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EFFECT OF DIMPLES ON FLOW PERFORMANCE OF ENHANCED SURFACE TUBES

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ABSTRACT - *Heat exchangers, which transport fluid to either gain or dissipate heat, are extensively used in various industrial applications, including refrigeration systems, petroleum, and solar collectors. Ever-increasing energy requirements have prompted industries to adopt all measures to develop high-performance thermal systems. The extended surface is an enhancement technique that can improve the heat transfer efficiency without additional consumption or requiring the addition of materials to the surface. Enhanced surfaces have a larger heat transfer surface area and offer increased turbulence, allowing higher heat exchange performance.*

In this work, a numerical simulation is proposed to simulate the geometric design of enhanced tubes for increased flow performances. This work investigates outward and inward dimple flow and heat transfer characteristics and studies the influence of dimples on heat and flow characteristics. The corresponding changes in performances and variation in flow and heat characteristics with changes in Reynolds number will be analyzed. Using commercial CFD software, simulations will be carried out to obtain heat transfer and pressure drop characteristics of smooth and enhanced tubes.

***Key Words*: Dimple shape, Thermo-hydraulic, Simulation, Heat Transfer, CFD**

1.INTRODUCTION

High-performance heat transfer components for thermodynamic processes should be adopted to reduce energy consumption and increase economic benefit. The roughness enhancement method is one of the most effective ways to improve the heat transfer performance with small increases of pressure drop. There are two kinds of tube side artificial roughness methods: (i) two-dimensional roughness, such as spirally corrugated, transverse, and spiral fins, and wire coil inserts; and (ii) three-dimensional roughness, such as sand grain roughness, spoon-type spirally corrugated, and dimples. Compared to other passive enhancement geometric forms, three-dimensional dimensional roughness methods hold interest because of the high enhancement levels and energy efficiency.

A great deal of research effort has been devoted to developing apparatus and performing experiments to define the conditions under which an enhancement technique will improve heat transfer. Heat transfer enhancement technology has been widely applied to heat exchanger applications in refrigeration, automobile, process industries, etc. The goal of enhanced heat transfer is to encourage or accommodate high heat fluxes. The need to increase the thermal performance of heat exchangers, thereby affecting energy, material, and cost savings has led to the development and use of many techniques termed heat transfer augmentation. These techniques are also referred to as Heat Transfer Enhancement or Intensification.

Augmentation techniques increase convective heat transfer by reducing the thermal resistance in a heat exchanger. Many techniques have been proposed to improve the heat transfer efficiency and operation safety of heat transfer equipment, such as treated surfaces, rough surfaces, extended surfaces, swirl flow devices, shaped pipes, surface tension devices, technical aids, electrostatic fields, suction, or injection. However, all the above techniques will inevitably bring too much flow resistance, resulting in unnecessary power consumption. An effective method of heat transfer enhancement is required to greatly improve the heat transfer and minimize the flow resistance as much as possible. In recent years, the concept of using an indented (dimpled) surface instead of protruding devices has gained attention because of the combination of high heat transfer enhancement and a lower pressure loss penalty.

1.1 PROBLEM STATEMENT

In this work, a numerical investigation was carried out to see the effects of providing dimples on heat transfer characteristics in a tube. These effects were observed for dimples on the wall of the tube for turbulent flows. The effects were investigated using a 3D steady viscous computational fluid dynamics package. The heat transfer characteristics were studied as a function of the Reynolds number based on the hydraulic diameter of the tube. The tube diameter and dimple depth ratio were kept constant while holding the diameter of 0.005m of the dimple. The heat transfer was quantified by computing the heat transfer coefficient and Nusselt number. The pressure drops and flow characteristics were also analyzed. The Nusselt number was compared with that of a smooth tube without dimples to assess the dimple's heat transfer enhancement. This investigation was carried out to observe if the use of dimples in a tube can enhance heat transfer characteristics without severe penalties associated with pressure drops for turbulent airflows.

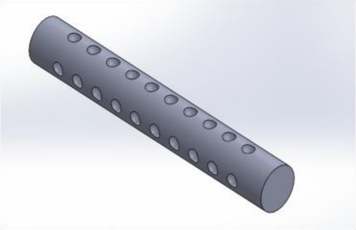
1.2 BOUNDARY CONDITIONS:

Inlet(thermal)	305.5k
Outlet	Pressure Outlet (0-gauge pressure)
Wall (Friction)	No-Slip BC
Wall (Thermal)	Constant Heat Flex 10KW/m2
Up and Down Stream	Adiabatic Condition
Working Fluid	Water, with constant Properties

2. METHODOLOGY

2.1 COMPUTATIONAL GEOMETRY

The computational domain was a tube of internal diameter Dh=17.272 mm with dimple diameter Dp, depth H, and pitch P, as shown in Fig. The length of the tube is 120 mm; however, the effective enhanced tube length was selected to be 100 mm to eliminate any spurious effects of inlet and outlet boundary conditions. The outward-facing dimples in the tube were positioned in the in-line arrangements, as presented in Fig.



2.2 MATHEMATICAL FORMULATION

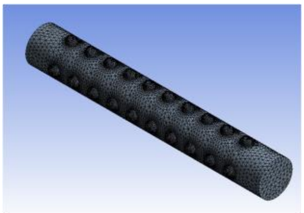
Continuity equation: $\frac{\partial u_i}{\partial x_j} = 0$

Momentum equation: $\frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[(\mu + \mu_t)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right]$

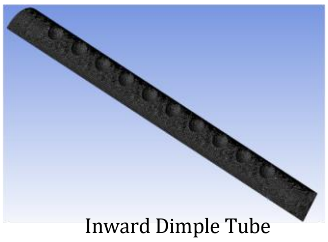
Energy equation: $\frac{\partial u_i T}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\frac{\mu}{\mathrm{Pr}} + \frac{\mu_t}{Pr_t}\right)\frac{\partial T}{\partial j}\right]$

2.3 MESHING

The domain discretization was performed by generating a structured mesh with refinement at the near plane wall and dimple surface, as presented in Fig. A high-quality mesh around the dimples was imperative since the flow separation, attachment, vortex formation, and flow mixing take place in the vicinity of the dimple. Therefore, additional care was taken while generating the mesh around the dimples. The fully developed flow can be divided into three regions, the viscous sublayer, the overlap region, and the outer turbulent layer throughout the center portion of the flow. To resolve the sub-layer, near-wall meshes should be fine enough, usually an indicator of near-wall mesh resolution y+ ≈1.

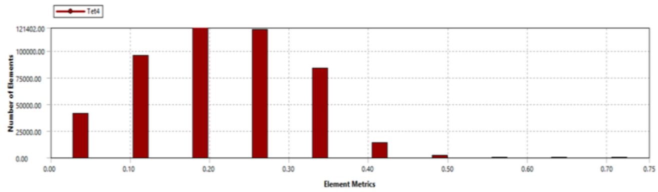


Meshing Outward Dimple Tube



Inward Dimple Tube

Element vs the number of elements of plain tube case, solver preference is selected as fluent with element order linear here mesh metric skewness is selected to get the quality mesh. The maximum value obtained is 0.75344 with an average value of 0.21358 and the standard deviation obtained is 9.646.



