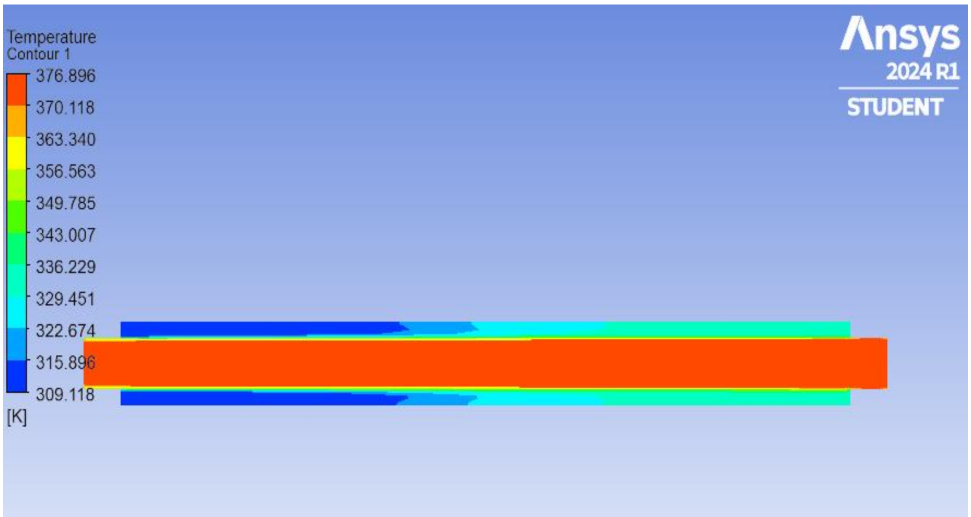


Fig 4.02. Water- nanofluid contour

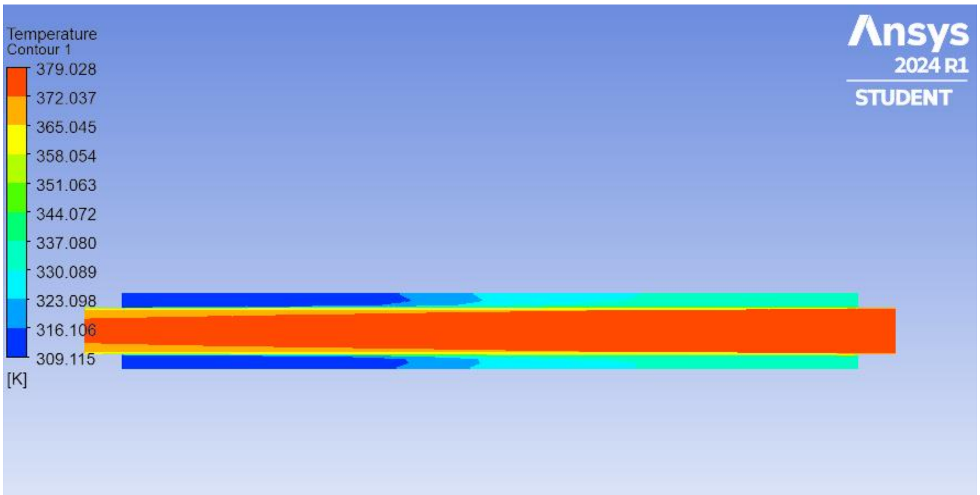


Fig. 4.03. MHD effect contour

Triangular ribs

The same effect as the rectangular ribs but the hot fluid cooling is much faster than the rectangular ribs

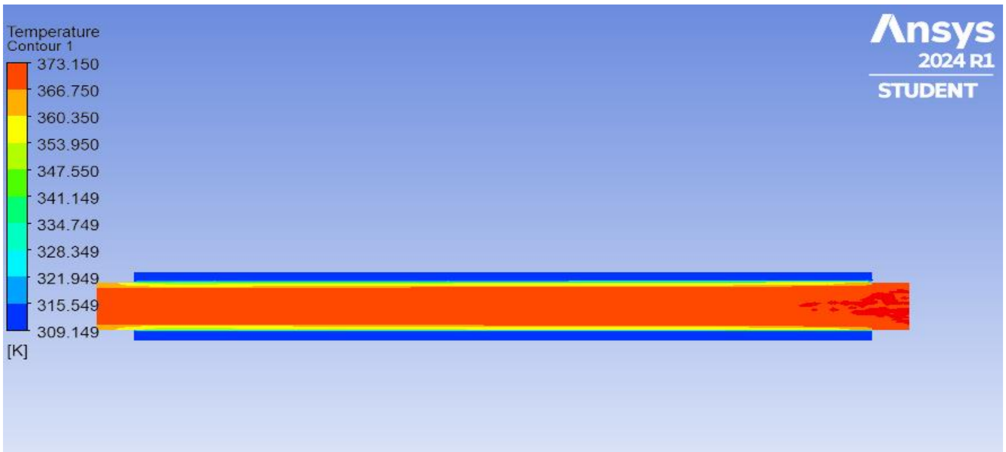


Fig. 4.04. Water- nanofluid contour

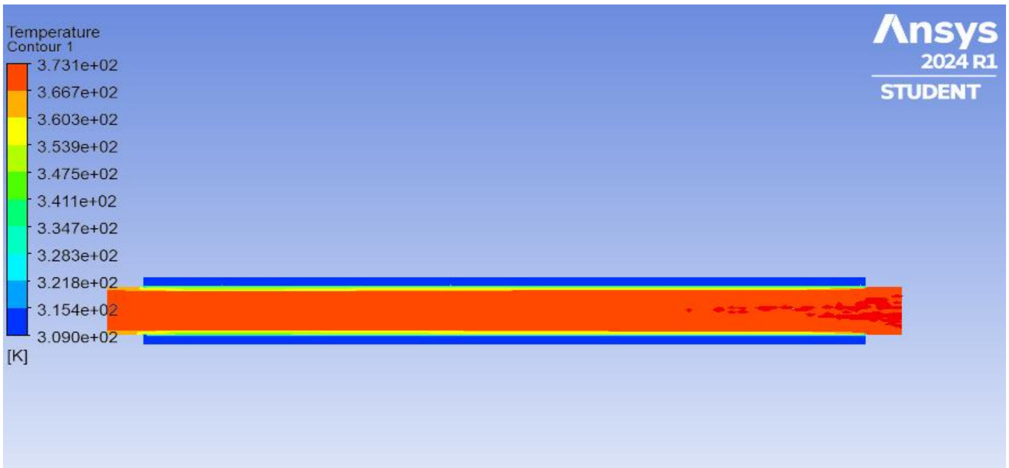


Fig. 4.05. MHD effect contour

Representation of the graph.
Circular is series 2, rectangular rib is series 3, triangular rib is series 1

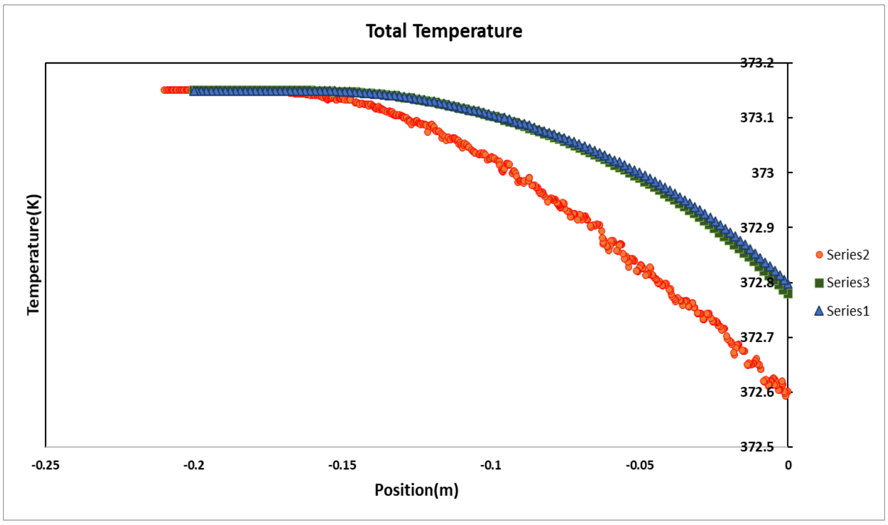


Fig. 4.06 Comparative of MHD effect of the three geometry

5.0 CONCLUSION :

It is concluded that;

- The shape of the ribs have an effect on the heat transfer of the fluid
- The triangular ribs have an effective heat transfer rate.
- The MHD affect only the distribution of the heat but does not change the net temperature of the heat exchanger and it is the same as the water - water HEX

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