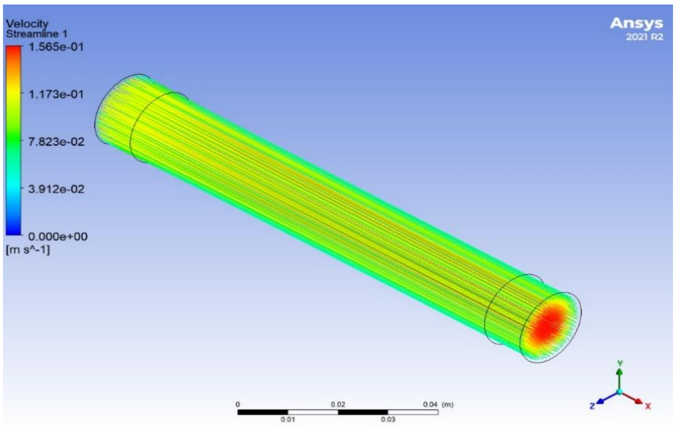
2.4 ANSYS SETUP

Numerical simulation was carried out using ANSYS Fluent 2021 R2 software. Reynolds numbers 2500,5000,7500 is given as input. The input boundary condition for the mass flow rate is given in kg/s and velocity in m/s. The Reynolds equation, which has been presented in $Re = \frac{\rho U D_h}{\mu}$

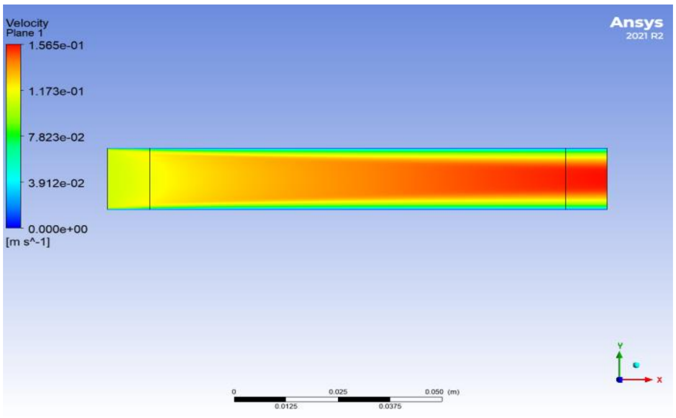
Where U is velocity, Dh is the hydraulic diameter of the tube and μ is the dynamic viscosity respectively which is the geometric diameter of the tube. Dh is taken as .017272 m in as of plane tube for Re equal to 2500 and density of fluid 997kilograms per meter cube. Flow analysis suitable shape is circular but inward and outward tube has a non-circular shape so hydraulic diameter needed to be considered in that case.it can be calculated using Solid works by cutting the cross-section view into 4 parts and then evaluating by which area and perimeter value can be found. Double precision, a three-dimension setup was selected for analysis even though it takes more time the quality of the analysis will be high and highly precious. When comes to the mesh quality model energy equation is set with K-epsilon with realizable. Working fluid is selected as water-liquid with material selected as stainless steel. The boundary condition for the inlet is set to be 0.10908 m/s for plain tube, initial gauge pressure 0 Pa. The hydraulic diameter is 0.01727 m and turbulence intensity are set to be 5% with a temperature of 305.5K. Outlet pressure is selected as zero-gauge pressure with heated wall thermal temperature as 300K as default with adiabatic heat-flux as zero. For the solution, a simple pressure equation is used with hybrid initialization selected.

3. RESULTS AND DISCUSSIONS

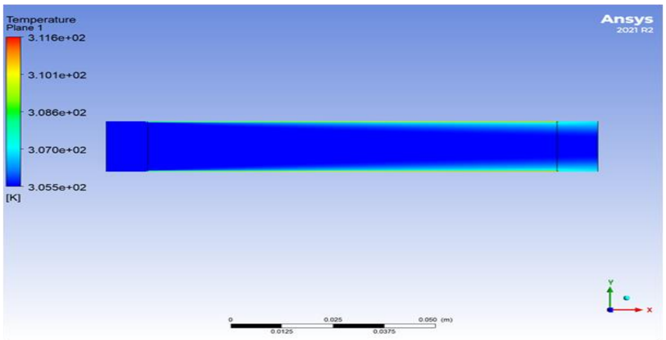
Following figure shows the plain tube's velocity streamlines during Reynolds number 2500.The maximum streamline is observed in the middle of the tube with a maximum velocity of 1.565.



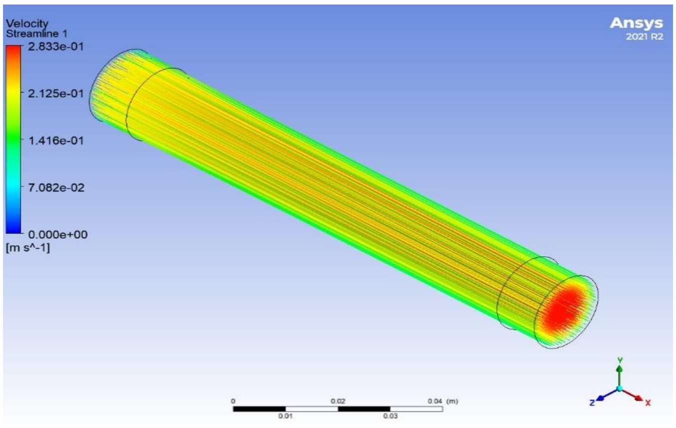
Following figure shows the velocity of the plain tube under Reynolds number 2500. The maximum velocity was recorded as 1.565 in the middle of the tube which is shown by red lines.



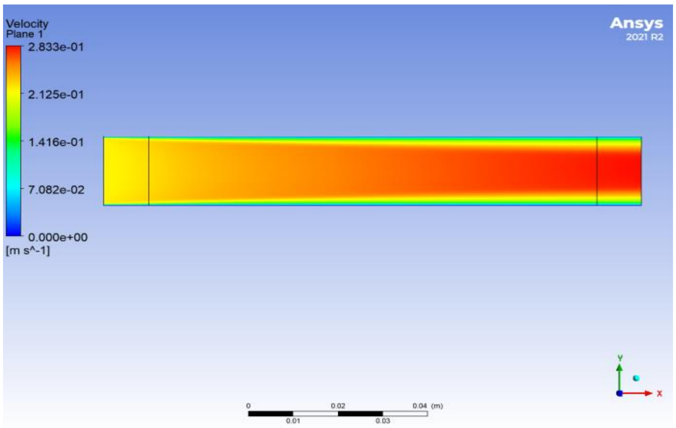
Following figure shows the temperature of the plain tube under Reynolds number 2500. The maximum temperature was recorded as 311.6k and the minimum temperature is observed as 3.055k



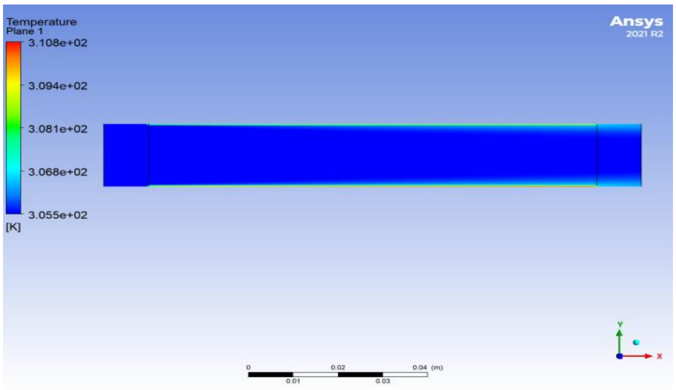
Following figure shows the plain tube's velocity streamlines during Reynolds number 5000.The maximum streamline is observed in the middle of the tube with a maximum velocity of 0.2833.



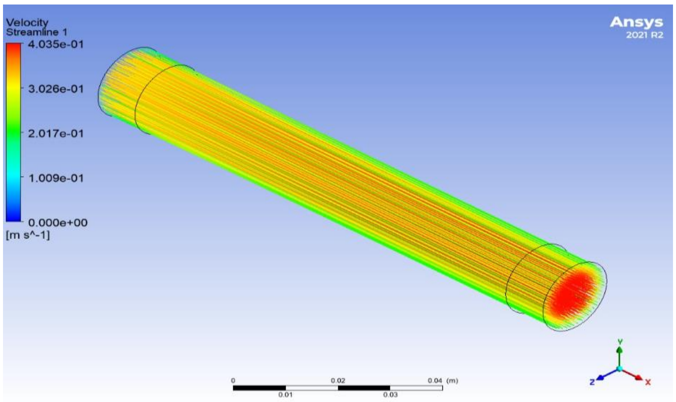
Following figure shows the velocity of the plain tube under Reynolds number 5000. The maximum velocity was recorded as 0.2833 in the middle of the tube which is shown by red lines. Here we can identify from the above figure that maximum streamline velocity is present in the middle of the tube.



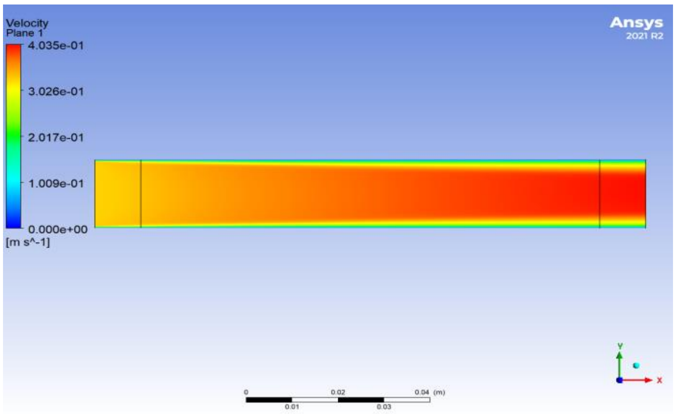
Following figure shows the temperature of the plain tube under Reynolds number 5000. The maximum temperature was recorded as 310. 8k and the minimum temperature is observed as 3.055k.



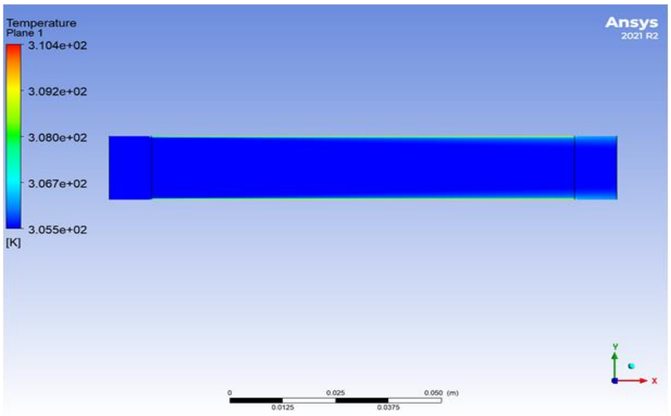
Following figure shows the plain tube's velocity streamlines during Reynolds number 7500. The maximum streamline is observed in the middle of the tube with a maximum velocity of 0.4035. The red streamlines indicate the maximum value whereas the blue streamline indicates the lowest value.



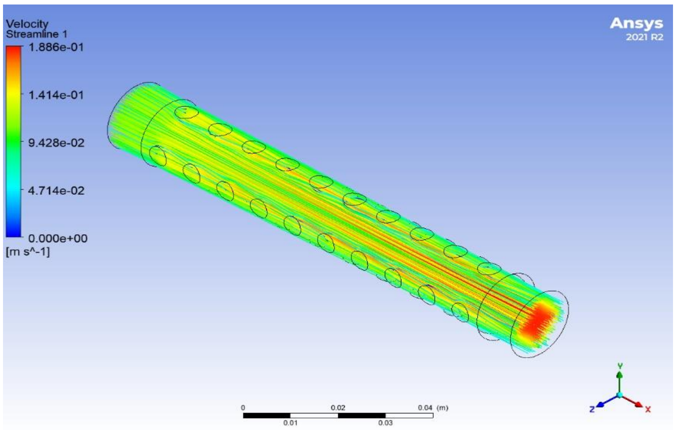
Following figure shows the velocity of the plain tube under Reynolds number 7500. The maximum velocity was recorded as 0.4035 in the middle of the tube which is shown by red lines. Here we can identify from the below figure that maximum streamline velocity is present in the middle of the tube.



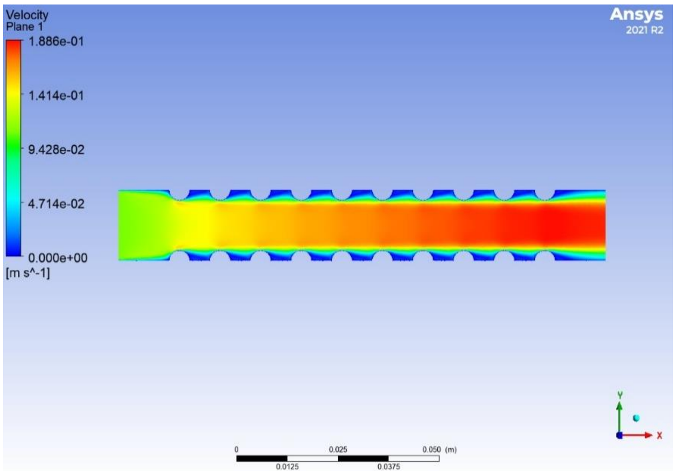
Following figure shows the temperature of the plain tube under Reynolds number 7500. The maximum temperature was recorded as 310.4k and the minimum temperature is observed as 3.055k.



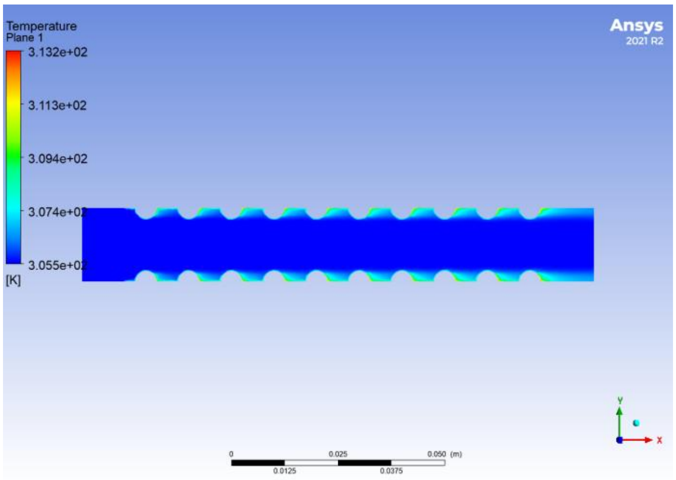
Following figure show the velocity streamline of the inward tube during Reynolds number 2500. The maximum streamline is observed in the middle of the tube with a maximum velocity of 0.1886 m/s. The minimum streamlines are observed nearer to the walls of the inward tube in this case.



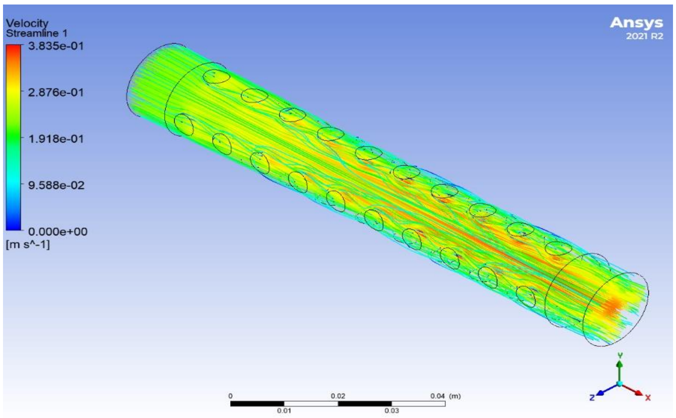
Following figure shows the velocity of the inward tube under Reynolds number 2500. The maximum velocity was recorded as 0.1886 in the middle of the tube which is shown by red lines. Here we can identify from the below figure that maximum velocity is present in the middle of the tube.



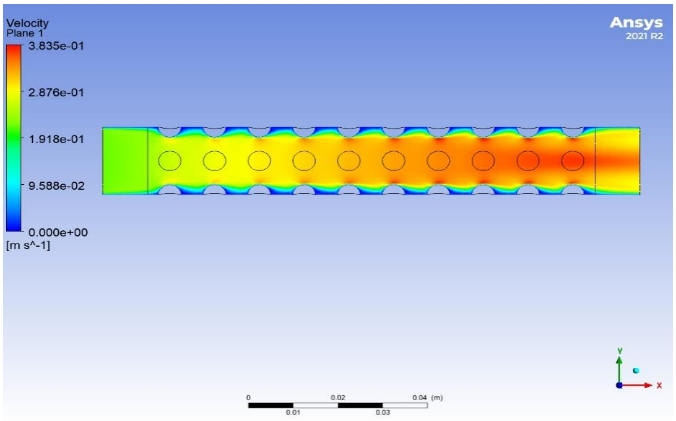
Following figure shows the temperature of the inward tube under Reynolds number 2500. The maximum temperature was recorded as 313.2k and the minimum temperature is observed as 3.055k. The maximum temperature is indicated by the red color and it is nearer to the walls of the tube and the minimum temperature is observed in the middle of the tube.



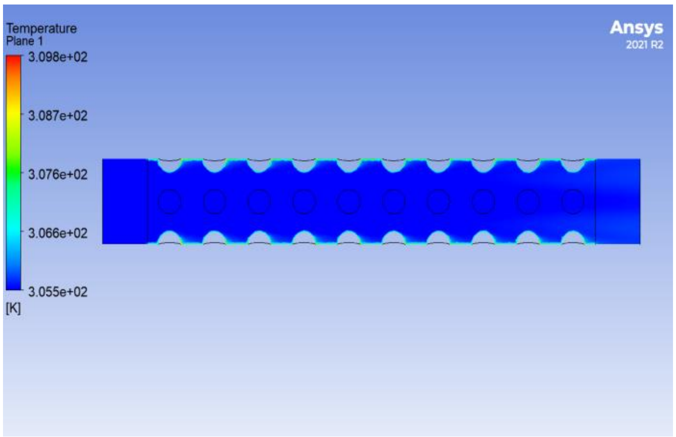
Following figure show the velocity streamline of the inward tube during Reynolds number 5000. The maximum streamline is observed in the middle of the tube with a maximum velocity of 0.3835 m/s. The minimum streamlines are observed nearer to the walls of the inward tube in this case.



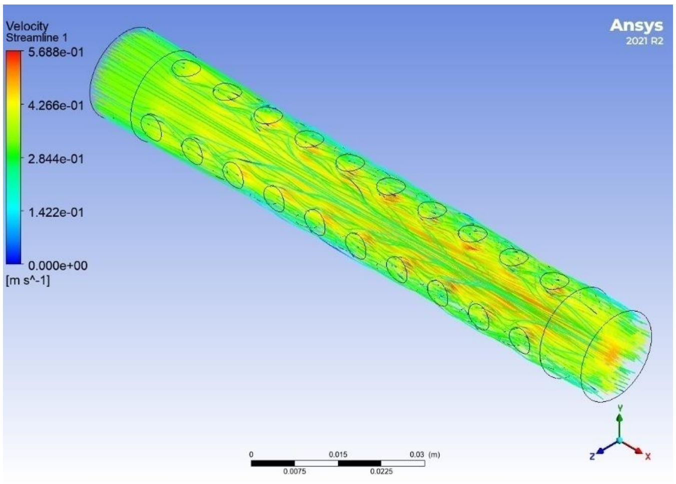
Following figure shows the velocity of the inward tube under Reynolds number 5000. The maximum velocity was recorded as 0.3835 in the middle of the tube which is shown by red lines. Here we can identify from the below figure that maximum velocity is present in the middle of the tube.



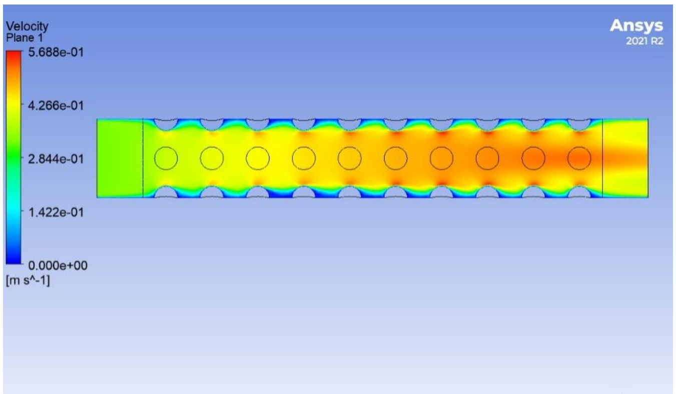
Following figure shows the temperature of the inward tube under Reynolds number 5000. The maximum temperature was recorded as 309.8k and the minimum temperature is observed as 3.055k. The maximum temperature is indicated by the red color and it is nearer to the walls of the tube and the minimum temperature is observed in the middle of the tube.



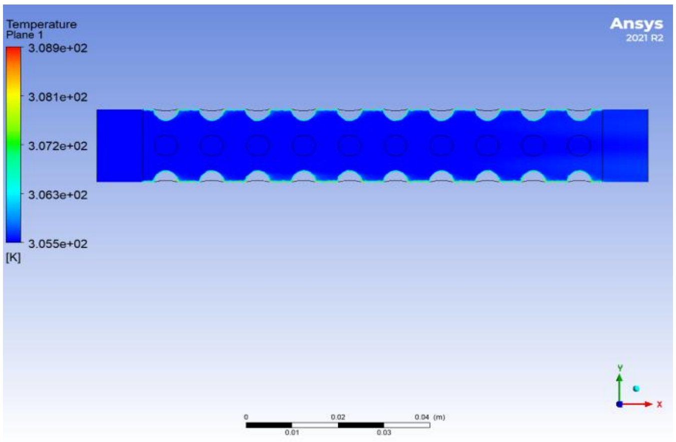
Following figure show the velocity streamline of the inward tube during Reynolds number 7500. The maximum streamline is observed in the middle of the tube with a maximum velocity of 0.5688 m/s. The minimum streamlines are observed nearer to the walls of the inward tube in this case.



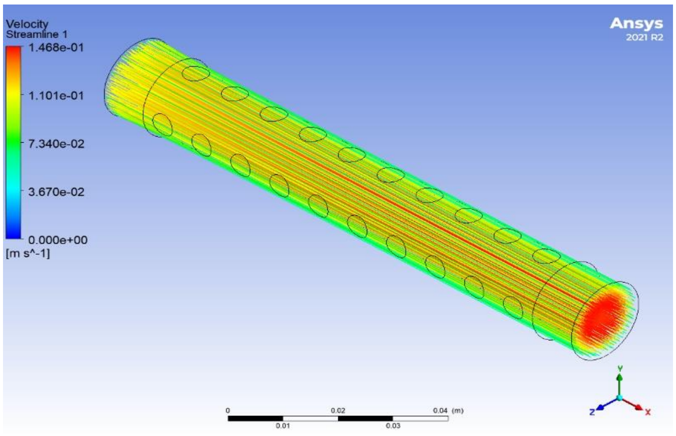
Following figure shows the velocity of the inward tube under Reynolds number 7500. The maximum velocity was recorded as 0.5688 in the middle of the tube which is shown by red lines. Here we can identify from the below figure that maximum velocity is present in the middle of the tube.



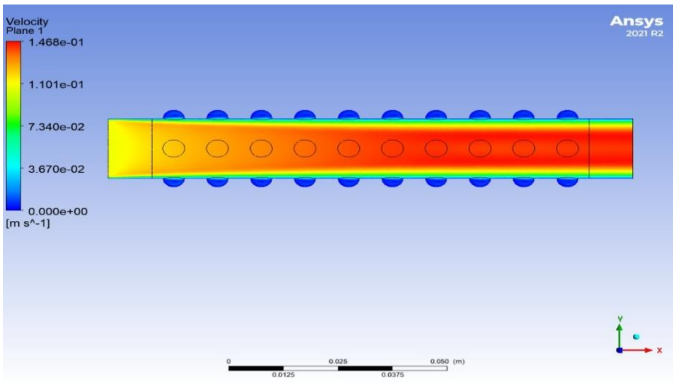
Following figure shows the temperature of the inward tube under Reynolds number 7500. The maximum temperature was recorded as 308.9 k and the minimum temperature is observed as 3.055k. The maximum temperature is indicated by the red color and it is nearer to the walls of the tube and the minimum temperature is observed in the middle of the tube.



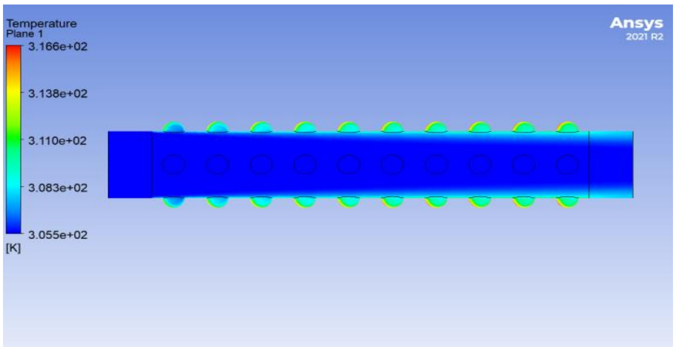
Following figure shows the outward tube's velocity streamlines during Reynolds number 2500. The maximum streamline is observed in the middle of the tube with a maximum velocity of 0.1468 m/s. The minimum streamlines are observed nearer to the walls of the inward tube in this case.



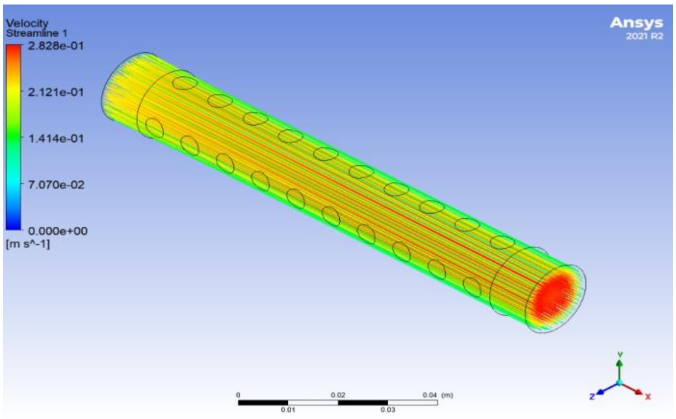
Following figure shows the velocity of the tube under Reynolds number 2500. The maximum velocity was recorded as 0.1468m/s in the middle of the tube which is shown by red lines. Here we can identify from the below figure that maximum velocity is present in the middle of the tube.



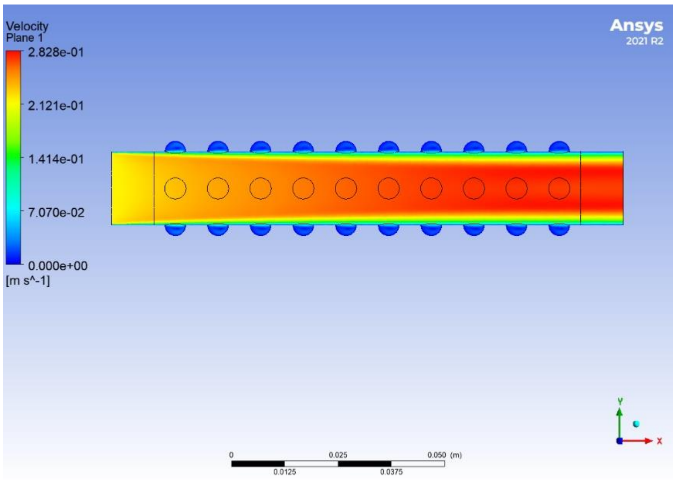
Following figure shows the temperature of the outward tube under Reynolds number 2500. The maximum temperature was recorded as 316.6 k and the minimum temperature is observed as 3.055k. The maximum temperature is indicated by the red color and it is nearer to the walls of the tube and the minimum temperature is observed in the middle of the tube.



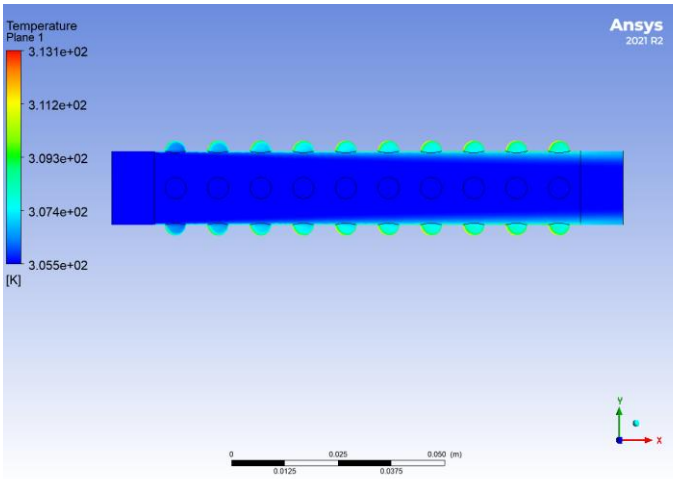
Following figure shows the outward tube's velocity streamlines during Reynolds number 5000. The maximum streamline is observed in the middle of the tube with a maximum velocity of 0.2828 m/s. The minimum streamlines are observed nearer to the walls of the inward tube in this case.



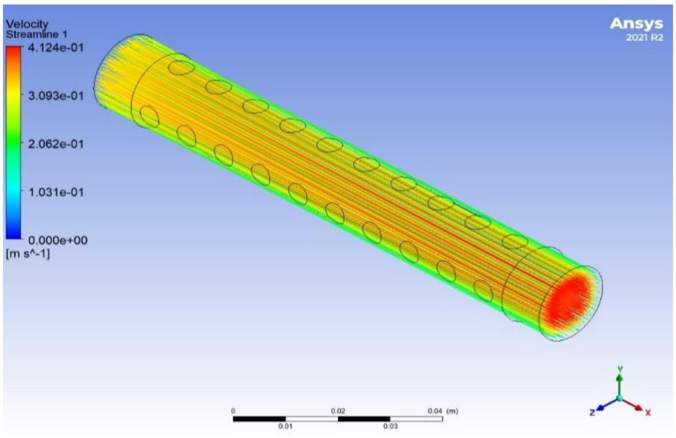
Following figure shows the velocity of the tube under Reynolds number 5000. The maximum velocity was recorded as 0.2828 m/s in the middle of the tube which is shown by red lines. Here we can identify from the above figure that maximum velocity is present in the middle of the tube.



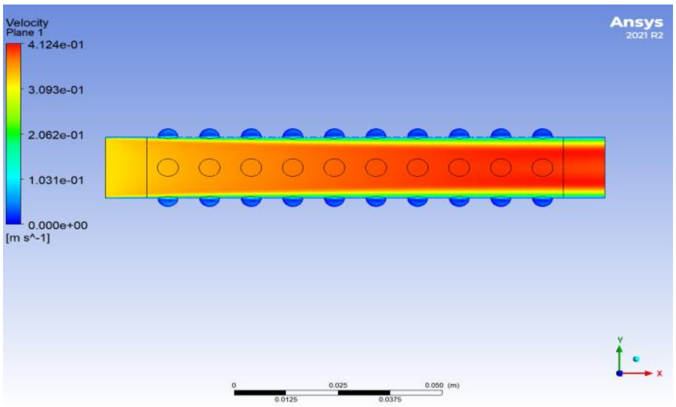
Following figure shows the temperature of the outward tube under Reynolds number 5000. The maximum temperature was recorded as 313.1 k and the minimum temperature is observed as 3.055k. The maximum temperature is indicated by the red colour and it is nearer to the walls of the tube and the minimum temperature is observed in the middle of the tube.



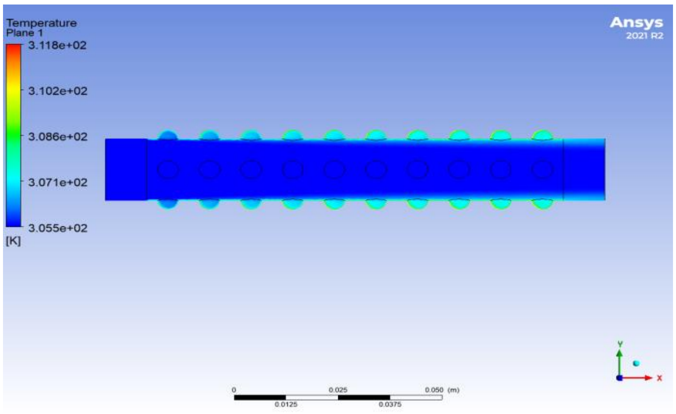
Following figure shows the outward tube's velocity streamlines during Reynolds number 7500. The maximum streamline is observed in the middle of the tube with a maximum velocity of 0.4124 m/s. The minimum streamlines are observed nearer to the walls of the inward tube in this case.



Following figure shows the velocity of the tube under Reynolds number 7500. The maximum velocity was recorded as 0.4124 m/s in the middle of the tube which is shown by red lines. The red color indicates the maximum value whereas the blue color indicates the lowest value. Here we can identify from the below figure that maximum velocity is present in the middle of the tube.



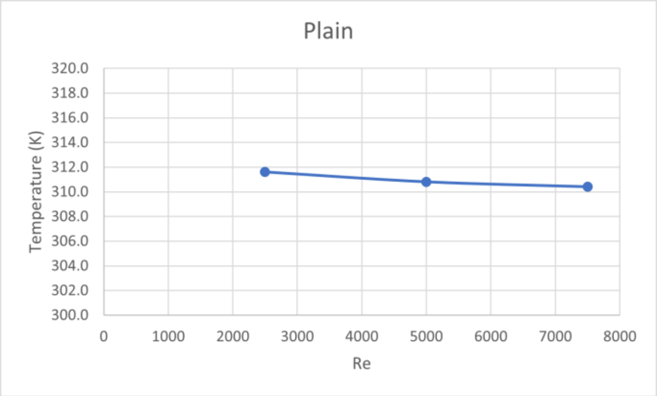
Following figure shows the temperature of the outward tube under Reynolds number 7500. The maximum temperature was recorded as 311.8 k and the minimum temperature is observed as 3.055 k. The maximum temperature is indicated by the red color and it is nearer to the walls of the tube and the minimum temperature is observed in the middle of the tube.



4. CONCLUSIONS

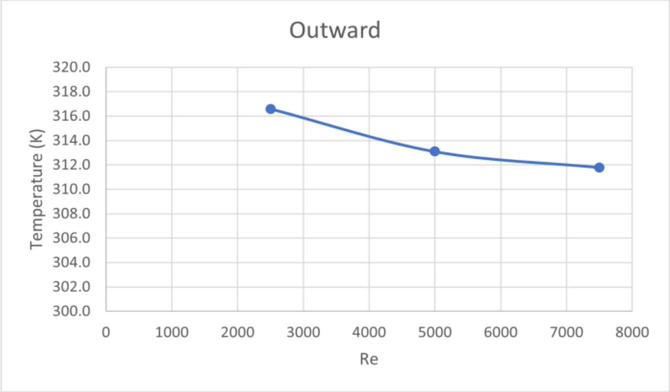
Reynolds number was varied from 2500 to 7500 for the working fluid is water. Numerical simulation was carried out using ANSYS Fluent 2021 R2 software. Major conclusions can be summarized as follows:

From following graph the Plain tube with Reynolds numbers 2500,5000 and 7500 has a temperature of 311.6 K,310.8 K and 310.4 K.when the level of turbulence increases the temperature decreases and heat transfer increases.

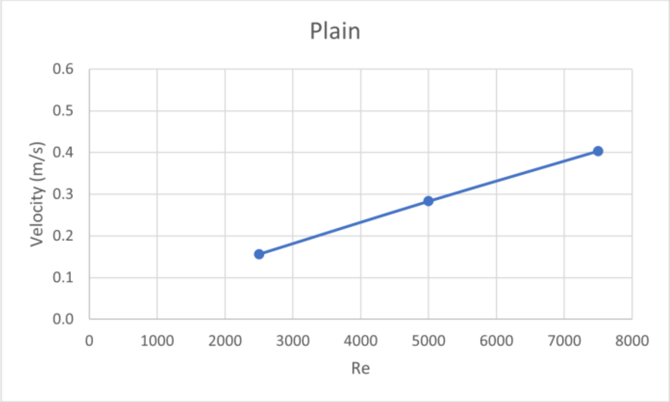


In the case of the Inward tube with Reynolds numbers, 2500,5000 and 7500 has a temperature of 313.2 K,309.8 K and 308.9 K as shown in following graph. The inward tube is better than the plain tube in heat transfer maximum temperature at laminar condition is 311.6 whereas in the inward laminar is 313.2 K.

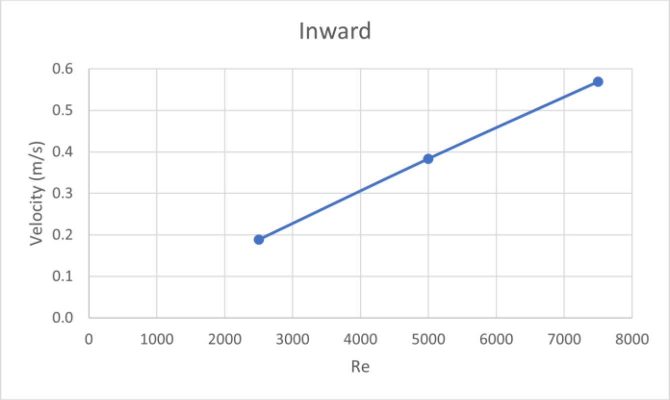
In the case of the outward tube with Reynolds numbers, 2500,5000 and 7500 has a temperature of 316.6 K,313.1 K and 311.8 K as shown in following graph. Outward dimple is better than the inward and plain tube in heat transfer. The interesting fact is that the minimum outward temperature is greater than the maximum temperature in case of pain number. The maximum temperature that can be attained in the plain tube is 311.6 K in the case of Re No. 2500 and at maximum turbulence, the temperature decreases but the temperature that an outward dimple can attain is 311.8 K in Re No. 7500.



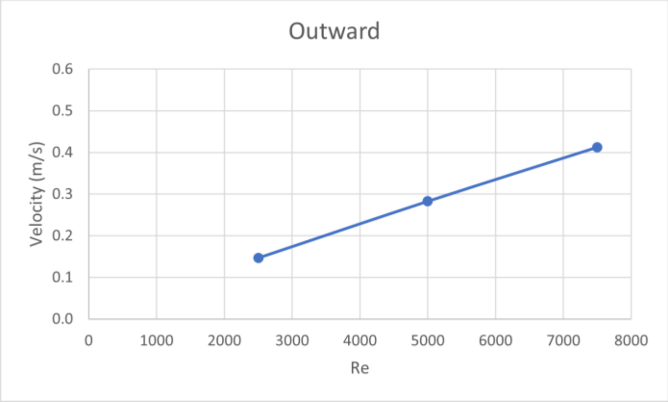
From following graph, the Plain tube with Reynolds numbers 2500,5000 and 7500 has a velocity of 0.1565 m/s,0.2833 m/s and 0.4035 m/s. At Reynolds, number 7500 inward tube has recorded a maximum velocity of 0.4035m/s.



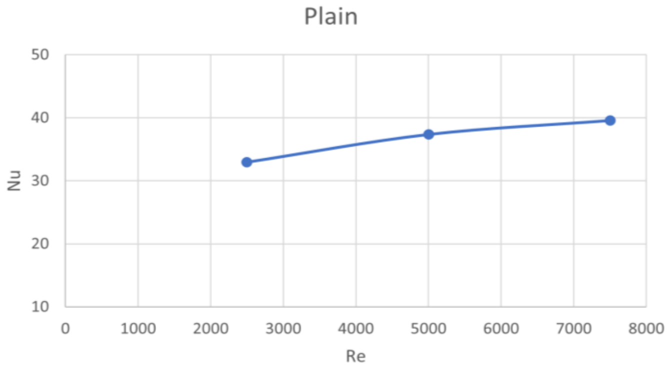
In the case of the inward tube shown in following graph, Reynolds number 2500,5000 and 7500 has a velocity of 0.1886 m/s,0.3835 m/s and 0.5688 m/s.



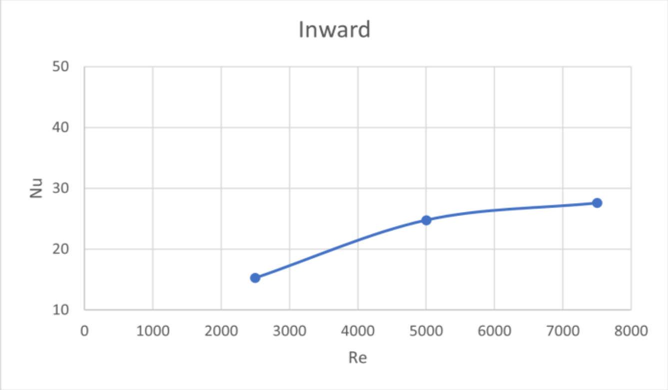
The inward tube has a maximum velocity than the plain tube in the maximum turbulence condition given. The outward tube with Reynolds numbers 2500,5000,7500 has a velocity of 0.1468 m/s, 0.2828 m/s,0.4124 m/s. The inward tube is more preferred when a greater flow is required than the outward tube. The velocity vs Reynolds number of the outward tube is plotted in following graph.



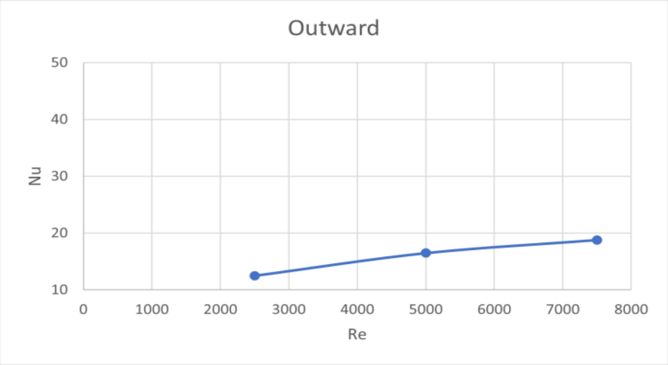
From following graph, the Plain tube with Reynolds numbers 2500,5000 and 7500 has a Nusselt number of 32.93551,37.34384,39.5638. The minimum Nu No. is recorded in the case of Re No. 2500 and the maximum is recorded in the case of 7500 which is 39.5638.



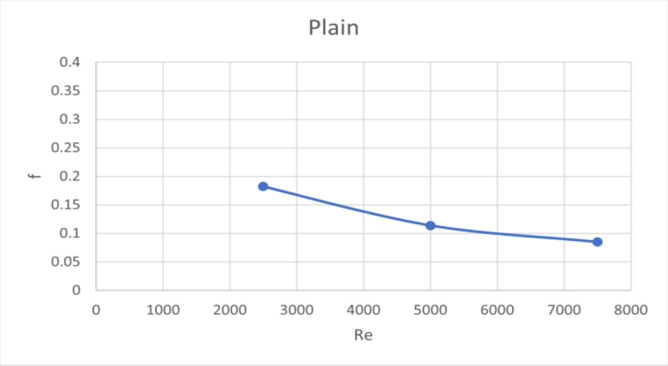
From following graph, the inward tube with Reynolds numbers 2500,5000 and 7500 has a Nusselt number of 15.29796,24.76617 and 27.57217. The minimum Nu No. is recorded in the case of Re No. 2500 as 15.29796 and the maximum is recorded in the case of 7500 which is 27.57217.



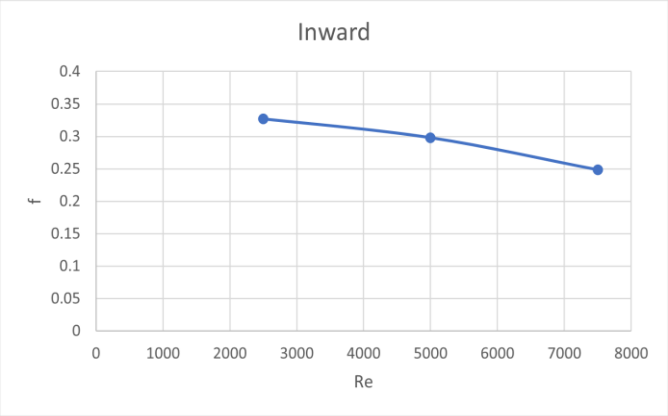
The outward tube with Reynolds numbers 2500,5000,7500 has a Nusselt number of 12.51034,16.48537,18.78393.The minimum Nu No. is recorded in the case of Re No. 2500 as 12.51034 and the maximum is recorded in the case of 7500 which is 18.78393.The Nusslet vs Reynolds number of the outward tube is plotted in following graph.



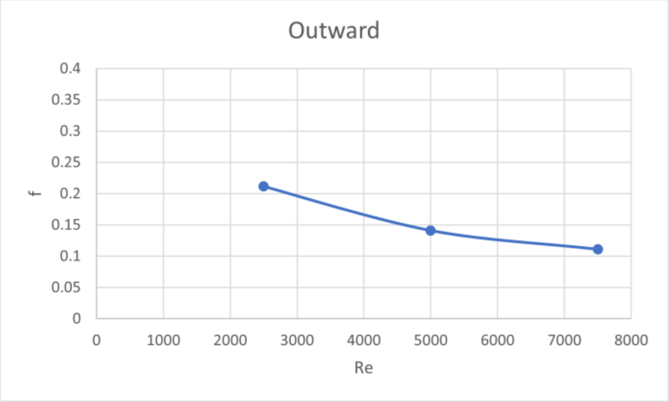
Following graph shows the friction factor for Plain is calculated and with Reynolds numbers 2500,5000 and 7500 the friction factor obtained are 0.18235,0.1138 and 0. 2487.The minimum friction factor obtained in the case of the Reynolds number 5000 is 0.1138 and the maximum friction factor obtained in the case of Re No. 2500 is 0.18235



Following graph shows the friction factor for inward is calculated and with Reynolds numbers 2500,5000 and 7500 the friction factor obtained are 0.32679,0.29798 and 0.2487. The minimum friction factor obtained in the case of Reynolds number 7500 is 0.2487 and the maximum is obtained in the case of Reynolds number 2500 as 0.32679.



Following graph shows the friction factor for outward is calculated and with Reynolds numbers 2500,5000 and 7500 the friction factor obtained are 0.211785,0.14112 and 0. 11114.The minimum friction factor obtained in the case of Reynolds number 7500 is 0.11114 and the maximum obtained in the case of Reynolds number 2500 is 0.21178.



5. FINDINGS

- The heat transfer coefficient increased with the increase in Reynolds number.
- Frictional factor decreases with an increase in Reynolds number.
- Introducing outward protruded dimples on the surface of the tube increases the heat transfer rate of inward and plain tubes.
- At the same time introducing dimples against the flow in the inward tube increase the velocity of flow.
- Heat transfer enhancement of outward dimple was found to be more than 163% as compared to an equivalent smooth tube.

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